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SOVIET ATOMIC ENERGY

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(ATOMNAYA ÉNERGIYA)

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SOVIET ATOMIC ENERGY

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July, 1978

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SIXTY YEARS OF SOVIET SCIENCE*

A. P. Aleksandrov†

Atomic Energy in the USSR

An enormous revolution took place in physics at the start of the 20th century — the special and general theories of relativity of Einstein appeared and the principle of mass — energy equivalence was established, and the quantum theory introduced by Planck appeared.

Rutherford showed in an investigation of the scattering of α particles by atoms that a positively charged nucleus exists in the atom and advanced the planetary theory of atomic structure, consisting of a positively charged nucleus and external electrons revolving around the nucleus. This theory was attractive but internally contradictory, since based on classical notions such an atom could not be stable. Bohr, who applied the quantum ideas of Planck to the planetary atom theory, introducing his own brilliant postulates, removed the contradictions and laid the foundation for the contemporary quantum theory of the atom.

Finally, in 1919 Rutherford, bombarding nitrogen atoms with α particles, produced nuclei of oxygen and hydrogen as the result of the first artificial nuclear reaction performed. This accomplishment essentially marked the beginning of a new direction in science — nuclear physics.

Much research has followed that of Rutherford, including work in the Soviet Union. His method of investigating nuclear transformations by means of bombarding nuclei with high-energy particles of natural origin and later artificially accelerated ones (evidently the first proposal in this direction was made by the Soviet scientist L. V. Mysovskii in 1922) has been widely applied right up to the present time.

The 1930 papers of W. Bothe and H. Becker, in which the production of penetrating radiation was detected upon the bombardment of light elements (e.g., beryllium) with α particles, are especially noteworthy. It was initially supposed that these were α rays; however, in 1932 J. Chadwick in England showed that they were uncharged particles with a mass equal to the mass of the proton. Thus, the neutron was discovered. The discovery of the neutron began a new age in nuclear physics; there appeared a new projectile which could not be repelled by the atomic nucleus, and its use promised completely new results.

The new situation in nuclear physics drew increased attention from Soviet scientists. The period of development of the science had not been passed — starting from 1932 the young I. V. Kurchatov, A. I. Alikhanov, and other scientists began to develop research in nuclear physics at the A. F. Ioffe Institute.

Research in the area of nuclear physics was being conducted still prior to this at the Radium Institute, where they attempted to realize the idea of Mysovskii on artificially accelerated particles, but technical limitations at the time did not allow them to do this.

The Kharkov Physicotechnical Institute (KPTI) was working in this direction. What was the state of readiness of Soviet scientists for research in the field of nuclear physics? This is evident, e.g., from the fact that the historic experiment of J. Cockcroft and E. Walton on the fission of lithium nuclei by protons, carried out in April 1932 in England, was repeated at Kharkov by K. D. Sinel'nikov and Kurchatov in October of the same year; it was necessary to create an accelerator in order to perform this experiment.

After a number of attempts at developing the idea of a cyclotron the large cyclotron of E. Lawrence at Berkeley (U.S.A.) with a diameter of 700 mm for the poles was started up in 1932. The first small cyclotron outside of Berkeley — at the Leningrad Physicotechnical Institute (LPTI) in Kurchatov's laboratory — was started up in 1933.

In 1932 a decision was adopted to create at the Radium Institute a cyclotron with poles 1 m in diameter. The cyclotron was started up in 1936. It was the first large cyclotron in Europe, and only in 1937 was the

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cyclotron chamber at Berkeley replaced by a new one with poles about 1 m in diameter. In 1933 construction was begun of the large LPTI cyclotron to upgrade the laboratory of I. V. Kurchatov and A. I. Alikhanov. It was almost finished before the war, but it proved possible to start it up only in 1946.

Electrostatic and cascade accelerators of various kinds were constructed at the KPTI and at the Leningrad Polytechnical Institute, i.e., a fundamental experimental basis was then created for research in the field of physics of the atomic nucleus. In addition to the physics of cosmic rays, the subjects of the interaction of radiation with matter also began to be developed at the P. N. Lebedev Institute of Physics of the Academy of Sciences of the USSR.

The biggest new event was the discovery by Irene and Frederick Joliot-Curie of artificial radioactivity. The work of E. Fermi on artificial radioactivity produced by neutrons slowed to thermal velocities opened up new paths suitable for experiment. The radium–beryllium sources of neutrons prepared at the Radium Institute, paraffin moderating units, and colleagues grabbing the irradiated targets and running headlong to the counting apparatus in the laboratory of Kurchatov and Alikhanov — it was possible to witness such a scene in the LPTI at that time.

Nuclear physics of the Soviet Union had emerged onto the level of world science. It began to bear fruit: more than 100 papers were published by Soviet scientists during the period 1932-1935; important discoveries were made. At the Lebedev Institute P. A. Cherenkov and S. I. Vavilov discovered the radiation which has received the name Cherenkov (Cerenkov) radiation. Its nature was explained by I. E. Tamm and I. M. Franck, who formulated a complete theory of this phenomenon. The discovery of Cerenkov radiation was later distinguished with the Nobel Prize. Kurchatov with his colleagues discovered nuclear isomerization, Alikhanov with his colleagues discovered the phenomenon of the ejection of electron — positron pairs by excited nuclei, and L. A. Artsimovich and Alikhanov proved conservation of momentum in connection with the annihilation of a positron with an electron, and so on. Our country became one of the leading nations in the field of nuclear physics.

Research was rapidly developed and moved to the leading edge in a number of other areas of physics in which periods of growth deserving attention appeared. Thus, e.g., P. L. Kapitsa discovered the superfluidity of helium, and L. D. Landau gave it a quantum interpretation. Fundamental or first developments were carried out in the Soviet Union in the fields of dielectric physics, semiconductor physics, luminescence, polymer physics, and electron diffraction and microscopy, and in many other directions. The directions named by me are only some examples and reflect the large contribution of research by Soviet scientists in the field of physics.

This fine position of Soviet physics was due to a large extent to the very high level of the research of Soviet theoreticians. Already in 1922 the Soviet theoretician A. A. Fridman (Friedmann) published the paper "On the curvature of space." In this paper Friedmann showed that Einstein permitted a certain arbitrariness when he sought a solution for the structure of space in a steady-state form. After discussion Einstein acknowledged that the Friedmann solution was "a correct one and sheds new light." The contemporary notion of an expanding universe was contained in the Friedmann solution, which was evaluated only following his death after the redshift of spectral lines had been discovered. Such scientists as V. A. Fock, Ya. I. Frenkel', and I. E. Tamm belonged to a small group of the leading theoretical physicists of the world. An uncommon possession of mathematical tools was characteristic of Fock. He approached a problem rigorously, introducing simplifications only where it was possible to prove their acceptability. Fock made an enormous contribution to the development of various aspects of quantum mechanics: he generalized Schrödinger's equations to the case of a magnetic field, derived the scalar relativistic equations (the Klein — Fock equation), proved together with M. Born the adiabatic theorem, worked out an exceptionally powerful method (the Hartree — Fock method) for the calculation of multielectron atomic and molecular systems, and developed the methods of quantum field theory, second quantization, and quantum electrodynamics.

He was very resourceful: he did a lot on relativity theory, the diffraction and propagation of radio waves, and even on logging theory.

The research of the remarkable theoretician Frenkel' had a completely different style. The basis of his activity was an unusual physical problem-solving ability. Frenkel' drew on mathematics mainly for approximate estimates; an exceedingly clear physical idea was always of paramount importance to him. His credo was: "It is not necessary to search for the old in the new, but it is necessary to find the new in the old."

Frenkel' brought an amazingly large number of new ideas into contemporary physics. He often advanced them in sketchy form, so to speak, and some of them were retained in science without any connection with his name, which would succeed in evaporating. He created the principles of the quantum theory of metals, which was developed further by F. Bloch and other authors. Frenkel' first treated the current in a metal as the propagation of electron waves, which can be scattered by lattice irregularities, including thermal fluctuations of the density. The principles of the contemporary physics of imperfect crystals were completely expounded by Frenkel'. The concepts of vacancies, displaced atoms, and exitons were introduced by Frenkel'. He was the first theoretician who decided to consider the physics of crystal impurities, and he was the first to introduce the idea of near and distant order in condensed media, and so on. He was responsible for the first model treatment of the atomic nucleus as a liquid drop. Frenkel' was the first to apply this model to the investigation of nuclear fission. These ideas were later developed by Bohr and J. Wheeler.

Tamm, who worked at the Lebedev Institute in Moscow, was a constant participant in seminars at the LPTI. His creative and unusual benevolent discussion of all research exerted an exceedingly stimulating effect on all physicists who associated with him, both theoreticians and experimentalists. His research on the scattering of γ rays by electrons based on the quantum theory of light scattering in matter and the relativistic quantum theory of light scattering by electrons significantly developed the physical ideas in these areas. His investigation touching on the nature of nuclear forces played a large role in the development of contemporary views in this area.

One cannot overestimate the role also of those great physicists of the older generation, to a portion of whom fell the honor and burden of organizing new scientific schools and the new Soviet physics. These were physicists such as A. F. Ioffe, L. I. Mandel'shtam, N. D. Papaleksi, G. S. Landsberg, P. N. Lebedev, P. P. Lazarev, P. L. Kapitsa, I. I. Lukirskii, V. K. Frederiks, D. A. Rozhanskii, S. I. Vavilov, D. S. Rozhdestvenskii, N. N. Semenov, and many others whose contribution to world science has been universally recognized. The schools which they created determine the state of the Soviet physics of our time. We must also count among them such remarkable physicists as L. D. Landau, I. Ya. Pomeranchuk, M. A. Leontovich, N. N. Bogolyubov, M. A. Markov, Ya. B. Zel'dovich, and many other theoreticians, and such experimental physicists as I. V. Kurchatov, L. A. Artsimovich, Yu. B. Khariton, P. P. Kobeko, A. M. Prokhorov, N. G. Basov, and many, many others.

Approximately the same process took place in other areas of science.

We see in the example of physics that the system of science development created in the Soviet Union after October and the system of training personnel and of education generally resulted in the advancement of our science to the leading edge of world science. Any scientific problems are now within the power of our country.

We will continue our discussion of this example, since the development of nuclear physics soon acquired a vitally important meaning for the judgement of our Fatherland.

Intensive research on the physics of the atomic nucleus was continued in numerous laboratories of the world. The discovery of new isotopes produced as the result of radioactive decay, the transmutation of certain chemical elements to others, and the discovery of new types of nuclear reactions followed one after the other. The ideas of the transformation of elements under the action of neutrons began to acquire universal recognition.

It is interesting that the great Austrian physicist L. Szilard described a hypothetical reactor with a chain reaction by neutrons and introduced the concept of the critical mass and an estimate of it five years prior to the discovery of uranium fission and before the start of the research of Fermi on the irradiation of various elements by neutrons. He suggested using irradiation by neutrons in this reactor to produce the isotopes of all the elements. This was the claim, and its publication occurred in 1932.

Already in the middle of the 1930s Joliot advanced the assumption in his Nobel speech that the energy of the atomic nucleus would be used by mankind. Events ripened. At the end of 1938 O. Hahn and F. Strassmann in Germany proved that an isotope of barium is produced upon the action of neutrons on uranium. This was published at the start of January 1939. Two colleagues of N. Bohr — O. Frisch and L. Meitner — advanced the hypothesis that upon the capture of a neutron the uranium nucleus sometimes splits into two parts similar in mass. If this is so, then the isotopes produced should be neutron-rich, and a process of the fission of the uranium nucleus should be accompanied by the production of several neutrons. And this indicated that the organization of a chain reaction of the fission of uranium by neutrons is conceivable. There followed literally an explosion of papers on the investigation of fission. Already in the middle of January 1939 American, Danish, and French papers in this field were published, and by the end of 1939 about one hundred papers, including a number of Soviet ones, had already been published. It became clear towards the middle of 1939 that an enormous energy is released by the fission of a nucleus, that the fission is actually accompanied by the emission of 2-3 neutrons, and that a chain reaction can be arranged both with slow and with fast neutrons.

Already at this time the cross sections of fission by fast and thermal neutrons were being refined, and Zel'dovich and Khariton made correct estimates of the conditions for a fission chain reaction to arise. Soon G. N. Flerov and K. A. Petrzhak at the laboratory of Kurchatov discovered the spontaneous fission of uranium.

Towards the end of 1940 Kurchatov and Khariton developed a detailed plan of research for the accomplishment of a fission chain reaction with the suggestion to construct a device for the realization of a nuclear chain reaction, i.e., a nuclear reactor. One might expect that with a good neutron modulator a nuclear reactor based on natural uranium is possible. The construction of such a device was of doubly important significance. In the first place, approaching the "critical conditions" gradually by increasing the amount of uranium, it was possible to count on the possibility of a detailed investigation of the factors affecting the development of a chain reaction and on the fact that it would be possible to control it, since according to theory the chain reaction should develop or die down very slowly near the critical mass (the fact that delayed neutrons exist in connection with the fission reaction, significantly facilitating the problem of regulation, was not known at that time). In the second place, it was known at that time from a published paper of the Americans E. McMillan and P. Abelson that the element with atomic number 93 is produced from the isotope ^{238}U upon its capture of a neutron. This element was, according to McMillan, β radioactive with a half-life of 2.33 days. This was the first discovery of an artificial transuranic element. Finally, after β decay the element 93 should have been transformed into the element with atomic number 94. McMillan and Abelson did not notice the radioactivity of element 94, i.e., it was possible to assume that an element (stable or weakly radioactive, long-lived) with atomic number 94 and atomic weight 239 will gradually accumulate in a nuclear reactor due to the capture of part of the neutrons of ^{238}U. It later received the name of plutonium.

This element should have been chemically different from uranium due to the different charge of its nucleus, thanks to which it was possible to count on its chemical separation. One could assume that this element would turn out to be fissionable both by slow and fast neutrons, so that it, just as ^{235}U, was of parity. All of these were only assumptions, and it was necessary to check them.

It should be said that the possibility of the realization of a reactor based on slow neutrons with natural uranium, although very tempting, did not seem very sound, since it relied on calculations at the very limit.

Nuclear constants were known at that time with very poor accuracy, and the positive answer obtained in the calculations was devoid of any margin for error, i.e., extremely unreliable. It was undoubtedly possible to accomplish reliably a chain reaction by using uranium in which the ^{235}U content would be enhanced with respect to natural uranium. However, the process of separation of the isotopes of uranium seemed possible but very expensive and complicated from an engineering point of view.

Kurchatov wrote a lecture in which he outlined the possible military and industrial value of the problem of obtaining the energy of uranium fission, and he delivered it at the end of 1940 to the Presidium of the Academy of Sciences of the USSR. In this lecture Kurchatov suggested putting before the government the question of assigning means to the uranium problem in connection with its exceptional significance. In November 1940 the uranium problem was discussed openly for the last time during this period at the All-Union Conference on the Atomic Nucleus.

At this time a "strange," and later real, war was going on against Hitlerian Germany already for 1 year. Many great physicists from countries where fascism was approved fled to England and the U.S.A. It seemed natural that scientific publications were reduced in the European scientific journals — this was the result of the war. But all publications on fission, and later on isotope separation, began to be reduced in the American journals in 1939 and finally disappeared in 1940. It was impossible to think that this was simply a general curtailment of scientific activity, since scientific papers in other areas were published on their previous scales. The authors who had worked earlier in the field of nuclear physics disappeared not only from the pages of the scientific journals — they also did not teach, and they did not give lectures. An unprecedented situation became clear: an entire prominent division of science had evidently been made secret, possibly in connection with its exceptional military significance.

Actually, it is now known that in 1939 a group of scientists in the U.S.A. headed by Szilard, fearing that scientific research on nuclear physics would help Nazi Germany produce an atomic weapon, agreed on his initiative to curtail publications. They appealed to President Roosevelt through Einstein and communicated to him concerning the possibility of a nuclear weapon and the fact that Nazi Germany was probably working on its realization, and they posed the question of the development of this research in the U.S.A. And this research was expanded in large scale and under conditions of complete secrecy in specially created secret centers. The scientists who had emigrated from fascist countries and the scientists of England and the U.S.A. began working on the creation of the atomic bomb.

It was also obvious that research on a nuclear weapon was being conducted in Germany. All of this caused great anxiety for the Soviet physicists. N. N. Semenov also appealed to government agencies with the suggestion of expanding research on the atomic problem. However, soon Germany attacked the Soviet Union, and a most brutal war began. The main nuclear laboratories ceased operation — the evacuation of the Leningrad, Kharkov, and Moscow scientific institutions began.

A significant portion of the scientists were in the army or were switched to research on military tasks. In particular, Kurchatov and a large portion of the staff of his laboratory were engaged in research on antimine protection of ships, which was conducted at the laboratory of the author.

Development of the Uranium Problem during the War and during the Postwar Period

At this time there repeatedly arose the question: should not research on the uranium problem be revived? Flerov, who served in the army, appealed to Ioffe, and then he sent a letter to Kurchatov with an urgent request not to postpone further the development of this research. He appealed with such a letter in the summer of 1942 to the State Defense Committee, and soon he was summoned to Moscow for a lecture. It is obvious that some information about research in Germany had also been obtained by our government.

And here at the most difficult period of the war in the fall of 1942 Kurchatov was summoned to Moscow, and the first discussion occurred of the advisability of the development of research on the uranium problem. M. G. Pervukhin and S. V. Kaftanov, whom the government had assigned to discuss this problem with competent individuals from among the scientists, arrived at the conviction that the research should begin.

They began to recall scientists from the army and from military research of different purpose, from blockaded Leningrad and from the evacuation, and they sent them to the disposition of Kurchatov, who was designated the scientific director of the problem. Nuclear research began gradually to redevelop at Kazan, where the LPTI was located in the evacuation. At this time the battle of Stalingrad began, and the country turned all its attention to it. Finally, a colossal victory was established, which everyone perceived as a victory predetermining the outcome of the war and which marked the turning point in it.

The situation improved in the country. The withdrawal of our forces ceased, and the need of further evacuation passed. Industry which had been relocated in the east was now operating at full speed, and artillery, tanks, and airplanes flowed to the front in a steady stream. Confident systematic preparation for total victory was carried out.

The development of the machines intended for production after the end of the war gradually got underway in the construction departments of industry. But more and more often threats of the use of a "superweapon" reached our ears from Germany. It was known that Germany was attempting to take supplies of heavy water out of Norway and that this convoy was blown up by the English.

It was impossible not to adopt countermeasures. On the instructions of the Central Committee of the Party Kurchatov organized in Moscow at the start of 1943 a new scientific institution intended for the solution of the uranium problem. The research was broad-based, and there even appeared the possibility of continuing research on cosmic rays; the Alikhanov brothers organized a mountain expedition into Armenia to Alagez.

The main directions of the research were determined to a significant extent still as before the war, but now everything became broader and more specific.

The Central Committee of the Party demanded the expansion of research on a broader front. It was necessary to duplicate the principal research for confidence in the results.

It was necessary to realize a chain reaction with natural uranium as far as possible. It was first of all necessary to improve the theory of the reactor.

Then the young theoreticians I. Ya. Pomeranchuk and I. I. Gurevich with the assistance of Ya. B. Zel'dovich, who developed the theory of neutron moderation, also investigated while working out the reactor theory the problem of the effect of the position of the uranium in the moderator on the neutron multiplication, which appeared decisive for reactors based on natural uranium. It was already known earlier from research on artificial radioactivity that distributed and concentrated targets behave differently and that the absorption cross section is less in thick targets.

It seemed that in the case of a reactor a uniform arrangement of uranium in the modulator and an arrangement in the form of separate massive blocks separated by pure modulator differed significantly, with the block arrangement giving a significant advantage in the neutron multiplication coefficient. Calculations made with the block-effect taken into account, whose significance was quickly confirmed experimentally by G. N. Flerov, V. A. Davidenko, and I. S. Panasyuk, showed that a reactor with natural uranium and graphite could be built with a sufficiently high purity of the graphite. The calculations provided the parameters of the optimal lattice of reactors, i.e., the basis for their construction.

A plan was entirely clear with regard to the problem, but it was incredibly difficult, especially under wartime conditions, to begin intensified searches for uranium deposits and to organize the mining, to develop a technology for its extraction suitable for large-scale operations, and to work out the metallurgy of uranium, refining methods, and methods of analysis unprecedented with respect to accuracy.

In addition to uranium, a moderator was necessary. This could be heavy water or graphite. But the calculations were incomplete, and a reactor using graphite was likely not to work, especially if the graphite were not very pure. This meant that it was necessary to organize the production of heavy water and to find cheaper technology for its production and methods of analysis in addition to the well-known electrolysis method. Perhaps somewhere in nature conditions were produced under which the natural water contains more deuterium?

It was necessary to organize expeditions and to examine the water of various isolated reservoirs.

The electrode graphite produced by industry was insufficiently pure. It was necessary to develop a new technology and produce the purest graphite. And again analysis methods were needed which permit detecting neutron-absorbing impurities in trace amounts. Academicians A. P. Vinogradov and I. I. Chernyaev successfully directed the creation of unique new methods of analysis, and a group under the direction of Academician A. A. Bochvar and Corresponding Member of the Academy of Sciences of the USSR R. S. Ambartsumyan were occupied with problems of metallic materials.

Many engineers, scientists, and technologists worked on the solution of these problems. On the part of the Institute of Atomic Energy supervision of the graphite research was placed on N. F. Pravdyuk and V. V. Goncharov.

Finally, it was necessary to coat the uranium with a weakly absorbing envelope — it was necessary to work out the material, the coating technology, and the technology for the control of these manufactured articles, as well as to develop a material, the technology for its preparation, and the technology for control of pipes to organize cooling of the uranium in the reactor.

The second major direction was the separation of the isotopes of uranium. Here also several possibilities occurred: the electromagnetic separation method, the diffusion method, the centrifuge method, the thermal diffusion method, and various alternatives of them. All of these methods were exceedingly expensive and cumbersome; however, research was organized in all these areas.

Finally, the third direction was the development of an intrinsically nuclear weapon — the methods of creating the needed large supercriticality. The possibilities of using systems with a moderator and the possibilities of systems based on fast neutrons without a moderator were investigated for this purpose. The principles of the calculation of such systems had been created just before the war.

Scientists and engineers of the most diverse specialties were drawn on for the solution of these essential problems. In addition to the specially created prominent scientific institutions in Moscow, Kharkov, and other places, individual areas of the research were assigned to practically all physics, physical chemistry, and chemistry institutes and to numerous institutes of industry. Industry was widely included in the research: machine construction, chemical, nonferrous and ferrous metallurgical, aviation, and other branches of industry. The construction departments, which had been designing tanks, airplanes, and other forms of armament not long before, busied themselves with the new unprecedented work. The requirements put forward by the scientists often seemed unattainable, but they were carried out all the same. The supervisors and participants in all these efforts made an enormous invaluable contribution to the solution of the most difficult problem of mastering atomic energy [I was unable to cite in this section the family names of many scientists who played a large role in the solution of the problem, nor even the family names of the supervisors of important activities. Therefore, I restricted myself in general to a very small number of family names in order to avoid giving false impressions.]

The applied subjects enumerated above could not have been carried out on the proper level without basic research in nuclear physics: investigation of nuclear cross sections, development of the theory of the nucleus, investigation of numerous nuclear reactions, and numerous exploratory researches in areas bordering on the atomic "problem." Solid-state physics, especially the behavior of matter at ultrahigh pressures and in ultrahigh magnetic fields, the behavior of matter under the action of radiation and other areas, metal physics, radiochemistry, gasdynamics and explosion theory, mechanics, biology, genetics, and methods of analysis, including mass spectrometry, were substantially developed in a short time. New kinds of equipment and new materials were created in a short time; a cyclotron was constructed in a year altogether, and all of this took place while the war, approaching the great victory, was still going on.

Finally came May 1945, and with it the greatest victory. Nazi Germany did not have time and was unable to develop a nuclear superweapon. It would appear that the acuteness of the problem diminished.

But right after the victory information arrived about tests of an atomic bomb in the U.S.A. and about its horrible destructive power. And right after this there followed the explosions at Hiroshima and Nagasaki, which disposed of hundreds of thousands of lives among the civilian population at a time when victory in the war with Japan was already predetermined without atomic explosions.

Why was this completely unjustified massive slaughter carried out? The purpose could only be the single one of showing the world that the U.S.A. would not hesitate to use a nuclear weapon for the attainment of its own political goals. These political goals were made clearer and clearer with each succeeding day. A monopoly in atomic power would, it seemed, give the U.S.A. enormous advantages and the American aggressive circles began to develop ideas of a preventive war against the Soviet Union, and one could have expected any military and political adventures.

Immediately after the capitulation of Japan the psychological preparation got underway in the United States for a new war, a war against the Soviet Union. The speech of Churchill at Fulton and the start of the organization of U.S.A. military bases around the Soviet Union were supplemented by the open discussion in the press of the U.S.A. of how the atomic war against the Soviet Union should be organized. Diagrams were presented in which the tracks of American nuclear bombers aimed at Moscow and other large cities were shown by arrows, and the possible costs for an atomic attack, which, it was suggested, should be organized prior to when the Soviet Union solved the problem of producing an atomic bomb, were cynically estimated.

It became evident that it was necessary to destroy the monopoly on nuclear weapons before the United States developed the production of such weapons on a scale which would represent a real threat to our country. This realization was the main driving force for further development of the research. The Central Committee of the Party and the Government continually and broadly supported research on the "atomic problem" and rendered all the help needed.

Kurchatov and the great institute organized by him (now the I. V. Kurchatov Institute of Atomic Energy) fulfilled the first of the tasks imposed on him and produced a uranium — graphite reactor.

In Dec. 1946 a chain reaction was accomplished by Kurchatov and his colleagues in the first reactor in Europe, and in 1948 the first industrial uranium — graphite reactor was started up. The starting up of these reactors and the production in the first of them of negligible microgram amounts of plutonium and in the second of industrial amounts was the culmination of the enormous efforts of geologists, mining engineers, metallurgists and metallographers, chemists and radiochemists, nonferrous metal specialists, graphite specialists, designers, and, of course, physicists — experimentalists and theoreticians.

The organized work in the development of the uranium problem played an enormous role, and it was successfully solved by a specially created government agency under the direction of B. L. Vannikov.

Kurchatov as the scientific director of the problem determined together with Vannikov and the other supervisors the next tasks, and an undertaking of enormous size grew at rates previously unknown. The Americans assumed that the second way of solving the atomic problem, isotope separation, was generally unattainable for Soviet industry. However, an experimental factory was operating in the USSR already in 1947. Alikhanov, who had developed the approach of heavy-water reactors earlier at the Institute of Atomic Energy, and then in a special institute created by him which has now received the name of Institute of Theoretical and

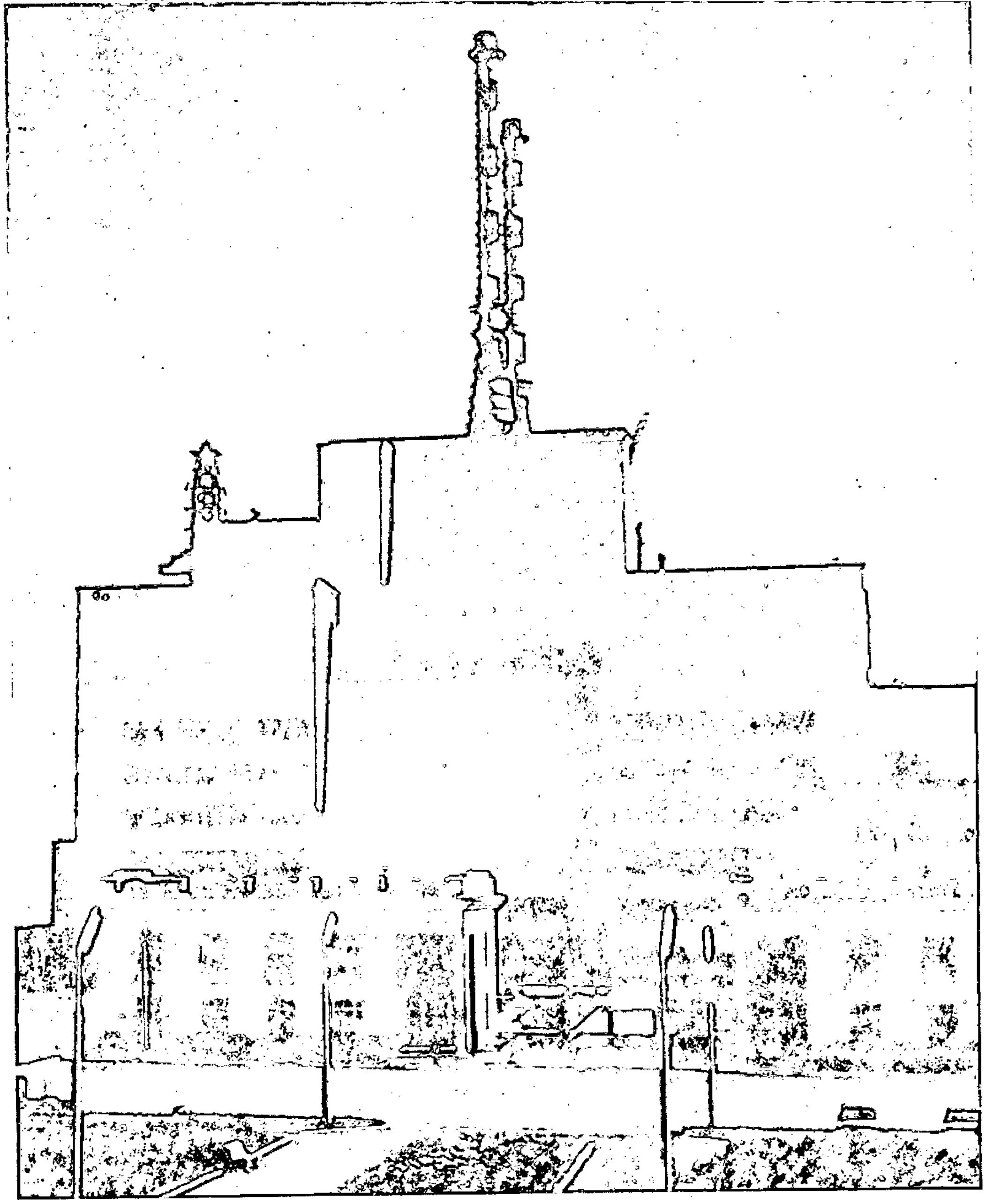

Fig. 1. Beloyarskaya I. V. Kurchatov atomic electric power station.

Experimental Physics, also achieved success. The organizations drawn into the development of heavy water set up this factory; a heavy-water experimental reactor successfully began to operate, and the first industrial heavy-water reactor was created. The radiochemists successfully developed the technology of plutonium using ≈20 μg of it produced by the manual uranium — graphite reactor. On the basis of their research, a plant for the radiochemical extraction of plutonium from irradiated uranium was built which began producing plutonium at the start of 1949. The majority of the physical measurements, further metallographic investigations, numerous simulated explosion experiments which permitted finding the optimal means of producing supercriticality, and finally the most detailed theoretical calculations which permitted finding the various principles of producing nuclear charges preceded the first test.

And then we come to Aug. 29, 1949, when the successful test of an atomic bomb carried out under the direction of Kurchatov (as the scientific director of the problem) shocked the whole world. The Americans assumed that a nuclear weapon would not be produced in the USSR prior to 1954, and the supporters of a preventive war in the U.S.A. appealed for it to be unleashed before 1954, i.e., prior to the instant at which one could expect the creation of a "Soviet atomic bomb."

The creation of atomic bombs continuously increasing in power, the development of explosion theory, and the detailed investigation of phenomena arising during an explosion made it possible to justify the idea of a thermonuclear weapon. The theoreticians who suggested the idea of a thermonuclear bomb did not see any fundamental limits to its power. The fusion bomb could be far more powerful than the fission bomb.

In order to create it, it was necessary to solve a number of complex technical problems: in particular, it was necessary for some types of this weapon to develop methods for producing tritium and the light isotope of lithium — ^{6}Li. The cumulative experience of solving large applied problems allowed carrying out these processes on an industrial scale in a comparatively short time. The most complex research was concluded, and on Aug. 12, 1953, a test of this monstrous superbomb was performed under the direction of Kurchatov. .

Nuclear Power

Right now the development of nuclear power marks the next stage of growth in our country.

Already in 1948 ideas for the development of atomic power arose upon the solution of the uranium problem. Back then this idea encountered at best a smile. It was assumed that this was an "amusement" of the scientists which would never be of practical significance.

Developments of channel uranium — graphite reactors for atomic electric power stations with water and helium cooling, respectively, were being carried out at the Institute of Atomic Energy and at the Institute of Physical Problems. The reactor with water cooling was selected for further development, and the first atomic power station was designed by chief designer Academician N. A. Dollezhal'. It was constructed and put into service in 1954 at the FÉI in Obninsk. Although the power of the station was only 5000 kW in all, it proved itself as a reliable source of electricity. A series of atomic power stations of continuously increasing power was developed and constructed.

Right now many atomic power stations are constructed in our country and overseas based on our designs.

Of course, the use of atomic power not only for the production of electrical energy but also in other areas of consumption of organic energy resources is important for the conservation of organic fuel. The immediate areas are the production of heat for heating cities and the production of heat, electricity, and regenerators for the metallurgical industry. Large-scale research is going in this direction.

Of course, all of this is meaningful only when one considers the inclusion in power generation of fast breeder reactors with a short nuclear fuel breeding time. Only in this case can the nuclear fuel reserves provide the needs of mankind for many centuries. The widespread development of atomic power brings with it many complex problems, such as, e.g., the lengthy and dangerous storage of radioactive wastes. However, these problems are solvable, although difficult in the engineering sense. Atomic power is a very timely gift of science to mankind and a supreme blessing, and it would be senseless to use this blessing for the destruction of mankind.

Along with the development of the atomic power of fission of heavy nuclei, research is going on now on the atomic power of nuclear fusion and thermonuclear power having practically inexhaustible resources. This is one of the most difficult scientific problems; however, it is being successfully developed. The mastering of the energy of controlled thermonuclear fusion will fundamentally solve the problem of the long-term development of human society on the earth.

THE BIRTH OF NUCLEAR POWER

N. A. Dollezhal'

UDC 621.039

> Every beginning is difficult — this truth holds for every science.
>
> K. Marx

In our time, nuclear power has become an ordinary concept and there is no question about the need for its development. In the USSR, as in many other countries, long-range plans are being elaborated for its development, studies aimed at the improvement of the technical methods used are continually being made, and both traditional and new basic and engineering–scientific disciplines are being developed. However, it is not out of place to recall that the first nuclear power station in the world providing current to a commercial grid was constructed in the Soviet Union and that I. V. Kurchatov was the initiator and director of its construction. Under the direction of Kurchatov, the author of these lines was fortunate enough to be at the head of the majority of engineering and structural developments from the very first days of nuclear technology. Since many of them found application in subsequent accomplishments, these recollections, which are associated with them, may be of interest.

My acquaintance with Kurchatov goes back to the end of 1945 and the beginning of 1946. At that time, I was the head of the Scientific-Research Institute for Chemical Machinery Construction and apparently for that reason Kurchatov decided to bring me in as the chief designer of a large reactor for achieving a self-sustaining chain reaction through fission of uranium nuclei. There was no one with any experience in this field in the USSR at that time, but probably he guessed that the field of chemical machinery construction was the closest. Kurchatov said in jest that the only difference was that the reaction would proceed, so to speak, not on a molecular level as occurs in chemical production, but on a nuclear level.

The first task in the development of a commercial nuclear reactor was set by I. V. Kurchatov in January, 1946. However, the very first studies showed that its realization was bound up with the need to overcome very complex computational and technical difficulties. In Mar. 1946, the task was reviewed, a draft plan approved, and the development of a technical plan was begun. By this time, many outstanding specialists of our country were attracted to the solution of the completely new problem, and the outstanding talent of Kurchatov for interesting people in the work and for arousing their enthusiasm about its prospects played its part in this.

The technical design for the reactor was reviewed by a commission of eminent specialists and construction was begun in Aug. 1946. Yet another quality of Kurchatov became apparent in this. You see, the start-up of the zero-power experimental F-1 reactor had not yet been accomplished (it was started up only in Dec. 1946). Therefore, Kurchatov based his reliance on the correctness of the decisions made on a large number of intermediate local studies intensively carried out under his direction through an extensive program in various institutes and in factories. To some extent, this can also explain the success which attended the start-up of the experimental reactor [1].

It can be shown that such a means for solving a completely new problem, in both scientific and engineering aspects, has its risks. There is no doubt, however, that the main thing which Kurchatov did not question was the need not "to delay," to solve the problem as quickly as possible. Later we all understood that it was necessary to act in such a way because mankind was in an uneasy state at that time because of the tragic consequences of the nuclear explosions above the Japanese cities of Hiroshima and Nagasaki. Concern was aroused by the one-sidedness of the ownership of this type of weapon. It is noteworthy that such a method for the solution of complex new problems became a part of practice and even now we do not see how it could have been done otherwise.

The first commercial reactor, as is well known, was started up in 1948 [1]. It was for technical purposes and no provisions were made for use of the heat created by the fission of uranium nuclei. However, the means for realization of such a possibility under various circumstances were discussed throughout the period

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of reactor construction. Specific forms were accepted at the end of 1949 when ideas had matured about the construction of an experimental device which would demonstrate the possibility of using heat from fission for the production of electrical power. After preliminary discussions of a number of suggestions, the decision was made to construct an experimental nuclear power station with an output of 5000 kW (electrical) in conjunction with a turbine of that output which was available at that time. Of course, the steam parameters which would be developed by means of the reactor were determined by the turbine characteristics.

Several basic requirements were formulated which had to be satisfied by the reactor: the possibility of using for its construction knowledge already obtained about the performance of nuclear-physics reactor calculations, and this meant that the reactor must operate with thermal neutrons; the neutron moderator had to be graphite and the coolant ordinary water. Measures had to be taken to eliminate the consequences associated with the entrance of uranium or its fission products into the coolant, which meant a tubular fuel element. These and many other requirements were aimed at eliminating the possibility of producing any sort of trouble during reactor operation, because that would inevitably compromise the idea of peaceful use of nuclear energy and, it seemed to me, Kurchatov considered that unacceptable. This could explain the exceptional attention he devoted to all the leading problems that arose during the construction of the reactor and nuclear power station.

The events connected with the construction of the First Nuclear Power Station (and so it appears in international listings) have been described in detail [2]. Its role as the first-born of nuclear power and that of Kurchatov as father were universally recognized; its importance for future development of power reactors will never be downgraded just as the importance of the work of Mozhaiskii in the development of aviation and the outstanding work of Tsiolkovskii in rocket technology will never be forgotten.

The study of the possibilities of peaceful use of the heat from nuclear reactors was not limited to stationary power alone. Shortly after the decision was made to construct the Obninsk Nuclear Power Station, a search was begun for possible ways to use this form of energy in ship construction. The vigorous measures undertaken in this field by Kurchatov, as is well known, led to the construction in 1957 of the icebreaker Lenin with a nuclear power plant by means of which extremely important problems for our country were solved that had to do with prolongation of the period of Arctic navigation and with the possibility of piloting ships under heavy ice conditions.

The First Nuclear Power Station was started up in 1954. But even before that, Kurchatov continually raised the question of the need for development of more powerful plants. His faith in the future of nuclear power was evidently so great that he unhesitatingly approved a suggestion to include draft studies of a nuclear power station with a capacity of 100 MW in a report on the operation of the First Nuclear Power Station presented at the First Geneva Conference (1955) [3]. This produced a vigorous positive response from conference participants. At this time, that number caused smiles, but at that time it was a daring challenge to those who were inclined to be skeptical about the possible use of uranium for peaceful power. There were many of such a mind even among very respected specialists.

As is well known, stainless steel was used in the tubular construction of the fuel elements in the First Nuclear Power Station; this is a material that is not very favorable from the viewpoint of efficient use of neutrons, and therefore of uranium. A search was then undertaken which was directed toward the construction of a power reactor using materials with favorable properties. A thorough analysis of possible solutions led to the creation of the reactor which served as the basis for the construction of the Sibirsk Nuclear Power Station with a capacity of 600 MW (electrical). A film of such a reactor was shown to the participants at the Second Geneva Conference in Aug. 1958 [4]. The reactor was designed and constructed in an exceptionally short time and one cannot help but see the talents of Kurchatov in this. At the present time, science is enriched by knowledge in many fields such as the radiation resistance of structural materials, the behavior of uranium at various temperatures and in various nuclear-physics conditions, the production of corrosion effects, etc. At that time, this knowledge was only being developed and decisions had to be made at times only on the basis of initial experimental data with the addition of scientifically valid foresight. However, it was necessary to act in this way because there was no other way to gain the desired time.

The steam parameters developed by the reactors at the Sibirsk Nuclear Power Station were not high. This was determined by the temperature allowed by the materials used. The undisputed tendency of power engineers always was toward a possible increase in plant efficiency, which is particularly related to a rise in the initial temperature of the coolant. It was necessary to find a reactor design which would make it possible to achieve the required superheating of the steam. After a large number of studies and experiments, such a solution was found — reactors with nuclear (i.e., within the reactor) superheating of steam designed in 1956 and constructed by 1963 for the Beloyarsk Nuclear Power Station that now bears the name of I. V. Kurchatov. The reactors of this nuclear power station produce steam at a pressure of 90 kgf/cm^2 and a temperature of 510°C. In this sense, they are unique even in world technology [5].

Among the many problems which continually attracted the attention of Kurchatov were those involved with the organization of methods which would make it possible to perform scientific and engineering studies on a broad scale directed toward the development of nuclear engineering. Since the possibility of evaluating results obtained in this way was usually directly dependent on the intensity of neutron fluxes with which the experiments were performed, the construction of a research reactor with a high neutron flux was necessary. A design was produced in 1956 and by 1961 the special materials-testing SM-2 reactor was constructed in which the neutron flux density in the test cells was $5 \cdot 10^{15}$ $neutrons/cm^2 \cdot sec$. This value was not exceeded in any country during the course of the next few years. The boldness of the basic scheme and the original structural solution for the reactor are cause for admiration even today. This reactor is faithfully serving science even now [6].

Even while building the SM-2 reactor, Kurchatov had the idea of producing even higher neutron flux densities, possibly in a pulsed mode. Thus, a reactor was created which was first called DOUD-3 and then IGR. I remember Kurchatov called me in January, 1958 and asked me to come over to discuss an important question. The question was the construction of a reactor which would consist of two graphite piles with the required amount of uranium that, when brought together, would create criticality conditions for the occurrence of a fission reaction, that would develop high neutron flux densities at required locations, and that would be shut down by appropriate control methods in order to stay below permissible temperature limits. Several structural hypotheses were discussed and the necessary engineering experiments performed; as a result of all this, the reactor, despite its completely unusual structural arrangement, was approved for construction (the reactor was started up in 1961). Important scientific and engineering problems are being solved with its help at the present time [7].

However, Kurchatov did not consider all this sufficient. Possessing an outstanding capability for foreseeing technical development far into the future, before long (1958) he advanced the idea of constructing a powerful materials-testing research reactor (MIR) with a large number of ports with high neutron fluxes for experimental work [8]. The main thing that concerned Kurchatov was the need for testing fuel-element construction before installation in a reactor. This can be done in a large number of special experimental loops provided in the MIR structure (the reactor was started up in 1966). It must be recognized that it is quite likely that for several years afterwards (indeed, even till today) everything related to the creation of nuclear reactors owes a great deal to the farsightedness and correctness of the measures taken by Kurchatov in the development of experimental work in nuclear engineering.

Unfortunately, Kurchatov did not get to see and actually become aware of the great fruitfulness of the measures he took directed toward the development of nuclear science and technology in our country. We learned to construct powerful reactors for nuclear power stations and we have available original types of power reactors created completely out of his own independent and profound understanding of the physical, engineering, and economic aspects of nuclear power. The foundations for this understanding were laid down by Kurchatov and this was one of his historic services to his native land.

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THE PAST BECOMES HISTORY

L. M. Nemenov

Leningrad Physicotechnical Institute. The year was 1925. I. V. Kurchatov had just settled in at the institute and was involved in the conductivity of dielectrics under the direction of Academician A. F. Ioffe. K. D. Sinel'nikov was working with him. I was assigned to this laboratory as a laboratory assistant. Kurchatov's appearance made a strong impression on me. He was dressed very simply. A velvet blouse, a casually tied tie, dark trousers, and brown shoes worn at the heels. A tall, slender, dark-haired man who carried himself well, he was very handsome. His eyes, dark and lustrous, were striking. He greeted me affectionately, and asked what interested me and what I was able to do. All was simplicity and calm with him. Shyness vanished at once. Kurchatov worked very intensely without thought for time. If he was not in the laboratory, he was in the library. He had the distinctive hands of an experimenter. He did not avoid work of any kind. Everything was done quickly but thoroughly. Everything was written down in a notebook. He said there were no trivial details in our activities, everything was important, and the results must be written down exactly. I worked with Kurchatov for only 2 months; A. F. Ioffe took me into his laboratory. I acquired my oldest comrade and friend in the person of Kurchatov. Over the course of an entire lifetime our friendship went unstrained by anything.

In 1935 Kurchatov proposed that I work together with him on a study of artificial radioactivity induced by irradiation with neutrons.

He was already the head of a large section. As before, he worked day and night. However, his human qualities remained unchanged. His treatment of all was even-handed and benevolent; he was not authoritarian and he exhibited a great sense of tact. His ability to get away from extraneous matters was startling. When working, he thought only of the problem he was solving at that moment. Our joint effort continued for about a year.

In 1939 Kurchatov, having made arrangements with A. F. Ioffe, proposed that I transfer into his section and participate in the construction of a large cyclotron with a pole diameter of 1200 mm. This cyclotron would have been the largest in Europe. I accepted Kurchatov's proposal with pleasure and had the good fortune to work under his leadership from that time until his death.

At that time, Kurchatov was also the head of a laboratory in the Radium Institute where the first cyclotron in the Soviet Union with poles 1000 mm in diameter was put into operation under his direction and with his direct participation. Kurchatov acquired considerable experience in the course of this activity.

The design and manufacture of individual elements of the cyclotron went ahead and a special building was constructed. The outstanding organizational talent of Kurchatov was then revealed for the first time. The construction of such a large cyclotron was an immense problem at that time. It must be pointed out that this was extra work since the main efforts of Kurchatov were concentrated in the field of neutron physics. Start-up of the accelerator was planned for Jan. 1942. However, the war upset all plans. Instead of going into operation, the cyclotron had to be shut down.

At the beginning of the war, we were walking along the street with Kurchatov. A military unit was approaching us. "You know, if I do not find real work needed by the country at this time, I will enter the militia," said Kurchatov. How typical this was of him! He was a man of action and a true patriot. After a few days, Kurchatov, having made arrangements with A. P. Aleksandrov, joined in the work on degaussing warships and served with the Black Sea Fleet in Sevastopol. A novel could be written about his activities there.

In Feb. 1943 I was called to Moscow by official telegram at the request of Kurchatov. A. I. Alikhanov had received a similar telegram somewhat earlier. Having located Alikhanov in Moscow, we went together to Pyzhevsk where the seismic laboratory of the Academy of Sciences of the USSR was situated. There we found Kurchatov and I. K. Kikoin.

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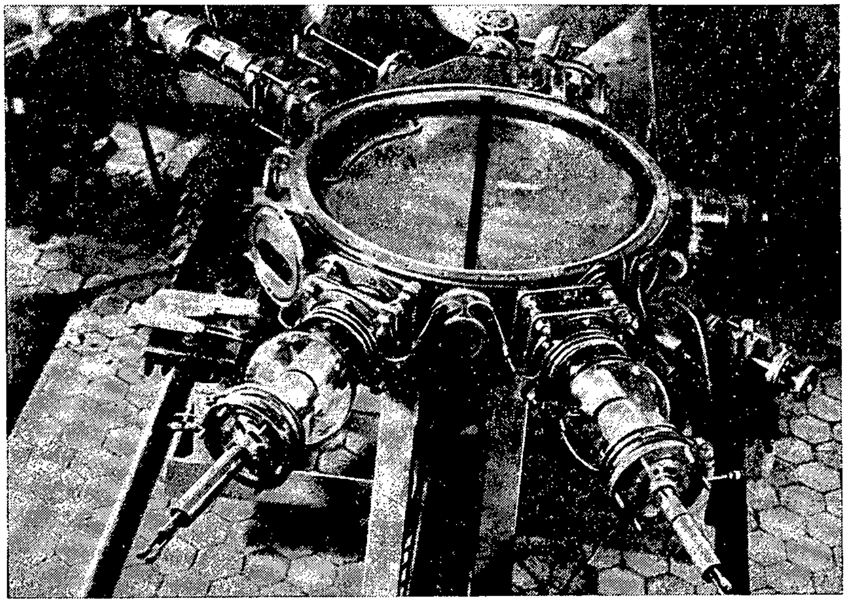

Fig. 1. Acceleration chamber of cyclotron.

We got down to business. Kurchatov reported briefly on a problem presented by the government. It was a question of using subatomic energy for military purposes. I and my future group were charged with the problem — to produce the transuranic element 94 with the aid of a cyclotron in the shortest possible time. It must be produced even if in trace amounts. A theoretical prediction was made of an important property of this element, which is not encountered in nature (later, it was called plutonium). It was hypothesized that the nucleus of element 94 could be split by neutron action just like the nucleus of ^{235}U. This would mean the appearance of a second material in which a fast chain reaction of the explosive type could occur. Microamounts of plutonium were needed in order to carry out chemical studies on its separation in pure form.

It was proposed to produce element 94 in the following manner: the reaction

$${}^{7}_{3}\mathrm{Li} + {}^{2}_{1}d \rightarrow {}^{8}_{4}\mathrm{Be} + {}^{1}_{0}n$$

would be achieved by bombarding a lithium target with deuterons accelerated to 4-5 MeV in a cyclotron. The neutron flux would be used to irradiate uranyl nitrate mixed with paraffin (the paraffin acted as a moderator). It was proposed to produce element 94 by the following scheme:

$${}^{238}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{239}_{92}\mathrm{U} + \gamma;$$
$${}^{239}_{92}\mathrm{U} \rightarrow {}^{0}_{-1}e + {}^{239}_{93}\mathrm{Np};$$
$${}^{239}_{93}\mathrm{Np} \rightarrow {}^{0}_{-1}e + {}^{239}_{94}\mathrm{Pu}.$$

In order to obtain a flux of deuterons with energies not less than 4 MeV, the pole diameter of the electromagnet had to be 0.73 m and the magnetic field intensity 14 kOe. The wavelength of the high-frequency oscillator had to be 28.3 m.

Sixteen months were allowed for the design, manufacture, and start-up of the cyclotron. The period seemed incredibly short but it was approved by the government.

As already mentioned, a cyclotron was designed and partially constructed before the war at the Leningrad Physicotechnical Institute. Kurchatov proposed to speedily deliver to Moscow its high-frequency oscillator, which was stored in Leningrad. There was no other way out; it was impossible to place an order for so complex a device in Moscow at that time.

On the next day, we began to prepare for a flight to Leningrad. The trip to Leningrad was not easy. Although our troops had broken through the blockade ring in one place in Jan. 1943, the fascists still surrounded the city. We had to fly to Khvoina, wait there until darkness, and then make a low-level flight over Lake Ladoga landing at Okhtinskii airport. In Leningrad, I was joined by engineer P. Ya. Glazunov.

The flight up was uneventful. The following day we set out for Smolnyi and delivered two letters. They contained requests to the Leningrad managers to lend us all possible assistance. We had to report regularly to Kurchatov on the way the assignment was being carried out.

Kurchatov's assignment was fulfilled; all the equipment destined for dispatch to Moscow was loaded on two freight cars and shipped on the railroad loop from Lesnyi to Tikhvin.

Before my departure from Moscow, Kurchatov asked me to visit his Leningrad flat and see what was going on there. I quickly fulfilled his request. His flat was on Lesnyi Avenue in a building for specialists. Going into the courtyard, I saw that an aerial bomb had demolished the outer wall of the house in which Kurchatov lived. It seemed as if one was looking at a fantastic stage setting. Reporting any information about the destruction in Leningrad was not permitted; therefore, in a telephone conversation with Kurchatov, I said that I was at his house but did not go upstairs since I saw the color of the wallpaper in his rooms from the courtyard.

We reported to Kurchatov after our arrival in Moscow. He was pleased.

The group headed by Kurchatov was now called Laboratory No. 2 of the Academy of Sciences of the USSR. Little by little, new workers began to arrive at Pyzhevsk, brought in a Kurchatov's request from various cities in the Soviet Union and recalled from the army.

Kurchatov went to inspect the future home of Laboratory No. 2. This was an unfinished building at the All-Union Institute of Experimental Medicine in Pokrovsk-Streshnev. The place was bare and without vegetation of any kind. A dump was 50 m from the building. Railroad spurs were buried in mud. In time, new buildings appeared, and a beautiful park, all of which is now called the I. V. Kurchatov Institute of Atomic Energy.

While I was in Leningrad, Kurchatov drew up orders and placed them with Moscow factories for manufacture of the cyclotron electromagnet. Because of his energetic efforts, the forgings for the electromagnet were ready at the end of May and were shipped to the Novo-Kramatorsk factory. Machining had to be accomplished to the required accuracy in the shortest possible time.

At the same time, design of the acceleration chamber was begun. All the small parts were handed over to the experimental factory at the Institute of Combustible Minerals of the Academy of Sciences of the USSR, and the large units to the Prozhektor factory.

Having arrived at the Prozhektor factory, we found out that there was a small shop at our disposal in which there was a turret lathe. The chief engineer of the factory, having acquainted himself with the drawings and tolerances for manufacture of the acceleration chamber, asserted that this was not in his line and that he could not take on himself the responsibility for filling the order. He proposed that we ourselves work out the technology and run the shop. Only 2 weeks were spent on the manufacture of the acceleration chamber.

Construction of a new building at Pokrovsk-Streshnev went ahead at a rapid rate. Removal was planned for the beginning of 1944.

Kurchatov worked like one possessed. He slept little, but was always cheerful and friendly. No one ever knew anything about his state of mind. Looking at him, one would think there were no difficulties whatever.

At night, I used Kurchatov's desk as a bed. Kurchatov lingered over his work for a very long time, but I had to get up at six in the morning in order to catch the train to Noginsk where the magnet was being manufactured. At one in the morning, I began to be concerned about when Kurchatov was going to quit. Somehow, he could not contain himself and demanded "Do you want a job as my nurse?" But when he realized what was occupying my "bed," he was a little embarrassed and from then on began to leave for home a little earlier.

We worked intensely at Pyzhevsk despite the crowded conditions. We helped one another any way we could. A monolithic and friendly group was established. This was yet another service rendered by Kurchatov. Typical of his style of leadership was complete confidence in those doing a job and the absence of petty oversight. However, at the same time, he checked with great tact the quality of the work and the time taken to fulfill a task. Extremely demanding of himself, he was able to impose the same demands on his associates, and they regarded this as proper.

Subsequently, he succeeded in establishing large groups made up of people of high qualifications possessing extremely individualistic characters. Such groups were united by a common purpose and by the indisputable authority of Kurchatov. No one could deny that he was a charming person. He always asked that things be done, but these requests were more forceful than any order. Because of his high principles, fairness, and humanity, Kurchatov enjoyed the high esteem of all the groups with which he had to deal.

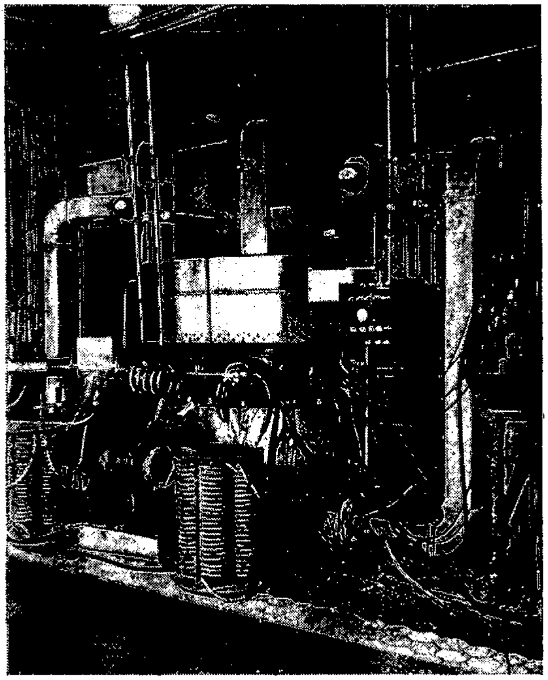

Fig. 2. General view of cyclotron.

The day came for removal of the magnet from the factory. Early in the morning, the riggers, having taken charge of the load, moved it along the route previously agreed upon by the militia. The magnet was set up on a trailer and safely fastened with ropes. By noon it was in position, and 4 h later it was in place on its base. Kurchatov dropped in several times to see how the magnet was being set up.

It was necessary to achieve a high vacuum in the acceleration chamber of the cyclotron and the system had about 100 rubber gaskets. Now one had to consider under what difficult conditions one would have to perform assembly and adjustment of the accelerator. Every trifle was converted into a problem. Leak detectors did not exist at the time. We tightened the chamber by means of bolts and, with the lids clamped between two cross-pieces, submerged it in a tank of water where a powerful electric lamp was installed for illumination. Air from a compressor at a pressure of 3-4 atm was forced into the chamber. Looking for bubbles of air, we determined the location of leaks, marked them, and then carefully sealed them.

Despite his tremendous work load, Kurchatov either dropped in on us or phoned, asking "if there was any progress." He was in very much of a hurry, but we ourselves knew how important it was to get the job done in the assigned time. You see, start-up of the cyclotron was the first "note" which Kurchatov had to "meet" on the way to a solution of the entire gigantic problem.

After the elements of the accelerator were tested individually, assembly of the entire machine began. Of course, not everything went smoothly. Small accidents occurred, but we pushed ahead with confidence. Finally, assembly was completed and one could proceed to the acceleration of deuterons. On that day, Kurchatov left at eight in the evening for a conference with B. L. Vannikov. However, knowing that a trial start-up was being readied, he asked that we telephone him if "there was progress."

With a high vacuum in the acceleration chamber and the magnetic field on, it was necessary to apply a high-frequency potential difference to the dees. For this, several hours of chamber "conditioning" were required in order to outgas its internal surface. After several hours, it began to hold the voltage.

We set the deuteron source into operation. We established the design wavelength of the high-frequency oscillator and the intensity of the magnetic field. Small troubles showed up but we eliminated them rather quickly. We adjusted the intensity of the magnetic field. Accelerated deuterons bombarded the target located between the dees. It should have produced a neutron flux. The decisive moment had arrived. Everyone froze in anticipation. A Geiger counter set up several meters from the cyclotron began to operate. There were neutrons !

Everyone was worried if this were by chance. We increased the potential difference on the dees and the number of clicks from the counter rose. Yes indeed, the deuterons circulating in the chamber traveled to its

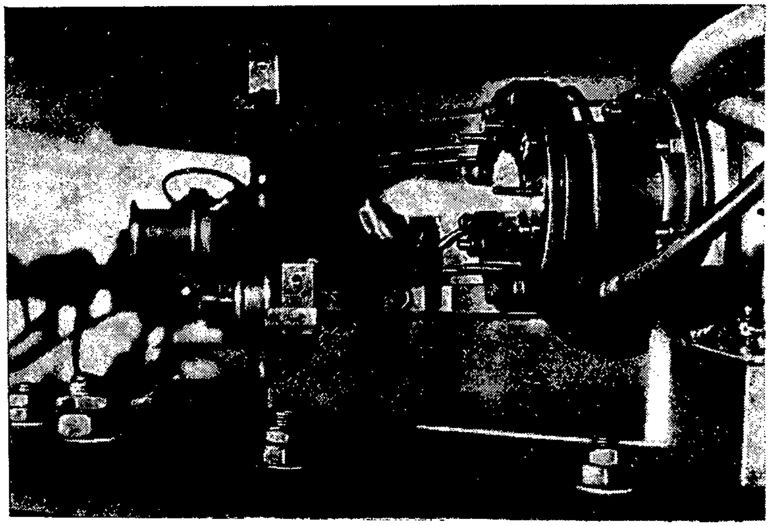

Fig. 3. Deuteron beam emerging from cyclotron.

periphery and struck the lithium target. Conditioning with the beam of accelerated deuterons was continued. We began to measure the deuteron current directly with a measuring probe. We adjusted the intensity of the magnetic field. We measured the maximum current. Fifty microamperes! This was a triumph indeed! Everything operated perfectly. We attempted to bring the beam out of the chamber. We installed a glass plate with a fluorescing screen in place of the exit window. Once again we turned on the machine, applied a negative potential to the deflection system, and varied the voltage — the screen began to glow brightly. Stop! We removed the glass plate and installed a previously prepared thin aluminum window.

This operation lasted for about 1 h. Everyone waited impatiently for the result. It took great effort to perform the operation without undue haste. We turned on the magnetic field and the high-frequency oscillator, and applied potential to the deflection system. Everybody held their breath. A deuteron beam emerged into the air! It was quite visible. We turned out the lights and the bluish-violet plume at the window of the acceleration chamber showed even more clearly in the darkness. We shut down the cyclotron.

I telephoned B. L. Vannikov. He himself picked up the receiver. I greeted him and asked to talk to Kurchatov. "Well, did the cyclotron work?" asked Vannikov. "No, it's simply that Kurchatov asked me to call." Kurchatov came to the phone and immediately asked, "Did it work?" What was the current? "Something over 50 μA. We extracted the beam and saw it by its own light," I replied. "Turn it off so that nothing goes bad. Expect me in 1 h. I congratulate you and give my congratulations to the boys."

It was two in the morning. In the laboratory notebook was written "On Sept. 25, 1944, a deuteron beam was extracted from a cyclotron for the first time in the Soviet Union and Europe."

As promised, Kurchatov arrived in 1 h, cheerful, laughing, and excited. "Nothing happened?" was his first question.

We turned on the machine and the long-awaited beam appeared once again. Kurchatov was satisfied and asked us to measure the internal current with the probe. It turned out that the chamber had become conditioned and the current increased to nearly 100 μA. Then Kurchatov asked for neutron irradiation of a silver foil in a lump of paraffin. We brought the irradiated foil toward the Geiger counter; the counter "jammed" when we were 2 m away.

It was already four in the morning. Kurchatov congratulated us once more and invited us to his house. He was so pleased and happy that it was impossible to refuse him. We went there and woke up his wife. She was frightened but laughed when she found out what this was all about. Kurchatov brought out a bottle of champagne and we split it. Taking leave of us, he said, "Tomorrow we shall make additional measurements with paraffin blocks and the day after tomorrow we shall begin the irradiation of uranyl nitrate."

Thus ended a remarkable working day for us that almost lasted 24 h.

Kurchatov divided the entire staff into brigades for performing the experiments on the development of irradiation techniques. He headed one of the brigades himself. The experiments went on around the clock. Then the irradiation of uranyl nitrate began. It continued until Dec. 1945. The irradiated material was sent for separation of plutonium to the laboratory of the chemist Boris Vasil'evich Kurchatov, the brother of Igor Vasil'evich.

B. V. Kurchatov and his associates developed the so-called sulfate method (coprecipitation from an aqueous solution) for separation of the plutonium produced as the result of uranyl nitrate irradiation in the cyclotron.

This method was worked out with the first microamounts of plutonium first produced in the Soviet Union by B. V. Kurchatov in Oct. 1944 from 1.5 kg of uranium irradiated with neutrons from a Ra — Be source. The first cyclotron plutonium in Europe was separated by this same method. Thus, the problem formulated by I. V. Kurchatov in March 1943 was solved.

The war was coming to a victorious conclusion. However, the pace of the work at Laboratory No. 2 did not slacken. The number of staff members increased considerably. Kurchatov had new concerns.

No scientist in the Soviet Union had to direct such large groups before this and no scientist enjoyed such confidence from the party and government as I. V. Kurchatov. In this man, nature combined the talents of an outstanding scientist with the talents of a remarkable organizer.

SPONTANEOUS FISSION OF HEAVY NUCLEI

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Since the discovery of the spontaneous fission of uranium — work done under the scientific guidance of I. V. Kurchatov — almost 40 years have passed. During these years spontaneous fission has become an important branch of the physics of the atomic nucleus. Today, interest in spontaneous fission is due, on the one hand, to the fact that it is the simplest example of a large-scale nuclear phenomenon connected with the motion of a large amount of nuclear material. On the other hand, it is a fundamental process determining the stability of heavy nuclei, so that the question of spontaneous fission is closely related to the problem of the boundaries of D. I. Mendeleev's periodic system of the elements, and hence to some problems of chemistry, geophysics, and astrophysics.

Paying tribute to the memory of our teacher, we give below a summary of some fundamental results and endeavor to outline future prospects in the study of spontaneous fission, a new form of radioactive disintegration of heavy elements.

Brief Historical Outline

In 1934 E. Fermi and his co-workers, attempting to obtain transuranium elements by bombarding uranium with slow neutrons, discovered a considerable number of activities which they attributed to various isotopes of radium and hypothetical transuranium elements. This was the beginning of a kind of "gold fever" in nuclear physics, which led in 1939 to the discovery of nuclear fission [1,2].

The classical works of Frenkel' [3], Bohr and Wheeler [4] developed the first theory of fission, based on the liquid-drop model. Bohr and Wheeler also indicated the possibility of spontaneous fission, but they estimated that the lifetime of uranium nuclei with respect to this process had the astronomically high value of 10^{22} years. Also in 1939, Libby of the University of California made an attempt to discover the process of spontaneous fission of uranium and thorium nuclei [5]. The first series of his experiments concluded with the search for radioactive fragments in a natural mixture of isotopes, the second with an attempt to detect secondary neutrons formed during fission. Both series of experiments led to negative results, and the lower bound of the lifetime of uranium and thorium with respect to spontaneous fission was estimated at 10^{14} years.

At that time, nuclear-physics research was only beginning to develop in our country. The teams of young scientists headed by I. V. Kurchatov at the Physics and Technology Institute and the Radium Institute in Leningrad were confronted with a complex problem: to make Soviet research catch up in as short a time as possible and to bring their work out into the "world arena."

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Thanks to his profound scientific intuition, I. V. Kurchatov was able to appreciate the importance of the fission process as soon as it was discovered, and he concentrated the energies of the teams under his guidance on the study of fission. This was a demonstration of one of I. V. Kurchatov's fundamental characteristics — the ability to select an important line of investigation and to formulate problems whose solution would determine the fate of the problem as a whole. It was possible to make qualitative progress along this path by the development of experimental methods whose sensitivity would be considerably higher than that of the methods existing abroad at that time.

To us, who were still very young investigators at that time, I. V. Kurchatov assigned the problem of determining with high accuracy the threshold of natural fission of a natural mixture of uranium isotopes. It was decided to record the fission fragments by means of an ionization chamber with a sensitivity much higher than those used previously. As a result of many experiments, we set up a multilayer chamber with a working area of the plates equal to about 1000 cm^2, on which we were able to place about 30-50 times as much uranium as usual. Later we designed a chamber 200 times as sensitive as the usual kind. In the course of the work we had to overcome a great many technical difficulties connected with the design of a special amplifier tuned to the fragment pulses, the problems produced by noise, the microphone effect, etc. Overcoming these difficulties meant essentially that we had to work at a level considerably higher than that of the technology prevailing at the time.

In the first experiments we observed spontaneous pulses in the absence of a neutron source. The number of pulses was small — about 6 per hour — and it was therefore quite understandable that they had not been discovered earlier, with chambers of the usual type. When we informed I. V. Kurchatov of these remarkable results, he said that if this was really spontaneous fission, we would have to throw everything else aside and spend all our time on this ! There followed a great many discussions, as a result of which the necessary control experiments were designed and carried out. They successively eliminated the possibilities that the "spontaneous" pulses were caused by radio noise, the repeated application of pulses from α particles, etc. A comparison of the amplitude distributions of the "spontaneous" pulses and pulses from induced-fission fragments showed that they were identical and convinced us still more firmly that we were indeed observing spontaneous-fission fragments.

Although preliminary estimates had indicated that the fission of uranium by cosmic rays made only an extremely small contribution to the observed effect, we had to verify this experimentally. Here we saw a demonstration of another characteristic of I. V. Kurchatov's — the ability to change the course of an investigation quickly, bringing it into new conditions: on his recommendation, we began to conduct our further investigations in a shaft of the Moscow subway, at a depth of 50 m. In the first place, at that depth the intensity of cosmic rays is reduced by a factor of about 40, and in the second place, the new conditions themselves excluded to a considerable extent the influence of unforeseen factors acting at the surface of the earth, particularly at an industrial and technological center such as Leningrad. As the series of experiments conducted in the Moscow subway showed, the spontaneous-fission effect underground was the same as on the surface. This gave the answer to the critics (quite numerous at that time) who asserted that the effect was entirely due to the action of cosmic rays. It must be stated that a large part of the difficulty consisted in the fact that very little was known at that time even about induced fission. Naturally, this inevitably led to a considerable increase in the number of control experiments we had to conduct. As a result of this intensive and lengthy program of work, we concluded that "the effect we have observed should be attributed to fragments obtained as a result of the spontaneous fission of uranium" [6].

The success of the experiments conducted in Leningrad was due primarily to the qualitative improvement in the sensitivity of the methods used, making it possible to detect events which occurred very seldom. In the course of this work we acquired a store of experience in the recording of infrequent events which was often extremely helpful in our later investigations.

Although I. V. Kurchatov was the scientific leader of the entire cycle of investigations, he scrupulously refused to become a co-author of the publications on spontaneous fission. Commenting on his invaluable contribution, we wrote in the first article: "... We wish to express our sincere gratitude for the guidance of the work by Professor I. V. Kurchatov, who planned all the control experiments and took a very direct part in the discussion of the results of our investigations" [6].

In 1943 Pose [7], recording neutrons accompanying the spontaneous fission of uranium, confirmed our results. In 1944 M. I. Pevzner and G. N. Flerov, having considerably improved the sensitivity of the method, radiochemically isolated some radioactive isotopes of iodine. This proved the presence of spontaneous-fission fragments in a natural mixture of isotopes, i.e., achieved what Libby had been unable to do earlier.

The war interrupted our investigations on spontaneous fission, forcing us to devote our primary attention to questions which were of enormous importance to the state. The outstanding role played by I. V. Kurchatov in the successful solution of the problems that arose in that connection is well known.

The renewal of basic research in nuclear physics in the 1950s made it possible to continue the study of spontaneous fission along two main lines which developed in close interaction with each other.

The first line of research was related to the detailed investigation of the mechanism of spontaneous fission and included not only the determination of the probability of spontaneous fission for various transuranium elements but also the study of the characteristics of the process that were related to each individual spontaneously fissionable nucleus [8-10].

The 1960s brought a qualitatively new stage in the study of the mechanism of spontaneous fission: the Soviet atomic industry, whose establishment and development is inseparably connected with the name of I. V. Kurchatov, began to make appreciable quantities of artificial transuranium elements available to researchers. It became possible to measure in detail the characteristics of the process — the energy distributions of the fragments, the yields of fragments of different masses which helped to explain the effect of quantum effects on the fission process, neutrons and γ quanta accompanying the fission, etc. [11-13]. It gradually became clear that for the study of such a complex phenomenon it is not enough to measure any single parameter characterizing the fission process for a particular nucleus. Further progress in the study of such a problem as, e.g., the dynamics of the fission process, is the result of multiparameter investigations which were begun during the late 1960s, involving the simultaneous measuring of three, four, and even five fission characteristics [14-16].

A special place in the investigation of the mechanism of spontaneous fission is occupied by the study of the fission that accompanies the emission of light charged particles — protons, tritons, α particles, etc. [17-19]. Since the emission of light particles takes place at an instant close to the separation of the fragments, the investigation of this process could and did provide valuable information on the properties of a fissioning system. Fission with the emission of a third light particle is a process with very low probability (e.g., for 500 cases of binary fission there is one emission of an α particle, and the probability of the emission of other particles is even lower), and therefore in order to study it, it was necessary to devise complicated experimental methods designed for the recording of very infrequent occurrences. In the investigation of the composition of light particles it was unexpectedly found that during the process of ternary fission there are emitted light nuclei with a large excess of neutrons (e.g., helium isotopes from ^{5}He to ^{8}He), the investigation of whose structure is a matter of interest in itself [20, 21].

The investigation of some characteristics of spontaneous fission is also of considerable applied significance. This involves primarily the exact determination of the number of neutrons per spontaneous fission of ^{252}Cf, a very important reference parameter for many relative measurements whose results are directly utilized for the calculation and forecasting of fast reactors, the measurement of spectra of prompt fission neutrons of transuranium elements, the cross sections of fission of heavy nuclei by neutrons from the spontaneous fission of ^{252}Cf, etc. [22-24].

The second line of research on spontaneous fission was connected with the explanation of its role as one of the decisive factors in the problem of the stability of heavy nuclei, and consequently in the question of the boundary of the periodic system of the elements. At the beginning of these investigations, eight transuranium elements were already known, including fermium ($Z = 100$), obtained by multiple capture of neutrons in high-density neutron fluxes.

Qualitative progress on the path of artificial synthesis of even more remote transuranium elements could be made only by utilizing nuclear reactions caused by heavy ions.

Such reactions would make possible a "jump" increase of several units in the atomic number of the synthesized elements. The problem consisted in proving the theoretical possibility of accelerating ions whose mass was 10-20 times the mass of a proton.

With the ideological guidance and strong support of I. V. Kurchatov, in 1954 the first experiments on the acceleration of nitrogen ions were begun on the 150-cm cyclotron of the Institute of Atomic Energy in Moscow, and by the end of the 1950s, as a result of the creation of a powerful source of multicharge ions that was capable of providing a monoenergetic beam of nuclei of carbon, nitrogen, and oxygen with the necessary energy, researchers were able to complete the first cycle of investigations designed to explain the main features of the interaction of multicharge ions with nuclei [25, 26]. The very first studies of the cycle showed the exceptionally promising nature of the use of heavy ions for the artificial synthesis of new transfermium elements, and in 1956 experiments aimed at obtaining the previously unknown element 102 were begun.

The successfully developing new line of investigation in nuclear physics continued to receive the consistent attention and strong support of Academician I. V. Kurchatov, on whose recommendation it was decided that the investigations with heavy ions should be considerably expanded. In 1957, at the Joint Institute for Nuclear Research (JINR) at Dubna, the Nuclear Reactions Laboratory was established, on the basis of a new accelerator designed especially for accelerating heavy ions.

A classical cyclotron with poles measuring 310 cm in diameter was designed; it became operational in 1960. It remains one of the leading installations in the world to this day in intensity and in the variety of accelerated particles. As a result, it became possible to pass to systematic basic research aimed at the synthesis of new transfermium elements lying on the boundary of the region of nuclear stability.

On the basis of many methodological developments and investigations of the mechanism of nuclear reactions between complex nuclei, in 1964-1970 new transfermium elements with atomic numbers 102, 103, 104, and 105 were synthesized, and their physical and chemical properties were studied [27,28]. In recognition of the outstanding scientific services rendered by Academician I. V. Kurchatov, element 104, discovered by Soviet scientists in 1964, was given the name of "kurchatovium."

Detection of the α disintegration of nuclei was preferentially used for identifying elements 102 and 103. For elements 104 and 105, another approach to identification, based on the recording of their spontaneous fission, was developed and applied. The reasons for this were the following. In the first place, while spontaneous fission is a rather infrequent form of disintegration for nuclei with $Z < 100$, in the region $Z \geq 100$ it becomes the main form. In the second place, the identification of new nuclides on the basis of their spontaneous fission has some obvious advantages: the fission fragments are recorded with the highest sensitivity, thanks to their high energy and the relatively small number of known spontaneously fissionable nuclei. In the third place, the study of spontaneous fission of far transuranium elements is of considerable interest in itself, since, as has already been noted several times, it is precisely spontaneous fission that determines the stability of the heaviest nuclei. When it was considered, in addition, that such an approach made it possible to investigate the spontaneous fission of nuclei with a highly exotic nucleon composition, it was reasonable to expect that we would discover both new laws governing the fission mechanism and new effects.

Skipping ahead a little, we may note that the preferential orientation toward spontaneous fission proved to be correct and fruitful; we did in fact discover qualitatively new phenomena and laws connected with the fission of heavy nuclei.

The possibilities afforded by spontaneous fission as a method for identifying new transfermium elements were most fully demonstrated in the synthesis of elements 106 and 107, in 1974-1976.

Progress in the synthesis of new elements with $Z > 105$ by the traditional method — the irradiation of targets made of heavy transuranium elements (Cm, Cf) with relatively light ions (O, Ne) — was considerably complicated by the fact that when we use targets which themselves have a high fragment activity, there is a sharp increase in the probability of the formation of spontaneously fissionable isotopes of fermium as a result of nucleon-transfer reactions. Both of these factors lead to the formation of a high fragment background. Furthermore, the compound nuclei obtained in such combinations have an excitation energy of ~40-50 MeV, and the successive emission of neutrons can reduce only 10^{-9}-10^{-10} of them to the ground state. As a result, the formation of each successive new element by this method becomes a more and more infrequent process.

Continuing along the path of accelerating heavier and heavier particles and utilizing nonradioactive targets, the workers of the Nuclear Reactions Laboratory developed a method for synthesizing transfermium elements which was based on the formation of weakly excited compound nuclei during the bombarding of targets made of lead with accelerated ions of argon, titanium, chromium, etc. [29]. This method is free from many difficulties that arise in the traditional approach to the synthesis of new elements, and the absence of a background makes it a highly sensitive method for the detection of spontaneous fission. The use of this method did in fact lead to the discovery of the elements with atomic numbers 106 and 107 [30,31].

Further prospects are connected with the utilization of accelerated ions of the ^{48}Ca type, which offer exceptional possibilities for the artificial synthesis of elements [32]. The structure of this nucleus is such that above the filled doubly magic core of ^{40}Ca there are eight neutrons. Its restructuring upon coalescence with another nucleus requires a large expenditure of energy, which means that the resulting compound system has a low excitation energy, and the "excess" neutrons prove to be very important in making advances toward the region of large values of Z and N. Despite many difficulties, by today we have obtained fairly high-intensity beams (more than 10^{12} particles per second) of these very exotic nuclei, and work has been begun on the synthesis of elements 108 and 109.

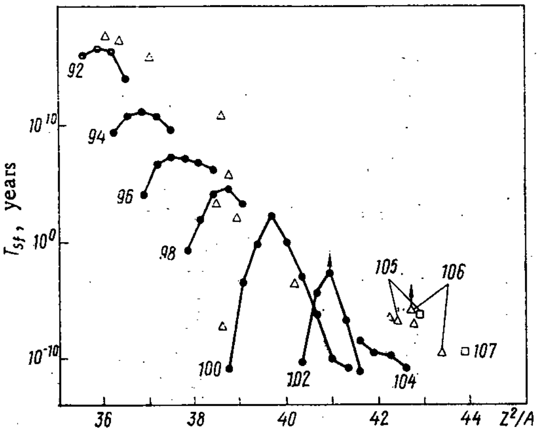

Fig. 1. Relation between the half-life periods of heavy nuclei with respect to spontaneous fission, T_{sf}, and the fissionability parameter Z^2/A: ●) even — even nuclei; Δ, □) odd nuclei.

We will not dwell at this point on other lines of development of heavy-ion physics, such as the artificial synthesis of light and intermediate nuclei far from the region of β stability [33], the study of deep-inelastic transfer reactions [34], delayed protons [35], the synthesis and investigation of new isotopes of rare-earth elements [36], the problems of atomic physics and electrodynamics involved in the collision of heavy ions [37], etc. Present-day achievements and prospects of development in this promising direction of nuclear physics are enormous [38]: by the early 1970s, researchers had formed the opinion that the nuclear physics of the coming decade or two will be primarily the physics of heavy ions. We cannot fail to note, of course, that the use of heavy ions also offers unique opportunities for the solution of many applied problems of today [39].

Some Important Achievements in the Study of Spontaneous Fission

During the 38 years that have passed since the discovery of spontaneous fission, more than 100 isotopes in the transuranium region have been synthesized. About 50 nuclei out of the 100 undergo spontaneous fission. For most of these nuclei the half-life periods for spontaneous fission have been determined fairly accurately; for some, only the lower bounds of the periods have been obtained. For many nuclei in this region the values of the fission barriers have also been experimentally determined.

The first attempts to systematize the spontaneous-fission periods, which made it possible to clarify the overall picture of the stability of heavy nuclei with respect to this form of disintegration, date from the early 1950s [40,41]. It was established at that time that the periods of spontaneous fission of even—even nuclei decrease according to an approximately exponential law as the fissionability parameter Z^2/A increases. This agreed qualitatively with the predictions made on the basis of the classical drop model, according to which the probability of spontaneous fission can be directly determined from the parameter Z^2/A, a measure of the ratio of repulsive Coulomb forces to the surface-tension forces that stabilize the nucleus. For a critical value of the parameter, $(Z^2/A)_{cr} \sim 48$, the fission barrier completely disappears, and then the lifetime of the nucleus with respect to spontaneous fission is $\sim 10^{-22}$ sec. It would appear that we obtain a rather simple picture: the periods T_{sf} of spontaneous fission of all the transuranium elements lie in an interval between $\sim 10^{16}$ years, the spontaneous-fission period for ^{238}U as measured in 1940, and $\sim 10^{-22}$ sec, corresponding to the lifetime of an absolutely unstable nuclear system. All other points lie on an exponential curve drawn between the extreme values, so that the 1940 measurement yields, in a certain sense, a large-scale calibration of the stability of nuclei with respect to spontaneous fission.

However, the appearance of new data concerning spontaneous-fission periods of transuranium elements, and later those of transfermium elements, made it necessary to correct the simple liquid-drop picture. From the relation shown in Fig. 1 it follows that there are substantial effects that cannot be explained within the limits of the classical model. In the first place, there is the large (10^3–10^6) forbiddenness parameter for isotopes with an odd number of nucleons. Thus, for ^{238}Pu the value of T_{sf} is $4.9 \cdot 10^{10}$ yr, whereas for ^{239}Pu it is $5.5 \cdot 10^{15}$ yr, for ^{256}Fm it is 2.7 h ($2 \cdot 10^{-4}$ yr), and for ^{257}Fm it is 10^2 yr; the addition of one nucleon to an even — even core leads to a sharp increase in the stability of the system. In the second place, in the liquid-drop

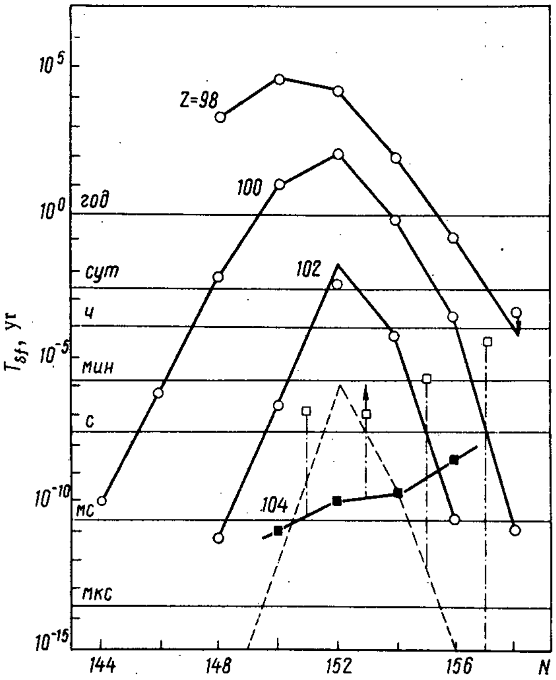

Fig. 2. Half-life periods for spontaneous fission, T_{sf}, as functions of the number of neutrons N for the heaviest even — even nuclei: ○, ■) even — even nuclei; □) odd nuclei.

model the fission barrier, and consequently T_{sf} for isotopes of a single element, must increase monotonically as A increases, i.e., as Z^2/A decreases. However, in the curves connecting the values of the spontaneous-fission periods of different isotopes of a single element we usually find maxima.

As the number of protons in the nucleus increases, the half-life periods of isotopes of a given element become more strongly dependent on the number of neutrons N; e.g., for isotopes of fermium or of element 102, a change of two units in the number of neutrons leads to a decrease in stability with respect to spontaneous fission by a factor of 10^4, as can be seen from Fig. 2.

At the same time, the nature of the variation of the stability of even — even isotopes of kurchatovium as a function of the number of neutrons is radically different from the analogous functions for californium, fermium, and element 102. As was shown by Oganesyan et al. [42], the variation of T_{sf} for isotopes of kurchatovium indicates a monotonic increase in the lifetime of even — even nuclei of Ku with increasing mass without any substantial variation in the region N = 152, whereas for other nuclei there is a great deal of variation.

From all of these facts we can draw the physical conclusion that the drop model represents only a crude average picture and that the internal structure of the nucleus plays a very important role in the fission process.

Many attempts have been made to take account theoretically of the effect produced on the probability of spontaneous fission by the structure of the nucleus, but for a long time they remained unsuccessful. Without discussing all these investigations in detail, we should recall the work of Myers and Swiatecki [43], who attempted to combine the liquid-drop model with the independent-particle model. They assumed that the shell correction to the liquid-drop mass of the nucleus, related to the reduced or increased density of single-particle levels near the Fermi boundary, is maximal for near-magic and spherical nuclei and decreases exponentially as the deformation increases. On the basis of such assumptions, they calculated the equilibrium deformations of the nuclei and also the height and shape of the fission barriers. Myers and Swiatecki extrapolated their calculations to the region of superheavy nuclei, and, as it turned out, near the assumed magic numbers Z = 126, N = 184, taking account of the shell correction leads to the appearance of a barrier ~9 MeV high, i.e., to the possibility that superheavy nuclei which have a high stability with respect to spontaneous fission may exist in this region.

The Myers — Swiatecki model was proved wrong by a systematic study of the fission thresholds of heavy nuclei (Z^2/A = 34-38) which are deformed in the ground state. The experiments showed that in this region of nuclei the fission thresholds remain almost constant, whereas according to the calculations they should decrease by a factor of several units. The fact that these fission thresholds were constant contradicted Myers and Swiatecki's fundamental assumption that the shell correction has a stabilizing effect only in the region of spherical near-magic nuclei and disappears in the region of deformed nuclei. The divergence between theory and experiment was impossible to explain even qualitatively.

Equally unsuccessful were the many attempts at purely microscopic calculations to describe strongly deformed nuclei in the fission process on the basis of a scheme of single-particle levels in the deformed Nilsson potential [44,45]. The use of this method proved to be possible only for small deformations. The fission barrier in calculations of this type was obtained as a small difference between two energies with large absolute values — the surface energy and the Coulomb energy — and the schemes of levels were not well enough known to calculate the surface energy accurately.

The situation changed considerably when in 1962, in Dubna, during experiments on the synthesis of a new element with atomic number 104, it was found that the nucleus of ^{242}Am undergoes spontaneous fission with a half-life period of about 0.014 sec [46]. This period was impossible to attribute either to induced fission (the lifetime of such a system is less than 10^{-16} sec) nor to spontaneous fission from the ground state ($T_{sf} \sim 10^{14}$ yr).

The investigations conducted in Dubna and at other leading laboratories throughout the world showed that the existence of two half-life periods of this nucleus with respect to spontaneous fission was by no means a unique phenomenon.

Today more than 30 such nuclei have been identified in the region from uranium to berkelium with "anomalous" half-life periods of 10^{-9}-10^{-2} sec, obtained both in reactions with heavy ions and upon the irradiation of heavy nuclei with neutrons of different energies, down to thermal neutrons, gamma quanta, and light charged particles [47].

Bohr and Flerov [48] proposed interpreting this very interesting phenomenon as fission from an isomeric state whose deformation considerably exceeds the equilibrium deformation, i.e., as an isomerism of shape.

The discovery of fission from the isomeric state stimulated the development of a new theoretical approach [49,50] both to the problem of stability of heavy nuclei and to the shell model as a whole, which in turn made it possible to give more concrete content to the hypothesis of isomerism of shape. This was done by V. M. Strutinskii.

In the original variant of his theory the quantum correction to the total nucleus energy was due to the nonuniformity of the single-particle spectrum in the region of the Fermi boundary. However, as V. M. Strutinskii showed, the correction does not disappear when the shape of the nucleus differs from the spherical — the quantum nonuniformities near the Fermi boundary may be preserved up to very high deformation values, stabilizing the system. Therefore, the phenomenon of "magicness" may occur even in severely deformed nuclei. In particular, during the fission process there is a periodic redistribution of the nonuniformities of the levels, leading to increased stability of some shapes of the fissionable nucleus. The potential energy of the nucleus, for certain deformations, has minima corresponding to filled "large shells" — regions of increased density of the single-particle levels.

For nuclei undergoing isomeric fission, there are two such minima (and corresponding maxima). The first minimum corresponds to the ground state of the nucleus, and the second to the isomeric state. If in the fission process the nucleus falls into the second well and its energy is less than the height of the barriers surrounding the well, it is captured. It is possible in this process to have either fission from the second well, the probability of which is determined by the shape of the second barrier, or radiative transition from the isomeric state to the ground state through a tunnel transition under the first barrier. This theory offers a possibility of correctly calculating the energy of the nucleus for large deformations, and consequently the shape and height of the fission barriers.

Many calculations carried out by Strutinskii's method showed [51-53] the existence of a rather broad region of nuclei in the region of the doubly magic nucleus ^{298}114, where the height of the fission barriers reaches 10 MeV.

However, it should be stipulated that the errors due to the extrapolation of the parameters of the single-particle potential in the region of superheavy nuclei may be very large, and this affects the accuracy of the calculation of the potential energy of the nucleus as a function of its deformation, in particular the height and shape of the fission barrier.

This applies even more to the calculation of the periods of spontaneous fission of heavy and superheavy nuclei, which is an extremely complicated problem. The potential energy of the nucleus, calculated as a function of its shape, is not yet enough to determine the dynamics of the motion of the fissioning system up to the point of separation. A knowledge of the potential energy makes it possible to calculate the forces acting in the nucleus; however, the further solution of the complete dynamic problem requires a determination of such properties of the fissioning nucleus as its inertia or the related dissipation of collective energy on the basis of other degrees of freedom. Thus, e.g., it becomes necessary to introduce effective coefficients of inertia which have been subject to the influence of the shell structure of the nucleus to no less a degree than the potential energy itself.

At the same time, the calculations of effective coefficients of inertia is a problem which is less clearly defined in principle than the calculation of the potential energy, since its solution requires the introduction of additional assumptions which are not always justified.

Up to the present time, theoretical calculations [54-56] have been carried out for the spontaneous-fission half-life periods of the heaviest nuclei, and on the whole, they have reproduced the experimental data reasonably well — the functional relations with "maxima" for fermium and element 102, the considerable variation in the systematization when we go from $Z = 102$ to kurchatovium, the even — odd effects, etc. Although these attempts are of considerable importance for the further development of the theory of fission, their sensitivity to details of the calculation is such that each of the indeterminacies — 1 MeV in the height, 5% in the width of the barrier, or 10% in the mass parameter — leads to a variation in T_{sf} by a factor of about 100 [57].

Therefore, it is still impossible to expect an accuracy in the calculation of the periods of spontaneous fission of heavy nuclei, and especially of superheavy nuclei, better than $10^{\pm 8}$ yr.

Superheavy Nuclei

For the physics of the atomic nucleus, one of the most important consequences of the experimental and theoretical investigations of the spontaneous-fission process is the prediction of a possible region of superheavy elements. The sum total of our knowledge of the atomic nucleus and its quantum stability, obtained over the past four decades, makes this prediction fairly reliable and independent, in general, of the choice of any particular variant of the shell model. An answer to the question of the existence of superheavy elements, obtained experimentally, would perhaps signify the most critical verification of the very concept of the shell structure of the nucleus, the fundamental nuclear model, which has stood the test of time very successfully but nevertheless is still a model.

More concretely, the stability of heavy nuclei is determined chiefly by their spontaneous fission, and therefore a necessary condition for the existence of such nuclei is that they have a barrier with respect to fission. For nuclei from uranium to fermium the shell component of the fission barrier, leading to some very interesting physical phenomena, nevertheless does not have a critical effect on their stability, appearing in superposition with the liquid-drop component of the barrier. In the region of superheavy elements the drop component of the barrier completely disappears, and the stability of superheavy nuclei is determined by the penetrability of a purely shell-type barrier. Thus, the existence or nonexistence of superheavy elements is directly related to the question of whether or not the fundamental ideas concerning the structure of the nucleus, based on the shell model, are valid. On the other hand, while the presence of a barrier is sufficient for the theoretical existence of superheavy nuclei, for experimental verification of such a prediction we must have a knowledge of the lifetime of the superheavy nuclei with respect to spontaneous fission, since for any concrete formulation of the search experiment it is impossible to include the entire lifetime range from 10^{10} yr to 10^{-10} sec. The choice of the principle of the experiment is determined essentially by the lifetime interval in which the investigation is conducted.

As has already been said, the indeterminacy of the theoretical calculation is too great — 8-10 orders of magnitude. This indeterminacy does not a priori exclude any of the possibilities of obtaining or discovering superheavy elements, and for a line of experimental investigation to solve the problem we may choose either a search for superheavy nuclei in nature (on earth, in objects of cosmic origin, in the composition of cosmic rays, etc.) or the artificial production of elements in accelerators (in nuclear reaction between complex nuclei).

We would like to make some remarks concerning the search for superheavy nuclei in nature. It is obvious that the search for superheavy elements in terrestrial objects can bring success only if the lifetime of these elements is comparable to the lifetime of the earth, which is $4.5 \cdot 10^9$ yr. Such investigations have been conducted on an extensive scale during the past decade, and we can say even today that a number of objects that are very promising in this respect have already been determined.

Equally promising is the search for superheavy elements in objects of extraterrestrial origin — meteorites, cosmic rays, etc. Searches along this line, which are being conducted in the Nuclear Reactions Laboratory of the JINR and other laboratories throughout the world, may bring success even if the lifetime of the superheavy elements is much less than 10^{10} yr; these objects may prove to be considerably "younger" than terrestrial specimens.

In a brief discussion of the possible mechanisms of the formation of superheavy elements in processes of nucleosynthesis in the universe, we may note that the explosions of supernovas have long been regarded as a fundamental source; during such explosions there takes place what is known as the r-process, a process of rapid multiple capture of neutrons by nuclei. Although the estimates of the probability and abundance of superheavy elements obtained as a result of the r-process are highly contradictory [58-60], it remains a possibility in principle that they can be formed in such a process. Other sources and mechanisms of formation of superheavy elements in stellar objects have also been discussed — pulsars [61], reactions between heavy nuclei accelerated in the universe [62], etc.

Thus, in the question of the search for superheavy elements in nature, nuclear physics has yet one more point of contact with astrophysical problems. There is a curious inverse connection: the problem of the stability of heavy nuclei, raised by the discovery of spontaneous fission, developing further in the "depths" of nuclear physics and leading to the prediction of the existence of superheavy elements, may find a solution at the astrophysical level. In the event of a successful solution, this problem, enriching our ideas on nucleosynthesis in the universe, will again return to the field of nuclear physics and give us an answer to the question of the fundamental properties of nuclear structure.

Having given a brief introduction to the problem of the search for superheavy elements in nature, we will not go into a detailed discussion of the results of specific studies — these have already been reported on more than once (see, e.g., [63-65]). Instead, using as an example the investigations conducted during the past 10 years in the Nuclear Reactions Laboratory of the JINR, we describe one of the possible — and, in our opinion, successful — approaches to the search for superheavy elements in nature [66-68].

We are referring to the search for superheavy elements in meteorites of the carbonaceous and nonequilibrium chondrite type, in which, according to indirect indications, the presence of such elements is most probable. In experiments aimed at discovering infrequent events of spontaneous fission, use has been made of detectors of the multiple emission of neutrons on the basis of proportional counters with ^{3}He, which make it possible without destruction of the specimen to attain record-breaking sensitivities of 10^{-15} g/g. (It should be borne in mind that a method similar in principle to this was used earlier by Libby [5] and Pose [7] for detecting spontaneous fission in uranium. The sensitivity of the method has been improved since that time by a factor of 10^7). Measurements were made in a salt mine at a depth of 1100 m of water equivalent. In order to suppress the cosmic background, the detector was surrounded by a sheath of Geiger counters connected for anticoincidence. The average neutron-recording effectiveness was 12-30% for various detectors. Special attention was paid to the problem of background from the spontaneous fission of ^{238}U and of technogenic transuranium isotopes.

After many months of measurements on specimens from the Saratov, Efremovka, and Allende meteorites, researchers observed a multiple-neutron-emission effect, the explanation of which required the assumption that the specimens contained a new long-lived spontaneously fissionable nuclide [66-68], most probably belonging to the region of superheavy elements.

It is difficult to suppose, however, that superheavy elements can be present only in meteorites; most likely, it is merely a question of their concentration. Therefore it is by no means impossible that other objects may prove to be very promising in the search for heavy elements — in particular, objects of terrestrial origin, such as the geothermal waters of the Cheleken peninsula (in the southern Caspian region), Armenian basalts, etc.

One of the first objects of terrestrial origin on which an intensive search for superheavy elements was conducted was the geothermal water of Cheleken, which the JINR Nuclear Reactions Laboratory began working on some years ago. Water from the geothermal source was passed through a large column with an anion-exchange resin. The mineral fraction was then washed off and placed in the sensitive area of a neutron detector. The investigators recorded 160 events, of which only six can be attributed to spontaneous fission of the uranium impurity in the specimens. If, as in the case of the meteorites, we assume that the observed effect is due to the spontaneous fission of a long-lived nuclide belonging to the region of superheavy elements, then its concentration in the mineral fraction of the resin can be estimated at $2 \cdot 10^{-13}$ g/g, and the half-life is assumed to be 10^9 yr.

One of the methods of identifying a new radiation emitter by the methods of nuclear physics was proposed by Yu. Ts. Oganesyan: when a target obtained by chemical enrichment [66] and containing the element under investigation is bombarded with a beam of α particles, induced fission can be observed in it. The fission will take place with a frequency 10^6 as high as spontaneous fission. As calculations have shown, varying the energy of the α particle, on the basis of the fission-reaction threshold, we can determine the atomic number of the fissioning nucleus to within two units if the monochromaticity of the beam is no worse than 150 keV.

Similar experiments are being conducted today in Dubna on the U-200 cyclotron, on which it has been possible to obtain a beam of α particles ($\Delta E = 60$ keV) with an energy value smoothly varying from 24 to 40 MeV. As was shown in preliminary experiments, this method makes it possible to detect nuclei of superheavy elements if the number of such nuclei in the target is $\geq 5 \cdot 10^8$. Making use of this method, it will be possible to carry out one of the most rigorous and critical checks of whether a new spontaneously fissionable natural radiation emitter is in fact a superheavy element.

The search for superheavy elements has been conducted on specimens of terrestrial and cosmic origin by various methods in various laboratories all over the world, but until very recently it has been unsuccessful. Repeated announcements of the discovery of superheavy elements have all, on closer examination, proved to be premature. However, on the basis of the most recent results [66-68], it seems to us that the question of the existence of superheavy elements in nature has by no means been exhausted, and the search for more promising natural objects of a new type in combination with the continuous improvement in the sensitivity of experimental methods gives reason to hope for success in the final solution of this very important problem.

A second line of research is, of course, the artificial synthesis of superheavy elements in reactions between complex nuclei. Such studies have been conducted since the late 1960s both in Dubna and in other laboratories throughout the world, making use of various experimental methods and various beams of accelerated ions. Researchers have also used diverse approaches to the problem of obtaining superheavy nuclei on heavy-ion accelerators; however, the many attempts made thus far have not yet brought the desired results. Without discussing in detail any specific attempts (this has been done, e.g., in [69, 70]), we will nevertheless point out that investigations on the artificial synthesis of superheavy elements have substantially deepened our ideas about the mechanism of interaction between two complex nuclei; e.g., they have led to the discovery of a new class of nuclear reactions — reactions of deep-inelastic transfer — and have provided an exceptionally powerful stimulus for the development of many new ideas in heavy-ion physics.

Until recently, all the experimental attempts to synthesize superheavy elements in nuclear reactions have yielded only the upper bounds of their cross sections of formation. From these data, with certain assumptions, we can make estimates of the limiting values of the lifetimes of superheavy nuclei, usually related to spontaneous fission. However, as has already been noted, the half-life with respect to spontaneous fission is determined not only by the structure of the barrier but also by the dynamic aspects of the process, in particular by the mass coefficient. Therefore, on the basis of the limiting values of the lifetime with respect to spontaneous fission it is difficult to draw any definite conclusions concerning the fission barriers of superheavy nuclei. The foregoing relates to spontaneous fission.

However, Oganesyan and his co-workers [71, 72] have recently proposed another approach to the problem of the artificial production of superheavy elements. It was assumed that the fission barriers exist in excited nuclei as well, to the degree that the shell effects persist as the temperature and angular momentum of the nucleus increase. Therefore it may be supposed that for an excitation energy ~20-30 MeV the shell effects in the nuclei are still quite pronounced, and this must have an influence on their disintegration characteristics. Thus, the question of the character of the fission of weakly excited superheavy nuclei may be related in principle to the presence of a fission barrier in these nuclei. Superheavy nuclei with relatively low excitation energy $E^* \sim 20$-40 MeV can be obtained in reactions with ions heavier than argon (see [29, 32]).

Taking advantage of this possibility, Oganesyan and his co-workers studied the mass and energy distributions of the products formed in nuclear reactions when ^{208}Pb is bombarded with ^{48}Ca ions having energies of 220 and 250 MeV, and also when ^{243}Am is bombarded with ^{40}Ar ions in the 214-300 MeV energy range [71, 72]. In the case of the $^{208}\text{Pb} + {}^{48}\text{Ca}$ reaction the mass distribution of the fission fragments of the compound nucleus turned out to be asymmetric for $E^* = 25$ MeV, which indicates that the shell effects persist in the nucleus of

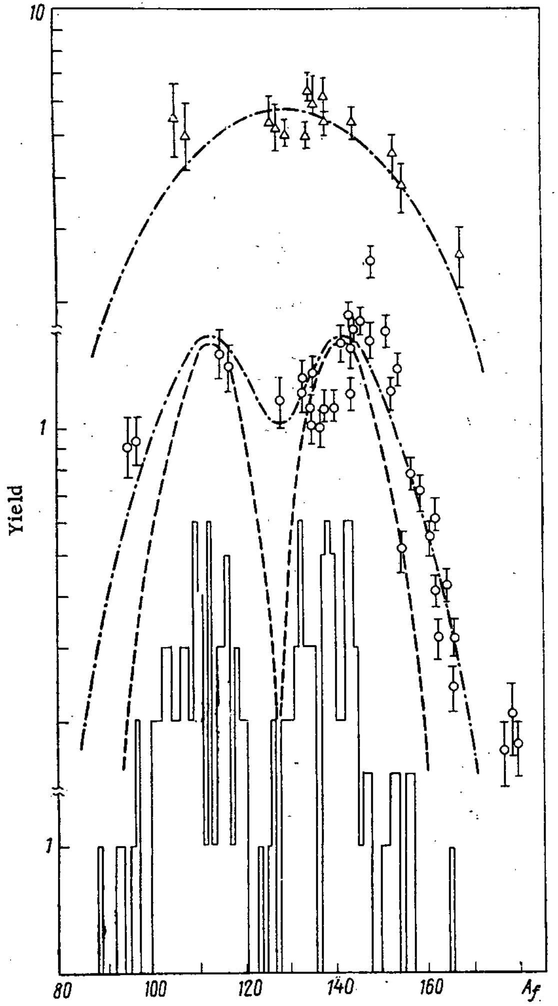

Fig. 3.

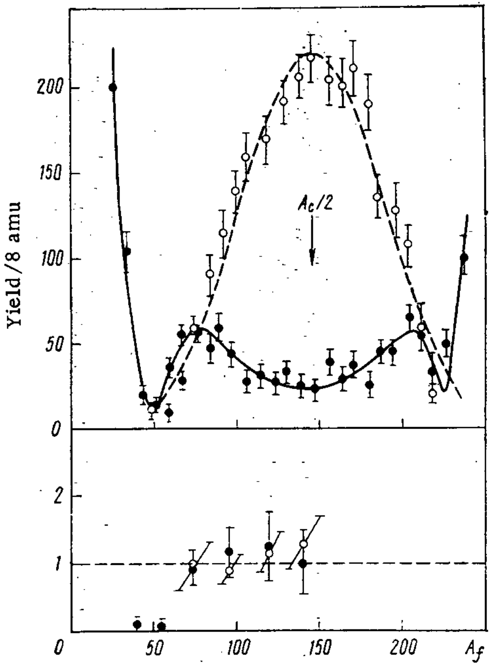

Fig. 4.

Fig. 3. Mass distribution of fission fragments from the compound nucleus $^{256}102$ at excitation energies of 25 MeV (O) and 53 MeV (∇). The histogram and the dashed curve represent the distributions of spontaneous-fission fragments for the isotopes $^{252}102$ and ^{256}Fm, respectively.

Fig. 4. Mass distribution and angular anisotropy of the products of the ^{243}Am + ^{40}Ar reaction at energies of 214 MeV (●) and 300 MeV (O).

$^{256}102$ at this excitation energy. As the excitation energy increases to 50 MeV, the mass distribution of the fragments becomes practically symmetric (Fig. 3).

While the mass distribution in the first case was determined by a radiochemical method, the energy and mass distribution for the products of the ^{243}Am + ^{40}Ar reaction were measured on an ion beam, making use of a pair of semiconductor detectors, the angle between which was uniquely determined from the kinematic conditions and distinguished cases of complete transfer of impulse to the two fragments (two-particle process). It was found that at an argon-ion energy of 300 MeV a wide distribution of reaction products is observable, including the region from 60 to 220 amu and having the shape of a symmetric curve with a maximum near $(A_{\text{ion}} + A_{\text{target}})/2 \sim 140$ (Fig. 4), as might have been expected for the fission of an excited compound nucleus. However, as the energy of the bombarding ions decreases to 214 MeV and the excitation energy correspondingly decreases to 40 MeV, the most probable event seems to be strongly asymmetric fission with a fragment mass ratio $A_{\text{heavy}}/A_{\text{light}} \sim 2.5$, the heavy fragment having a mass of 200-210 amu. Apparently the asymmetric nature of the fission for an excitation energy of 40 MeV is a consequence of the occurrence of shell effects, which in the present case are related to the magic numbers $Z = 82$ and $N = 126$ (^{208}Pb).

From all of these investigations it appears that the mechanism of fission of a weakly excited superheavy nucleus with $Z = 113$ and $A = 283$ is subject to a substantial influence from shell effects. Therefore, it will be of great interest in the future to study other combinations of ions and targets leading to the formation of heavy and superheavy compound nuclei over a wide range of Z and N. Such investigations may be of very great significance for the solution of the problem of artificial synthesis of superheavy elements.

CONCLUSIONS

During the time since O. Hahn and F. Strassmann first observed the fission of uranium under the action of neutrons, an enormous amount of work has been done on the study of this phenomenon. Researchers have not only obtained new experimental information but also made a number of discoveries each of which made it possible to look at the problem from a new and sometimes unexpected viewpoint and substantially affected our ideas about the structure of the nucleus and the mechanism of fission in particular.

Perhaps it was no accident that the classical experiments of Hahn and Strassmann on the radiochemical detection of the products of interaction of neutrons with uranium nuclei were conducted in Germany and not elsewhere and that Lise Meitner was able to give them a correct interpretation which differed so strongly from the generally accepted ideas about nuclear reactions. Meticulousness and finickiness in the formulation of experiments and boldness in the explanation of the results — a successful combination of the concrete and the abstract that is characteristic of the German school of physics — occupy an important place among the circumstances that led to the discovery of fission in those early days.

While a uranium nucleus absorbing a neutron gains an excitation energy ~6 MeV and the process of fission of the excited compound system becomes highly probable, spontaneous fission starts from a state with zero excitation energy and therefore is an incomparably more infrequent event. However, the observation of spontaneous fission and its comparison with induced fission have made it possible to explain how the excitation energy of the nucleus affects the probability and other characteristics of the fission: while the lifetime of uranium with respect to spontaneous fission is $\sim 10^{23}$ sec, when we pass to superbarrier fission, as is now shown by direct measurements making use of shadow effects (see, e.g., [73]), it decreases to $\sim 10^{-16}$ sec, i.e., by 39 orders of magnitude.

The development of investigations on spontaneous fission, the entire course of which reflects the beneficial influence of the traditions of the scientific school of the Leningrad Physicotechnical Institute and the Radium Institute, the style and methods of I. V. Kurchatov's scientific activity — giving keen attention to new and sometimes even collateral effects, constantly improving experimental methods, increasing their sensitivity — have led to the discovery of a number of new phenomena. The discovery of spontaneously fissionable isomers, e.g., made it possible to study the fission of nuclei with an excitation energy of 2-3 MeV, characterized by anomalously large deformation. Of great interest was the phenomenon of delayed fission [74], starting from a state with an excitation energy comparable to the height of the potential barrier. Here the excitation of the nucleus arises as a result of the weak interaction — β transition — and in magnitude it is intermediate between those taking place during fission from the isomeric state and those taking place under the effect of slow neutrons. These new effects have "filled in" the excitation-energy interval from zero to ~6 MeV and the deformation interval from equilibrium deformation to deformation that is twice as great. It should also be noted that a useful supplement to this picture was provided by experiments on deep subbarrier photofission [75, 76], which realized the possibility of smooth variation of the excitation energy of the fissioning nucleus. All of this, in general, has substantially deepened our ideas concerning the stability of heavy nuclei with respect to fission and concerning the mechanism of the process.

The fission process lies at the base of the nuclear chain reaction, the mastering of which has fundamentally altered the face of our times. In the Soviet Union, work aimed at mastering the chain reaction was begun under the leadership of I. V. Kurchatov even before the war, and this was decisive in the solution of the extremely important problems involved in the creation of the well-known structures that guarantee the peaceful development of the socialist countries. There is reason to think that the experience gained in conducting basic research, the success of which is usually determined by the possibility of establishing installations whose qualitative level exceeds the level of contemporary technology, has played a significant role in this respect.

After the solution of the problems of importance to the state, it was natural for the people participating in this work to tackle the extremely complex theoretical problems of basic nuclear physics. It was possible to bring into the investigations that style and those scales of effort that were characteristic of the scientific and organizational activity of I. V. Kurchatov. In particular, with his warm support, work was begun in 1954 on the synthesis of new elements: first the transuranium, then the transfermium, and finally, during the last decade, the superheavy elements.

As the basis for the method of synthesizing new elements, Soviet researchers took reactions between complex nuclei: although in the United States work was still actively being conducted at that time on the production of new transuranium elements in high-density neutron fluxes, it became clear that a theoretical breakthrough was not to be expected along that line.

The installation chosen for obtaining multicharge ions was the cyclotron. Its "heart" — the source of multicharge ions — was designed essentially by Academician L. A. Artsimovich in the course of the solution of problems involving the effective separation of isotopes.

The choice proved to be the right one: for the past 17 years the U-300 cyclotron has been a leader among the heavy-ion accelerators of this generation in the basic parameters of its accelerated-particle beams.

We have already said a good deal about the results obtained in the synthesis of new elements and the investigation of the actual mechanism of spontaneous fission, which proved to be considerably more complex than had been supposed in those early pre-war years.

The study of spontaneous fission — a new type of radioactivity whose discovery is closely linked to the name of I. V. Kurchatov — is developing at a rapid rate. We have tried to describe for our reader the main landmarks on the almost 40-yr path along which we and many other physicists have advanced in our investigations and to give an idea of its future prospects. It may be that a few years from now we will look back and smile at our present ideas on the question in what direction and just how the future development of these investigations will proceed. One thing is beyond question: the place occupied by spontaneous fission not only in nuclear physics but also in related fields of knowledge is a guarantee of unflagging interest in this phenomenon. The fate of the island of stability of superheavy nuclei, the possible existence of a new region of elements in Mendeleev's periodic table, and many other aspects of nuclear physics depend almost entirely on how strongly subject to spontaneous fission are the nuclei which were at first merely a dream and have now become an object of experimental investigation.

The present-day situation with regard to the search for superheavy elements is surprisingly reminiscent of the events preceding the final discovery of spontaneous fission. Only 1 year ago, we were able to observe no more than a few events of spontaneous fission of a new natural nuclide per year. Thanks to the constant improvement of methods of search, enrichment, and identification, today we are recording several spontaneous fissions every day. Just as it did 40 years ago, the discovery of the truth requires many highly diverse and perhaps even more laborious control experiments. Furthermore, at the time of the first experiments on spontaneous fission very little was known concerning induced fission. Today we have a scarcely better idea of the possible properties of superheavy elements. Therefore, notwithstanding the enormous effort already expended in the attempts to discover or synthesize superheavy elements, even greater efforts will have to be made.

However, we hope that this next turn of the spiral along which nuclear physics is developing will lead in any case to a deeper understanding of the fundamental properties of matter.

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ISOMERS IN THE MILLISECOND REGION

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Nuclear isomers have provided a subject of constant interest at all stages of the research into the structure of atomic nuclei. From a theoretical viewpoint, the interest in isomeric nuclei is associated with the investigation of intranuclear processes leading to the formation of long-lived excited states and with the determination of the level of prohibition for the corresponding decay channels; from a methodological viewpoint, isomers are a convenient means of investigating processes of very short duration that occur within the nucleus. In addition, the lifetime of nuclei in isomeric states may be sufficient to allow the practical use of isomers with given special properties.

The study of isomeric states and their decay has played an important part in the development of current theoretical models of atomic nuclei. Its contribution is widely known: the uniform distribution of long-lived isomers over N or Z (isomer islands) agrees with the shell structure of single-particle nucleonic models in nuclei; the generalized model of the nucleus is confirmed by the existence of a strong prohibition on asymptotic quantum numbers; the discovery of fissioning isomers offers a unique opportunity for the investigation of large nuclear deformations and for fission physics. At present, the interest in isomers is not only growing but is extending to more fundamental matters: the search for density isomers, rotational isomers, etc.

Broad research into nuclear isomers began in [1], where the excitation of isomeric states in the products of nuclear reactions was first shown to be possible. In [2] a historical account is given of the discovery of isomers of artificially radioactive nuclei, while in [3] there is a discussion of the importance of the pioneer work in this field carried out over a period of 30 years in I. V. Kurchatov's laboratory and, in particular, the constant interest in this topic generated by Kurchatov in the country's research institutes.

Kurchatov's research on the decay of the isomer ^{80m}Br may be regarded as the starting point for one of the important research topics in current nuclear physics: nuclear spectroscopy using nuclear reactions. In the work on ^{80m}Br it was shown that radiative transitions in the nucleus or internal electron conversions form an important decay channel for isomeric states and the multipolarity of the isomeric transition was determined by measuring the internal-conversion coefficients [4].

Nuclear reactions provide the most universal and at present also the principal means of investigating the structure of excited nuclear states. However, because of the complexity of the radiation accompanying the decay of the reaction products spectroscopy in a beam of bombarding particles poses difficult methodological problems. Until precision semiconductor radiation detectors are developed, spectroscopic investigation is

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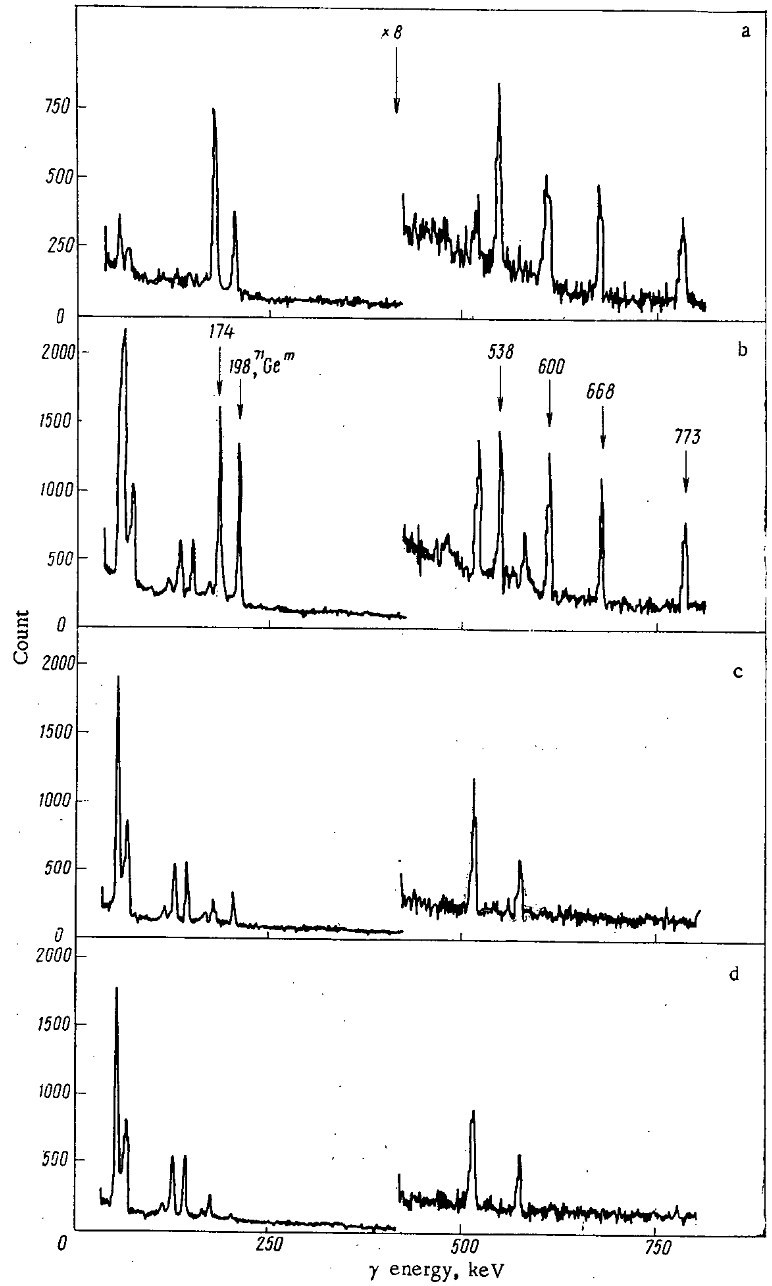

Fig. 1. γ spectra of decay of millisecond isomer ^{132m}Xe ($T_{1/2}$ = 8.7 msec). Analyzer time mode with duration 6.4 msec (a) and 51.2 msec (b, c, d).

only possible in certain special cases. For example, the large cross section of (n, γ) reactions for a number of rare-earth isotopes has enabled L. V. Groshev and co-workers to complete a large program of research on this topic; light nuclei with a relatively simple energy-level structure have been studied in (p, γ) and (p, nγ) reactions at the Kharkov Polytechnical Institute (KPI), where (α, xn) reactions have been effectively used to investigate the lower rotational state in deformed nuclei.

The search for millisecond isomers began in the mid-1950s, on the initiative of O. I. Leipunskii. Investigations were carried out at the Institute of Chemical Physics of the Academy of Sciences of the USSR using a 14-MeV neutron beam and at KPI using a linear proton accelerator with a maximum energy of 20.8 MeV. At first, the abundance of isomers of lifetime 10^{-4}–10^{-1} sec and the probability of their excitation in nuclear reactions were the main centers of attention.

A large number of isomers were found in the millisecond-lifetime range; several of these are of high excitation energy and hence sufficiently high spin. Thus, it is possible to investigate the properties of excited nuclear states in the region inaccessible for investigation by radioactive isotopic decay.

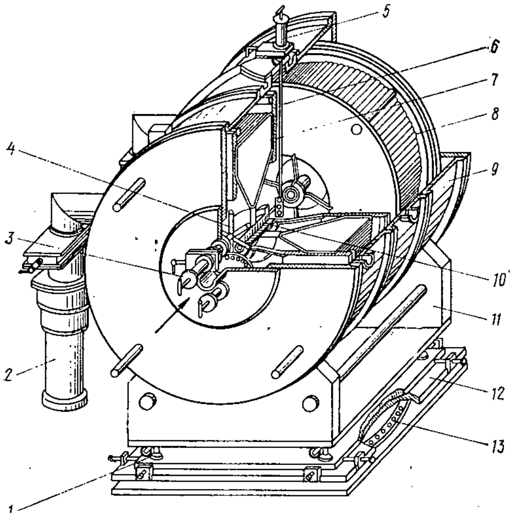

Fig. 2. Apel'sin-type β spectrometer: 1) height regulation; 2) diffusion pump; 3) side vacuum valve; 4, 6) target holder; 5) central vacuum valve; 7) lens body; 8) coil of toroidal lens; 9) vacuum jacket; 10) Pb shield; 11) support; 12) regulation in horizontal plane; 13) rotational track. (The arrows indicate possible paths of the accelerated-particle beam to the target.)

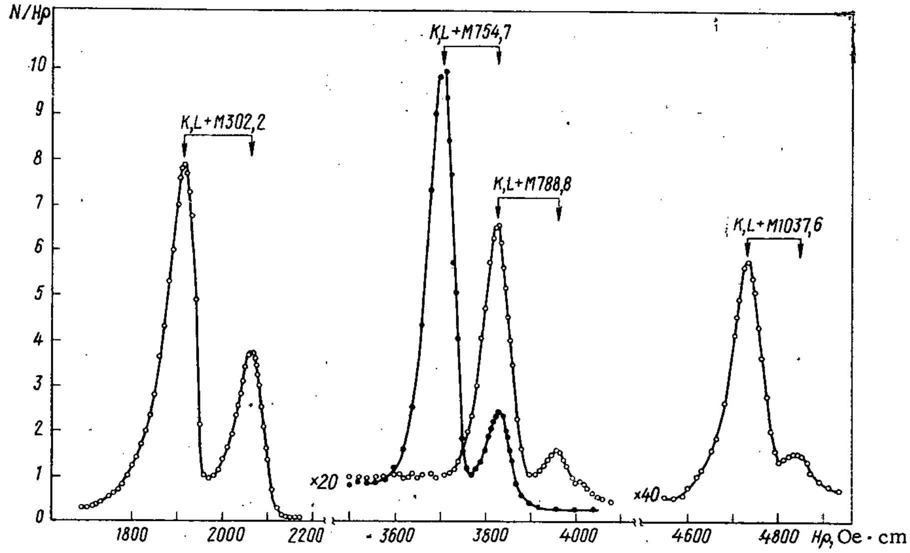

Fig. 3. ICE spectra of isomers: ○) ^{138m}Ce ($T_{1/2}$ = 8.6 msec); ●) ^{139m}Ce ($T_{1/2}$ = 60 sec), obtained in the reaction (α, 3n). The spectrum of ^{139}Ce was obtained in the second recording interval, beginning 100 msec after the beam pulse, and subtracted from the readings obtained in the first recording interval (of equal duration), beginning 1 msec after the current pulse.

Measurement Procedure

The activation method or the delayed-collison method cannot be used to investigate nuclei with half-life $T_{1/2} = 10^{-6}$–1.0 sec. In this case, an effective method is pulse irradiation of a target, recording the radiation in the intervals between accelerator current pulses.

In the present work, a linear proton accelerator with energy E_p = 20.8 MeV and a linear α particle accelerator with energy E_α = 38 MeV were used. The pulse-repetition frequency of both the accelerators was

TABLE 1. Isomers with Lifetimes of 10^{-4}–10^{-1} sec

Isomer	Reaction	$T_{1/2}$, msec	Isomer-state energy, MeV	J^{π}	Energy and multipolarity of isomer transition	Literature source
^{43}Sc	^{41}K $(\alpha, 2n)$ ^{40}Ca (α, p)	0,45	0,15	$3/2^{+}$	0,15; $M2$	[22]
^{46}V	^{46}Ti (p, n)	1,0	0,96			
^{71}Ge	^{71}Ga (p, n) ^{72}Ge (p, pn) Zn (α, xn) ^{69}Ga (α, pn) ^{72}Ge $(\alpha, \alpha n)$	22,4	0,198	$9/2^{+}$	0,024; $M2$	
^{75}As	^{76}Ge $(p, 2n)$ ^{75}As (p, p') ^{75}As (α, α')	17,1	0,305	$9/2^{+}$	0,305; $E3$ 0,025; $M2$	[23]
^{78}Br	^{75}As (α, n)	0,145	0,181	4^{+}	0,15; $M2$	[24]
^{88m_1}Y	^{88}Sr (p, n) ^{89}Y (p, pn) Rb (α, xn) ^{86}Sr (α, pn) ^{89}Y $(\alpha, \alpha n)$	14,8	0,673	8^{+}	0,442; $E3$	
^{88m_2}Y	^{87}Rb $(\alpha, 3n)$	0,3	0,393	1^{+}	0,393; $E3$	[25]
^{90}Nb	^{90}Zr (p, n) ^{89}Y $(\alpha, 3n)$	6,5	0,382	1^{+}	0,256; $E3$	
^{101}Tc	^{98}Mo (α, p)	0,8	0,19	$5/2^{-}$	0,19; $M2$	[22]
^{103}Ru	^{100}Mo (α, n) ^{104}Ru $(\alpha, \alpha n)$	1,8	0,21			[22]
^{109}In	^{107}Ag $(\alpha, 2n)$	215	2,11	$19/2^{+}$	0,68; $M3$	[26]
^{114}In	^{114}Cd (p, n) Cd (α, xn)	42	0,5	8^{-}	0,311; $E3$	[24]
^{115}Sn	^{116}Sn $(\alpha, \alpha n)$	0,155	0,725	$11/2^{-}$	0,107; $M2$	[27]
^{114}Sb	^{114}Sn (p, n) ^{112}Sn (α, pn)	0,23				
^{117}Sb	^{115}In $(\alpha, 2n)$	0,35	3,13	$25/2^{+}$	0,058; $M2$	[28]
^{117}Te	Sn (α, xn)	101	0,3			[29]
^{122}I	^{121}Sb $(\alpha, 3n)$	0,07	0,5			
^{132}Xe	^{130}Te $(\alpha, 2n)$	8,9	2,754	10^{+}	0,537; $E3$	[30]
^{128}Cs	^{127}I $(\alpha, 3n)$	4,4	0,071			
^{131}La	^{132}Ba $(p, 2n)$	0,16	0,17			
^{136}La	^{136}Ba (p, n) ^{137}Ba $(p, 2n)$ ^{133}Cs (α, n)	100	0,096			
^{137}La	^{138}Ba $(p, 2n)$	12	1,1			
^{138}Ce	^{139}La $(p, 2n)$ Ba (α, xn)	8,65	2,126	7^{-}	0,302; $E3$	
^{140}Nd	^{141}Pr $(p, 2n)$ ^{138}Ce $(\alpha, 2n)$	0,6	2,2	7^{-}	0,43; $E3$	
^{142}Pm	^{142}Nd (p, n) ^{143}Nd $(p, 2n)$ ^{141}Pr $(\alpha, 3n)$	2,28	0,885	8^{-}	0,435; $E3$	
^{146}Eu	^{147}Sm $(p, 2n)$	0,24				
^{153}Gd	Sm (α, xn)	0,08	0,12			[31]
^{155}Gd	^{154}Sm $(\alpha, 3n)$	30,8	0,122	$11/2^{-}$	0,014; $E1$	[31]
^{153}Tb	^{154}Ga $(p, 2n)$ ^{151}Eu $(\alpha, 2n)$	0,18	0,08			
^{159}Dy	Ga (α, xn)	0,14	0,356	$11/2^{-}$	0,118; $M1$ 0,218; $E2$ 0,09; $M1$	[32]
^{172}Lu	^{173}Yb $(p, 2n)$	0,45	0,133	1^{-}	0,07; $E1$	
^{176}Ta	^{175}Lu $(\alpha, 3n)$	1,1	1			
^{180}W	^{181}Ta $(p, 2n)$ Hf (α, xn)	5,6	1,530	8^{-}	0,39; $E1$	
^{183}Re	^{181}Ta $(\alpha, 2n)$	0,82	1,907	$25/2^{+}$	0,194; $E2$	[33]
^{187}Os	W (α, xn)	0,24	0,157	$5/2^{+}$	0,157; $M2$	[34]
^{187}Ir	^{188}Os $(p, 2n)$ ^{185}Re $(\alpha, 3n)$	30	0,187	$9/2^{-}$	0,187; $E3$ 0,077; $M2$	
^{188}Ir	^{187}Re $(\alpha, 3n)$	4,0				
^{189}Ir	^{190}Os $(p, 2n)$ ^{187}Re $(\alpha, 2n)$	13,4	0,372	$11/2^{-}$	0,72; $M2$	
^{192m_1}Au	^{191}Ir $(\alpha, 3n)$	32,5	0,135	5^{+}	0,258; $E3$ 0,63; $M2$ 0,103; $E3$	
^{192m_2}Au	^{191}Ir $(\alpha, 3n)$	164	0,431	11^{-}	0,06; $E3$	
^{194m_1}Au	^{193}Ir $(\alpha, 3n)$	600	0,092	5^{+}	0,011; $M2$ 0,056; $E3$	
^{194m_2}Au	^{193}Ir $(\alpha, 3n)$	39,2	0,46	11^{-}	0,07; $E3$	
^{199}Tl	^{200}Hg $(p, 2n)$ ^{197}Au $(\alpha, 2n)$	27,8	0,749	$9/2^{-}$	0,382; $E3$	[35]
^{201}Tl	^{201}Hg (p, n) ^{202}Hg $(p, 2n)$	1,8	0,93	$9/2^{-}$	0,23; $M2$ 0,6; $E3$	
^{204m_1}Bi	^{203}Tl $(\alpha, 3n)$	13	0,806	10^{-}	0,752; $E3$	
^{204m_2}Bi	^{203}Tl $(\alpha, 3n)$	1,07	2,793	16^{+}	0,275; $E3$	
^{206}Bi	^{205}Tl $(\alpha, 3n)$	0,89	1,044	10^{-}	0,905; $E3$	
^{207}Bi	^{205}Tl $(\alpha, 2n)$	0,2	2,1	$21/2^{+}$	0,743; $E3$ 0,456; $E3$	[34]
^{205m_1}Po	^{204}Pb $(\alpha, 3n)$	57	1,46	$19/2^{-}$	0,58; $E3$	
^{205m_2}Po	^{204}Pb $(\alpha, 3n)$	0,64	0,88	$13/2^{+}$	0,161; $M2$	

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*The works cited describe investigations of the isomers at KPI and not necessarily the first observation of the isomers.

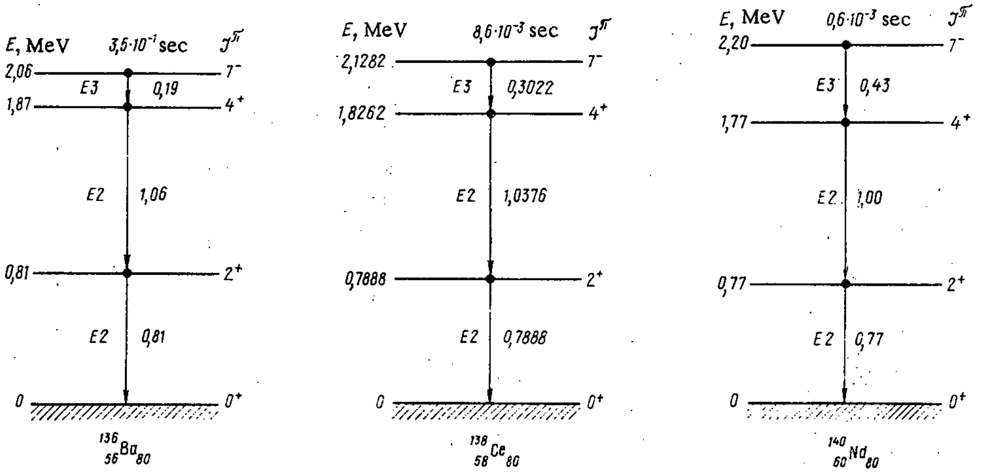

Fig. 4. Decay of two-particle isomeric states in even — even nuclei with 80 neutrons.

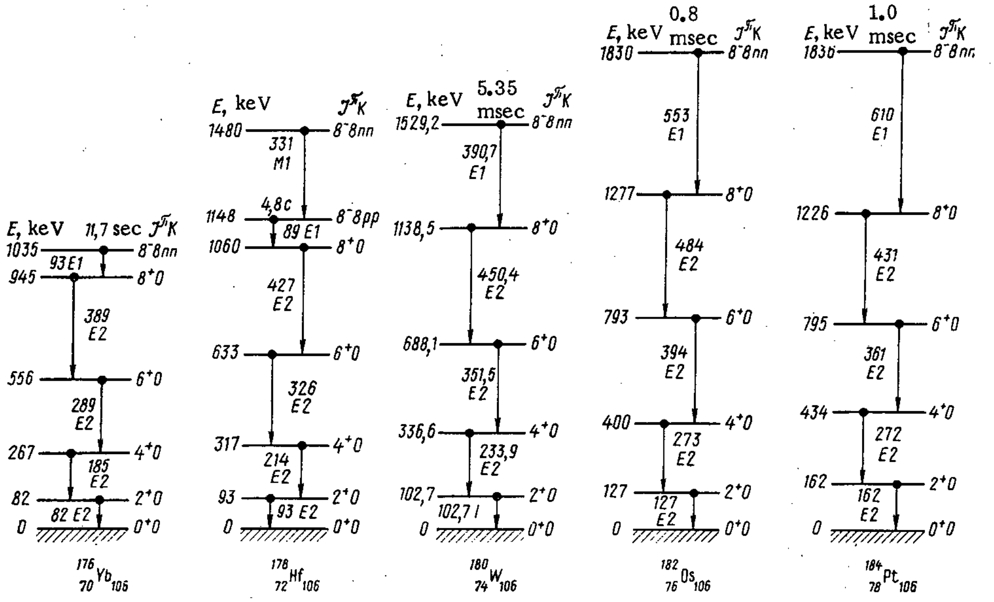

Fig. 5. Decay of two-particle isomeric states in even — even deformed nuclei with 106 neutrons.

2 sec^{-1}, with a pulse length ~500 μsec. These target-irradiation conditions ensured high selectivity in isolating the millisecond-isomer decay spectrum from the intense and complex γ radiation accompanying the decay of the reaction products formed with protons and α particles at these energies. "Instantaneous" radiation from the target was eliminated by obstructing the detector and the recording equipment during the irradiation, and the contribution due to the radioactive decay of the isotopes produced in the reactions was taken into account by time analysis of the spectra, which was facilitated by the half-life (>1 sec) of the background activity. This method allowed the decay of isomers with formation cross section ≥1 mb to be investigated against a background of activity with excitation cross section 1 b.

All the stable elements from carbon to bismuth (except the rare gases) were irradiated by protons and an α-particle beam. Information required for further investigations was obtained, regarding the background conditions associated with the use of various constructional materials in the beam path close to the detector or with the choice of chemical compounds for the targets when pure elements cannot be used. In addition, appropriate γ and β emitters for energy calibration of the spectrometers were chosen. The main isomer-excitation reactions were (p, n), (p, 2n), and (p, pn) for protons and (α, 2n) and (α, 3n) for α particles.

Measurement of Spectra of γ Radiation and Internal-Conversion Electrons

The energy spectrum of γ radiation was investigated using a scintillation NaI(Tl) spectrometer or a

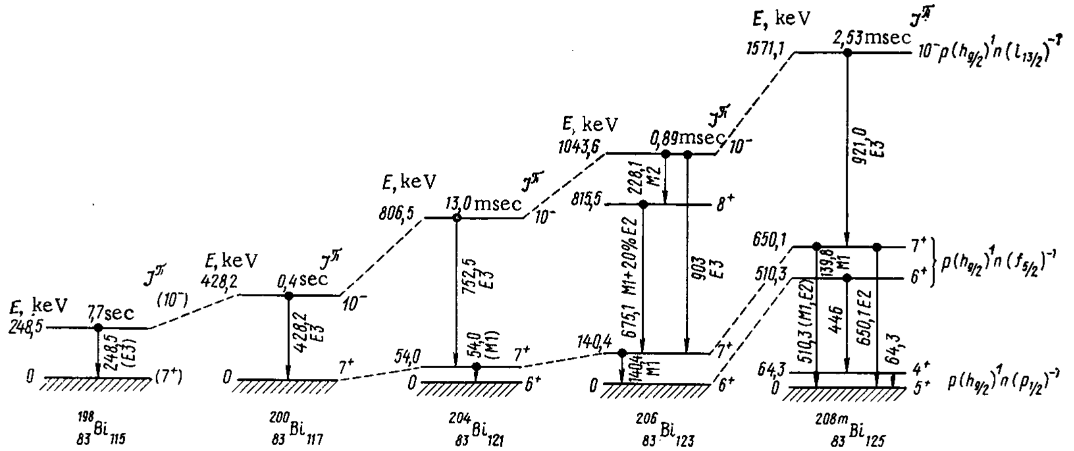

Fig. 6. Decay of 10^- two-particle isomeric states in odd — odd bound isotopes.

semiconductor Ge(Li) instrument. At various stages of the investigation an AI-100 single-channel pulse-amplitude analyzer (with division of the channels into two groups) and an AI-4096 multidimensional analyzer were used as the recording equipment. In all cases, recordings were made in two or more time intervals. In the first interval the spectrum of the isomeric γ radiation plus the background from long-lived activity was obtained. This interval follows, with some given delay, an accelerator current pulse of duration equal to 2-5 isomer-activity half-lives. In subsequent intervals (time groups) the longer-lived radiation was recorded. By this method, the background radiation could be reliably eliminated, or the spectra of several isomers appearing simultaneously at the target could be separated (Fig. 1).

The spectrum of internal conversion electrons (ICE) was investigated using magnetic analyzers: for the proton beam a spectrometer with improved focusing [5] and for the α-particle beam a nonferric two-lens spectrometer of Apel's in type (aperture ratio 20% of 4π) [6] (Fig. 2), which allowed (e, e) and (e, γ) reactions to be measured. As in the investigation of γ spectra, measurements of the electrons in the β spectrometer were made in two time intervals for each point of the spectrum. The exposure time was determined by monitoring the beam current. ICE spectra for cesium isotopes are shown in Fig. 3.

The half-lives were measured on multichannel time analyzers. The pulses from the γ detector were

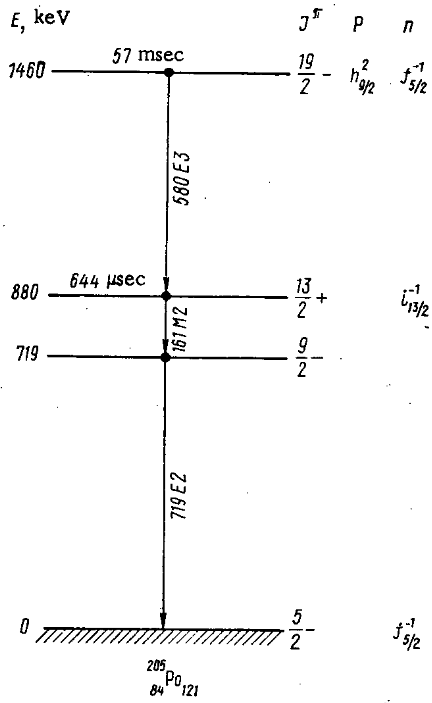

Fig. 7. Decay of isomeric states in ^{205}Po nucleus.

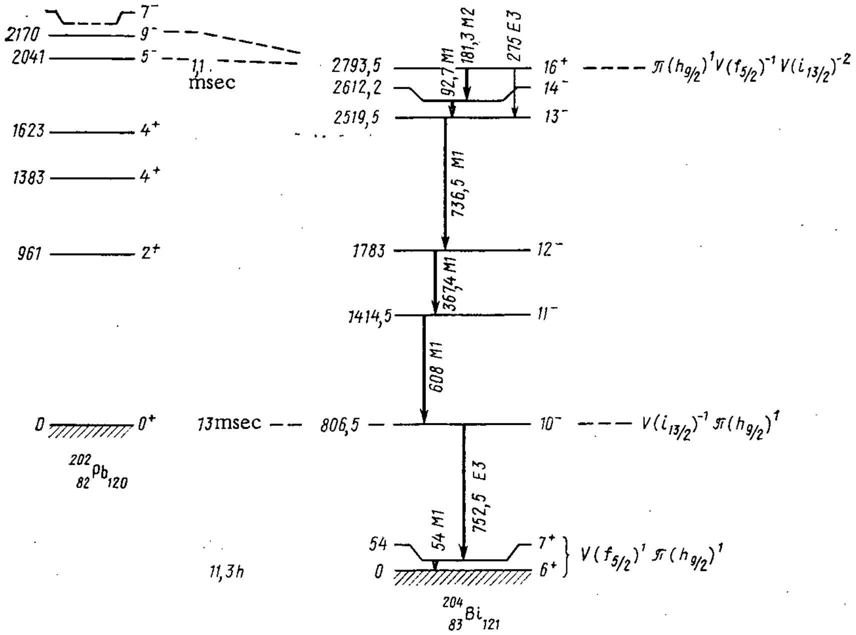

Fig. 8. Decay of high spin (16^+) isomeric state in ^{204}Bi nucleus.

preliminarily analyzed using a differential analyzer tuned to one of the peaks in the energy spectrum of the particular isomer. In the case of the ICE spectra, the magnetic analyzer was tuned to one of the conversion lines.

Identification of Reactions Leading to Isomeric Nuclei

The isotopes responsible for the formation of an isomer state are determined by comparing the yields of a given activity from targets excited by different isotopes of the same element. The type of reaction leading to the isomer is determined from the reaction threshold and the form of the excitation function for the given activity. For certain isomers the atomic number Z is determined from the energy of the x-ray K line (by absorption in filters [7]) or from the energy difference between K and L conversion lines in the electron spectrum.

Table 1 summarizes the results for nuclear isomers with lifetimes in the millisecond range, observed and studied at KPI.

The detailed study of multiparticle isomeric states with high excitation energy and spin is of particular interest, in connection with residual nucleon interactions in the atomic nucleus.

From an analysis of the experimental material obtained and the results of other experimenters, it is possible to identify certain patterns for various groups of nuclei, some of which are illustrated in Figs. 4-8.

Isomers ^{136m}Ba [9], ^{138m}Ce, and ^{140m}Nd [10]

These isomers belong to a rare group of isomers in even—even nuclei. In this group, the excitation energy of the isomeric state is relatively large (~2 MeV), the spin and parity are $I^{\pi} = 7^-$, and decay is by electric octupole transition to the collective level 4^+ (Fig. 4). The appearance of these levels in even—even nuclei is due to rupture of a neutron or proton pair, with the formation of a two-particle state. In this range of mass numbers a large nuclear spin may develop as a result of rupture of the neutron pair in the state $h_{11/2}$, when one neutron passes to the level $d_{3/2}$. In this case the spin of the isomeric state is determined by the configuration $n_1(h_{11/2})n_2(d_{3/2})$.

Isomers ^{176m}Yb [11], ^{178m}Hf [12], ^{180m}W [13], ^{182m}Os [14], and ^{184m}Pt [15]

These isomers also belong to a group of two-particle states in even—even deformed nuclei, formed by the rupture of neutron pairs. The spin and parity of the isomer level is 8^- for K = 8 and transition from this level to the rotational band of the ground state is due to radiation of type E1 with a strongly hindered prohibition on the quantum number K (Fig. 5).

Isomers $^{204m_1}Bi$ and ^{206m}Bi

In reactions between odd — odd bismuth isotopes with mass numbers 204 and 206 and α particles an isomeric state with spin and parity $I^{\pi} = 10^{-}$ has been observed and investigated; this state may be attributed to the particle-vacancy configuration $p(h_{9/2})^1 n(i_{13/2})^{-1}$. As well as these bismuth isotopes, the decay of the isomers ^{198m}Bi, ^{200m}Bi, and ^{208m}Bi [16] is shown in Fig. 6. Isomer states with $I^{\pi} = 10^{-}$ were also observed in ^{194m}Bi and ^{196m}Bi in [17].

The situation in ^{202}Bi remains unclear. To date, no isomer states with the above characteristics have been observed, although there exists a neutron-vacancy state $n(i_{13/2})^{-1}$ in the ^{201}Pb nucleus.

Isomer ^{205m}Po [18]

The three-particle isomeric state in the ^{205}Po nucleus with $T_{1/2} = 57$ msec was investigated in the reaction $^{204}Pb(\alpha, 3n)^{205m}Po$. This state with excitation energy 1460 keV and spin and parity $I^{\pi} = 19/2^{-}$ is discharged by electric octupole transitions to the 880-keV level ($I^{\pi} = 13/2^{+}$), which is a single-particle isomeric state with configuration $n(i_{13/2})^{-1}$ [19].

The three-particle isomeric state in odd isomers of polonium is due to a combination of two-proton excitation of the nuclear core of polonium and single-neutron excitations known in the corresponding lead isotopes (isotones of polonium). Such states are known in ^{205}Po, ^{207}Po, ^{209}Po, and ^{211}Po [20]. The decay of states in ^{205}Po is shown in Fig. 7.

Isomer $^{204m_2}Bi$

In the ^{204}Bi nucleus a four-particle isomeric state with excitation energy 2795 keV and spin and parity $I^{\pi} = 16^{+}$ has been discovered and investigated. It decays by a directed cascade of transitions to the isomeric state $I^{\pi} = 10^{-}$. The large spin (16) of this isomer cannot be described by a two-particle configuration because the interaction of two particles at the level $i_{13/2}$ gives a maximum spin $I = 12$. It was shown in [21] that the spin 16^{+} arises as a result of a combination of configurations of two-neutron states in the neighboring even — even nucleus $^{202}_{82}Pb_{120}$ with configurations responsible for isomers in odd — odd bismuth isotopes.

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ANNIHILATION AS AN ENERGY SOURCE

N. A. Vlasov

UDC 539.1

I. V. Kurchatov discovered for his native land how to use the energy from nuclear transformations. The progress in nuclear power, which began in his lifetime and under his leadership, has stimulated the search for new possibilities. The possibility of using annihilation as a fuel process appears to be the most tempting of all possibilities. You see, a kilogram of annihilating antimatter is equivalent to a ton of nuclear fuel. The use of annihilation fuel has already been discussed in the technical literature. However, because of the lack of systematic data about the physical characteristics of the annihilation process, inventive technical ideas at times go off in unreal directions. The required physical data are either completely unavailable or scattered throughout a vast set of original papers and reports. Although the outlook for technical use of annihilation is still far from clear, the search for it will, of course, continue. The known physical characteristics of annihilation are presented in this paper. They may be useful in selecting a path along which to search and in limiting unnecessary flights into wild fantasy.

The annihilation of antiparticles in collisions with particles usually turns out to be the conversion of a pair into lighter or massless (with zero rest mass) particles such as photons. Consequently, annihilation transforms rest energy either into kinetic energy of particles of lesser mass or into radiated energy which is transmitted at the speed of light. In the known power processes of combustion and explosion, the same thing occurs; some portion of the rest energy is converted into heat, i.e., into the kinetic energy of atoms and molecules. Qualitatively, annihilation is a typical energy process. Quantitatively, it is the most intense. The specific energy release (heating power) of annihilation is extremely high; rest energy is completely converted into heat and radiation. The most intense of the known processes — thermonuclear fusion of light nuclei — converts only ~0.5% of the rest energy. Theoretically conceivable, but as yet unknown, methods for extraction of gravitational energy by means of bodies such as black holes essentially promise no more than 30% of the rest energy. The outstanding heating power also draws attention to annihilation. Laboratory studies of annihilation yielded many interesting results in the physics of elementary particles [1]. In nature, the formation and annihilation of pairs takes place on a grandiose scale in all likelihood. For example, it is assumed that matter in the "hot" universe during the early stages of its evolution consisted predominantly of an equal number of nucleons and antinucleons which were annihilated during expansion [2]. It is possible that some cosmic explosions now being observed were the result of annihilation. Little is known about this as yet, but experience demonstrates that nature provides a wealth and variety of conditions and that it uses lavishly and positively phenomena which man manages to observe with difficulty here on earth.

Annihilation Products. Any antiparticle can annihilate with the corresponding particle (opposite in sign of charge). However, we focus our attention on the annihilation of pairs of stable particles and antiparticles, i.e., of positrons and electrons and of antiprotons and protons. The lifetime of unstable particles is too short

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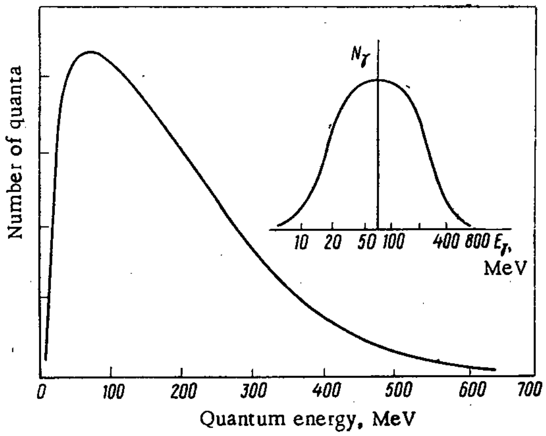

Fig. 1. γ-ray spectrum for annihilation of nucleon pairs at low energy (in inset, a logarithmic energy scale).

on an everyday scale. Of the unstable particles, only the annihilation of the antineutron, which has much in common with the annihilation of the antiproton, has been observed thus far. The annihilation of antinucleons and nucleons, which are the main carriers of the rest energy of matter, is most worthy of attention.

The annihilation of nucleon pairs ($\bar{p} + p$, etc.) occurs predominantly through the strong (nuclear) interaction. The effective annihilation cross section is about half the total interaction cross section over a very broad energy range [3]. At low energy (<100 MeV), the annihilation cross section can be represented in the form $\sigma = \sigma_0 E^{-1/2} = 1100E^{-1/2}$ (σ, mb; E, MeV).

The annihilation probability ($k\sigma v = 1.5 \cdot 10^{-15} k\ \mathrm{sec}^{-1}$) is practically independent of energy. The lifetime of an antiproton in a medium with a proton density k (cm^{-3}) is $\tau = 1/k\sigma v = 0.66 \cdot 10^{15}/k$ sec. Protonium — an atom made up of the pair $\bar{p} + p$ bound by electromagnetic forces — can be formed at low relative energy with appreciable probability. The lifetime of free protonium (~10^{-6} sec) is determined by radiative transitions from highly excited states. Annihilation becomes more probable than radiative transitions in the lower states starting with the first excited state. The probabilities and lifetimes of protonium in s and p states are [4]

$$\lambda(n, s) = 5.3 \cdot 10^{18}/n^3,\ \mathrm{sec}^{-1};\quad \tau_s = 0.2 \cdot 10^{-18} n^3,\ \mathrm{sec};$$
$$\lambda(n, p) = 4.3 \cdot 10^{14}/n^3,\ \mathrm{sec}^{-1};\quad \tau_p = 0.24 \cdot 10^{-14} n^3,\ \mathrm{sec}.$$

Here, n is the principal quantum number.

The primary annihilation products are pions. Of the other products, one need only mention kaons, but they are relatively few and, like the even rarer and heavier mesons, decay very quickly into pions (~10^{-8} sec). The number of pions ranges from 2 to 12 but is ~5 on the average. This means that the average energy of a pion is $2Mc^2/5 = 380$ MeV including a kinetic energy $380 - 140 = 240$ MeV. Each pion (π^+, π^0, or π^-) is formed with equal probability on the average and one fifth of the total annihilation energy can be assigned to each. It is, of course, necessary to average over the complex shape of the pion spectrum in making rigorous calculations of the energy balance and other qualitative characteristics of the process. However, for many current problems it is sufficient to use averaged values in the hope that the exact values will be sufficiently close to them.

At ≈10^{-6} cm from the point of birth of a π^0 meson, which has a lifetime of $0.8 \cdot 10^{-16}$ sec, it decays into a pair of photons. In practically any medium, a π^0 meson fails to interact and lose energy so that the spectrum of quanta from π^0 decay does not depend on the medium until the interaction with the medium of the quanta themselves is taken into consideration.

The annihilation spectrum for π^0 mesons has not been studied but one can assume that it is similar to the spectrum for charged pions. The spectrum of γ rays from the decay of annihilation pions shown in Fig. 1 was calculated on the basis of this assumption [5]. The spectral maximum is at 70 MeV, which corresponds to the decay of a π^0 meson at rest. The kinetic energy of a π^0 meson is transferred to decay quanta and the spectrum is broadened as the energy increases. If the energy scale is made logarithmic (inset in Fig. 1), the spectrum takes the form of a bell-shaped curve which is symmetric with respect to the maximum at 70 MeV. The width of the curve at half-height (~250 MeV) agrees with the average kinetic energy of the π^0-meson spectrum; only the width and shape changes. Thus a broader symmetric curve corresponds to the decay of cosmic π^0 mesons, which are of a greater energy on the average. Distortion of the primary spectrum may

TABLE 1. Final Products and Energy Distribution for $\bar{p} + p$ Annihilation in Vacuum

Product	Average number	Average energy, MeV	Total energy, MeV	Energy fraction, %
e^-	1,6	100	150	
e^+	1,6	100	150	16
γ	3,3	190	600	34
$\nu + \bar{\nu}$	10	100	900	50

become noticeable if the thickness traversed by the quanta exceeds a radiation length, which is ~40 g/cm^2 for a hydrogeneous medium.

Charged pions decay in accordance with the scheme

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu});\ \mu^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_{\mu}(\bar{\nu}_{\mu}).$$

The final decay products are neutrinos, electrons, and positrons (see Table 1).

Neutrinos carry off about half the annihilation energy. However, their fraction can be significantly less if annihilation occurs in a dense medium where the charged pions are slowed down before decay. The slowing-down range of a pion becomes equal to the decay range (~20 m) at a density of ~0.05 g/cm^3. In condensed matter, pions decay after complete loss of kinetic energy so that the neutrinos carry off only a fraction of the pion rest energy. This fraction is ~9% of the energy of the annihilating pair [5]. In the decay of a stopped pion, approximately one-third of the energy (3%) is transferred to electron neutrinos and two thirds (6%) to muon neutrinos. Half of the muon neutrinos have the same energy (~30 MeV) and the other half form a continuous spectrum up to 50 MeV.

If one has in mind the technical use of annihilation, it is clear that it is not difficult to realize conditions in which the neutrinos carry off only 9% of the energy with the remaining 90% kept in a device. It is known that neutrinos carry off about 3% of the fission energy from a nuclear reactor, and ~5% and more of the energy of thermonuclear fusion in the sun and stars. Hawking [6] recently made a theoretical prediction of still another energy source — the decay of black holes. In this decay, which takes place more rapidly the smaller the mass of the black hole, rest energy is completely converted into radiation energy, and the decay leads to disappearance of the baryon charge contained in the nucleons of the black hole. Neutrinos may be one of the radiations into which black holes decay. The fraction of the energy carried off by the neutrinos is ~50% depending on the initial mass of the black hole [7]. Therefore, with respect to energy loss to the elusive neutrinos, annihilation is similar to other energy sources and is even more favorable than the most intense of them.

Positrons and electrons obtain energy during annihilation from decaying muons and their spectra depend on the density of the medium. If pions are slowed down before decay, the positrons have an average energy of ~40 MeV, but π^- mesons may be captured by nuclei and cause spallation resulting in a transfer of the energy to nucleons. The positron lifetime in a vacuum is infinite (they are stable), but in a medium containing electrons it is limited by the possibility of annihilation and depends on the electron density n ($\tau = 10^{14}/n$ sec).

The γ-ray spectrum from e^+e^- annihilation depends on conditions. If the initial energy of the positrons is about 100 MeV and they are slowed down by collisions with electrons, ~25% annihilate during deceleration. The γ-ray spectrum is similar to the spectrum shown in Fig. 1, but the maximum occurs at 0.5 MeV and the "right-hand tail" stretches to 100 MeV. The majority (~75%) of positrons are thermalized and their kinetic energy can usually be neglected. The γ-ray spectrum for the annihilation of slow positrons has the form of a γ line with an average energy $E\gamma = mc^2 = 0.511$ MeV and a width of ~10 eV. However, there can be conditions where positronium, i.e., an e^+e^- atom, is formed before annihilation. If the positronium lives freely till annihilation, the γ line at $E = 0.511$ MeV carries away only one fourth of the energy of the e^+e^- pair. In the remaining cases, orthopositronium is formed. It undergoes three-quantum annihilation with a continuous spectrum over the range from 0 to 0.511 MeV. Parapositronium, which undergoes two-quantum annihilation, is formed one third as often as orthopositronium. Suitable conditions exist in interstellar space, for example, where the time between particle collisions is greater than the lifetime of orthopositronium (~10^{-7} sec).

Muons are the longest-lived intermediate products of the annihilation of nucleon pairs. Their lifetime at rest is ~2 μsec. Allowance for velocity increases this time by factors of 2.5-3. Consequently, only the final products — electrons, positrons, γ rays, and neutrinos — remain at <3 km (in a vacuum) from the point

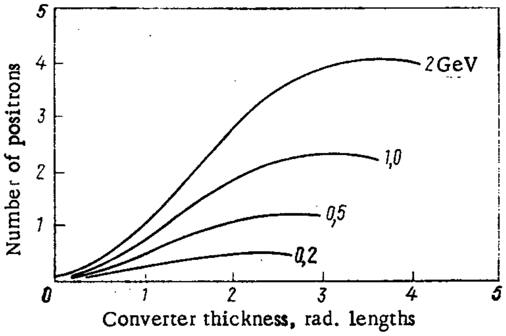

Fig. 2. Positron yield for tungsten targets of varying thickness bombarded by electrons of varying energy.

of annihilation of nucleon pairs before 10 μsec has elapsed. These products are stable in a vacuum. In an actual medium, the positrons annihilate and the quanta exchange energy with the medium. The neutrinos carry off energy into the boundless void of the universe, but the amount of this energy can be controlled by changing the density of the medium.

Production of Antimatter. Annihilation might acquire practical importance for power engineering if methods were known for the accumulation of antimatter in macroscopic amounts. There are no reserves of antimatter in reachable regions of space, at least in the solar system. Consequently, there are only artificial technical means for the production of antimatter.

Many methods for the production of antiparticles are known from laboratory studies in physics. Practically any type of particle collision can create a pair (antiparticle plus particle) if the kinetic energy of the colliding particles exceeds the rest energy of the pair to be created. Both positrons and antiprotons have been used for some time in various studies in physics laboratories. Positrons were discovered earlier, their mass is smaller, and they are simpler to produce than antiprotons so that there is more abundant experience in their use. Positrons from radioactive sources are widely used. However, these experiments are performed by piecewise counting of events occurring with individual positrons. The largest of the radioactive positron sources used thus far has a power of no more than 10^{-3} W. Obviously, there is great interest in a direct method for the production of positrons which are used in devices with clashing electron — positron beams. For quite a few years now positrons have been circulated in the storage rings of such devices in several laboratories, particularly the one at Novosibirsk [8, 9]. Devices with clashing beams are mainly intended for fundamental studies in elementary-particle physics and in electrodynamics. Methods for the formation of positron beams were studied both theoretically and experimentally in a search for optimal conditions for the production of positrons and their introduction into a magnetic ring.

In outward appearance, the method for positron production consists of bombardment of a solid target with fast electrons. Bremsstrahlung from the electrons forms pairs; positrons from the pairs emerge from the target. Consequently, transformation of a part of the electron beam into a positron beam occurs in the target and therefore such a target is usually called a converter in laboratory practice. The positron yield from the target is quantitatively characterized by the conversion coefficient — the ratio between the number of positrons and the number of bombarding electrons. Figure 2 shows the results of a calculation [10] of the conversion coefficients for tungsten targets of varying thickness and for bombarding electrons with energies up to 2 GeV. At small thicknesses, the positron yield depends linearly on thickness (T) and can be represented by the expression

$$N_+N_- = 2.4 \cdot 10^{-4} E^{3/2}\ \mathrm{T}.$$

The yield reaches a broad maximum at a thickness of 2-3 radiation lengths. One positron can be produced for each 2-3 electrons at E = 200 MeV.

Using the curves in Fig. 2, one can determine the coefficient for transformation of electron energy into rest energy of a pair, which is released during annihilation. Figure 3 shows the dependence on electron energy of the ratio N_+/N_-E_-, which can be taken as the energy transformation coefficient if the energy is expressed in MeV. The transformation coefficient reaches a maximum value (~0.003, i.e., 0.3%) at E = 100-200 MeV and then falls slowly.

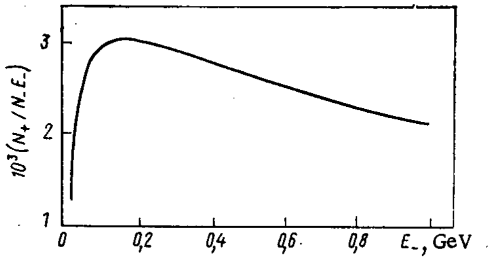

Fig. 3. Coefficient for transformation of electron energy into pair rest energy.

If there were a method for storage of positrons for subsequent use as annihilation fuel, the entire storage and utilization cycle would operate at no more than 0.3% efficiency. However, positron storage is a difficult problem. Positrons can be kept for an infinitely long time in a vacuum. However, they annihilate rapidly in matter by colliding with electrons. In matter with an electron density n, the lifetime is $\tau = 10^{14}/n$ sec. For condensed matter, $n \approx 10^{23}$ cm^{-3} and $\tau \approx 10^{-9}$ sec. Positrons quickly annihilate by striking the walls of a storage chamber. To keep them from contact with the walls is more difficult than for a hot plasma since the accumulation of their positive charges builds up a repulsive electric field. Neutralization of the charge with electrons once again leads to annihilation and limitation of lifetime.

In principle, it is convenient to store neutral antiatoms, antihydrogen for example, if the possibility of contact with matter is eliminated. Therefore, the storage of antimatter must inevitably begin with the production of antiprotons. This first and most important step primarily limits the efficiency of antimatter storage, i.e., the efficiency of conceivable power devices.

Antiprotons can be produced by using various mechanisms for the formation of nucleon—antinucleon pairs. The most effective of known methods is the bombardment of nuclei by accelerated protons. In this case, pairs are formed as a result of the strong interaction. The threshold energy for the proton is $6Mc^2 = 5.6$ GeV if the target consists of individual nucleons (hydrogen). The threshold for complex nuclei is lower, but a marked rise in the cross section is observed for energies exceeding $6Mc^2 =$ Pions — the lightest hadrons [11] — are formed with greatest probability in p—p collisions. The probability for formation of nucleon pairs increases monotonically with increase in proton energy. However, the coefficient (ξ) for transformation of proton energy into rest energy of a pair reaches a maximum at ~10 GeV [5] ($\xi = 0.7 \cdot 10^{-3} = 0.7\%$). If there were no excessive consumption of energy in the acceleration of the protons and no loss in the collection of the antiprotons, this value might be considered the maximum transformation efficiency. In fact, those and other losses are rather large and the actual efficiency is at least an order of magnitude less.

In principle, the formation of nucleon pairs is possible by means of any of the known types of interaction such as the electromagnetic interaction. The formation of antiprotons by high-energy photons was observed in Hamburg [12]. In the bombardment of nitrogen by bremsstrahlung with a maximum energy of 6.2 GeV, 178 antiprotons with a momentum of 2 GeV/sec were recorded per $5.9 \cdot 10^{13}$ quanta. Furthermore, $\bar{p}/\pi^- = 5.25 \cdot 10^{-4}$.

The formation of pairs in the gravitational field was also discussed in cosmological papers [2, 7]. Fomin [13] found that the gravitational field creates instability of the vacuum and that this can lead to dissociation of the vacuum into pairs. Hawking [6] showed that in the strong gravitational field near a black hole "splitting" of the vacuum into pairs must occur with one of the components of the pair being emitted to the outside.

In the cosmological model of a "hot" universe, the thermodynamically stable concentration of nucleon —antinucleon pairs is maintained by electromagnetic interaction of quanta with electrically charged particles, and the number of pairs with $Mc^2 \leqslant kT$ (T is temperature) is roughly equal to the number of quanta. If there are regions of the universe in which the temperature is so high that $kT \sim Mc^2$ or the force fields are sufficient to split the vacuum into pairs, the formation of matter and antimatter should occur in such regions on a macroscopic scale.

In the elementary collisions of particles studied in current physics, short-term conditions are created for single splitting of the vacuum into a pair, i.e., for formation of one pair, or more rarely, two pairs. If future science finds a means for creating such conditions and maintaining them for a longer time, it will have found an efficient method for the production of antimatter.

The production of electrically neutral atoms of antihydrogen is possible through recombination of antiprotons with positrons. Such a problem has already been practically solved in the physics laboratory. To do this, it is necessary to mix beams of antiprotons and positrons having selected similar velocities for those and other antiparticles. Recombination with the formation of antihydrogen is unavoidable in the mixed beam. Similar recombination of protons with electrons was observed in Novosibirsk [14], where a method for "cooling" a proton beam with electrons was devised and tested. The interaction of antiprotons with positrons is in no way different from the interaction of protons with electrons and the probability of recombination is identical under like conditions. The problem of storage and buildup of neutral antimatter is considerably more complex and still far from solution. From this viewpoint, it is more advantageous to deal not with antihydrogen but with antimatter in a slightly condensed state. However, the production of complex antinuclei is considerably more difficult than the production of antiprotons. First, beams of protons with energies considerably above 10 GeV are necessary since the threshold for pair formation is increased. The threshold for formation of a pair with mass number A in a nucleon—nucleon collision is 4A(1 + A/2) for A = 0.94 GeV. Protons with energies greater than 90 GeV are necessary for the formation of $^6\overline{\text{Li}}$. Second, even with sufficiently high energy, the emergence of individual antinucleons is more probable than the emergence of a combination of them in a complex antinucleus. This reasoning has already been verified by the experiments performed thus far. In Serpukhov, e.g., at $E_p = 70$ GeV, five ^{3}He antinuclei were produced in a background of $2.4 \cdot 10^{11}$ other negatively charged particles [15] and the yield of antideuterons was five orders of magnitude less than the antiproton yield. The yield ratio $\overline{d}/\overline{p}$ increased, but rather slowly, as the energy of the proton beam increased. Thus, when $E_p = 300$ GeV, this ratio was $\sim 10^{-4}$ [16]. Thus far, lithium antinuclei have yet to be produced in the laboratory.

The energy resources of mankind are growing and are approaching unlimited capabilities with the mastery of thermonuclear fusion of light nuclei. Under certain specific conditions such as in space flight, a compact annihilation fuel may prove to be a definite necessity. Perhaps mankind might find it acceptable to consume several megawatt-years of terrestrial sources in order to produce a kilowatt-hour of such a fuel. However, it is not known how to do this as yet. Unfortunately, the difficulties are more clearly visible than the actual means for technical mastery of annihilation as a fuel source.

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THIRTY YEARS OF WORK AT THE FIRST NUCLEAR LABORATORY AT DUBNA

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UDC 539.12:539.14:539.1.07:537.532.4

The development of nuclear physics in the Soviet Union in the post-war period has included many notable events. One such took place in the small township of Novo-Ivankova (new Dubna), situated on the Volga River near Moscow, where on Dec. 14, 1949, the first high-energy particle accelerator in the Soviet Union — a 5-m synchrocyclotron — went into operation. This occurred in the branch of the Institute of Atomic Energy (IAE) established in the town in 1948. The complex startup of this accelerator, at that time the largest in the world, and the production first of 280-MeV deuterons and 560-MeV α particles and then of 480-MeV protons, opened up a whole new field of nuclear physics in the Soviet Union — the physics of high-energy particles. In 1953 the synchrocyclotron was reconstructed: the diameter of the magnetic poles was increased to 6 m and the proton energy to 680 MeV [1].

The inspiration for the building of this then-unique accelerator came from I. V. Kurchatov. A man of exceptionally broad scientific vision, encompassing both scientific and important state matters, Kurchatov not only devoted himself to the nationally important and very considerable problems of developing an atomic capability for national defense and practical applications for atomic power, but also showed great concern for the development of nuclear physics and the creation of the necessary base for fruitful fundamental research in the fields of nuclear and elementary-particle physics.

Kurchatov's role in the solution of fundamental problems, both in the construction of the accelerator and in the organization of physical research after its completion, was inestimably large. As is known, it was on his initiative that the large-scale international nuclear center of the socialist countries — the Joint Institute for Nuclear Research (JINR) — was founded at Dubna in 1956. Opened under the auspices of the Institute of Nuclear Problems of the Academy of Sciences of the USSR, the Nuclear Reactions Laboratory (NRL) with the 680-MeV synchrocyclotron became the first modern physics research center for the international team of scientists from JINR member-nations.

As a result of improvements made largely after the founding of JINR, the NRL synchrocyclotron remains today the best accelerator of its type in the world, in terms of the intensity of the accelerated particles and the reliability of accelerator operation. Whereas the accelerated-proton current was 0.25 μA in 1956, today it is 3.5 μA ($2.2 \cdot 10^{13}$ protons/sec). The high reliability of the synchrocyclotron ensures 155-160 h of research work each week. The accelerator can provide a large number of different beams of protons, neutrons, pions, and muons.

At present, the reconstruction of the NRL synchrocyclotron as a high-current phasmotron is under preparation. After this reconstruction and the introduction of a more efficient system of particle output, the beam intensity will be increased by a factor of 50-100.

For many of the scientists at the NRL, the logical continuation of research on the synchrocyclotron is to carry out experiments on the 10-GeV synchrophasmotron of the JINR High-Energy Laboratory (HEL), on the 76-GeV accelerator of the Institute of High-Energy Physics (IHEP), or on the 6-GeV accelerator of the Erevan Physics Institute (EPI). However, research on synchrocyclotron particle beams remains the main preoccupation of the NRL team.

In recent years it has become clear that proton accelerators with a particle energy of ~1 GeV and high beam intensity may be used to investigate various applied problems. Of these, the best known are research into proton and pion cancer therapy, medicobiological research associated with radiation safety on human spaceflights, research on the radiation stability of materials and electronic equipment, and the production of a great number of radioactive isotopes, both for medical use and in various other fields of science and technology.

It is fitting, in an issue commemorating the 75th anniversary of the birth of I. V. Kurchatov, to review

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the most important results obtained in almost 30 years of research on the 680-MeV synchrocyclotron, by scientists from the Soviet Union and the other socialist member-countries of JINR.

Elastic Nucleon — Nucleon Scattering

The NRL has a long tradition of research in this field and its contribution is very well known and internationally recognized.

The first results obtained at Dubna on the elastic scattering of neutrons by high-energy protons [2] was completely unexpected and quickly drew the attention of physicists everywhere. The scattering of neutrons by protons was investigated at energies of 200-590 MeV. The scattering of protons by protons at particle energies of 460-670 MeV has been more thoroughly investigated on the synchrocyclotron [3]. The aim of the series of experiments of nucleon — nucleon scattering was to determine the amplitude of the scattering and its individual components, not only by highly accurate measurements of the cross sections for elastic and inelastic interaction between unpolarized particles, but also by the detailed study of the polarization characteristics of the scattering [4]. The results of the polarization experiments were very informative, although a number of difficulties attach to the experiments, since it is necessary to observe events of double and triple particle scattering. Special methods were developed at the NRL to overcome these difficulties. One of these which has been adopted throughout the world is an original method of obtaining superlow temperatures, by dissolving liquid ^{3}He in ^{4}He [5]. By this means, a highly effective polarized proton target can be obtained and experiments that were previously impossible to carry out with the necessary accuracy become possible. Theoreticians have played an important part in developing the research programs on nucleon — nucleon scattering [6]. Another approach by which spin dependences of nuclear forces may be investigated is the study of nucleon collisions with deuteronic nuclei, in which nucleons effectively lie in a polarized target [7].

As a result of a broad program of experiments at the NRL, it has been possible to conduct a detailed phenomenological analysis of nucleon — nucleon interactions, to make a unique determination of the amplitude of proton — proton scattering, and to estimate the most important characteristics of neutron — proton interactions in the investigated energy range.

The experimental verification of the general symmetry principles underlying strong particle interactions is of great importance. In investigating elastic nucleon — nucleon scattering, one of these principles was experimentally verified — the charge symmetry of nuclear forces. This was demonstrated in unique experiments at the NRL on the scattering of neutrons by high-energy neutrons [8], in which it was also possible to demonstrate another fundamental property of nucleon — nucleon interactions — their reversibility in time. This was shown with an accuracy that has yet to be surpassed [9]. Knowing the amplitude and phase of nucleon — nucleon [10] and pion — nucleon [11] scattering, it is possible to make an independent determination of the pion — nucleon interaction constant, characterizing the mesonic charge of the nucleon.

Meson Formation in Nucleon — Nucleon Collisions and Pion — Nucleon Interactions

A second important research area in which the NRL has a long tradition of activity is the study of processes leading to pion formation in collisions of protons, neutrons, and pions with protons and atomic nuclei. A brief idea of this great volume of research may be obtained by noting two of the most important and scientifically best known results: the most direct and accurate proof of the isotopic invariance of strong interactions [12], and the detailed and reliable experimental data on pion production in nucleon — nucleon collisions [13], which led subsequently to the construction of a resonance model [14] accounting for the main features of meson production in the subbillion energy range.

The energy spectra of charged and neutral pions formed in nucleon — nuclear collisons at 660 MeV were analyzed at the NRL. The pion spectra were found to be dependent on the size of the irradiated nuclei, and intense charge exchange of pions in the nucleus was observed [15].

The study of the interaction between two unstable particles which are quanta of strong interactions — pions — is an exceptionally pressing and complex problem. At the NRL the photoemulsion method has been used to investigate the formation of pions by pions close to the energy threshold for their creation, and the length of the pion — pion interaction has been determined [16].

A systematic study of pion — proton interactions at particle energies up to 370 MeV has been completed at the NRL, with the determination of total and differential cross sections for various processes of pion scattering and recharging and also the polarization in pion — proton scattering [17].

As a result, the dispersion relations rigorously derived by N. N. Bogelyubov have been experimentally verified. The direct verification of the most fundamental ideas of theoretical physics is of the greatest importance, especially as the dispersion relations are based on such fundamental principles of field theory as unitarity and microcausality.

Elementary-Particle Structure

Research on the scattering of high-energy electrons at various accelerators throughout the world has yielded data on the distribution of charge density and magnetism in atomic nuclei. The next important step is to study the structure of elementary particles.

In a certain range of transferred momentum, the structure of pions, nucleons, and the pion — nucleon resonance Δ(1236) may only be investigated in the process inverse to the generation of a pion from an electron $\pi^- + p \rightarrow e^+ + e^- + n$, and cannot be investigated in other processes. A specially developed complex and very effective electronic apparatus has been used at the NRL to obtain previously unavailable experimental data in the nucleon and pion form factors in the range of small momentum-transfer times [18].

Some years ago it was discovered that the electrical radius of the proton is not sufficiently reliably defined, since there is a lack of data directly in the range of small transferred momenta in elastic e — p scattering. A new program of research, in which particles corresponding to low-energy transfer were recorded by semiconductor detectors, was conducted jointly by physicists from Dubna, Erevan, and Bucharest [19] on the EPI accelerator. As a result, the charge radius of the proton was determined directly from experimental data on e — p scattering at the limit of small angles, without assuming any dependence of the proton form factor in the range of large transferred momenta. Similar experiments on the scattering of high-energy electrons by deuterons led to the direct determination of the electrical radius of the deuteron.

Weak Interactions

A number of important scientific results have been obtained at the NRL in experiments on weak interactions, most notably the discovery of the β decay of pions, which involved the use of an exceptionally sensitive method [20]. These experiments proved the fundamental law of weak-interaction theory — the law of vector-current conservation, proposed by the Soviet theoreticians Gershtein and Zel'dovich [21].

Another major scientific event was the demonstration by Pontecorvo and Markov of the possible existence of a new type of neutrino — the muonic neutrino — and also Pontecorvo's proposal for an experiment to observe such a neutrino on a high-energy accelerator [22]. When such experiments were carried out (in the U.S.A.), the muonic neutrino was indeed observed.

In experiments on the capture of negative muons in ^{3}He at the NRL [23], the transfer of a muonic neutrino was observed for the first time. These experiments allowed an upper limit to be set on the muonic neutrino mass, and established the fundamentally important result that in weak interactions the properties of the muon and the electron are identical.

The investigation of the nuclear capture of negative muons by protons ($\mu^- + p \rightarrow n + \nu_\mu$) is of great interest for the physics of weak interactions. At the NRL a difficult experiment using an electronic method and a gaseous hydrogen target led to a determination (with good accuracy) of the main characteristics of this process — its probability. The results proved that the theory of the universal Fermi weak interaction is correct and provided accurate information on the constants of this interaction [24]. To verify the theory of the universal weak interaction, a group of scientists from the IAE and the NRL carried out precision experiments on the synchrocyclotron to determine the asymmetry coefficient in the angular distribution of positrons emitted in muon decay ($\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$). The value obtained for this coefficient (0.326 ± 0.005 [25]) is the most accurate and one of the strongest arguments in support of the theory of a longitudinal neutrino.

The existence or otherwise of certain particle-decay processes is an important source of information on the fundamental symmetry laws of weak interactions. Analysis of the reasons for the absence of the decays $\mu \rightarrow e + \gamma$ and $\mu \rightarrow 3e$ led to the suggestion that there may be two types of neutrino — electronic and muonic. When it became clear that the search for muon decays to an electron and a γ quantum and to three electrons provided a means of direct verification of the lepton conservation laws, an extremely thorough search was conducted at the NRL, and the limiting value obtained at Dubna for the probability of the process $\mu \rightarrow 3e$ was $R < 2 \cdot 10^{-9}$ [26], several orders of magnitude less than that obtained earlier in other laboratories.

The same series of experiments also provided, for the first time, an upper limit on the probability of processes such as $\pi \to 3e\nu$, and hence it was concluded that the possibility of existence of multifermion weak interactions is strictly limited, and estimates of the weakly electromagnetic pion form factors were obtained [27]. Being the best available, these data are included in international tables of data on elementary-particle properties.

Recently, there has been a sharp upsurge of interest, throughout the world, in the search for the decays $\mu \to e+\gamma$ and $\mu \to 3e$. It has been shown that such decays may be expected to occur as a result of interactions with heavy leptons in an intermediate state [28]. A very sensitive method of detecting muon-charge disruption may be provided by the observation of so-called neutrino oscillations ($\nu_e \rightleftharpoons \nu_\mu$; $\bar{\nu}_e \rightleftharpoons \bar{\nu}_\mu$), the existence of which has been predicted theoretically [29].

Recently, the volume of data on muon properties obtained in original research at the NRL has been further swelled by new data of previously unattained accuracy on the muon lifetime [30]. These accurate data on the muon lifetime may be used to determine the weak-interaction constants, and also in formulating experiments to investigate the radiational correction in weak-interaction processes. The importance of such investigations cannot be overemphasized, as has been shown by recent developments in physics (the discovery of a Lamb shift of the levels of the hydrogen and deuterium atoms, the determination of the anomalous magnetic moment of the electron and the muon). Muon decay has been of particular interest, since, of the weak interaction processes involving only leptons (particles which do not participate directly in strong interactions), it was for many years the only one that could be experimentally investigated.

The first neutrino experiment in an accelerator was that by the NRL scientists conducted in 1961 on the JINR HEL 10-GeV accelerator [31]. Experiments were carried out at Dubna in connection with the question posed by L. B. Okun' and I. Yu. Kobzarev as to the possibility of an anomalously large neutrino interaction with matter at high energies. As a result of experiments in which an interaction cross section of 10^{-32} cm^2 was achieved, this interesting theoretical possibility was ruled out.

Research into the physics of neutral K mesons led to many unexpected discoveries. At the JINR, research into K-meson decays was conducted jointly by the NRL, HEL, and a group of Georgian physicists. An extensive series of experiments [32] dealt with all the main problems of the physics of neutral K mesons. As a result of work with a Wilson cloud chamber, the forms of weak interaction leading to semileptonic K decay were determined, together with the degree of prohibition of weak interactions involving neutral currents for transitions with change in strangeness.

Inelastic Interactions at 5 GeV

In the late 1950s a large complex of apparatus with a 1-m propane — Freon bubble chamber in a 17,000-G magnetic field was built at the NRL [33]. On this apparatus, which was highly efficient in recording γ quanta and beams of 5-GeV π^- mesons from the JINR synchrophasotron, the NRL scientists and physicists from the nuclear institutes of Czechoslovakia, Armenia, Belorussia, and Georgia have carried out a series of experiments on the creation of ordinary and strange particles. A large number of new results have been obtained on the processes of instantaneous particle formation, in particular for neutral particles (γ, π^0, K^0, Λ^0, Σ^0) [34]; there had previously been little study of these processes, because of the difficulties involved. The scale-invariant properties of pion — hadron interactions were also investigated. It was discovered that even at 5 GeV behavior similar to that in experiments at significantly higher energies (40-1500 GeV) is observed [35]. Diffractional dissociation of pions at carbon nuclei was investigated close to the threshold and it was established that it occurs predominantly through the formation of A_1^- mesons decaying in the chain $A_1^- \to \pi^- + \rho^0$, $\rho^0 \to \pi^- + \pi^+$ [36].

Physics of Mesoatoms of Hydrogen Isotopes

It is known that nuclear muon capture directly precedes a stage when the muon and one of the atoms of the surrounding medium form a new system — a μ mesoatom. The lifetime of this system for a hydrogen atom is large enough for various processes to occur in the system itself or with its participation. The mesoatoms of hydrogen atoms have been studied in most detail at the NRL. Interest in this subject arises because quantitative information on the processes occurring at the mesoatomic stage are very important if reliable data are to be obtained on the nuclear capture of a muon by a proton. It is necessary to discover at which states of the hydrogen mesoatom or mesomolecule muon capture occurs, to determine the rate of mesomolecule formation for various hydrogen isotopes, to measure the cross section for the elastic scattering of hydrogen and deuterium mesoatoms by protons and deuterons, to investigate the rate of interception of muons from protons by deuterons and complex nuclei, to determine the rate of synthesis reactions catalyzed by muons, etc. This whole set of phenomena was studied in detail in a comprehensive series of experiments using cloud-chamber and electronic methods [37]. The theoretical basis for the experiments was the work by Gershtein and Zel'dovich [38]. Many of the experimental results are of considerable interest in their own right: for example, the observation of a mechanism of deuterium-mesomelecule formation that involves a resonance with respect to the deuterium μ atom, or the determination of the rates of nuclear synthesis reactions in the $p\mu d$ and $d\mu d$ μ mesomolecules. The new experimental data have stimulated further theoretical work on the problem [39].

Nuclear Structure. Nuclear-Reaction Mechanisms

Synchrocyclotron experiments on the interactions of pions with nuclei led to the observation of a previously unknown process of double pion charge exchange at nuclei [40]. This discovery was accorded official recognition by the committee responsible for inventions and discoveries of the Council of Ministers of the USSR. A detailed investigation of this process has been carried out; at present, in this connection, there are plans to search for unusual nuclei. Many nuclear centers throughout the world are now engaged in scientific and theoretical work on double pion charge exchange.

One clear result of the investigation of nuclear pion and meson capture is the discovery and investigation of the heaviest known isotope of helium — the ^{8}He nucleus [41]; this is another discovery that has been accorded official recognition.

An important part of the work at the NRL is the investigation of intranuclear nucleon association — the so-called cluster structure of the nucleus. Early work led to the first observation of the quasielastic scattering of ~660-MeV protons by two-nucleon associations in light nuclei: deuterons with energies of several hundred MeV are expelled from the nucleus [42]. These observations were interpreted in terms of bulk fluctuations of the nuclear material by Blokhintsev [42]. In other experiments, the magnetic analysis of secondary-proton spectra yielded quantitative data on the momentum distribution of nucleons inside beryllium and carbon nuclei [43]. Detailed study of the elastic scattering of protons at small angles on carbon nuclei led to the determination of the spin-dependent scattering amplitude and it was also concluded that growth in proton intensity is accompanied by a decrease in intensity of the nuclear spin — orbital interaction [44].

Subsequently, considerably rarer processes of quasielastic proton scattering by three- and four-particle associations in nuclei (with the ejection from the nucleus of ^{3}He and ^{4}He with momenta of 1800-1900 MeV/sec) were observed and investigated, the accuracy of the results was much improved, and the momentum range for the ejected particles was broadened. As a result of detailed experimental observations, it was possible to determine the probability of nucleon association in light nuclei, and the energy dependence of the cross section for the quasielastic scattering of protons by two-nucleon associations. Meson formation at two-nucleon associations in light nuclei was observed for the first time [45]. The cluster structure of the nucleus was also investigated in experiments at the NRL on the ejection of relatively high-energy ^{2}H and ^{3}H nuclei accompanying the capture of negative pions and muons by various nuclei. Hungarian and East German physicists are engaged in new research in this field.

An important contribution to the investigation of the mechanism of nuclear reactions at high energies has been made by new experiments with polarized proton beams, the results of which are more sensitive to the mechanism of the interaction [46].

In experiments by a group of physicists from the NRL and the Institute of Theoretical and Experimental Physics (ITEP), a new type of excitation of nuclear levels has been observed — the so-called radiationless transition in mesoatoms of heavy elements [47]; this discovery has been accorded official recognition. Essentially, what happens is that, in transtions between levels in μ mesoatoms of these elements, emission of a photon is accompanied by excitation of the nucleus, which is then removed either by neutron emission or as a result of fission. The existence of this effect offers a unique possibility for the study of shape isomers of excited nuclei arising as a result of electromagnetic interactions between an orbital muon and the nucleus [48].

In investigating pion capture by nuclei in 1975, a new effect was observed — the excitation, with high probability, of nuclear levels with high spins [49]. When this occurs, a π^- meson is captured by an n — p pair, energy close to the pion rest energy is liberated, and the remaining nucleus acquires a torque.

The NRL scientists discovered resonance excitation of the nucleus in μ-meson absorption, by observing the linear structure in the energy spectrum of the ejected neutrons (an officially recognized discovery) [50]. This opens up new possibilities for the investigation of the quasisteady state and the mechanism of nuclear reactions at high energies.

Using a new apparatus with a high-pressure streamer chamber, a group of the NRL physicists with others from Rumania and Italy carried out a broad program of research into pion interactions with ^{4}He and ^{3}He nuclei in the region of the resonance $\Delta(1236)$. The results obtained with ^{3}He are unique and are of particular importance for the development of theoretical ideas regarding the interactions of systems containing only a few nucleons [51]. Following investigations of the interactions between pions of both signs and ^{4}He nuclei, the electromagnetic radius of the π meson has been determined.

Nuclear Spectroscopy and Radiochemistry

In the first few years of operation of the NRL synchrocyclotron, teams from a number of Soviet institutes began to investigate reactions at complex nuclei involving particles with energies of several hundred mega electron volts. In 1955 it was shown [52] that deep-fission reactions may lead to the formation of neutron-deficient isotopes, remote from the β-stability band, the production of which by other means is either very difficult or completely impossible. These isotopes are formed in sufficient numbers to permit the investigation of their emission spectra using precision spectrometers.

The rapid development in the nuclear-spectrometric investigation of isotopes produced by the irradiation of targets in the NRL synchrocyclotron began in 1956. The success of this work greatly facilitated the increase of the synchrocyclotron beam intensity by almost an order of magnitude in the period 1957-1962, the development of methods for the rapid radiochemical separation of radioactive elements in amounts of 10^{-10} g, without a supporting medium and without significant losses, from a target of a few grams, and also the creation of methods of obtaining prepared sources of high total and specific activity [53]. A factor greatly complicating the solution of the problems was the high activity of most of the initial targets (5-10 g-eq Ra).

To investigate the nuclear spectra, modern magnetic α and β spectrometers were introduced at the NRL [52, 54]: a β spectrometer with two-stage double-focusing of the beam, β spectrographs with a constant magnetic field, and a large magnetic α spectrograph with double-focusing. Soviet semiconductor γ and β detectors corresponding to the best world standards have been developed. A high-transmission β spectrometer of Apel'sin type is in operation. Modern electronic equipment and computer methods for the analysis of complex spectra have been developed. On the electromagnetic mass separators built at the NRL, the systematic separation of radioactive isotopes has been begun for the first time in the USSR [55]. The original and highly efficient ion source developed for the mass separators has been operating successfully [56]. In 1966-1970, a complex of equipment was built to investigate short-lived ($T_{1/2} \approx 1$ min) isotopes remote from the β-stability band; this is the YaSNAPP installation [54, 57].

Among the more important physical results obtained in the nuclear-spectroscopic investigations are the following:

the detection of more than 100 radioactive isotopes and the investigation of their properties [52, 54];

the measurement of the nuclear-deformation parameters for a number of rare-earth elements ($150 < A < 190$) — single-particle, multiparticle, and collective levels were identified in studying the decay of deformed nuclei with odd mass numbers, thereby confirming the conclusions of the generalized Bohr — Mottelson model and the Solov'ev superfluid model and providing the basis for their further development;

the detection and detailed investigation of fine structure in α spectra in the region of the rare-earth elements [52].

Mesochemical Research

The production of intense pion and muon beams on accelerators led inevitably to the appearance of a number of new research areas utilizing the properties of such exotic objects as mesoatoms, mesomolecules, and muons. Experiments with mesoatoms and mesomolecules open up new prospects for the investigation of the electronic structure of materials, and also the kinetics and mechanisms of chemical reactions and atomic processes. This research — later called mesochemical research — began with work on π^- and μ^- mesons at the NRL, in which it was reliably established, for the first time, that the transition of negatively charged ions to a bound state is sensitive to the electronic structure of the material in which the meson is captured. In experiments with μ^- mesons, atomic capture in oxides and the change in structure of the series of elements giving meso-x-ray spectra were found to depend periodically on their chemical surroundings. The structure of the meso-x-ray spectra was also found to be sensitive to the mesoatomic charge transfer of a μ^- meson, which is analogous to atomic charge transfer [58, 59]. As a result of this work, an Inventor's Certificate on a new method of determining the properties of materials was prepared. In view of the relatively high energy of meso-x-ray emission by the elements, and hence its great powers of penetration, it may be used to investigate the physicochemical properties of thick samples, and to study any part of a large sample without the need for its destruction, including the composition of individual organs of live organisms. Subsequently, this possibility was realized in experiments conducted at the NRL in conjunction with specialists of the Institute of Medicobiological Problems of the Academy of Medical Sciences of the USSR.

An even larger-scale effect of the chemical state of elements is observed in the capture of slow negative pions by bound hydrogen, observed in the NRL synchrocyclotron [60]. The interpretation of these phenomena requires the introduction of completely new objects into scientific discourse — large mesomolecules forming in the initial stage of muon transition to the bound state [61]. Further work in this field gave the first quantitative results obtained in mesochemistry, in the form of relations between parameters characterizing pion capture by bound hydrogen and the physicochemical characteristics of the material. The effect of π^- meson charge exchange was investigated in mixtures of hydrogen with other gases [62].

Considerable successes were achieved in investigating the kinetics of chemical reactions. The method of investigation was based on the use of meson-depolarization processes in muons and μ mesoatoms. The μ^+e^- system is an analog of the hydrogen atom and so, by studying the behavior of muons it is possible to obtain unique information on chemical processes involving atomic hydrogen [63].

Chemical reaction of mesoatoms [64] offer wide possibilities for the investigation of chemical processes involving elements in the atomic state.

Thorough spectral investigation of electronic x radiation led to the detection [65] of a shift in the electron energy levels on muon capture.

In experiments with μ^+ mesons, physicists from the IAE and from Dubna discovered and investigated the two-frequency precession of muons, and observed subbarrier diffusion of muons in the crystal lattice.

High Energies

The introduction of the IHEP accelerator provided scientists of the socialist countries with opportunities for research using particles of previously unattainable energies.

The main research topics chosen by the NRL were fundamentally important problems in the solution of which experiments with high-energy particles are of crucial importance.

Dirac Monopole. For many years, the world's great theoreticians (Dirac and Schrödinger) speculated on the existence of unusual sources of magnetic fields — magnetic monopoles. On various accelerators throughout the world, at various times, there have been many experiments on the detection of monopoles. In contrast to earlier experiments, the NRL physicists used a completely new method based on Frank's observation that the Cerenkov radiation of a monopole differs in polarization from the Cerenkov radiation of other particles. In comparison with the previous methods, this is much less dependent on detailed assumptions regarding the behavior of monopoles in matter. The experiments showed that monopoles are not formed by 70-GeV protons with cross sections of more than 10^{-40} cm^2 [66].

Antinuclei. Although the existence of antinuclei is predicted by modern theories, until recently the only known representative was the antideuteron. The ^{3}He nucleus was discovered by the IHEP physicists in the 76-GeV accelerator. One difficult achievement in this fundamentally important field was the discovery of an antitritium nucleus in a complex high-precision experiment to detect antinuclei and new heavy particles, carried out by a group of scientists from the NRL and the IHEP.

Polarization Effects. Polarization effects in the interactions of high-energy particles give direct experimental information on the spin dependence of the interactions, and are therefore of particular interest for the quantitative investigation of strong interactions. The NRL physicists and others from the IHEP, Saclay (France), and the ITEP investigated polarization effects in the elastic scattering of pions, K mesons, protons, and antiprotons by protons at a maximum energy of 40-45 GeV. It was shown that spin effects do not disappear even at such high energies [68].

Great opportunities for the investigation of inelastic interactions at energies of tens of giga electron volts became available to scientists of the NRL and other institutes of JINR member-nations with the development and introduction into service in 1974 of a 5-m magnetic spectrometer with a magnetic-field volume of 11 m^3. The initial research program, carried out in collaboration with CERN physicists, was concerned with the diffractional dissociation of particles at a number of atomic nuclei and also instantaneous particle creation at pion and K-meson energies of up to 40 GeV. At present, four new experimental installations for urgent research on the IHEP accelerator are being developed at the NRL.

Theoretical Work

It is a feature of the theoretical work that its subject matter is intimately related to the experimental research on powerful particle accelerators. The concept of a "total experiment," necessary for the unique determination of the amplitude of the interaction between strongly interacting particles, was introduced and theoretically developed [6, 69]. It was suggested that the P, T, and C invariance of strong interactions at high energies could be verified in experiments with polarized particles [70]. The most detailed verification of the isotropic invariance of strong interactions was proposed and realized at the NRL [71].

In connection with the large-scale program of experimental research on the interaction of high-energy particles with atomic nuclei, a method generalizing Glauber's well-known results was developed [72]. The interaction cross section and polarization effects were investigated in a number of high-energy processes [73]. Double K-meson charge exchange was predicted [74]. On the basis of dispersion relations, a theory of γ-quantum scattering by nucleons over a broad energy range was proposed. It was established how the sign of the amplitude of neutral-pion decay into two γ quanta depended on the model of the interaction. A sum rule was obtained for the magnetic and electrical dipole moment of the nucleon. The first theoretical estimate of the magnetic polarizability of the proton was made [75].

Data on elastic and inelastic $e-p$ and $\mu-p$ interactions were analyzed. Accurate data on the nucleonic form factors were obtained. The need was demonstrated for new experiments which should lead to considerably more accurate information on muon—electron universality at small distances and on the validity of scaling fo the structural functions of the proton [76]. Attention was drawn to the existence of interesting effects associated with the interference of strong and electromagnetic interactions in polarization effects in the case of small momentum transfer. This interference leads to a considerable effect in the elastic scattering of mesons and nucleons by protons and atomic nuclei and also in the diffractional dissociation of particles. It was shown that experimental investigation of polarization effects in the case of small momentum transfer offers the possibility of direct study of the spin dependence of strong-interaction amplitudes; the spin dependence is significant in analyzing high-precision experiments with particle energies of up to 1 GeV [77].

In recent years, a theoretical scheme has been developed for strong interactions at superhigh energies, leading to a total interaction cross section that increases with energy.

Electronic Equipment for Physical Research

Most modern physical experiments on nuclear-particle accelerators involve electronics. The improvement of the electronic equipment at the NRL is a continual preoccupation, since the performance of this equipment largely determines the scientific level of the experiments.

A system of logical modules in the nanosecond range developed at the NRL to record pulses from scintillation detectors and to isolate individual events is now in widespread use. The system includes modules of 50 types [79]. The speed of operation of the modules reaches 100 MHz and the resolution of the coincidence circuit is 1 nsec. These modules may be used to produce logical recording equipment of almost any complexity, and also time spectrometric channels operating from scintillation detectors.

Considerable successes have been achieved in developing high-precision spectrometric equipment for operation with semiconductor detectors [80]. By means of charge-sensitive preamplifiers, both amplitude and time spectroscopic measurements can be made simultaneously. Some of the equipment developed has previously unequalled characteristics. At the NRL, multiwire spark chambers and proportional chambers of various kinds are used, together with appropriate systems for recording the information and transferring it to computer storage. At the NRL wide use is made of the international standard CAMAC, which relates to electronic recording and control equipment and also apparatus for computer linkage and information output. The CAMAC standard includes modules of more than 50 types [81]. Systems based on the CAMAC standard have successfully been used in many experiments.

A semiautomatic data-processing system was developed at the NRL and the Computer-Technology and Automation Laboratory and used successfully in the analysis of results from a 1-m PK-200 propane chamber; the system has a two-way link to a computer, and ensures the simultaneous operation of several semiautomatic units [82].

No modern physical experiment is possible without the extensive use of computer technology, both in the experiment itself and in the analysis of the results. Therefore a data-storage and processing center is an indispensible part of the general laboratory equipment [83]. The basis of the system is formed by small computers and commercial multidimensional analyzers connected in a single automatic system, to which the apparatus used in the different physical experiments is attached. The main computer of the center, to which the small computers are connected, is an ES1040. The electronic equipment developed at the NRL has generated much interest and has been introduced at many institutes in the USSR and other JINR member-nations.

Applied Research

In addition to the fundamental research in pure nuclear physics, the NRL has successfully carried out work of great practical importance, with applications in scientific fields which seemed quite recently to be unrelated to the physics of high-energy particles. Work with mesons and negative pions (mesochemistry) is only one example of the incursion of elementary-particle physics into modern chemistry and solid-state physics.

Work on the medical and biological uses of heavy charged particles from a synchrocyclotron is of great importance in connection with the possibility of greatly increasing the effectiveness of radiation therapy for cancer patients. Proton irradiation differs from all previous forms of radiation therapy in that it allows the absorbed energy to be accurately concentrated in the tumor and considerably reduces the radiation load on the healthy tissue surrounding the tumor. In 1967, the NRL and the Institute of Experimental and Clinical Oncology of the Academy of Medical Sciences of the USSR used high-energy proton beams in the experimental treatment of cancer patients. For this purpose, a proton beam of dose rate ~200 rd/min was developed in the synchrocyclotron, and in 1972-1974 a new design of wide-angle focusing meson lens was built and an intense pion beam of dose rate ~5 rd/min was developed [84].

Neutron multiplication was investigated in blocks of uranium; this is important in determining whether high-current accelerators can be used to process nuclear fuel for atomic power stations, nuclear-powered ships, etc.

Development of Particle-Detection Methods

The scope of experimental research is limited not only by the level of accelerator development but also, to a large extent, by the development of methods of submicroscopic-particle detection.

The specific radiation of relativistic particles (Vavilov — Cerenkov radiation) is used extensively, in research centers throughout the world, for the detection of particles and the measurement of their energies. One of the first proposals for the use of the properties of Vasilov — Cerenkov radiation in this way was made at the NRL in 1950. The most up-to-date Cerenkov system was developed and the proton energies in the synchrocyclotron beams were measured. Special equipment was built and a broad program of research was carried out on various properties of Vasilov — Cerenkov radiation [86]. First of all, the properties of this radiation when high-energy protons are passed through crystals was investigated. The so-called "needle" radiation was discovered [87] and experimental confirmation was obtained for the theory developed by Ginzburg and Muzikarzhe (Czechoslovakia).

At the NRL, interesting research was carried out on the development of a liquid-hydrogen ultrasonic bubble chamber [88]. The results indicate that it may be possible to develop a new particle-track detector.

Since the early years of research on modern elementary-particle accelerators, there has been a pressing need for a new type of particle-track detector, with a much larger time resolution than earlier types. The idea of creating a controlled fast-action particle-track detector arose independently in the Soviet Union and in Italy in 1955. The principle of controlled pulse supply to gas-discharge detectors [89], proposed at the Laboratory for Fiber Counters and in Italy, suggested a new line of development for methods of particle-track detection.

A high accuracy of coordinate measurement was achieved by researchers implementing the principle of controlled pulse supply for plane spark counters. The spark chambers constructed from these counters have found widespread use in all high-energy-physics laboratories. Great attention has been paid to the further improvement of spark chambers with discharge along tracks inclined to the electric field, and discharge chambers in projection conditions of recording. If the electric field rises sufficiently rapidly in a chamber with metal electrodes and a mean gap size of 20 mm, a discharge along the particle track will be obtained even for large angles of inclination. A nine-electrode chamber developed at the NRL was the first of its kind to be used in physical research [90]. In 1961 it was shown that by increasing the interelectrode gap it becomes much easier to obtain discharges along inclined particle tracks, up to limiting angles of 50°. This finding had considerable influence on the further development of spark-chamber techniques, stimulating research into wide-gap track chambers.

In 1964 a new method of producing a completely isotropic discharge chamber was proposed and implemented at the NRL [91]. The necessary localization of the discharge was achieved by using an incomplete discharge with a reduced potential applied to the chamber. The loss in brightness was compensated by means of an electronic — optical light amplifier. The streamer chamber was also considerably improved: the first high-pressure streamer chamber was produced [92] and the possibility of streamer operating conditions in a helium chamber was demonstrated. As a result of these improvements, the chamber could be used as an instrument combining the properties of a track detector and a gas target. These investigations demonstrated the possibility of constructing a hydrogen streamer chamber.

In 1964 a method of investigating elastic and inelastic interactions between high-energy particles with low momentum transfer was proposed at the NRL [93]. The distinguishing feature of the method is that transfer particles with very low energies are detected by semiconductor detectors. This method, which allows the interference of strong and Coulomb interactions between hadrons to be investigated, was successfully used by scientists from the NRL and the HEL to study p — p scattering at 4 GeV in the HEL accelerator. Later, the semiconductor detectors were used by the JINR physicists in research on the 70-GeV IHEP accelerator and the 400-GeV accelerator at Batavia in the U.S.A.

Gas-discharge proportional counters were used in the first accelerator experiments as fast-acting particle detectors; however, the complicated and unwieldy amplifiers prevent any considerable increase in the number of channels in the equipment. The revival of systems using fiber proportional counters was stimulated by proposals made independently at the NRL [94] and at CERN in 1968. Many specialists regard the appearance of wire proportional chambers as a revolution in particle-detection techniques. The advantages of this method, which combines very rapid action with high accuracy in measuring the particle-track coordinate, are so great that such systems are in use and under development in all high-energy-physics laboratories.

Research into New Accelerators

An important and successfully developing aspect of the scientific research at the NRL is exploratory work toward the development of new types of high-current cyclic high-energy particle accelerators with a steady magnetic field [95]. This work exploits the opportunities presented to accelerator technology by the utilization of the periodic structure of magnetic fields with spatial variation. The staff of the new-accelerator section are carrying out a program of theoretical work and producing research accelerator installations to model the basic physical processes in the new accelerators.

Of the research accelerators in operation, two deserve particular mention. In 1959, the world's first isochronous cyclotron with a spiral structure of the magnetic field went into operation at the NRL [96]. On this accelerator, the main theoretical results of linear and nonlinear theories of particle motion in magnetic fields of tightly spiral structure were verified, and the possibility of particle acceleration in isochronous conditions over several thousand revolutions was demonstrated. In 1968, an electronic ring cyclotron with fixed focusing went into operation [97]; on this accelerator, experimental confirmation was obtained for the possibility, noted at NRL, that the isochronicity of orbits of different energies and fixed focusing may coincide. Theoretical calculations and experimental research on beam space-charge effects in this electron cyclotron led to the fundamental conclusion that ring cyclotrons with fixed focusing may be used for the acceleration of protons with energies up to 1 GeV at currents up to hundreds of mA [97].

The new-accelerator section is carrying out a large-scale program of theoretical research in particle dynamics; developing modern design methods for the establishment of complex magnetic-field structures over a wide range of induction; developing and constructing a series of devices and instruments with previously unattained levels of sensitivity and accuracy for the measurement and stabilization of these fields; creating new high-frequency systems for accelerator installations; and developing modern accelerator control systems.

As a result of the theoretical work on particle dynamics, linear and nonlinear theories of charged-particle motion in magnetic fields with spatial variation have been developed. It has been shown that by using spiral magnetic-field structures in synchrocyclotrons the internal-beam intensity may be increased by an order of magnitude (to $\approx 5\ \mu A$). In collaboration with the design organizations, plans for the reconstruction of the synchrocyclotron in operation at the NRL as a 700-MeV high-current phasotron have been developed and are presently being implemented. By using new methods, the proton and meson beams produced may be increased in intensity by 1.5-2 orders of magnitude as a result of the construction.

The dynamic processes in the isochronous cyclotron have been investigated over a wide range of energy variation for different ions (p, d, ^{4}He, ^{3}He) and a high-quality beam. Such an accelerator was built at the NRL on the basis of the electromagnet of the standard U-120 cyclotron, and transported to the Institute of Nuclear Physics of the Czechoslovak Academy of Sciences [99].

In 1971-1972 theoretical work at the NRL revealed a new effect associated with closed orbits in periodic magnetic-field structures [100]. It was found that the density factor of closed orbits in such fields depends on the change in the magnetic-field variation over the radius, and may change significantly in a narrow region of the radius. This suggests broad possibilities for 100% particle output from the accelerator.

Orbital broadening in the region of rapid change in magnetic-field variation was observed experimentally on the electron ring cyclotron [100], showing that the theretical conclusions are correct. It seems that a ring cyclotron with fixed focusing is the most satisfactory type of accelerator with beam power of the order of hundreds of megawatts, since it utilizes a standard magnetic field and its efficiency approaches 70-80%. The very high intensity of particle beams from such an accelerator (a "supercyclotron") not only offers the possibility of solving fundamental physical problems that were not previously susceptible to investigation but may also facilitate the widespread use of the most recent achievements of nuclear physics in solving important practical problems [101].

CONCLUSIONS

In the past 30 years the Nuclear Reactions Laboratory has grown into a major scientific institute, the international staff of which includes around 900 highly qualified scientists, engineer, and technicians with various specialist skills, from the 11 member-nations of JINR.

The scientific research conducted at the NRL has made a large, generally recognized contribution to one of the most important areas of science in the world today — the physics of elementary particles and the atomic nucleus, and accelerator physics and technology.

The scientists and engineers of the NRL enjoy high scientific status and respect among specialists. Today, many great experimental physicists and specialists in methodological research trained at the NRL lead large scientific teams and are successfully conducting work in the major nuclear centers of the Soviet Union and other JINR member-nations.

Founded in 1948 as the national nuclear center of the Soviet Union, the Nuclear Reactions Laboratory provides a base for fruitful scientific research by scientists of many of the central institutes (IAE, ITEP, the Institute of Chemical Physics of the Academy of Sciences of the USSR, the N. I. Vernadskii Institute of Geochemistry and Analytical Chemistry of the Academy of Sciences of the USSR, and the V. G. Khlopin Radium Institute) and universities (Leningrad State University, Moscow State University, etc.), and also the institutes of a number of Siviet Republics (Georgia, Uzbekistan, Kazakhstan, etc.).

The successes of the NRL staff in nuclear-physics research, the design of improved modern accelerators, the development of new equipment and methods for physical experiments, and also its role in training young scientists and engineers have received wide recognition.

Throughout the whole of its 30 years of existence, the NRL has received — and continues to receive — understanding and support from the State Committee of the Institute of Atomic Energy of the USSR, the Committee of Official Representatives of JINR member-nations, and the JINR authorities.

The laboratory is proud that, among the works of its scientists awarded the Lenin and State prizes, there is work that has won the I. V. Kurchatov gold medal and prize.

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THERMALIZATION OF NEUTRONS

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After successfully solving the problems of atomic weapons, Kurchatov and Aleksandrov turned their attention to the peaceful uses of nuclear and thermonuclear energy and the development of the corresponding areas of science. In particular, they proposed, as the most promising line of development, a program for the creation of atomic electrical power stations and atomic ice-breakers on the basis of uranium — water reactors. A broad-based team of scientists at the Institute of Atomic Energy set about the groundwork for such atomic-power projects and the solution of the attendant problems.

It was already known that the cross section of the fissile isotopes does not correspond to the 1/v law. Accordingly, the neutron spectrum in the reactor, in particular its shape in the region of the first plutonium resonance (0.3 eV) is of primary importance for the calculation of the neutron multiplication factor and the accumulation and burnup of isotopes. The importance of knowing the neutron spectrum if the physics of uranium — water reactors is to be understood was emphasized by Kurchatov in his address at Harwell in 1956 [1]. In the physics of thermal and subthermal reactors there arises an important new problem, the thermalization of neutrons, which involves the study of the concluding stages of neutron-spectrum formation when energy transfer between the neutrons and atoms of the moderator becomes collective in character.

In principle, knowing the absorption cross section and the double differential scattering cross section, the space — energy distribution of neutrons in any system may be calculated by solving the kinetic equation. However, in the absence of data on the double differential cross sections, a method of calculation, and the necessary computer technology, it was decided to study neutron spectra in several specific uranium — water piles, so as to obtain a qualitative picture of the space — energy distributions of neutrons in them. The first experiments were begun in 1956 on the VVR-2 reactor by Mostov and Saltykov [2], who were soon joined by Egiazarov and Dikarev. The very first experiment produced interesting and unexpected information on the thermal region of the spectrum and the retardation region and on their spatial dependences. It was shown that the neutron spectrum in a block of uranium differs significantly from both the Maxwellian and the Fermi distributions.

On the basis of the experiments, a qualitative estimate was made of the effect of absorption and the chemical bonds of the moderator atoms on the spectra.

At the end of the first stage, a detailed study of thermalization was begun, including the following main topics:

1) the law of slow-neutron scattering in the common moderators;

2) the development of thermalization over time in the moderators;

3) the space — energy and angular distributions of slow neutrons close to the boundary of media differing in temperature and also in moderator and absorption properties;

4) the spectra of neutron moderation and thermalization in homogeneous and heterogeneous media.

Those who participated in this program were Sadikov, Chernyshov, Eremeev, Taraban'ko, Safin, Ishmaev, Khmyzov, Abdullaev, and Lysov. The experimental part of the program was carried out at the Institute of Atomic Energy and the Institute of Nuclear Research of the Academy of Sciences of the Ukrainian

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SSR in close cooperation with the theoretical groups of Marchuk (Energy-Physics Institute) and Maiorov (Institute of Applied Physics, Academy of Sciences of the USSR), who developed methods of solving the kinetic equation and produced (and tested against experimental results) programs for accurate and approximate calculations of scattering cross sections, space — energy distributions of neutrons, and the most important integral characteristics of the spectra in the experimental piles and in reactors at the operational and design stages.

Research on the thermalization of neutrons was completed in 1971, shortly after Kurchatov's death. On the 75th anniversay of his birth, those who carried out the thermalization work feel it their duty to give an account of those investigations, which were initiated by Kurchatov and subsequently benefited from his continuing interest and valuable assistance.

The thermalization of neutrons has also been investigated at other institutes in the Soviet Union, and has attracted widespread attention outside the USSR. However, the present account restricts itself to work directly related with Kurchatov's activity. The main results obtained at different stages of the research are summarized in [3-5]. The present paper describes the methods of investigations and the results obtained in each of the topics mentioned above.

Scattering Law for Slow Neutrons in Moderators Containing Hydrogen and in Graphite [3,4,6-8]*

The measurement of the double differential cross section is, methodologically speaking, a very complex problem, the solution of which was necessary for the development of fundamentally new spectrometers with the double analysis of neutron energy and the angular dependence of the scattered radiation. Combined methods of rendering monochromatic and interrupting the neutron beams (a mechanical monochromator — interrupter and crystal monochromators) were developed, as well as highly efficient large-area detectors, instruments for multidimensional analysis of information, and effective protection from the fast-neutron background. In 1961 and 1966, two such spectrometers were installed at the VVR-M reactor of the Institute of Nuclear Research of the Academy of Sciences of the Ukrainian SSR.

One of these allowed measurements to be made over wide ranges of the energy of the primary monochromatic neutrons (0.015-0.35 eV) and of the energy (0.005-0.5 eV) and angle (10-120°) of the scattered neutrons. A pulsing beam of monochromatic neutrons was obtained in this spectrometer using a mechanical monochromator — interrupter with parabolic slits or an ordinary interrupter and a crystal monochromator. Scattering of the neutron beam from a sample was recorded by detectors sited at a distance of flight of 3 m at angles of 10-120° with respect to the incident beam.

The double differential cross section was measured for water (at 22 and 90°C), zirconium hydride (ZrH_2), monoisopropyldiphenyl ($C_{15}H_{16}$), and reactor graphite in the temperature range 25-1400°C. The measured cross sections were used to calculate the scattering law, and to find a generalized frequency spectrum which characterizes the dynamics of the moderator-atom collisions and contains the initial information for calculations of the double differential cross section over the whole range of energy and angles important for the thermalization process.

The research showed that water has the best thermalizing properties and the greatest scattering anisotropy, which decreases with rise in temperature. The main mechanism determining these properties is the excitation of retarded rotations of the H_2O molecule. In zirconium hydride, the strong hydrogen bond in the crystal lattice leads to a sharp decrease in the moderating properties at neutron energies below the first optical-vibration level of the lattice (0.135 eV). In graphite, there were considerable incoherent-scattering effect, which are not completely averaged even though it is a polycrystalline sample. The experiments showed that the double differential cross section depends on the kind of chemical bonds on the moderator atoms and is greatly different from the results calculated on the basis of simple model assumptions. They provide an opportunity of testing more realistic models.

Calculations of the cross section on the basis of the generalized frequency spectra were found to be in good agreement with the experimentally measured differential cross section of water [5,9]. For graphite, calculations of the scattering law in the incoherent approximation with a model generalized frequency spectrum correctly described the temperature dependence of the cross section over the whole of the investigated range. Comparison with experiment led to an improved value of an important parameter of the model — the Debye temperature (2600°K).

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Experimental and theoretical results on the neutron scattering law of the moderators, with the addition of data from other laboratories in the Soviet Union and abroad, provide the basis for the creation of a system of microconstants that can be used to calculate the neutron spectra in reactors.

Development of Neutron Thermalization over Time in Moderators [4,10-17]*

Direct measurements of the evolution of the neutron spectrum over time after a fast-neutron pulse is introduced in the moderator constitute one of the most effective and physically instructive methods of investigating thermalization. By this means, it may be established at what stage of the retardation process the chemical bonds and thermal motion of the atoms begin to have a significant effect, and also what influence they have on the shape of the spectrum, on the rate at which dynamic equilibrium is established between the neutrons and the medium, and on the corresponding time of this process.

The measurement of nonsteady neutron spectra was begun in 1960 on the IAE linear electron accelerator. Two spectrometers were developed on the basis of a phased interrupter and a crystal monochromator in conjunction with a time-of-flight method. On this equipment a higher level of time resolution has been obtained (2.5 μsec). This allowed the first detailed measurements of the nonsteady spectra to be made in all the moderators that are of practical importance for reactor building — graphite, beryllium, zirconium hydride, and water — for a wide range of times (0-2500 μsec) and neutron energies (10^{-3}-2 eV). Note the particular difficulties of experimental investigations of water, which is a result both of the short thermalization time and of the observed nontrivial effect of perturbations introduced into the channel for neutron-beam output.

Investigation of the nonsteady spectra gave a series of new physical results. In particular, the approach to equilibrium observed experimentally differed from earlier assumptions that a Maxwellian spectrum for the current temperature is formed. This was one of the reasons for the analysis of the fundamental question of the existence of discrete eigenvalues of the kinetic equation [18-20], i.e., the correct determination and physical substantiation of moderator characteristics, such as the relaxation length and time of the neutron flux, required for engineering calculations. It was shown that for graphite, beryllium, and zirconium hydride the rate of neutron thermalization over time cannot be described by a single parameter. For water, it was found that the first eigenvalue exists and the thermalization time is 5.8 ± 0.6 μsec at 300°K and 55.5 ± 1.5 μsec at 77°K.

For the first time experiments were carried out on the effect of sodium leakage from the finite moderator volume on the shape of the asymmetric spectrum and the time for it to be established. It was shown that in zirconium hydride pronounced differential cooling of the spectrum appears with decrease in size of the medium. This is because of a sharp decrease in the inelastic scattering cross section and the diffusion coefficient below the energy of the optical level.

In coherently scattering moderators (small beryllium blocks) the first direct observations were made of the "neutron-trap" effect — the relative accumulation of neutrons in the energy range corresponding to a Bragg peak in the transport cross section.

The measured spectra provided the basis for a determination of the neutron-physical constants of the moderator: the mean diffusion coefficients and neutron migration lengths in the thermalization region, necessary for small-group calculations of reactors. These experiments stimulated the development of methods of solution for the nonsteady kinetic equation and of appropriate computer programs [5,11,13,19-21].

The nonsteady spectra were found to be very sensitive to the energy dependence of the scattering nucleus and were used to verify theoretical models and data on the moderator scattering law. It was shown, for example, that the heavy-gas model, previously in wide use for graphite and beryllium, greatly overestimates the thermalizing properties of these moderators. Comparison between experiment and calculation for zirconium hydride leads to a value of an important parameter of the scattering model: the weight of the acoustic vibrations of hydrogen in the frequency spectrum.

The results obtained in studying nonsteady spectra also set a limit on the applicability of the pulse method widely used at present to study integral parameters of moderators and multiplication media.

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*S. N. Ishmaev, V. I. Mostovoi, I. P. Sadikov, and A. A. Chernyshov.

Space — Energy and Angular Distributions of Slow Neutrons Close to the Boundary between Media with Different Moderators, Absorption, and Temperature

The determination of the space — energy distribution of neutrons close to the boundary of two regions is a very difficult problem with regard to both calculation and experiment, and is very pressing for practical reactor construction. Spectral measurements in actual reactor piles do not give sufficiently detailed information because of the methodological differences associated with the investigation of spectral anisotropy, the creation of a temperature gradiant, its variation over broad limits, etc. Therefore, the features of the space-energy and angular distributions of neutrons at the boundary of regions with different moderators, absorption, and temperature were studied in detail on plane models for a boundary between water and a black absorber and that between graphite and water.

Close to the Boundary between Water and a Black Absorber [22,23].* In 1965-1966 on the IAE linear electron accelerator an experimental apparatus was developed and used for measurements of the spectra of neutron vector fluxes $\Phi(E, X, \theta)$ in the water — black-absorber system over a wide range of energies (0.005-5 eV), angles (0-180°), and coordinates. It was shown that a strong spatial gradient of the thermal-neutron density leads to a considerable angular dependence of the spectrum. For example, at a distance $X = 2.5$ cm the effective temperature of the spectrum of thermal neutrons incident on the absorber ($\theta = 180°$) is twice the temperature of the neutrons leaving it ($\theta = 0°$). It was established that the important factor determining the formation of the spectra close to the boundary is the anisotropy of the neutron scattering in water; this effect is more significant in the transitional energy range (~0.1 eV).

Close to the Boundary between Water and Graphite in the Case of a Temperature Gradient [4,24-28].† In 1964 at the IAE VVR-2 reactor, an experimental apparatus was built to measure the space — energy distribution of thermal neutrons in the temperature range 133-823°K. The comprehensive experimental results that were obtained remain the only ones of their kind. For graphite, there is a sharp decrease in the neutron-temperature relaxation length with rise in graphite temperature (from 17.6 cm at 133°K to 4 cm at 823°K). It was shown that for water the relaxation length is little dependent on the temperature of the medium in the range investigated (297-343°K).

The experimental data were used to determine important integral characteristics of the moderator: the thermalization cross section and the relaxation length of the effective neutron temperature in graphite and water, and also their dependence on the temperature of the medium [26-28].

By detailed theoretical analysis of these results it was possible to establish whether the fundamental and first eigenvalues of the steady Boltzmann equation exist and to set limits on the applicability of these integral characteristics in considering thermalization in media with a temperature gradient [28,29].

Spectra of Neutron Moderation and Thermalization in Homogeneous and Heterogeneous Media [2-4, 30-34]‡

These experiments, as already noted, marked the beginning of the neutron-thermalization studies. The space — energy distribution was investigated in homogeneous (water, monoisopropyldiphenyl, water with boron and cadmium at different values of absorption and temperature) and heterogeneous systems (uranium — water and uranium — graphite piles with different moderator temperatures) and also in single blocks of uranium, tungsten, and tantalum in graphite.

In realizing this research program, the construction of the experimental installations proved a serious problem. A number of them were practically as complex and difficult to construct as the reactor itself. The experiments were carried out on the VVR-2 reactor, the system under investigation being positioned close to its active region. A method was developed for the detailed study of the spatial dependence of the spectrum using microbeams taken from various points of the system. The neutron spectra were measured by the time-of-flight method using mechanical separators over a broad range of energies: thermal (0.005-0.3 eV) and resonance (0.3-1000 eV) with resolutions of 20 and 0.3 μsec/m, respectively. A method of analyzing the

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‡V. S. Dikarev, M. B. Egiazarov, V. V. Lysov, V. I. Mostovoi, Yu. S. Saltykov, and V. A. Taraban'ko.

experimental data was developed, taking into account all the necessary corrections that are customary in such measurements; corresponding computer programs were written [35,36].

As a result of the investigations it was shown that the chemical bonds of the moderator atoms and the absorption play a significant role in the formation of the neutron spectra. This is the reason why the thermal-neutron spectrum differs considerably from an equilibrium Maxwellian distribution in the moderator and especially in the absorber. In the moderator the spectrum may be described by a Maxwellian distribution but with a "temperature" considerably exceeding the temperature of the medium. It was shown that for a heterogeneous medium this temperature difference may be calculated in the same way as for a homogeneous medium (in terms of the ratio between the absorbing and moderating properties) but taking into account the thermal-use coefficient. In a uranium block, the clearly non-Maxwellian form of the spectrum makes the idea of a neutron temperature quite meaningless.

It was found that the spectrum of neutron moderation in a uranium block has a clearly expressed resonance structure, as a result of neutron absorption at levels of ^{238}U and ^{235}U, and may be approximately described, in the moderator, by a Fermi distribution. It was shown to be possible to determine the accumulation and burnup of isotopes — including short-lived isotopes — in the block using measurements of the resonance-neutron spectrum in a microbeam taken from the block.

Investigation of the spatial dependence of the spectrum showed that in a heterogeneous multiplication medium remote from the boundary the neutron spectrum is largely unchanged. However, close to a boundary between media differing in moderators, absorption, and temperature, the spectrum varies very greatly, and this variation is relaxational in character.

The theoreticians Marchuk and Maiorov used the results of thermalization measurements to test the calculation methods developed and to improve the approximations used in the theory [5,18,37-39]. This facilitated the development of modern methods of nuclear-reactor design, allowing sufficiently reliable predictions of their basic characteristics to be made [29,40-43].

The results of research on neutron thermalization have been reported to many All-Union Conferences, to the Second and Third Geneva Conferences, and to IAEA and COMECON international conferences. They have been included in a number of Soviet and non-Soviet monographs and reviews on reactor physics.

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SHELL AND ISOTOPE EFFECTS IN NEUTRON — NUCLEUS INTERACTIONS

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UDC 539.171.015

While solving problems of great national importance, I. V. Kurchatov devoted much attention to the development of science in the republican Academies of Sciences, and especially to nuclear physics in the Ukraine.

A VVR-M experimental reactor was built and started up in Kiev under the famous "I. V. Kurchatov program." I. V. Kurchatov found the time to personally check the start-up operations on the reactor and to visit our laboratories (Jan. 1960). The nanosecond precision neutron spectrometer at the Institute of Nuclear Research of the Academy of Sciences of the Ukrainian SSR (IYaI AN USSR) was based on the ÉG-5 electrostatic generator which the I. V. Kurchatov Institute of Atomic Energy gave to our institute as a gift. I. V. Kurchatov supported the proposal for the establishment of a nuclear center in Kiev.

The present paper gives the results of research which led to the discovery of a nuclear shell in deformed nuclei with ~100 neutrons as well as new isotope effects in the interaction of neutrons with nuclei. The paper is dedicated to the bright memory of I. V. Kurchatov.

Shell Effects during High Excitations of Nuclei. In the last quarter-century the concepts about the shell structure of nuclei expanded so much as to become current in nuclear physics. These concepts arose from the analysis of the properties of nuclei in the ground state. It was established that the fundamental nuclear properties do not vary monotonically with increasing mass number and atomic number but display specific periodicities, i.e., atomic nuclei have a shell structure reminiscent of the electron shell structure of atoms. At the same time the nuclear shells have their own characteristic features: they are filled for numbers of nucleons which do not coincide with the numbers of electrons in the closed shells of inert gases. This is due to the existence of a strong spin — orbital interaction between nucleons in the nucleus. Nuclei with closed shells were dubbed "magic" [1].

The next step on the road to ascertaining the shell structure of nuclei was the discovery of shell effects during intermediate excitations of nuclei as the result of inelastic scattering of fast neutrons [2]. It was shown that the cross section for the inelastic scattering of fast neutrons ($E = 1$-4 MeV) from nuclei with 50, 82, or 126 neutrons is appreciably smaller than for intermediate nuclei. The higher the mass number, the more pronounced the anomaly in the cross section. This dependence is in accord with data about the binding energy of the 51st, 83rd, and 127th neutrons in nuclei and with other nuclear characteristics. The discovery of these effects played a certain role in the elaboration of criteria for the selection of structural materials for fast-neutron reactors.

The commissioning of the VVR-M experimental reactor enabled us to study the energy levels of compound nuclei at excitation energies comparable with the neutron binding energy, and to do so with a high resolution not accessible to other methods.

The narrow collimated beams at the exit of the horizontal reactor channels, which have a flux of 10^9 neutrons/cm^2, make it possible to measure samples in the form of separated isotopes in milligram quantities. The level parameters, mean level spacings, neutron strength functions, radiative widths, and potential scattering amplitude were determined for 32 isotopes in the range $A = 130$-200, including a considerable number of uncommon isotopes of Ba, Ce, Eu, Yb, Os, and Pt [3-5].

It is of great interest to compare the level density of the excited nuclear states of isotopes from one group, e.g., even — even isotopes. To do this it is necessary to bring them to one excitation energy and also to take account of the difference in the pairing energies; various variants of semiempirical formulas were used for the level density.

Comparison of the reduced level densities or level spacings indicates the existence of a dependence on the neutron number N and the mass number A.

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Measurements performed on separated isotopes yielded the distributions of the level spacings from which it follows that: the level density near the Fermi limit is not a monotone function of the mass number. In closed-shell nuclei with N = 82 and 126 the level spacings are maximum; additional maxima are detected in the level spacings D(N) in the range of nuclei with neutron numbers ~100.

Correlations are also observed in the behavior of D(N) and other nuclear-physical properties. All of this led to the conclusion that deformed nuclei with a neutron number of the order of 100 also have closed shells; this served as a basis for reviewing all concepts of nuclear shells. According to the traditional concepts, the magic property is due to the spherical structure of nuclei and should break down when the degeneracy associated with the spherical shape vanishes. This is precisely why we assumed that the shell structure which leads to magic properties should not appear in deformed nuclei whose shape differs from the spherical even in the ground state.

It was established that the magic property is not only linked with the spherical shape of the nucleus but can also be observed in highly deformed nuclei and this was demonstrated with rare-earth elements as an example.

All of the laws noted are in agreement with theoretical calculations which showed that as their deformation increases nuclei may fall into a region of enhanced stability, analogous to the stability of spherical magic nuclei.

The development of a new concept of the shell structure of nuclei and its application to fission processes in [6] led to new ideas about the fission process and to the prediction of islets of stable nuclei in the far transuranium region of the periodic table.

Isotope-Spin Dependence of Nuclear Potential. With the mean nuclear excitations which occur in the process of inelastic scattering of fast neutrons shell effects are associated not only with the level density but also with the position of the first excited states which depend to a great degree on the number of nucleons in the nucleus.

The processes of the interaction of fast neutrons with nuclei are described by means of the optical model of the nucleus, the application of which to calculations of elastic and inelastic scattering gives results which are only in rough agreement with experimental data. A more detailed verification of this model and its capabilities for the calculation of neutron cross sections which do not lend themselves to measurement has become possible only after elastic and inelastic scattering measurements on separated isotopes by neutron spectrometric methods.

As is well known, nanosecond time-of-flight spectrometers are required for investigations on the spectra of fast neutrons. The pulsed mode of the ÉG-5 electrostatic generator was used to create such a spectrometer. The duration of the pulses on the target was 1 nsec, pulse repetition frequency 4 MHz, mean current 3-5 μA, and the intrinsic time resolution of the electron channel of the spectrometer was 2 nsec. This spectrometer was used to take the spectra of neutrons with an initial energy of 1.5, 2.0, 2.5, 3.0, 3.5, 4, and 4.5 MeV, scattered from isotope nuclei at various angles. After introducing corrections for the attenuation of the flux in the sample, multiple scattering, and the angular resolution with allowance for the geometric conditions of the experiment, from the set of spectral curves we found the differential cross sections for inelastic scattering with excitation of several nuclear levels. With this method we studied ^{48}T, ^{50,52,54}Cr, ^{54,56}Fe, ^{58,60,62,64}Ni, ^{64,66,68}Zn, and ^{209}Bi. The results match the data for natural mixtures of isotopes, the data of other authors, and theoretical calculations within the framework of the optical model and the statistical theory of nuclear reactions.

As is known, in the optical model the nuclear potential is often taken in the form

$$V(r) = -V_c f(r) - iW_c g(r) + (V_{so} + iW_{so}) h(r) \sigma l,$$

where

$$f(r) = \left[1 + \exp\left(\frac{r-R}{a}\right)\right]^{-1},$$

$$g(r) = \exp\left[-\left(\frac{r-R}{b}\right)^2\right] h(r) = \left(\frac{\hbar}{\mu_\pi c}\right)^2 \frac{1}{r}\frac{df}{dr},$$

V_c and W_c are the real and imaginary parts of the central potential; V_{so} and W_{so} are the real and imaginary parts of the spin – orbital binding potential; $R = r_0 A^{1/3}$ is the nuclear radius; and a and b are diffusivity parameters.

The parameters of this potential are found by comparing the experimental data on scattering and polarization of neutrons and protons from nuclei with calculations according to the optical model of the nucleus. The calculated curves were fitted to the experimental curves on a computer by variation of parameters. Unlike the Oxford and Florida schools of theoretical physics which chose to increase the number of fitting parameters of the form factor of the model, we investigated the physical nature of the separate components of the nuclear potential. This end was served by the establishment of a simple dependence of the optical potential on the nuclear symmetry parameter $\alpha = N - Z/A$ in the study of the interaction of fast neutrons with the nuclei of many elements. Careful analysis of published experimental data shows that the diffusivity parameter a is also a function of the symmetry parameter α. On a wide range of mass numbers of nuclei and neutron energies E the parameters of the potential are approximated by the simple formulas $V_C = 48.7 - 16.9\alpha - 0.3E$ and $a = (0.56\text{-}0.813)\alpha$.

The optical model of the nucleus now is not only of heuristic importance but can also be used to calculate the neutron cross sections for the nuclei of those isotopes for which measurements cannot be made, e.g., the nuclei of many fission fragments.

A great deal of experimental information about neutron cross sections has been systematically presented to interested organizations for use in reactor calculation.

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RESEARCH ON TOROIDAL PLASMA CONFINEMENT AT THE KHARKOV PHYSICOTECHNICAL INSTITUTE OF THE ACADEMY OF SCIENCES OF THE UKRAINIAN SSR

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Recollections. It was my fortune to meet and work with Academician I. V. Kurchatov in the last month of his remarkable life. Up to then I had heard much about him, mainly from the realm of "scientific folklore," where it is difficult to separate truth from legend, and had read his speeches at meetings of the Communist Party of the Soviet Union, at sessions of the Supreme Soviet of the USSR, or in front of voters. The director of our institute, the late Kirill Dmitrievich Sinel'nikov also told stories about Igor Vasil'evich. They had been friends from boyhood and were relatives.

After Kurchatov's speech at Harwell, England, which initiated international cooperation in the field of controlled thermonuclear fusion, an obvious need arose for an expanded research effort.

At that time our physicotechnical institute in Kharkov also became involved in solving this problem at Kurchatov's initiative. Academician K. D. Sinel'nikov of the Ukrainian Academy of Sciences directed this work. His knowledge made it possible to develop an effort in several areas of plasma physics in a short time. Together with theorists from Academician (Ukrainian Academy of Sciences) A. I. Akhiezer's section, he began research in magnetohydrodynamics, the physics of plasma flows, the rf properties of plasmas, and the collective processes which occur when beams of charged particles interact with a plasma. However, this research

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Fig. 1. Igor Vasilevich Kurchatov and Kirill Dmitrievich Sinel'nikov.

acquired an especially wide scope after I. V. Kurchatov came to Kharkov in Jan. 1960.

I, and many of my colleagues, saw him for the first time then. We noticed that I. V. Kurchatov walked with difficulty and leaned on a cane, but he surprised us with his vitality and energy. He often came to the laboratories and had a lively interest in our work. It was easy to talk with him. His good will and candor in dealing with people lay in his openness. As he toured the laboratories he held the arm of the person with whom he was speaking. From the side this resembled a quiet, friendly conversation between old acquaintances.

I. V. Kurchatov stopped for some time next to the rf plasma heating device "Sneg" (snow). He sat at the control panel and asked in detail about the results of the experiments. Even then we had been able to excite ion cyclotron waves in a plasma and to observe their damping on "magnetic beaches," which leads to ion heating. Kurchatov was interested in the possibility of rf heating of plasmas to high temperatures in large volumes. We caught his every word. It was unbelievable that a living legend, Academician Kurchatov himself, simply sat next to our machine and spoke about fusion as a perfectly ordinary thing. It is then that I first heard from him about a new project, the building of a large stellarator at Kharkov. He next asked cheerfully and simply what we thought of this and whether we were in agreement. There was a lot of enthusiasm and not much knowledge, but we saw Kurchatov's great confidence and felt his immense inner force.

Early the next morning I was invited to Sinel'nikov's office, where Kurchatov was. He sat in a big armchair, smoked, and looked at me attentively. There was one question, whether I was willing to undertake the construction of a large stellarator and do research on it. The proposal was unexpected. I understood that someone would have to do this work, but I had not imagined myself in that role. Up to then I only had experience in developing and building a high-current linear electron accelerator and in the first work on rf plasma heating. It was a compelling offer and I agreed.

Kurchatov's presence at our institute was, naturally, a big event. The prospects for expanded research on plasmas were discussed by one and all. Igor Vasil'evich gave a definite direction to these discussions. At his suggestion a special seminar with participants from the Institute of Atomic Energy and the Scientific-Research Institute of Electrophysical Apparatus was held and was of great interest.

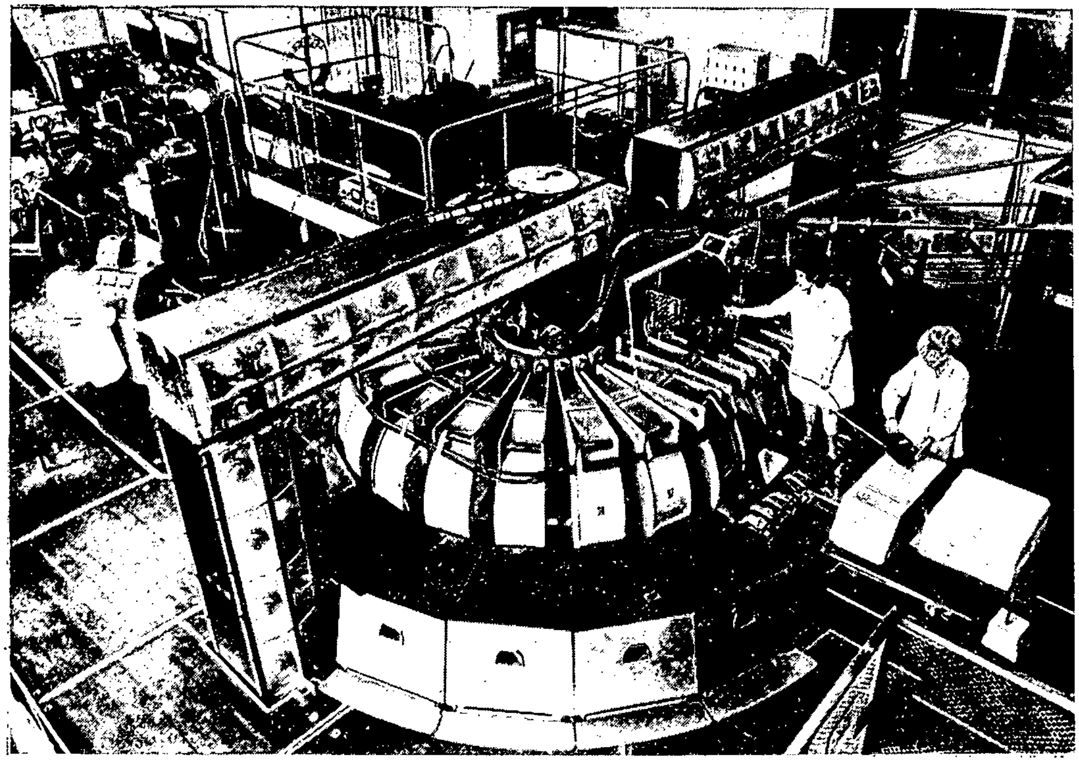

Fig. 2. The "Uragan" stellarator.

After that the days passed quickly. I was quickly dispatched to Moscow at the orders of Kurchatov. I remember the session of the scientific—technical council of the Institute of Atomic Energy at which Kurchatov raised the question of constructing a large stellarator at the Kharkov Physicotechnical Institute. It was a memorable session. The proposal was accepted but it was clear then that there were serious opponents of the idea.

During a discussion of possible power supplies for the magnetic field windings on the new machine it was decided to examine a variant of the motor generators used at Dubna for the proton synchrophasotron. At Kurchatov's command K. N. Meshcheryakov, a photographer, and I went immediately to Dubna. Late in the night files were found and photographs were taken, and by the morning it was all on Kurchatov's desk.

Preparations for building the machine went at full speed and the tempo was extremely fast. Each day of my working week in Moscow was scheduled by the hour. In Kurchatov's office in the morning the problems for the day were set, and in the evening, the results were reported. Saturday evening if the situation permitted it was possible to go to Kharkov, but on Monday morning it was necessary to be in Moscow.

Many people took part, working actively and with initiative, in the building of the machine. But the main organization was by Kurchatov himself. He included the Scientific-Research Institute of Electrophysical Apparatus in the design of the project and held talks with various ministries and organizations about their participation in planning and building the stellerator.

At times one held one's breath as on a fast ride over an unknown mountain road. But the main feeling was always one of uplift and participation in a great serious matter, done happily in a broad stroke with all involved wanting to help one another and leaving out many formalities. In this way I came to know the Kurchatov work style.

I saw Kurchatov for the last time on Friday, Feb. 5, 1960. I went to his home at the end of the day, told him briefly about what had been done during the day, and asked permission to take the night train to Kharkov. He was in a superb frame of mind and walked about the apartment singing something. He wouldn't let me go to Kharkov as he planned another meeting the next morning. I said Sinel'nikov was waiting for me on Saturday. Kurchatov settled everything at once by calling Sinel'nikov and agreeing that I should come on Sunday. At the end of our conversation he said that he had decided to rest and go to the Conservatory to hear Mozart's Requiem. Who could know that on Sunday he would not ... .

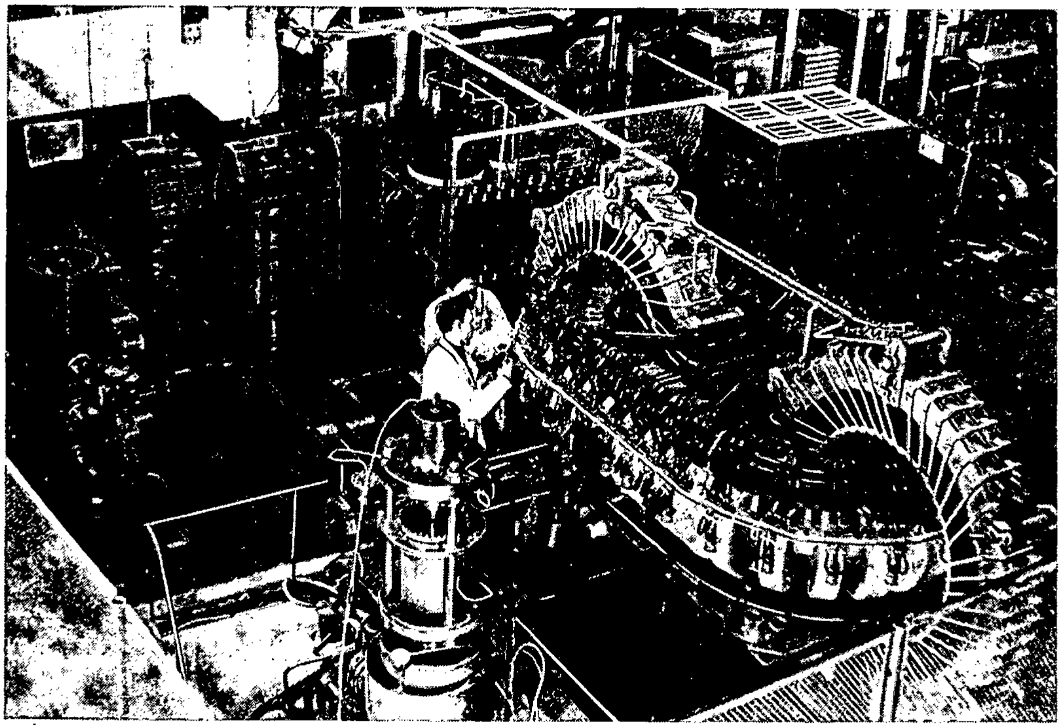

Fig. 3. "Sirius," the first stellarator at the Kharkov Physicotechnical Institute.

On Feb. 7, 1960, the day Kurchatov died, an article of his written after his visit to the Kharkov Physicotechnical Institute was published in Pravda. In it he wrote: "The staff of the institute created the strongest impression on me and they are really its gold reserve." Summing up the first results on plasma physics, new ultrahigh vacuum techniques, and other work we had done, he stated: "All this makes it possible to proceed now to design and build large machines for thermonuclear research in the Ukraine." To many, these seemed binding words of trust. They seemed to be words of farewell and, at the same time, an order to continue the work he had begun.

Already in Kharkov Kurchatov had specified the main parameters of the new stellarator. He felt that the cross-sectional diameter of the plasma in it should be 1 meter and the magnetic field strength should be as high as 75 kgf. The machine should considerably exceed the American C-stellarator at Princeton, about which much was being written at that time. Of course, the planned parameters were very high. During the planning, in which E. K. Zavoiskii took an active part, the magnetic field strength was lowered to 50 kG, but Kurchatov would not allow a reduction in the plasma diameter.

Since then 18 years have passed and time has answered many difficult questions. Research has led to the building of large toroidal machines. One cannot avoid noting that the largest tokamaks in the USSR and the U.S.A., T-10 and PLT, have basic parameters equal to those of the machine proposed by Kurchatov. However, after Kurchatov died; caution won out in the final choice of dimensions for the new stellarator. Stellarators seemed, especially to those who opposed the idea, to be too complicated compared with tokamaks. In the end the "Uragan" machine (Fig. 2) was built at Kharkov and had the same dimensions as the C-stellarator.

Nevertheless, "Uragan" was to play an important and responsible role as a leader in stellarator research.

Stellarators and Tokamaks. The basic feature of a toroidal plasma confinement system is the rotational transform of the magnetic field lines, which ensures equilibrium and stability of the plasma torus within the magnetic trap. Toroidal systems are divided into two types according to how the rotational transform is produced. In tokamaks the magnetic field of the current flowing in the plasma takes part in creating the rotational transform while in stellarators the field of a current in the outer windings surrounding the toroidal chamber is involved. In both cases a toroidal (main) field, which is produced by a solenoid surrounding the toroidal chamber, is used.

The first tokamaks were attractive because of their structural simplicity. It was relatively easy to build

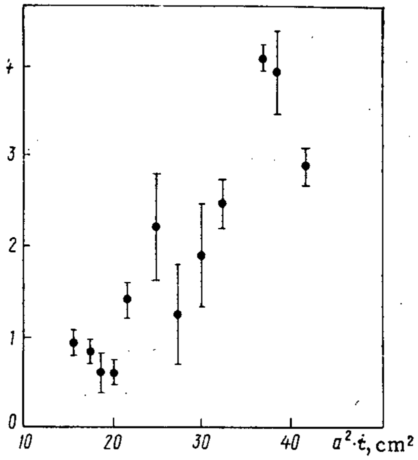

Fig. 4. The dependence of the particle lifetime for ohmic heating of the plasma in the "Uragan" stellarator, τ_n, on the product of the square of the plasma radius and the rotational transform angle $\dot{t}$.

them and results were obtained faster. From year to year the I. V. Kurchatov Institute of Atomic Energy reported success in obtaining higher plasma parameters and containment times as machines of larger size were built.

But it was always obvious that it was more convenient to study the physics of toroidal plasma confinement in stellarators. There the quality of the magnetic surfaces can be strictly monitored in the vacuum before the machine is filled with plasma and heating may be achieved independently of confinement. It is possible to study the containment of a "current-free" plasma. Stellarators have an additional helical winding compared with tokamaks. This complicates construction of the machine and requires the solution of new technical problems.

In those years the stellarator situation was complicated by yet another significant circumstance, the very modest results from the American C-stellarator at Princeton. The Bohm law, which defines an anomalously high diffusion of the plasma particles, seemed to be an insuperable barrier for the C-stellarator.

As is known, the successes of the Soviet tokamaks led the Princeton physicists to quickly convert the C-stellarator into the ST-tokamak. The turn away from stellarators at Princeton was not motivated by their unsuitability for plasma containment. On the whole the decision did not have a convincing scientific basis.

In fact, soon after the "Uragan-1" stellarator was started, it overcame the famous "Bohm barrier" as successfully as the tokamaks. This was ensured by the high quality of the magnetic surfaces which confine the plasma and are controlled by an electron beam technique first proposed at the Physical Institute of the Academy of Sciences of the USSR. The plasma particle lifetimes in "Uragan-1" exceeded the "Bohm" time by 30 times.

The Bohm diffusion observed in the C-stellarator seems to have been mainly due to destruction of the peripheral magnetic surfaces due to inaccurate winding of the coils. Our studies have shown that this defect in the magnetic system can be eliminated by careful adjustment [1].

Experiments on Stellarators at Kharkov. At the Kharkov Physicotechnical Institute experiments on containment and heating of hot dense plasmas in stellarators have been done on the "Uragan-1" (hurricane), 'Uragan-2, "Sirius," "Saturn," and "Vint-20" (screw) machines.

On the "Sirius" stellarator, built in 1964 (Fig. 3), it was shown with the aid of electron beams that closed magnetic surfaces exist and the critical value of the gas kinetic pressure of the plasma contained in a stellarator was determined for the first time [2].

Experiments done in later years on stellarators at Kharkov in the intermediate collision frequency regime (plateau) showed that diffusion of the plasma and the electron thermal conductivity in stellarators with ohmic heating are anomalously large and obey the same laws as in tokamaks. In these experiments the plasma was electron-hot i.e., $T_e \gg T_i$ [3].

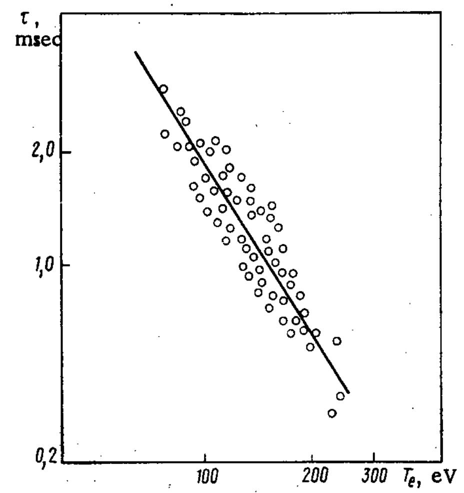

Fig. 5. The dependence of the particle lifetime for ohmic heating of the plasma, τ_n, on the electron temperature in the "Uragan" stellarator in the "plateau" regime.

The electron thermal conductivity was well described by the pseudoclassical formula first proposed by L. A. Artsimovich to explain the results of experiments on the T-3 tokamak [4]:

$$\varkappa^e = A^2 \rho_{H\theta} \nu_{\text{eff}}, \tag{1}$$

where $\rho_{H\theta}$ is the electron gyroradius in the poloidal field, ν_{eff} is the effective collision frequency determined from measurements of the plasma electrical conductivity, and A is a constant equal to 3 for the T-3 tokamak and lying between 2 and 3 for stellarators. The experiments were done at a plasma density $n \leq 10^{13}$ cm^{-3} and with a rotational transform produced by the plasma current of $t \leq 0.5$. As opposed to tokamaks, for stellarators the total value of the poloidal field due to both the external helical windings and the plasma ohmic heating current must be substituted in this formula.

The plasma particle diffusion coefficient D_{turb} in these experiments depends on the main discharge parameters in a way similar to the neoclassical coefficient D_{pl} in the "plateau" but exceeds the theoretical abslute value by 10-20 times [5, 6]. This result may be explained by turbulent diffusion at the drift instability in a current-carrying plasma studied in [7].

$$\frac{D_{\text{turb}}}{D_{\text{pl}}} = \frac{0.4}{\sqrt{\pi}\,\varepsilon^2} \left(\frac{V_{\text{cur}}}{V_{\text{th}}} \right)^{3/2} \left(\frac{m_i}{m_e} \right)^{1/2}, \tag{2}$$

where $\varepsilon = a/R$ (a is the plasma radius and R is the radius of the torus), m_i and m_e are the masses of an ion and an electron, respectively, and V_{cur} and V_{th} are the velocity of the electrons in the current and the thermal velocity of the electrons. In general the value of the turbulent diffusion coefficient depends on the magnitude of the plasma current. For the conditions in the "Uragan" stellarator we may obtain $D_{\text{turb}}/D_{\text{pl}} = 20$ from Eq. (2) [8]. This ratio is also given by Eq. (2) for the stellarators "Cleo" and "Torso" (England) and "Wendelstein-2B" (West Germany).

At Kharkov detailed studies have been made of the dependence of the particle lifetime τ_n on the magnetic field strength H, the electron temperature T_e, and the rotational transform angle $\dot{t}$ (Figs. 4 and 5) [9].

This analysis allows us to assume that in experiments on the confinement of an ohmically heated plasma in stellarators both the electron thermal conductivity and the particle diffusion are determined by turbulent processes as the drift instability is excited in an inhomogeneous current-carrying plasma. The existence of the drift instability was confirmed in direct experiments on "Uragan" by studying the spectra and localization of turbulent fluctuations in the local fields and plasma density [10].

Many of the results on the confinement of current-carrying plasmas in the stellarators at Kharkov have been confirmed on other machines of this type, of which we must mention the stellarators "Liven" (shower) at the Physical Institute of the Academy of Sciences of the USSR [11] and "Cleo" at Culham, England [12].

In an isothermal plasma, even when anomalous pseudoclassical heat losses occur through the electrons, ion thermal conductivity is the main mechanism by which the plasma is cooled for moderate impurity concentrations. In small experimental devices it is usually not possible to attain complete equilibration of the electron

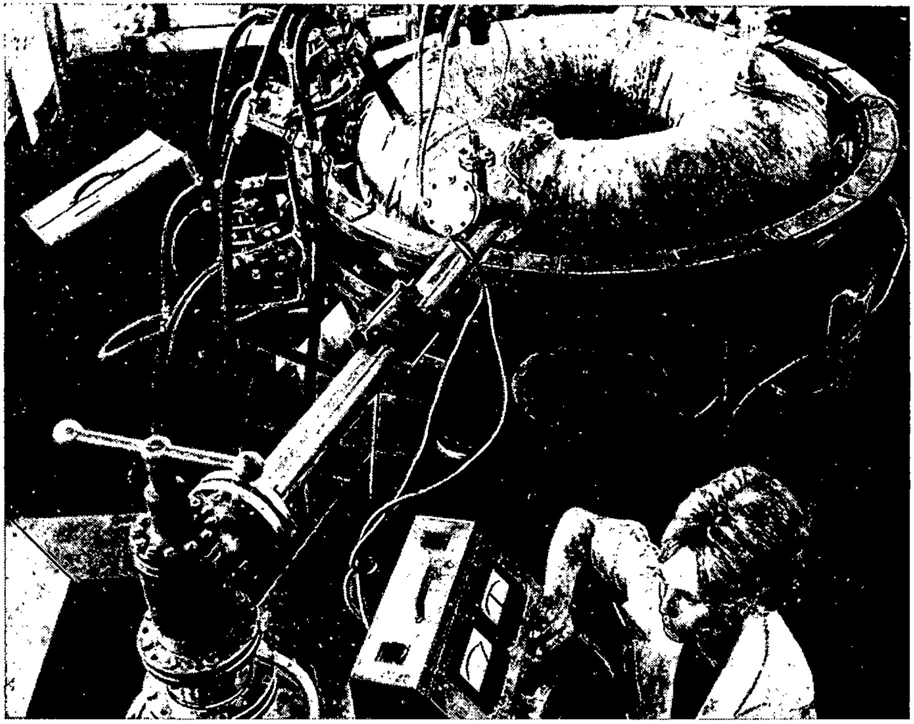

Fig. 6. The stellarator-torsatron "Saturn."

and ion temperatures so model experiments on containment of ion-hot plasmas in stellarators are of great interest.

This type of experiment was first done on the "Uragan-1" stellarator in 1974 [13,14]. The ion thermal conductivity in a current-free plasma was studied by rf heating at the ion cyclotron resonance. Efficient and uniform rf heating of a dense plasma along the length of a closed magnetic trap is achieved by exciting nonaxisymmetric electromagnetic waves in the plasma which can propagate freely in the toroidal magnetic field. This possibility for rf heating of a plasma in a closed magnetic trap was first demonstrated in [15,16] in which both ion cyclotron and ion — ion (on a mixture of two types of ion) nonaxisymmetric waves were excited. An important advantage of such waves is that for them the rf field strength was greatest on the axis of the plasma column and the conditions for best energy transfer in the plasma were realized at much higher plasma densities than in the case of symmetric waves. With ion cyclotron heating the ion temperature was much greater than the electron temperature and reached 600 eV at a plasma density of $(2\text{-}4)\cdot 10^{12}$ cm^{-3}. Ion heating took place during damping of the field on inhomogeneities in the confining magnetic field.

In these experiments it was shown that, as opposed to confinement of a current-carrying plasma, confinement of a current-free ion-hot plasma with rf heating differs little from the predictions of the neoclassical theory [13].

The most important distinguishing features of the diffusion coefficient in the low collision frequency region are its inverse dependence on the collision frequency and its complicated dependence on the rotational transform angle.

An analysis of experiments on the stellarator-type machines "Saturn" and "Vint-20" at Kharkov and "Protocleo," "Spak," and "Heliotron-D" in other countries showed that in every case the diffusion coefficient is less at reduced collision frequencies than predicted by the neoclassical theory [17]. In "Saturn" (Fig. 6) these experiments were done with an injected plasma having a low density $n = 10^{10}$ cm^{-3} and $T_e = 10$ eV. In the $l = 1$ torsatron "Vint-20" this result has been confirmed for a fairly dense ($n = 10^{13}$ cm^{-3}) and hot ($T_e = 100$ eV) plasma [18].

The observed discrepancy is evidently due to the fact that the neoclassical theory was developed for a quiet plasma while under experimental conditions the collective electric fields of the plasma turbulence usually play a signficant role. Including the effect of these fields on the motion of the "trapped" particles (as done in [19]) shows that when a resonance exists between the frequencies of the waves in the turbulent spectrum and the frequencies of oscillation of the localized or "trapped" particles between the corrugations in the magnetic

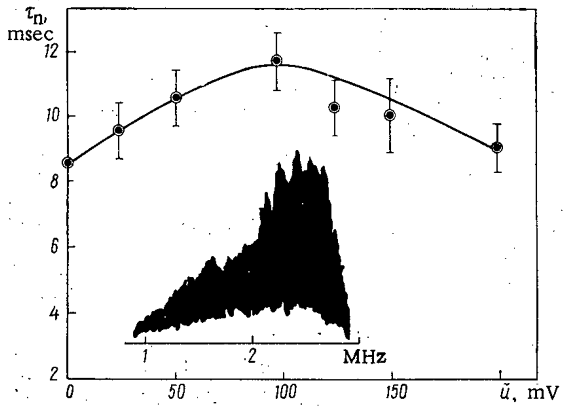

Fig. 7. The dependence of the particle lifetime τ_n in the low-collision-frequency region for the "Saturn" stellarator with an injected plasma on the magnitude $\tilde{u}$ of the broad-band rf signal delivered to the plasma. The frequency spectrum of the rf signal is shown in the insert.

field there is a transformation of "trapped" particles into "passing" particles. It may be assumed that in stellarators this process causes a reduction in the diffusion coefficient in the low-collision-frequency range.

On the "Saturn" torsatron it has been demonstrated [20] that the diffusion of particles in the "superbanana" region can be acted on externally. Here it was important to ensure resonance of the external signal with the frequency of the "trapped" particles in the entire plasma volume within which the parameters of the magnetic field and, therefore, the frequencies of the particle oscillations on superbanana trajectories have a strong radial dependence. This required the excitation of broad-band oscillations in the plasma covering the entire frequency spectrum of the "trapped" particle oscillations. The observed resonant (with respect to the excited spectrum) increase in the particle lifetime and the absence of any effect on confinement due to purely harmonic oscillations confirm the assumption that longitudinal rf electric fields act on electrons localized in "bananas" (Fig. 7).

An important step in the stellarator development program was the development of the torsatron magnetic system, proposed independently at Kharkov by B. F. Aleksin and in France by S. Gourdon. The "Saturn" machine built in 1970 was the first practical realization of this idea. The equivalence of the magnetic systems of a stellarator and a torsatron for the containment of plasmas was first shown experimentally on "Saturn" [21].

Later, of course, torsatrons came to replace stellarators in the Kharkov "Uragan" program. The results of engineering and physical studies on the "Saturn" torsatron demonstrated the advantages of this system. The design of a torsatron without a longitudinal magnetic field winding seemed much simpler than a stellarator and the possibility remained of extensively controlling the magnetic field parameters with a small transverse magnetic field whose strength did not exceed a few percent of the main field. For a special choice of parameters of the torsatron helical winding the winding may be substantially relieved of ponderomotive forces acting on its elements and the magnetic field level at the conductors will not exceed the field strength at the plasma center by more than a factor of two. The latter circumstance is especially important for superconducting magnetic windings in a controlled thermonuclear reactor based on the torsatron. Yet another advantage of the torsatron configuration is that it forms a poloidal diverter made up of the main magnetic field windings.

It is proposed that a diverter will, on one hand, protect the plasma from cold working gas atoms and impurities from the vacuum vessel walls and, on the other, take particles which have diffused to the periphery out of the working volume so as to keep them from knocking impurities out of the wall [22]. In principle this may create a vacuum gap between the plasma column and the wall and greatly improve the thermal isolation of the plasma, thereby increasing the energy lifetime to the level of the particle lifetime. A reduction in heat losses from a toroidal trap due to a diverter may occur under fully realizable conditions when the transverse thermal conductivity of the electrons becomes less then the ion thermal conductivity.

It is planned to solve the main problems of the physics of toroidal confinement of hot plasmas in the "Uragan" program using the large "Uragan-3" machine which is under construction (Fig. 8). This machine is an $l = 3$ torsatron without a longitudinal magnetic field winding and with a spatial poloidal diverter. Different rf techniques will be used to create and heat the plasma. In addition, ohmic heating and plasma and neutral

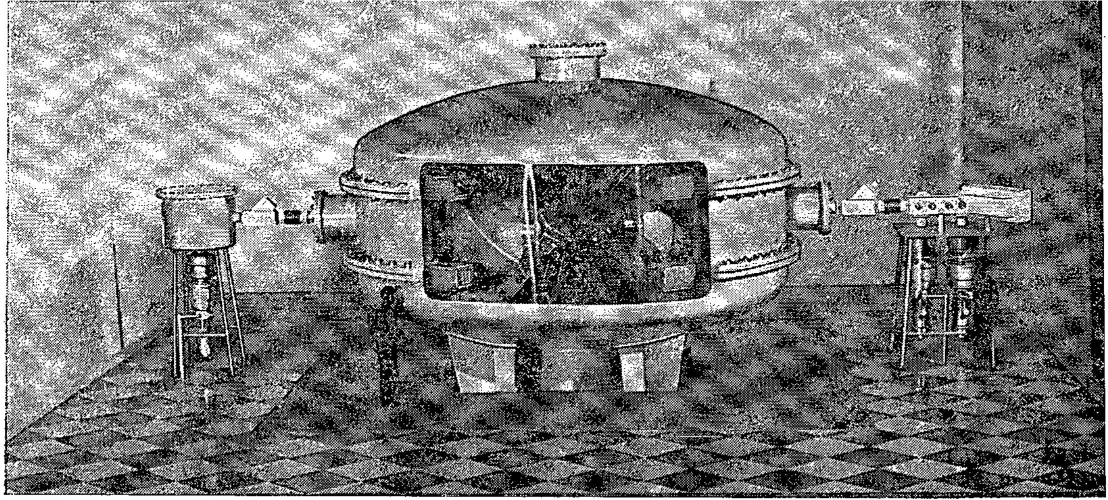

Fig. 8. The "Uragan-3" torsatron with a poloidal diverter (model).

particle injection will be used. A cryogenic vacuum system with a total pumping speed of $3 \cdot 10^6$ liters/sec will play an important role in the "Uragan-3". The main physical research problem on this machine is to study long confinement of pure plasmas with densities of 10^{13}–10^{14} cm^{-3} and temperatures of 0.5–5 keV over a wide range of collision frequencies.

CONCLUSIONS

The research on the physics of hot plasmas in stellarators at the Kharkov Physicotechnical Institute as part of the "Uragan" scientific program has yielded a number of important conclusions.

1. Plasma confinement in stellarators or torsatrons with ohmic heating seems to be at least as good as in tokamaks. In a stellarator with a plasma current the helical windings give an additional "rigidity" to the entire magnetic configuration and create a magnetic limiter for the plasma. This ensures reliable startup conditions and highly reproducible discharges. The initial rotational transform angle produced by the helical winding in the vacuum makes it possible to operate in an ohmic heating regime with a total stability safety factor close to unity.

2. Because it is possible to contain a "current-free" plasma in stellarators, it is possible to study the physics of toroidal confinement more thoroughly.

3. The possibility of correctly studying the magnetic system of stellarators (alignment and monitoring the quality of the magnetic surfaces in the vacuum) has permitted work to be done at Kharkov on the improvement of stellarators. At the present time a modification of the stellarator, a torsatron with only one main helical winding to simultaneously create closed magnetic surfaces and a poloidal diverter, seems to have a simpler design than a tokamak with a diverter. In a tokamak a system of additional windings is required, which complicates the construction. An important feature is the ability to create a quasi-force-free magnetic system by choosing the appropriate angle for the winding. This in turn opens up the possibility of building a torsatron magnetic system with a high magnetic field strength.

4. Among the disadvantages of stellarator magnetic systems are the lack of axisymmetry and the occurrence of enhanced transport in "superbananas" at the very low collision frequencies characteristic of the operating regime of a thermonuclear reactor. Thus, further improvement in ways of reducing the effect of "superbananas" is important.

Research on controlled thermonuclear fusion in the USSR begun by Academician I. V. Kurchatov, is proceeding successfully. Toroidal plasma confinement occupies a leading position at present. Its development has shown that the research on stellarators initiated by Kurchatov has become an important branch of the program for studying toroidal confinement of hot plasmas.

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V. I. Bochenin

RADIOISOTOPE TECHNIQUES IN THE ANALYSIS OF INDUSTRIAL MATERIALS*

Reviewed by E. R. Kartashev

Nuclear physics techniques for determining the elementary composition of matter are becoming more widespread both in scientific laboratories and under industrial or field conditions. Neutron activation analysis has advanced from a special analytic technique to become the standard method for determining several elements (e.g., titanium) in factory laboratories. Radioisotope x-ray fluorescence analysis (or, as it is most often called in the Soviet literature, roentgenoradiometric analysis) is gaining ever wider use. Other methods based on various interactions of ionized radiation with matter have been developed and are in use. Hence V. I. Bochenin's book, which generalizes his own research on developing radioisotopic methods of analyzing industrial materials from Central Kazakhstan, should be of interest.

The book touches mainly on two methods of element analysis, by recording the fluorescence radiation and by backscattering of gamma radiation, and gives examples of their practical application. Interesting data is also obtained when ^{55}Fe is used as a source in x-ray structure analysis. The author presents results of studies of the structural transformations which occur during heat treating of carbon steel, and of a study of microstresses in alloy steel with the aid of laboratory apparatus containing an ^{55}Fe source.

Unfortunately, the book is overloaded with general information which is either sufficiently well known to specialists or is found in widely available literature. Thus, extensive descriptions are given of a single channel analyzer (the commercial apparatus "Mineral-4"), of the principles of scintillation spectrometry, of the basic problems in the theory of sampling, and so on. Almost one-third of the book is devoted to ways of evaluating the results of an analysis. The practical examples given in this chapter are separated from the main content of the book.

In my opinion in the modern literature it is unnecessary to point out the advantages of apparatus using semiconductor devices over apparatus made of vacuum tubes. Each time the author of this book describes an experimental apparatus he lists in detail the types and names of the equipment used. This makes the book cumbersome.

Certain inaccuracies can be found. For example, the author writes that in using accelerated monitoring methods, "the samples are taken from the conveyor and the element to be analyzed is determined at once. However, the accuracy of the analysis is reduced in this case" (p. 23). In this case the accuracy of the determination is independent of how the sample is chosen. The result of the analysis, however, may not be representative of the entire mass of the material.

These shortcomings reduce the impression given by Bochenin's book, which on the whole is certainly full of very interesting material illustrating the broad prospects for various techniques for the nuclear analysis of matter.

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*Atomizdat, Moscow (1977), 80 pp., 25 kopecks.

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OPTIMIZATION OF RADIATION MONITORING IN REGIONS AROUND ATOMIC POWER PLANTS

L. I. Piskunov, V. M. Gushchin,
and S. I. Treiger

UDC 621.039.76

Radiation monitoring in regions around atomic power plants consists of detecting significant deviations from the background radioactivity in objects in the environment as the result of discharges into the atmosphere, effluent, and burial of radioactive waste. If the physicogeographical and demographic conditions of the observed zones are taken into account, any atomic power plant can be broken up into sections so that each section constitutes an element of a Latin square [1]. It is expedient to take the sector lines and the arcs of the belts for the arbitrary boundaries of the sections, with the point marking the location of the atomic power plant serving as the natural center of the construction.

The main properties of the Latin square and their advantages in comparison with other methods of mathematical planning of observations are well known [1]. In particular, planning with a Latin square scheme ensures the necessary minimum number of observations permitting nonuniformity effects to be detected. Statistical analysis of the Latin square is possible with no interaction, or only a weak one, between the factors and it is not necessary to assume a normal distribution of the quantitative values of these factors. The algorithm for processing the Latin square can be executed on simple computers. These and other advantages recommend use of the Latin square in radiation monitoring in the observed zones of atomic power plants.

Tables 1 and 2 give a portion of the planning and processing of the monitoring in the observable zone of the I. V. Kurchatov Atomic Power Plant at Beloyarsk in 1975 according to a 4 × 4 Latin square scheme. The sampling points were arranged with allowance for the probability distribution of the atmospheric discharges from the Beloyarsk Atomic Power Plant [2].

In the given case the ^{90}Sr concentration in the objects from the windward side, i.e., west of the atomic power plant, was taken to be unity whereas in other cells of the square it is expressed as a fraction of this activity, i.e., in dimensionless quantities. Dispersion analysis showed that there are no differences in the dispersions over the belts A_i, over the sectors B_i, and over the environmental objects C_k at a significance level of 0.05. Therefore, no contamination of the environment with discharges from the Beloyarsk Atomic Power Plant was detected.

Optimization of the radiation monitoring in the observable zones of atomic power plants makes it possible to reduce the volume of observations without loss of quality, to standardize the processing of results and to assess the results on the basis of object statistical criteria. As experience shows, such a monitoring scheme proves to be also appropriate for the cooling points of atomic power plants.

TABLE 1. Plan of Observation and Results of ^{90}Sr Monitoring in Region of Beloyarsk Atomic Power Plant

Belt km	^{90}Sr content in environmental objects by sectors, sec. units				$\overline{A}_i$
	north	east	south	west	
2—4	Snow 1,75	CN* 0,63	Grass 0,22	Turf 1	0,90±0,32
4—6	CN* 0,69	Grass 0,38	Turf 0,84	Snow 1	0,73±0,13
6—8	Grass 1,24	Turf 0,60	Snow 0,93	CN* 1	0,94±0,13
8—10	Turf 1,42	Snow 4,12	CN* 0,54	Grass 1	1,77±0,80
$\overline{B}_j$	1,28±0,22	1,43±0,90	0,63±0,16	1	1,08

*CN) Conifer needles.

TABLE 2. ^{90}Sr Content in Monitored Objects

Object	North	East	South	West	$\overline{C}_k$
Snow	1,75	4,12	0,93	1	1,95±0,72
CN*	0,69	0,63	0,54	1	0,72±0,03
Grass	1,24	0,38	0,22	1	0,71±0,24
Turf	1,42	0,60	0,84	1	0,96±0,17
$\overline{B}_j$	1,28±0,22	1,43±0,90	0,63±0,16	1	1,08

*CN) Conifer needles.

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USE OF CHANNELING METHOD TO STUDY RADIATION DAMAGE IN ALKALI-HALIDE CRYSTALS

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UDC 539.16.04+539.12.04

We studied the channeling of H^+ and He^+ ions with an energy of 1.0-1.2 MeV in irradiated crystals of LiF, KF, KCl, NaCl, and CsI(Tl). To determine the damage to the crystal lattices we measured the dependence of the minimum yield and the critical angle of the channeling on the depth of the crystal and the rate of dechanneling during elastic scattering of the ions through an angle of 135°.

The radiation-induced defects were produced by 50-keV Li^+ and K^+ ions and H^+ and He^+ ions with an energy of 0.4-1.2 MeV. We measured the profiles of the defect distribution over the depth of the crystal, determined the positions of interstitial ions and the displacements of atoms in the crystal lattice, and found the cross section and rate of defect formation as a function of the radiation dose, the orientation of the bombarding beam relative to the crystallographic axes, and the radiation energy.

With channeling of the bombarding particles the rate of defect formation for the irradiated layers of the crystal fell off and the depth at which the defects lie increased. The cross section of defect formation in the crystals studied was 10^{-17}-10^{-18} cm^2 for H^+ and He^+ ions. The defect formation rate in the initial stage of irradiation dropped by a factor of 1.9 and 1.6 for 0.5- and 1.2-MeV H^+ ions and the <100> axis of the NaCl crystal, by a factor of 1.9 for 1-MeV He^+ ions and the ⟨100⟩ axis of the KCl crystal, and by a factor of 3.5 for 0.47-MeV He^+ ions and the ⟨111⟩ axis of the CsI(Tl) crystal.

The volume density of defects rose when the irradiation increased and at a radiation dose of $4 \cdot 10^{14}$-10^{15} ions/cm^2 reached a maximum value equal to 5-10% of the atomic density of the crystal. The channeling of H^+ and He^+ ions in the crystals was improved by irradiating the crystals with these ions at a dose exceeding 10^{15} ions/cm^2; this is due to the formation of defect clusters in the crystals and an increase in the rate of recombination of interstitial atoms with vacancies. The effects of the irradiation was more pronounced in crystals with a high lattice energy. The rate of damage formation in crystals increased when an external constant electric field was applied.

Analysis of the results shows that inelastic mechanisms play an important role in the formation of radiation of the crystals with the fast light ions H^+ and He^+. The method of backscattering and channeling of H^+ and He^+ ions makes it possible to study the characteristics of the process of radiation damage formation in alkali-halide crystals under irradiation by ions as well as to observe the redistribution of defects and interstitial ions (atoms) in the lattice of crystals.

ISOTOPIC ANOMALIES OF XENON FROM NATURAL NUCLEAR REACTOR

(Deposited at Okhlo, Gabon, Africa)

Yu. A. Shukolyukov and Dang Vu Minh

The paper presents the results of detailed study of five samples from borehole SC20 in ore zone 2 where isotopic anomalies of xenon and krypton had been discovered earlier. The primary task was that of ascertaining the nature of the isotopic xenon anomaly which the authors had found and which had never before been observed in any object.

The isotopic composition of xenon was measured on an inhomogeneous-field mass spectrometer with a resolution of about 5000, with an electron multiplier, and operating in a quasistatic vacuum mode.

The mineral carrier of the anomalous xenon was separated by three methods: roasting of the samples, separation of the mineral fractions by physical methods, and differential dissolution of the mineral constituents. We determined the isotopic composition and quantity of xenon in each mineral fraction at a given temperature.

When samples from near the ore were roasted we observed a slight enrichment of the xenon with isotopes with the mass numbers 129-134 relative to ^{136}Xe. At 400-800°C sample 1348 right from the zone of the natural chain reaction released xenon with an unusual isotopic composition ^{134}Xe/^{136}Xe up to 1.441, ^{132}Xe/^{136}Xe up to 2.30, ^{131}Xe/^{136}Xe up to 1.045, and ^{129}Xe/^{136}Xe up to 0.260 (when ^{235}U is fissioned by thermal neutrons the corresponding ratios are 1.241, 0.672, 0.411, and 0.105). The anomalous isotopic compositions, which varied with the temperature and changed from weighed quantity to weighed quantity, are linearly correlated with each other, which indicates that the xenon isotopes originate from one process.

This effect cannot be explained by the fractionation of xenon isotopes during the laboratory roasting because of the different numbers and energy of the β-decay of radioactive precursors of the xenon in the chains since such anomalies do not arise in artificially irradiated UO_2. The migration of xenon atoms in the crystalline structure of the minerals under natural conditions could not result in the isotopic anomalies. This is proved by lack of such anomalies in the natural uraninites and nasturans studied. Nor can the anomalous character of the xenon in sample 1348 be explained by the interaction of neutrons with the nuclei of barium, tellurium, and other elements present in the sample. In experiments with the artificial irradiation of barium and tellurium with thermal neutrons we obtained xenon with completely different isotopic ratios: ^{132}Xe/^{136}Xe ≈ 1, ^{131}Xe/^{136}Xe ≈ 20, ^{132}Xe/^{136}Xe ≃ 2 and ^{131}Xe/^{136}Xe ≃ 50, ^{130}Xe/^{136}Xe ≃ 8.

When sample 1348 was separated into mineral constituents according to density, magnetic properties, color of the minerals, and grain size, we noticed that the isotopic anomalies are maximum in samples depleted of uraninite, with low density, and with small grain size. When these mineral constituents were roasted in some temperature fractions (300-800°C) the ratio ^{134}Xe/^{136}Xe reached 1.59; ^{132}Xe/^{136}Xe, 3.46; ^{131}Xe/^{136}Xe, 1.19; and ^{129}Xe/^{136}Xe, 0.358. The anomalous isotopic ratios are linearly correlated for various mineral constituents and temperature fractions.

The crystals which remain after treatment with HNO_3 (3-68%) and (2-8) N HCl are enriched to the maximum with light isotopes of xenon relative to ^{136}Xe: ^{134}Xe/^{136}Xe up to 1.600, ^{132}Xe/^{136}Xe up to 4.633, ^{131}Xe/^{136}Xe up to 1.325, and ^{129}Xe/^{136}Xe up to 0.412.

Assuming a two-component composition of xenon, we calculated the ratio of anomalous (Xe_a) and ordinary fission xenon (Xe_U) for each fraction. In uraninite crystals $Xe_a/Xe_U \simeq 0.015$ whereas in light mineral fractions this ratio ≃70. It is expected that with the fission chain reaction in the deposit the progenitor of Xe_a which had a sufficiently long lifetime and appropriate chemical properties diffuses from the uraninite and enters into the composition of the secondary minerals. Up to $8 \cdot 10^{-7}$ cm^3/g of the anomalous Xe_a is accumulated when the hypothetical progenitor in these minerals decays.

γ-RAY ALBEDO FOR IRON PLATES

V. I. Kulikov, K. K. Popkov,
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UDC 621.039.51.17

The Monte Carlo method was used to obtain the current differential spectral, numerical, energy, and dose albedoes of γ rays for iron plates of various thicknesses. An attempt was made to describe the results of the calculations by means of semiempirical formulas. It proved to be appropriate to separate the contribution to the albedo from single-scattering processes, i.e., the total albedo a is given by the sum

$$a + a_1 + a_2, \tag{1}$$

where $a_1 = a_{1S} + a_{1p}$ is the contribution from single scattering (a_{1S}) and annihilation γ rays (a_{1p}) and a_2 is the contribution from multiple scattering. It can be shown that

$$a_{1s}=\frac{\sigma_s(E_0)}{\sigma_{\text{tot}}(E_0)}\,\frac{(d\sigma_k/d\Omega)\,(E_0,\ \cos\theta)}{\sigma_k}\,\frac{\mu(E_0)/\cos\theta_0}{\mu(E_0)/\cos\theta_0+\mu(E_s)/\cos\theta}\times$$
$$\times\left\{1-\exp\left(-\left[\frac{\mu(E_0)}{\cos\theta_0}+\frac{\mu(E_s)}{\cos\theta}\right]d\right)\right\}; \tag{2}$$
$$\sigma_{1p}=\frac{1}{2\pi}\,\frac{\sigma_p(E_0)}{\sigma_{\text{tot}}(E_0)}\,\frac{\mu(E_0)/\cos\theta_0}{\mu(E_0)/\cos\theta_0+\mu(0.511)/\cos\theta}\left\{1-\exp\left(-\left[\frac{\mu(E_0)}{\cos\theta_0}+\frac{\mu(0{,}511)}{\cos\theta}\right]d\right)\right\}.$$

The calculations showed that the following approximation is admissible:

$$a_2=[a_\infty-a_1(d\to\infty)]\left\{1-\exp\left(\left[-A\frac{\mu(E_0)}{\cos\theta_0}-\frac{B}{\text{ccs}\,\theta}\right]d\right)\right\}, \tag{3}$$

where $\sigma_s(E_0)$, $\sigma_p(E_0)$, and $\sigma_{tot}(E_0)$ are the scattering, pairing, and the total cross section for γ rays of energy E_0; $d\sigma_k/d\Omega$ $(E_0,\ \cos\theta)$ and σ_k are the differential and total cross sections for Compton scattering; θ_s is the angle of single scattering; $\mu(E_0)$, $\mu(E_s)$, and $\mu(0.511)$ are linear coefficients of γ-ray attenuation with an initial energy of 0.511 MeV, respectively; a_∞ is the albedo for a semi-infinite scatterer; and A and B are empirical constants.

To calculate the energy (a_E) or dose (a_D) we rewrite the first term of Eq. (1) as

$$\begin{aligned} a_{1E}&=\frac{E_s}{E_0}a_{1s}+\frac{0.511}{E_0}a_{1p},\\ a_{1D}&=\frac{k_D^sE_s}{k_D^0E_D}a_{1s}+\frac{k_D^{0.511}0.511}{k_D^0E_0}, \end{aligned} \tag{4}$$

where k_D^0, k_D^S, and $k_D^{0.511}$ are the conversion factors of the density of the flux of γ rays with an energy of E_0, E_S, and 0.511 MeV.

The empirical constants A and B were calculated on a computer by the maximum probability method. The following values of the constants were obtained: for the differential spectral albedo and the numerical albedo A = 0.358 and B = 0.272; for the differential energy albedo A = 0.376 and B = 0.284; and for the differential dose albedo A = 0.379 and B = 0.284.

LETTERS TO THE EDITOR

CONTROL OF SPACE — TIME DISTRIBUTION OF XENON IN NUCLEAR REACTOR

T. S. Zaritskaya and A. P. Rudik

UDC 539.172.4

Space — time oscillations of the energy distribution are one of the main obstacles to the normal use of nuclear reactors. These oscillations, which are a consequence of inadequacy of the control system for fluctuations in ^{135}Xe concentration, may lead to technical malfunction of the reactor.

The detailed theoretical study of space — time oscillations of the energy distribution was considered in [1]; the approach usually adopted is as follows [2]. Consider, as an illustration, a one-dimensional reactor in which the ^{135}I and ^{135}Xe concentrations — I(z, t) and X(z, t), respectively — and the neutron flux density N(z, t) depend on the space coordinate z and the time t. Assume that when $t < 0$ ^{135}I and ^{135}Xe are in equilibrium and the reactor is critical, with a steady distribution of neutron flux density $N(z, t < 0)$. At $t = 0$ there is a fluctuation $\delta X(z, 0)$ in the ^{135}Xe distribution; with the given control method (uniform introduction of absorbent over the reactor height) there is a change in the ^{135}I concentration $\delta I(z, t)$ and in the neutron flux density $\delta N(z, t)$. The fluctuations $\delta X(z, t)$, $\delta I(z, t)$, and $\delta N(z, t)$ are expanded in series with respect to the time of the form $\delta N(z, t) = \sum_n R^{(n)}(z)e^{\omega_n t}$, and these expansions are substituted in the initial equations describing the space — time variation of the neutron flux density and the ^{135}I and ^{135}Xe concentrations; $R^{(n)}(z)$ are the eigenfunctions of the unperturbed problem

$$\frac{d^2N(z, t)}{dz^2} + \alpha^2\{z, X(z, t)\}N(z, t) = 0; \tag{1}$$

$$\frac{dI(z, t)}{dt} = \gamma\Sigma_f N(z, t) - \lambda_I I(z, t); \tag{2}$$

$$\frac{dX(z, t)}{dt} = \lambda_I I(z, t) - [\sigma N(z, t) + \lambda_{Xe}]X(z, t). \tag{3}$$

The next step is to linearize Eqs. (1)-(3) with respect to the fluctuations and hence to determine an approximate value for the mean neutron flux density $\overline{N_M(z, t)}$, taken over the reactor volume, at which a term Re $\omega_n > 0$ first appears. This value $\overline{N_M(z, t)}$ is called the critical neutron flux density.

In this approach, it is not entirely clear what role is played by the chosen means of compensating the change in reactor reactivity, and also there is a certain lack of accuracy both in the derivation of approximate equations for the various time components of the fluctuations δI, δX, and δN and in the observance of the condition of constant reactor power. Therefore, it is expedient to consider a somewhat different approach, involving the use of perturbation theory on the basis of the conjugate functions usually introduced in optimizing the physical characteristics of nuclear reactors [3].

The main aim of these investigations is not to establish a criterion of asymptotic stability, but to find a control system that will ensure sufficiently rapid suppression of fluctuations in the spatial distribution of ^{135}Xe.

It is expedient to rewrite Eq. (1) in canonical form, introducing the phase variables

$$X^{(1)}(z, t) = N(z, t); \quad X^{(2)}(z, t) = \frac{dN(z, t)}{dz};$$

$$\frac{dX^{(1)}(z, t)}{dz} = X^{(2)}(z, t); \tag{4}$$

$$\frac{dx^2(z, t)}{dz} = -\alpha^2 X^{(1)}(z, t), \tag{5}$$

while the Laplacian α^2, which depends on X(z, t), is written as a linearized function of the ^{135}Xe concentration

$$\alpha^2(z, t) = \alpha_0^2(z) - \frac{\beta}{M^2}X(z, t), \tag{6}$$

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where $\alpha_0^2(z)$ is the value of the Laplacian when ^{135}Xe contamination is disregarded (the dependence of $\alpha_0^2(z)$ on z may be the result, for example, of nonuniform distribution of the nuclear fuel); M^2 is the square of the neutron migration length; β is a proportionality constant.

If the reactor dimension is H, the boundary conditions for $X^{(1)}(z, t)$ are

$$X^{(1)}(0,\ t) = X^{(1)}(H,\ t) = 0. \tag{7}$$

Suppose that when $t < 0$ the reactor is in a steady state with $\alpha^2(z,\ t < 0) = \alpha^2(z)$. This state corresponds to steady values of $X^{(1)}(z,\ t < 0)$, $X^{(2)}(z,\ t < 0)$, $I(z,\ t < 0)$, and $X(z,\ t < 0)$. The problem takes the following form. At $t = 0$ there is a fluctuation of the ^{135}Xe concentration $\delta X(z,\ 0)$, leading to a fluctuation in the Laplacian

$$\delta\alpha^2(z,\ 0) = -\frac{\beta}{M^2}\,\delta X(z,\ 0). \tag{8}$$

To maintain a critical state in the reactor, the control system introduces a reactivity

$$\delta\alpha_c^2(z,\ 0) = \varepsilon f(z), \tag{9}$$

where f(z) is a given function determining the spatial properties of the control activity; ε is a parameter depending on the condition for a critical state. Thus, the total perturbation of the Laplacian is

$$\Delta\alpha^2(z,\ 0) = -\frac{\beta}{M^2}\,\delta X(z,\ 0) + \varepsilon f(z). \tag{10}$$

As a result of the perturbation $\Delta\alpha^2$ in Eq. (10), the neutron flux density at each point z_0 changes by an amount $\delta N(z_0,\ 0)$, where

$$\delta N(z_0,\ 0) = -\int_0^{z_0} \frac{\partial \mathscr{H}_{z_0}}{\partial\alpha^2}\,\Delta\alpha^2\,dz. \tag{11}$$

The Hamiltonian $\mathscr{H}_{z_0}$ is defined as

$$\mathscr{H}_{z_0} = -X^{(2)}(z,\ t<0) + \psi_1(z;\ z_0)\,X^{(2)}(z,\ t<0) - \widetilde{\alpha}^2(z)\,\psi_2(z;\ z_0)\,X^{(1)}(z,\ t<0). \tag{12}$$

The conjugate functions $\psi_i(z\,;\ z_0)$, $i = 1,\ 2$, which depend on the current value of the coordinate z and on the point z_0 at which the perturbation of the neutron flux density is sought, satisfy the equations

$$\frac{d\psi_i(z;\ z_0)}{dz} = -\frac{\partial\mathscr{H}_{z_0}}{\partial X^{(1)}} \tag{13}$$

and the boundary conditions at $z = z_0$

$$\psi_i(z_0;\ z_0) = 0, \quad i = 1,\ 2. \tag{14}$$

In these conditions the expression corresponding to a critical state of the reactor, from which ε may be determined, is

$$\int_0^H \psi_2(z;\ H)\,X^{(1)}(z,\ t<0)\,\Delta\alpha^2\,dz = 0. \tag{15}$$

When $t < 0$, the reactor power W is

$$W = \int_0^H \Sigma_f X^{(1)}(z,\ t<0)\,dz, \tag{16}$$

and the change in the power due to the change δN given by Eq. (11) is

$$\delta W = \int_0^H \Sigma_f\,dz_0 \int_0^{z_0} \psi_2(z;\ z_0)\,X^{(1)}(z,\ t<0)\,\Delta\alpha^2(z)\,dz, \tag{17}$$

so that, when the reactor power is held constant, the change in neutron flux density $\Delta X^{(1)}(z_0)$ at the point z_0 is *

$$\Delta X^{(1)}(z_0) = \delta N(z_0,\ 0) - X^{(1)}(z_0,\ t<0)\,\frac{\delta W}{W}. \tag{18}$$

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*The derivation of Eqs. (18)-(20) is based on the standard theory of perturbations in the first order with respect to small quantities.

TABLE 1. Parameters of Eq. (20) when α^2 = const

h_1/H	h_2/H	$e\frac{M^2}{\beta\delta X}$	$\frac{Az\sigma\cdot 10^2}{\gamma\Sigma_f\beta}$	$z_{\max}$	$\frac{\delta W}{W}\frac{M^2\cdot 10^2}{H^2\beta\delta H}$
0,000	0,125	0,012	0,630	0,000	0,630
0,125	0,250	0,078	1,220	0,125	1,200
0,250	0,375	0,172	0,993	0,281	0,800
0,375	0,500	0,237	0,593	0,406	—0,097
0,438	0,563	0,247	0,533	0,500	—0,525

Suppose that in Eq. (8) $\delta X(z, 0)$ is larger than zero. Then Eqs. (2) and (3) can be used to determine the change $\Delta X(z, \Delta t)$ at a time Δt close to zero if at $t = 0$ there is a fluctuation $\delta X(z, 0)$. When $t > 0$, the neutron flux density differs from the steady value by an amount $\Delta X^{(1)}(z)$ given by Eq. (18). Then the condition for controllability of the reactor with respect to spontaneous space—time oscillations of the energy distribution may be expressed as an inequality

$$\Delta X(z, \Delta t) < \delta X(z, 0), \tag{19}$$

which may conveniently be written in a form similar to that used in [1]

$$\frac{A(z)}{[1+B(z)(10^{14}/N_M]^2} < \frac{M^2}{H^2}, \tag{20}$$

where N_M is the maximum neutron flux density in the reactor; M^2 is the square of the neutron migration length; H is the reactor size.

The functions A(z) and B(z) are given by the expressions

$$A(z) = -\gamma\frac{\Sigma_f}{\sigma}\frac{\Delta X^{(1)}(z)}{X^{(1)}(z, t<0)}\frac{1}{\delta x(z, 0)}\frac{M^2}{H^2}; \tag{21}$$

$$B(z) = \frac{\lambda_{Xe}}{\sigma\cdot 10^{14}}\frac{N_M}{X^{(1)}(z, t<0)}. \tag{22}$$

The condition for controllability of the reaction in Eq. (20) is valid for a perturbation $\delta X(z, 0)$ of any kind and for control f(z) of any kind; change in the form of $\delta X(z, 0)$ and f(z) simply leads to change in form of the function A(z) in Eq. (20).

Such comments should be made with respect to the controllability condition in Eq. (20). First, the term "controllability" is here taken in the narrow sense of the capability of quenching at once any fluctuations that appear in the reactor, for the chosen control system and the given reactor size and power. In this sense, the reactor is controllable if Eq. (20) is satisfied. In [1] the condition for asymptotic stability was obtained; the physical meaning of this is quite different, and therefore it cannot be compared with Eq. (20).

Secondly, a control system which ensures controllability may be found as follows. First, some control system is chosen — i.e., the function f(z) in Eq. (9) is specified — and, for the given reactor power, the value H' which satisfies Eq. (20) for the most dangerous fluctuation $\delta X(z, 0)$ is determined. If H' is larger than the given reactor size H, the control system under consideration ensures controllability; if H' < H, another control system, corresponding to a different function f(z) in Eq. (9), is chosen for analysis.

Table 1 gives the maximum values of $A(z_{\max})$ and the corresponding $z_{\max}$ calculated under the assumptions that the Laplacian α^2 in Eq. (6) is constant*; that the fluctuation $\delta X(z, 0)$ is constant, and only affects the section $h_1 \leq z \leq h_2$; and that $f(z) = 1$ for the control system adopted. With the chosen normalization, the values in Table 1 depend only on geometrical factors.

The data in Table 1 may be used, together with Eq. (20), to find for each value of N_M the limiting height at which the reactor is controllable for any chosen fluctuation in xenon concentration.

This method may be extended to the case of fluctuations of the neutron flux density with xenon feedback and for transient processes with other kinds of feedback. However, the practical details of its application to

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*If α^2 is constant, this means, in physical terms, that corresponding spatial distributions of nuclear fuel (or absorbent) over the reactor volume are selected.

the analysis of specific reactors falls outside the scope of the present paper, which is intended primarily to outline the new approach to the selection of a control system for the spatial energy distribution in a reactor.

It remains to thank A. M. Pavlovich for his valuable comments.

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KINETICS OF SOLUTION OF SOLID SODIUM HYDROXIDE IN SODIUM

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In the second loop of power stations with fast-neutron reactors, leakage of sodium in the steam generators leads to the reaction of sodium and water to form sodium hydroxide. If the temperature in the loop is below the melting point of sodium hydroxide (~318°C), solid hydroxide is precipitated on the tube surfaces. The solution of sodium hydroxide in liquid sodium may occur if it is preceded by chemical reaction with the sodium [1,2]. When the solution rate is low, the limiting factor may be the rate of purification of the sodium in the loop by a cold trap.

When the mass-transfer conditions at the boundary between the sodium and the sodium hydroxide are not limiting, the solution of solid sodium hydroxide in liquid sodium may be described by the equation

$$dp/d\tau = -KS, \tag{1}$$

where p is the mass of the sodium hydroxide; S is the contact surface between the sodium and the sodium hydroxide; K is the rate constant of solution.

The present article describes the method and results of an experimental determination of the solution of solid sodium hydroxide in liquid hydrogen at 200-280°C.

The experiment was carried out in a circulation sodium loop. Samples of solid sodium hydroxide were held in a sodium current of given flow rate and the sample mass was measured after a certain period of time. The samples took the form of a cylinder of diameter 16-27 mm and length 28-100 mm or a hollow cylinder, the inner cavity of which was filled by a stainless-steel former of diameter 22 mm. Sodium at the experimental temperature passed at a certain rate through the working section containing the sodium hydroxide sample (the sample was immersed longitudinally in the sodium flow). After a certain time the sample was removed from the loop and weighed.

In the experiments, the flow rate of sodium in the working section, the initial mass of the sodium hydroxide samples, and the duration of their suspension in the flow were varied; sodium temperatures in the loop of 200, 240, and 280°C were investigated.

Taking into account that the solution of a cylinder occurs mainly on the side surfaces, the equation for the rate of change in mass of the sample may be written in the form

$$\frac{dp}{d\tau} = -2K\sqrt{\frac{\pi l}{\gamma}}\sqrt{p + \frac{\pi d_f^2 l}{4}\gamma}, \tag{2}$$

where l is the length of the sodium hydroxide sample; γ is the density of solid sodium hydroxide; d_f is the diameter of the steel former in the sample. For samples without a former, $d_f = 0$ in Eq. (2).

For the initial conditions $\tau = 0$ and $p = p^0$, the solution of Eq. (2) may be written in the form

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TABLE 1. Experimental Conditions and Results for K

Expt. No.	T, °C	v, cm/sec	$p°$, g	p_τ, g	τ, min	K · 10^2, g/cm^2· min
1		45	23	19	60	0,243
2	200	35	28,5	17,5	195	0,202
3		35	31,4	16	60	0,906
4		35	31	7,8	90	1,045
5	240	35	30,8	17,7	40	1,13
6		120	19,6	2,5	60	0,68
7		120	21,5	2,7	60	0,736
8		30	29,5	9,3	20	4,05
9		30	34,5	9,8	40	2,41
10		30	31	15,8	15	3,60
11	280	30	28,5	0	45	4,01
12		35	28,5	0	45	4,01
13		40	87,3	42	30	2,40
14		15	34	21,5	20	2,04
15		15	27,4	11	40	1,62
16		15	18	1,1	100	1,50

$$\sqrt{p^0+\frac{\pi d_b^2}{4}\gamma l}-\sqrt{p+\frac{\pi d_1^2}{4}\gamma l}=K\sqrt{\frac{\pi l}{\gamma}}\tau. \qquad (3)$$

Equation (3) may be used for the analysis of the experimental results and the calculation of K.

Table 1 gives the experimental conditions and the results obtained for K for solid sodium hydroxide in liquid sodium. In experiments 6 and 7 samples with an internal steel former were used.

The length of the sodium hydroxide samples was 100 and 28 mm, respectively in experiments 13 and 14, and 55 mm in the others.

Experiments 2, 7, 13, and 14 were carried out immediately after the experiments preceding them, i.e., without preliminary purification of the sodium in the loop by means of a cold trap. At the beginning of all these experiments the temperature of "seizing up" of the internal indicator (the crystallization temperature of the impurity in sodium) was practically equal to the sodium temperature. In the other experiments it was 150-170°C.

The values of K calculated from Eq. (3) depend significantly on the sodium temperature (see Table 1). In experiments 6, 7, 9, and 13, for reasons which are not known, the values of K were lower than under the same conditions in other experiments.

At 280°C the velocity flow rate was found to affect the observed value of K. With reduction in the flow rate from 20 to 15 cm/sec, the value of K is approximately halved. This indicates that at 280°C and a sodium flow rate of 15 cm/sec the mass-transfer conditions limit the rate of solution of the sample of solid sodium hydroxide.

At sodium temperatures of 200 and 240°C and the chosen sodium flow rates, the hydrodynamic conditions (as is evident from Table 1) do not have a limiting effect, and K is determined solely by the kinetics of solution of the sodium hydroxide.

Assuming that the solution occurs in the kinetic region in the experiments at 280°C and a sodium flow rate of 30-40 cm/sec, the data of experiments 1-13 lead, by least squares, to a temperature dependence in the form

$$\lg k = A/T + B, \ \mathrm{g/cm^2 \cdot min}. \qquad (4)$$

The constants A and B (with their mean-square deviations) are —4060 ± 160 and 5.9 ± 0.3.

These results may be used to estimate the efficiency of cold traps in purifying the sodium loops from solid sodium hydroxide.

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HEAT STRENGTH OF GRAPHITE FOR POWER REACTORS

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UDC 621.039:532.21

With the construction of high-temperature nuclear reactors there is a need for radiation- and heat-stable materials. One of the most heat-stable materials is graphite. The calculated heat strengths of several Soviet industrial graphites, at room temperature and at 1000°C [3], are given in Table 1. Heat strength is a complex property, depending on the properties of the material, the size and shape of the sample, and the treatment to which the sample is subjected. In steady conditions at a low rate of heat transfer in the course of reactor operation, the Kingery number R' [1] may be used, on the assumption that the thermal stress reaches the limiting strength of the material

$$R' = \sigma\lambda/[E\alpha(1-\mu)],$$

where R' is the heat-strength coefficient; σ is the limiting strength; E is the modulus of elasticity; λ is the thermal conductivity; α is the thermal expansion coefficient (TEC); μ is Poisson's ratio.

Since μ is largely independent of the form of the graphite, Eq. (1) may be replaced for calculations by the expression $\sigma\lambda/E\alpha$, which was used in [2] for a preliminary estimate of the radiation strength of graphite. The heat strength was calculated at room temperature and at 1000°C. It is known that $\sigma/E\alpha$ is largely independent of the form of the graphite. The ratio σ/E, i.e., the strain, decreases by a factor of 1.5-2 on passing from high-strength graphites with an uncalcined coke filler to a graphite based on calcined petroleum coke (type GMZ) but, at the same time, the thermal-expansion coefficient α decreases by a factor of approximately 1.6. As a result, the decrease in $\sigma/E\alpha$ is slight. Note that graphite materials of low TEC are distinguished by a high rate of radiational compression at the operating temperature.

The thermal conductivity of graphite varies over a broad range, determining the heat strength of the material. Hence to improve the heat strength of graphite, the thermal conductivity must be increased, by increasing both the temperature of its preparation and its density. In VPG and VPP graphites, which are prepared at 2800°C and increased in density by additional impregnation with pitch, the heat strength R is significantly higher than in GMZ graphite, which is produced by the same technological process but at 2400°C and without additions of pitch.

The density and properties of the graphite are also improved by thermomechanical treatment (TMT), which leads to a sharp rise in the anisotropy of the physical properties. The heat strength increases in the direction perpendicular to the application of TMT, whereas in the parallel direction it is markedly less than in the untreated graphite. As a result, low-temperature irradiation of samples of such a graphite (RG graphite) leads to cleavage in the direction parallel to the previous TMT.

The values of R' for graphite are significantly higher than for refractory compounds [4]

Material	Graphite	$ZrC_{0.95}$	$NbC_{0.93}$	BeO	ZrO_2
R', 10^3 W/m	20-100	2.3	1.9	1.15	0.27

On passing from room temperature to 1000°C, the graphite is still characterized by brittle fracture, and its thermal conductivity decreases. As a result, R' falls by a factor of up to five (see Table 1). However, above 1500°C R' begins to rise as the graphite becomes plastic [5], which is confirmed by experimental measurements of the heat strength of cylindrical samples.

Low-temperature neutron irradiation leads to considerable changes in the properties of graphite, which are rapidly stabilized. Increase in the temperature of irradiation is accompanied by an exponential decrease in the effect [3]. The available data may be used to estimate the heat strength of graphite irradiated until the changes in property have stabilized. A neutron flux of approximately 10^{21} neutrons/cm^2 is sufficient for the stabilization of the properties that determine the heat strength.* The ratio σ/E for GMZ and related graphites

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*Here and below, the flux is assumed to be of neutrons with E ≥ 0.18 MeV.

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TABLE 1. Properties and Heat Strength of Graphites Obtained by Electrode Technology

Graphite	20 °C					1000 °C				
	σ, kgf/cm^2	E, 10^5 kgf/cm^2	α, 10^{-5} (°C)$^{-1}$	λ, kcal/m·h·deg C	R', 10^3 W/m	σ, kgf/cm^2	E, 10^5 kgf/cm^2	α, 10^{-6} (°C)$^{-1}$	λ, kcal/m·h·deg C	R', 10^3 W/m
GMZ	90/70*	0,66/0,48	3,7/4,1	103/89	44/41	100/75	0,76/0,54	5,1/5,4	37/30	11/9
VPP	135†	0,91	4,0	169	72	180	1,03	5,3	54	21
VPG	210‡	1,18	3,7	165	94	—	—	5,1	64	—
MPG-6	310/335	1,05/1,05	6,6/6,0	82	42/50	335/365	1,13/1,13	7,9/7,2	41	18/21
MPG-8	155/175	0,98/1,15	6,9/5,9	75/105	20/31	175/205	1,06/1,33	8,3/7,2	30/41	7/12
PG(GTM)	35/100	0,29/1,43	9—12/0,55—1,30	164/195	8,1/174	50/140	0,33/1,55	11,0—14,0/1,7—3,0	19/76	2.9/34

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*The numerator gives data in the direction parallel to the axis of the bar and the denominator data for the perpendicular direction.

†Radially.

‡Parallel to the axis of the bar.

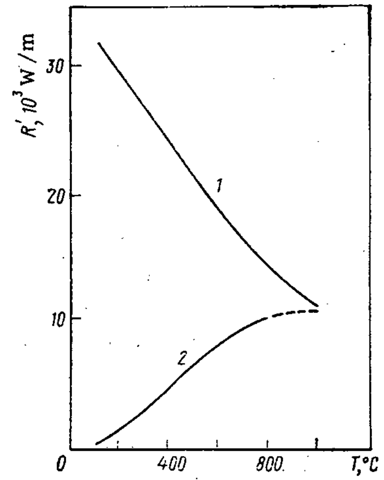

Fig. 1. Temperature dependence of heat strength for GMZ graphite before (1) and after (2) irradiation by a neutron flux up to stabilization of its properties.

changes insignificantly on irradiation [6]. The TEC for graphite rises on irradiation by no more than 50-80% at 140°C and by 5-10% above 250-300°C [3]. The thermal conductivity falls by a factor of about 100 after irradiation at 100°C, of 10 at 300°C, and of 3-5 above 600°C [3]. Thus, the heat strength of irradiated graphite is again determined mainly by the thermal conductivity. The radiational decrease in thermal conductivity is sharply reduced as the irradiation temperature rises, and the temperature coefficient of the conductivity is positive. Therefore, R' increases, approaching the value for unirradiated graphite at 1000°C (Fig. 1).

It may be assumed, as an approximation, that the relative change in thermal conductivity is independent of the form of the graphite [7]. Therefore, a graphite with a higher initial thermal conductivity will be more heat-stable after irradiation. Graphite irradiated by a moderate neutron flux at high temperature should have a lower tendency to fracture under heat stress than that irradiated at low temperatures.

It is known that irradiation by a flux $>5 \cdot 10^{21}$ neutrons/cm^2 at temperatures above 500°C leads to the replacement of radiation—thermal contraction by more rapid secondary "swelling." There are also new changes in the physical properties, which have previously been at "saturation." For example, irradiation of graphite samples by fluxes of up to $4.2 \cdot 10^{22}$ neutrons/cm^2 at temperatures up to 725°C [8] leads to a reduction (in comparison with unirradiated materials) in the TEC and the flexure strength by 30-50% and in the strain by 60-85%.

The coefficient characterizing the resistance to thermoshock (the ratio of the strain on flexure to the mean TEC) falls by 30-65%. Hence, high-temperature irradiation by a flux of $>10^{22}$ neutrons/cm^2, leading to intense secondary growth, may sharply reduce the heat strength of graphite.

Thus, it appears from calculations of the heat strength of graphite under steady heat conditions at high heat-transfer rates that R' is mainly determined by the thermal conductivity of graphite both before and after irradiation; R' falls with increase in neutron flux and with decrease in the irradiation temperature, and is additionally reduced when secondary "swelling" appears.

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CALCULATION OF LOCAL HEAT FLUXES IN CIRCULAR CHANNEL WITH LIQUID METAL

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In investigating heat transfer in models of sodium — water steam generators, it is necessary to know the distribution of local heat fluxes over the tube length. From the balance equation for the local heat flux

$$q=-\frac{Gc_p}{2\pi R}\frac{d\bar{t}(z)}{dz} \qquad (1)$$

it is evident that this distribution can be determined if the distribution of $\bar{t}(z)$, the mean-mixed temperature over the length of the tube, is known. Usually, $\bar{t}(z)$ is replaced by $t_{\max}(z)$, measured at the adiabatic wall. When the heat flux is rapidly changing (in particular, in regions of impaired heat transfer), this substitution gives a result substantially different from Eq. (1).

However, $\bar{t}(z)$ may be determined if $t_{\max}(z)$ is measured, and the velocity and temperature profiles in the sodium flow are known. Hence, it is possible to eliminate the error in determining the heat flux and the heat-transfer coefficient to the water in regions of impaired heat transfer.

Consider a method of calculating $\bar{t}(z)$ and the local heat fluxes for a sodium — water steam generator with sodium in tubes and water in the intertube space. The temperature in the steam generator is measured by a thermocouple in a measurement channel on the tube axis. When the measurement-channel diameter is considerably less than the tube diameter, it is possible to use expressions describing the velocity and temperature profiles for a circular tube.

The appropriate expression for $\bar{t}$ is

$$\bar{t}=t_{\max}-(t_{\max}-t_w)(1-k), \qquad (2)$$

where t_w is the temperature of the internal wall, and

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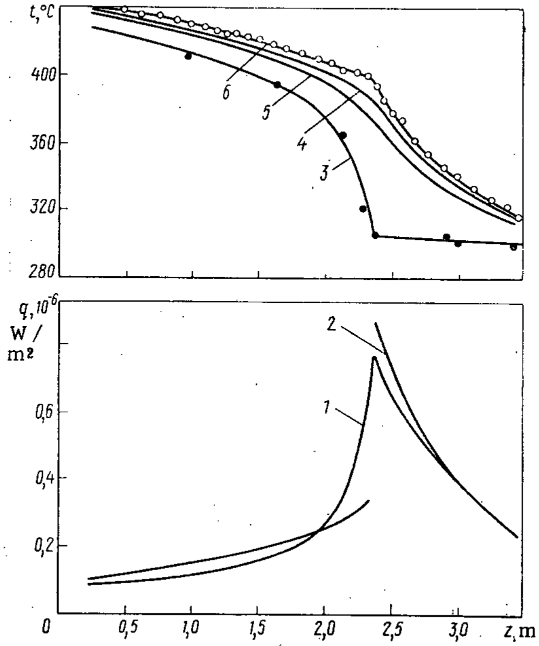

Fig. 1. Distribution of temperatures and heat flux over the length of the steam-generator model: ○) maximum sodium temperature (experiment); ●) tube-wall temperature on the water side (experiment); 1, 2) heat fluxes calculated from Eq. (1) and the maximum-temperature gradient, respectively; 3, 5) tube-wall temperature on the water and sodium sides (calculation); 4) mean mixed sodium temperature; 6) maximum sodium temperature obtained by approximating experimental points.

$$k=\frac{\int\limits_0^R [t(r)-t_W]\,w(r)\,r\,dr}{(t_{\max}-t_W)\int\limits_0^R w(r)\,r\,dr}. \qquad (3)$$

Using the dimensionless temperature profile obtained in [1], Eq. (2) may be written in the form

$$\bar t = t_{\max} + b\frac{d\bar t}{dz}, \qquad (4)$$

where

$$b = T^+_{\max}\frac{G(1-k)}{2\pi R\rho v^*}; \qquad (5)$$

$$k=\frac{2a^2}{T^+_{\max}\bar w R^2 v^*}\int\limits_{y^{++}_{\max}}^{0} T^+(y^{++})\,u^+(y^{++})\,y^{++}\,dy^{++}; \qquad (6)$$

$T^+ = (t - t_w)/T^*$ is the dimensionless temperature; $T^* = q/\rho c_p v^*$ is the frictional temperature; $u^+ = W(y^{++})/v^*$ is the dimensionless velocity; $y^{++} = yv^*/a$ is the dimensionless coordinate; y is the distance from the heat-transfer surface; $v^* = w\sqrt{\xi/8}$ is the "frictional velocity"; a is the thermal diffusivity.

Calculation shows that when the temperature changes by 250°C b changes by 3-5%. The solution of Eq. (4) with b = const is

$$\bar t(z) = \exp(z/b)\left[\bar t_0 - \frac{1}{b}\int\limits_0^z \exp(-z/b)\,t_{\max}(z)\,dz\right],$$

where $\bar t_0$ is the initial value of the mean-mixed sodium temperature. The error in choosing $\bar t_0$ gives a diverging solution for $\bar t(z)$. When the deviation of the z axis is changed, the solution of Eq. (4) takes the form

$$\bar{t}(z)=\exp(z/b)\left[\bar{t}_0+\frac{1}{b}\int_0^z \exp(z/b)\, t_{\max}(z)\, dz\right]. \qquad (7)$$

Then the error in determining $\bar{t}_0$ is negligibly small at small distances from z_0.

When the measurement-channel radius R_1 is comparable with the tube radius R_2, it is necessary to consider the heat transfer in an annular channel with an adiabatic internal wall. For this case, the first step is to find values of $T^+_{\max 1}$ and k_1 to substitute in Eq. (5). For an annular channel and a circular tube the variation of T^+ on the heat-transfer wall is given by the relation

$$\left(\frac{dT^+}{dy^{++}}\right)_{y^{++}=0}=\left(\frac{dT_1}{dy^{++}}\right)_{y^{++}=0}.$$

Using the temperature distribution over the radius, the corresponding Nusselt numbers may be written in the form

$$\mathrm{Nu}_1=\frac{2(R_2-R_1)(dt/dr)_{r=R_2}}{(\bar{t}-t_W)_1}; \qquad (8)$$

$$\mathrm{Nu}=\frac{2R\,(dt/dr)_{r=R}}{\bar{t}-t_W}. \qquad (9)$$

Assuming that $2(R_2 - R_1) = 2R$ and $\bar{w}_1 = \bar{w}$, Eqs. (6), (7), and (9) lead to the result

$$T^+_{\max 1}=T^+_{\max}\frac{k}{k_1}\frac{\mathrm{Nu}}{\mathrm{Nu}_1}. \qquad (10)$$

Nu is taken from the formula for a circular tube [1]; Nu_1 is obtained analytically from the determination of the heat transfer in an annular channel with an internal adiabatic surface for $1.948 < R_2/R_1 < 6$ [2].

Assume that for an annular gap the variation in dimensionless temperature with increasing distance from the heat-transfer wall differs from the universal profile by some factor $T_1^+ = ST^+$ (as confirmed experimentally [3]); then, in calculating k_1 from Eq. (3) and k/k_1, T_1^+ may be replaced by T^+:

$$\frac{k}{k_1}=\frac{R_2^2-R_1^2}{R^2}\,\frac{\int_0^{y^{++}} T^+(y^{++})\,u^+(y^{++})\,y^{++}\,dy^{++}}{\int_{y_1^{++}}^{y_2^{++}} T^+(y^{++})\,u^+(y^{++})\,y^{++}\,dy^{++}}. \qquad (11)$$

In [3] it was suggested that the region of similarity of the dimensionless temperature profiles is characterized by the condition $\mathrm{Gr}/\mathrm{Re}^2 < 0.15$. Using Eqs. (3), (10), and (11), the value of b for an annular channel may be calculated from Eq. (5). The proposed method has been used in the analysis of experiments on a seven-tube model of a sodium — water steam generator (internal tube diameter 11 mm). The calculations were carried out for an annular channel, since $R_2/R_1 = 3.54$. The range of Pe was 500-1000. Using a computer, $\bar{t}(z)$ was calculated from Eq. (7) for sections in which the temperature varied by no more than 20°C; the value of b was calculated for each section and assumed to be constant.

The preliminary treatment of the experimental data for $t_{\max}(z)$ was by the least-squares method. In the boiling region, $t_{\max}(z) = t_W + d_1\exp(-d_2 z)$ and for the transcritical region $t_{\max}(z) = \sum_{i=0}^{n=3} a_i z^i$. In the individual sections $t_{\max}(z)$ was approximated by a linear relation, and the integrals for Eqs. (6) and (11) were calculated by the Simpson method. The physical properties were taken at the maximum temperature. The velocity profile for an annular channel was calculated according to the 1/7 law [4].

After determining $\bar{t}(z)$, the temperature of the inner wall $t_W(z)$ and the outer wall $t_{W_1}(z)$ was calculated, together with the local heat fluxes (see Fig. 1).

Using the method outlined, the local heat fluxes over the whole length of the steam-generator channel can be calculated from the measured sodium temperature at the adiabatic wall. At the boiling point, the difference between the heat fluxes calculated from $t_{\max}(z)$ and those obtained from $\bar{t}(z)$ is significant. The agreement between the calculated and measured values of the temperature at the outer tube wall confirms that the assumptions made are correct.

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EFFECTIVE PHOTON ATTENUATION COEFFICIENTS FOR HETEROGENEOUS MEDIA

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UDC 550.835

In the analysis of rocks and ores by nuclear geophysics methods using photon or γ radiation, homogeneous and heterogeneous media are studied which consist of an element A to be determined and a filler F. Analysis of a homogeneous medium corresponds to analysis of finely dispersed powder samples while a heterogeneous medium corresponds to conditions in a natural ore bed.

It is well known that photon attenuation in homogeneous and heterogeneous media obeys the exponential Beer law [1-3]

$$N = N_0 \exp(-\bar{\mu}\rho x), \tag{1}$$

where N_0 is the flux of quanta with energy ε at the surface of the medium; N is that same flux at the depth x; ρ is the density of the medium; $\bar{\mu}$ is the photon mass attenuation coefficient in the medium. If the test medium is homogeneous, $\bar{\mu}$ is understood to be its average mass coefficient, which for a two-component system is

$$\bar{\mu}_{av} = \bar{\mu}_A q + \bar{\mu}_F (1-q), \tag{2}$$

where q is the concentration in the medium of the element A to be determined; $\bar{\mu}_A$ and $\bar{\mu}_F$ are the values of the mass coefficient for the element to be determined or for the filler. The effective mass attenuation coefficient is $\bar{\mu}_{ef}$, which depends not only on the concentration of the ore grains of the element to be determined but also on their shape, size, and orientation. There are several methods for calculating this coefficient. For example, the effective photon mass attenuation coefficients for particles of different shapes were calculated in [2]. A shortcoming of this calculation was that the effect of the medium enclosing the ore grains was not taken into consideration and the resultant values of $\bar{\mu}_{ef}$ referred only to the ore phase, which consists of grains, and not to the heterogeneous medium as a whole. This shortcoming was eliminated in the calculations in [3] and in those of other authors who used the scheme proposed in [1]. In particular, for a heterogeneous medium with cubic ore grains having an edge length D,

$$\bar{\mu}_{ef} = \frac{\rho_H}{\rho}\bar{\mu}_F + \frac{q}{\rho_A D}\left[1 - e^{-(\bar{\mu}_A\rho_A - \mu_F\rho_F)D}\right], \tag{3}$$

according to the computational scheme in [3], where q is the concentration of ore grains in the medium; ρ is the average density of the heterogeneous medium, which is expressed through the density ρ_F of the filler and the density ρ_A of the ore grains in the following manner,

$$\rho = \rho_A\rho_F / [\rho_A + (\rho_F - \rho_A) q].$$

It is apparent from Eq. (3) that the quantity $\bar{\mu}_{ef}$ can assume negative values when $\bar{\mu}_F \rho_F > \bar{\mu}_A \rho_A$. This limits the applicability of the expression for $\bar{\mu}_{ef}$ obtained from the scheme in [3] to cases where $\bar{\mu}_A \rho_A > \bar{\mu}_F \rho_F$. At the same time, the introduction of effective attenuation coefficients considerably simplifies the solution of theoretical problems associated with the passage of γ rays through heterogeneous media. Therefore the demonstration of methods for calculating this parameter which are free of deficiencies and limitations is of great importance for development of the theory of gamma methods, and particularly for the methods of applied nuclear geophysics.

We consider the attenuation of a flux of monochromatic γ rays with energy ε in a semi-infinite heterogeneous medium which consists of a homogeneous filler and cubic ore grains having an edge length D. We

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assume the surface of the medium is flat, the radiation is normally incident on it, and the orientation of the cubic grains in the medium is such that their faces are parallel to the interface. If the γ-ray flux on the surface of the medium through an area D^2 is N_0, its attenuation in the filler during passage through a layer x can be taken into account through the factor $\exp(-\bar{\mu}_F \rho (1-q)x)$, where ρ is the average density of the heterogeneous medium; q is the average concentration of the ore grains in this medium; $(1-q)$ is the average concentration of the homogeneous filler with a mass attenuation coefficient $\bar{\mu}_F$. Attenuation of the flux in ore grains depends on their number and is taken into account through the factor $\exp(-\bar{\mu}_A \rho_A kD)$, where ρ_A is the density of the ore material making up the grains; $\bar{\mu}_A$ is its mass attenuation coefficient; k is the number of ore grains in the heterogeneous medium found in the volume $v = D^2x$ along the path x. The γ-ray flux at the depth x is then

$$N = N_0 \exp[-\bar{\mu}_F \rho (1-q) x] \exp(-\bar{\mu}_A \rho_A k D).$$

If it is assumed the random distribution of ore grains in the heterogeneous medium obeys the Poisson law, the probability for the appearance of k ore grains on the path x is $P_k = n^k e^{-n}/k!$, where n is the average number of ore grains in a volume $v = D^2x$ of the test medium for an average concentration q, so that $n = \rho q x/\rho_A D$. Then the γ-ray flux at the depth x is

$$N = N_0 \exp[-\bar{\mu}_F \rho (1-q) x] \sum_{k=0}^{\infty} \exp(-\bar{\mu}_A \rho_A k D) P_k = N_0 e^{-x\rho \left\{ \bar{\mu}_F (1-q) + \frac{q}{\rho_A D} [1 - e^{-\bar{\mu}_A \rho_A D}] \right\}},$$

where the expression in the braces in the exponent of the exponential is none other than the effective photon mass attenuation coefficient in a heterogeneous medium with cubic ore grains, i.e.,

$$\bar{\mu}_{ef} = \bar{\mu}_F (1-q) + \frac{q}{\rho_A D} [1 - e^{-\bar{\mu}_A \rho_A D}]. \tag{4}$$

If the grain size is reduced $(D \to 0)$, $\bar{\mu}_{ef} \to \bar{\mu}_{av} = \bar{\mu}_F (1-q) + \bar{\mu}_A q$, i.e., the expression for the effective radiation mass attenuation coefficient in a heterogeneous medium transforms into the expression for the average mass attenuation coefficient in a homogeneous medium. Equation (4) differs from the solution in [2] in that the effective attenuation coefficients here characterize not the ore-grain phase but the heterogeneous medium as a whole. From a comparison with the calculated results of L. I. Shmonin [3], it is clear that Eq. (4) does not contain the factor $(\bar{\mu}_A - \bar{\mu}_F)$ in the exponent of the exponential and, consequently, it is valid for any relations between $\bar{\mu}_A$ and $\bar{\mu}_F$, including cases where $\bar{\mu}_F > \bar{\mu}_A$. If $\bar{\mu}$ in Eq. (4) is replaced by $\bar{\tau}$ or $\bar{\sigma}$, we obtain the corresponding expressions for the effective photoabsorption or scattering coefficients in a heterogeneous medium. Expressions for $\bar{\mu}_{ef}$ in heterogeneous media with particles of a different geometric shape can be obtained in similar fashion. For example, in a two-component heterogeneous medium consisting of a uniform filler and spherical ore grains of diameter D we have

$$\bar{\mu}_{ef} = \bar{\mu}_F (1-q) + \frac{3}{2} \frac{q}{\rho_A D} \left\{ 1 - \frac{2}{\bar{\mu}_A^2 \rho_A^2 D^2} [1 - (1 + \bar{\mu}_A \rho_A D) e^{-\bar{\mu}_A \rho_A D}] \right\}. \tag{5}$$

The solutions obtained are easily generalized to multicomponent heterogeneous media. In particular, in a three-component heterogeneous medium consisting of a homogeneous filler F and cubic ore grains of types A and M with dimensions D_A and D_M, the effective mass attenuation coefficient is

$$\bar{\mu}_{ef} = \bar{\mu}_F (1 - q_A - q_M) + \frac{q_A}{\rho_A D_A} [1 - e^{-\bar{\mu}_A \rho_A D_A}] + \frac{q_M}{\rho_M D_M} [1 - e^{-\bar{\mu}_M \rho_M D_M}], \tag{6}$$

where q_A and q_M are the concentrations of grains A and M in the heterogeneous medium; ρ_A and ρ_M are the densities of the ore material making up grains A and M. It is also easy to calculate $\bar{\mu}_{ef}$ for a heterogeneous medium in which the ore phase is represented by grains of a single shape but different sizes. If a multicomponent heterogeneous medium contains a uniform filler and cubic ore particles of varied kinds,

$$\bar{\mu}_{ef} = \bar{\mu}_F \left(1 - \sum_{(i,j)} q_{ij} \right) + \sum_{(i,j)} \frac{q_{ij}}{\rho_{ij} D_{ij}} [1 - e^{-\bar{\mu}_{ij} \rho_{ij} D_{ij}}], \tag{7}$$

where i is the classification of particles with respect to composition and j is their classification with respect to size.

The expressions obtained for the effective photon attenuation coefficients in heterogeneous media can be used for the calculation of γ fields and also for the solution of problems in shielding theory or in applied geophysics, especially in the determination of the intensity of secondary radiations (scattered γ rays, atomic fluorescence, etc.) from heterogeneous media such as rocks and ores.

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SIXTIETH BIRTHDAY OF EVGENII IVANOVICH VOROB'EV

In Jan. 1978 Professor E.I.Vorob'ev, well known as a scientist and an administrator, winner of the State Prize of the USSR, and doctor of medical science, celebrates his 60th birthday.

After leaving the I. M. Sechenov First Moscow Medical Institute in 1942, E. I. Vorob'ev worked as a doctor in charge of the functional-diagnostics department of clinic No. 7. As the director of the medical-radiology section of the Ministry of Public Health of the USSR from 1948, he did much to promote the establishment and development of medical radiology in the Soviet Union, and supervised the introduction of a number of important measures extending the use of atomic power in medicine. From 1961 to 1967, Vorob'ev was the director of the Central Scientific-Research X-Ray and Radiological Institute in Leningrad, and simultaneously led the clinical radiation-pathology section. His work in this post has facilitated the development of scientific research on urgent problems of medical radiology. Since 1967, he has been the director of the third main administration at the Ministry of Public Health of the USSR.

E. I. Vorob'ev is a scientist of broad interests, ranging from radiobiological problems to the practical use of radioactive isotopes in biology and medicine. The first book in the Soviet Union on the practical use of radioactive isotopes for medical purposes was published, under joint authorship, more than twenty years ago. Vorob'ev was one of the active co-authors of this book.

The scientific research by Vorob'ev and his colleagues in the field of radiation cardiology is the first comprehensive investigation, both in the USSR and elsewhere, of the effect of ionizing radiation on the cardiovascular system. The processes of damage and recovery in the myocardium have been subjected to a profound analysis, using dosimetric methods which determine the absorbed radiation dose with high accuracy.

This research was summarized by Vorob'ev in the monograph Radiation Cardiology, which has received due acknowledgement from Soviet and non-Soviet specialists.

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Vorob'ev has given much attention to the complex problems of automatic control systems in the realm of public health. The results of many years' research were summarized in the book, The Automation of Information Processing and Control in Public Health, written in collaboration with A. I. Kitov and published in 1976. In this fundamental work, the problems associated with the development and use of automatic control systems (ACS) in the field of public health were analyzed. The creation and introduction of ACS is necessary because of the ever increasing volume of information and the growing complexity of control processes in the field of public health and elsewhere. As well as general information, the book gave specific data on some of the individual problems first encountered in the development and introduction of automatic control systems in public-health institutions.

In developing the basic principles of automated control systems, the authors took as their starting point the direct subordination of medical — prophylactic and sanitary — epidemiological institutions to a controlling body, i.e., a two-level structure for public-health control (regional health departments in large towns, urban health departments, and district health departments).

The Automation of Information Processing and Control in Public Health proved to be of great value to specialists involved in the development and application of such systems, including specialists in public-health administration, programmers and systems engineers engaged on the development of algorithms and programs for public-health data processing. In addition, it has become a useful text for undergraduate and graduate students of these disciplines.

Much of Vorob'ev's strength and energy has been devoted to his work as a scientific administrator. As the director of the Central Scientific-Research X-Ray and Radiological Institute, he was concerned on a daily basis with the development of a modern scientific basis for the institute. At present, the institute boasts a complex of up-to-date and fully equipped buildings and laboratories, allowing research to be conducted at a high scientific level.

While at Leningrad, Vorob'ev organized the Public University of Medical Radiobiology and was its director. He was an active member of the Leningrad Society of Roentgenologists and Radiologists, and a member of the Praesidium of the All-Russian Society of Roentgenologists. At present, he is a member of staff of the Ministry of Public Health of the USSR, and a member or chairman's assistant of a number of scientific committees and commissions considering special problems in the Ministry of Public Health of the USSR and the Academy of Medical Sciences of the USSR. The activities of these commissions are of great importance for the solution of the great economic problems of the Soviet Union.

Since Dec. 1973 Vorob'ev has run the scientific laboratory on radioisotope research methods at the Scientific-Research Institute of Medical and Biological Problems of the Ministry of Public Health of the USSR. The team which he leads is making a notable contribution to the solution of the urgent problems in space biology and medicine.

For several years Vorob'ev has been the Professor of Medical Radiology at the Central Institute for the Advancement of Medicine.

Vorob'ev was among those who initiated the publication of the new well-known journal, Meditsinskaya Radiobiologiya. From 1956 to 1967 he was scientific secretary and then assistant to the journal's principal editor. Vorob'ev's work with this journal has facilitated the creation of a school of Soviet radiologists and the more rapid introduction of the achievements of medical radiology into public-health practice. In May 1977, Vorob'ev joined the editorial board of the journal Atomnaya Énergiya.

A well-known researcher and talented scientific administrator, Vorob'ev is a frequent participant in scientific gatherings and conferences both inside and outside the Soviet Union. In 1967, he became a member of the COMECON Standing Commission on the Peaceful Uses of Atomic Energy.

Vorob'ev has given serious attention to the training of young specialists. Under his personal guidance, a number of young specialists have successfully submitted a Candidate's Dissertation in the medical sciences.

As well as all his productive, scientific and administrative work, E. I. Vorob'ev takes an active part in public life. He was chosen as a Deputy of the Petrograd Regional Council of Leningrad Worker's Deputies, Chairman of the Commission of Deputies, and a member of the Party Bureau of the Central Scientific X-Ray and Radiological Institute and of the third main administration at the Ministry of Public Health of the USSR.

He has twice been awarded the Labor Red Star, and also medals for labor prowess, for labor distinction, and for valiant labor.

All who work or have worked with E. I. Vorob'ev know him as an experienced leader and a considerate and sympathetic colleague.

E. I. Vorob'ev has great creative strength and energy. The editors wish him many years of active creative work, stout health, and personal happiness.

TENTH WORLD POWER ENGINEERING CONGRESS

Yu. I. Koryakin

The Congress, which was held under the motto "Assurance of Energy Resources and Their Rational Utilization" in Istambul (Turkey) in Sept. 1977, was attended by some 4500 representatives from 80 countries and international organizations. The Soviet delegation was led by K. D. Lavrinenko. A welcoming address to the opening session was delivered by the Turkish Prime Minister, Suleiman Demirel; a welcoming message was sent to the Congress by the Turkish President Fahri Korutürk.

Some 150 papers presented to the Congress had been sent to the participating countries along with general and review papers before the Congress. Therefore the papers were not read in the traditional manner but instead the delegates had a discussion and exchanged views at the many different Congress functions (technical sessions, roundtable meetings, special meetings, discussions, press conferences, etc.).

The technical program comprised four sections:

Section 1. "Developments in the domain of traditional energy resources" (improvements in prospecting methods, extraction of useful minerals, assurance of energy resources for the present and the future).

Section 2. "Energy saving by consumers" (use of energy in industry, commerce, homes, transport, and agriculture, and the effect of savings).

Section 3. "Conversion of primary energy" (improvement of technology of energy conversion, atomic energy, joint production of heat and electricity, conversion of solid fuel into liquid and gaseous fuels, hydrogen energy systems, direct generation of electricity, processing and use of natural and casing-head gas, oil processing).

Section 4. "Nontraditional energy resources" (thermonuclear fusion; solar and geothermal energy; wind, tidal and wave energy; other energy sources and the prospects of nontraditional energy sources).

Nuclear and thermonuclear energy were taken up directly in 16 papers. They dealt with the development of nuclear energy in some countries (Japan, Federal Republic of Germany, Turkey, South Korea), standardization of atomic power plants (Federal Republic of Germany, Japan), use of reactors for central heating (Finland, Sweden, Poland), improvement of the efficiency of atomic power plants (Federal Republic of Germany), the history of legislation on nuclear energy (U.S.A.), prospects for the development of fast reactors (France, Great Britain), the state of and ways of improving the radiation conditions of atomic power plants (Canada), the technology of extracting and obtaining nuclear fuel (Japan, Turkey), and the thermonuclear program (IAEA). The USSR presented three papers on the role of nuclear power in the fuel and energy balance of the country, about the Bilibinsk Atomic Heat and Power Plant, and about thermonuclear fusion (the first time the latter was discussed at a world power engineering congress as a separate topic).

Some papers, while not pertaining directly to nuclear power, did consider various aspects of it along with others of nuclear power production.

It follows from the papers that, as before, nuclear power is continuing to develop at a high rate; as before, it is considered as the most promising component of an increase in energy production over the next several decades. Nevertheless in recent years earlier plans and predictions concerning the introduction of new atomic power plants have been cut back considerably because of financial difficulties, the rising costs of atomic power plants, the increased safety requirements for these plants, and other causes. The total capacity of atomic power plants is now expected to be 1300-1650 million kW in the year 2000 and 3200-4300 million kW in 2020, which is two to three times less than was envisaged at the previous power engineering congress in Sept. 1974. At the same time, the share of atomic power plants in the structure of generating capacities remains as high as before; 45% in 2000 and 50-60% in 2020. No major changes of any sort have been observed in the strategy of development of generating facilities. As before, the general line of development in the overwhelming majority of countries consists in the gradual transition to the large-scale use of fast breeder reactors

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Fig. 1. Ataturk Cultural Center, Istanbul, where World Power Engineering Congress was held.

and consequently the gradual reduction of the growth of the power of thermal reactors. However, in contrast to the predictions of the previous congress, the latter are expected to be either light-water reactors (as the best mastered) and heavy-water reactors (as quite well mastered) which can be changed over to the thorium cycle (to save uranium) with slight changes in construction. An extremely restrained attitude is taken to the capabilities and prospects of constructing high-temperature commercial reactors with helium coolant and graphite moderator. It has been noted that large expenditures are required to make atomic power plants with such reactors economically competitive and to attain success in this area only provided that the countries on either side of the Atlantic unite their technical and financial endeavors.

The construction costs of atomic power plants are continuing to rise because of inflation and safety requirements. By 1984 the cost of an atomic power plant with LWR reactors with a power rating of ~1 million kW (electrical) will increase to 860-950 dollars/kW. In view of this and in view of the small unit powers required from atomic power plants in developing countries (100-200 MW) a question arises about the development of nuclear power in these countries. Views were expressed about the cooperation of such countries on the construction of atomic power plants and it was suggested that an international energy bank be established for financing such construction.

For the first time some papers at the Congress were devoted to atomic heat and power plants employing power reactors of the mastered LWR types. It was noted that the necessary economic effect is achieved through the combined production of electricity and heat; the question of atomic boilers was not considered. Different systems are used for connecting the central heating facility, with steam bleeding or with counterpressure. An unusual system is envisaged for the atomic heat and power plant at Olkiluoto (Finland). The condensing power of this plant is to be located together with the reactor at Olkiluoto. The central heating facility, including turbines with counterpressure and steam bleeding, will be installed 14.5 km away at Rauma which needs the heat. The central heating turbine so arranged is called a "satellite." In the opinion of the authors of the project, transportation of the steam over such a distance makes it possible to utilize the pressure difference between the outlet from the steam generator and the inlet of the satellite turbine. In this way a considerable proportion of the energy expended for pumping is saved in comparison with transportation of hot water over the same distance. At the same time the heat losses, and hence the energy losses, during transportation of the steam are low (the pressure loss in the turbine is 12 bars). The electrical rating of the satellite turbine is 37 MW, the heat release is 196 MW (136 MW for industrial purposes and 60 MW for central heating). Provision has been made for a pressurized water reactor with a nominal power of 1000 MW (electrical).

It is characteristic that all schemes for atomic heat and power plants described in the papers envisage condensing turbines. Such a "link" between the condensing power and the central heating power is logical because it permits reactors of high unit energy to be used and this improves the economic indices of the plant.

French and British papers described the state of the art and the prospects for the development of sodium-cooled breeder reactors. Successful experience in constructing and operating the famous Rapsodie and Phenix in France and DFR and PFR in Great Britain have made it possible to start construction of the second generation of reactors of this type. In France the Superphenix reactor rated at 1200 MW(electrical) is to be brought up to full power by 1983 and by the end of the century the country is expected to have ~25 million kW(electrical) installed capacity from such reactors. In Great Britain a project for a 1300-MW(electrical) reactor is being implemented. In 1978 Dounreay is to start up an experimental facility for regenerating spent fuel from fast reactors on the site. Construction of a large regenerating plant for commercial fast reactors has been planned for the 1980s. Thus, in fact the first nuclear energy center (part) with a complete closed cycle of utilization and reprocessing of nuclear fuel has started to come into being at Dounreay.

It was also pointed out that fast reactors are more expensive than the thermal type. They will become economically competitive as prices change on the uranium market. Therefore, breeder reactors will at first play a strategic and not an economic role. The same can be said of regeneration. Considerable financing is therefore required, and it should be state financing.

Mass construction of commercial atomic power plants with fast reactors is not expected before the 1990s. Their fraction of the structure of nuclear power in industrially developed countries is expected to be about 20% by the year 2000. Therefore, the principal effects in relation to saving uranium by the utilization of fast reactors will not be forthcoming until the next century.

For the first time papers on thermonuclear fusion were presented at the Congress. And although this subject was put under nontraditional energy sources, the very fact that it had been put on the Congress agenda, traditionally devoted to applied aspects of power production, reflects the successes achieved on the road to the realization of controlled thermonuclear fusion. Both the Soviet paper and papers from other countries to a significant extent contained descriptions of the principles involved in achieving the thermonuclear reaction. Particular attention was devoted to presenting the state of work in this field and the prospects for the future. It was noted that the expenditures on the establishment of thermonuclear power engineering to put it on a commercial level in the U.S.A. are estimated at the considerable figure of 15-20 billion dollars.

The subject matter discussed at the Congress proved to be much broader than in the papers presented. Various aspects of the use of nuclear reactors for power engineering purposes were considered at:

a special meeting of technical session No. 3 "Conversion of primary energy;"

the rountable meeting on plutonium;

the roundtable meeting on "Atomic energy and nontraditional energy sources;"

the roundtable meeting on the combined production of electricity and heat with particular attention to atomic heat and power plants;

the roundtable meeting on nuclear ships;

technical session No. 4 "Atomic energy and nontraditional energy sources."

Some of these meetings had either not been planned initially or else had had topics pertaining to nuclear energy added to their agenda. All of this reflects the interest of the delegates to the Tenth World Power Engineering Congress in nuclear power engineering and the attention they paid to it.

The conclusion stemming from the many discussions and contributions is that in the complicated fuel and energy situation only solid fossil fuel (primarily coal) as a fuel resource boasts the same scale of potential expansion of utilization as atomic energy does. Hence the second problem discussed, that of fuel. A characteristic feature of the contributions from delegates (once again in contrast to the previous Congress) was an attempt to estimate the scales of demands for nuclear fuel for different variants of development (so-called "scenarios") of nuclear power engineering over a period beyond the year 2000. From a comparison of these "scenarios" it followed incontrovertibly that only the gradual restructuring of the nuclear power industry so as to increase the fraction of fast breeder reactors will enable the fuel problem to be resolved.

A closed external fuel cycle is a necessary and obligatory condition for the normal development of nuclear power. A question, therefore, unavoidably arises as to the production of plutonium and the control of its use. At the roundtable meeting on this topic (chaired by IAEA Director General S. Eklund) participants noted the substantial work done and the experience with plutonium and regeneration of spent fuel. Particular attention was drawn to the nuclear and radiation safety of facilities which come within the realm of the nuclear power industry. It was noted that there were problems which had not been solved or had been only partially solved but the unanimous opinion was that it was technically possible for plutonium and spent fuel to circulate safely within the limits of the fuel cycle. The U.S. delegate D. Davies was restrained in formulating his position. He remarked that it was technically feasible to construct commercial atomic power plants with fast reactors in the next ten years but he ended his contribution with a statement about the necessity to continue to study the uranium — plutonium situation.

The representative of the United Kingdom Atomic Energy Authority, J. Hill, noted that the solution of the problem might be furthered by nuclear energy centers (parks). He said that national centers were inappropriate for countries with modest plans for the development of nuclear power; for greater prospects for the development of nuclear power such centers were undoubtedly advisable. Centers established on an international or regional basis were also desirable and this road should be considered the most promising.

A new aspect of the discussions at the Congress was the serious attention paid to the need to develop atomic heat and power plants. A. Pierre (France) spoke about a design for such a plant with a power of about 600 MW. The reactor section would be sunk two-thirds into the ground and, moreover, provision is made for a double protective envelope. A temperature of 160°C has been chosen for the hot water. The French delegate expressed confidence that the project for this atomic heat and power plant would be realized.

The discussion on atomic ships did not go beyond engineering and economic studies of versions of such ships, a cursory description of the experience from experimental ships built, presentation of the conditions for entering into foreign waters and ports, and a cursory description of land-based prototype facilities.

On the whole the impression is that, notwithstanding the optimism in the views of the contributors discussing the problems of nuclear power, in the present situation they are to a great extent anxious about the task of maintaining the positions already won, although they are enthusiastic about conquering new positions.

RADIATION EFFECTS IN STRUCTURAL MATERIALS OF FAST REACTORS

V. N. Bykov

Radiation damage to structural materials remains one of the most pressing problems in both the operation of fast reactors and in the elaboration of projects for future breeder reactors and thermonuclear facilities. The reason for this is that at the high fluence and elevated temperature characteristic of reactor installations of this type radiation damage may lead to a considerable macroscopic increase in the volume of structural elements, alter their shape, and reduce the long-term strength and plasticity of the materials.

Research on radiation effects in the structural materials of fast reactors was the subject of an international conference held at Scottsdale (Ariz.) from June 19 to 23, 1977. It was attended by more than 100 delegates, including three Soviet specialists, from all countries which are developing reactors.

At a plenary session the conference considered the national programs of Britain, France, the Federal Republic of Germany, and the United States on research on radiation effects in materials, including the basis for choosing materials for the construction of nuclear power facilities. Working sessions heard more than 60 papers on the results of investigations on mechanical properties, radiation creep, swelling, and changes in the microstructure of materials, as well as on the applied theory of radiation effects.

In the papers on the national programs of research on radiation effects in materials the countries engaged in the development of fast reactors confirmed their results (the U.S. program is being amended appreciably). For reactors in operation or under construction cold-worked (20%) grade-316 steel has been chosen as the main material for the fuel-element cans and sheaths of fuel-element clusters in the case of the Phenix and Superphenix (France), EBP II and FFTF (USA), JOYO and MONJU (Japan), whereas cold-worked (20%)

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FV-548 and 321 steel as well as PE-16 nimonic have been chosen for the PFR (Britain). Grade 1.4970 steel (austenitization + cold working 15% + annealing 800°C) has been chosen for the fuel-element cans of the SNR-300 (Federal Republic of Germany) and grade 1.4981 steel is being considered for cluster sheaths. New materials for future prototype reactors and high-power nuclear power facilities are being sought on the basis of austenitic steel with optimal alloying, high-nickel alloys, and ferritic steels, including precipitation-hardened materials.

Charged particles and high-voltage electron microscopes are used extensively for work on the simulation of reactor irradiation. The goals of simulation experiments are to obtain comparative data on swelling, to make a tentative choice of radiation-stable materials, and to ascertain the laws governing radiation damage.

Radiation-induced swelling of structural steels continues to attract great attention by researchers. Besides studying the nature of the effect, which was characteristic of the first stage, at the present time intensive research is being done to determine how swelling is affected by the alloying of the principal structural materials, austenitic steels. The search for new alloying principles and the development of new compositions on the basis of austenitic and ferritic steels and high-nickel alloys has been stimulated by the fact that results recently obtained in accelerator simulation of irradiation of traditional steel to a dose corresponding to 200-300 displacements/atom do not reveal saturation of swelling. Irradiation in reactors to a fluence of $1.4 \cdot 10^{23}$ neutrons/cm^2 ($E > 0.1$ MeV) and more confirms these data and shows that foreign steels of the 300 series, e.g., 304, 316, and other traditional reactor steels, experience considerable swelling in the austenitized state. It was found that cold working has a favorable effect under limited irradiation conditions.

For some compositions of alloys based on the ternary system Fe — Cr — Ni it has been established that a considerable effect on swelling is exerted by the content of carbon, nickel, the stabilizing components titanium and niobium, as well as silicon, boron, sulfur, and phosphorus. Particularly noteworthy results have been obtained in reducing swelling by alloying with silicon, titanium, and boron. As shown by accelerator irradiation of model alloys, by a favorable combination of alloying components radiation swelling can be suppressed to a considerable extent. It follows from alloying experiments that swelling depends on how the steel and the technological admixtures are obtained.

The data presented at the conference confirm preliminary reports of low swelling of nickel alloys (PE-16, Incoloy 625, etc.) and ferritic steel.

The mechanical properties of austenitic steel were considered in conference papers in relation to the irradiation conditions, and the composition and structural state of the materials. Much attention was paid to the interrelation between the mechanical properties and changes in the microstructure. Characteristics of the effect of irradiation on fracture processes have been revealed in three intervals: below 0.4 of the melting point the matrix is hardened and the plasticity is reduced owing to the development of a high concentration of radiation-induced defects; at the temperature of formation of vacancy pores and a network of extended dislocations and loops there is a new deformation mechanism which leads to the formation of local cracks which reduce the breaking stress; above 0.6 of the melting point the deformation is complicated by radiation-stimulated second-phase precipitates as well as the release and coagulation of helium which is formed in nuclear reactions. In this case fracture is due in the main to helium weakening of grain boundaries.

Conference papers also discussed the results of research on the mechanical properties and long-term strength of austenitic steels and nickel alloys, gave data on the bursting of fuel-element cans under operating conditions, and proposed criteria for fracture and for estimates of reliability.

Irradiation creep has again received increased attention in view of the correlation discovered between creep and swelling. It has been established that under the conditions of swelling the creep rate is an order of magnitude higher than under weak neutron fluxes and may exceed allowable values. As shown by experiment, creep is proportional to the stress and in the absence of swelling does not depend on the temperature but increases with the flux. This relation can be written as

$$\varepsilon/\sigma\Phi t = 2.2 \cdot 10^{12}\ \mathrm{MPa}^{-1}\ (\text{displacements/atom})^{-1}.$$

Creep strain with allowance for swelling is expressed by the Boltax formula $\varepsilon/\sigma = C\Phi t + DS^{\lambda}$, where C and D are constants, S is the swelling, and $\lambda = 0.54$.

It should be pointed out that the results of measurements of creep strain in various materials under various conditions are frequently contradictory and require a precise approach to the isolation of the irradiation creep component from the total deformation when swelling also makes an appreciable contribution.

Many problems remain for the study of mechanisms of irradiation creep and the effect of various factors on it, including the structural state of the material and the irradiation conditions.

The conference paid considerable attention to the applied theory of radiation damage to materials. A characteristic feature of this theory is that creep and swelling are considered within the framework of a single model based on the division of the flux of point defects among the various microstructural sinks — dislocations and pores.

Investigations of the effect of irradiation on the phase stability have shown that with a high fluence irradiation-induced defects store up energy; this appreciably displaces the equilibrium and may result in the formation of phases which are unstable under ordinary conditions. There was a discussion of various molecular-kinetic mechanisms which lead to the formation of radiation-induced unstable phases and to the displacement of the lines on the phase diagram.

An interesting computer model was proposed for predicting the effect of the properties of a material and the irradiation conditions on the evolution of the microstructure. This model can serve as a guide for the formulation of simulation experiments. In particular, for accelerator simulation of creep experiments it is recommended that the samples be previously irradiated in a reactor so as to produce a distinct microstructure characteristic of irradiated materials.

The proceedings of the conference contain much useful information and data about the effect of irradiation on the properties of metals and structural steels and are undoubtedly of interest to a wide range of specialists.

FOURTH SESSION OF SOVIET—AMERICAN COORDINATION COMMISSION ON THERMONUCLEAR ENERGY

G. A. Eliseev

The regular session of the Commission coordinating cooperation in the realm of controlled thermonuclear fusion was held from June 1 to 3, 1977, at Princeton (U.S.A.). Having considered the results of collaboration in 1976, the Commission noted that the program for 1976 had been carried out in full and had yielded considerable results of mutual benefit. On the whole, the 1977 program was being carried out successfully as well. In the discussion of the draft program of exchange for 1978 as well as prospects for further collaboration, the Commission felt it was advisable to implement planned long-term joint research on such key aspects of controlled thermonuclear fusion as theoretical investigations and numerical simulation of the behavior of plasma in systems with magnetic confinement, development of methods for supplementary heating of plasma in tokamaks, development of superconducting magnetic systems for large thermonuclear machines, research on bulk radiation damage of materials and on the effects of the plasma-wall interaction, conceptual design of blankets for thermonuclear reactors, and systems analysis of thermonuclear power plants.

It was agreed that the principal task of the collaboration for the immediate future was to carry out joint work on the confinement of plasma in tokamaks [primarily refinement and comparison of results obtained on the T-10 (USSR) and PLT (U.S.A.) tokamaks] and to investigate the possibilities of improving plasma confinement in open magnetic traps.

According to the now established tradition the delegation leaders, E. Kintner (U.S.A.) and E. P. Velikhov (USSR), presented reports on the results obtained in 1976 in work on controlled thermonuclear fusion in both countries. This was followed by a broad discussion devoted to the analysis of future prospects for the development of the thermonuclear program as a whole.

The reports by the American delegation noted that the new program for solving the energy problems of the U.S.A. had resulted in some reduction of funds for work on nuclear power. In particular, the budget on controlled thermonuclear fusion had been cut by roughly 20%. As a result, for the 1978 fiscal year 433 million dollars (instead of the requested 496 million dollars) have been allocated for work on controlled thermonuclear

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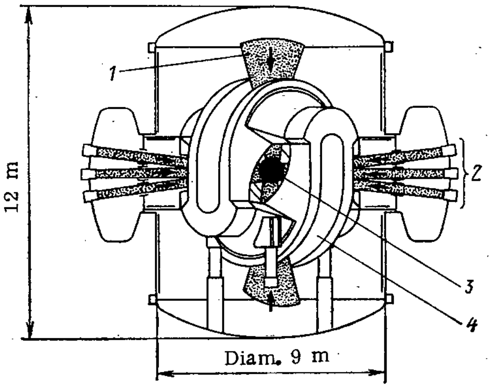

Fig. 1. The Mirror Fusion Test Facility: 1) injection of target-plasma; 2) injection of beams of fast neutral atoms; 3) zone of plasma confinement; 4) windings of magnetic trap.

research, 318 million dollars for systems with magnetic confinement of plasma and 115 million dollars for laser and beam systems.

In the year since the third session, the most important results in the U.S.A. were obtained on the tokamaks Alcator, PLT, and ORMAK, as well as on the 2HPV magnetic trap.

In the Alcator tokamak (MIT) the plasma density n was successfully brought up to 10^{15} cm^{-3} with a toroidal magnetic field of 85 kG. The plasma is characterized by a high degree of purity (effective charge $z_{eff} \sim 1$). As a result a record confinement parameter was achieved: $n\tau = 2 \cdot 10^{13}$ cm^{-3} $\cdot$sec (τ is the plasma energy lifetime). Construction is being completed of a new tokamak, the Alcator-C, with a toroidal magnetic field of 140 kG. Experiments on it are to begin in Jan. 1978.

The larger tokamak PLT (Princeton Large Torus) with a plasma density of $\sim 10^{14}$ cm^{-3} and a magnetic field of 32 kG gave a parameter of $n\tau \sim 10^{13}$ cm^{-3} $\cdot$sec. Thus far it has not been possible to obtain plasma with a sufficiently small z_{eff} with discharges in hydrogen. The plasma contains a high percentage of admixtures of heavy elements, primarily tungsten, and this leads to appreciable radiative energy losses. The study of the problems of impurities is at the present time the basis of the program of research on the PLT. Along with this preparations are being made for experiments with the injection of beams of fast neutral atoms into the plasma. A 500-kW injector has been assembled. By the end of 1977 the power of the PLT injection system will have been increased to 3 MW.

In the tokamak ORMAK (Oak Ridge) injection of beams of neutral atoms with a total power of 500 kW made it possible to raise the ion temperature of the plasma from 500 to 1800 eV, while the electron temperature rose from 400 to 800 eV. The facility has not been in operation since a breakdown in 1976. It is planned to rebuild ORMAK and to use it for further research on the possibility of injection of pellets of solid hydrogen measuring $\sim 200\ \mu$ to be injected into the tokamak with a velocity of $\sim 10^4$ cm/sec.

In the open magnetic trap 2HPV (Livermore) the injection current was increased to 600 equiv $\cdot$A with 20-keV atoms. As a result a plasma was obtained with an ion temperature of 13 keV, density $2 \cdot 10^{14}$ cm^{-3}, and parameter $\beta_{max} \sim 2$. Intense experimental work is under way on producing in the facility a magnetic configuration with inverted magnetic field. Work has advanced on the design of a magnetic trap of the next generation, the MFTF (previously it had the label MX).

The MFTF (Mirror Fusion Test Facility) is designed to obtain plasma with an ion temperature of 50 keV, density $\sim 10^{14}$ cm^{-3}, and $n\tau \sim 10^{12}$ cm^{-3} $\cdot$sec. The facility is to have a superconducting magnetic system with a field of 20 kG in the region of the mirrors, a spacing of ~3.4 m between mirrors, and a 2:1 mirror ratio. The energy stored in the system is to be ~500 MJ. The plasma in the trap is to be produced by means of injectors of "cold" target-plasma and injectors of beams of 20-keV neutral atoms with a total current of 1000 equiv $\cdot$A, designed for 10 msec of operation. Then 24 other injectors (750 equiv $\cdot$A, 80 keV, 0.5 sec) are to be switched on to heat the plasma and to maintain the plasma density. The main vacuum chamber of the MFTF (cf. Fig. 1) will have a diameter of 9 m and a height of 12 m. Construction of the MFTF is to be completed in 1982.

Upon completion of the session the Soviet delegation visited the principal thermonuclear centers in the United States: the Princeton Plasma Physics Laboratory, the Plasma Physics Laboratory of the General Atomic Co. in San Diego, the Lawrence Laboratories at Livermore and Berkeley, the Los Alamos Scientific Laboratory, and the Massachusetts Institute of Technology.

In Princeton, in addition to becoming acquainted with the PLT experiments, the delegation visited the building site of a tokamak with PDX diverter and became acquainted with the work on the design of the TFTR experimental tokamak reactor. The designing work is being done jointly by the companies Ebasco and Grumman under the scientific supervision of Princeton. The target date for putting TFTR into service was 1981. However, work is now about 6 months behind the original schedule owing to the previously mentioned cuts in funds for controlled thermonuclear fusion.

A large tokamak, Doublet III, being assembled in San Diego will become operational in the spring of 1978. The power of the flux of the neutral atoms injected into Doublet III is to be increased to 5 MW by mid-1979.

Major changes are being made at present in the fusion research program at Los Alamos. Work on the SCYLAC program has been halted and work on the construction of the intense neutron source INS has been wound up because of a lack of funds. Much attention is to be devoted to research on the Z-pinch effect; in particular, a decision has been made to build the ZT-40 reverse field Z-pinch with a 40-cm diameter. As a whole, the Los Alamos thermonuclear laboratories are to be used for research keeping up two main lines of work on controlled thermonuclear fusion in the U.S.A. (tokamaks and open magnetic traps).

MEETING OF TECHNICAL COMMITTEE 45 OF THE INTERNATIONAL ELECTROTECHNICAL COMMISSION ON NUCLEAR INSTRUMENTATION

L. G. Kiselev

The 15th regular meeting of Technical Committee TC 45 was held in Karlsruhe and Baden-Baden (Federal Republic of Germany) Mar. 3-12, 1977. At the same time Subcommittees SC 45A (Reactor Instrumentation) and SC 45B (Dosimetric Instruments and Radiation Safety Instruments) held their meetings as did 12 working groups of the Committee and Subcommittees.

The meetings, which were characterized by further activation of the work of TC 45, were attended by 81 experts from 14 countries of Europe, Asia, and America, as well as IAEA representatives. The first meeting of working group WG 12 discussed a document on the technical requirements and methods for testing analog counting-rate meters. The meeting decided to set up two new working groups to prepare documents on radiation monitoring systems for atomic power plants. The National Committee of Japan was the first to name their experts to many working groups.

Twelve new publications had been prepared since the previous meetings. One of them was Publication 532 specifying the technical specifications and general methods for testing stationary monitors and signal indicators for x-ray and γ-ray exposure in the energy range from 80 keV to 3 MeV. Publication 547 stipulates the dimensions of modular plug-in units and a 19-inch rack for holding them. The dimensions are based on the NIM Standard.

The organization of multicrate CAMAC systems and the specifications of the interrack dataway and type-A1 crate controller are given in Publication 552. Publication 568 contains the specifications of instruments for in-reactor monitoring of the neutron flux. Publication 576 presents the general characteristics of drilling equipment. Publication 577 deals with radioisotope thickness gauges and Publication 579, with meters and monitors for radioactive aerosols. The dimensions of flasks for liquid scintillators are specified in Publication 582 and those of glass and plastic test tubes for radioactive measurements are given in Publication 583. Publications 231E and 231F spell out more precise principles for the construction of apparatus for high-temperature and heavy-water reactors, respectively.

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Publication 578 on "Multichannel Pulse-Height Analyzers. Types, Main Characteristics, and Technical Specifications," which had been drawn up by WG 10 (Multichannel Analyzers) on the basis of the Soviet standard GOST 16957-71, was prepared for print.

At its plenary meeting TC 45 passed a resolution calling for the Central Bureau to have 11 more documents translated and sent to the national committees for voting under the six-month rule. These include a standard on the organization of series connections for crates in the CAMAC system; standard methods for testing high-purity germanium detectors; standard methods for testing multichannel analyzers; and general principles for the communication lines for the reactor safety systems of atomic power plants. The 11 documents also include a new edition of Publication 340 "Methods of Testing Amplifiers and Preamplifiers Used with Semiconductor Detectors of Ionizing Radiation" and Publication 325 "Meters and Monitors of α-, β-, and $\alpha - \beta$-contamination."

The working groups are continuing to draw up certain documents. Thus, WG 3 is preparing documents on the CAMAC system for publication as International Electrotechnical Commission standards. In particular, it has been decided to draw up new documents as Secretariat documents: "Block Data Transfer in the CAMAC System" and "Distributed 'Intelligence' in the CAMAC System." Both documents should subsequently supplement the main CAMAC standard specified by Publication 516. The first of the documents under revision expands the interface of a crate for ensuring the transfer of blocks of data (several words) in response to a single command. The second establishes a protocol of priority when one crate contains several controllers. Working Group 5 is beginning work on a document concerning radiometric equipment for aircraft, whereas WG 6 is working on the document "Analog Radioisotope Densimeters" and is beginnig to draw up a document on x-ray fluorescence thickness gauges. Two new documents will come from WG 9, "A Graduated-Scale Type of Calibrator for Semiconductor Detectors" and "Standard Dimensions of Semiconductor Detectors." Working Group 10 will continue to establish standards for multichannel analyzers. A document to be elaborated will deal with time analyzers used in time-of-flight measurements and another will concern analyzers for signal averaging. Working Group 12 will prepare a document spelling out the technical specifications and methods for testing digital meters for average counting rates.

Subcommittee 45A is continuing work on documents about systems for in-reactor temperature monitoring, about electrical flows through reactor vessels, about the technical specifications of electrical safety equipment, etc. Work has started on a new version of Publication 231. At meetings of Subcommittee 45A and its working groups the IAEA representative spoke of three recommendations being prepared by the IAEA concerning reactor apparatus. These recommendations are to be studied for delimiting the ranges of application of elaborated documents and for eliminating parallelism in the work.

Subcommittee 45B is preparing documents on equipment for monitoring radioactivity in gaseous discharges, on portable meters and monitors for the equivalent neutron dose, on the specifications of thermoluminescence dosimeters, etc. It does not plan to begin elaboration of documents on systems of radiation monitoring in atomic power plants in relation to internal and external dosimetry.

While TC 45 was in session in Baden-Baden the working group on interface systems was also meeting; this working group was established by a resolution of the IEC Consultative Council on Electronics and Telecommunications (ACET), consisting of the chairmen and secretaries of the 17 technical committees. This resolution had been adopted in response to the initiative of Soviet experts on TC 45 for regulating and coordinating work on interface measuring systems.* The meeting was attended by representatives of TC 45, TC 62 "Electrical Equipment in Medicines," TC 65 "Control Systems for Industrial Plants," TC 66 "Electronic Measuring Apparatus," as well as TC 97 of the International Organization for Standardization "Computers and Data Processing" and others. It was pointed out that a single interface system cannot satisfy all requirements. Thus, TC 45 is developing CAMAC systems for use in experiments on physical facilities. Technical Committee 66 does not satisfy CAMAC as an interface for systems for programmable measuring instruments; a standard document 66 (Central Bureau) 22 is being prepared for such systems. At the same time, neither CAMAC nor the interface for programmable measuring instruments meet the requirements of TC 65 for systems used in industry. At the present time the systems are not compatible but compatibility is extremely desirable, especially in regard to such aspects as the code for data representation, format, etc. The best way of ensuring compatibility of various interfaces is that of collaboration among the working groups of various technical committees. In this connection attention was drawn to the joint meetings held by working groups of TC 65 and TC 66. It was felt that experts from TC 45 must participate in the meetings of the relevant working groups of TC 65 and TC 66.

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*At. Energ., 41, No. 2, 156 (1976).

On the whole, the work of Technical Committee 45 in the period preceding the meetings and during the meetings was intensive and successful. The Soviet Union was represented by a delegation consisting of L. G. Kiselev, L. M. Isakov, and Yu. K. Kulikov.

SYMPOSIUM OF AMERICAN ELECTROCEMICAL SOCIETY

Yu. I. Tisov, A. F. Kapustin,
and V. N. Smagin

The Symposium was held in Philadelphia, Pa., from May 8 to 15, 1977. It had sections on current sources, corrosion, dielectrics and insulators, electronics, electrothermics and metallurgy, physical electrochemistry, electrochemistry in biology, electrochemistry of organic substances, and industrial electrolysis. A delegation of the State Committee of the Council of Ministers of the USSR for Atomic Energy (GKAÉ SSSR) participated in the work of the last section which encompassed a wide range of applications of ion-exchange membranes: industrial processes, desalination of water by electrodialysis, and engineering improvements in electrodialysis and other processes.

At the plenary session of the Symposium G. Steever covered the present state of research in the principal areas of activity by the American Electrochemical Society as well as achievements of electrochemistry in a number of countries of Europe and Asia.

The review paper in the industrial electrolysis section was devoted to the development of the electrolysis industry, particularly chlorine production and the production of a number of metals (aluminum, beryllium, chromium, copper, etc.) and electricity. The paper devoted much attention to environmental protection and pointed out the current tendency to equate chemical reagents, especially chlorine-containing organic substances, to carcinogens.

The Symposium discussed the use of ion-exchange membranes in various electrochemical processes. This was the subject of two papers by Japanese specialists. In their paper "Regeneration of etching solutions by using ion-exchange membranes," T. Kawahara et al. presented the flow-sheet of a pilot plant for the treatment of sulfuric acid solutions from iron etching. The plant incorporates dialysis and electrodialysis and makes it possible to obtain a practically closed system with sulfuric acid being regenerated and iron being deposited on the cathode. Selemion DMV Selemion AAV and CMV ion-exchange membranes, measuring 550 × 1570 mm, are used in the dialysis and electrodialysis apparatuses, respectively. The current density is 360-780 A/m^2.

The creation of a special membrane possessing high selectivity and minimum electroosmotic transport of water was reported in the paper by H. Ukihara and T. Asabi, "Ion-exchange membranes for electrolysis of common salt." A commercial monopolar electrolyzer of the filter-press type with a 220 × 120-mm membrane has been developed and built. In 2 years of operation the apparatus has provided stable service and has had a current yield of 95% with a power consumption of 2800 kWh/ton alkali.

In comparison with diaphragm methods electrodialysis permits a higher quality alkali to be obtained at lower cost.

The paper "Poisoning of membranes by colloidal silicon during the electrodialysis process" gave the result of the operation of an electrodialysis plant in the town of Brindisi (Italy). After eight months of operation the total electrical resistance of the electrodialyzers had increased by 35% with an appreciable decrease in the degree of desalination. When the apparatuses were dismantled a brownish-red deposit consisting mainly of colloidal silicon was found on the anion-exchange membranes. The authors of the paper considered the silicon layers to be a cation exchanger and the behavior of a membrane with such a layer to be analogous to that of – a bipolar membrane. Tests on removing the film formed on the surface of the membrane demonstrated that the membranes could be regenerated only by electrochemical treatment.

A paper by V. Iaconelli presented the principal areas of the commercial use of electrodialysis processes in the U.S.A.:

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oxidation—reduction: the membrane acts as a selective barrier for separating products of electrode reactions while at the same time passing certain ions from one chamber to the other. In this way sulfuric acid and an alkali are obtained from a solution of sodium nitrate, tetramethyl ammonium hydroxide from its chloride salt, chlorine from common salt;

electroorganic synthesis (obtaining hydroquinine from benzene, adiponitrile from acrylonitrile, etc.): the function of the membrane is analogous to that considered and, moreover, prevents the transport of organic molecules from one chamber to the other;

desalination—concentration: electrodialysis is especially common in desalination of brackish water. This method is used to regenerate chemical substances from industrial effluents, and to desalinate albuminous whey and chemical and pharmaceutical intermediate products. Cation- and ion-exchange membranes are placed in pairs and, together with special interlayers (frames), form desalination and concentration chambers;

electroosmosis: the use of membranes in this area has not yet received widespread currency and the process is in the stage of development and mastery; nevertheless, it is used on a limited scale to separate lactose (milk sugar) from albuminous whey. The membranes for this process should have a low electrical resistance, high electroosmotic transport of the solvent, and pores of a certain size ensuring transport of substances with a certain molecular weight;

ion replacement: replacement of ions of one kind by others is used to transform sodium citrate into citric acid, to eliminate radioisotopes from solutions they contaminate, etc.

Papers by A. Zelman et al. (U.S.A.), D. Demisch and V. Pusch (Federal Republic of Germany), I. Oren and A. Soffer (Israel), and T. Winnicki and A. Mika-Gibala (Poland) were devoted to the theoretical and laboratory investigations on electrodialysis processes and the study of the electrochemical properties of ion-exchange membranes.

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