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ELASTIC SCATTERING OF NEUTRONS BY ATOMIC NUCLEI

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[Note: The following represents excerpts taken from an article that appeared in Uspekhi Fizicheskikh Nauk, Volume 37, No 4 (April 1949), pages 414-458. As far as possible the excerpted portions given here either refer to purely Russian sources or express the author's comments on related foreign scientific works. Omitted here are the author's summaries of foreign (mostly American), articles dated 1935 to 1940. The introduction and conclusion are given in full, however. Parts omitted are indicated by a series of dots, thus . . . . .]

At the ~~stage~~ development stage recently attained by atomic nuclear science, the problem of systematically outlining the ~~huge~~ vast experimental material and numerous theoretical works scattered throughout the pages of scientific journals has assumed first importance. Such an exposition is all the more important as nuclear physics became a regular scientific discipline.

For a clear exposition of any science, systematization by subdivision and unification by general ideas are necessary. Nuclear physics does not yet possess such solid systematization and this makes the exposition more difficult. In the author's opinion the most natural way, at least at present, should be the division based on the interaction of various particles with atomic nuclei (alpha-particles, deuterons, protons, neutrons and photons). Approximately such a subdivision is used in the well known monograph by Livingston and Bethe [1].

Another serious difficulty in exposition is the unreliability of the facts described. A generally acknowledged strict theory does not exist, and many conclusions derived from experimental data will later prove to be erroneous. However such a situation is unavoidable.

The science of the nucleus is not as definite a system as, for example, the statistical theory of gases. At this stage of development the most reliability belongs to experimental results, if these experiments are performed with maximum possible accuracy. At the present time, therefore, maximum attention should be paid to the systematic exposition of the most reliable experimental facts, associating them in such a way as to facilitate the concept of a general criterion or a cohesive notion.

It seems to the author that the elastic scattering of neutrons by atomic nuclei may at the present time be placed in such a section of nuclear physics. In the above-mentioned monograph, published in 1937, little space is given to it, because the experimental material was scarce at that time. But during the more than past ten years, a great amount of work has been done in this field, leading to very interesting and unexpected results.

1. Some General Concepts and Premises

As is generally known, the many-body problem cannot be solved ~~accurately~~ exactly in either classical or quantum mechanics. Nevertheless this problem could, until now, be solved more or less successfully: in astronomy and the atomic system by means of the perturbation theory, and in mechanics of gases by means of the introduction of statistical laws. These familiar methods proved to be inapplicable in the theory of the atomic nucleus.

For a successful application of statistical laws it is necessary to deal with a system consisting of a large number of particles. But the most complex nuclei possess barely over 200 particles. Such a number is definitely too small for a successful application of statistical laws in physics; and if the number of particles, as in light nuclei, is only 10-20, even an approximate application is entirely impossible. If we further take into consideration the fact that, in applying statistical laws, we ignore right at the start any notion of structure in the nuclear system, it becomes obvious that we can expect by means of the statistical theory to obtain only roughly approximate solutions in some cases.

On the other hand the method of small perturbations cannot be fully used, because any particle joining the nucleus interacts with all other nuclear particles with the same force that binds them together.

Therefore a rather hopeless picture is created. For a successful solution of the nuclear problem some entirely new methods of mathematical analysis should be invented, or after creating various nuclear models their experimental verification should be performed. It is possible that such methods will be found in the future, but for time being they are unavailable, and the only possibility is to apply the usual familiar methods. These are applied in the modern nuclear theory. Because of the above-mentioned reasons we should consider the conclusions of this theory with great care, for they may be either entirely erroneous, or only roughly approximate. Taking these difficulties into account, we may assume that the empirical method will be more productive than the logical derivations of a theory based on doubtful preconceptions.

After N. Bohr indicated the necessity of dealing with the many-body problem in any interaction of particles with the nucleus, Breit, Wigner, Bethe and Placzek [2, 3, 4] and other theoreticians created the "dispersion theory" of scattering, still trying to apply the perturbation method. This theory had little success. The application of the basic equation to different particular cases involved difficulties, due to the already mentioned fundamental and mathematical hardships.

Thereupon Bohr, Frenkel and Weisskopf [5, 6, 7] and others constructed a statistical theory of the nucleus, considering it to be an evaporating liquid drop. The transition of the initial nucleus, after capture of the external particle, into a compound nucleus is thought to be likened to the heating of the drop; the release of the particle is likened to evaporation. This theory is simple mathematically, and therefore enjoyed more progress than the dispersion theory; as previously said, however, this theory from the start does not take into account any notion of structure in the nucleus and is completely inapplicable to light nuclei. This theory satisfactorily explains phenomena of interaction of heavy nuclei with high-energy particles, because in such a case the internal structure of the nucleus plays a much smaller role than in the interaction of low-energy particles. (Note: The entirely unsatisfactory state of the modern nuclear theory is clearly characterized by the words of the most famous expert of this theory, Bethe, in one of his last articles ....).

It may easily be seen that in the case of elastic scattering of low-energy neutrons (approximately 0.03 eV to 3 MeV), mostly used in the numerous experiments described in this article, the application of the theory of the evaporating liquid drop appears to be very doubtful. In this nearly unique case the dispersion theory was applied with some success. We shall give a short exposition of its conclusions in order to compare it thereafter with experimental results.

2. Theoretical Interpretation of Elastic Scattering of Neutrons

In accordance with the ideas of N. Bohr (Note: Two original articles by Bohr were translated and published in this journal UFN, /9, 10/. This theory is also fully expounded in the article by Bethe /11/), every nuclear process may be described in the following way . . . . . . /Note by translator: Here the author goes into a mathematic discussion of Bohr's theories of 1935 and follows the exposition given in an article by Bethe, Rev Mod Phys. 9, 69 (1937), mentioned in the Bibliography here/.

3. Scattering of Neutrons by Atomic Nuclei; Experimental Data.

A. The Relation $\sigma = f(A)$

Systematic study of the interaction of neutrons with atomic nuclei starts with the voluminous work of Dunning et alii with the measurement of the "absorption" cross-section of thermal-energy neutrons /13/. . . . . . /Note by translator: Here the author describes the experiments performed by Dunning et alii, Phys. Rev. 48, 265 (1935); Mitchell and Murphy: Phys. Rev 47, 881 (1935); 48, 653 (1935); M. Goldhaber and Briggs, Proc. Roy. Soc. A 162, 127 (1937). He also appends a table of cross sections of scattering of slow neutrons by atomic nuclei, obtained by the above-mentioned scientists and published in the articles referred to above./

The results of these works are represented in Table II, Figure 1. Full evidence is given of the irregular scattering of σ from element to element, as was found with thermal neutrons, but the amplitude of fluctuation is considerably smaller. Therefore the first verifications showed that with decreasing neutron energy fluctuations in σ appear, but the general tendency of monotonic increase holds. Therefore from these experimental results some empirical rule in the functional relation $\sigma = f(A)$ takes shape. In order to confirm this rule it proved of extreme importance to investigate with all possible completeness the scattering of neutrons of intermediate energy, let us say from 0.1 to 0.5 MeV. These investigations were mostly performed by Soviet physicists [33-38].

The most convenient sources of uniform neutrons in the specified energy ~~getic~~ interval are nuclear reactions : (C,D), (γ ThC"), (γ ThC", Be) and (γ RaC,Be). The three last have a rather small intensity as compared with the first source; however, photoneutrons of this origin possess an important quality: their energy blurring, produced by different output directions relative to the direction of the γ-quantum, reaches on the average only 15%, while in the case of neutrons, obtained by bombarding various targets in discharge tubes with deuterons, the energy blurring, due to various causes, reaches 0.1 MeV and more.

Therefore photoneutrons appear to be the most suitable for such measurements. (Note: Due to some strange misunderstanding V. N. Kondrat'yev pretends in his article [47] that photoneutrons have the greatest energy uncertainty. This statement is entirely erroneous). The first verification was performed with neutrons from the reaction (γ ThC",D). The binding energy of the deuteron, according to agreement reached after many investigations [39-43], has recently been set equal to 2.18 MeV. On the other hand it was established that in the γ-spectrum of ThC" above 2.18 MeV only one line with an energy above 2.623 MeV is present (the presence of the line with ~3 MeV energy in the amount of ~2 - 3% is doubtful [44-46]. Therefrom it is easy to find that photoneutrons, to which we shall refer further as the second group, have an energy of 0.22 MeV. As a source of neutrons for measurements a small sphere 5 cm in diameter filled with heavy water was used; an amount of nearly 100 mC of RaTh was located in its center. As the detector an artificially radioactive element (Dy, Rh, or Ag) was used. For maximum activation it was placed in the center of a paraffin sphere 13 cm in diameter. The activity of the detector was measured by Geiger-Müller counter with a scatterer located between the source and detector, and also without it. These data, used in a general formula with a correction for nonparallel neutrons, served for the computation of cross sections. The results of measurements are given in Table II, Figure 1.

Statistical errors of measurements, due to the weak source, average 10-15%. We see from Figure 1 that the assumed empirical rule is completely comfirmed by measurements. The general tendency to monotonic increase is kept, and the magnitude of fluctuations of σ assumes an intermediate place between fluctuations obtained by thermal neutrons (D,D).

A second verification of photoneutrons (γThC",Be), performed by a method similar to that in the preceding work, shows the same regularities. The energy of these photoneutrons is agreed to be 0.4 MeV. The binding energy of the beryllium nucleus, as well as the binding energy of the deuteron, are nowadays solidly established quantities. On the basis of many determinations [39-43] it is accepted to be 1.63 MeV. Therefore photoneutrons from this reaction should have 0.88 MeV $\left[(2.623 - 1.63)\frac{8}{9}\right]$, but in a special work by the author [48] it is shown that this energy does not surpass 0.4 MeV. The decrease is probably due to the existence in the beryllium nucleus of an excited energy level of the order of 0.45 MeV, not yet known at the present time. We shall further refer to these photoneutrons as the 4-th group. As seen from Figure 1, the amplitudes of σ fluctuations, measured by these photoneutrons, are less noticeable then those observed by scattering of photoneutrons of energy 0.22 MeV, but they nevertheless remain higher than with neutrons (D, D).

Verifications with photoneutrons (γ RaC, Be) were performed too. But in the specified case, the study of the dependence $\sigma = f(A)$, these measurements effect but little the general picture. Their meaning will appear more clearly when we start to study the functional relation $\sigma = f(E)$, where E is the energy of scattered neutrons. The values of σ found are represented in Table II.

Amaldi et alii [49] performed a voluminous and accurate work with neutrons (C,D). We shall refer to it in detail while expounding the results of neutron scattering by protons. The method used in the work was that of passing neutrons. The obtained values of σ are given in Table II, Figure 1, together with measurements of photoneutrons.

Terminating this review of experimental works in the study of the relation $\sigma = f(A)$, we may make some conclusions. First of all, by analyzing these data, we note a quite clear "attenuation" of σ fluctuations, which we have already mentioned. The cross sections measured by Dunning lie well on a straight line, even within the limits of statistical errors. In this case however, we should keep in mind that the neutrons (Rn, Be) are non-uniform, and it is quite possible to admit that the measured σ represent average values. If we could separate uniform groups of this neutron spectrum and measure σ scattering of each group, probably we would obtain the same fluctuations as for neutrons (D, D).

It is easy to notice that a number of values of σ, as measured by means of these neutrons and distributed on one and the other side of the straight line of Dunning, are nearly equal. Assuming that such a relation would be justified for σ measured by uniform neutrons in an energy interval 3-5 MeV and that the amplitudes of fluctuations will be of the same order, we come to the conclusion that the cross sections measured at scattering of any energy from 0 to ~5 MeV will have the limit marked on Figure 1 by the line AB.

We do not know the cause of the observed sharp fluctuations in σ, but the most probable reason could be the resonance interaction of the neutrin with the nucleus. In this assumption we have to take into account the fact that in the scattering, characterized by cross sections distributed within the limits of error of measurements along the straight AB, the resonance interaction is completely absent. This is in agreement with the conclusions of the theory, showing that for sufficiently high neutron energies the widths of energy levels start to overlap among them (see section 2 and also the article by Weisskopf et alii [50]). Under such conditions the dependence of σ on the nuclear radius has a simple form: $\sigma = \pi R^2$. By computing here from R_1 for the start of the limit AB and R_2 for its end, we obtain: $R_1 = 4.7 \cdot 10^{-13}$ cm and $R_2 = 12 \cdot 10^{-13}$ cm. These values coincide well with nuclear radii, computed on the basis of other data.

Therefore the line AB indicates the geometrical boundary of nuclei. In reality this boundary should have the shape of a curve slightly convex toward the axis of abcissae in its middle part, because the most solid nuclei occupy the middle part.

Recently the σ of neutron scattering with an energy of 90 MeV was measured. Unfortunately these measurements stop with σ_{Cu}. Among heavy elements only σ Pb was measured. As seen from Figure 1 these σ in the region of light elements have values lying below the limit AB, those of Cu and Zn somewhat higher. These fluctuations already cannot be explained by resonance effects, but it is quite obvious that at such great energies the neutrons can freely traverse the superficial layer and penetrate the depth of the nucleus. For the determination of the nuclear boundary it would probably be most convenient to make systematical measurements of the σ of neutrons scattering with an energy ~8 - 10 MeV.

In Figure 1 the dotted lines parallel to AB characterize the average values of σ for neutrons of each energy used in the measurements. On the various sides of these lines, the number of σ values measured with neutrons of specified energy is approximately equal. The gradual lowering of these lines with increase of neutron energy indicates without doubt that the resonant fluctuations decrease regularly with increase of energy of the scattered neutrons and the values σ approach AB. It is interesting to note that the line characterizing the average σ values measured with neutrons (C, D), agrees accurately with the line of photoneutron (γ ThC", Be) of 0.4 MeV energy.

This arises our suspicion that the neutron energy (C,D) used by Amaldi et alii. was higher than the value indicated by them, 0.1 - 0.18 Mev.

The occurring increase of oscillation of σ with a decrease of energy of scattered neutrons does disagree completely with the conclusions of the scattering theory. As we saw in section 2 the theory predicts for slow neutrons a monotonous increase of σ , according to formula (6). This relation should still be justified for neutrons of ~~an~~ energy ies ~~until~~ up to 1 MeV. Resonant oscillations are admissible by the theory, but as it was shown in the derivation of σ_{res} they cannot exceed ~~sur~~pass more than 10% of the full value of cross sections.

The observed empirical rule of increase of resonant interactions with decrease of energy of scattered neutrons clearly contradicts the rough nuclear model of structure-less liquid drop. It is indubitable ~~out-of-doubt~~ that it is connected with a still unknown structure of the atomic nucleus. Below we shall discuss several such structural models, for time being, by terminating our conclusions we may say that the efforts of many investigators who have measured the cross sections of elastic scattering were not done in vain, but led to interesting rules, which will be doubtlessly solved completely in further investigations *). (*) Note: Recently new phenomena of resonant scattering were found [51-53]. In the case of some elements having high cross sections of capture (Ag, Rh, Co, Mn) of the resonance type, also high cross sections of resonant scattering were observed. It is possible that this phenomenon will show a strong connection ~~to~~ with the indicated rule).

B. The Relation $\sigma = f(E)$

This functional relation was most clearly determined after measurements of the cross sections of photoneutron scattering (γ RaC,Be), which could be divided into two groups.

It is known that in the γ-spectrum of RaC, 6 lines of various intensity are found above 1.63 MeV (Table III). By use of the strong energy difference between the strong second line and the fifth and sixth lines, we may separate neutrons into a group created by the second γ-line (group 1) and a group produced by the γ-lines 5 and 6, by surrounding the detector (Ag,Rh,Dy or boric camera) by paraffin layers of various thickness. It was found experimentally [48] that in the case of a paraffin sphere 6 cm in diameter maximum activity of the detector, located in the center of this sphere, is observed for neutrons of the first group. In the case of a 10-cm sphere neutrons of the first group are mostly absorbed by the paraffin on their way to the detector and the activation is mainly produced by the neutrons of the 5 and 6 γ-lines. The separation of these close groups by the same way is no more possible. It is easy to find that the energy of neutrons of group I nearly exactly equals 0.1 MeV $(1.75-1.63)\frac{8}{9} = 0.107$. Computation of neutron energy of the following mixed group gives values 0.51 and 0.71 MeV, but it was found experimentally by comparison with uniform photoneutrons (γThC",D) that the average neutron energy of this group does not exceed 0.3 MeV. This decrease of energy, as with neutrons (γThC",Be), is explained by the existence of an excited energy level at Be^8 near 0.45 MeV.

Such separation led to the possibility of measuring the σ of neutrons of the four groups corresponding to energies ~0.1, 0.2, 0.3 and 0.4 MeV, and also of obtaining for many elements 4 points of the curve $\sigma = f(E)$. The experimental method did not differ in principle from the formerly accepted one. Complete results of measurement are represented in Table II, and typical curves for some elements are shown in Figure 2.

Besides these data with photoneutrons, less numerous studies were performed on the relation $\sigma = f(E)$ for neutrons (D,D) by Aoki [55] and MacFaill [56]. Results for Si and Mg are represented in Figure 2, and full data in Table IV. The variation of neutron energy (D,D) in these works were obtained by varying the angle between the directions of deuterons and neutrons. Therefore, as shown in Table IV, the energy interval 0.63 MeV may be investigated. Diffusion Energy ~~blurring,~~ according to data by Aoki, reached 120 keV; it was considerably less, ~ 40 keV, in MacFaill's.

Study of the curves of Figure 2 leads to the conclusion that in contrast to the disorderly irregular variation of σ as a function of A, we have here fully regular variations, thus indicating the distribution of resonance levels in nuclei.

However, it becomes immediately obvious that these resonance processes do not fit within the framework of existing nuclear theories. As is familiar from Bethe's [5] and other writers' computations, the intervals (D) between resonance levels and the widths of these levels (Γ) are very small in heavy nuclei. The values D vary according to an exponential law and depend on the atomic weight of the element and on the energy of the scattered neutrons. In heavy elements D does not exceed a fraction of a volt, and Γ is of the order of 0.001 eV.

It is fully obvious that, in the scattering of neutrons differing in energy by 0.1 MeV and having an energy ~~blurring~~ diffusion of 20 keV, it is impossible to expect resonance phenomena in such close levels. Under such conditions the probability of falling on a separate level equals the probability of hitting with a football between the lines of a diffraction grating or of obtaining by this grating a dispersion of radio waves several meters long. Because of overlapping by the energy blurring diffusion of scattered neutrons possessing a great number of energy levels, we may expect only a monotonic decrease of σ with increasing E. But on curves of Figure 2 we see that the intervals of fluctuations and amplitudes do not essentially differ in the region of light nuclei, where energy intervals of $D \sim 150$ keV and more are possible, from the region of heavy nuclei; the only explanation of this phenomenon may be the assumption that resonance levels divided into intervals of hundreds of thousands of electron-volts, may exist without exception in all nuclei.

Another typical mark of the observed phenomena, to which we have already called attention, is maintenance of the general monotonic increase of σ during transition from light to heavy elements. The minimums of heavy elements do not surpass a certain limit, determined on Figure 1 by the line AB. At the end of the previous section we assumed that this line nearly corresponds to the boundary of nuclei. If this assumption is justified, we should now assume that in all elements the external shells of atomic nuclei have nearly the same structure as light nuclei.

Until now our conclusions seemed to be the most probable explanation of the open phenomenon of "anomalous" scattering. Now we shall introduce a hypothesis, which although less sure than the one previously expressed, nevertheless seems to be rather probable. If we assume it possible, as suggested by many writers, that light nuclei consist of alpha particles, we should also assume that the shells of heavy atoms also consist of alpha particles. Therefore this hypothesis automatically divides the heavy nucleus into an internal part, namely a sub-nucleus consisting mostly of superfluous neutrons, and into a shell consisting of alpha particles. During excitation of the whole nucleus the system of levels may approach that predicted from statistical theories; but interaction of nuclei with neutrons (or other particles) is also possible, when the internal sub-nucleus does not take part in this process. From the liquid-drop point of view such interaction may be considered as a local heating of the nuclear surface. We do not exclude the possibility that during elastic scattering the neutron interacts with a separate nuclear particle (alpha-particle, proton), which for some reason is more weakly bound to the nucleus.

As already mentioned in the computations of σ, all investigators assumed that the main process during the passage of neutrons through the elements studied is purely elastic scattering without loss of energy (Note: In the case of elastic collisions of neutrons with great masses of atomic nuclei the energy loss may be neglected). This assumption is justified for neutrons of energy up to 0.5 MeV. It has been experimentally verified [33]. But during scattering of neutrons (D,D) with an energy of ~2.5 MeV, as shown by Nonaka [58], hard γ-radiation is observed emitted by the scatterer. The appearance of this radiation may be ascribed only to the excitation of atomic nuclei, and not to absorption, because the measured σ appears to be of the same magnitude as measured by Aoki. Also observed are fluctuations similar to those found in the works of Aoki and MacFaill.

The angular distribution in the scattering of neutrons (D,D), considered in the computation of σ as spherically symmetrical in the laboratory coordinate system, proved to be sharply asymmetrical, at least in the case of some elements. [Translator's Note: Results of Aoki [55] are mentioned confirmed by Kikuchi [59]; the results by Barschall and Ladenburg [60] are also described].

These results do not distort much the relations $\sigma = f(A)$ and $\sigma = f(E)$. Changes which have to be introduced in the σ found are small and possibly do not exist in all elements (probably mostly in heavy ones). The general monotonic increase of σ remains, which indicates that processes of not only elastic, but also nonelastic scattering occur mainly, and perhaps exclusively on the surface of atomic nuclei.

As is well known, Niels Bohr suggested a demonstrative model to illustrate the formation of a compound nucleus .... [Translator's Note: Reference is made to Niels Bohr's works listed in the bibliography].

Graham and Wilson [61, 62] came to the same conclusions....

As seen from Table II, the functional relation $\sigma = f(E)$ was studied in detail only within the energy interval 0.1 -0.4 MeV. In the interval 2 - 3 MeV, measurements of heavy elements are nearly unavailable; besides, the measurements of Nonaka and Barschall had to be corrected for inelastic scattering and for asymmetry of angular distribution. Regions from 0 to 0.1 MeV and from 0.4 to 2 MeV were for a long time empty. Only quite recently two works appeared in the literature which widened a little the region 0.1 - 0.4 MeV in both directions.

In works by Russell et alii [63] photoneutrons from artificially radioactive elements were used...

Barschall et alii [64] used neutrons from the reaction (Li,p)....

4. Scattering of Neutrons by Protons

A. Theoretical Premises

The theory of the deutrons was created, as is well known, by Bethe and Peierls, and was based on the unique postulate of small radius of action of nuclear forces. (Note: This theory is expounded in an excellent way in the monograph by Bethe and Becher, "Nuclear Physics", translated into Russian in 1938 and published in Khar'kov.)

Many experimental results, to be described below, sharply contradict the Bethe-Peierls deuteron theory, and theoreticians had to introduce several changes. We shall now discuss two of them.

Morse et alii [67] introduced a special potential function ....

Share and Stein [69] considered the potential well ....

The Bethe-Peierls theory as well as contemporary meson theories of the deuteron, leading to forces possessing small radius of action, probably are only a particular case of a future more general theory which will take into account the experimentally found possibility of action of nuclear forces at considerably greater distances.

B. Experimental Data

After the introduction of the second (singulet) level of the deuteron experimenters worked long to verify the following formula:

$$\sigma = \frac{\pi \hbar^2}{M} \left\{ \frac{3(1 + \alpha_1 r_0)}{\varepsilon_t + E_0/2} + \frac{(1 - \alpha_2 r_0)}{\varepsilon_s + E_0/2} \right\} \qquad (15)$$

The first experimental result by Goldhaber (70) disagreed sharply with this formula ....

The second work by Tuve et alii [71] was also in this connection .....

The third work by Leypunskiy et alii [73] was performed also with photoneuterons, but not from the reaction $(\gamma\ \mathrm{ThC''}, D)$, but from the reaction $(\gamma\ \mathrm{RaC}, \mathrm{Be})$. Neutrons, obtained from the last source are, as seen previously not uniform. Silver, located in the center of a water sphere 13 cm in diameter, was used as the detector. The authors admitted that the neutrons had an average energy of 0.15 MeV. They found, by using a paraffin scatterer, the value $\lambda = 1.5 + 0.6$ cm, which corresponds to $\sigma = 8.5 \cdot 10^{24}$ cm^2. Although this value is below the theoretical one, it still agrees with it within the limits of experimental errors.

By comparing these two results we may make the following conclusions: 1) Goldhaber's measurements contain some error which is difficult to find; 2) both results (also the third one, by Tuve) are correct, the difference between them being possibly explained by different neutron energy, i.e. formula (15) is not correct. All specialists perferred the first explanation, because during three years no verifications of these importent deviations were made.

In 1939 Amaldi et alii [49] in their already mentioned work, besides measuring the σ of 38 various elements, thoroughly measured σ_H obtaining the value $3.3 \cdot 10^{24}$ cm^2, which is in excellent agreement with the result of Goldhaber.

In view of the importance of this problem for the theory of the deuteron and for the whole theory of the atomic nucleus and because of some strange further consequences of this work we shall analyze it in more detail........ [Reference is made to Amaldi's work [49].]

In order to get out of the difficulty created by the mentioned works, it was first necessary to repeat the measurements by Goldhaber with greater accuracy. This was done by the writer of this article [75]. Table II shows σ_H found by scattering with H_2O. The value $\sigma = (5.0 \pm 1.0) \cdot 10^{-24}$ cm^2 is in better agreement with Goldhaber's value than with the theoretical one. However this result is unreliable, because the measurements were done with poor experimental geometry of the equipment. After separation of photoneutrons into two groups (γ' RaC,Be), described in the previous section, and after many measurements of cross sections with four groups of photoneutrons, measurements of four values of σ of hydrogen were performed. The performance of such work naturally was a verification not only of Goldhaber's results, but also of all other works in the interval 0.1-0.4 Mev.

The main condition governing this work was the necessity of attaining the greatest possible decrease of the solid angle from the scatterer on the detector. During scattering of neutrons by heavy atoms the computations may be performed by assumption that they are spherically symmetrically distributed, and that the correction introduced in the neutrons reaching the detector after their scattering is not big. But during scattering by protons this correction increases strongly, because the neutrons proceed mostly straight ahead after scattering. For this reason in the specified work the distance between the source of photoneutrons and the detector was made as far as possible - 40 cm. With the amount of RaTh ~ 100 mC used for the work it was necessary to repeat the measurements many times with the scatterer and without it, in order to reduce statistical errors. Measurements performed with a width of the paraffin scatterer equal to 0.5 cm to 1 cm practically showed no differences, and final computations led to the value $\sigma = 3.0 \cdot 10^{-24}$ cm^2, which is in good agreement with data by Goldhaber, Amaldi and others with former results.

The same measurements with neutrons of the first group, as expected, agreed with measurements by Leypunskiy and others. Verification with group III led to the same result as obtained by group I. This indicated that the minimum so long sought for on the Breit-Wigner curve is probably very narrow, and a deviation to one or another side leads to values of σ, rather close to the theoretical ones. This circumstance confirms our ideas on the reason for the divergence of two σ values by Amaldi and others.

Measurements with photoneutrons of the group IV led again to a small value of $\sigma = 3.2 \cdot 10^{-24}$ cm^2. This result, found for the first time for neutrons of this energy, was confirmed in the work by Good and Goldhaber [76] who found $\sigma = 2.6 \cdot 10^{-24}$ cm^2. Results of these measurements are represented in Table VI, and Figure 4.

This verification of formula (15) was the last made in 6-year period. In 1947 two works appeared, among which one was made with photoneutrons [77] obtained from reactions (Na,Be,D), (Mn,Be,D), (Ga,Be,D), (La,Be,D). The applied measurement methods were similar to those used in the quoted work by Russel et alii. The measurements of σ with a paraffin scatterer, as seen from Figure 4, do not diverge much from the theoretical curve.

In the second work Bennett et alii [78] used reactions (Li,p), (C,D) and (D,D) in order to obtain suitable neutrons. During bombardment of a thin lithium target with protons of various energies it was possible to obtain neutrons with energies from 0.35 to 0.97 MeV. By using the second reaction, neutrons with energies of 1 to 2 MeV were obtained; and from the third one, 2.6 to 6 MeV. Results of Measurement made by the use of an ionizing camera are represented in Table VI and are plotted on curve Figure 4.

By analyzing all data of σ_H measurements starting with the first work by Goldhaber and ending with the two last ones, we may make two conclusions: 1) Anomalous discrepancies of points outside the curve expressing the relation (15) exist probably only in the range of small energies, nearly up to 0.5 MeV; 2) The last data on photoneutrons make again the reality of anomalous discrepancies doubtful.

Let us first analyze the second conclusion. The energies of photoneutrons (Na,D) and (ThC",D) are nearly equal to 0.27 and 0.22 MeV respectively; or, taking into account the possibility of decrease of neutron energy in the source itself, as suggested by the writers, we see they are equal to 0.22 and 0.17 MeV. If we had to deal only with one work (e.g. with the first work by Goldhaber), we probably would not be bold enough to state that the difference of 5000 eV leads to such a sharp anomaly in the value of σ. But, as we have seen from analysis of all previous works, the anomalous value of σ stubbornly appeared in four works, and it was measured more than 10 times by the author of this article, while its average value did not differ more than 20% from each separate measurement of σ. It is quite obvious that such amazing coincidences cannot be accidental. On basis of the last data by Wattenberg [7] we may conclude that the range of the σ discrepancy is rather narrow and of the order of 10 - 15 keV.

Sources (Ga,D) and (Ga,Be) supply neutrons of energies 0.16 and 0.32 MeV (or 0.13 and 0.27 MeV). The first and the second energy are near energies of groups I and II of photoneutrons (RaC,Be). The values σ as seen from the corresponding table and from Figure 4 agree here well, and we have nothing more to say on this matter. Unfortunately, among photoneutrons obtained from artificially radioactive sources there are none with energies near 0.4 MeV, i.e. to the group IV of photoneutrons (ThC",Be); but in the following work we find neutron energies (Li,p) 0.35 and 0.46 MeV and two cross sections measured by these neutrons that do not diverge from the theoretical curve. Therefore, for neutron energies near 0.4 MeV, probably the same anomaly repeats itself as for energy 0.17 or ~ 0.2 MeV.

Therefore a detailed analysis of the results of all the works leads us to conclude that on the curve illustrating the relation $\sigma = f(E)$ we can observe two sharp minimum in the regions ~ 0.2 and 0.4 MeV and a maximum between them. We still do not possess a theoretical explanation of this phenomenon in the literature; however, the writer of this article got a private report by M. Benge, who attempted with the help of Beck to explain it by introduction of a third level P (virtual). Four values of cross sections, computed by him are represented in Table VI.

Considering the first conclusion, we may say that it is rather probable, but we cannot guarantee that similar discrepancies of σ will not occur during further researches in other regions.

At present we are unable to make a definite conclusion on the reality of the described anomaly. Many specialists share the point of view that this anomaly does not exist. A definite solution of this problem may be found only after further and more accurate research.

5. Angular Distribution of Neutrons During Their Scattering by Protons.

To verify the correctness of our concepts on the nature of nuclear forces and the law of their action, the simplest method is to study the interaction of neutron with proton, as two elementary particles. This study consists first in the investigation of the relation $\sigma = f(E)$, and secondly in the investigation of the angular distribution of neutrons during scattering by protons. The angular distribution is the most sensitive indicator of the details of the potential well; i.e. of the details of mutual interaction of neutron with proton. If the nuclear forces may be represented in the form of a deep and narrow potential well, then the scattering of all neutrons will be practically spherical symmetric in a central system of coordinates.

Every deviation from spherically symmetric distribution, fixed experimentally, will be an important fact, because it may be explained only by the assumption that the action of nuclear forces extends distances for above $(1 - 2)\cdot 10^{-13}$ cm.

It may be seen from the preceding how important it is, together with relation (15), to study angular distribution. It was studied by many experimenters over a long period of time after the discovery of the neutron; as seen below, however, success did not accompany the experimenters.

In one of the first works Meitner and Filipp, using a neutron source (Rn,Be), measured in a Wilson camera 100 tracks of recoil protons. They divided these tracks into 5 groups according to angular intervals and found a spherically symmetrical distribution.

The next work in this connection was performed by Auger and Monod-Herzen [79]....

Contradictory results were found by F. Kurie [80].....

Studies of a similar nature were conducted by Dunning [81, 82] .....

Wider allied measurements were performed by Harkins et alii [83] .....

All this research can be generalized into one group. Characteristic is the use of sources that give neutrons of nonuniform energies. Simultanously with the initial part of the neutron spectrum, containing neutrons averaging 0.2 to 0.4 MeV, a central part with energies of the order of 3 - 5 MeV exists; and the end of the spectrum contains a small amount of high-energy neutrons. Neglecting the last part, we see that in all researches, except that by Dunning, the angular distribution of neutrons of two ranges, overlapped each other.

The second group consists of rather accurate researches with a Wilson Cloud camera, of the angular distribution of uniform-energy neutrons (D,D). The most extensive and accurate work was performed by Dee and Gilbert [84] ....

In the second work Bonner [85] used a target of $P_2O_5 + D_2O$...

In the third work Kruge et alii [86] used the cyclotron ...

In the fourth work Lampson et alii [87] chosed the method of photographic emulsion...

In 1940 appeared a work by Barschall and Kanner [88], and in 1946 the author of this article [89] also published his work. We shall discuss the last work after a critical analysis of results of the mentioned works which stimulated it. As for the work by Barschall and Kanner, as they themselves indicated, their investigation was started not to verify the angular distribution which they consider correct, but to verify a method suggested by them for determining this distribution by a ionization camera.

Table VII gives full summary of all works according to year. At first sight it becomes evident that the most accurate measurements always lead to spherically symmetrical distribution; therefore for all neutrons of energies up to 15-20 MeV, we should consider this law of scattering as verified.

Nevertheless, upon more thorough analysis some doubts in the absolute accuracy of this conclusion arise. The fact that the strongest divergence is observed in works of the first group, in which nonuniform neutrons were used, may be explained, as done by experimenters, by the assumption of systematic errors originating in the nonuniformity; we may assume, however, that the asymmetry is real. It may exist for a distribution of neutrons of low energy of the order 0.2 -0.4 MeV and vanish for higher-energy neutrons. Such ideas arise upon analysis of the results by Monod-Herzen, Kurie and Harkins. In these works the anomalous scattering seems to be created by low-energy neutrons. It overlaps the strong background of fast neutrons having symmetrical distribution, and its part is so small that in the general distribution the deviations lie within the limits of errors of measurement.

It is natural that, for the experimental verification of this suggestion, the best method would be to weaken the effect of fast neutrons by separating the slow ones and studying their distribution.

Such a method as seen in works on measurements of σ was effected by filtering the neutrons by paraffin layers of various thickness. In this case it was applied rather successfully. In the study of angular distribution its application, as may be expected, will be still more effective, because it is necessary to separate neutrons differing in energy by several million electron-volts.

On the basis of these concepts experiments on angular distribution in the beginning of the spectrum (Re,Be) were performed.

It was found in a special investigation that this part consists of a uniform group with an energy ~0.2 MeV. The method of ring-shaped scatterers was chosen for measurements. Rh located at the center of a paraffin ball 5 cm in diameter was used as the detector. It is quite evident that for fast neutrons not only is this paraffin ball a scatterer, but also neutrons possessing energy of the order of 0.2 MeV colliding with it are considerably slowed down to thermal velocities, or nearly so, and activate the detector. For the study of scattering under a certain angle, use was always made of a separate ring-shaped scatterer of definite diameter, located between source and detector. Such a method secured more accuracy of measurements than in the shifting of the scatterer from source to detector, or vice versa, because the neutrons traverse the same path before and after scattering. During measurements with angles 25°, 45° and 68° the distance between source and detector was 20 cm, and during measurements with greater angles, it was reduced to 10 and 6 cm. The angular distribution of neutrons at scattering by carbon was measured separately, and the values found were deducted from the general effect with a paraffin scatterer. The scattering by carbon, as expected, was very small; namely, ~ 10% of the general effect. The results of these measurements are represented in Table VIII and Figure 5, together with data by Monod-Herzen and Harkins. As seen from this figure our assumption of the existence of asymmetry of scattering in the region of low energies was entirely justified. The results agree completely with the data by these investigators, but the asymmetry, blurred in their measurements by the large number of fast neutrons, appears much sharper in our measurements.

As seen from Table VIII, regular fluctuations in neutron scattering were unexpectedly observed for angles greater than 90°. This effect vanishes in the distribution of higher-energy neutrons (which is achieved by an increase of the size of the paraffin ball surrounding the detector) and appears again in distribution of lower-energy neutrons. This counter scattering in the laboratory system of coordinates does not agree with the usual concept of elastic interaction of two bodies of equal mass, and in order to verify its existence, further research is necessary.

A general conclusion derived from a critical analysis of all experiments on angular distribution seems rather apparent. In the energy range 0.2 - 0.4 MeV a sharp asymmetry of neutron scattering by protons exists. In the energy range 2 - 3 MeV the scattering does not deviate from a spherically symmetrical one in a central coordinate system. The law of action of nuclear forces is probably near the suggestion by Share and Stein. Nuclear forces near the center are strong and decrease rapidly with distance, but later on their decrease slows down and the action of weak forces probably extends distances probably 10 to 20 times greater than the width of the potential well.

6. Interaction of High-Energy Neutrons with Protons

During scattering of high-energy neutrons (of the order of 15 MeV and above, the wavelength of which is comparable with the width of the central potential well) deviations from spherical symmetry of angular distribution and from the relation $\sigma = f(E)$, expressed by formula (15), should be observed. The first σ measurements with neutrons (Li,D) having an energy around 15 MeV, performed by Roberts et alii [90], led to the value $\sigma = 0.61 \cdot 10^{-24}$ cm^2......

Amaldi et alii [91] measured the angular distribution of neutrons, using reactions (Li,D) and (B,D).....

The study of the asymmetry of the angular distribution of neutrons and the deviation of σ from the relation (15) assumes importance in connection with the meson theory of the deuteron and of nuclear forces in general, as developed by many theoreticians. As is known, in order to obtain a correct order of magnitude of binding of nucleons in the nucleus it is necessary to introduce a new particle with a mass of the order of 200 electron mass (m). This chargeless particle was named "neutretto". The theory of nuclear forces using only the neutretto for exchange forces among nucleons was developed by Bethe [92]. It was named the "neutral" theory. After the discovery of the meson in cosmic rays, theories were created which took into account the exchange among nucleons by particles of three types with masses of the order of 200 m. Two of them possess positive and negative charges, and the third one is neutral. These theories were named "symmetrical".

As shown by Rarita and Schwinger [93] the symmetrical and the neutral theories should lead to different values of R. The symmetrical theory by Meller and Rosenfeld [94] leads in the case of 14 MeV neutrons to the value R = 1.63 [95]. This value contradicts strongly that by Amaldi et alii. By comparing their results with the theoretical ones, these writers conclude that they agree rather well with data by Feretti [98], derived from the neutral theory by Bethe [92]. Such a conclusion, excluding from the interaction mechanism governing nuclear particles the known and observed charged mesons, naturally could not satisfy physicists and provoked new experimental and theoretical work.

By bombarding Li with 10 MeV deuterons, Sherr [97] obtained neutrons with an energy of 25 MeV. He found the value $\sigma = (0.39 \pm 0.03) \cdot 10^{-24}$ cm^2. The theoretical value of σ, computed from data of the symmetrical theory by Rarita and Schwinger [98] for such neutron energy, equals $0.395 \cdot 10^{-24}$ cm^2; computed from the neutral theory the value is $\sigma = 0.89 \cdot 10^{-24}$ cm^2. Therefore the found value of σ agrees better with the symmetrical theory.

Ageno et alii [98] repeated the measurements by Amaldi et alii with neutrons of three energies: E_1 = 4.1 MeV, reaction (Be,D); E_2 = 12.5 MeV, reaction (B,D); and E_3 = 13.5 MeV, reaction (Li,D). Thoroughly measuring the variation of neutron intensity by means of a complicated arrangement of three Geiger-Muller counters, set for coincidences, they found the corresponding values:

$$\sigma_1 = (1.73 \pm 0.06)\cdot 10^{-24}\ \text{cm}^2\ ; \qquad \sigma_2 = (0.69 \pm 0.11)\cdot 10^{-24}\ \text{cm}^2;\ \text{and}$$

$\sigma_3 = (0.69 \pm 0.019)\cdot 10^{-24}\ \text{cm}^2$. By analyzing the previous theoretical and experimental data they conclude that their results agree better with the data of the neutral theory.

The last theoretical research indicates that for a more complete clarification of the problem further investigations of neutron scattering are necessary with energies of the order of 100 - 200 MeV. Probably such measurements, quite realizable in recent times, will help in completely solving this interesting but confusing problem.

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Table I. Cross sections of elastic scattering of slow neutrons by atomic nuclei

Таблица I

Поперечники упругого рассеяния медленных нейтронов атомными ядрами

Элемент Element	σ·10²⁴ см²			
	Дэннинг и др. Dunning a.	Митчелл и Мерфи Mitchell Murphy	Гольдгабер и Бриггс Goldhaber	Разные исследователи Others
D	4,0		6,3	3,3
Li	46,0			
Be	5,3		1,9	6,10
B	300			
C	4,1	3,4	4,8 (4,8) *)	4,8
N	11,3		8,2	~ 3
O	3,3		4,2	
F	2,5		4,1	3,7
Na	4,2		3,6	~ 4,7
Mg	3,5	3,0	4,2	~ 8,6
Al	1,5	1,0	1,6	1,5
Si	2,5		1,7	4,2
P	14,7		10,4 (13,6)	9,1
S	1,4	0,9	1,1	1,3
Cl	39		10	
K	8,2		1,5	
Ca	11,0		9,5	
Ti	11,9		6,2	
V	10		4,0	
Cr	4,9	1,4	3,6	
Mn	14,3	2,2	2,1	
Fe	12,0	10,6	10,3 (13,6)	11,1
Co	35		~5	3,7
Ni	15,4	16,0	12,6 (19,7)	10,1
Cu	7,5	8,3	8,0 (11,9)	8,3
Zn	4,7	4,7	5,2	4,2
Ga			< 4	
Ge	75			
As	8,6		9,1	9,3
Se	19,8		19,7 (20,4)	19,0
Br	11,8		7	
Sr	9,0		9,5	
Y			14	
Zr	10,7		16	
Nb	14		5	
Mo	7,1		6,7	
Ru	12,6		5,9	
Rh	118			
Pd	10,0			9,0
Ag	56	6,3	(6,8)	9,5

*) Числа, поставленные в скобки в 4 колонке, обозначают полные σ, измеренные Гольдгабером и Бриггсом методом прохождения через рассеиватель нейтронов.

*) Numbers in parentheses in the 4th column indicate full σ measured by Goldhaber and Briggs, using method of neutrons traversing scatterer.

Продолжение табл. I

Элемент	σ·10²⁴ см²			
	Дэннинг и др.	Митчелл и Мерфи	Гольдгабер и Бриггс	Разные исследователи
Cd	3300	5,6		
Sn	4,0	4,1	4,9	3,7
Sb	6,1		6,6	5,7
Te	6,2		5,5	5,0
J	94			
Ba			8,2	2,7
La	80			
Ce	25			
Pr	25			
Nd	220			
Sm	4700			
Eu	1000			
Gd	30000			
Ta	27		~10	
W	30		7,8	9,3
Re	80			
Os	27		10,6	
Ir	285			
Pt	25		8,3 (21,5)	
Au	88			
Hg	440	4,7		
Tl	11		14,2	12,0
Pb	8,6	7,2	12,9 (19,5)	9,6
Bi	8,2	10,2	8,9 (8,8)	8,7

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Table II.

Cross sections of elastic scattering of fast neutrons by atomic nuclei relation $\sigma = f(A)$

Таблица II

Поперечники упругого рассеяния быстрых нейтронов атомными ядрами, зависимость $\sigma = f(A)$

Элемент Element	$\sigma \cdot 10^{24}$ см²								
	3–5 MeV	2,4 MeV	2,88 MeV	0,1–0,18 MeV	0,22 MeV	0,4 MeV	0,1 MeV	0,3 MeV	90 MeV
D			2,17						0,117
Li	1,6	2,10		2,0	2,3	2,5	0,9	1,0	0,814
Be				2,6	2,8	1,7	2,8	2,8	0,431
B		1,67	1,98	2,1	4,2	2,0	4,7	6,5	
C	1,7	1,47	1,07	2,1	1,7	3,3	3,6	4,0	0,550
N	1,8	1,02	1,38	2,1				1,6	0,656
O		1,25	1,25	2,1	3,0	2,2		1,8	0,785
F		2,20		2,7	6,4	3,7		6,4	
Na		2,24	2,47	3,4	3,2	3,3		3,5	
Mg		1,86	2,25	3,3	3,5	3,7	6,5	8,5	1,03
Al	2,4	3,17	2,34	3,7	4,0	3,5	4,4	3,7	1,12
Si		2,90	2,77	3,2	7,2	4,4	3,8	2,3	
P		2,18		4,4	2,4	1,8			
S	2,7	2,40	4,12	2,6	2,3	2,5	1,1	1,0	
Cl		2,80	3,42	2,7	3,8	4,6		3,5	1,38
K		4,18	3,13	3,8	7,4	4,3			
Ca		3,83		4,9	4,1	5,2			
Ti		2,08		4,4					
Cr		3,27		3,6	5,7	4,2	2,5	3,3	
Mn		4,18	3,82	4,9	7,2	1,6	5,2	5,6	
Fe	3,0	4,10	3,15	3,7	3,6	3,1	3,4	2,8	
Co		2,60		5,2	6,8	4,5		6,5	
Ni		2,62		6,6	5,9	3,0	5,7	6,9	
Cu	3,2	2,61	2,82	3,6	4,8	2,5	3,4	4,8	2,22
Zn	3,3	2,65	3,28	3,6	4,0	2,8	5,1	5,7	2,21
As				4,7	6,3	5,8	8,2	7,1	
Se			4,06	4,5	5,8	5,0	6,9	8,3	
Br				6,6	7,8	7,3			
Sr				6,4					
Mo			4,06		9,6	7,9	9,8	9,8	
Ag				5,3	8,1	6,6		5,6	
Cd				4,9	10,0	7,1	7,0	5,5	
Sn	4,3		4,[illegible]	5,2	14,9	4,9		4,1	
Sb				5,4	5,8	4,3	5,4	1,7	
Te					5,7	5,3		5,1	
J	4,6			6,6	4,7	7,8			
Ba					7,1	5,1		8,1	
W	5,3				9,4	6,3	7,2	10,4	
Hg	5,8		6,34	6,8	7,8	6,4		9,7	
Tl					7,0	7,2	11,3	10,0	
Pb	5,7		6,74	7,2	5,7	4,5	8,8	9,0	4,53
Bi				7,7	6,4	5,4		8,1	
Th				17,3					
U				17,0					5,04

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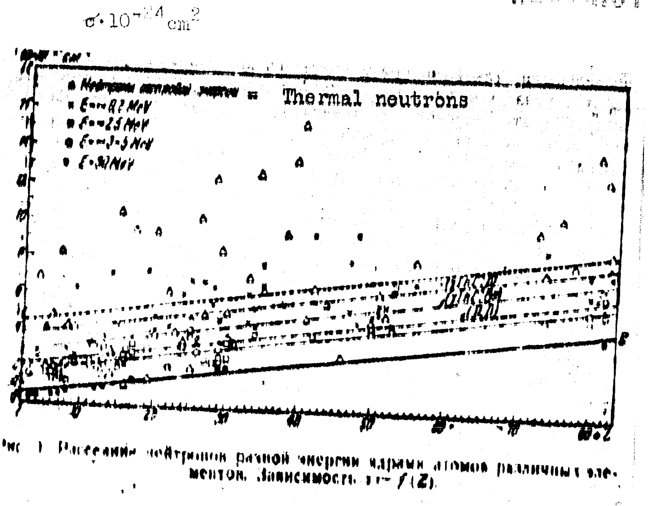

Рис. 1. Рассеяние нейтронов разной энергии ядрами атомов различных элементов. Зависимость σ = f(Z).

Fig.1. Scattering of neutrons of various energies by atomic nuclei of various elements. Relation σ = f(Z)

Table III

Таблица III

№ линии No. of line	1	2	3	4	5	6
E MeV	1,69	1,75	1,82	2,09	2,20	2,42
Относительная интенсивность	0,40	2,42	0,41	0,47	1,00	0,53

Relative intensity

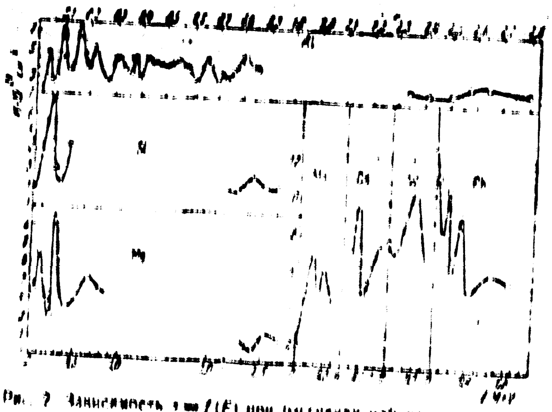

Рис. 2. Зависимость σ = f(E) при рассеянии нейтронов различными элементами.

Fig.2. Relation σ = f(E) in neutron scattering by various elements.

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Table IV.

Relation σ = f(E) according to data by various writers.
(σ in unities 10^{-24} cm^2)

Таблица IV

Зависимость σ = f(E) по данным разных авторов
(σ в единицах 10^{-24} см^2)

Энергия в MeV / Energy Элемент / Element	2,14	2,[illegible]	2,[illegible]	2,[illegible]	2,77		Примечания, цитированная литература / Remarks Quoted Bibliography
D	2,3[illegible]	[illegible]	2,3[illegible]	[illegible]	2,11		
C	1,5[illegible]	1,4[illegible]	1,4[illegible]	[illegible]	1,[illegible]		
O	1,22	[illegible]	1,10	[illegible]	1,25		
Si	2,22	2,24	2,27	2,30	2,43		
Sn	4,10	4,09	3,90	3,69	3,70		
Pb	[illegible]	[illegible]	5,30	5,1[illegible]	5,43		
Bi	5,28	5,56	5,01	5,30	6,00		Δσ ~ 5%

Энергия в MeV Элемент	2,34	2,41	2,49	2,57	2,63	2,80	
C	1,41	1,39	1,39	1,33	1,45	1,57	
N	1,33	1,22	1,27	1,39	1,28	1,25	
Na	2,74	2,69	2,69	2,00	2,50	2,38	
Mg	2,19	1,94	1,76	2,14	2,54	2,34	
Al	2,19	2,19	2,18	2,04	2,04	2,48	Δσ ~ 3%

Энергия в MeV Элемент	0,36	0,72	0,97	2,0	4,0	5,5	
D	3,53	3,46	2,8	2,60	1,70	1,53	
O	4,00	2,01	5,0	[illegible]	2,90	0,90	Δσ ~ 3%

Энергия в MeV Элемент	10,6	12,9	16,5	18,0	19,6	21,1	
C	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1,77	Δσ 4-8%

Продолжение табл. IV

Энергия в MeV Элемент	[illegible]	[illegible]	[illegible]	[illegible]	0,[illegible]	0,41	Примечания, цитированная литература
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Δσ ~ 10%

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Table V. Energy of Photoneutrons and γ- rays.

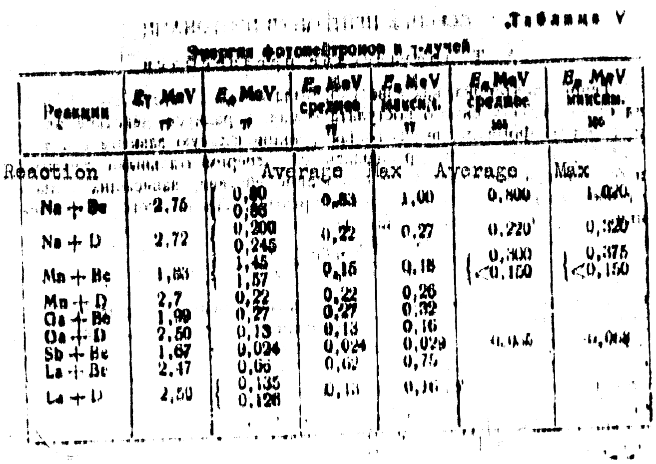

Таблица V

Энергия фотонейтронов и γ-лучей

Реакции	E_γ MeV [97]	E_0 MeV [97]	E_n MeV среднее [97]	E_n MeV максим. [97]	E_n MeV среднее [100]	E_n MeV максим. [100]
Reaction			Average	Max	Average	Max
Na + Be	2,76	0,80 0,86	0,83	1,00	0,800	1,000
Na + D	2,72	0,200 0,245	0,22	0,27	0,220	0,320
Mn + Be	1,83	1,45 1,57	0,15	0,18	0,300 < 0,150	0,375 < 0,150
Mn + D	2,7	0,22	0,22	0,26		
Ga + Be	1,99	0,27	0,27	0,32		
Ga + D	2,50	0,13	0,13	0,16		
Sb + Be	1,67	0,024	0,024	0,029	[illegible]	[illegible]
La + Be	2,47	0,66	0,62	0,75		
La + D	2,50	0,135 0,126	0,13	0,16		

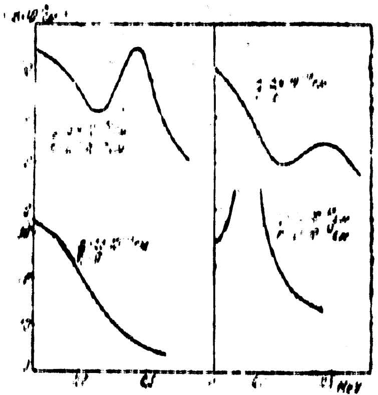

Рис. 3. Рассеяние нейтронов протонами. Зависимость σ = f (E) при потенциале Морзе

Fig.3. Scattering of neutrons by protons. Relation $\sigma = f(E)$ at Morse potential.

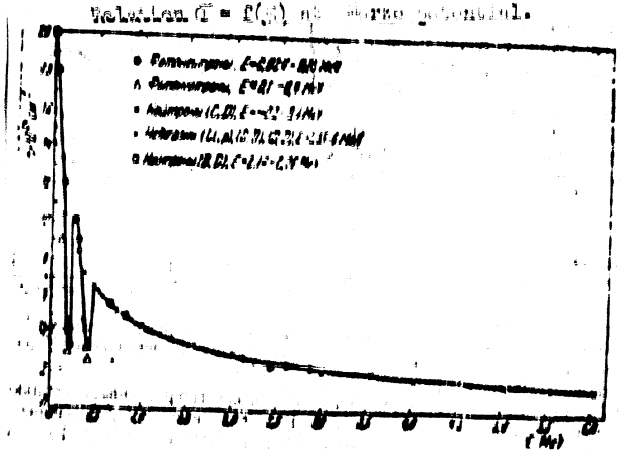

Рис. 4. Зависимость σ = f(E) при рассеянии нейтронов протонами. Теоретическая кривая, за исключением области 4,1 — 0,4 MeV, построена по данным [illegible] Бома и Ричмана [100].

Fig. 4. [illegible] $\sigma = f(E)$ [illegible]

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Fig. 4 [illegible] scattering [illegible]

Table VI. Cross sections of neutron scattering by protons.

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Таблица VI

Поперечники рассеяния нейтронов протонами

Remarks, quotations of bibliography.

Энергия нейтронов в MeV ~~Neutron energy in MeV~~	$\sigma \cdot 10^{24}$ см^2	Примечания, ссылки на литературу
0,024–0,029	18,2	
	17,5	
0,13–0,16	11,8	
	12,0	
(0,15–0,18)*)	11,4	
	11,1	
	10,9	
0,22–0,27	10,0	
	9,2	
0,27–0,32	8,7	
	9,1	
0,62–0,75	5,6	
	6,1	
0,83–1,00	5,1	
	4,9	Δσ ~ 10% 11
0,35	7,16	
0,46	6,52	
0,72	5,22	
0,97	4,45	
1,00	4,16	
1,6	3,46	
2,0	2,96	
2,6	2,60	
3,0	[illegible]	
3,5	2,09	
4,0	1,85	
4,5	1,83	
5,0	1,63	
5,5	1,48	
6,0	1,32	Δσ ~ [illegible]% [illegible]
0,1	9,0	(9,05)**)
0,2	4,0	(4,10)
0,3	8,5	(6,78) Δσ ~ 10%
0,4	3,2	(3,74) 75
0,1–0,18	3,3	Δσ ~ 5% 69
0,2	3,0	70
0,15	8,0	Δσ ~ 30% 74
~0,4	2,63	Δσ ~ 10% 70
0,35	4,7	71
0,2	5,0	86

*) Энергия сомнительна, ввиду присутствия в источнике второй линии (см. табл. V).

**) Теоретические значения, полученные при предположении существования у дейтерона виртуального P-уровня.

*) Energy doubtful, because of presence of a second line in the source.

**) Theoretical values, obtained with the assumption, that a P-level exists in the deuteron.

Продолжение табл. VI

Энергия нейтронов в MeV	$\sigma \cdot 10^{24}$ см^2	Примечания, ссылки на литературу
2,14	2,78	
2,27	2,70	
2,43	2,61	Δσ ~ 5%
2,60	2,51	
2,76	2,40	80
2,64	2,32	88
2,4	2,40	81
4–5	1,6	[illegible]
25	0,39	92
6,5	1,40	
9,3	0,92	
10,6	0,78	
12,8	0,63	
14,8	0,61	
16,5	0,60	
18,1	0,55	
19,[illegible]	0,52	Δσ ~ 10%
21,1	0,41	104
40	0,193	101
4,1	1,53	
12,5	0,77	88
13,5	0,70	
15	0,61	86
14	0,70	91
15	0,69	
1 eV	20 ± 1,0	104

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Table VII.
Angular distribution of neutrons in scattering by protons.

Таблица VII
Угловое распределение нейтронов при рассеянии их протонами

Investigator.	Исследователь Investigator	Метод исследования Method of investigation	Энергия нейтронов в MeV	Результаты исследования. Данные приведены в центральной системе координат	Results of investigations. Data are according to central coordinate system/	Год опубликования работы Year of publication
F.N.D.Kurie	Ф. Н. Д. Кюри	Камера Вильсона	2,5—14,0	Больше нейтронов идёт назад	More neutrons backwar	1933
Auger and Monod-Herzen	Оже и Моно-Герцен	То же Wilson camera	0,5—14,0	Сферически симметричное	Spherically symmetric	1934
Meitner and Filipp	Мейтнер и Филипп	Ring scatte	<0,5 0,7—14,0	Больше вперёд Сферически симметричное	More forwards Spherically symmetric	1934
Dunning	Даннинг	Кольцевой рассеиватель	0,5—14,0	Сферически симметричное	Spherically symmetric	1934
Harkins et al.	Гаркинс и др	Камера Вильсона	0,1—15,0	Больше назад	More backwards	1936
Lee and Gilbert	Ди и Джильберт	То же	2,4	Сферически симметричное	Spherically symmetric	1937
Bonner	Боннер	camera	2,6	То же	Same	1937
Kruger et al.	Крюгер и др	Photogr emulsion		"	Same	1937
Lampson et al.	Лампсон и др.	Фотографическая эмульсия	2,55	Больше назад	More backwards	1937
Barshall and Kanner	Баршалл и Каннер	Ионизационная камера	2,5	Сферически симметричное	Spherically symmetric	1940
Amaldi et al.	Амальди и др.	Камера Вильсона	14,0	Больше вперёд	More forwards	1941
Golobordko	Голобородько	Кольцевой рассеиватель Ring scatterer	0,2	Распределение асимметричное, максимумы под углами 45° и 135° и минимумы под углами 90° и 180°	Asymmetric distribution Max under angles 45° and 135° and minima under 90° and 180°	1947

Таблица VIII
Угловое распределение нейтронов энергией ~0,2 MeV в лабораторной системе координат

Angle of scattering Угол рассеяния φ	Intensity ratio with scatterer / without scatterer Отношение интенсивностей $\frac{I}{I_1} = \frac{\text{с рассеивателем}}{\text{без рассеивателя}}$
23° ± 12°	1,55 ± 0,06
45° ± 12°	1,05 ± 0,05
68° ± 12°	1,46 ± 0,06
90° ± 13°	1,11 ± 0,05
113° ± 13°	1,46 ± 0,05
135° ± 13°	1,02 ± 0,04
155° ± 13°	1,45 ± 0,04

Table VIII. Angular neutron distribution of energy ~0.2 MeV in the laboratory coordinate system.

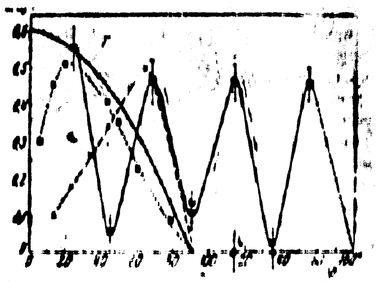

Рис 5. Угловое распределение нейтронов при рассеянии на протонах. Точками ● обозначается распределение нейтронов с энергией ~0,2 MeV; ▲ — с энергией > 0,2 MeV; ■ — обозначают данные Моно-Герцена; × — данные Кюри и Гаркинса. Линия 1 соответствует сферически симметричному распределению в центральной системе координат.

Fig.5. Angular neutron distribution in scattering by protons. Dots designate neutron distribution of energy ~0.2 MeV; ▲ = energies > 0.2 MeV. Squares = data by Monod-Herzen; × = data by Kurie and Harkins. The line 1 corresponds to the spherically symmetrical distribution in a central coordinate system

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