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ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

ЛАБОРАТОРИЯ ТЕОРЕТИЧЕСКОЙ ФИЗИКИ

M.A.Markov

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THE NEUTRINO

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Дубна 1963

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M.A.Markov

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THE NEUTRINO

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12. Natural Neutrino Fluxes

14. Prospects of Neutrino Physics

[redacted]

Preface

This survey is essentially confined to neutrino flux processes. Some problems of weak interactions involving neutrino physics are also dealt with.

There has been growing evidence of the importance of neutrino processes in nature. New and varied neutrino effects are being discovered.

There are good grounds to believe that the solution of many astrophysical problems depends on the advance of neutrino physics. It is not impossible that neutrino processes are of essential importance in cosmology and cosmogony.

Neutrino astronomy is not perhaps a matter of a far-away future.

Experimental results in high energy neutrino physics may prove decisive in constructing the future theory of elementary particles. This will require adequate data on the behaviour of neutrino processes at very high energies.

Some of these data can in principle be obtained on accelerators and in cosmic ray experiments. Finally, the accelerators of the decade to come--colliding beams and competing accelerators of enormous intensities affording very high experimental accuracies--will probably culminate the programmes and accomplish the targets of neutrino physics holding our imagination today.

The Author

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Introduction

The discovery of the neutrino, a particle so striking in many respects, was neither spectacular nor dramatic. As a matter of fact, it cannot even be associated with any definite date.

The neutrino was being discovered on and off for nearly a quarter of a century.

Contemporary reminiscences seem to show that the neutrino was first introduced as a hypothetical particle by W.Pauli^{1}) (1931).

The hypothesis originated from the consideration of conservation laws in the analysis of β -decay effects of different complex nuclei^{2}).

It was with caution and hesitation that the neutrino was admitted to the holy precincts of the elementary particles: there were years of doubt as to whether it was a real particle or a quantitatively conceptualized disappearance of energy and angular momentum in different reactions.

Finally, Reines and Cowan^{3}) showed that the neutrino can be absorbed and not only emitted. Thus, once a "semi-particle" (capable of only being "emitted") the neutrino became a full-fledged member of the community of "elementary" particles.

In other words, just like all "elementary" particles the neutrino is described by the four-dimensional vector of energy momentum and angular momenta. Possessing semi-integral spin momentum, the neutrino belongs to the class of fermions along with the electron, muon and baryons.

The consensus of opinion tends to regard the rest mass of the neutrino as vanishing.[4)]

At any rate the experimental value of the neutrino eigen mass is given by the quantity $m_\nu < 1/2500 \times m_e$ where m_e is the electron mass.

The theory of β -decay and the theory of weak interactions was in general pioneered by Fermi[5)] (1934). The theory of weak interactions was constructed as a theory of interactions between electron-neutrino and proton-neutron fields on the pattern of electrodynamics.

The four-vector, a mathematical analogue of the vector field of electrodynamics, was constructed out of electron-neutrino functions while a new constant (G) indicated the smallness of the interaction of the new field with the nucleons.

The theory underwent a long process of immanent development. Initially, a more thorough study of the inherent possibilities of the theory led to deviations from the electromagnetic pattern.

There were attempts, for example, to bring into play higher field derivatives, on the one hand, and electron-neutrino fields in the non-vector form, on the other. It appeared that not only the vector field (V), but also the scalar (S), pseudoscalar (P), pseudovector (A) or tensor (T) fields could be constructed out of electron-neutrino spinor functions.

The deamon of physics rebelled against the imaginary narrowness of the electrodynamic prototype and it was hoped that nature would accept the new alternatives. Nature, however, proved to be less imaginative or perhaps harder to please.

The higher derivatives in weak interactions were soon abandoned (1937) on the insistence of experiments.

As for the other non-vector variants of the theory, it seemed for a while that the nature had been coaxed by theorists into accepting the tensor and scalar variants of interaction.

Yet quite recently (1957) the theory of β -decay returned to its electrodynamic prototype^{6,7}).

The comeback was so sweeping that it gave rise to the suspicion that vector interactions were at work in nature in general and hence to the trend to "vectorize" physics^{8}).

For all its affinity to electrodynamics the theory of weak interactions has so far preserved that peculiarity which it received at Fermi's hands: the postulating of the interaction of four fermions localized at any one space-time point. Thus there arises an essentially new class of interactions quite unlike anything known in electrodynamics or meson field theory (the problems of renormalization, the character of divergences, the character of the cross section energy dependences, etc.).

Some physicists, dissatisfied with this peculiarity, are working for the unification of all types of interactions (the idea of an intermediate vector meson). Others expect that it is precisely this peculiarity that will help them to surmount the notorious fundamental difficulties of the current field theory by imparting a fundamental meaning to the four-fermion interaction.

It is to be hoped that the dilemma will be solved within a few years and the theoreticians will thus have less ambiguous experimental indications of new possibilities for constructing the elementary particle theory. Neutrino experiments loom prominently in the expected solution of the problem.

1. Peculiarity of Four-Fermion Interactions

In accordance with the well-known neutron β -decay processes, the interaction Lagrangian describing the decay, can be written as the products of nucleon and lepton currents^{6,7})

$$\mathcal{L} = \frac{G}{\sqrt{2}} \sum_{\alpha} (j_{\alpha}^{n})^{+} j_{\alpha}^{e} \tag{1}$$

[redacted]

where

$$j_\alpha^n = \bar{\Psi}_n \gamma_\alpha (1+\gamma_5) \Psi_p \qquad (2)$$

$$j_\alpha^e = \bar{\Psi}_e \gamma_\alpha (1+\gamma_5) \Psi_\nu \qquad (3)$$

$\bar{\Psi}$ is the operator of the production of a particle or the annihilation of an antiparticle, Ψ is that of the annihilation of a particle or the production of the antiparticle,

$j_\alpha(V) = \bar{\Psi}\gamma_\alpha\Psi$ is a vector,

$j_\alpha(A) = \bar{\Psi}\gamma_\alpha\gamma_5\Psi$ is a pseudovector,

$$G = (1.40 \pm 0.01)\, 10^{-49} \text{ erg cm}^3, \qquad (4)$$

and G is a specific constant governing the weak interactions.

If we introduce the muon current

$$j_\alpha^\mu = \bar{\Psi}_\mu \gamma_\alpha (1+\gamma_5) \Psi_\nu \qquad (5)$$

the Lagrangian in the same form (1) with the same interaction constant

$$\mathcal{L} = \frac{G}{\sqrt{2}} \sum_\alpha (j_\alpha^\mu)^+ j_\alpha^e \qquad (6)$$

[redacted]

describes well the muon decay[+] ($\mu \to e + \nu + \bar{\nu}$).

Hence the natural impulse to write the Lagrangian

$$\mathcal{L} = \frac{G}{\sqrt{2}} (j_\alpha^n)^+ j_\alpha^\mu \tag{7}$$

describing the weak muon-nucleon interaction and in general universalize the weak interaction of four fermions

$$\mathcal{L} = \frac{G}{\sqrt{2}} (j_\alpha^x)^+ j_\alpha^y \tag{8}$$

where j_α^x and j_α^y are the currents of the form (2),(3),(5),etc. composed of Fermion functions.

However,the attempt to universalize the interaction in the general form (8) proves to be too ambitious.In this form it appears to include many possibilities which are not effected in reality (decays of the type $\mu^- \to e^- + e^+ + e^-$, decays with a change of the strange number more than by unity, etc.).

Hence the need,in a sense unpleasant,for devising different forms of forbiddenness which are not justified intrinsically and quite often are sheer acts of violence with

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[+] The life time of the muon is here meant: τ_{theor} = (2.26 ± 0.04) 10^{-6} sec, τ_{exp} =(2.22 ± 0.02) 10^{-6} sec.

respect to formalism. The situation is made none the better by scientific opinion having in recent years recognized and accepted the universal application of some rules which can by no means be claimed to have originated as a result of exhaustive experimental research. Sometimes these rules sound rather like invocations[+].

In other words, a broad universal theory of weak interactions is only in the making now.

Returning to the analysis of the peculiarities of four-fermion interactions, the dimension of the weak interaction constant is worth noticing, viz.,

$$\sqrt{\frac{G}{\hbar c}} = l_0 \quad ; = 7.10^{-17}\ \text{cm} \tag{9}$$

The difficulties of the current theory of the elementary particles are often associated with the absence in the theory of the fundamental length which would essentially

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[+] The rule $|\Delta S| = 1$: in the decay of particles the strangeness cannot change by more than unity.

The rule $\Delta Q = \Delta S$: this rule regulates the variation of the electrical charge and strange number.

The rule $\Delta T = 1/2$: this rule regulates the variation of isobaric spin in weak decays.

modify interactions at small distances.

Inside the current theory (electrodynamics, meson field theory) there are no intrinsic limitations of the applicability of the space-time description: the theory is of meaning for any parameters of the collision of elementary particles.

In this respect four-fermion interactions exemplify a theory incorporating a new world constant of the dimension of length: the fundamental length ℓ_0 regulating the interaction.

The formalism of four-fermion interactions itself contains a restriction of its applicability. Namely, for the collision parameters $\ell \leq \ell_0$ the theory in its current form proves inacceptable and has to be essentially modified.

Weak four-fermion interactions are known to lead to the cross sections for effects with quadratic energy dependence in the centre-of-mass system of the colliding particles

$$\sigma \approx E_i^2 \tag{10}$$

Viewed in terms of the current theory, the cross section (10) is correct up to 10^{11} eV in the c.m.s. [+]. It is

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[+] The unitarity condition is fulfilled only if $E \leq \left(\frac{4\pi}{G^2}\right)^{1/4}$, i.e., if $G^2E^2 \leq \frac{4\pi}{E^2}$.

The conventional perturbation theory is known to be unitary only accurately to higher approximations. In electrodynamics this circumstance leads to no difficulties since the cross sections themselves as a rule decrease or practically do not increase with energy. In the four-fermion interaction the cross sections rapidly increase with energy and therefore the conventional perturbation theory, non-unitarian in each given order does not apply.

Consequently, at higher energies it is necessary to use the $\mathcal{S}$-matrix (for instance) in the Cayley form

$$\mathcal{S} = \frac{1-\frac{i}{2}K}{1+\frac{i}{2}K}$$

or

$$\mathcal{S} = 1 - i\bar{R}$$

where $\bar{R} = \bar{K} - \frac{1}{2} i \bar{K} R$ and $\bar{K} = \sum^{\infty} \bar{K}_n$

The form of $\bar{K}_n$ is given by Schwinger (Phys.Rev. 74(1948)439). In this form, for each $\bar{K}_n$ the $\mathcal{S}$-matrix is unitary.

The covariant radiation damping theory was then elaborated by J.Pirenne (Phys.Rev. 86 (1952) 395).

Calculated by means of the unitary $\mathcal{S}$-matrix, the cross sections of the four-fermion interactions prove to be decreasing with energy at higher-than-critical energies ($G k^2 > 1$). The problem reduces to the following: are there other circumstances which would decrease the cross sections of the four-fermion interactions at lower energies (when $G\kappa^2 < 1$) when the radiation damping effect is still inessential, and what is the nature of these factors if they do not arise naturally in the framework of only the theory of weak interactions?

implied that perturbation theory via which the cross section (10) is obtained does not hold for $E_i > 10^{11}$ eV since the cross sections given by the higher approximations of the theory begin to compare with, and for high energies be larger than, the cross sections described by the lower approximations of perturbation theory. The critical energy value in question lies somewhere near the value $E_c = 3.10^{11}$ eV. This circumstance is connected with the fact that the formalism of the four-fermion interaction theory contains the fundamental length dimension constant, and the dimensionless expansion parameter in the series obtained by perturbation theory is, roughly speaking, the ratio of the impact parameter to the given fundamental length $\left(\frac{l_0}{\rho}\right)$.

The increase of effectiveness of weak interactions with the energy of colliding particles has been experimentally confirmed in various decay effects up to the energies of the order of tens of millions eV.

The study of the effects of direct interactions of high energy neutrinos with nucleons confirms the further increase of the corresponding cross sections with the neutrino energy. The latest experimental data61) have been brought to energies ~ 1 GeV.

There are many important considerations which impel us to seek an answer to the question of how weak interactions behave at still higher energies of the particles.

At very high energies the intensity of weak interactions could in principle compare with that of strong interactions, which would result in a quite peculiar situation in this field.

At extremely high (from the viewpoint of modern concepts) energies weak interactions could become comparable with electromagnetic, and, for example, the conversion of a photon and electron into a muon and two neutrinos could compete with the Compton effect.[9)]

By the estimates of an extremely relativistic case the cross section of the effect $\gamma + e \rightarrow \mu + \nu + \tilde{\nu}$ is of the form[10)]

$$\sigma_\mu = \frac{e^2 G^2}{4\pi} E_\nu^2 \left(\ln^2 \frac{E_\nu}{m_\mu} - 0{,}7 \right), \qquad (12)$$

where E_ν is the photon energy in the c.m.s.

It is clear from eq. (12) that the cross section increases somewhat more rapidly than E_ν^2.

On the other hand, the Compton effect cross section decreases approximately as $1/E^2$.

$$\sigma_\gamma \sim \pi r_0^2 \frac{m_e^2}{E^2} \ ; \quad r_0 = \frac{e^2}{m_e c^2} \qquad (13)$$

For energies $E \sim 250$ GeV we have in the c.m.s.

$$\sigma_\mu > \sigma_\gamma$$

Way back at the dawn of physics of weak interactions W.Heisenberg drew attention in several papers[11]) to the special role of the length parameter (ℓ_0) in the four-fermion interaction and to the possible peculiarity of physics of weak interactions at very high energies. In particular he pointed to the possibility of a peculiar situation at very high energies in the multiple particle production effects.

Four-fermion interactions are known to lead to interparticle forces for which a strong dependence on the distance is characteristic.

Thus the β -field (electron-neutrino field) gives the potential between nucleons at rest (eg.,a proton and neutron) in the form[12])

$$V \sim \frac{\ell}{r^5} \qquad (14)$$

At distances $\sim 10^{-13}$cm these forces are very weak because of the smallness of the weak interaction constant in the coefficient of eq.(14),but at shorter distances close to the weak interaction range ($\sim 0.7.10^{-16}$ cm) these forces could be enormous on the scale of the known forces.

There have been proposals to regard bosons[13]),for example,as compound site particles,pions as systems of a nucleon and antinucleon and K -mesons as systems of nucleons,antihyperons and antinucleons[14-16]).

The formation of systems with such enormous mass defects requires very strong forces acting at small inter-particle distances.Four-fermion interactions meet these requirements.It is precisely four-fermion weak interactions have been used in the concrete attempts to construct the models of compound site particles[15,17-19]).

The success or failure of such attempts again depends on our knowledge of the behaviour of weak interactions at small distances,at distances close to the fundamental length of weak interactions.In the concrete calculations of compound particles it was assumed that weak four-fermion interactions cut off just at the distances $\sim 0.7.10^{-16}$ cm.Under this assumption it is possible to obtain,in what is known as chain approximation summing a class of Feynman graphs,a number of results showing that such suggestions are not unreasonable and deserve a further more rigorous analysis.

Not only bosons ,pions and K -mesons could in principle prove compound site particles,but such fermions like muons and electrons could also represent systems made up of an odd number of baryons and antibaryons[20,21]) bound by four-fermion interactions increasing so powerfully at small distances.

It is well known,for example,that the nuclear forces give the largest mass defect in the system of four nucleons (α-particle).

It is not impossible that such systems,more condensed in this sense are muons,electrons and even photons and neutrinos[20,21]).

Tentative estimates show that,obtained with the aid of weak interactions,the pions as systems of nucleons and antinucleons interact,in turn,with nucleons whose effective constant is of the order of unity.In other words,strong interactions (nuclear fields) can,from this point of view,be interpreted as the result of "weak interactions".

This curious outcome deserves in itself more thorough studies by more elaborate methods.However,this unquestionably attractive possibility can be realized only if the above energy dependence in the weak interaction cross sections persists nearly up to the critical value $\sim 3.10^{11}$ eV in the c.m.s.

In other words,the development and substantiation of this set of interesting problems also require data on the behaviour of four-fermion interactions in the region of very high energies.

One can well extend the list of fundamental problems the solution of which depends on the answer to this question: how far does the growth of weak interactions with energy go?

The electromagnetic part of the proper electron energy,for example,is known to diverge logarithmically.It is only for length far smaller than the electron gravitation radius ($r_{grav} \sim 10^{-58}$ cm) that the electromagnetic proper mass of the electron becomes equal to its experimental value.

On the other hand,weak four-fermion interactions, e.g.,interactions involved in the transition of an electron into a muon and back $e \to \mu + \nu + \bar{\nu} \to e$, yield the experimental value of the electron mass already at distances close to ℓ_0.

Thus, four-fermion interactions involving, in particular, neutrinos could be fundamental in the theory of the elementary particles themselves.

Finally, the entire range of these problems could be formulated in more general terms.

The main fundamental difficulty of modern field theory consists in that for several major quantities such as the proper particle mass or particle charges the theory leads to expressions given by divergent integrals in the region of high energies (or small lengths).

One gets the impression that the appearance in the theory of any fundamental length at which the interactions would cut off might lead to the bona fide theory of elementary particles. One of the candidatures to the role of this universal length is the length of weak interactions.

The competing length has so far been assumed to be the length connected with the proper energy of the nucleon:

$$\ell_N = \frac{\hbar}{M_N c} \cong 2.10^{-14} \text{ cm.} \qquad (15)$$

At first glance there seems to exist a decisive argument in favour of the nucleon length. The fact is that for lengths smaller than ℓ_N the above integrals to which strong interactions lead would give unreasonably large values for the masses of baryons and their specific charges.

It should be borne in mind, however, that the last argument is meaningful only when the strong field quanta (π - and K -mesons) are treated as elementary, point ones. If, however, the matter is viewed in terms of the complex structure of these particles, the sizes of the systems representing π - and K -mesons could figure as lengths natural for the given class of interactions and cutting off the corresponding divergent integrals where necessary[+].

The above considerations also intensify the interest in high energy neutrino physics characteristic of physics today in general.

Unfortunately, the energies of the order 10^{11} eV (in the c.m.s.) will not be accessible at least in the next few years. Such energies could be obtained with colliding electron-

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[+] It should be emphasised that a universal length close in its value to the nucleon length would cut off all the divergent integrals of weak and electromagnetic interactions at too large distances. What is meant here is that the corresponding contributions to, say, the proper energy of particles would prove insignificant as compared with the experimental masses: this would mean that the electron and muon masses would have no field origin, for example.

electron and electron-positron beams with particle energies $\sim 10^{11}$ eV in each beam.

This possibility is unlikely to become a reality in the near future. Therefore it is worthwhile for the time being to try to get answers to these questions in a less direct way.

One of such indirect ways is connected with the consideration of the higher effects of the perturbation theory for weak interactions. In the calculation of these effects in intermediate state the modern mathematical formalism allows the possibility of any large momenta close to the critical ($K_c \approx \hbar / \ell_0$).

The magnitudes of many of these effects essentially depend on the maximum momenta allowed in the intermediate state. Thus, comparison of the theoretical and experimental values for the effects of this kind can in principle yield valuable data on the allowable magnitudes of the limiting momentum.

Several effects[23-25]) have been analyzed from this point of view[22]). The analysis leads to several new fundamental problems of the theory of weak interactions which also await their experimental verification.

One of the effects of this kind is the conversion of a muon into an electron in muon-proton scattering. This process is described by a Feynman graph of the type

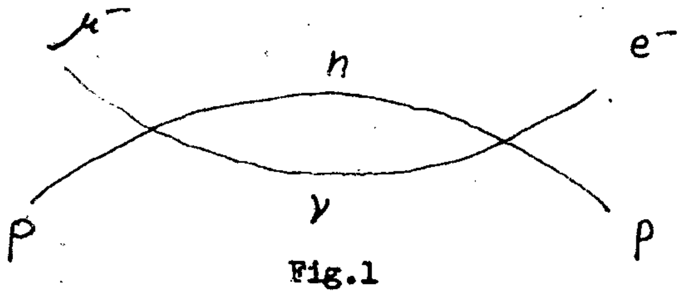

Fig.1

The ratio of the probability of this effect to that of the lower approximation ($\mu^- + p \to n + \tilde{\nu}$) is given by the expression[24])

$$\frac{\sigma_{II}(\mu^- p \to e^- p)}{\sigma_{I}(\mu^- p \to n\nu)} \approx \frac{G^2 K^4_{max}}{16\pi^4} \qquad (16)$$

At present ratio (16) is limited, according to experimental data, by the value[26])

$$\frac{\sigma_{II}}{\sigma_{I}} \leq 2.4.10^{-7}. \qquad (17)$$

In the gross estimate (16) the effects of the first and second orders begin to compare ($\sigma_{II} \sim \sigma_{I}$) approximately for momenta $\sim 1000\, M_N \approx K_c$.

The experimental ratio of these cross sections, considerably less than unity (17) indicates that the intermediate momenta in the effect $\mu^- + p \to e^- + p$ cut off at the maximum momenta which are perhaps fractions of the critical ones.

Unfortunately, the effect under discussion has not been detected experimentally and so far only its upper limit is experimentally given.

It is desirable to make ratio (17) more accurate in further experiments. It should be borne in mind, however, that ratio (16) depends on the momentum (K_{max}) in fourth power and the experiment should be improved in accuracy at least by two orders in order to decrease the quantity K_{max} only by a factor of 3.

Obviously, in the future theory there must arise certain circumstances cutting off the growth of four-fermion interactions at some maximum momenta, but the physics of the nearest future will have to determine within what limits the magnitude of this K_{max} lies and what mechanism is responsible for the weakening of the interactions when this energy region is approached.

The analysis of experimental and theoretical data on the cross sections σ_I and σ_{II} would warrant the conclusion that $K_{max} < K_{crit}$ if it were certain that the process $\mu^- + p \rightarrow p + e^-$ is not forbidden in general by some attendant circumstances.

Such circumstances may arise in a theory assuming the existence of, say, two kinds of neutrinos, the existence of an intermediate boson, and, specially for the given effect, the possible role of the formfactors of strong interactions.

All aspects of these possibilities require wide experimental research in high energy neutrino physics. Of course, weak interactions can in principle be investigated in np and μe collisions as well. But the participation of these particles in the pattern of other stronger interactions gives rise to a great variety of effects, and against the background of these it is difficult to isolate the rare events due to weak interactions.

The neutrino is a unique particle in this sense--it interacts with other particles via weak interactions only. Therefore, the high penetrating power of the neutrino makes it possible to absorb in large shielding layers the admixtures of all other kinds of radiation in the neutrino flux and eliminate in toto the undesirable background of the effects due to other kinds of interactions.

2. Dynamically Deformable Formfactors

At present there are certain grounds to believe that the neutrino-nucleon interaction[+] cuts off at the electromagnetic nucleon radius, i.e., at a considerably larger distance than the critical weak interaction length. But this is still

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[+] Or rather the process $\nu + \mathcal{N} \rightarrow \mathcal{N}' + \mu$ corresponding to the first non-vanishing approximation of perturbation theory for the weak interaction.

a hypothesis to be checked experimentally.

It can be visualized how strong interactions are at all capable of smearing out the source of weak interactions. For the vector part of the Hamiltonian of weak interactions the same picture can be drawn more convincingly.

Indeed, the electromagnetic formfactor of the nucleon (Hofstadter[30]) weakens correspondingly the interactions of electromagnetic fields with nucleons. The weak vector interaction can formally be treated as a kind of "weak electromagnetism". Assuming that the equation of continuity for the corresponding currents is fulfilled we can conclude that the Hofstadter formfactor, which gives the distribution of the electrical charge of the nucleon, is also a formfactor at least for the vector part of the weak interactions.

The situation with the A -interaction (axial-vector interaction) is much more complicated. The above analogies do not hold here. True, in this case as well there are considerations according to which the behaviour of the matrix elements of the A -interaction becomes, in the limit of very high energies, identical, in a sense, with the V -interaction. However, it is unknown at what energies the differences between the V -and A -interactions are actually (in this sense) erased.

Finally, it is possible that what we have in reality is a more complicated case. Perhaps, the vector interaction is indeed cut off by the Hofstadter formfactor, while the axial-vector interaction still continues its increase over a considerable energy interval.This possibility has its attractive aspects.But in this case the effects of the $\mu^- + p \to p + e^-$ type must be suppressed by some other mechanism.

The idea of the cut-off of weak interactions by the formfactors of baryons produced as a result of strong interactions has gained wide recognition very easily[27-29].Its popularity,however,does not correspond to its tenability. If the experimental data on the existence of the Hofstadter formfactor are used in the argument,it should be borne in mind that the experimental data refer to relatively small momentum transfers[30],viz., $q^2 \lesssim 40\,(m_\pi c)^2$,i.e.,the corresponding lengths are no smaller than the nucleon length ($l_N = \frac{\hbar}{M_N c} \approx 2.10^{-14}$ cm).It is not impossible that farther on the electrical formfactor turns to a constant,for example.

At any rate the extrapolation of the experimental Hofstadter formfactor expression for arbitrarily small lengths is still unwarranted.

It is worthwhile to emphasise the fact that the popular contention about the cutting-off role of strong interactions in elastic nucleon-neutrino processes tends to a kind of universality[+] without weighty theoretical and

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[+] I.e.,to the spread onto inelastic processes,virtual states for which $p_0^2 - \vec{p}^2 \neq m^2$.

experimental grounds. If the problem is discussed in a purely theoretical aspect, taking into account the role of strong interactions in electromagnetic processes and weak effects actually leads to the appearance in the matrix elements of some factors dependant on the momenta transferred to the nucleon 136). If these factors could always play the role of formfactors suppressing large momentum transfers, in particular the large momenta of the virtual states, this would mean the absence of the notorious difficulties with divergences in electromagnetic and weak fields. That would be an inference of fundamental importance if it were just.

Some vague grounds (or rather hopes) for such a possibility have been discussed in literature 31).

It is well known that the phenomenological ("rigid") formfactor cannot be introduced in modern theory without violating such fundamental properties as causality and unitarity.

Actually, however, this is the question of formfactors which arise automatically in relativistically invariant and unitary theory: by definition they must be free from the defects of the rigid phenomenological formfactor.

In other words, these "natural" formfactors must, in contrast to the "rigid" ones, be deformable so that the finiteness of the propagation of the signal over the formfactor region be conserved and, thus the causal description of modern theory be conserved as well.

A special term: "dynamically deformable formfactor" has been introduced[31]) to distinguish such a desirable natural formfactor from its defective rigid counterpart. But so far the dynamically deformable formfactor is merely a terminological expression of hopes.

No case of the dynamically deformable formfactor has been constructed phenomenologically. Such a "non-rigid" system of charges acts as cutting-off formfactor only for small momentum transfers, or rather when elastic scattering cases are specially selected. It has become habitual to connect the visualizable concepts of the nucleon structure with the formfactors of nucleons arising in elastic electron-nucleon scattering. In this case as well it is perhaps more correct to stress merely the peculiarity of the given kind of elastic process.

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† ~~Suppression of elastic processes in large momentum transfers must to a certain extent be a manifestation of unitarity: inelastic process channels due to, in particular, strong interactions and arising in increasing numbers with the increase of the incident particle energy must suppress the elastic scattering channel. It is not accidental that the total scattering cross section is connected with elastic forward scattering of which small momentum transfers are characteristic. For the total cross section, the "elastic formfactor" thus seems inessential.~~

Rather, the visualizable concepts of the origin of the particle sizes because of the "smearing-out" of nucleons due to strong interactions are justified in the non-relativistic region when the formfactor in the ρ-representation depends on the spatial part of the momentum vector.

The electron cloud of the hydrogen atom furnishes a certain illustration of the dynamically deformable formfactor. In the non-relativistic region for very slow electrons incident on the hydrogen atom, the electron cloud of the atom, becoming somewhat deformed, acts as an actually distributed charge.

Furthermore, the electromagnetic proper energy of the bound electron can be calculated, taking into account the possibilities for its transition to any discrete levels, and this energy will even prove finite. However, taking into account any possible deformation of the electron cloud, viz., taking into account the possibility of the transition to the continuous spectrum (inelastic process), returns the problem to the divergent integrals.

The absence of the observed effect $\mu^- + p \rightarrow p + e^-$ would seem a strong argument in favour of the existence of the nucleon formfactor capable of cutting off the momenta of virtual states as well. At this stage it is perhaps not even very essential whether the formfactor appears naturally, as a result of strong interactions, or a new, essentially different theory will be required for the introduction of such formfactors. In the light of what has been said above, this amounts to the same. Or rather we cannot in the frame of the conventional theory describe consistently such a situation even if it exists.

Thus the problem is whether we should believe that precisely <u>this</u> situation has already arisen in the experiment $\mu^- + p \rightarrow p + e^-$ or the interpretation of it cannot be regarded unambiguous.

Unfortunately, it must be admitted that the latter is the case. No unambiguous inference on the existence of the formfactor can be drawn only on the basis of the absence of the effect[+] .

The fact is that it is not only the $\mu^- + p \rightarrow p + e^-$ effect proves to be forbidden. For some reason or other a whole string of effects is not realized though each of them should have been observed if the formulation of weak interactions in the form (8) has any general meaning.

[+] If the effect $\mu^- + p \rightarrow p + e^-$ did exist, but with small probability on the basis of which the corresponding K_{max} could be calculated, this would essentially narrow the arbitrariness of the interpretation. Especially if K_{max} coincided with the corresponding quantity for the Hofstadter nucleon. Unfortunately, the accuracy of the experiment[26)] has to be increased by 5 or 6 orders to have the possibility of registering the latter effect if it exists.

Some of the forbidden reactions do not contain strongly interacting particles at all. Thus, the reactions $\mu^+ \to e^+ + \gamma$ and $\mu^+ \to e^+ + e^- + e^+$ which can by no means be suppressed by the formfactors due to strong interactions are not observed. The idea of looking for some common causes for the entire set of the known cases of forbiddenness might seem more natural.

The conversion of a muon into electrons ($\mu \to 3e$) can be forbidden in the first order of perturbation theory by assuming that there are no "neutral" currents in Lagrangian ($\mathcal{L}$). This hypothesis was put forward in refs.^{6,7}) as a certain contention generalizing the experimental data on weak interactions without any thorough theoretical grounds.

But even these violations over the theory of weak interactions prove insufficient. Effects of the type $\mu \to 3e$ may, bypassing the forbiddenness thus established, arise in the higher approximations of the perturbation theory^{22}).

In the lowest non-vanishing approximation the graph of the $\mu \to 3e$ process is of the form

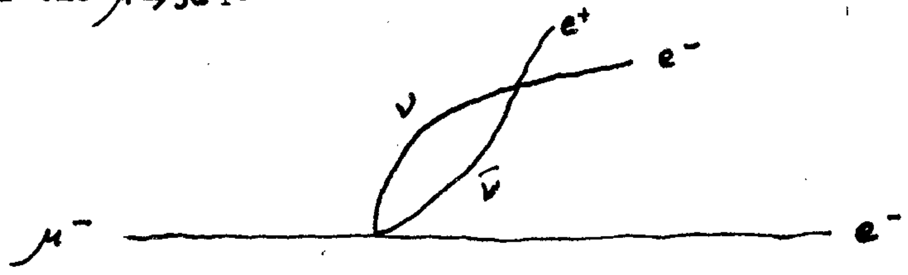

Fig.2

or

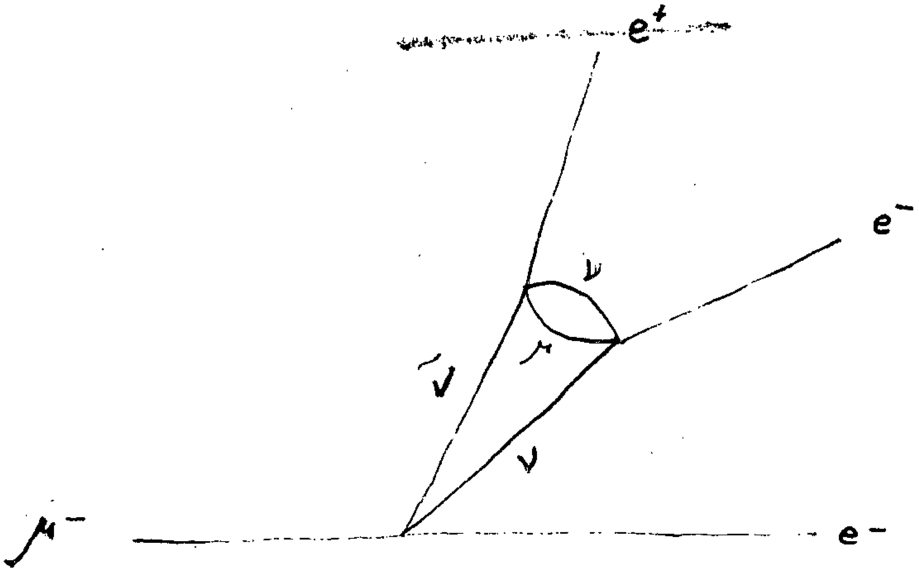

Fig.3

A rough gross estimate of the probability for the effect by the graph[24]) of fig.2 yields for the ratio of the effects of the second and first order an expression of the same type as (16)

$$\frac{W(\mu \to 3e)}{W(\mu \to e\nu\tilde{\nu})} \sim G^2 \frac{K^4_{max}}{16\pi^4}$$

A more detailed estimate of the effect[32]) leads to the relation

$$\sim \frac{3G^2 K^4_{max}}{256\pi^4} \approx \frac{10^{-10}}{85\pi^4}\left(\frac{K_{max}}{m_p}\right)^4 \qquad (18)$$

The experimental value of this relation is known accurately to within[33])

$$< \sim 5.10^{-7}. \qquad (19)$$

Comparing eq.(18) and eq.(19) we ought to take

$$K_{max} \leq 90 \text{ GeV.} \tag{20}$$

From the same point of view the conceivable possibility for the decay of a muon into an electron and γ - quantum given by the graphs of fig.4

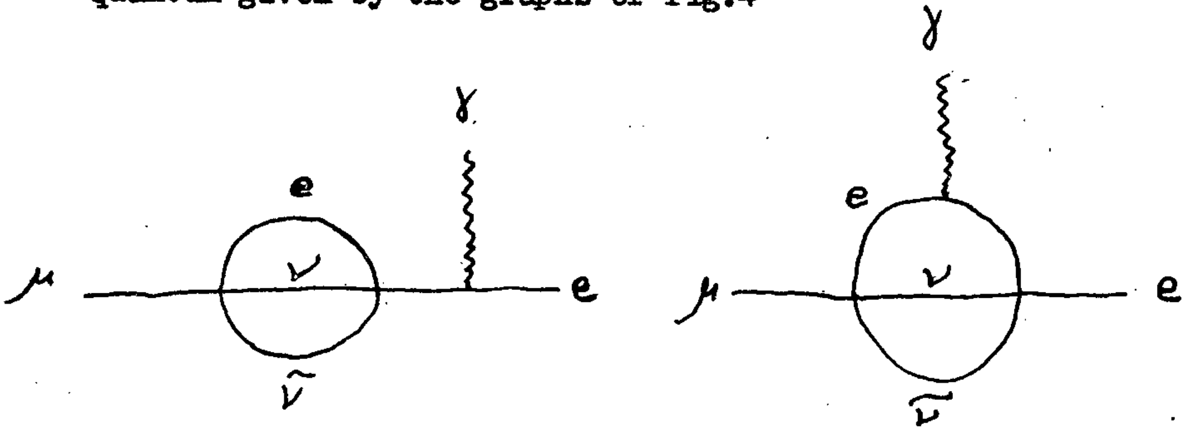

Fig.4

seems also interesting.The estimate of the contribution of these graphs to the probability for the $\mu \rightarrow e + \gamma$ decay leads to the expression[24])

$$\omega \sim \frac{\alpha}{(4\pi)^4}\left(G\mu^2\right)^2\left(\frac{G\,K_{max}^2}{4\pi^2}\right)^2\mu \tag{21}$$

where α is the fine structure constant and μ is the muon mass.A more accurate estimate of the same effect given by Ioffe[25]) (if his arguments about the a priori smallness of the contribution of some graphs are accepted) is expressed by the relation

$$R = \frac{W_{e+\gamma}}{W_{e+\nu+\bar{\nu}}} = \frac{2}{3\pi^5} e^2 G^2 K_{max}^4 \left[\ln \frac{K_{max}^2}{m_\mu^2} \right]^2 \qquad (22)$$

The latest experimental data give[34])

$$R < 4.3 \times 10^{-8} . \qquad (23)$$

This means that from eq.(22) and (23) follows the upper limit for the cut-off interaction of the momentum

$$K_{max} < 25 \text{ GeV} . \qquad (24)$$

A common feature of all the effects $\mu^- + p \to p + e^-$, $\mu \to 3e$, $\mu \to e + \gamma$, $\mu^+ + e^- \to \mu^- + e^+$ [23]) etc. under consideration is that none of them has been observed.

Of course, more accurate experimental data may well lead to the effect under study and hence to the establishment of the true value of K_{max} in weak interactions.

The list of unrealizable reactions may be extended. Thus a question arises why there are no decays of the form

$$K^{\pm} \to \mu^{\pm} + e^{\mp} + \pi^{\pm} \qquad (25)$$

$$\Lambda^0 \to n + \mu^{\mp} + e^{\pm} \qquad (26)$$

$$K^{\pm} \to \mu^+ + \mu^- + \pi^{\pm} \qquad (27)$$

etc.

Therefore the idea that a certain common rule of forbiddenness is operative in all these cases is also natural.

The search for this forbiddenness has led to the idea of two kinds of neutrinos.

3. $\nu_\mu \neq \nu_e$? (Two Types of Dirac Fields)

The $n \to p + e^- + \tilde{\nu}$ decay yields an electron and neutrino (antineutrino). The $\pi \to \mu^- + \tilde{\nu}$ decay yields a μ^- -meson and neutrino (antineutrino).

Query: is the neutrino associated with an electron identical with that associated with a muon, or are these neutral particles different by nature?

Though the latter contention does not trespass against the laws of logic and there are no a priori grounds for identifying the particles produced in different processes our mind is unwilling to accept this possibility and merely yields to a sheer necessity. If these particles prove to be different in their manifestiations, the theorists will attach different symbols to them and then will impart the corresponding meanings to these symbols.

If the particles are actually different the decays of a neutron and pion should be written, for example, like this

$$n \to p + e^- + \tilde{\nu}_e \qquad (28)$$

$$\pi^- \to \mu^- + \nu_\mu \qquad (29)$$

It can readily be seen that in the case of different muon and electron neutrinos all the effects described by graphs 1,2,3 and 4 are actually forbidden.

The possible existence of two different kinds of neutrinos has been considered theoretically by several authors.

The earliest papers date from 1957[35-37]).In a large group of papers following these investigations of Schwinger[35]) and Nishijima[36]) the difference of neutrinos follows from certain postulated conservation laws.Under this assumption the left-handed and right-handed polarized neutrinos lead, by combining with a muon and electron,to several forms of desirable forbiddenness.

In ref.[21]),in accordance with the concept of the baryon structure of the non-baryon particles[20,21]) leptons proved to possess strange numbers.The need of ascribing different strange numbers to the muon and electron as a result of the different systems of baryons representing these particles led to the need of ascribing different strange numbers to the muon and electron neutrinos.

Zeldovich[38]) introduces the doublet structure of the lepton groups ($e\nu$) and ($\mu\nu$) whence it is only one step to two kinds of neutrinos.

It should be emphasized that the forbiddenness of the reactions $\mu^-\to e^-+e^++e^-$, $\mu^-\to e^-+\gamma$, $\mu^-+p\to p+e^-$ and $\mu^++e^-\to\mu^-+e^+$ can be obtained at a cheaper price,so to speak by returning to the old idea put forward by Konopinsky and Mahmoud[39]). According to this idea, the μ^--meson is, in contrast to the e^- (electron), an antiparticle. In the family of muons (μ^+, μ^-), unlike the family of electrons (e^-, e^+), the particle is μ^+. It can readily be seen that all the reactions of the type ($\mu^+ \rightarrow e^+ + e^- + e^+$, $\mu^- + p \rightarrow p + e^-$, etc.) are forbidden by the conservation law of the number L_μ representing the difference of the number of particles and that of antiparticles.

The idea of treating μ^+ and e^- as particles and μ^- and e^+ as antiparticles is in itself interesting. We have long been used to the thought that the concept of the particle and antiparticle is not connected uniquely with the sign of the charge. The proton (p^+) has always been considered a particle and the antiproton (p^-) an antiparticle. The most salient example of the absence of the unique connection between the concept of a particle and the sign of the electrical charge is furnished by the existence of Σ^+ and Σ^- particles. The argument can be sustained by the example of the cascade hyperon whose charge is negative.

Besides, there are cases when the concept of a particle and antiparticle is not connected with any electrical charge at all (neutrinos, antineutrinos, K^0- and $\tilde{K}^0$-mesons).

The Konopinsky-Mahmoud hypothesis is also attractive because for the first time a certain attempt is made by it to find a real difference between the muon and electron which would show up in several observed effects. The muon is for the first time considered not simply as a "heavy electron", and this is perhaps the beginning of the path on which the enigmatic inequality of the masses of these particles will be explained.

In a subsequent formulation of the theory of weak interactions^{6,7}), wide-spread at this writing, the Konopinsky-Mahmoud idea was abandoned since it contradicts, in its direct form, the experimental value of the Michel parameter. The latter vanishes in this theory^{7}) instead of being close to 3/4.

However, a more elaborate analysis of the problem has shown that in the framework of the theory of two non-identical neutrinos it is possible, while preserving the Konopinsky-Mahmoud hypothesis, to avoid the contradiction with the experimental value of the Michel parameter as well.

The most elaborate exposition of the idea of two neutrinos differing in right- and left-handed polarization can be found in a paper by Kawakami^{40}).

Proceeding from the four-component ψ -function satisfying the Dirac equation, the wave functions of the "right-handed" and "left-handed" neutrino are given by the expressions

$$\psi_{\nu R} = \frac{1}{2}(1-\gamma_5)\psi_\nu ; \qquad (30)$$

$$\gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4$$

$$\psi_{\nu L} = \frac{1}{2}(1+\gamma_5)\psi_\nu ; \qquad (31)$$

with the aid of charge conjugation the fields $\psi_{\nu R}$ and $\psi_{\nu L}$ transform into the anti- R -neutrino ($\psi_{\nu R}^{c}$) and anti- L - neutrino ($\psi_{\nu L}^{c}$) fields

$$\psi_{\nu R}^{c} = C\bar{\psi}_{\nu R}^{T} = \frac{1}{2}(1+\gamma_5)\psi_{\nu}^{c} \qquad (32)$$

$$\psi_{\nu L}^{c} = C\bar{\psi}_{\nu L}^{T} = \frac{1}{2}(1-\gamma_5)\psi_{\nu}^{c}$$

where $C^{+}C = -C^{-1}C^{T} = +1$ and $\psi^{c} = C\bar{\psi}^{T}$

Thus the R -neutrino and anti- L -neutrino are right-handed polarized particles and the L -neutrino and anti- R -neutrino left-handed polarized neutrinos.

The subsequent assumptions are:

(a) lepton number conservation law in the form

$$L = n(\mu^{+}) - n(\mu^{-}) + n(e^{-}) - n(e^{+}) + \qquad (33)$$

$$+ n(\nu_R) - n(\nu_R^{c}) + n(\nu_L) - n(\nu_L^{c})$$

The quantity L conserves in all processes involving leptons; $n(\alpha)$ is a number relating to the particle of the type α .

In this formulation of the lepton number conservation law it is assumed that the particles are μ^{+}, e^{-}, ν_R, ν_L and antiparticles μ^{-}, e^{+}, ν_R^{c}, ν_L^{c} . In other words, the formulation of the law incorporates the idea of Konopinsky and Mahmoud referred to above.

Furthermore to explain the largest number of the observed cases of forbiddenness another conservation law is introduced viz.,

(b) conservation law of the neutrino charge $\mathcal{N}$:

$$N = n(\mu^+) - n(\mu^-) - [n(e^-) - n(e^+)] + \\ + n(\nu_R) - n(\nu_R^c) - [n(\nu_L) - n(\nu_L^c)] \qquad (34)$$

Because of the conservation law for the lepton number μ^+ cannot transform into e^+ or μ^- into e^- and visa versa. Thus the same forms of forbiddenness as in the Konopinsky-Mahmoud theory are preserved. The neutrino charge conservation law forbids the transitions μ^+ to e^-. μ^+ and e^+, μ^- and e^- cannot arise or vanish in pairs i.e., processes of the type

$$K^{\pm} \to \mu^{\pm} + e^{\pm} + \pi^{\mp} \qquad (35)$$

are forbidden.

The adopted conservation laws (a) and (b) allow the processes

$$\pi^+ \to \mu^+ + \nu_R^c \; ; \; \pi^+ \to e^+ + \nu_L \\ \pi^- \to \mu^- + \nu_R \; ; \; \pi^- \to e^- + \nu_L^c \qquad (36)$$

$$\mu^+ \to e^+ + \nu_R + \nu_L \; ; \; \mu^- \to e^- + \nu_R^c + \nu_L^c \qquad (37)$$

$$\nu_R + p \to n + \mu^+ \; ; \; \nu_R^c + n \to p + \mu^-$$

Processes of the type $\nu_R + p \rightarrow n + e^+$ are forbidden.

Thus, the field ν_R is always connected in this theory with μ -field and ν_L with electron field.

The decay of muons in form (39) leading to the production of two neutrinos (decay of μ^+) or two antineutrinos (decay of μ^-) is characterized according to ref.[40]) by the correct value of the Michel parameter. The theory proves in this sense perfectly equivalent to the theory of Sudarshan and Marshak[6]) and Feynman and Gell-Mann[7]) in which the decay of muons yields a neutrino and a corresponding antineutrino: in both theories the polarization of these particles is the same. From a more general viewpoint it can be said that in the case[35,36]) and in the case[37]) new "quantum numbers" are introduced for leptons, and the the wanted forbiddenness can be obtained using these numbers[+].

It is perhaps no accident that in the formalism of modern theory there is room for the Konopinsky-Mahmoud

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[+] Ascribing the numbers L = +1 to the particles μ^+, e^-, ν_R, ν_L
L = -1 " $\mu^-, e^+, \nu_R^c, \nu_L^c$
N = +1 " $\mu^+, e^+, \nu_R, \nu_L^c$
N = -1 " $\mu^-, e^-, \nu_R^c, \nu_L$

and assuming the conservation of numbers L and N in the reactions all types of allowed and forbidden processes can readily be written out.

hypothesis and the idea of two neutrinos.

The second order equation for spinor field is meant. As applied to electrons this equation was discussed many years ago[41]).

The corresponding Lagrangian was written as

$$\mathcal{L} = -\frac{1}{2m}\sum_{\mu\rho}\frac{\partial\bar{\phi}}{\partial x_\rho}\gamma^\rho\gamma^\mu\frac{\partial\phi}{\partial x_\mu} - \frac{m}{2}\bar{\phi}\phi \qquad (39)$$

Such a theory proves capable of describing the electron as a particle of positive energy and negative electrical charge e^- and the positron as a hole in the occupied electron states of negative energies.

The same theory, however, has also room for another particle of positive charge and positive energy and for its antiparticle, a hole in the distribution of the levels occupied by particles of positive charge and negative energies.

The electron can annihilate with the positron (hole), but not with the other positively charged particle.

According to this equation, there would have to exist a "second electron". Its properties must, in a sense, be inverse to the electron: the particle is a field quantum, charged positively, while the antiparticle is charged negatively.

Since there is no "second electron" in nature, it seems, it is attractive to regard the μ^+-meson as the second particle in this theory. This view is possible if the second order equations are treated as equations for bare particles with equal masses ($m_e = m_\mu = m$) and if it is assumed that the degeneracy with respect to the masses is removed by the interaction.

The new possibility in the second order equation arises because the equation is equivalent in the case under study to the Dirac first order equation, except that the former is for eight-component functions. The transformation of this equation can lead to the two independent Dirac equations[41])

$$(i\hat{p}+m)\psi_I = 0 \tag{40}$$

$$(i\hat{p}-m)\psi_{II} = 0 \qquad \hat{p} = -i\gamma_\mu \frac{\partial}{\partial x_\mu} \tag{41}$$

These equations can be united as

$$(i\hat{P}+\Gamma m)\psi = 0; \; \psi = \begin{vmatrix}\psi_I \\ \psi_{II}\end{vmatrix}; \; \hat{P} = \Gamma_\mu P_\mu \tag{42}$$

where Γ_μ is the eight-row matrix

$$\Gamma_\mu = \begin{vmatrix}\gamma_\mu & 0 \\ 0 & \gamma_\mu\end{vmatrix}; \; \mu = 1,2,3,4. \; \Gamma = \begin{vmatrix} I & 0 \\ 0 & -I\end{vmatrix} \tag{43}$$

The Lagrangian of this equation can be written as

$$\mathcal{L} = \frac{1}{2}\left(\bar{\psi}\Gamma_\nu \frac{\partial \psi}{\partial x_\nu} - \frac{\partial \bar{\psi}}{\partial x_\nu}\Gamma_\nu \psi\right) - m\bar{\psi}\psi \tag{44}$$

We can readily obtain the current conservation law

$$\frac{\partial}{\partial x_\nu} \bar{\Psi} \Gamma \Gamma_\nu \Psi = 0 ; \quad \Psi \to e^{-i\beta\Gamma} \Psi \qquad (45)$$

and charge density in the form

$$\rho = -(\Psi_I^* \Psi_I - \Psi_{II}^* \Psi_{II}); \quad \mathcal{J}'_\nu = -\bar{\Psi} \Gamma \Gamma_\nu \Psi \qquad (46)$$

The above Lagrangian is also invariant with respect to the transformations

$$\Psi \to e^{+i\alpha} \Psi ; \quad \Psi^* \to \Psi^* e^{-i\alpha} \qquad (47)$$

This property of the Lagrangian involves the second conservation law

$$\frac{\partial}{\partial x_\nu} \bar{\Psi} \Gamma_\nu \Psi = 0 \quad ; \quad \mathcal{J}''_\nu = \bar{\Psi} \Gamma_\nu \Psi \qquad (48)$$

The second law allows the interpretation of the expression $\mathcal{J}''_4 = \bar{\Psi} \Gamma_4 \Psi$ as the density of the number of particles

$$\eta = \Psi_I^* \Psi_I + \Psi_{II}^* \Psi_{II} \qquad (49)$$

After the quantization according to the positive metrics$^{x)}$ the conservation laws are re-written in the form similar to eqs.(33) and (34).It can be said that there are "two Dirac equations": one for the electron $(i\hat{p} + m)\Psi_e = 0$ and the other for the muon $(i\hat{p} - m)\Psi_\mu = 0$.

We shall call the Fermi fields satisfying eq.40 fields 4I and the fields obeying eq.II fields II.

These fields are conjugate in the sense of the Konopinski-Mahmoud hypothesis.

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x $[\Psi^e(x), \bar{\Psi}^e(y)]_+ = (-\hat{p} - im)\Delta(x-y)$

$[\Psi^\mu(x), \bar{\Psi}^\mu(y)]_+ = (-\hat{p} + im)\Delta(x-y)$

In this respect the difference between the fields ψ_I and ψ_{II} can more clearly be illustrated as follows.

The Lagrangian of the second order equation for spinor functions leads to this expression for the charge density

$$\rho = -\frac{i}{2mc}\left(\sum_\rho \frac{\partial\bar{\phi}}{\partial x_\rho}\gamma^\rho\gamma^4\phi - \bar{\phi}\gamma^4\sum_\rho\gamma_\rho\frac{\partial\phi}{\partial x_\rho}\right) \qquad (50)$$

Eqs. I and II differ in that[1]) eq. I, for example, selects ψ_I for which ρ is negative (electron solutions, $-\sum_\eta \gamma_\eta \frac{\partial\psi_I}{\partial x_\eta} = m\psi_I$). Eq. II selects ψ_{II} for which ρ is positive (μ - meson fields, $-\sum_\eta \gamma_\eta \frac{\partial\psi_{II}}{\partial x_\eta} = -m\psi_{II}$). Only in this interrelation of the fields of eqs. I and II is it expedient to discern the fields ψ_I and ψ_{II} conjugate in this sense.

Dirac derived his equation by expanding into factors the operator

$$p_\mu^2 - m^2 = (i\hat{p}+m)(i\hat{p}-m)$$

and taking only one factor as the operator of his equation.

The symmetries of the Dirac equation for the eight-component ψ-function are analogous in many respects to those of the Dirac equation for the four-component function if it is assumed in the latter case that $m = 0$.

Indeed, in the transformations

$$\psi_I \to \gamma_5\psi_{II}\ ; \qquad (51)$$
$$\psi_{II} \to \gamma_5\psi_I\ ; \qquad \bar{\psi} \to -\bar{\psi}\gamma_5$$

eq.(40) takes on the form of eq.(41) and vice versa.

In this sense the four-spinor (bi-bispinor) of eq.(42) is as much an integral whole as the bispinor of the Dirac equation in the case $m=0$.

Either of eqs.(40) and (41) is invariant with respect to the Lorentz transformations, but one bispinor passes into the other in the transformations $\psi \rightarrow \gamma_5 \psi$.

These new properties of symmetry arise because and only because the masses in eqs.(40) and (41) are put to be equal.

Naturally, only such kinds of interactions can remove the degeneracy with respect to the masses of the bare particles which will be not invariant with respect to the transformations $\psi \rightarrow \gamma_5 \psi$.

There are no general considerations on the basis of which we could discriminate one of eqs.(40) and (41) for electrically neutral Fermi fields.

It is natural to assume that for the neutrino as well we can write two analogous equations

$$(i\hat{p} + m_\nu)\psi_\nu^e = 0 \qquad (52)$$

$$(i\hat{p} - m_\nu)\psi_\nu^\mu = 0 \qquad (53)$$

For the sake of generality m_ν^μ and m_ν^e are not put equal to zero in this case.

The conservation laws arising for the neutrino (52)(53) fields have in general the same meaning as the electron-muon fields. $\bar{\psi}_\nu \Gamma_4 \psi_\nu = J^{\mu}_{\nu_4}$ still characterize the density of the particles $\psi_\nu^{*e}\psi_\nu^{e} + \psi_\nu^{*\mu}\psi_\nu^{\mu}$

The fourth component of the vector $J_\eta = \bar{\Psi}_\nu \Gamma \Gamma_\eta \Psi_\nu$ has the meaning of the weak charge density [+]

$$-G(\psi_\nu^{*e}\psi_\nu^{e} - \psi_\nu^{*\mu}\psi_\nu^{\mu}) \qquad (54)$$

for neutrino fields

$$-G(\psi_e^{*}\psi_e - \psi_\mu^{*}\psi_\mu) \qquad (55)$$

for electron-muon field.

If it is held that all leptons make up an isolated system of fermions, that the general lepton Lagrangian is invariant with respect to the transformations of the same form for all lepton functions

$$\psi_L \to e^{i\alpha}\psi_L \quad ; \quad \psi_L^{*} \to \psi_L^{*} e^{-i\alpha} \qquad (56)$$

,

then the generalized conservation law of the lepton number will be written just in the form (33).

Assuming that the transformations of the type

$$\psi_L \to e^{-i\beta\Gamma}\psi_L \quad ; \quad \psi_L^{*} \to \psi_L^{*} e^{+i\beta\Gamma} \qquad (57)$$

[+] Different neutrino charges for the electron and muon have been introduced by Zeldovich[137]) and Marx[138]). The purpose of introducing neutrino charges is to forbid effects like $\mu \to e + \gamma$ etc.

[redacted]

also leave the general lepton Lagrangian unchanged we obtain the generalized conservation law of weak charge (G) precisely in the form (34).

If the neutrino masses $m_\nu = 0$ then for the neutrino functions the role of the matrix Γ is played by the matrix γ_5 in diagonal representation[41]) and the entire situation with two types of neutrinos tallies with that described above by the work of Kawakami.

In terms of two types of fields the case $m_\nu = m_\nu^e = m_\nu^\mu = 0$ can also be presented in this way.

For the two-component functions ψ_I^ν and ψ_{II}^ν we can write such two equations

$$\frac{\partial \psi_I^\nu}{\partial t} + i\bar{\sigma}\bar{p}\,\psi_I^\nu = 0 \tag{58}$$

$$\frac{\partial \psi_{II}^\nu}{\partial t} - i\bar{\sigma}\bar{p}\,\psi_{II}^\nu = 0 \tag{59}$$

where ψ_I^ν and ψ_{II}^ν are two fields with different transformation properties

$$\psi_I^\nu \to e^{-i\beta}\psi_I^\nu \; ; \quad \psi_{II}^\nu \to e^{+i\beta}\psi_{II}^\nu \tag{60}$$

These fields differ in the same sense as the fields ψ_I and ψ_{II} described by the four-component functions. In the representation in which the equations for neutrino (58) (59) functions are written the matrix γ_5 is diagonal

$$\gamma_5 \begin{vmatrix} I & 0 \\ 0 & -I \end{vmatrix} \tag{61}$$

In deriving the conservation laws the matrix γ_5 plays, for the neutrino field in the given case, the same role as the matrix Γ for the electron-muon field. From this point of view two types of neutrinos (ν_e and ν_μ) constitute a

[redacted]

particular case of two types of Dirac fields conjugate in the sense of the Konopinski-Mahmoud hypothesis.

In the problem $m_\mu \neq m_e$ it is the identity of all known interactions for the electron and muon that is enigmatic.

If the bare electron and bare muon are described by the same equation, then, given the identity of all interactions of the muon and electron, it is impossible to interpret the differences in the masses of these particles in terms of field theory.

In the above formalism we have a somewhat different situation which requires further analysis.

When writing the equations in the form $(i\hat{p}+m)\psi_e=0$ and $(i\hat{p}-m)\psi_\mu=0$ it is required that the additions to m in these equations due to the interaction introduced should be of the same sign[+] e.g.,

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[+] For details see preprint [41]).

$$m_e = m - \delta m \qquad ; \qquad -m_\mu = -m - \delta m \qquad (62)$$

With a bare particle mass equal to, say, roughly half the real muon mass and δm close to this value, we could in principle explain the difference in the muon and electron masses. This possibility is analyzed more elaborately in sect. 9.

Thus it seems more expedient to interpret the problem $\nu_e \neq \nu_\mu$ from a wider point of view, as a problem connected with the existence of two different types of Dirac fields.

The existence of these two types is not restricted to the lepton cases. Probably, there are similar baryon doublets

$$(p^+, n) \quad ; \quad (\Xi^-, \Xi^0)$$

which can be correlated with the lepton doublets

$$(\mu^+, \nu_\mu) \quad ; \quad (e^-, \nu_e)$$

Perhaps, the baryons Σ^+, Σ^- should be correlated (?) with the neutral components

$$Y = \frac{\Lambda^0 - \Sigma^0}{\sqrt{2}} \quad \text{and} \quad Z = \frac{\Lambda^0 + \Sigma^0}{\sqrt{2}}$$

But the discussion of these points is beyond the scope of the survey.

* * *

Search for the solution of the problem in other possible directions is also of interest.

Though the hypothesis of the complex structure of leptons expressed graphically in ref.20) has elements of oversimplification, it corresponds in spirit, I daresay, to the trends in the contemporary theory of elementary particles.

There has been a growing conviction that in the region of strong interactions the picture of any of the so-called elementary particles receives essential contributions from all other elementary particles. The concept of the neutron, for example, is unthinkable without the pion field which essentially determines the structure of the neutron and its major properties. The pion cloud determines the properties of the proton and neutron to such an extent that the pions enter "structurally" into the proton and neutron. The same apparently applies to the K-meson field and the connected field of hyperons, the field of ω- and ρ-mesons, etc.

In other words, as particles are discovered, they are styled elementary, classified and duly labelled, but then it appears that the relations among them are so close that each "elementary" particle begins to be conceived as a complex composition of all "elementary" particles[+].

[+] There is an extremist point of view according to which it is of no importance what material has been used to build the elementary particles in strong interactions. The result must be the same. In its very general form the validity of this idea is well-nigh self-evident.

For example, the possibility of different models of baryons and K-mesons can illustrate this idea.

1. In many propositions the K-meson is known to be regarded as a complex particle

$$K^0 \equiv n + \tilde{\Lambda}^0 \qquad \text{I}$$

2. The hyperon is regarded as a complex particle[42]

$$\Lambda^0 \equiv n + \widetilde{K^0} \qquad \mathrm{II}$$

3. The nucleon is supposed to be a complex particle[43]

$$n \equiv \Lambda^0 + K \qquad \mathrm{III}$$

The fact is, however, that in its general form the idea can be of no heuristic value. A certain analogy can be drawn with the possibility of using different systems of coordinates for describing physical phenomena. Such a possibility does exist. But it is also correct that the heliocentric system is more natural for the description of, say, the motion of Mercury than the geocentric system.

For example, the Heisenberg programme is known to be aimed at obtaining the "elementary" particles as complex effects of a certain universal Fermi field as a result of strong (non-linear) interactions. An attempt along the same lines to take as the basis the four-fermion interaction of baryons treated as excited states of nucleons has also been considered[20].

The production of new particles in this interaction (of π, K-particles) is manifest as the origin of poles in the corresponding S-matrix[19].

The programme of treating particles as the corresponding Regge poles is, in a sense, an attempt to realize in the given concrete formalism the same idea of the non-elementariness of elementary particles.

Unfortunately, leptons do not yet fit this programme. Strong interactions are needed for its realization+.

+ Evidently, the construction of elementary particles and leptons in particular, is only possible on the basis of strong interactions. Weak interactions can, if they remain weak in all cases, yield only "weak" corrections to the parameters characterizing a particle (its mass, etc.).

In this sense it is worthwhile to hope to find for leptons as well the corresponding strong interaction in the "weak" four-fermion one which becomes strong for high energies or small collision parameters.

Perhaps the new approach to the concept "elementary particles" which takes shape as the matter is viewed from various concrete vantage points is the most essential accomplishment of physics in the last decades.

From this point of view the idea of two types of neutrinos permits so far to assume, without contradicting experimental data, the correctness of the theory of four-fermion interactions up to energies close to the critical ($\sim$300 GeV).

However, a serious (so far purely theoretical) danger to the idea of the four-fermion interaction has arisen in recent years from the idea of the intermediate boson.

4. Intermediate Boson

Many years ago Yukawa[44]) suggested regarding the weak interaction as a more complex process than the direct 4-fermion interaction. According to this idea, there is an intermediate boson (say W) which emits, for example, nucleons and then decays into leptons

$$n \rightarrow p + W^- \quad ; \quad W^- \rightarrow e^- + \bar{\nu}$$

The idea has been revived in connection with the latest stage in the theory of weak interactions. To a certain extent it universalizes all known interactions: fermions interact with bosons. The field theory is patterned on its historical prototype: electrodynamics. The vector boson is thought to have some advantages in nature and there appears the natural trend to understand the hidden causes of the universality of vector field.

New vistas thus open for theoretical speculations which can point to further ways in the fundamental research of the near future.

The intermediate vector boson naturally explains the select nature of the vector variant of the four-fermion formalism of weak interactions, and the charged intermediate boson could naturally explain the fact that the "currents" in the weak interaction Lagrangian have to be written as charged.

On the other hand, there are arguments which make the introduction of the weak interactions of the intermediate vector meson by no means so attractive. Indeed, a too close analogy in constructing the theory of strong and weak interactions would seem to give no possibilities to understand the peculiarity of weak interactions. Why is the parity violated in weak in contrast to strong interactions if the structure of strong and weak interactions of the vector bosons with the nucleons (of the ω, ρ, W field) must, it would appear, differ only in the numerical values of the interaction constant?

Moreover, since the mathematical fact that a vector can be built of two spinors has become known the idea, attractive enough, that fermions are the basic material in constructing elementary particles has been vigorously alive.

But regardless of our tastes, the problem of the existence of an intermediate boson in weak interactions is an experimental problem of fundamental importance, and its solution will affect the development of the theory of field and elementary particles.

~~If, for example, the intermediate boson mass proves essentially less than the critical mass of weak interactions ($\sim$ 300 GeV) the latter will be of no vital importance in the theory of elementary particles. In this case the role of weak interactions will reduce to yielding weak corrections to the parameters of elementary particles (their masses,~~

[redacted]

~~effective charges, etc.).~~

At present there are several variants of the intermediate-meson-in-weak-interaction theory.

Unfortunately, in its present state, the theory, burdened as it is with a number of empirical rules of unproved, speaking strictly, validity, does not allow the unambiguous selection of a weak interaction scheme based on the intermediate meson.

Thus, in the theory of weak interactions formulated by Lee and Yang$^{45)}$ several requirements are taken into consideration^{+}.

$^{+}$ (a) Absence of weak interactions as the strange number changes by 2 ($\Delta S \pm 2$).

(b) The $|\Delta I| = 1/2$ rule holds for the strangeness non-conserving decay particles (I is the total isobaric spin of strong interaction particles).

To satisfy these requirements, the authors had to construct a rather intricate theoretical scheme incorporating four types of intermediate vector bosons. Two of them are electrically charged W^{+}, W^{-} and two are neutral. Thus, four new particles are introduced: a whole set of particles analogous in a sense to the well-known set of K-particles ($K^{+}, K^{-}; K_1^{0}, K_2^{0}$ ...). In isobaric spin these fields are duel: the W-field behaves as isospinor when it is

[redacted]

connected with strangeness non-conserving current and possesses the properties of isoscalar and isovector when it is connected with strangeness conserving current. This isospin duality of the intermediate meson has earned these still hypothetical particles the name of schizons.

In the intermediate meson theory evolved by D'Espagnat46), it is possible to avoid the above form of schizony and introduce two new sorts of particles represented as charged mesons. In this variant the weak decay

$$\Xi^- \longrightarrow n + e^- + \tilde{\nu}$$

i.e., a decay with change of strangeness by 2 units ($\Delta S=2$), is allowed. This decay is forbidden in the Lee and Yang theory. Strictly speaking, experimental evidence is not yet sufficient to warrant the $|\Delta S|=2$ decay forbiddenness, though in literature47) there are indirect indications in its favour. On the other hand, a more elaborate analysis of the problem (Glashaw47')) weakens somewhat the arguments in favour of the forbiddenness of the reaction under discussion. In general it should be noted that at present it is unjustifiable to refer to any finished theory of the intermediate meson: there is no sufficient substantiation as yet of many rules of the decay of strange particles, much as we are used to these rules. Thus, there has been a report48) that the rule $\frac{\Delta S}{\Delta Q} = +1$ is violated and a report49) that the decay $\Sigma^+ \rightarrow n + \mu^+ + \nu$ which is forbidden in particular by the Lee and Yang theory does exist. Incidentally, the Lee-Yang theory is essentially constructed in a way forbidding such effects by following the rule $\frac{\Delta S}{\Delta Q} = +1$.

These criticisms are by no means intended to underrate the importance of the intermediate meson problem if even in its original sense, in the sense of Yukawa, in the sense of the possibility of denying the direct four-fermion interaction.

Without going into the details of the intermediate boson theories, it can be noted that the intermediate boson mass must be larger than the masses of the existing relatively long-lived bosons in order to avoid the unobservable decays such as

$$K^- \to W^- + \gamma$$

Unfortunately, even a possible experimental discovery of two kinds of neutrinos will not be an essential argument in favour of the true four-fermion interaction. The two-neutrino hypothesis proves necessary for the theory of weak interactions based on the intermediate meson idea.

As G. Feinberg$^{50)}$ has noted, in such a theory there must be observed, with probabilities contradicting experiment, the same effects $\mu \to e + \gamma$ and $\mu \to 3e$ which give so much unpleasantness when discussing the true four-fermion interactions.

Here the situation is more tense since the coupling constant of the intermediate vector boson with fermion field is roughly the square root of the weak four-fermion interaction constant. Large magnitude of the coupling constant aggravates the situation. The two-neutrino hypothesis is called into play for obtaining the corresponding cases of forbiddenness.

Thus it appears from different angles that the experimental solution of the $\nu_\mu - \nu_e$ problem is something that physics has to attain within a few years. ~~This experiment has to be performed on accelerators in some form or other~~. Under the condition $\nu_\mu \neq \nu_e$ a reaction like $\nu_\mu + n \rightarrow p + e^-$ must be forbidden, and in the ν_μ beam (for example, in accelerators $\pi \rightarrow \mu + \nu_\mu$) only muons must be observed.

Interesting concrete suggestions on the $\nu_\mu - \nu_e$ problem experimentation can be found in papers of B. Pontecorvo[52,53]). In particular, attention is drawn to a possible use of monoenergy neutrino radiation. Indeed, monoenergy neutrinos originate in stoppages in a substance of π^+, K^+ and μ^--mesons.

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ yields $E_\nu = 29.8$ MeV

$K^+ \rightarrow \mu^+ + \nu_\mu$ yields $E_\nu = 235.7$ MeV

$\mu^- + A \rightarrow \nu_\mu + \ldots$ yields $E_\nu = 100$ MeV.

As an example of checking the identity of ν_e and ν_μ it is suggested that the cross sections of the reaction

$$\nu_\mu + C^{12} \rightarrow e^- + N^{12}$$

should be measured.

The enrgy of the emitted electrons induced by the incident monoenergetic ν_μ is known. The delayed positrons from the decay of N^{12} have to be registered in the process. The experiment is proposed to be made with electron methods of detecting particles as well as with the aid of a large bubble chamber.

The idea of using monoenergetic neutrinos is attractive because the experiment allows the neutrino-induced events to be interpreted kinematically.

With beam ~~intensities~~ of accelerated ~~particles~~ protons capable of producing pion beams (i.e., $E_p \leq$ 1 GeV) the count, in the author's estimate[52]), makes the proposed experiment feasible in principle on the strong-current accelerators in the nearest future. With approximately the same count another experiment proposed by Pontecorvo is feasible. In the latter experiment use is made not of neutrinos, as in the former, but of antineutrinos from the decay of the stopped μ^+-mesons $(\mu^+ \rightarrow e^+ + \nu_e + \tilde{\nu}_\mu)$, $E_{\tilde{\nu}_\mu} \sim 35$ MeV.

If $\tilde{\nu}_\mu$ and $\tilde{\nu}_e$ are identical the reaction

$$\tilde{\nu}_\mu + p \rightarrow e^+ + n$$

is possible.

If $\tilde{\nu}_\mu \neq \nu_e$ there is no such reaction. The number ν_μ is estimated to be roughly 10^{12} sec, i.e., assumed equal to the number of pions produced in the present-day synchrocyclotrons. If a Reines-Cowen type scintillation counter (1 to 2 m) is used the number of events (if $\nu_e \equiv \nu_\mu$) is estimated to be roughly 1 per hour.

Relatively low energies are characteristic of the neutrino experiments under discussion[52,53]). In principle neutrino beams of considerably higher energies are better to be used since the neutrino-nucleon interaction cross sections increase quadratically with energy, at least in the region $E_\nu < 1$ GeV. But on the other hand, synchrocyclotrons with $E_p \sim 700$ MeV can yield larger intensities, the reason which has prompted Pontecorvo to seak the solution of the problem in the low-energy neutrino region.

5. Possibilities for Neutrino Experiments on High-Energy Accelerators

The history of neutrino accelerator experiments is quite instructive in the sense that it exemplifies the astounding possibilities of modern experiment outstripping our imagination.

Neutrino experiments on accelerators have been contemplated for quite a time at many institutions of many countries. The relevant discussions + (1956) are mentioned by

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+ Cowen in Los Alamos.

Reines[129]) and about the same time these possibilities were discussed in Dubna (by Valuyev and the author).But the cross sections 10^{-38} cm^2 seemed to be so remote a prospect that no one would propose the experiment in good earnest.

In 1958 P.G.Fakirov[54]) presented his degree B.S. theses at Moscow University "Concerning the Possibility of Investigating the Interaction of a High-Energy Neutrino With Substance on Accelerators"[+] .

Given in this paper were the calculations of neutrino accelerator beams,the optimum distances of the detecting devices from the target yielding a pion beam,the machine and cosmic radiation backgrounds,adequate shielding as well as estimates of the necessary neutrino target mass ($\sim 1\ m^3$ of lead).Despite somewhat overestimated values of neutrino fluxes (almost by an order[+] since there were no reáliable data on the intensities of pion beams corresponding to the Dubna accelerator conditions and possible pion beams were estimated theoreti-

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[+] Evidently at this time the neutrino experiments on high-energy accelerators were discussed by CERN theoreticians, as is reported by Yamaguchi,a CERN preprint,61-2.

[+] These estimates of Fakirov were specified by Polubarinov[51]).

cally) and despite an optimistic conclusion of the author+ the experiment did not seem to us a matter of a very near future.

Finally, at the Kiev Conference for High Eneries+ B.Pontecorvo[52]) declared before an authoritative audience that the neutrino accelerator experiments were possible in principle.

+ "In other words, the discussion of an actual physical experiment with high-energy neutrinos on accelerators becomes expedient. Preliminary estimates show that given an adequate shielding against installation neutrons and cosmic radiation the background can be lower than the effect in question"[54]).

+ The report "On High Energy Neutrino Physics" tabled by a group of Dubna's theoreticians (Asanov, Valuyev, Markov and Polubarinov) was cancelled by the authors as "somewhat untimely". Later the materials of this report were published as a preprint (D-577, Dubna, 1960) and reported by the author at the next, Rochester Conference for High Energies (1960). The summaries of these papers united by the underlying basic ideas of high-energy neutrino physics had been published somewhat earlier[2]). The content of this survey is in its essential part a detailed elaboration of that short notice[22]).

Characteristically, even Pontecorvo whose boldness and allegiance to the neutrino is beyond cavil, believed that neutrino experiment would be realistic when the intensities of accelerators had increased by three orders or so.

Pontecorvo concluded his paper "Electron and Muon Neutrino" with these words:

"To sum up, the experiment to see whether ν_e and ν_μ are identical must, difficult as it may seem, be seriously contemplated in the designing of new accelerators". Medium energy accelerators ($E_p \leq 1$ GeV) were meant.

In 1960 M.Shwartz published a paper[55]) in which this experimentator gave, with what might have seemed a theorist's appealing detachment, the fantastic parameters of a fantastic neutrino experiment on a high-energy accelerator. Many physicists just shrugged as they read the item. The thing is that despite the matter-of-fact and concrete tone of Shwartz's proposal, it sounded anything but optimistic, especially in its concluding part: "These estimates place the experiment outside the capability of the existing machines by one or two orders of magnitude".

Incidentally, neither the CERN machine in the state of commisioning nor the Brookhaven accelerator about to go into operation figured in the item as accelerators suitable for the experiment. The item pointed to the possibilities of future accelerators with high intensities up to 10^{15} protons. This innocent excursion in the field of accelerators seemed to have neutralized the general effect of the item, somehow. ~~deflating~~. The same issue, however, carried an item by Lee and Yang[28]) who insisted on the fundamental importance of the neutrino experiment. The item was a spur for further efforts of theorists and experimenters in high-energy neutrino physics. In the autumn of the same year a detailed project of neutrino experiments on the CERN accelerator could be heard at the Rochester Conference for High Energy Physics.

Bernardini[56]) described the unique installation with the verve of a true Florentine.

At Columbia University the Brookhaven neutrino project was canvassed.

In his characteristic flegmatic manner, which carried special conviction, Lederman described the experiment.

Means of observation adequate to the problem seemed to have been found in the spark chambers.

Now the experiment has been carried through its initial stage under conditions worse than those contemplated by Shwartz's estimates. It has been made with a proton beam intensity by an order less than those minimum intensities with which the discussion of the experiment began. In other words, it has been made without awaiting strong current accelerators and even without magnetic focussings. It has been made with high-energy neutrinos--in the teeth of logic as might seem.

The first elaborate calculations of the neutrino experiment on accelerators (Fakirov[54]), Polubarinov[51])) were adjusted to the Dubna accelerator parameters. Unfortunately, the intensity of this machine ruled out the treatment of the experiment as real. To increase the count of the events under study recourse had to be made to a focussing magnetic field installation[51]).

The decay of a pion ($\pi \to \mu + \nu$) yields neutrinos of the energy ($\hbar = c = 1$)

$$\mathcal{E}_\nu = \frac{m_\pi^2 - m_\mu^2}{2(\mathcal{E}_\pi - P_\pi \cos\theta)} \qquad (63)$$

where m_π and m_μ are the rest masses of the pion and μ meson, $\mathcal{E}_\pi$ and P_π are the energy and momentum of the pion, θ is the angle between the original direction of the pion and the direction of movement of the neutrino. The maximum values of the neutrino energy ($\mathcal{E}^\nu_{max}$) from the decay of the pion of the given ($\mathcal{E}_\pi$) energy are listed in table 1.

Table 1

	1	2	3	4	5	6	7	8	9	10
$\mathcal{E}^\nu_{max}$ (GeV)	0.43	0.86	1.28	1.71	2.14	2.57	3.00	3.42	3.86	4.28

The probability of the decay of a pion of momentum $\vec{P}_\pi$ per time unit with the emission of a neutrino of momentum between $\vec{P}_\nu$ and $\vec{P}_\nu + d\vec{P}_\nu$ is

$$d\omega(\vec{P}_\pi, \vec{P}_\nu) = f(\vec{P}_\pi, \vec{P}_\nu) d\vec{p}_\nu = \frac{m_\pi^2 \, d\vec{p}_\nu}{\pi \tau(\mathcal{E}_\pi)(m_\pi^2 - m_\mu^2)\mathcal{E}_\nu} \delta[(P_\pi - P_\nu)^2 + m_\mu^2] \quad (64)$$

where P_π and P_ν are the 4-momenta of the pion and neutrino, $P_\pi^2 = -m_\pi^2$, $P_\nu^2 = 0$, and $\tau(\mathcal{E}_\pi)$ is the lifetime of the pion of energy $\mathcal{E}_\pi$.

The effects

$$\nu + n \to e + p \quad (65)$$

$$\tilde{\nu} + p \to \tilde{e} + n \quad (66)$$

$$\tilde{\nu} + e \to n + p \quad (67)$$

were calculated by I.Polubarinov[51]) proceeding from the Lagrangian

$$\mathcal{L}(x) = \frac{G}{\sqrt{2}} [\bar{p}(x)\gamma_\mu(1+\gamma_5)n(x)][\bar{e}(x)\gamma_\mu(1+\gamma_5)\nu(x)] + h.c. \quad (68)$$

with the value

$$G = 1.41 \times 10^{-49} \text{ erg.cm}^3.$$

The cross sections in this investigation were calculated without taking into account a possible nucleon formfactor since it had been found earlier [+] that the role of the

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[+] The cross sections with nucleon formfactors had been calculated and the possible role of the formfactor in the region of very high energies estimated still earlier by Zheleznykh[57]).

formfactor in the region $E_\nu \leq 1$ GeV is not decisive and for extremely high energies the formfactor is unknown. Furthermore, since the effect of the formfactors under discussion on the weak interaction cross sections is an experimental problem as yet, it is undesirable to invest in the expressions for the cross sections any hypothetical elements on the formfactors. At any rate it is desirable to have the estimates of the effects in their pure form for comparison with the future experimental data.

The total cross sections are obtained in the form

$$\sigma_{\nu+n\to e+p} = \frac{G^2}{4\pi\hbar^4}\,\frac{M^4c^4}{\varepsilon_n\varepsilon_\nu\beta_0}\sqrt{1-\frac{2(m_p^2+m_e^2)}{M^2}+\frac{(m_p^2-m_e^2)^2}{M^4}}\;\times$$

$$\times\left(1-\frac{m_n^2+m_\nu^2}{M^2}\right)\left(1-\frac{m_p^2+m_e^2}{M^2}\right) \qquad (69)$$

$$\sigma_{\tilde\nu+p\to\tilde e+n} = \frac{G^2}{12\pi\hbar^4}\,\frac{M^4c^4}{\varepsilon_p\varepsilon_{\tilde\nu}\beta_0}\sqrt{1-\frac{2(m_n^2+m_{\tilde e}^2)}{M^2}+\frac{(m_n^2-m_{\tilde e}^2)^2}{M^4}}\;\times$$

$$\times\left\{1-\frac{m_n^2+m_p^2+m_{\tilde\nu}^2+m_{\tilde e}^2}{2\cdot M^2}-\frac{(m_n^2-m_{\tilde e}^2)^2+(m_p^2-m_{\tilde\nu}^2)^2-2(m_n^2+m_{\tilde e}^2)(m_p^2+m_{\tilde\nu}^2)}{2M^4}\right. -$$

$$-\frac{(m_n^2+m_{\tilde e}^2)(m_p^2-m_{\tilde\nu}^2)^2+(m_p^2+m_{\tilde\nu}^2)(m_p^2-m_{\tilde e}^2)^2}{2M^6}+$$

$$\left.+\frac{(m_n^2-m_{\tilde e}^2)^2(m_p^2-m_{\tilde\nu}^2)^2}{M^8}\right\}\;\ldots\ldots$$

$$(70)$$

$$\sigma_{\tilde{\nu}+e\to n+\tilde{p}}=\frac{G^2}{12\pi\hbar^4}\cdot\frac{M^4c^4}{\mathcal{E}_e\mathcal{E}_{\tilde{\nu}}\beta_0}\sqrt{1-\frac{2(m_n^2+m_{\tilde{p}}^2)}{M^2}+\frac{(m_n^2-m_{\tilde{p}}^2)^2}{M^4}}\times$$

$$\times\Big\{1-\frac{m_n^2+m_{\tilde{p}}^2+m_{\tilde{\nu}}^2+m_e^2}{2M^2}-\frac{(m_n^2-m_{\tilde{p}}^2)(m_e^2-m_{\tilde{\nu}}^2)-2(m_n^2+m_{\tilde{p}}^2)(m_e^2+m_{\tilde{\nu}}^2)}{2M^4}-$$

$$-\frac{(m_n^2+m_{\tilde{p}}^2)(m_e^2-m_{\tilde{\nu}}^2)^2+(m_e^2+m_{\tilde{\nu}}^2)(m_n^2-m_{\tilde{p}}^2)^2}{2M^6}+$$

$$+\frac{(m_n^2-m_{\tilde{p}}^2)^2(m_e^2-m_{\tilde{\nu}}^2)^2}{M^8}\Big\}\ \ldots\ldots \qquad (71)$$

These cross sections are written in an arbitrary system of units and arbitrary system of coordinates; β_0 is the relative velocity of the colliding particles divided by that of light;the masses m and energies $\mathcal{E}$ are marked by subscripts ; M is the mass of the system expressed through the energies and momenta of colliding particles 1 (ν or $\tilde{\nu}$) and 2 (p, n, e) according to the formula

$$M^2=\frac{(\mathcal{E}_1+\mathcal{E}_2)^2}{c^4}-\frac{(\vec{p}_1+\vec{p}_2)^2}{c^2} \qquad (72)$$

In the system of coordinates where particle 2 is at rest, while the neutrino and antineutrino have a momentum P_1

$$M^2 = m_2^2 + 2m_2 P_1/c\,, \qquad m_1 = 0 \tag{73}$$

For the processes

$$\nu + e \rightarrow \nu + e$$
$$\tilde{\nu} + e \rightarrow \tilde{\nu} + e$$

if they exist and are governed by the universal Fermi interaction we have

$$\sigma_{\nu+e\to\nu+e} = \frac{G^2}{4\pi\hbar^4}\frac{M^4c^4}{\mathcal{E}_e\mathcal{E}_\nu\beta_0}\sqrt{1-\frac{2(m_\nu^2+m_e^2)}{M^2}+\frac{(m_\nu^2-m_e^2)^2}{M^4}}\times$$
$$\times\left(1-\frac{m_e^2+m_\nu^2}{M^2}\right)^2 \quad \ldots\ldots \tag{74}$$

$$\sigma_{\tilde{\nu}+e\to\tilde{\nu}+e} = \frac{G^2}{12\pi\hbar^4}\frac{M^4c^4}{\mathcal{E}_e\mathcal{E}_{\tilde{\nu}}\beta_0}\sqrt{1-\frac{2(m_\nu^2+m_e^2}{M^2}+\frac{(m_{\tilde{\nu}}^2-m_e^2)^2}{M^4}}\times$$
$$\times\left\{1-\frac{m_e^2+m_{\tilde{\nu}}^2}{M^2}+\frac{4m_e^2\,m_{\tilde{\nu}}^2}{M^4}-\right.$$
$$\left.-\frac{(m_e^2+m_\nu^2)(m_e^2-m_{\tilde{\nu}}^2)^2}{M^6}+\frac{(m_e^2-m_{\tilde{\nu}}^2)^4}{M^8}\right\} \quad \ldots\ldots \tag{75}$$

For energies $\mathcal{E}_\nu \geq 1$ GeV in the laboratory system

$$\sigma_{\tilde{\nu}+p\to\tilde{e}+n} = \frac{G^2}{3\pi\hbar^4 c}\,m_p P_{\tilde{\nu}} \simeq 0.48\times10^{-38}\,\frac{P_{\tilde{\nu}}}{m_p c}\ \mathrm{cm}^2 \tag{76}$$

There are simple approximate relations between the cross sections

$$\sigma_{\nu+n\to e+p} \approx 3\sigma_{\tilde{\nu}+p\to n+\tilde{e}} \tag{77}$$

$$\sigma_{\tilde{\nu}+e\to n+\tilde{p}} \approx \frac{m_e}{m_p}\sigma_{\tilde{\nu}+p\to n+\tilde{e}} \tag{78}$$

$$\sigma_{\nu+e\to \nu+e} \approx 3\frac{m_e}{m_p}\sigma_{\tilde{\nu}+p\to n+\tilde{e}} \tag{79}$$

$$\sigma_{\tilde{\nu}+e\to \tilde{\nu}+e} \approx \frac{m_e}{m_p}\sigma_{\tilde{\nu}+p\to n+\tilde{e}} \tag{80}$$

In Polubarinov's estimates it is put $|G_A| = |G_V|$ as is clear from ~~fig. (43).~~ eq.(68).

In the estimates of Yamaguchi[58]),Cabibbo and Gatto[27]) use is made of more latest data, according to which $|G_A| \neq |G_V|$ viz. $\lambda = -\frac{G_A}{G_V} = 1.25$.

Unlike Polubarinov's estimates these calculations are complicated by the introduction of formfactors and the cross sections are given in the laboratory system[+].

[+] It should be emphasized that the cross sections for the processes under consideration are given in Polubarinov's work for $m_\nu \neq 0$. The cross sections for two-component neutrinos ($m_\nu = 0$) are twice as large (T.D.Lee and C.N.Yang, Phys.Rev. 105 (1957) 1671) than the cross sections for $m_\nu \neq 0$ in a flux of unpolarized neutrinos.

These estimates are quite instructive and the hypotheses relating to the role of formfactors in weak interactions will doubtless become the object of experimental research.

Cabibbo and Gatto[27]) universalize the formfactors of nucleons of the Stanford type obtained from electron-nucleon scattering experiments

$$F(k^2) = \frac{1}{\left(1+\frac{k^2}{a^2}\right)^2} \quad ; \qquad a^2 = 37.5\, m_\pi^2 \qquad (81)$$

This expression is extrapolated to arbitrarily large K. Practlically, with selected formfactors, the cross sections for the effects $\nu + n \rightarrow e^- + p$ and $\tilde{\nu} + p \rightarrow \tilde{e}^- + n$ (unlike eqs.(77 - 78)) become comparable and turn to a constant $\sim 0.75 \cdot 10^{-38}$ cm^2 already in the region $\frac{E_\nu}{m_p} \sim 10$. It is precisely up to these values $\frac{E_\nu}{m_p}$ that the calculations of the cross sections under study are given in ref.[27]). The results are presented in the form of curves 5 and 6.

More elaborate calculations performed by Yamaguchi[58]) are fitted to the parameters of the CERN machine where the average heutrino energy lies close to 1 GeV. In this study concrete calculations are brought up to E_ν = 2 GeV. The analytical expression for the differential cross sections, taking into account the formfactors in the laboratory system is of the form[58])

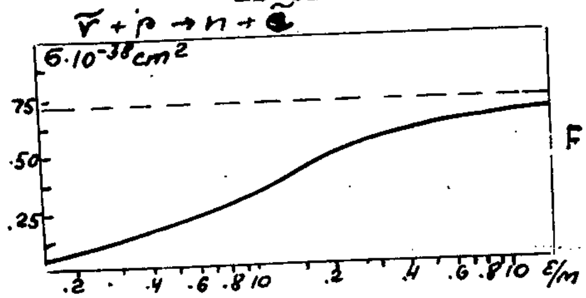


Fig 5

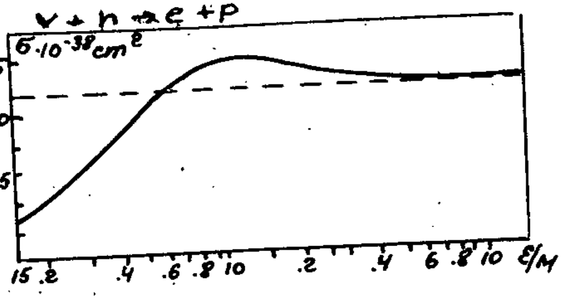


Fig 6

$$\frac{d\sigma}{d\Omega}\begin{pmatrix}\nu+n\rightarrow p+e^-\\ \tilde{\nu}+p\rightarrow n+e^+\end{pmatrix}=\frac{G_V^2}{2\pi^2}E_\nu^2\,\frac{\left(\cos\frac{\theta}{2}\right)^2}{\left[1+\frac{2E_\nu}{m}\left(\sin\frac{\theta}{2}\right)^2\right]^3}\times$$

$$\times\left[\left|F_1(q^2)\right|^2+\frac{q^2}{4m^2}\left\{2\left|F_1(q^2)+\mu F_2(q^2)\right|^2\left(\tan\frac{\theta}{2}\right)^2+\mu^2\left|F_2(q^2)\right|^2\right\}+\right.$$

$$+\left|\lambda^2F_A(q^2)\right|^2\left\{1+2\left(\tan\frac{\theta}{2}\right)^2+\frac{q^2}{2m^2}\left(\tan\frac{\theta}{2}\right)^2\right\}\pm$$

$$\pm\,2\mathrm{Re}\left\{\left(F_1(q^2)+\mu F_2(q^2)\right)^*\lambda F_A(q^2)\right\}\times$$

$$\left.\times\left\{2\frac{E_\nu}{m}-\frac{q^2}{2m^2}\right\}\left(\tan\frac{\theta}{2}\right)^2\right]\quad\ldots\qquad(82)$$

where m is the nucleon mass.

The calculations are made for $\lambda=1.25$ and $\mu=3.71$ (the difference of the anomalous magnetic moments of the proton and neutron).

All the formfactors are arbitraryly put identical

$$F_1=F_2=F_A=\frac{1}{\left(1+\frac{5q^2}{4m^2}\right)^2}$$

$$q^2=\frac{\left(2E_\nu\sin\frac{\theta}{2}\right)^2}{1+\frac{2E_\nu}{m}\left(\sin\frac{\theta}{2}\right)^2}$$

where q^2 is the four-dimensional momentum transferred to the nucleon. The tables of differential cross sections in the lab. (II) and (III) have been taken from a paper of Yamaguchi[58]).

[redacted]

Table II

Differential cross section in the lab. system

$(d\sigma/d\Omega)\Big/(G_V{}^2M^2/2\pi^2)$ for $\nu + n \rightarrow p + e^-$

E_ν = neutrino energy in lab. system

Θ = lab. angle between ν and e^-

E_ν/M Θ in deg.	0.25	0.50	0.75	1.00	1.50	2.00
0	0.16016	0.6406	1.441	2.563	5.766	10.250
2	0.16016	0.6403	1.439	2.554	5.717	10.089
4	0.16018	0.6392	1.432	2.528	5.573	9.626
6	0.16020	0.6374	1.419	$2.48\bar{5}$	5.343	8.910
8	0.16023	0.6348	1.402	2.425	5.039	8.017
10	0.16026	0.6314	1.380	2.351	4.678	7.030
12	0.16028	0.6272	1.353	2.263	4.279	6.027
14	0.16031	0.6221	1.322	2.164	3.861	5.070
16	0.16032	0.6162	1.286	$2.05\bar{5}$	3.442	4.202
18	0.16031	0.6094	1.247	1.939	3.036	3.444
20	0.16027	0.6016	1.204	1.819	2.654	2.800
22	0.16021	0.5930	1.159	1.696	2.304	2.266
24	0.16011	$0.583\bar{5}$	1.111	1.574	1.989	1.829
26	0.15997	0.5731	1.061	1.453	1.710	1.476
28	0.15978	0.5620	1.011	1.337	1.466	1.192
30	0.15954	0.5501	0.9596	1.225	1.255	0.9661
32	0.15924	0.5375	0.9086	1.120	1.074	0.7856
34	0.15887	0.5244	0.8581	1.0212	0.9192	0.6417
36	0.15844	0.5107	0.8086	0.9293	0.7875	0.5267
38	0.15794	0.4966	0.7604	0.8446	0.6759	0.4346
40	0.15736	0.4823	0.7139	0.7668	0.5813	0.3606
42	0.15672	0.4677	0.6693	0.6958	0.5012	0.3008
44	0.15600	0.4529	0.6268	0.6312	0.4334	0.2524
46	0.15520	0.4381	0.5863	0.5727	0.3758	0.2130
48	0.15434	0.4233	0.5481	0.5199	0.3270	0.1808

(cont.)

[redacted]

Table II (cont.)

E_ν/M Θ in deg.	0.25	0.50	0.75	1.00	1.50	2.00
50	0.15340	0.4087	0.5122	0.4722	$0.285\bar{5}$	0.1543
52	0.15239	0.3942	0.4784	0.4292	0.2501	0.1323
54	0.15131	0.3799	0.4468	0.3906	0.2198	0.1141
56	0.15017	0.3659	0.4174	0.3559	0.1939	0.0989
58	0.14897	0.3522	0.3899	0.3246	0.1716	0.0862
60	0.14771	0.3388	0.3644	0.2966	0.1524	0.0754
62	0.14639	0.3259	0.3407	0.2714	0.1359	0.0663
64	0.14503	0.3133	0.3187	0.2488	$0.121\bar{5}$	0.0586
66	0.14363	0.3012	0.2984	0.2284	0.1090	0.0519
68	0.14218	$0.289\bar{5}$	0.2795	0.2100	0.0981	0.0463
70	0.14071	0.2782	0.2621	0.1935	0.0886	0.0414
72	0.13920	0.2674	0.2460	0.1786	0.0802	0.0371
74	0.13766	0.2571	0.2311	0.1652	0.0729	$0.033\bar{5}$
76	0.13611	0.2472	0.2173	0.1530	0.0664	0.0303
78	0.13454	0.2377	0.2046	0.1420	0.0607	$0.027\bar{5}$
80	0.13296	0.2287	0.1928	0.1320	0.0556	$0.02\bar{5}0$
82	0.13137	0.2200	0.1819	0.1230	0.0511	0.0228
84	0.12979	0.2118	0.1718	0.1148	0.0471	0.0209
86	0.12820	0.2040	$0.162\bar{5}$	0.1073	0.0435	0.0192
88	0.12661	0.1965	0.1539	$0.100\bar{5}$	0.0403	0.0177
90	0.12504	$0.189\bar{5}$	0.1459	0.0943	0.0374	0.0164

Table III (cont.)

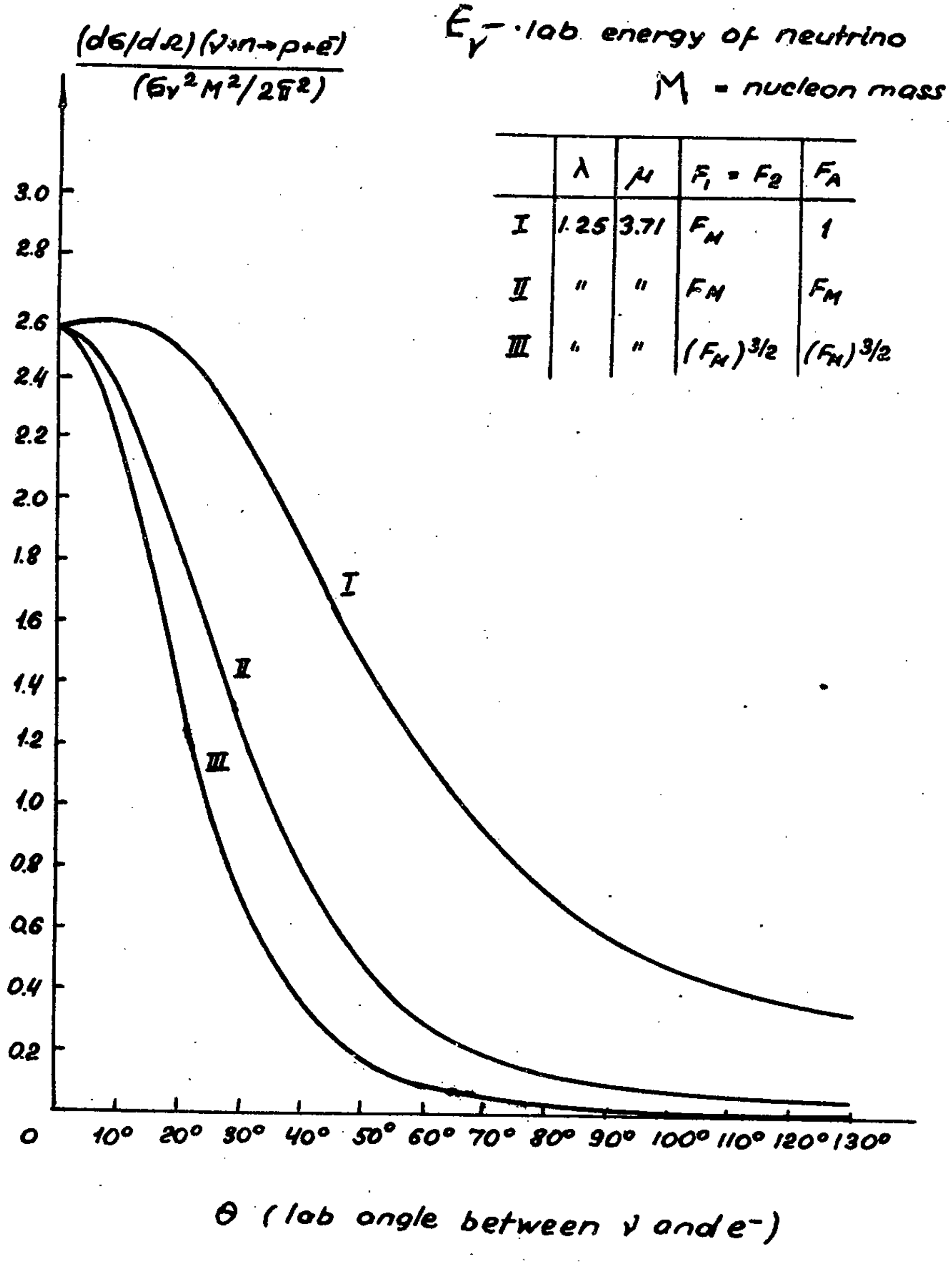
E_ν/M Θ in deg.	0.25	0.50	0.75	1.00	1.50	2.00
52	0.06942	0.0995	0.0878	$0.072\bar{5}$	0.0486	0.0313
54	$0.0654\bar{5}$	0.0883	0.0753	0.0617	0.0413	0.0264
56	0.06161	0.0781	0.0648	0.0528	0.0353	$0.022\bar{5}$
58	0.05793	0.0691	0.0557	0.0454	0.0304	0.0192
60	0.05440	0.0610	0.0481	0.0392	0.0263	0.0166
62	0.05103	0.0538	0.0416	0.0341	0.0230	0.0144
64	0.04782	0.0474	0.0361	0.0298	0.0201	0.0125
66	0.04476	0.0417	0.0314	0.0261	0.0177	0.01096
68	0.04186	0.0367	0.0274	0.0231	0.0157	0.00966
70	0.03912	0.0323	0.0240	$0.020\bar{5}$	0.0140	0.00855
72	0.03652	0.0284	0.0211	0.0183	0.0125	0.00761
74	0.03407	$0.02\bar{5}0$	0.0186	0.0164	0.0112	0.00680
76	0.03177	0.0219	0.0165	0.0148	0.01014	0.00610
78	0.02960	0.0193	0.0147	0.0134	0.00914	$0.005\bar{5}0$
80	0.02756	0.0170	0.0132	0.0122	0.00837	0.00497
82	0.02565	0.0149	0.0119	0.0112	0.00764	0.00451
84	0.02387	0.0131	0.0108	$0.0102\bar{5}$	0.00700	0.00411
86	0.02219	0.0116	0.00978	0.00945	0.00644	0.00376
88	0.02063	0.0102	0.00893	0.00876	0.00594	0.00345
90	0.01918	0.0090	0.00820	0.00814	0.00550	0.00318

Table III

Differential cross-section in the lab. system
$(d\sigma/d\Omega)\Big/(G_V^2 M^2/2\pi^2)$ for $\bar{\nu} + p \rightarrow n + e^+$

E_ν/M Θ in deg.	0.25	0.50	0.75	1.00	1.50	2.00
0	0.16016	0.6406	1.441	2.563	5.766	10.250
2	0.15994	$0.638\bar{5}$	1.433	2.540	5.669	9.978
4	0.15928	0.6321	1.408	2.472	5.392	9.216
6	0.15820	0.6216	1.367	$2.36\bar{5}$	4.968	8.106
8	0.15670	0.6073	1.313	2.224	4.443	6.827
10	0.15479	0.5894	1.247	2.058	3.868	5.543
12	0.15250	$0.568\bar{5}$	1.171	1.876	3.289	4.369
14	$0.1498\bar{5}$	0.5449	1.089	1.686	2.741	3.368
16	0.14686	0.5191	1.0032	1.496	2.247	2.556
18	0.14356	0.4917	0.9156	1.312	1.817	1.920
20	0.13998	0.4630	0.8286	$1.138\bar{5}$	1.455	1.435
22	$0.1361\bar{5}$	0.4337	0.7440	0.9793	1.1572	1.0716
24	0.13210	0.4041	0.6633	0.8359	0.9161	0.8017
26	0.12787	0.3747	$0.587\bar{5}$	0.7088	0.7238	$0.602\bar{5}$
28	0.12349	0.3457	0.5172	0.5979	0.5717	0.4556
30	0.11899	0.3176	0.4530	0.5023	0.4523	0.3471
32	0.11440	0.2905	0.3949	0.4207	0.3588	0.2667
34	$0.1097\bar{5}$	0.2647	0.3429	0.3516	0.2858	0.2067
36	0.10507	0.2403	0.2967	$0.293\bar{5}$	0.2288	0.1617
38	0.10040	0.2173	0.2560	0.2449	0.1842	0.1277
40	0.09574	0.1959	0.2204	$0.204\bar{5}$	0.1492	0.1017
42	0.09113	0.1761	0.1894	0.1709	0.1216	0.0818
44	0.08659	0.1579	0.1625	0.1431	0.0998	0.0664
46	0.08213	0.1412	0.1393	0.1201	0.0825	0.0543
48	0.07778	0.1259	0.1194	0.1011	0.0687	0.0448
50	0.07354	0.1121	0.1024	0.0854	0.0576	0.0373

(cont.)



	λ	μ	$F_1 = F_2$	F_A
I	1.25	3.71	F_M	1
II	"	"	F_M	F_M
III	"	"	$(F_M)^{3/2}$	$(F_M)^{3/2}$

Fig 7

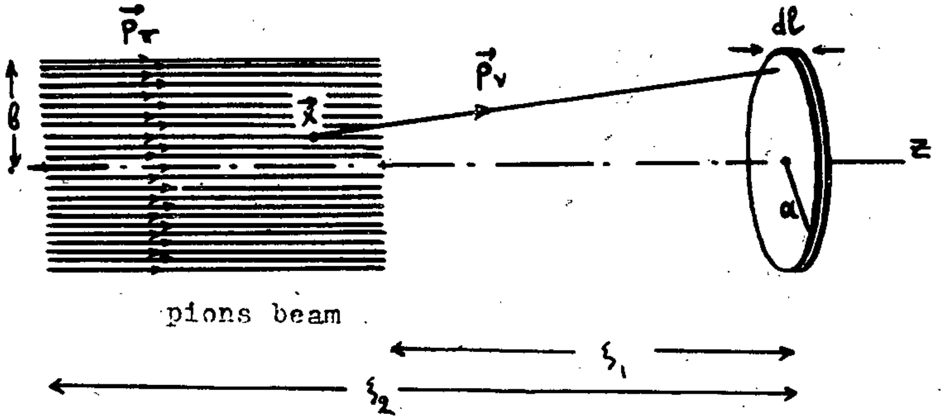


Fig. 8.

These tables show that the angular distributions in the effects $\tilde{\nu}+p \rightarrow e^{+}+n$ and $\nu+n \rightarrow p+e^{-}$ are essentially different. The total cross section for $\nu+n \rightarrow p+e^{-}$ is larger than the cross section for $\tilde{\nu}+p \rightarrow e^{+}+n$ due to a slower decrease vs. the angle (νe). These cross sections become comparable at higher energies E_{ν}, with taking into account the formfactors of nucleons which suppress the effects for large angles (large momentum transfers). Fig. 7 illustrates the angular dependence of the effect for the case E_{ν}/m =1 under three different assumptions concerning the formfactors.

Curve I corresponds to the assumption of a point formfactor of the axial interaction $F_1^V = F_2^V,\ F_A = 1$. Curve II shows the effect of the formfactor chosen for the axial interaction as well. Curve III takes into account the role of a possible intermediate boson of mass m_W =840 MeV. Formally, its role is equivalent to a certain change in the formfactor. This case possesses no well-pronounced peculiarity on the basis of which we could judge about the presence of an intermediate meson with a certain degree of confidence.

The later data on proton formfactors[30]) showed that while the magnetic formfactor falls off to zero more rapidly in the region of high momentum transfers, the charge formfactor emerges on to a plateau with a value close[+] to ~ 0.42.

[+] Strictly speaking, we can as yet only state as a certain slow-down in the decrease of the corresponding experimental values, though the appearance later on of a plateau in the region of large momentum transfers is not ruled out.

N.Cabibbo[59] recalculated the cross sections for the effects under study ($\tilde{\nu} + p \to n + e^+$; $\nu + n \to p + e^-$), taking into account the existence of such a core in the proton, extrapolating the results of measurements in the region of high energies. Table IV lists the results of these calculations.

Table IV

E_ν / M	α		β	
	$\sigma_\nu \cdot 10^{38}$	$\sigma_{\tilde{\nu}} \cdot 10^{38}$	$\sigma_\nu \cdot 10^{38}$	$\sigma_{\tilde{\nu}} \cdot 10^{38}$
0.43	0.60	0.15	0.60	0.15
0.62	0.75	0.22	0.75	0.22
0.89	0.925	0.29	0.865	0.31
1.28	0.845	0.38	1.024	0.44
1.84	0.832	0.46	1.31	0.60
2.66	0.81	0.53	1.68	0.81
3.83	0.79	0.56	2.48	0.97
5.52	0.76	0.59	3.69	1.72

Already in the first estimates made by Fakirov of the effectiveness of pion beams originating on accelerators in the production of a neutrino flux, it appeared that the geom-

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[+] α when the formfactor (56) and β the formfactor constant for a high value of q^2.

etrical factors (angular distribution of pions) made it worthwhile to locate the detecting neutrino target in direct proximity of the pion source. The neutrino-scattering "geometrical factor" proves to be stronger than the decrease of the number of neutrinos because only part of the pion beam has time to decay at close distances from the pion source. This is why recourse had to be made to the possibilities of the magnetic focussing of the pion beam.

It was supposed that a beam of monochromatic pions could be created with the aid of magnetic lenses.

The number of events $\tilde{\nu} + p \rightarrow n + e^-$ was calculated for the cases of (a) linear monochromatic pion beam and (b) wide pion beam.

In the latter case such a beam was described by the phase density of decaying pions given by the formula

$$\rho_\pi(\vec{x}, \vec{k}) = \begin{cases} \dfrac{J}{v_\pi}\, \delta(\vec{k} - \vec{p}_\pi)\, e^{-\frac{(\vec{p}_\pi \vec{x})}{p_\pi v_\pi \tau(\varepsilon_\pi)}} & \text{in } V_\pi \\ 0 & \text{outside } V_\pi \end{cases}$$

where J is the primary flux per surface unit, V_π is a cyllindrical region of a radius ℓ with the axis parallel to $\vec{P}_\pi$ (fig.8) and the detector being represented by a disc $d\ell$ thick and of a radius a, the axes of the disc and the flux coinciding.

If we put $a = b = 0.5$ m, $I = J\pi a^2 = 10^8$ pions/sec, $\mathcal{E}_\pi = 4.2$ GeV[+], the detector volume $V_{disc} = 0.52$ m^3 and $\rho_p = 1.2 \times 10^{24}$ protons/cm^3, the number of events $\tilde{\nu} + p \to n + e^+$ per day is given by

$$n = 0.075 \text{ events/day}$$

if the detector is situated at a distance of 50 m from the pion source and the latter at a distance of 25 m from the pion absorbing shielding.

Bearing in mind the idealized character of magnetic focussing, the values obtained did not look too encouraging and did not evoke any desire to recommend strongly enough this experiment for the experimenters' concrete discussion. Besides, it had become known by that time (spring 1959) that for the experimental solution of the $\nu_\mu - \nu_e$ -neutrino problem Pontecorvo proposed an experiment with a low-energy neutrinos (~ 35 MeV) on medium energy machines (under 700 MeV)

[+] In the collision of a 10 GeV proton and a nucleon 0.05 pions are produced, by an estimate60), in the energy interval of 3.7 to 5.1 GeV ($\bar{\mathcal{E}}_\pi = 4.2$ GeV) so that the above flux of pions of these energies originates from a flux $\sim 2.10^{11}$ protons/sec when 0.1 of it has been absorbed in the target, with the production of pions.

which can ensure more easily a high intensity of the pion beam. The advantages of Pontecorvo's suggestions were evident.

But actually the thing was done the hard way: the experiment was made on a high energy accelerator^{61}). The proton beam intensity was at a level of 2.4×10^{11} protons in pulse with 3000 pulses an hour which roughly corresponds to 2.10^{11} to $4 .10^{11}$ protons/sec.

It is noteworthy that the minimum proton beam intensity from which the estimates of Shwartz started was assumed equal to 5.10^{12} protons/sec. This is by an order larger than the intensity involved in the experiment.

The results are interpreted so that what we have are precisely reactions of the type

$$\nu + n \rightarrow p + \mu^-$$

$$\tilde{\nu} + p \rightarrow n + \mu^+$$

i.e., reactions with the production of a muon, and not an electron from a neutrino produced from the decay of pions. The absence of electron events($\begin{matrix} \nu + n \rightarrow p + e^- \\ \tilde{\nu} + p \rightarrow n + e^+ \end{matrix}$) warrants the conclusion that the hypothesis $\nu_\mu \neq \nu_e$ is confirmed by the experiment in question.

The main accomplishment of this experiment was that the cross section $\sim 10^{-38}$ cm^2 was measured for the first time on an accelerator.

The sensational result testifying in favour of the hypothesis of two kinds of neutrinos goes to the credit of nature as much as of the experiments. Though this author is in sympathy with the two-neutrino hypothesis, the final verdict would be premature[+] : statistics in the experiment

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[+] For example, Yamaguchi$^{58)}$ pointed out that the induced pseudoscalar interaction (M.L.Goldberger and S.B.Treiman, Phys.Rev.III (1958) 354) which is characterized by an effective pseudoscalar constant proportional to the charged lepton mass leads to an appreciable contribution to the cross sections, with the production of precisely a muon from a neutrino.

The contribution of this interaction which is usually discounted comes up to$^{58)}$ $\sim 0.17.10^{-38}$ cm^2 for $E_\nu/M_p=1$ and then decreases with neutrino energy (to $0.05.10^{-38}$cm^2 for $E_\nu/M_p=3$). True, according to these estimates, the induced pseudoscalar interaction cannot explain the pre-eminent appearance of muons in the Brookhaven experiments.

For the time being it is still possible by exercising a certain effort (hypothetically increasing the pseudoscalar interaction constant) to pull the estimates towards the pre-eminent production in the reaction under study of muons in the theory with one type of neutrinos as well (L.I.Lapidus "On the Interpretation of High Energy Neutrino Experiments", preprint, Dubna, 1962).

Recently there has appeared an item$^{139)}$ which gives

[redacted]

arguments somewhat strengthening the interpretation of the Brookhaven experiments in favour of the existence of two types of neutrinos. The item gives the lower limit of the expected number of electron events which could arise only from the vector part of the interaction if only one type of neutrinos existed. Under the conditions of the Brookhaven experiment $\mathcal{N}_e > 12$, which is considerably larger than the observed number given the most liberal selection of cases.

Of course, surprises are not ruled out.

The increase of statistics and the transition to higher neutrino energies for which the induced pseudoscalar interaction effect becomes smaller can in particular clarify the situation under discussion.

In this connection Pontecorvo's suggestion: neutrino experiment in the low neutrino energy region, i.e., experiment in a muon neutrino beam with an energy below the muon production threshold, has not yet lost its validity either.

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are too poor and any surprises in its interpretation are possible. Besides, weak interactions seem to be especially lucky in peculiar situations: once the presence of derivatives in the four-fermion interactions was thought to have been confirmed experimentally, and stowed on our bookshelves is a book[62]) expounding the theory of β-decay from the angle of the Uhlenbeck-Konopinsky ideas. Later experiment is known to have confirmed the four-fermion interaction

[redacted] 50X1-HUM

theory in its original Fermi form.

There was a time when experiment was believed to have confirmed the S, T -variant of the theory of β-decay and scientific opinion long clung to the S, T concept of weak interactions.

~~The consensus of opinion readily embraced the rule~~

$$\frac{\Delta S}{\Delta Q} = +1$$

~~which, as one may read in the fundamental papers of the time, "is extensively confirmed by experiment", while now experiment questions the rule itself.~~

God grant that this time the interpretation of the Brookhaven experiment may prove sufficiently unambiguous.

Further neutrino experiments are to solve, first and foremost, the problem of the existence of the intermediate meson. Trends in the further development of the elementary particle theory depend on the question: are there direct four-fermion interactions?

Unfortunately, the experimental possibilities for the solution of this problem also depend on where (energetically) lies the mass value of this as yet hypothetical intermediate meson (W).

If m_W lies near the nucleon mass value another stage in the neutrino experiment on the Brookhaven accelerator will be enough to settle the matter.

The immediate target of this experiment is the inquiry into the nature of the already observable events which are consistent with the intermediate meson hypothesis, according to the authors.

In this sense the authors have already altered scientific opinion by reporting five cases which can be interpreted as events pointing to the decay of the intermediate meson.

Two of these admit the interpretation $W^+ \to \mu^+ + \nu$, one can be treated as the decay $W^+ \to \pi^+ + \pi^- + \pi^+$, another allows its treatment as the electron decay of the intermediate meson ($W^+ \to e^+ + \nu$) and the fifth is possibly $W^+ \to \pi^+ + \pi^0$.

According to the estimates of ref.$^{63)}$, the experiment should have revealed 20 cases of the type $\nu + p \to W^+ + \mu^- + p$ if $m_W = 0.6\, m_p$ and two cases if $m_W = m_p$.

If all the five cases are actually W-meson cases, it is most probable that $m_K < m_W < m_p$.

Unfortunately, the interpretation of W cases of the above type is by no means unambiguous. The role of other processes under the conditions of the experiment, and in particular the spark chamber conditions which could simulate the appearance of a W-meson, has not been clear so far.

Here we have, for example, processes like

$$\nu_\mu + Z \to Z' + e^- + \mu^+ + \nu_e \qquad (\text{Fig } 18)$$

$$\nu + p \to \mu^+ + \pi^- + p$$

$$\nu + p \to \mu^+ + \pi^0 + n \; ; \quad \tilde{\nu} + n \to \mu^- + \underset{\overset{\downarrow}{\mu^+ + \mu^-}}{\omega} + p$$

$$\nu + n \to \mu^+ + \pi^- + n$$

$$\tilde{\nu} + n \to \mu^- + \underset{\overset{\downarrow}{\gamma + \mu^+ + \mu^-}}{\eta^0} + p \qquad \text{etc.}$$

$$\tilde{\nu} + n \to n + \tilde{\nu} + \underset{\overset{\downarrow}{\mu^+ + \mu^-}}{\omega}$$

Recently effects of the type

$$\nu+p\to e^-+\pi^++p\ ;\ \nu+n\to e^-+\pi^++n$$

$$\nu+n\to e^-+\pi^0+p\ ;\ \tilde{\nu}+p\to e^++\pi^0+n \qquad (83)$$

$$\tilde{\nu}+n\to e^++\pi^-+p\ ;\ \tilde{\nu}+p\to e^++\pi^-+p$$

have been evaluated proceeding from the peripheral model[64]). Here account is taken of only some graphs in the vector variant of weak interactions like

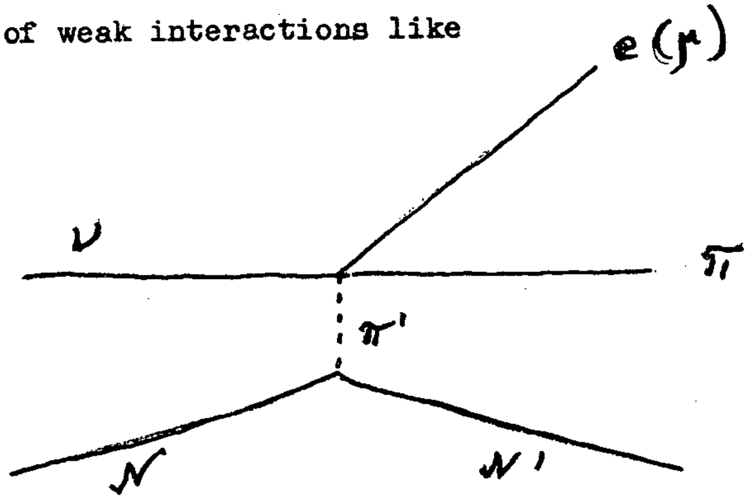


Fig.9

The graphs of the type

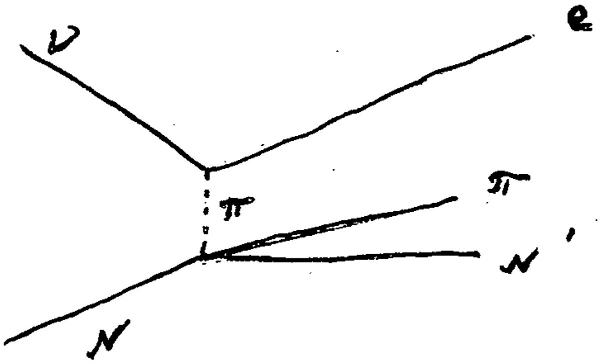


Fig.10

were neglected.

The results of numerical calculations are given in fig.11

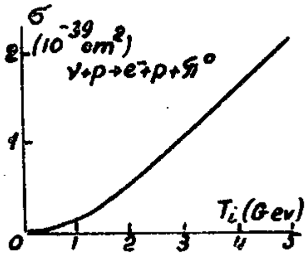


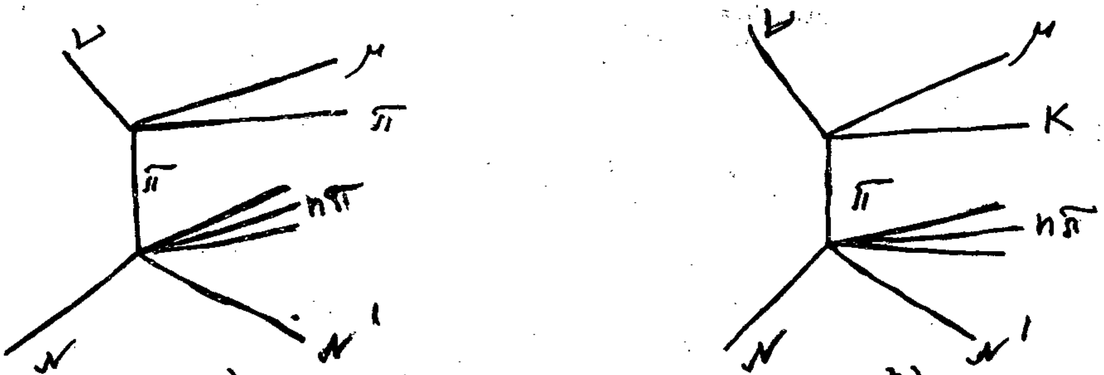
Fig.11

All cross sections of the processes under study (§3) are close to each other.

In their calculations the authors introduced for the corresponding ~~graph point~~ vertex the electromagnetic formfactor of a pion according to ref.$^{65)}$.

Of course, the use of the speculative electromagnetic pion formfactor in the concrete form$^{65)}$ and its extrapolation to arbitrarily large momenta are no less risky than, for example, the use in the asymptotic region of the Hofstadter formfactor for the reaction $\nu + p \rightarrow n + \mu$ .Still, some idea of the order of magnitude of the cross sections, not too far removed from the truth, can be gained along these lines as well.

A large number of channels of a reaction of type (83) and several graphs left out of consideration, in particular the graphs



a) b)

Fig 12

should be taken into account in the discussion of the level of background of the events due to different inelastic processes66). Despite the grossness of the estimates of the inelastic effects, it is probable that several events of this type could have been observed under the conditions of the Brookhaven neutrino experiment. Under the same conditions the cross section of the $\tilde{\nu}+p \to \underset{\Sigma^0}{\Lambda^0}+\mu^+$ process may come up to $\sim 10^{-39}$cm^2 140). Furthermore, it is shown by the estimates of the multiple production of pions in neutrino-nucleon collisions64) (reactions of the type $\nu+N \to \pi+e+N+\pi$) even among the observed cases of neutrino-nucleon interactions it is impossible to rule out single cases of pair pion production effects ($\to \mu+\pi+\pi$). According to the curves of fig.13 these cross sections account for a fraction of one percent of the main cross section observed.

The estimate given by Nguyen van Hieu[66]) for the pole graphs of the multiple pion-nucleon production accompanying the appearance of a π- and K-meson (fig.12a and fig. 12b) proves to be of the same order as in ref.[64]).

For the multiple production of pions on a nucleon from a neutrino of energy E_ν =1 GeV and E_ν =5 GeV the cross sections (fig.12a) are $2.10^{-40}cm^2$ and 3.10^{-39} cm^2 respectively.

For the multiple production of pions together with a K-meson (fig.12b) the cross sections are estimated as $10^{-40}cm^2$ for E_ν =2 GeV and $5.10^{-40}cm^2$ for E_ν =5 GeV.

The conspicuously high energy-dependence of the cross sections for inelastic processes in the asymptotic region ($\sigma \sim E^2$)[64]) is most likely due to the ~~grossness~~ roughness of the estimates.

It is possible that for high neutrino energies the inelastic process cross sections are actually larger than the cross section $\nu + N \to N + \mu$.

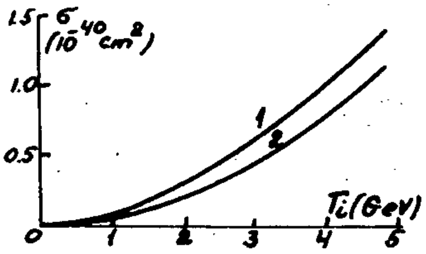


Fig.13

Curve I represents the cross sections $\nu+p$ and $\tilde{\nu}+n$.

Curve 2 corresponds to the cross sections $\tilde{\nu}+p$ and $\nu+n$.

Perhaps more statistics and a better resolving power of means of observation will be able to furnish an unambiguous interpretation of W events in the Brookhaven experiment as well.

It should be noted that the observation of the production of W^+, W^- pairs from photons[67]) under the conditions of the Boston electron accelerator may prove more effective in the solution of the problem if m_W does not exceed $2m_p$.

Here the selection of W cases by fast μ and e particles flying backward is all the more effective the higher the mass of the intermediate boson. Of course, in the observation of the electromagnetic production of W -mesons disintegrating over the channels $\mu+\nu$ and $e+\nu$ there will occur essential difficulties in the form of a strong background of e^+, e^-; μ^+, μ^- pairs. But it is not clear to what extent these difficulties are unsurmountable if the W-meson decay products are observed in the back halfsphere, in the backward direction. These problems require more thorough studies and estimates.

Unfortunately, the experiment in which a W -meson is produced by a neutrino ($\nu + Z \rightarrow Z' + \mu + W$) is not free either from the background making the identification difficult. These difficulties mount for larger masses of the contemplated W-meson.

Another major problem of neutrino experiments on large accelerators is concerned with the possible formfactors suppressing the growth of the weak interaction cross sections with energy.

The Brookhaven experimental data do not as yet answer this question.

Neutrinos with $E_\nu \sim 1$ GeV play the main role in a neutrino flux from 15 GeV protons[+]. Yet with these energies the expected effect of the formfactor on the total cross section is still not very significant.[+] The selection of cases $\nu + n \to p + \mu^-$ with large ($\nu\mu$) angles would be more indicative.

For example, according to table III for $E_\nu = 1$ GeV and 50^0 the cross section of the process is 0.47×10^{38} cm^2, and for the same angle, but for $E_\nu = 2$ GeV the cross section decreases by a factor of 3: $0.15.10^{-38}$ cm^2.

As follows from the curves of fig.7 this nearly two third decrease of the cross sections occurs mainly due to the formfactor accepted.

Unfortunately, the number of neutrinos originating in a flux of protons of the given energy decreases rapidly with energy.

As is clear from the curves of fig.14,

[+] A neutrino flux from 15 GeV protons was used in the Brookhaven experiment^{61}).

[+] Measurement of the absolute value of the cross section for one given value of neutrino energy will not clarify the situation essentially if $E_\nu \sim 1$ GeV. To be able to judge reliably about the role of a possible formfactor in the region $E_\nu \geq 1$ GeV it is necessary to track the variation of the cross section with energy E_ν. It is desirable to have relatively accurate

data at least for two values of energies E_ν ;for example, E_ν = 1 GeV and E_ν= 3 or 5 GeV.True,knowledge of the cross section in the region $E_\nu > 10$ GeV where it becomes a constant for many formfactors under discussion would be quite essential for the problem under consideration.

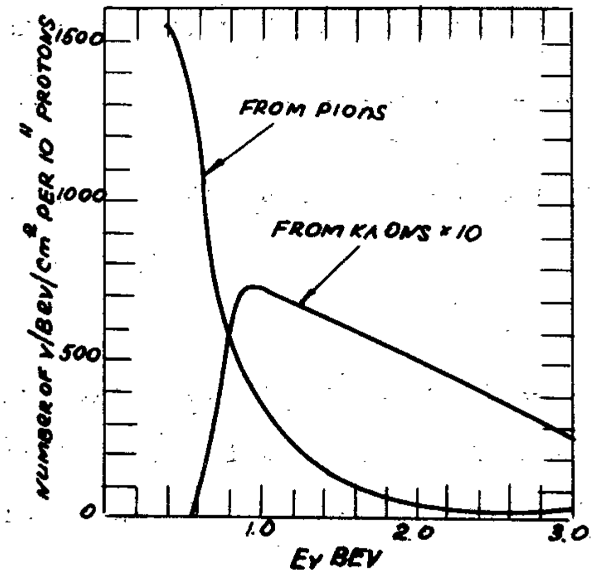


Fig.14

the energy neutrino spectrum expected under the Brookhaven experimental conditions from a 15 GeV proton flux actually decreases rapidly with the neutrino energy.

The number of neutrinos with E_ν =2 GeV decreases by more than a factor 10 as compared with the number of neutrinos with E_ν =1 GeV if the neutrinos from the decay of pions is meant.In the region E_ν =2 GeV a somewhat larger contribution to the neutrino intensity comes from the kaons.

Judging by the curves of fig.14 it might be supposed that in the future high-energy accelerators high-energy neutrinos will be supplied mainly by kaons.This conclusion is perhaps somewhat hasty since the experimental data on the production of particles by high-energy protons (cosmic rays) are very poor as yet and rather point to the fact that the energy of the primaries is spent in its essential part on the production in a separate event of pions.Perhaps the existence of a large number of resonance states rapidly disintegrating into pions

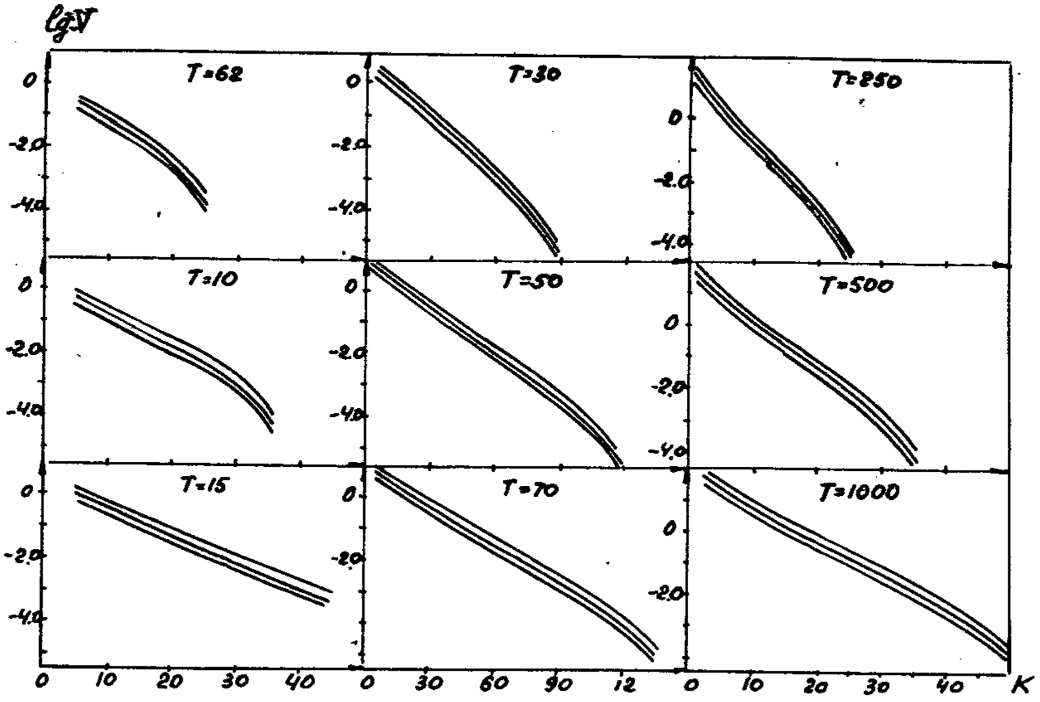

lgV
T=62
T=30
T=250
T=10
T=50
T=500
T=15
T=70
T=1000
0
-2.0
-4.0
0
10
20
30
40
0
30
60
90
12
0
10
20
30
40
K

Fig. I5.

strongly suppresses the kaon channel. The estimates of the neutrino intensity in the pion channel for different proton beam energies exceeding the limiting energies of the accelerators now in operation[68]) are given in fig.15.

These estimates are based on the relative magnitude of the corresponding phase volumes. Here T is the proton energy, K is the neutrino energy (GeV) and V is the number of neutrinos per proton collision ($E_\nu > K$; $\theta = 0$). The estimates are given for three different distances from the target.

The curves of fig.15 are interesting in the sense that neutrino energies equal to 3,10 and 20 GeV in 70,250 and 1000 GeV accelerators correspond to the neutron beam intensity with E_ν =1 GeV in a 15 GeV proton accelerator.

In other words, the cross section of a neutrino-nucleon interaction where it approaches the asymptotic value for the formfactors of ref.[27]) can only be measured on 250 to 1000 GeV accelerators.

If physics is out of luck and the intermediate boson mass proves to be of the order of dozens of GeV, the neutrino experiments for detecting intermediate mesons on ultra high energy accelerators will be increasingly difficult because of the origin of new channels simulating W-events. On the other hand, the electromagnetic method of the production of W^+, W^- pairs becomes in this case all the more convenient the higher W-meson mass. In other words, the role of the simulating $(\mu^+, \mu^-)(e^+, e^-)$ effects diminishes in this case when the products of W -meson decay (μ , e) are observed in the direction inverse with respect to the incident γ -quantum beam.

6. Possibilities for Neutrino Experiments in Cosmic Rays

Of considerable interest are the neutrino experiments for neutrino energies from $\sim 10^{10}$ to 10^{12} eV.

Acceleraters will not offer such opportunities too soon.

Estimates (fig.15) show that with the proton beam intensity $\sim 10^{11}$ proton/sec, only in 250 GeV proton accelerators does the neutrino beam intensity with $E_\nu = 10$ GeV roughly correspond to the neutrino beam intensity with $E_\nu \sim 1$ GeV under the conditions of the Brookhaven experiment. A 1000 GeV proton accelerator increases the neutrino beam energy to no more than 20 GeV.

To obtain the intensity under discussion for a neutrino beam with an energy of $4-5.10^{10}$ eV from a 1000 GeV proton accelerator it is necessary to raise the proton beam intensity by two orders or so (up to 10^{13} proton/sec). These estimates show that when designing the future proton accelerators of the highest energies attainable it is worthwhile to put in much time and effort to reach a proton beam intensity of 10^{13} proton/

sec. The accelerator experiment with neutrinos of the energy and intensity under discussion will hardly be feasible earlier than in a decade.

It should also be emphasized that the difficulties of the neutrino experiment become more formidable as we move into the region of high neutrino energies ($E_\nu \gtrsim 10$ GeV): high energy pions decay more slowly and the larger distances to the neutrino detectors lead to higher neutrino beam intensity losses per detector surface unit. The energy spectrum of the pion beam is intensity-deficient in the region of very high energies.

An important advantage of the current neutrino experiment for studying weak interactions is the purity of the neutrino beam behind a shielding absorbing all other kinds of radiation.

However, 2.10^{-11} eV μ-mesons can pass a layer of water 1 km thick. In other words, for such an energy the muon background will present formidable difficulties.

If the intermediate meson mass proves to be much larger than the nucleon mass (say, $m_W = 10\, m_p$ or $100\, m_p$) the neutrino method of detecting the intermediate meson will be complicated by many factors. Besides, the cross section for the production of the intermediate meson from the neutrino decreases rather rapidly as the W-meson mass increases.

A high energy neutrino flux originating from the decays of π and K-mesons generated in the atmosphere by cosmic radiation protons reaches the surface of the earth.

The energy spectrum of this neutrino flux can be determined by the corresponding experimental muon spectrum under the assumption that all muons observed in the cosmic rays originate in the pion decay.An error due to that part of the muon flux which originates from the K -meson decays is neglected in these estimates.The assumption underestimates somewhat the high-energy part of the neutrino spectrum.

In the $\pi \to \mu + \nu$ decay in the eigen system of coordinates the neutrino carries away roughly 30 percent of the proper pion energy.In the K -meson decay this proportion increases up to 90 percent.

Anyway,we do not overestimate high-energy neutrino fluxes by regarding pions as the sole source of muons.

The energy spectrum of the flux has practically its own upper limit;very rapid pions originating in the terrestrial atmosphere have no time to decay because of the relativistic increase of life time~~/~~As they reach the dense terrestrial strata they lose their energy as a result of strong and electromagnetic interactions.This natural limit lies somewhere near $\sim 10^{12}$eV (the free path being $\sim$ 30 km).

The unique possibilities for a neutrino experiment in cosmic rays stem from the fact that the small cross section for the neutrino-substance interaction allows the experiment to be made deep underground,separating the muon-producing (and perhaps electron-producing) reactions from the neutrinos coming from the lower half-sphere, i.e., passing through the earth.

Such conditions may in principle exclude the cosmic ray background completely.

In cosmic rays all known particles except neutrinos are absorbed by dosens of miles of substance and thus completely screened by the planet provided the depth of the detecting installation is sufficiently large to neglect a rather improbable high-energy muon scattering backward, which can in principle simulate the effect under study.

Another and perhaps the most essential peculiarity of the ~~origin~~ manifestation of the concrete effect $\nu + \mathcal{N} \rightarrow \mathcal{N}' + \mu$ under the conditions of cosmic experiment is that the detecting installation collects the effect from a vast mass of substance underneath.

The muons lose, indeed, their kinetic energy only in the ionisation of the substance. Muons with the primary energy of 10^{11} eV pass the layers of substance equivalent in absorbing capacity to roughly 50 atm or half a kilometer of water. It is from a target represented by such layers under the muon-detecting installation that the effect under discussion must accumulate.

Though the energy neutrino spectrum rapidly decreases with energy, the above muon accumulation effect leads (under the assumption of the linear increase of the cross section vs. energy) to the count of events being sensitive to the upper limit of the energy neutrino spectrum. It is precisely this peculiarity of observation of the production of muons from neutrino-substance interactions that makes it very convenient for checking the assumption of the linear increase of the cross section with energy.

A third essential peculiarity of the cosmic experiment is the possibility of using, under good screening conditions, a subterranian installation with large areas of detecting devises, viz., of the order of hundreds of square metres.

It is shown by elaborate estimates that these peculiarities of the cosmic experiment make it possible in principle, though difficult of realization.

The difficulty is rather on a psychological plane. The fact is that the physicists dealing with accelerators are well used to the industrial tenor of modern experimentation, while cosmic ray experiment is only in the first stage of its industrialization. The cosmic ray experimenter's psychology is still constrained in more respects than one by the outdated scale of experiment. Cosmic rays may yet contribute heavily to the physics of elementary particles if the experiment in this field has been revolutionized on the scale of modern accelerator techniques.

In some of the first papers concerned with this problem[29,57,69]) the neutrino spectrum was determined by the experimental muon spectrum[70]). The analytical form of the neutrino spectrum was approximated by the following expressions

$$f(E_\nu)\,dE_\nu = 5.5\times10^{-3}\,\frac{dE_\nu}{E_\nu^{2.5}} \qquad (1\ \text{GeV} < E_\nu < 30\ \text{GeV})$$

(84)

$$= 6\times10^{-2}\,\frac{dE_\nu}{E_\nu^{3.2}} \qquad (30\ \text{GeV} < E_\nu < 300\ \text{GeV})$$

where the energy is in GeV.

The path (R) of a muon in the ground (Z =10, A =20 and density ρ =2) can be taken to be

$$R = 2.3\times E_\mu\cdot10^{2}\ \text{cm.} \qquad (85)$$

The count of muons in the installation is proportional to the muon path in the ground or, on the basis of eq.(84), to its energy.

Unlike the muon, the electron is absorbed rapidly by the ground due to its low penetrating capacity. This means that the count of the $\nu_e + N \rightarrow e + N$ effect depends, unlike that of the $\nu_\mu + N \rightarrow N + \mu$ effect, on an extra degree of E_μ .

Observation of the $\nu_\mu + N \rightarrow N + \mu$ effect proves more expedient than $\nu_e + N \rightarrow N + e$ even if $\nu_\mu \equiv \nu_e$. If $\nu_\mu \equiv \nu_e$ the possibility of registering high-energy electrons will prove still poorer since high-energy neutrinos ($E_\nu \gg$ GeV) originate from the decays of pions (kaons) i.e., they must be in the main muon neutrinos.

In the framework of the available experimental facts and theoretical concepts the following reactions for neutrinos and antineutrinos produced from pion decays can be supposed:

$$\begin{array}{ll} \text{a.} & \nu_\mu + n \rightarrow p + \mu^- \\ \text{b.} & \tilde{\nu}_\mu + p \rightarrow n + \mu^+ \\ \text{c.} & \tilde{\nu}_\mu + n \rightarrow \Sigma^- + \mu^+ \\ \text{d.} & \tilde{\nu}_\mu + p \rightarrow \Sigma^0 + \mu^+ \\ \text{e.} & \tilde{\nu}_\mu + p \rightarrow \Lambda^0 + \mu^+ \end{array} \qquad (86)$$

These reactions can be accompanied by the production of one pion or many pions. Thus

$$\nu_\mu + n \rightarrow p + \mu^- + n_\pi \pi . \qquad (87)$$

where n_π is an integer.

+ The notations ν_μ and $\tilde{\nu}_\mu$ have a relative meaning here: it is inessential as yet which is a particle and which is an antiparticle "in point of fact".

Besides, kaons may be produced if the corresponding selection rules with respect to the strange number are fulfilled.

$$\tilde{\nu}_\mu + n \rightarrow \Xi^- + \mu^+ + K^0 \qquad (88)$$

$$\nu_\mu + n \rightarrow p + \mu^- + K^0$$

etc.

We can estimate the possibilities of the cosmic ray experiment for checking the energy dependence of effects like (86) in the energy region $E_\nu \gg 1$ GeV.

The cross section of reaction (a) when $E_\nu \gg 1$ GeV can be taken in the form

$$\sigma_\nu \approx 1.5 \times 10^{-38} E_\nu \, . \qquad (89)$$

For reaction (b) σ is less by a factor of 3

$$\sigma_{\tilde{\nu}} \approx 0.5 \times 10^{-38} E_\nu \, . \qquad (90)$$

For the other reactions (c),(d) and (e) the cross section also equal to (90) is taken. This assumption may prove to be wrong and the cross sections for these reactions may turn out to be smaller, but this circumstance will not change essentially the final result. It should be borne in mind that a large number of other channels of a reaction like (87), (88) etc. is neglected in this case, and these compensate, presumably, this error ("1/2 effect") **if it really** exists.

The muon energy spectrum in neutrino-induced reactions is homogeneous and in the reactions with antineutrinos $\sim E_\mu^2$ or rather

$$E_\mu \left(E_\mu - \frac{\mu^2}{m_d} \right) dE_\mu \qquad (91)$$

The paths of the muons produced in these effects can be respectively taken

$$R_1 = 2.3\left(\frac{1}{2} E_\nu - E_{thr} + \frac{E_{thr}^2}{2E_\nu}\right) \cdot 10^2 \, cm \qquad (92)$$

$$R_2 = 2.3\left(\frac{3}{4} E_{\tilde{\nu}} - E_{thr} + \frac{E_{thr}^4}{4E_{\tilde{\nu}}^3}\right) \cdot 10^2 \, cm \qquad (93)$$

Here $E_{thr.}$ is the threshold energy, and only muons with energies $E_\mu > E_{thr.}$ are registered. Because of a possible background from the scattered cosmic ray muons $E_{thr.}$ cannot be taken small. The lower allowable value of $E_{thr.}$ can be obtained from the background estimates for different depths of underground experimental installations. Further calculations are given for two values of $E_{thr.}$ equal to 0.5 and 5 GeV respectively.

The number of events—the flux of muons (N_μ) through a surface S in a solid angle π (120° cone) is

$$N_\mu = \pi \int \left(\sigma_\nu R_1 + 4\sigma_{\tilde{\nu}} R_2\right) \frac{f(E_\nu)}{2} \, dE_\nu \, \rho \, \frac{N_{Avog}}{2} \cdot S \qquad (94)$$

where σ_ν and $\sigma_{\tilde{\nu}}$ are given by eqs.(89) and (90), R_1 and R_2 by eqs.(92) and (93), $f(E_\nu)$ by the neutrino spectrum according to eq.(84) and ρ is the ground density assumed to be equal to 2 when counting the events. The factor 1/4 in eq.(94) arises because the number of ν_μ and $\tilde{\nu}_\mu$ in the spectrum (E_ν) is assumed equal. The number of neutrons and protons in the ground is also roughly equal.

If the muon registration energy threshold is assumed to be 0.5 GeV one meson per three days will pass through an area of 1000 m^2 (under the above assumptions). If the threshold is 5 GeV (i.e., 10 times as large) the count decreases to no less than 1 meson per 5 days. These estimates show that the effect under study (i.e., the count of events) proves actually sensitive to the upper limit of the neutrino spectrum (84) and is suitable in principle for detecting the growth of weak interaction cross sections in the region of $E_\nu \sim 10^{11}$ eV if this growth actually exists.

Several arguments are known to exist in favour of the fact that cross sections (89) must cut off at some energies. Obviously, these cross sections cannot increase infinitely with energy.~~For energies $E_\nu >$ 300 GeV in the c.m.s. the cross sections begin to contradict the unitarity property.~~But the question remains: at what energies $E_\nu < 300$ GeV the energy dependence of cross sections begins changing essentially?

The extrapolation of the experimental data with respect to the Hofstadter formfactor, its use as the formfactor for weak interactions as well leads, according to ref.[27]), to a constant (neutrino energy-independent) cross section (10^{-38} cm^2 approx.).

With such a formfactor, large momentum transfers to the nucleon will be suppressed and muons in the c.m.s. will be produced in a cone directed forward (in the direction of the incident $\tilde{\nu}$ or ν) and narrowing with the growth of energy.

In this case the muon energy in the laboratory system is close to the neutrino and antineutrino energies and their path can be estimated as

$$R_1 = R_2 = 2.3 \times (E_\nu - E_{th_2}) \cdot 10^2\,\mathrm{cm} \tag{95}$$

By a formula similar to eq.(94) we find that in the case of such an essential change of the interactions on the nucleon length one event (production of a muon) can be detected by the installation (with the same parameters as above) for 30 days. In other words, with a continuous growth of the cross section with energy, the muon flux through the detector surface is approximately 10 times as large.

Strictly speaking, in the cosmic neutrino experiment under discussion it is not the "elastic" process effect

$$\nu_\mu + N \rightarrow N' + \mu$$

that is measured but actually the measurement is made of the total cross section

$$\nu_\mu + N \rightarrow N' + \mu + \text{everything that may occur.}$$

It is not impossible that the large number of the channels of new reactions originating with the growth of neutrino energy make so essential a contribution to the total cross section that this effect may on the whole increase linerarly with energy up to close-to-critical values even taking into account all natural dynamically deformable formfactors in each of these channels.

Intermediate Boson

If weak interactions actually occur via the hypothetical intermediate boson W of mass $m_W > m_K$ decaying in particular by the scheme

$$W^\pm \rightarrow \mu^\pm + \nu(\bar{\nu})\;;\; W^\pm \rightarrow e^\pm + \nu(\bar{\nu})$$

probably the most suitable effect for detecting the W-meson would be the production of the W -meson from the neutrino in the Coulomb field[28]) [+]

$$\nu + Z \to W^{+} + \mu^{-}(e^{-}) + Z' \to \mu^{+} + \mu^{-}(e^{-}) + \nu' + Z', \text{ or, } e^{+} + \mu^{-}(e^{-}) + \nu' + Z'$$

$$\tilde{\nu} + Z \to W^{-} + \mu^{+}(e^{+}) + Z' \to \mu^{-} + \mu^{+}(e^{+}) + \tilde{\nu} + Z', \text{ or, } e^{-} + \mu^{+}(e^{+}) + \nu' + Z' \qquad (96)$$

where Z designates the nucleus of charge Z .

The part of the effect due to the Z^2 -dependence of the cross section is given by the expression

$$\sigma = \frac{1}{6\pi\sqrt{2}} \frac{Z^2}{(137)^2} G_W \left(\ln \frac{2E_\nu q_0}{m_W^2} \right)^3 \quad \text{when} \quad E_\nu \gg \frac{m_W^2}{2q_0} \approx 2\,\text{GeV}. \qquad (97)$$

For the intermediate boson the value of its mass equal to the kaon mass is accepted here. In other words, the lowest allowed value of the hypothetical intermediate boson mass is taken for the estimates.

It can be considered that eq.(97) estimates the effect from the spectrum of a neutrino with $E_\nu \geqslant$ 10 GeV.

[+] See also B.Pontecorvo and R.Ryndin, The High-Energy Conference in Kiev, 1959.

Putting $Z = 10$ we can write cross section (97), with parameters accepted, in the form

$$\sigma = 10^{-36} \times \left(\ln \tfrac{1}{2} E_\nu\right)^3 \qquad (98)$$

The flux of muons from the ground layers under the installation produced by the neutrino spectrum section with $E_\nu \geqslant 10$ GeV can be given by the formula

$$N_\mu = 3\sigma_0 \frac{N_{Avog}}{A} \rho\, 2.3 \times 10^2 S \int_{10}^{300} f(E_\nu) \frac{1}{3}\left(E_\nu - 2E_{thr} + \frac{E_{thr}^2}{E_\nu}\right)\left(\ln \frac{E_\nu}{2}\right)^3 dE_\nu \qquad (99)$$

If $S = 10^3$ m^2 and the detected muon energy $E_\mu > 1$ GeV ($E_{thr} = 1$ GeV) the number of counts proves, according to eq. (99) equal to 2 per day.

The peculiarity of the $\nu + N \rightarrow \mu + N'$ effect should be emphasized once again with respect to the cosmic ray experiment.

If the same effect from the same neutrino spectrum had been collected from a target 1 m thick and of the same area the number of counts would prove less in the case of an intermediate boson by a factor of 30 +.

\+ In the case of the direct $\nu + N \rightarrow \mu + N'$ interaction less by a factor of 15 to 20.

[redacted]

In other words, the accumulation of muons in the cushion under the installation yields in this case a roughly 30-time increase of the effect. Naturally, for $\nu+\mathcal{N}\rightarrow\mathcal{N}'+e$ electrons with their small path the count of events essentially decreases.

Estimates show that if there is an intermediate meson of a mass less than the nucleon or linear growth of the cross sections $\nu\mathcal{N}$ with energy the count of the number of events (muons) can be the same. Still, these two effects can be distinguishable. Qualitatively, these effects differ in that in the first case one muon is produced in the $\nu+\mathcal{N}\rightarrow\mathcal{N}'+\mu$ reaction and in the second case a pair of muons is produced ($\nu+Z\rightarrow$ $\rightarrow W^{+}+\mu^{-}+Z'\rightarrow\mu^{+}+\mu^{-}+\nu'+Z'$).

Thus, the registration of muon pairs in the experiment under discussion may point to the course of the process through the intermediate W -meson. The dependence of the number of events on the energy threshold of the registered muons also differs from effect to effect. The investigation of this dependence may also be a method for differentiating the effects.

The study of the Z -dependence of the effects is likewise a way, in principle, of differentiating them.

Cross section (97) decreases rather rapidly as the mass m_W of the intermediate meson increases.

In the estimates of the neutrino fluxes in the cosmic experiment the neutrinos which originated in the terrestrial atmosphere from muon decays were not taken into account.

[redacted]

The most detailed calculations of the neutrino fluxes in the terrestrial atmosphere are given by Zatsepin and Kuzmin$^{71)}$. The authors have shown that comparable neutrino fluxes are produced as a result of $\pi \rightarrow \mu + \nu$ and $\mu \rightarrow e + \nu + \tilde{\nu}$ decays. The estimate of the muon energy losses prior to the muon decay changes little the intensity of the neutrino flux from the $\mu \rightarrow e + \nu + \tilde{\nu}$ decay. The neutrino fluxes in the atmosphere are distributed anisotropically. The extent of anisotropy[+]

$$P^{\nu}(E, \pi/2) \Big/ P^{\nu}(E, 0)$$

increase with the neutrino energy growth up to 10^{12} eV, tending to approximately 10 for the $\pi \rightarrow \mu + \nu$ decay.

For the $\mu \rightarrow e + \nu + \tilde{\nu}$ decay neutrinos the anisotropy comes up to ~ 300 for these energies.

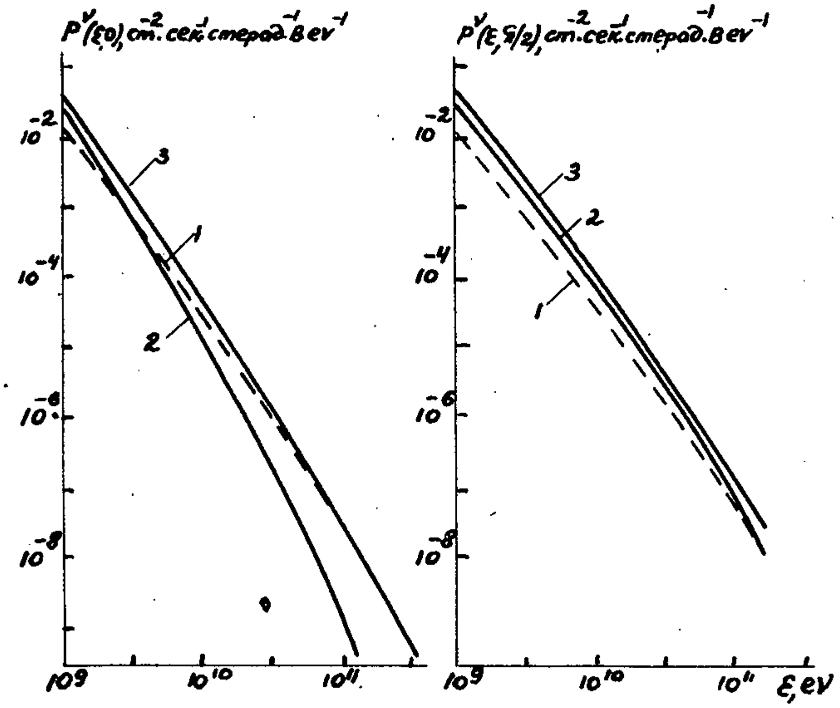
In other words, a higher energy muon may decay on a longer muon path in the atmosphere (slanting fall).

This also means that electron ($\mu^{+} \rightarrow e^{+} + \nu_{e} + \tilde{\nu}_{\mu}$) neutrinos of high energies should be expected "running from the horizon".

Fig.16 represents the neutrino energy spectra in ver-

[+] $\theta = 0$: vertical fall.

tical and horizontal fluxes[72]).



Differential neutrino energy spectra for $\pi \to \mu + \nu$ decay (curve 1), $\mu \to e + \nu + \tilde{\nu}$ decay (curve 2) and the summary one (curve 3) for the angles $\theta = 0$ and $\theta = \pi/2$.

Fig.16

The calculations of ref.[71]) increase, as against the estimates of ref.[69]), the vertical neutrino flux of energies $E_{\nu} \gtrsim 1$ GeV approximately 5 times. Probably, the largest error in the estimate of the neutrino flux originating in the terrestrial atmosphere comes from neglecting the role of kaons, but this error decreases the intensity of the high-energy part of the neutrino spectrum. As for high-energy neutrinos

($E_\nu \gtrsim 1$ GeV) coming from the depth of the universe, the cosmic neutrinos proper, the isotropic part of this possible radiation is probably considerably weaker in intensity than the neutrino spectrum originating in the atmosphere. Probably, there are grounds to believe that the cosmic rays are produced in the shells of new and supernew stars[73].

According to radioastronomic data, there are many relativistic electrons in the expanding shells of these stars. In the Crab Nebula the electron energy in the envelope is estimated to be 10^{50} to 10^{53} GeV ($E_e \gtrsim 0.25$ GeV), the electron spectrum decreasing as $1/E - 1/E^{1.5}$. If the electrons are produced as a result of nuclear collisions, there are three neutrinos of approximately the same energy for each electron. According to the estimates by maximum data (and assuming that the electrons have been accumulating for 900 years, $R = 5.10^{21}$ and $E_{max} = 10^3$ GeV it can be found that the high-energy neutrino flux from the Crab to the Earth may have the spectrum $\frac{3\cdot 10^{-5}}{E}\,\mathrm{sec}^{-1}\,\mathrm{cm}^{-2}$.

The presence of high-energy photons beyond the atmosphere might be an argument in favour of the existence of at least other such fluxes of bona fide cosmic neutrinos.

A peculiarity of the neutrino experiment in cosmic rays is the possibility of using giant "targets". Thus, in Reines'[141] installation now designed 10^9 g of water) is used as the "target". Since the muon detector receives a considerable part of muons from the deep layers under the detecting installation, the scheme represented in fig.17

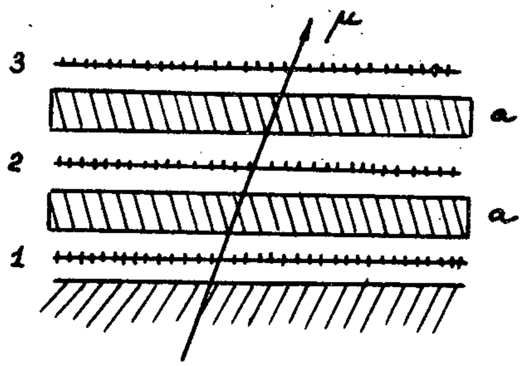


Fig.17

seems more expedient.

Here 1,2 and 3 are the mosaic layers of scintillation counters. These layers are situated sufficiently far from one another and with their aid the trajectory of a muon passing through the installation is determined and the relative delay times are measured, which makes it possible to isolate mesons going from the lower hemisphere. Located between the scintillators is an absorber whose total thickness determines the muon registration energy (E_{thr}).

One of the main difficulties of the neutrino experiment in cosmic rays is the muon cosmic radiation background. The experiment requires large areas and volumes of underground structures. Salt mines or vacancies in this mineral are probably the most convenient sites for this purpose. Reines has begun his experiment in a salt mine and it is there where its development is contemplated.

Unfortunately, there are no suitable deep lying vacuities that we know of. Therefore it is desirable to have the estimates of the muon background at depths of the order of hundreds of meters.

The estimates of the muon background for the underground neutrino experiment have been made by Zastavenko and Chilok^{74}). At a depth 4.10^4 gr the muon flux is 4.5×10^{-5} particles through 1 cm^2 per sec., i.e., 10^8 particles through 100 m^2 per month. Taken as such this number is by 7 to 8 orders of magnitude larger than the expected number of muons from the neutrino. It is assumed that the installation (fig.17) selects muons going "upwards". Therefore an estimate should only be made of the background produced by those muons which can, scattering in the ground, change their directions so that they can yield a spurious count in an installation like that of fig.17.

The effects of single as well as multiple scattering of muons leading to a change in the primary direction of a muon for a large angle θ are considered in ref.^{74}).

The angular and energy distribution of high-energy muons coming "from above" is assumed in the form

$$= \mathcal{N}_0 \frac{E^{-1.5}}{1 + \frac{E \cos \theta_c}{E_\pi}} \qquad (100)$$

$E_\pi = 100 GeV.$

$$\cos\theta_\varepsilon = \cos\theta \qquad \text{if } \cos\theta > 0.125$$

$$\cos\theta_\varepsilon = 0.125 \qquad \text{if } \cos\theta = 0.125$$

$$\mathcal{N}_0 = 0.033\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}\mathrm{str}^{-1}(\mathrm{GeV})^{1.5}.$$

The function

$$\varphi(x,\kappa,\tau)$$

giving the number of muons in the "back" cone $\vec{n}\vec{n}_0 < \tau$ at a depth x with energy κ passing through 1 cm^2 in 1 sec is expressed in the form

$$\varphi(x,\kappa,\tau) \approx 4\pi \mathcal{N}_0\, x^{-2.5} K(\kappa,\tau) \qquad (101)$$

where K is a certain function the values of which for κ =0.7,1,2,3 GeV for τ from -0.4 to -0.9 are given in table V.

The value x in eq.(101) is given in GeV; x are the ionisation losses of the muon on the vertical length of the path to a given point of the ground.

Radiation losses are essential for mesons of energies $>$ 1000 GeV.

The effect proves in the main to be determined by single scattering, with a certain correction due to multiple scattering.

At a depth 4.10^4 $\mathrm{gr/cm}^2$, i.e., for x =80 and $4\pi\mathcal{N}_0 x^{-2.5} \cong$ $=7.2\ .10^{-6}$ cm^{-2} sec^{-1}, for κ (threshold energy)= 1 GeV and

$\tau = -0.7$ we have $\varphi = 3.10^{-14}$ muons per sec. through 1 cm^2 or 3.10^{-2} muons per month through 100 m^2.

Table V

Function $K(\kappa, \tau)$

τ \ $1/\kappa$	4/3	1	1/2	1/3
-0.4	$8.29\ 10^{-7}$	$3.65\ 10^{-7}$	$2.94\ 10^{-8}$	$4.61\ 10^{-9}$
-0.5	$2.52\ 10^{-7}$	$9.47\ 10^{-8}$	$4.28\ 10^{-9}$	$3.20\ 10^{-10}$
-0.6	$7.13\ 10^{-8}$	$2.21\ 10^{-8}$	$4.96\ 10^{-10}$	$1.16\ 10^{-11}$
-0.7	$1.78\ 10^{-8}$	$4.24\ 10^{-9}$	$3.52\ 10^{-11}$	$1.71\ 10^{-13}$
-0.8	$3.49\ 10^{-9}$	$5.39\ 10^{-10}$	$9.5\ 10^{13}$	$5.65\ 10^{-16}$
-0.9	$2.90\ 10^{-10}$	$1.16\ 10^{-11}$	$3.23\ 10^{-16}$	

Resonance Antineutrino Scattering

The intermediate meson hypothesis leads to a peculiar resonance effect$^{75)}$ capable of increasing the weak interaction cross sections by many orders of magnitude.

The cross section of inelastic antineutrino-electron scattering

$$\tilde{\nu}_e + e^- \rightarrow \tilde{\nu}_\mu + \mu^-$$

estimated according to the conventional theory of the four-fermion weak interaction can be written as

$$\sigma_0 \approx \left(\frac{E_\nu}{m_e} \right) 10^{-45} \ cm^2 \qquad (102)$$

where E_ν is the energy of an antineutrino incident on an electron in the laboratory system.

The treatment of the same process via the intermediate meson

$$\tilde{\nu} + e^- \rightarrow W^- \rightarrow \tilde{\nu}_\mu + \mu^-$$

for certain antineutrino energies changes drastically the estimate of the cross section. The cross section increases by 5 to 8 orders depending on the value of the intermediate meson mass. Indeed, the cross section in this case takes on a typical resonance character

$$\sigma = \sigma_0 \frac{E_0^2}{(E_\nu - E_0)^2 + \Gamma^2} \qquad (103)$$

where E_0 is the resonance value of the incident neutrino energy

$$E_0 = \frac{m_W^2}{2 m_e}$$

Γ – designates the resonance width

$$\Gamma = \frac{m_W}{m_e} \cdot \frac{1}{\tau_W}$$

τ_W is the life time of the intermediate meson, m_W its supposed mass,

$$\tau_W = \left(\frac{m_N}{m_W}\right)^3 \cdot 10^6 \, m_N^{-1} \left(\hbar c^2\right)^{-1} \mathrm{sec} \qquad (104)$$

and the averaged cross section near the resonance is estimated in the form

$$\frac{1}{2\Delta}\int_{E_0-\Delta}^{E_0+\Delta} \sigma(E)\,dE \approx \frac{\pi}{4}\left(\frac{E_0}{\Delta}\right)\left(\frac{E_0}{\Gamma}\right)\sigma_0 \qquad (105)$$

It depends on the square of the coupling constant between the W-meson field and lepton field which is assumed identical in the case of electrons and muons (the hypothesis of universality of weak interactions).

Assuming $m_W = m_K$ where m_K is the kaon mass for resonance energy we obtain the value 2.3×10^{11} eV and width $\Gamma = 1.5 \times 10^5$ eV. The corresponding values of the quantities for $m_W = m_N$ (m_N is the nucleon mass) are $E_0 = 9.10^{11}$ eV and $\Gamma = 2.10^6$ eV.

The natural width of the resonance is very small but the resonance widens substantially because of the distribution of the target electron velocities. For the electrons with velocities equal to βc in the direction of the incident antineutrino beam the resonance energy value shifts to

$$E_0' = (1+\beta)^{-1} \cdot E_0$$

Thus the experimental value of the resonance width is estimated approximately by the expression

$$\frac{\bar{Z}}{137} E_0$$

where Z is the average atomic charge of the target substance.

In the region of resonance energies the cross section, by Glashaw's estimates, increases by eight orders of magnitude from 10^{-40} cm^2 to 10^{-32} cm^2.

Assuming an antineutrino flux of energy 9.10^{11} eV reaching the Earth's surface (antineutrinos from pion decays) as 10^{-11} cm^{-2} sec^{-2} GeV^{-1} and $E_{\nu} = 2.3 \times 10^{11}$eV as 10^{-9}cm^{-2}sec^{-1}GeV^{-1} the author points out that from one m^2 of an underground area (shielding against background) the experimenter can register two mesons ($m_W = m_K$) or 0.1 mesons ($m_W = m_\nu$) a day.

J.C.Barton[76]) reports about the results of meson flux measurements which were made at a depth equivalent to 5500 m of water for 21 days off a geomentric area equal to 0.08 m^2. The high-energy muon flux proved to be less than 0.5 m^{-2} per day. The author concludes that the mass of the intermediate meson if the latter exists is larger than the mass of the kaon.

It should be noted of course that statistics in this experiment are still very poor and it is premature as yet to pass any final judgements even on the intermediate meson mass equal to the kaon mass.

Moreover, estimates are given of the expected quantities based on the assumption of the identity of the muon and electron neutrino.

Otherwise (i.e., if $\nu_\mu \neq \nu_e$) the estimates of the neutrino fluxes involved in the $\tilde{\nu}_e + e^- \rightarrow \mu^- + \nu_\mu$ reaction lead, in the energy region of the resonance under consideration (10^{11} to 10^{12}eV), to quantities by three orders or so less since in this case only ν_e-neutrinos (or rather antineutrinos) produced in the atmosphere from muon decays ($\mu^- \rightarrow e^- + \tilde{\nu}_e + \nu_\mu$) are involved in the reaction.

In other words, if $\nu_\mu \neq \nu_e$ the expected effect (production of an intermediate meson) in the case $m_w = m_K$ falls to 0.002 mesons a day off one m^2 of target area and in the case $m_w \simeq m_W$ to 0.0001 mesons. Even if it is assumed that the neutrino flux estimates given by Glashaw are underrated by approximately by an order of magnitude[71]) all the same Barton's experiments do not yet furnish grounds for the conclusion that $m_w > m_K$.

The further search for the resonance effect in the $\tilde{\nu}_e + e^- \rightarrow \tilde{\nu}_\mu + \mu^-$ reaction is highly desirable. At installations with large target areas (1000 m^2) about 2 events a day (when $m_W = m_K$) and 0.1 events a day (when $m_W = m_N$) can be expected. If it is borne in mind that Glashaw's flux neutrino estimates are underrated by an order of magnitude the importance of this experiment becomes self-evident[+].

The peculiarity of this effect consists in that half of all muons which will originate from the intermediate boson decay will have energies > 10 GeV. The need of neutrinos of energies $> 10^{11}$eV for the realization of the resonance effect $\tilde{\nu}_e + e^- \to \mu^- + \nu_\mu$ makes this experiment intended by nature itself specially for cosmic rays[+]. For another decade or so this experiment will remain unfeasible on accelerators.

[+] More thorough estimates of the effect in general are necessary for comparison with the experiment and even for planning such an experiment. In his interesting item Glashaw$^{75)}$ gives in fact qualitative estimates.

[+] The data of ref.$^{86)}$ improve the result of ref.$^{76)}$ approximately by an order.

Perhaps, it is worthwhile to mention another possibility for the intermediate boson when the latter can be characterized by a baryon number.

For example,

$$\nu + n \rightleftarrows B \rightleftarrows e^- + p$$

Though the baryon boson has repeatedly been discussed in literature [145]) it remains a stepchild of scientific opinion. At any rate, of the lepton intermediate boson discussed above and the baryon boson the former is a definite favourite.

A very difficult experiment is undertaken for the search of the lepton intermediate boson. Though to confirm or refute the existence of the baryon boson is a problem easier by five orders or so, no special experiment seems to have been made on any existing accelerator. The ways of scientific opinion are unscrutinable. In this survey the intermediate baryon boson is in fact mentioned only in passing.

The production of an intermediate baryon boson under the resonance conditions has been considered by T.Kinoshita [146]).

Assuming the boson mass $m_B = 2300 m_e$ we can obtain the cross section for the process

$$\nu + n \to B \to \mu^- + p$$

in the resonance $\sim 7.10^{-27}\,\mathrm{cm}^2$. The resonance energy

$$E_0 = \frac{m_B^2 - m_n^2}{2m_n} = 265 \text{ keV}.$$

$$\Gamma_\nu = \frac{m_B}{m_n \tau_\nu} = 120 \text{ eV} \; ; \quad \Gamma_\mu = 0.88\,\Gamma_\nu$$

Taking into account the motion of neutrons in a real target we can come to the conclusion that the resonance conditions will be realized in a neutrino beam at 210 to 330 MeV.

Thus the effective cross section is estimated

$$\sim 2.10^{-32}\text{cm}^2.$$

This relatively simple experiment did not attract the experimenters' attention.

The decay of the baryon intermediate boson under discussion might yield slow muons, muons with energies of several tens of MeV. The argument that such effects have not been observed in Brookhaven type neutrino experiments is not always conclusive. The experiment must be specialized to detect such slow muons.

True, there are arguments which may, in the analysis of Brookhaven type experiments, bear serious evidence against the baryon intermediate boson.

The fact is that far from the resonance as well, at high energies of a nucleon-~~hitting~~ colliding neutrino, there may be numerous easily detectable inelastic processes, i.e., the production of an intermediate baryon boson with the emission of a pion, γ-quantum or, say, antinucleon is meant.

If the specific constant characterizing the interaction of a nucleon with a baryon, boson, and neutrino equals the square root of the weak interaction constant the enumerated cross sections for the effects will contain the weak constant in first power, and not squared, as is characteristic of the cross sections for the effects of the true four-fermion interactions.

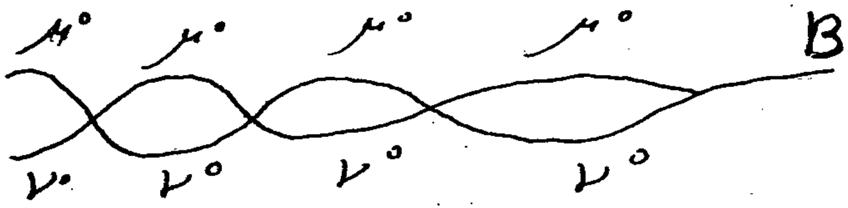
Therefore, the cross sections for the inelastic production of an intermediate baryon boson (with the emission of a pion, γ-quantum) may be by five or three orders respectively larger than the effect detected in the Brookhaven experiment.

* * *

Returning to the intermediate meson idea it should be noted that in principle there may exist a situation which is something of nature's practical joke at the theorist's expence. What is meant is the possibility of the existence of a bound state between, say, a muon and neutrino, a nucleon and neutrino in the form of a short-living vector meson, for example.+

+ The reference is to the bound states between two spinor particles one of which may possess a very small or even zero rest mass.

The four-fermion interaction in the chain approximation is graphically represented by a graph of the form



and is in general capable of leading to such pseudoscalar and vector states 19). The mass of such a boson may be considerable if the interaction of bare particles with large initial masses is involved

$$m_{\mu^0} \gg m_{\mu}^{Exp.}$$

It should be noted that in the chain approximation the mass of such a vector boson proves considerably larger than that of the pseudoscalar boson 19).

In other words, just as the effective interaction of nucleons with ρ and ω fields exists in strong interactions along with the interaction of nucleons with pion field, so, too, there might exist effective interactions with such a result as the "intermediate" meson in weak interactions along with the true four-fermion interaction.

Naturally, the intermediate-boson-minded theorists will take the path of creating a theory excluding the possibility of direct four-fermion interactions.

Many experimenters, well prepared for close cooperation with theorists, will find some further convincing evidence in favour of such a concept.

It will take years of further theoretical and experimental research to disentangle the weak interaction situation under foreseeable conditions.

Perhaps, the experiments in the region of neutrino energies of considerably larger masses of the "intermediate" mesons under discussion may furnish conclusive arguments for or against the existence of the true four-fermion interaction.

Nature has shown herself to be fond of untrivial combinations of what might seem at first glance to be mutually inconsistent concepts.

7. Neutrino-Lepton Interactions

For lepton-lepton interactions of the type $\nu + e \rightarrow \mu + \nu$ the expressions for the cross section in the c.m.s. has the same form (10).

If there are certain considerations connected with the "structure" of the nucleon concerning the restriction of the energy growth of the four-fermion lepton-baryon interaction cross sections, such considerations do not hold for lepton-lepton interactions. So far there are no experimental indications of the existence of any electromagnetic formfactor for the electron. A point electron is still used for interpreting the results of the Hofstadter type experiments.

Whereas neutrino-electron interactions are not cut off by any unknown causes at distances of the order of nucleon lengths, a peculiar formfactor smearing out the electrical charge[9]) originates at smaller distances because of the weak (νe)($\nu\mu$) interaction.

A charged muon field appears around the electron and this field distributes the electron electric charge density just as the pion field of the nucleon smears out its electromagnetic charge.

Four-fermion interactions give for the potential of such a field an expression of the type[77])

$$V \sim \left(\frac{l_e}{r}\right)^5 \frac{\hbar c}{l_0}\, e^{-\varkappa r} \sim \left(\frac{l_e}{r}\right)^5 \frac{\hbar c}{l_0} \qquad (10б)$$

where $1/\varkappa = \hbar/m_\mu c$ and m_μ is the muon mass.The muon length $1/\varkappa$ determines only a rapid decrease of the field at relatively large distances where the field is weak as it is on account of the smallness of the critical length l_0 .The charged field and the corresponding electrical charge density is distributed in the main over the region $r \sim l_0$ .If strong interactions do not suppress weak electron-baryon interactions the electron must acquire a formfactor connected with the antiproton-neutron field and charged baryon field in general.

A characteristic of four-fermion interactions is the region of the extension of these essentially different charge clouds being the same,viz. l_0 .

An inessential difference between them is only the rate of decrease in that region where the charge density is of vanishing value.This difference reduces to the difference of the quantum masses of the charged field forming the cloud around the electron,in the manifestation in eq.(10b) of the exponential factor $e^{-\varkappa_i r}$ containing the mass of the m_i, ith particle ($1/\varkappa_i = \hbar/m_i c \gg l_0$).Since what is meant in this case are the virtual processes of the graphs of the type of properly energetical graphs there are no grounds as yet to assume that the contributions of these graphs to the lepton-baryon interaction are naturally suppressed by strong interactions already in the frame work of the existing formalism.

Abstracting ourselves from this optimistic view of the difficulties of the modern field theory, we can sum up the above considerations as follows.

In the region $\ell \sim 10^{-16}_{cm}$ the electron can be expected to acquire a special formfactor of the nucleon (Hofstadter) type with a highly complex structure of the charge cloud.

If these concepts are correct the physical image of a particle like an electron receives essential contributions from all other charged particles of all masses.

It is easy to understand the tense interest of the expectation of the results of the current experiment (Panofsky) in which the electrodynamics in the scattering of colliding electron beams is checked up to the lengths 3.10^{-15}cm. If the electrodynamics is essentially violated in this region of lengths (i.e., 3.10^{-15}cm) that is some factors smearing out considerably the electrical charge of the electron originate already in this region, then weak-lepton interactions hardly can~~not~~ play an essential role in the structure of the elementary particles in general either.

If on the other hand the electron formfactor proves actually essential only in the region of the critical lengths of weak interactions, this result will at the same time mean that weak or at least weak-lepton lepton interactions actually increase with energy at any rate up to the close-to-critical energies and that weak interactions may be strong and take part in the formation of the structures of elementary particles.

Thus, a purely electrodynamic experiment (electron-electron scattering) in the high-energy region may have a decisive influence on the development of the theory of weak interactions.

The latter is not meant to underrate the fundamental importance of direct neutrino-lepton interaction experiments at ~~maximum~~ high energies.

Unfortunately, observation of neutrino-lepton interactions at high energies is still outside the capacity of the currently operating accelerators.

Indeed, cross section (10) in the laboratory system is of the form

$$\sigma \sim m_e E_\nu \qquad (107)$$

Consequently, for the neutrino energy in question the cross section of the (νe) interaction is less than the corresponding neutrino-nucleon cross sections approximately by a factor 10^3 (m_N/m_e).

If the detection of the neutrino-nucleon cross sections hovers on the margin of the experimental capacity of the most powerful accelerators of today, the cross sections smaller by three orders of magnitude require accelerators with proton intensities increased by the same three orders at least.

In detecting neutrino-electron interactions there are also specific difficulties. These interactions must be detected against the background of neutrino-nucleon effects with cross sections three orders larger than the electron-neutrino cross sections.

Only one kind of weak lepton-lepton interactions viz. $\mu \rightarrow e + \nu + \tilde{\nu}$ is known at present.

The existence of ($e\nu$)($e\nu$) interactions involves a hypothesis which deserves special discussion. The lepton-lepton interaction in its known form leads to only one type of effects: the production of a muon from a neutrino

$$\tilde{\nu} + e^- \rightarrow \mu^- + \nu$$

This effect does not depend on whether electron and muon neutrinos are identical, whether the intermediate boson hypothesis is accepted or rejected.

However, muons will originate in the target a thousand times more often from the reaction of the (νn)($p\mu$) type. Besides, and this is the main thing, the threshold of the reaction

$$\tilde{\nu} + e^- \rightarrow \mu^- + \nu$$

lies outside the energy capacity of the present day accelerators

$$E_{\nu}^{thr} \approx 11 \text{ GeV} \qquad (108)$$

The working neutrino fluxes of such energies can perhaps be obtained$^{68)}$ on proton accelerators of 250 GeV energy with $\sim 10^{14}$ protons/sec of proton beam intensity.

The latter remarks re-emphasize the importance of cosmic experiments in search of a possible resonance reactions. However, there are examples of lepton-lepton effects decreasing strongly the threshold energy of the reaction under specific conditions. For example, a neutrino can, while scattering on the nuclear Coulomb field, produce pairs of $e^- \mu^+$ particles

$$\nu + Z \rightarrow Z' + e^- + \mu^+ + \nu' \qquad (109)$$

The graph illustrating process (109) is given in fig.18

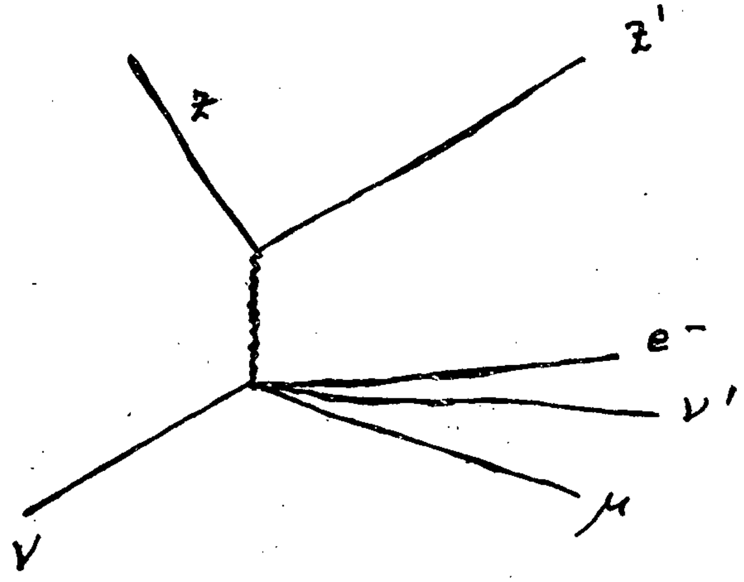


Fig.18

Participation in reaction (109) of a heavy nucleus receiving the recoil momentum decreases the energy threshold of the reaction as compared with (108) practically up to

$$E_\nu^{thr} = m_\mu + m_e + (m_\mu + m_e)\frac{(m_\mu + m_e)}{2M_Z}$$

$$E_\nu^{thr} \approx m_\mu + m_e \sim 100 \text{ MeV}. \qquad (110)$$

At a point Coulomb centre the cross section of the corresponding effect would contain in a formula of type (107) the mass of the heavy nucleus instead of that of the electron.

The specific role of the nucleus essentially changing the character of the effect drew attention to this effect[57]).

Unfortunately, the estimation of the real sizes of the nucleus strongly cuts the cross section[78]). But the advantage of process (109) as compared with the production of a muon on a free electron i.e., a sharp reduction of the energy threshold, remains essential. Bearing in mind the above remarks this circumstance is quite important, making as it does possible in principle the observation of the effect on the strong current accelerators of the nearest future. Furthermore, a characteristic of this effect--production of specific $\mu^+ e^-$-pairs--makes possible in principle to isolate the effect against the background of single muons produced in the (νN) (μN) interactions.

Not the effect (109) but the kindred effect

$$\begin{aligned} &\nu + Z \rightarrow Z' + e^+ + e^- + \nu' \qquad (1) \\ &\nu + Z \rightarrow Z' + \mu^+ + \mu^- + \nu' \qquad (2) \end{aligned} \qquad (111)$$

[+] The appearance of μe-pairs in effect (109) can easily be misinterpreted as resulting from the intermediate boson decay. Therefore, single cases of $\mu\mu$, μe-pairs cannot be considered as proof of the existence of the intermediate boson.

is calculated in ref.^{78}).

This effect implies the realization in nature of interactions of the $(e\nu)(e\nu)$ type the existence of which has not so far been evidenced by experimental data.

However, among graphs (1) estimated in ref.^{78}) there is a graph of the form of fig.18 for the case when the nuclear momentum is transferred by the electron produced.

Assuming that for energies $>$ 1 GeV the cross sections of the production of $\mu^+,\mu^-; e^+,e^-$ pairs do not differ strongly from the production of μ^+, e^- pairs (which must, of course, be specified by a detailed calculation), for lead the cross section of effect (109) may take a value close to $10^{-41}cm^2$ to $10^{-43}cm^2$.

Though this effect is too small as compared with the $(\nu N)(\mu N)$ effect it should be borne in mind that at neutrino energies lower than 11 GeV there is no $\nu + e \rightarrow \mu + \nu$ effect at all.

Some information on neutrino-lepton interactions at ~~maximum~~ high energies can be obtained, just as on neutrino-nucleon interactions, from a further analysis of the effects of higher approximation. B.Pontecorvo^{23}) drew attention to an interesting effect: in a system of a muon and electron (muonium) a muonium may, unless the process is forbidden, turn to an antimuonium

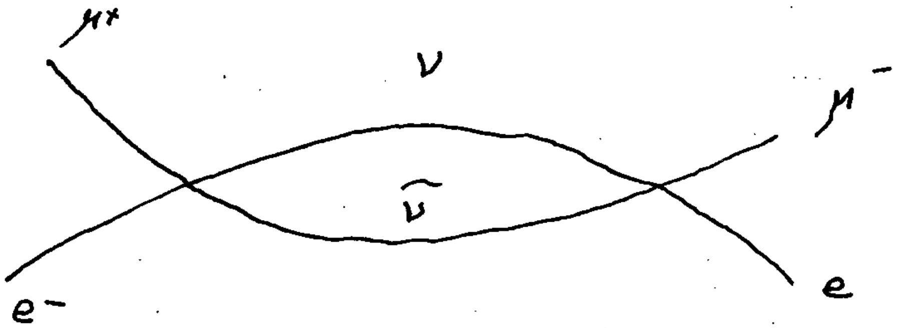


Fig.19

With the momenta of virtual states (ν and ν) cutting off at the critical value ~ 1000 MeV the probability for this process with respect to the probability of the μ^+ - meson decay is given by the quantity[24]

$$\frac{W(\mu^+e^- \to \mu^-e^+)}{W(\mu^+ \to e^+\nu\tilde{\nu})} \sim 10^{-5} \qquad (112)$$

In principle this experiment is possible though there are some specific difficulties involved in the movement of the muonium in substance.

Any experimental limits for ratio (112) cannot be indicated at present since there have been no relevant experimental attempts. If we really have $\nu_\mu \neq \nu_e$ the transition $\mu^+e^- \to \mu^-e^+$ is strictly forbidden.

In the light of the above the processes of higher orders (with respect to the weak constant) unforbidden by the possible existence of two kinds of neutrinos would be of

The weak interaction vector constant determined from O^{14} and the constant determined from the $\mu \to e\nu\tilde{\nu}$ decay are known to differ somewhat [79]).

This difference (2%) has not been explained by a rather thorough analysis of possible corrections either[79]).

As Ya.A.Smorodinski [80]) has noted, taking into account the higher approximations with respect to weak interactions could influence the difference of effective constants if the strong interactions are actually able to suppress the corresponding contributions to the effects from the high momenta of the interacting particles in the intermediate states.

It is then indeed would there arise a difference in the role of higher approximations in the $n \to p + e^- + \tilde{\nu}$ and $\mu^- \to e^- + \tilde{\nu} + \nu$ processes.

In the $n \to p + e^- + \tilde{\nu}$ process the role of the higher approximations with respect to the weak constant would be, say, negligible and taking into account the corresponding Feynman graphs (fig.20) in the $\mu^- \to e^- + \tilde{\nu} + \nu$ process would explain the observed differences in the values of the constants.

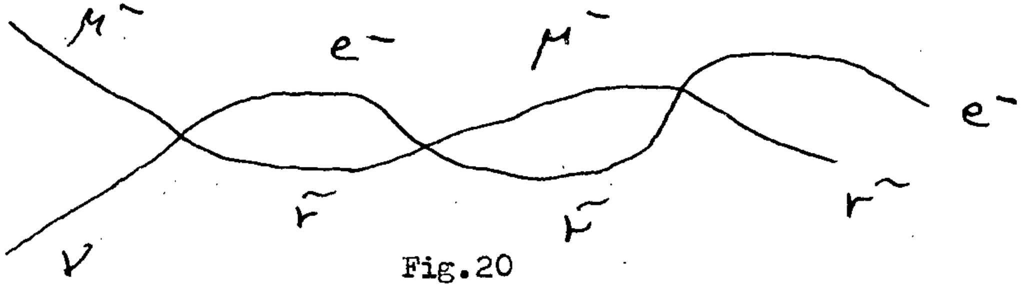


Fig.20

Unfortunately, the difference in the constants is so small that even assuming that it is entirely due to the role of strong interactions as it appears from ref.[24]), the conclusion is that the intermediate momenta in the $n \to p + e^- + \tilde{\nu}$ effect must cut off at values far removed from $K_{crit} = 300$ GeV.

It should be emphasized once again that with respect to the four-fermion interactions ($n p$)($e \nu$) there are no experimental grounds either to assume that the momenta of the intermediate states ($p_\mu^2 \neq m^2$) must be cut off at the values $K_{max} \ll K_{crit} = 300$ GeV.

This proposition is essentially connected with assumption $\nu_\mu \neq \nu_e$.

For the time being it leaves room for speculations about the existence of true four-fermion interactions up to the momenta of colliding fermions close to $K_{crit} = 300$ GeV in the c.m.s. at least in the virtual states.

8. Weak Interactions of the Type $(\alpha\beta)(\alpha\beta)$; $(\alpha\alpha)(\alpha\alpha)$

All known weak four-fermion interactions change essentially the nature of the primaries.

At present not a single case of weak interaction known can reduce to a mere scattering or colliding particles without any essential change of them.

Unless forbidden by conservation laws, all known cases of weak interactions are interpreted as the decay of the largest mass particle involved in the interaction.

Perhaps this property is a characteristic of weak interactions.Perhaps there are deeper reasons why such changes in the inner structures of particles cannot occur rapidly.Or perhaps the natural selection of weak interactions has so far restricted the range of the events observed.

Weak interactions irreducible to a decay of particles can,indeed,only be observed in weak scattering effects.Physics has merely tapped this field.

A natural question is whether there are interactions of the type $(\alpha\beta)(\alpha\beta)$ which reduce to the "weak" scattering of two particles of the type α and β into particles of the same type.In principle there may exist effects of weak neutron-proton $(np)(np)$,proton-proton $(pp)(pp)$, neutrino-proton $(\nu p)(\nu p)$,neutrino-electron $(\nu e)(\nu e)$, electron-electron $(ee)(ee)$,etc.scattering.For the time being these questions have to be addressed to nature,and not to the theory of weak interactions which does not yet exist, strictly speaking.

However,the theoretical stock contains many schemes of weak interactions of a varying heuristic value which should be scanned from time to time and compared with experiment,to test their worth under different conditions.In this respect a scheme proposed by S.A.Bludman$^{81,82)}$ a few years ago deserves notice under the assumption $\nu_\mu = \nu_e$. It appears that by expanding the M.S (6) and F.G. (7) scheme it is possible to introduce symmetrical neutral currents like $\nu\nu$, ee, nn, etc. and, which is the main thing, make them work against the effects of the type $(e\nu)(e\nu)$ leading in the graphs (figs.2,4) to the appearance of what has long been known as undesirable processes ($\mu \to e+\gamma$, $\mu \to 3e$).

Indeed, in the graphs like in figs.2,4 it is precisely the $(e\nu)(e\nu)$ interaction allowed by the conception of MC (6) FG. (7) leads to a low limiting value of the intermediate momentum.

In Bludman's scheme allowing, unlike the scheme(6)(7), neutral currents $(ee)(\nu\nu)$ along with charged currents (e.g., $e\nu$), the reciprocal effect appears82) to cancel the effects of the $(e\nu)(e\nu)$ type.

In other words, in this theory there are no effects $\mu \to e+\gamma$; $\mu \to 3e$ described by the graphs of type 2 or 4 corresponding to the second approximation of perturbation theory with respect to the weak constant.

True enough, this does not forbid25) the effect $\mu \to 3e$ occurring, according to graph 3, via the known $(\mu\nu)(e\nu)$ interactions. But this effect is of a higher order.

Thus, the neutral currents were banished from the theory to avoid the undesirable decays ($\mu \to e+\gamma$ etc.).

Then the neutral currents were re-introduced to avoid the same undesirable processes precisely in the theory with one kind of neutrinos.

Paradoxically, this interpretation of weak interactions[82]) had sprung up just before the experimental results testifying in favour of two neutrinos appeared.

But then perhaps such vagaries are typical of the theory of weak interactions.

Neutral Currents

It goes without saying that it would be highly desirable to extend the experimental facilities before any judgements on the role of neutral currents in the weak interaction effects are passed.

Under the existing experimental conditions (accelerators) the largest cross sections for possible weak interactions must be expected in different nucleon-involving effects.

Thus under the assumption of neutral baryon currents in the four-fermion interaction Lagrangian (with the same value of the universal constant) cross sections equal to $\sim 10^{-38}\mathrm{cm}^2$ ought to be expected with the energy of the particle incident on the nucleon ~ 1 GeV. Thus if the interaction leading to the $p+p \rightarrow p+\Sigma^+$ and $n+n \rightarrow n+\Lambda^0$ effects is introduced the first order of perturbation theory yields for these processes the cross section[83])

$$\sigma \sim 4.10^{-38}\mathrm{cm}^2. \qquad (113)$$

[redacted]

If the Lagrangian does not contain direct interactions between the neutral baryon currents the $n+n \rightarrow n+\Lambda^0$ processes can occur through different intermediate states. In such cases lower values of the cross sections are highly probable. A very rough estimate83) of such an indirect transition gives a cross section value by two orders smaller. At any rate should the cross section or its upper limit for, say, $n+n \rightarrow n+\Lambda^0$ prove confidently lower than (113), this result would be testimony in favour of the forbiddenness often imposed in the theory of weak interactions on the introduction in the Lagrangian of the neutral currents of the given type. The present-day accelerators producing proton beams with $E_p \leq$ 1 GeV furnish sufficient intensities for obtaining a reasonable count of events in $p+p \rightarrow p+\Sigma^+$ or $n+n \rightarrow n+\Lambda^0$ effects. Unfortunately, the background difficulties complicate a great deal the practical possibilities of such an experiment.

Of special interest is the search for a possible $(\nu\mathcal{N})(\mathcal{N}\mathcal{N})$ interaction84).

If terms of the type

$$L' = \frac{G}{\sqrt{2}} \tilde{\nu}\gamma_\mu (1+\gamma_5)\nu \tilde{\mathcal{N}}\gamma_\mu (1+\gamma_5)\tau_3 \mathcal{N} + h.c. \qquad (114)$$

are introduced in the interaction Lagrangian, as is done, for example, by Bludman81) and Zeldovich85) one can expect effects of the type

$$\nu + \mathcal{N} \rightarrow \mathcal{N}' + \nu'$$

[redacted]

with cross sections $\sim 10^{-38}\text{cm}^2$ for $\sim$ 1 GeV of neutrino energy.

If interactions of type (114) actually occur in nature stars without charged leptons could be observed in the neutrino beam.

The authors[84] also proposed a low energy neutrino (antineutrino) experiment.An antineutrino of rather low energies (from a reactor,for example) could excite the nucleus

$$\tilde{\nu} + Z \rightarrow \tilde{\nu} + Z^{*} \qquad (115)$$

and lead to the characteristic radiation

$$Z^{*} \rightarrow Z + \gamma \qquad (116)$$

For a concrete case,viz. the neutrino excitation[+] of Li^7 ,the authors give the cross sections

$$\sigma_{Li^7} \gtrsim 2.10^{-42}\text{cm}^2.$$

The effect can in principle be isolated from the background via,for example,the specific properties of the

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[+] First excited level $Li^7 : J = 3/2^- \rightarrow J = 1/2^-$

$$\Delta E = 480 \text{ keV}.$$

given γ -radiation (energy, polarization).

By the data reported by Indian physicists[86]) on the intensity of charged particles at large depths it is easy to make the upper estimate of the possible neutrino-nucleon scattering effect[118]). Assuming that all charged particles observed at a depth of 6388 m of water equivalent are recoil protons in the neutrino-proton scattering effect ($E_\nu > 1$ GeV) and taking for the neutrino the spectrum and angular distribution by a paper of Zatsepin and Kuzmin[71]) we can obtain the estimate

$$I \sigma_{\nu N} N \cdot R_{nuc} \leq 1.6 \times 10^{-10} \mathrm{cm}^{-2} \mathrm{sec}^{-1} \mathrm{ster}^{-1} \qquad (117)$$

where $I = 2.10^{-2} \mathrm{cm}^{-2} \mathrm{sec}^{-1} \mathrm{sr}^{-1}$ is the vertical intensity of neutrinos produced in the terrestrial atmosphere[71]), R_{nucl} is the proton ~~absorbability~~ absorption mean-free-path ($\sim$ 150 gr/cm) and N is the number of nucleons in 1 g of substance. Hence we have

$$\sigma_{\nu N} < 10^{-34} \mathrm{cm}^2. \qquad (118)$$

Thus we obtain the estimate of the upper limit for the effective constant of four-fermion interactions of the given type

$$F \leq \frac{3 \cdot 10^{-3}}{m_N} \qquad (119)$$

which is only by two orders of magnitude larger than the weak interaction constant.

It is noteworthy that cosmic ray data compete effectively here with the respective accelerator data$^{87)}$ where the upper limit for the same cross section is by two orders higher. If we bear in mind relatively primitive organization of cosmic research as compared with its accelerator counterpart it will become evident that cosmic rays still hold considerable possibilities.

As for stronger hypothetical interactions of muon neutrinos with nucleons$^{88)}$ which could in principle explain the difference between the muon and electron masses, this possibility seems to be closed by underground experiments$^{86)}$ which already give a difference smaller than by two orders between the weak and hypothetical interaction constant.

But, of course, the existence of $\nu\mathcal{N}$ scattering ($\nu+\mathcal{N}\rightarrow\nu+\mathcal{N}'$) with a weak interaction constant remains an open question and an experiment registering neutrino interactions by recoil nucleons in the cross section region $\sim10^{-38}$cm^2 is certainly very desirable.

It is also desirable to study the $\nu+\mathcal{N}\rightarrow\nu'+\mathcal{N}'$ process for still smaller cross sections. If there are no direct $(\nu\mathcal{N})(\nu\mathcal{N})$ interactions it must exist as a second order effect, according to these graphs, for example

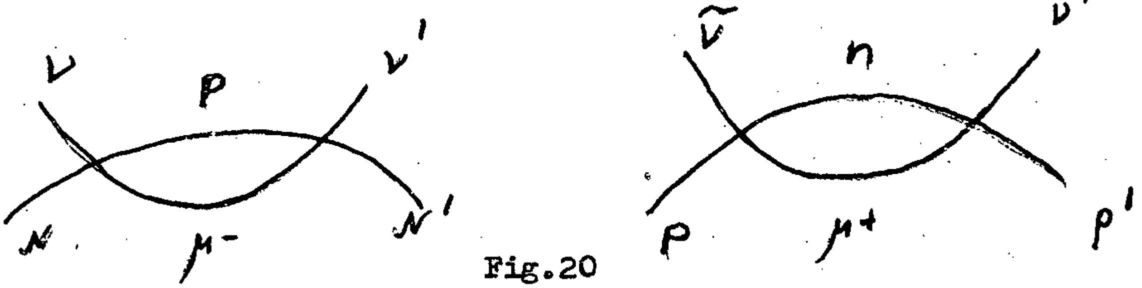

Fig.20

Unlike all the second approximation effects we have discussed, this effect cannot be forbidden by anything except a low upper value of the intermediate momentum.[+]

A rough estimate of the ratio of the cross section for the first and second-order effects is given by the same relation

$$\frac{\sigma(\nu N, \nu' N')}{\sigma(\nu n, p\mu^-)} \sim \frac{G^2 K^4_{max}}{16\pi^4}$$

~~When $K_{max} \rightarrow K_{crit}$ this relation tends to unity.~~

In the next few years it will evidently become possible to check the cross sections under discussion in the region $\sim 10^{-40}cm^2$ and perhaps lower. It is not impossible that precisely this experiment will answer many questions we are discussing here.

The possibility of weak interactions of the $(nn)(nn)$ and $(ee)(ee)$ type is not ruled out in principle, but the need of detecting these effects against the background of strong and electromagnetic interactions relegates tnese experimental problems to a not too near future.

The existence or absence of lepton interactions of the $(e\nu)(e\nu)$ type is perhaps one of the most interesting problems in the field of weak interactions and it deserves special treatment.

[+] Rather the process is not forbidden in the case $\nu_\mu \neq \nu_e$ either.

9. Is the Neutrino Aspect of Weak Interactions Hopeless?

At present there are some grounds to suppose that the current formulation of the theory of weak interactions may undergo essential evolution. The development of the theory of weak interactions may take several courses (incorporation of neutral currents, up to ten intermediate mesons, etc.) but an answer must ultimately be obtained to the fundamental question: why is non-parity conservation characteristic of weak in contrast to strong interactions? And why is the weak interaction so weak in comparison with the strong one?

It would be very attractive to connect the peculiarity of weak interactions with the participation in them of such a peculiar particle like the neutrino and to try in this direction to find a clue to understanding the place of weak interactions among strong ones ("Why is God a weak left-hander?")

The phenomenological description of weak interactions as a contact interaction between four-fermions proves in its general form too broad: it allows several possibilities which do not all occur in nature for some unknown reasons. Therefore the four-fermion formulation of the theory is restricted by several postulatory requirements. One of these is the expression of the interaction Lagrangian through charged currents This idea has proved valuable heuristically. At any rate the attempt to impart a physical meaning to this restriction led to the idea of a charged intermediate meson and the corresponding interesting experiments. Analysis of the possibilities for other postulatory restrictions on four-fermion interactions may prove heuristically valuable as well.

Let us consider one of such possibilities[89]. Experimental data on the weak interactions between fermions can so far be fitted into the following restrictive definitions.

1. The Lagrangian of weak four-fermion interactions is made up of four different functions

$$\mathcal{L} = \cdots\bar{\psi}_1\cdots\psi_2\cdots\bar{\psi}_3\cdots\psi_4 + h.c. \qquad (120)$$

In the language of particles this means that four essentially different particles take part in the interaction. In the language of Feynman graphs the corresponding vertex is represented by four different lines, e.g.

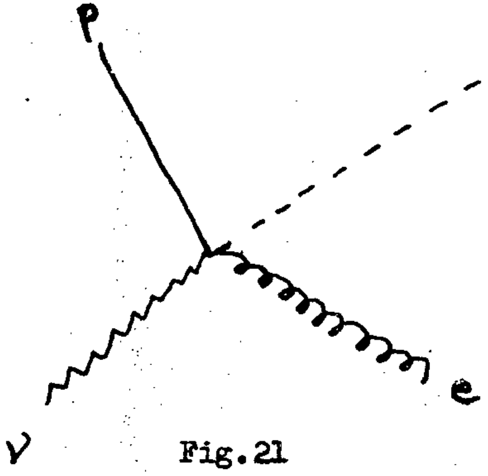

Fig. 21

Particles and antiparticles are represented by identical lines.

Corollaries

(a) Definition 1 forbids decays of the type

$$\Lambda^0 \to n + e^+ + e^-$$

$$\mu^+ \to e^+ + e^- + e^+ \qquad (121)$$

$$\mu^+ \to e^+ + \gamma$$

(b) Definition 1 requires the non-identity of the muon and electron neutrinos

$$\nu_\mu \neq \nu_e \quad , \quad \mu^- \to \tilde{\nu}_e + e^- + \nu_\mu \qquad (122)$$

(c) Interactions of the type

$$(e\nu)(e\nu);\ (\mu\nu)(\mu\nu);\ (pn)(pn);\ (\Lambda^0 p)(\Lambda^0 p) \qquad (123)$$

allowed in M.S.$^{6)}$ and F.G.$^{7)}$ by the formulations of weak interactions are forbidden.

The second restrictive definition can be written in the form:

2. Either muon or electron numbers conserve.

By the two definitions the interaction Lagrangian must incorporate only charged electron and muon currents

$$j_e^{\gamma} = \bar{\psi}_e \gamma (1+\gamma_5) \psi_e^{\nu} \ ; \quad j_\mu^{\gamma} = \bar{\psi}_\mu \gamma (1+\gamma_5) \psi_\mu^{\nu} \qquad (124)$$

The second definition forbids decay of the type

$$\Lambda^0 \rightarrow n + \mu^- + e^+ \qquad (125)$$

Strong Interactions

The question is whether there is any hope or a gleam of hope to understand the vast difference in the values of the strong and weak interaction constants.

In nature there is one specific process capable of increasing the effects by many orders, and this process occurs when resonance situations are realized.

There are some considerations which hold out a certain hope for the emergence of such resonance situations in four-fermion interactions so that the latter could show effectively as the usual strong interactions.

If, indeed, we take as an example the four-fermion interaction as a contact interaction of two fields with the Lagrangian

$$\mathcal{L}(x) = G\,\bar{\Psi}\gamma_\mu\Psi\,\bar{\varphi}\gamma_\mu\varphi + h.c. \qquad (126)$$

and calculate the scattering cross section by solving the corresponding the Bethe-Salpeter equation in the chain approximation[19]), in the cross section obtained there actually arise resonance-type denominators in the expression for the effective interaction constant.

The scattering cross section due to the four-fermion interaction has an intricate pattern in this approximation. Apart from the momentum dependence of the incident particle (p) the cross section contains factors depending on the maximum momenta of virtual states (K_{max}). The structure of the characteristic term of the cross section is given in eq.(127)

$$d\sigma \sim \frac{f(p^2)}{1 - b K_{max}^2 + \text{small terms}} \qquad (127)$$

The denominator of eq.(127) has a typical resonance structure.

Two circumstances are noteworthy.

1) With close-to-critical values of the maximum momentum of intermediate states in the case of a vector interaction, cross section (127) is by eight orders larger than the cross sections calculated by perturbation theory. Thus a strong interaction originates from a "weak" one[+].

2) In the $V-A$ variant of the interaction the expression that appears in the denominator for the corre-

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[+] I.e., with a weak initial constant.

sponding cross section (Polubarinov) is such that the main dependence on K_{max} falls out, only the logarithmic term ($\ln \frac{K^2_{max}}{m^2}$) remains, and the denominator vanishes (resonance) only when $K_{max} \gg K_{crit}$ = 300 GeV. In other words, the four-fermion $V-A$ -interaction of type (126) leads, with the cut-off parameters $K_{max} \lesssim K_{crit}$, to scattering cross sections which do not differ from the first approximation of perturbation theory with respect to the weak constant.

Thus it is not impossible that even with the same initial constant G and with the same maximim momentum of the intermediate states (K_{max}) the contact interaction of four fermions, taking into account the infinite chains of high approximations, becomes essentially stronger if there is no neutrino among these fermions; or rather if instead of the $V-A$ variant of interactions there remains only, say, the A -variant, or any other variant (T, S, V), or their combination ensuring spatial parity conservation. Another circumstance may also prove essential: some baryons involved in a four-fermion interaction leading to an effective strong interaction may (say, in contrast to weak interactions) be identical.

From this point of view the scheme of four-fermion interactions is more natural if it is close to the Bludman scheme^{71}). Close in the sense that in it, just as in the Bludman scheme, (pp)(nn); (ee)(ee), (ee)($\mu\mu$), etc. interactions with the same initial constant G are assumed. In the neutrino aspect of weak interactions, four-fermion interactions of such a type need not show up as weak interactions, i.e., they may lead to strong and electromagnetic interactions. Unfortunately, the existence of non-lepton decays is a weighty argument against this viewpoint.

Bearing in mind, however, the attractiveness of the neutrino hypothesis for weak interactions it is hardly expedient to jump to negative conclusions without discussing other possibilities slight as they may seem.

Let us consider the non-lepton decay situation more closely.

Weak Non-Lepton Decays

Weak non-lepton decays could, it may seem, be naturally explained by the interaction of the baryon currents j_n^γ, $j_{\Lambda^0}^\gamma$ where

$$j_n^\gamma = \tilde{\psi}_p \gamma (1+\gamma_5) \psi_n \; ; \quad j_{\Lambda^0}^\gamma = \bar{\psi}_p \gamma (1+\gamma_5) \psi_{\Lambda^0} \qquad (128)$$

and the decay of, for example, a Λ^0-particle be represented by graph 22.

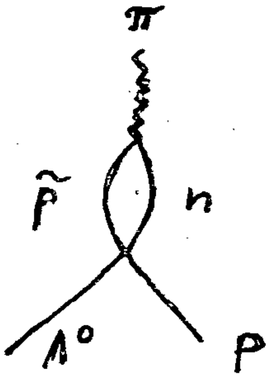

Fig.22

but strictly speaking we have no theory of non-lepton decays since graph 22 is purely illustrative as yet. The point is not even that strong interactions preclude concrete calculations.

It is precisely graphs like that in fig. 22 that are discussed in connection with the idea of reducing strong interactions to an infinite chain of weak interactions[18-20,90]). This idea has not yet been exhausted. It seems desirable to reserve graphs like that of fig. 23 for the future theory of strong interactions.

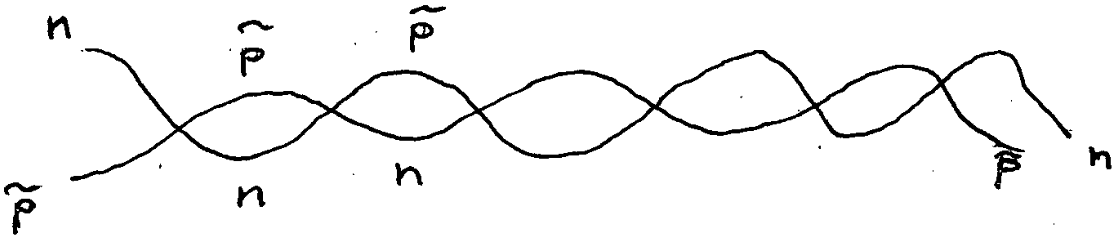

Fig. 23

At present it cannot be said with certainty that graphs like 24 or 25, complicated by strong interactions, cannot interpret non-lepton weak decays:

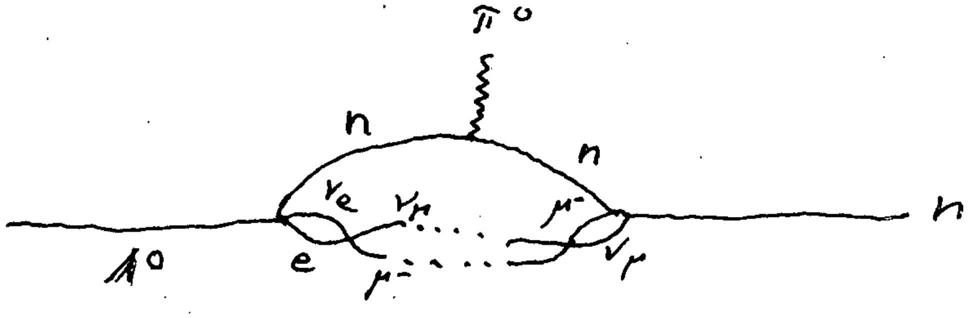

Fig. 24

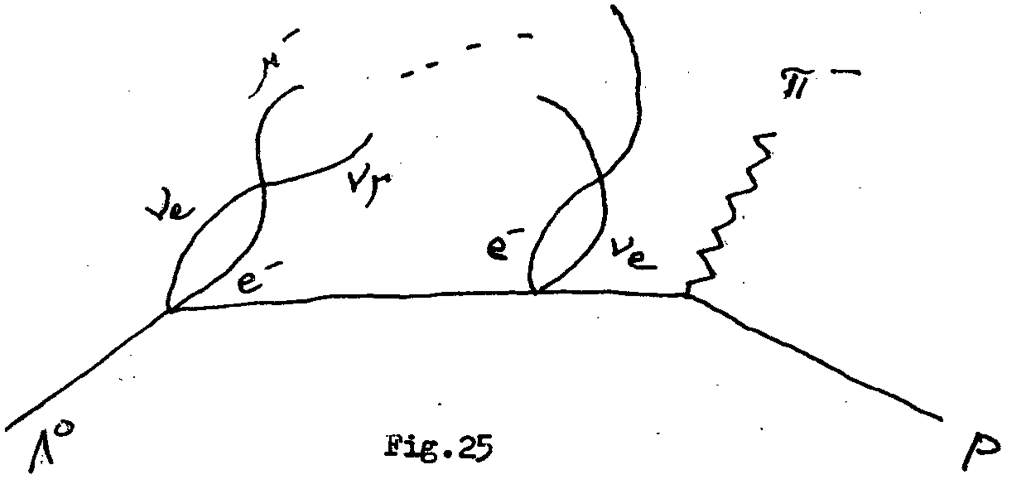

Fig.25

The summation of infinite chains of type 24 and 25 also leads to expressions like ($|\lambda 7$), to the appearance of an effective constant in the function K_{max}.

With a universal K_{max} the effective constant essentially depends on the character of the graph chains summated. It is not impossible that the summation of infinite interaction chains of type 24 and 25, modified by the incorporated strong interaction, will change the denominator of an expression of type ($|2 7$) to such an extent that all the expression will prove essentially different from the first approximation of perturbation theory, though not so drastically different as to lead to strong interactions.

The following analogy can be drawn between the strong interaction of baryons with pions and weak interaction of pions with the same baryons.

According to the Fermi-Yang theory, the strong pion-baryon interaction can be interpreted as a four-fermion interaction leading to the emission of, say, a nucleon-antinucleon pair by a nucleon.These make up a pion according to graph 22.

However,graph 22 can also be drawn in this form 22'

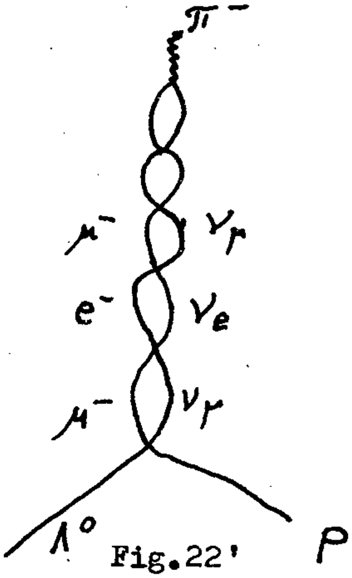

Fig.22'

In other words, Λ^0 emits a pair: μ -meson and neutrino which make up a pion.Owing to a strong nucleon-antinucleon interaction[+] which may lead to the production of a pion it is precisely a pion originates in graphs of type 22.

It can also be said that for the same reason (μ-meson-neutrino interaction) graph 22' leads as a rule to a weak pion decay.

In this presentation of the possible situation there is even a certain gleam of explanation of the difference

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[+] The bare particles whose masses may differ from physical particles are here meant.

between strong and weak pion-baryon interactions.

In the interpretation of graphs of type 24 and 25 there arise problems which cannot as yet be solved in the framework of the present-day theory. Magnitudes of the allowed momenta of the intermediate states in these processes (factors like GK^2_{max}) are still unknown; there are no methods of calculating the probabilities of the effects for high values of these factors when perturbation theory does not apply any longer; nor are clear the problems of the initial charge constants of weak interactions, i.e., non-renormalizable theories.

It is still possible that the question "why is God a weak left-hander?" will be answered in the aspect of four-fermion interactions

* * *

Another consideration in favour of neutral currents in four-fermion interactions can be pointed out.

Probably the only theoretical possibility so far to understand the difference in the muon and electron masses (sect. 3) on the basis of experiment-allowed interactions is the introduction of neutral currents leading to $(\mu\mu)(\mu\mu)$ or $(ee)(ee)$ interactions.

Indeed, the weak interaction written in the form

$$V^w = -G(\bar{\psi}_e \gamma_\eta \psi_e \bar{\psi}_e \gamma_\eta \psi_e - \bar{\psi}_\mu \gamma_\eta \psi \bar{\psi}_\mu \gamma_\eta \psi) \qquad (129)$$

is non-invariant with respect to the transformation

$$\psi_e \rightarrow \gamma_5 \psi_\mu \quad ; \quad \bar{\psi}_e \rightarrow -\bar{\psi}_\mu \gamma_5$$

Therefore, according to the considerations expounded in sect. 3, this interaction must lead to different contributions to the equal masses of bare muons and electrons.

It can, indeed, readily be seen that such opposite-sign additions to the electron and muon masses arise in the graphs of odd powers in the weak constant. What is meant are the graphs of the form[41])

I

II

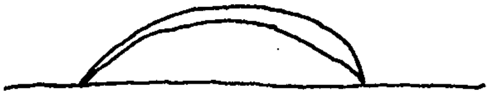
III

etc.

- - - - - photon line.

True, the simplest graph of type I can be eliminated by the selection of certain form of the normal product of the interaction term.

The graphs even in the powers of G (type IV)



IV

give the same contribution to the masses of bare particles, as is shown by calculations, and decrease thair bare mass.

Thus the bare mass of an electron or muon can exceed considerably the real muon mass[+].

Of course, what is meant here is the possibility to understand in principle the difference in the muon and electron masses. The state of theory being what it is (divergence, absence of the method of summation of graph chains if $G K^2_{max} \sim 1$, etc.) it does not appear possible to obtain any concrete values.

* * *

[+] Estimates 41) show that the contribution to the magnetic moment can be compatible with experimental data.

The existence of weak interactions provokes what might seem at first glance a childish question: why does nature need weak interactions? On first thought it appears that the existence of weak interactions is an absolutely unjustified luxury. It appears that nature would be none the worse if it had confined herself to strong and electron-magnetic interactions.

Consummately perfect constructions are realized in nature as a rule. It can be thought therefore that our comprehension of the hierarchies of interactions is very superficial as yet and the dispensation with weak interactions would make a consistent picture of world impossible.

The above considerations in favour of a single picture of weak and strong interactions are not at all decisive or even convincing. They merely indicate that in the framework of four-fermion interactions there is some scope for further theoretical research, and it is in this direction, perhaps, that essential results will be obtained for understanding the correlation of strong and weak interactions.

In a more specific aspect the above considerations focus attention on the possibility of checking experimentally the existence of truly weak interactions of the type $(np)(np)$; $(e\nu)(e\nu)$.

Of decisive importance in the neutrino concept of weak interactions would be the establishment of non-parity-conserving $(np)(\Lambda^{\circ}p)$ or $(np)(np)$ weak interaction. Now that the $(\nu N)(\mu N')$ effect detection experiment has been successful the point is the search for the effect of the same order of a possible $(\nu N)(\nu' N)$ interaction.

Already now the experimenters must seriously discuss and seek the most effective methods of detecting a possible non-parity conserving $(np)(np)$ interaction.

The most natural trend of this search is an attempt at detecting longitudinal polarization in nucleon-nucleon scattering 147). Longitudinal polarization is caused by the term due to the interference of strong interactions with that part of weak interactions which violates parity. With nucleon energies ~ 200 to 300 MeV the effect proves equal to 10^{-6} to 10^{-7} of the main effect 148). At present the experimental possibilities of detecting the effect are by three orders or so lower than the expected effect in this energy region.

However, with the advent of strong current accelerators the situation may improve radically and the effect may appear detectable.

In the high-energy region the situation may prove more favourable.

Obviously, purposeful efforts should be taken in this direction. The prize is worth it.

10. $(e\nu)(e\nu)$-Interaction

Of all the "still undiscovered" weak interactions the $(e\nu)(e\nu)$-interaction enjoys the greatest popularity. Numerous effects possible with this interaction are discussed so often and in so many ways that one is almost convinced that the $(e\nu)(e\nu)$-interaction exists in reality. The popularity of this interaction can be traced to the fact that it is not forbidden by the M.S.[6]) F.G.[7]) theory. Besides, this interaction acquires additional prominence due to the fact that the $(\nu p)(\nu p)$-interaction proves to be forbidden in this theory.

But the main reason is that the $(e\nu)(e\nu)$-interaction reminds one strongly of the much-used-to electrodynamics: electrons interact with a certain vector (pseudovector) field made up of neutrino-antineutrino fields.

The set of processes that arises is analogous to the processes of electrodynamics.

Scattering on an electron, a neutrino may yield a "Compton electron" of a kind. In an excited atom the electron may jump to another orbit, with the emission of a neutrino-antineutrino pair instead of a photon. The neutrino is capable of exciting the circuit.

Slowing down in the Coulomb field, the electron is capable of emitting neutrino-antineutrino bremsstrahlung.

This peculiar interaction might have a decisive effect on many astrophysical processes.

Though an elaborate analysis of the possibilities opened by the existence of the $(e\nu)(e\nu)$-interaction is a kind of counting chickens before they are hatched, the discussion of various effects induced by the interaction is quite valuable heuristically. This discussion may bring into existence an essential experimental idea which could eventually help confirm or reject the existence of the direct electron-neutrino interaction.

In the general aspect of the theory of weak interactions this possible interaction has proved to be so peculiar and important that an experimental analysis of the situation is a direct must.

Regardless of our attitudes, the trends in the development of weak interaction physics has made the detection of the as yet purely speculative ($e\nu$)($e\nu$)-interaction an experimental problem of fundamental importance.

Elementary ($e\nu$)($e\nu$)-Interaction Effects

Neutrino-Electron Scattering

The neutrino-electron-scattering cross section has been given in the most general form by I.Polubarinov[51]).It is valid in any energy region,in any system of coordinates and also for a non-zero mass neutrino.

The latter circumstance can be essential for the muon neutrino whose experimental mass upper limit is still high ($\sim$ 1 MeV).

For extremely high energies cross sections (74) and (75) assume the same analytical form (102) and (107) with the concrete value of the coefficient given by (130)

$$\sigma_{\nu+e\to\nu'+e'} = \frac{G^2}{\pi\hbar^4} m_e^2 \frac{p_\nu}{m_e c} \sim 4.10^{-45} \frac{p_\nu}{m_e c}\, cm^2 \qquad (130)$$

$$p_\nu c \gg m_e c^2$$

For low neutrino energies,in case m_ν =0,the expressions for cross section (74) also become much simpler

$$\sigma_{\nu+e\to\nu+e}=\frac{2G^2m_e^2}{\pi\hbar^4}\frac{p_\nu^2}{(m_ec)^2}\approx 8\cdot 10^{-45}\left(\frac{p_\nu}{m_ec}\right)^2 \qquad (131)$$

Unlike the photon-electron scattering effect, here there is no specific Thompson limit: when $p_\nu \to 0$ cross section (131) tends to zero, and not to a constant. The quadratic dependence on neutrino energy $\sim\left(\frac{E_\nu}{m_ec^2}\right)^2$ makes unjustified the attempt to seek the effect in the region of neutrinos of very low energies even if (as will be clear from the following) neutrino fluxes of considerable densities are realized.

The situation is somewhat different if the neutrino mass does not vanish

$$\sigma_{\nu+e\to\nu+e}=\frac{2G^2m_e^2}{\pi\hbar^4\beta_0}\,\frac{m_\nu}{m_e+m_\nu}\cdot\frac{p_\nu}{(m_e+m_\nu)c}\;;\; p_\nu<m_ec \qquad (132)$$

Since $\beta_0=\frac{v_\nu}{c}=\frac{p_\nu}{m_\nu c}$, cross section (132) becomes a constant

$$\sigma_{\nu+e\to\nu+e}=\frac{2G^2m_e^2}{\pi\hbar^4}\,\frac{m_\nu^2}{(m_e+m_\nu)^2} \qquad (133)$$

If the neutrino muon possesses a mass $m_\nu > m_e$ and can be scattered on an electron (?) the cross section proves equal to

$$\approx \frac{2G^2 m_e^2}{\pi \hbar^4} \approx 8.10^{-45}\,\mathrm{cm}^2 \qquad (134)$$

regardless of the neutrino energy in the region $p_\nu < m_e c$.

Neutrino-Atom Interaction

The excitation of a hydrogen-like atom by neutrino of an energy E_ν :

$$m_e \gg E_\nu \gg |\varepsilon_f - \varepsilon_i|$$

where f and i are the final and initial states of the electron in the atom for the K and L transitions is described, according to A. Komar, by the cross section

$$\sigma = \frac{7 \cdot 10^{-36}}{Z^4} \left(\frac{E_\nu}{m_e} \right)^6 \qquad (135)$$

The neutrino-atom scattering with the transition of the electron into a continuous spectrum is given for low-neutrino energies by the expression (A. Komar)

$$\sigma = \frac{5 \cdot 10^{-36}}{Z^4} \left(\frac{E_\nu - E_j}{m_e} \right)^3 \left(\frac{E_\nu}{m_e} \right)^2 \left(1 - \frac{3\varepsilon_j}{4E_\nu} + \frac{3\varepsilon_j^2}{8E_\nu^2} \right) cm^2 \qquad (136)$$

where $E_\nu \geq \varepsilon_i$ (ionisation energy).

In this case the electron momentum

$$P_e \ll Z \alpha m_e .$$

Cross section (135) is written for transitions from K - shells. When $E_\nu = 2\varepsilon_i$, $Z = 1$ we have

$$\sigma \sim 3.5 \times 10^{-58} \mathrm{cm}^2. \qquad (137)$$

For high neutrino energies the corresponding cross section tends naturally to eq.(130).

In other words, the neutrino-atom interaction cross section decreases catastrophically in the low-energy region.

The structure of the formulae cited is such that, in addition to those troubles which the smallness of the weak interaction constants entails, there appear high powers (E_ν / m_e) which decrease sharply the cross sections for small energies ($E_\nu \ll m_e$) and even Z in high power departs into the denominator....

It can be recalled that the cross section of ionisation of an atom by a photon (photoeffect) contains high-power photon energy precisely in the denominator

$$\phi = \phi_0 Z^5 \alpha^4 4\sqrt{2} \left(\frac{m_e}{E}\right)^{7/2}$$

while in the numerator Z is in the fifth power.

Nature seems to guard jealously the mystery of weak interactions.

Furthermore, when the cross section has a favourable structure, a high power of Z appears in the numerator and the creation of special conditions increasing the count of events by many orders proves possible--the events turn out to be such that they are not in fact detectible as yet. The irradiation of the resonance excited atom by a $\nu\tilde{\nu}$ pair is meant.

The cross section is here expressed (A.Komar) in the form

$$\sigma(\varepsilon_\gamma) = 2.10^{-53} \cdot Z^4 \text{ cm}^2. \qquad (138)$$

The formula is derived under the assumption $Z\alpha < 1$ for $1s-2p$ transitions.

Here the cross section increases with Z, the number of excited atoms under the conditions of lazars is immense. The number of events per time unit increases by dozens of orders as compared with other neutrino effects. But how can the radiation by the atom of a neutrino-antineutrino pair be detected?

If it were possible to reverse the effect: to observe the resonance absorption of neutrino-antineutrino pairs with the subsequent emission of a photon. But such random correlations of $\nu\tilde{\nu}$ are improbable even in a very dense neutrino-antineutrino flux.

Such an effect will prove possible if there exists a strong correlation of the $\nu\tilde{\nu}$ pair when they are emitted by an electron in slowing down at the Coulomb centre. There are no realistic indications in favour of such a possibility except general considerations concerning the obtaining of bound states on the basis of four-fermion interactions in the spirit of the Fermi-Yang ideas. If one can in the case of nucleons expect the production of pions as the bound states of nucleons, ~~one can expect, say, photons in the case of e^-e^+ interactions,~~ +

~~+ e^-e^+ and $\mu^-\mu^+$ as bare particles.~~

one can then expect also strong correlations or "scalar light" (pseudoscalar) ~~In~~ the case of $\nu\tilde{\nu}$ pairs.

Speaking of pseudo"scalar light", it is perhaps in place to complain against nature or our knowledge of it: there is a zero mass particle with spin 1, with spin 1/2 and there are their analogues with non-zero masses. But among the latter there are also pseudoscalar particles, both charged and neutral (π -meson).

The question is whether there does not exist a pseudoscalar neutral particle of zero mass or there is a serious gap in our knowledge? In the spirit of Dirac's maxim it can be said that it will be strange if nature had not used this possibility.

Incidentally, there have been several considerations in literature in recent years in favour of the existence of pseudoscalar light[91].

It is not impossible that the consistent elaboration of the idea of the production of particles out of ψ-field with $e^{i\lambda\gamma_5}$ invariant initial Lagrangian is feasible only when, along with the production of particles with violating this invariance, there arises pseudoscalar light compensating this violation[91,92].

The effective constant of the interaction between this light and the substance need not lead to appreciable effects on the cosmic scale[+].

[+] If it is assumed that the calculation of the effective interaction constant for the complex Fermi-Yang field in the chain approximation of the Bethe-Salpeter has any suggestive implication, it must be said that the effective constant thus calculated contains in its approximate expression the mass of the quanta of the fields forming this particle so that when this mass tends to zero (e.g., $\nu\bar{\nu}$) the effective interaction constant of the complex field tends to zero as well. Thus[18]

$$G_{\pi} = \frac{2\sqrt{\pi}}{\left(\log\frac{\Lambda^2}{\varkappa^2}-2\right)^{1/2}}$$

where Λ is the limiting momentum value in the four-fermion interactions, $\varkappa = \frac{m_N}{c}$. These considerations are no proof but they make it possible to continue the discussion of the possible existence of pseudoscalar (scalar) light with a small interaction constant.

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11. Can Weak Interactions Show Macroscopically?

The ($e\nu$)($e\nu$)-interaction hypothesized according to the universal interaction theory may prove essential in astrophysics, as was first noted by B.Pontecorvo[93]. The neutrino bremsstrahlung

$$e+Z \to e+Z+\nu+\tilde{\nu}$$

i.e., the emission of a neutrino-antineutrino pair by an electron in the Coulomb field of the nucleus, with charge Z, is in its absolute value small as compared with the photon bremsstrahlung

$$e+Z \to Z+\gamma$$

which is at any rate the case if we have electrons with energies considerably lower than the critical energy of weak interactions ($E_e \ll 300$ GeV in the c.m.s.).

A rough estimate of the corresponding probabilities leads to the expression

$$\frac{W_\gamma}{W_{\nu\tilde{\nu}}} \approx \frac{\left(e^2 \cdot \frac{Z}{\hbar c}\right)^2 \frac{e^2}{\hbar c}}{\left(e^2 \cdot \frac{Z}{\hbar c}\right)^2 G^2 \left(\frac{E}{m_e c}\right)^4} = \frac{1}{A} \qquad (139)$$

where $G \approx \frac{g m^2 e}{\hbar^3}$ is a dimensionless weak interaction constant, $g = 1.4 \times 10^{-49}$ erg cm^3 and m_e is the electron mass.

For the astral temperatures dealt with in astrophysics the parameter A under consideration is very small.But a considerable difference in the penetrating capacity of the neutrino as compared with that of a photon may under certain conditions lead to situations when neutrino radiation will account for an essential part of the emanation of astroenergy. These considerations have been confirmed via quantitative calculations by G.M.Gandelman and V.S.Pinayev[94]).They showed that in the region of temperatures $kT > 30$ keV and with the density of a star $> 10^5$ g/cm^3 the energy carried by neutrinos from the star ($Z \sim 10$) may exceed the energy irradiated in the form of γ -quanta.

The neutrino radiation of stars had been discussed before.Many years ago Gamow and Schoenberg[95]) pointed to a possibility for neutrino radiation which can materialize via nuclear reactions in the depths of stars given high densities and temperatures.

It is under suitable conditions that electrons can be captured by nuclei with the subsequent decay of the latter.

$$\mathcal{N}_{Z}^{A}+e^{-}\rightarrow\mathcal{N}_{Z-1}^{A}+\gamma\ ;\ \mathcal{N}_{Z-1}^{A}\rightarrow\mathcal{N}_{Z}^{A}+e^{-}+\nu \qquad (\beta)$$

Of course the cross section of this process is very small. Nevertheless, it can be essential in the energy losses of stars. Furthermore, in certain conditions the energy losses in the form of neutrino radiation accompanying the nuclear reactions under consideration may exceed photon radiation since photons have short paths in astrosubstance and are actually radiated by the outer envelope of a star. However, the neutrino radiation mechanism indicated by Pontecorvo differs essentially from the process considered by Gamow and Schoenberg in that the electron neutrino bremsstrahlung is a non-threshold process [+].

[+] The (β) process depends on the presence of nuclei with a low energy threshold.

True, the Gamow-Schoenberg effect is based on the established interaction while the existence of the $(e\nu)(e\nu)$-interaction "is still to be discovered".

V. I. Ritus[96]) has recently indicated another important mechanism for neutrino astral radiation: photoproduction of a neutrino on an electron

$$\gamma+e\rightarrow e'+\nu+\tilde{\nu}$$

The latter is a first order process with respect to the weak interaction and electromagnetic interaction constants.

The cross section for the photoproduction of a neutrino-antineutrino pair on an electron and the power of the photoneutrino radiation of electron gas (degenerate as well as non-degenerate) are calculated in ref.96) against temperature and density. It is shown that the power of the photoneutrino radiation of electron gas at temperatures $kT \gtrsim 40$ keV is by two orders larger than that of neutrino bremsstrahlung under the same conditions. This sharp difference is due in particular to the fact that the cross section of the photoproduction of neutrino pairs increases more strongly with photon energy as compared with the growth of the neutrino bremsstrahlung cross section vs. ~~stopping~~ slowing down electron energy. It is essential that the photon energy spectrum is shifted towards higher energies as compared with the electron spectrum at the same temperature.

The author expresses the power of the photoneutrino radiation of electron gas when there is no degeneracy in the form

$$Q_\nu = 3.32 \times 10^{-8} T^8 \frac{\rho}{\mu_e} \quad \text{erg sec}^{-1}\text{cm}^{-3} \qquad (140)$$

where T is the temperature of the substance (keV) and ρ is the density of the substance. The latter is assumed to be completely ionised so that the electron density is connected with the density of the substance by the relation

$$n_e = 6.10^{23}\, \rho/\mu_e \,.$$

Here we have

$$\mu_e^{-1} = \Sigma\, c_i Z_i / A_i$$

c_i is the weight concentration of an element with atomic number A_i and charge Z_i .

For strongly degenerate electron gas eq.(140) takes on the form

$$Q_\nu = 1.5 \times 10^{-7}\, T^9 \left(\frac{\rho}{\mu_e}\right)^{2/3} \text{erg sec}^{-1}\text{cm}^{-3}. \qquad (141)$$

Table VI lists the powers Q_ν of the photoneutrino radiation of degenerate and non-degenerate electron gas vs. temperature for a given density $\rho = 10^5$ g cm^{-3} in erg $sec^{-1}cm^{-3}$. The last column of the table lists the corresponding powers q_ν of neutrino bremsstrahlung calculated by the formulae given by Gandelman and Pinayev[94]).

Estimates of photoneutrino and photon radiation under the conditions close to the real conditions of the state of substance in new stars and stars transforming into white dwarfs confirms the essential importance of the photoneutrino mechanism of energy losses in the energy balance of stars.

Eqs.(141) and (140) allow the neutrino-carried energy be estimated if, of course, the density and temperature distributions vs. the radius of the star are known.

Table VI

	T (keV)	Q_ν	q_ν
Degenerate gas	1	$2.08.10^{-4}$	$1.41.10^{-1}$
	5	$4.06.10^{2}$	$1.17.10^{3}$
	10	$2.08.10^{5}$	$4.66.10^{4}$
	20	$1.06.10^{8}$	$1.20.10^{6}$
	30	$1.09.10^{9}$	$3.05.10^{7}$
non-degenerate gas	40	$1.08.10^{10}$	$1.10.10^{8}$
	50	$6.50.10^{10}$	$3.05.10^{8}$
	70	$9.55.10^{11}$	$1.38.10^{9}$
	180	$1.66.10^{13}$	$6.87.10^{9}$

In the case of the non-degenerate state of electron gas in a star the photon luminosity (L_γ) can be connected with its temperature T_c and density ρ_c at the centre of the star by the relation[98])

$$L_\gamma = c\,\mu^{-0.5}\rho_c^{-2.5}\,b\,T_c^{8}$$

b is the constant in the Kramer's formula for the photon path

$$l = b\rho^{-2}T^{3.5}$$

$$\mu^{-1} = \sum c_i(z_i+1)/A_i$$

The value of the constant c_i and the temperature and density distributions in a star can be obtained, for example, by the numerical integration of the equilibrium equation under the assumption of some model of distribution of the energy-releasing sources.

For the point energy source model when it is assumed that the entire energy of a star is released at its centre Cowling^{99}) has found the distributions of the temperature $T(r)$ and density $\rho(r)$.

Since the temperatures and densities change rapidly vs. the distance from the centre of the star it is worthwhile to introduce their averages for further estimates since these averages characterize the temperature and density of the main mass of the star better than their values at the centre.

$$\bar{T} = \frac{1}{M}\int \rho T dv \; ; \; \bar{\rho} = \frac{1}{V}\int \rho dv \; .$$

Using the expressions for $\rho(r)$ and $T(r)$ calculated by Cowling one can obtain^{96}) the relations between the values of the density at the centre of the star and its average density as well as express the value of this quantity through the radius R and mass $\mathcal{M}$ of the star

$$\rho_c = 37.0\,\bar{\rho} = 8.84\,\mathcal{M}R^{-3} \qquad (142)$$

Similar relations exist for T as well

$$T_c = 1.85\,\bar{T} = 6.28\cdot10^{-23}\,\mu\,\mathcal{M}R^{-1} \qquad (143)$$

where the densities are expressed in g cm^{-3} units and the temperatures in keV.

Using the values found by Cowling for the constants the author expresses L_γ as

$$L_\gamma = 7.22\cdot10^{35}\,\mu^{-0.5}\rho_c^{-2.5}\,\beta\,T_c^{8} = 1.19\cdot10^{34}\,\mu^{-0.5}\,\bar{\rho}^{-2.5}\,\beta\,\bar{T}^{8} \qquad (144)$$

Integrating Q_ν over the volume of the star and using $\rho(r)$ and $T(r)$ for the same model and eqs.(143) the author obtains

$$L_\nu = 1.45\times10^{25}\,\mu_e^{-1}\,\mu^{-1.5}\,\rho_c^{-0.5}\,T_c^{9.5} =$$

$$= 0.822\times10^{27}\,\mu_e^{-1}\,\mu^{-1.5}\,\bar{\rho}^{-0.5}\,T^{9.5} \qquad (145)$$

The ratio of photoneutrino and photon luminosities is given by the expression

$$\frac{L_\nu}{L_\gamma} = 2.01\times10^{-11}\,T_c^{1.5}\,\rho_c^{2}/\beta\mu_e\mu = 0.69\times10^{-7}\,\bar{T}^{1.5}\,\rho_c^{2}/\beta\mu_e\mu \qquad (146)$$

For stars with parameters $T_c \approx 40$ keV and $\rho_c = 5{\cdot}10^4$ g cm^{-3} we have $L_\nu / L_\gamma = 10$. These parameters are evidently characteristic of stars transforming into white dwarfts[100]).

The ratio L_ν / L_γ approaches unity when $\bar\rho = 3{\cdot}10^2$ g cm^{-3} and $T = 10$ keV: these parameters correspond to subdwarfs which flare up sometimes as new stars[101]).

In the case of the degenerate state of the electron gas of a star, its photoneutrino luminosity is estimated by the author as

$$L_\gamma = 1.29\cdot 10^{-7}\,\mathcal{M}T^{9} \Big/ \mu_e^{2/3}\cdot\bar\rho^{1/3} \tag{147}$$

The photon luminosity in this case is written, according to Schatzman[102])

$$L_\gamma = 2.88\cdot 10^{-3}\,\mathcal{M}T^{7/2} \tag{148}$$

Hence

$$\beta' = \frac{L_\nu}{L_\gamma} = 4.48\cdot 10^{-5}\,T^{5.5} \Big/ \mu_e^{2/3}\cdot\rho^{-1/3} \tag{149}$$

For $\bar\rho = 10^5$ g cm^{-3} and $T = 20$ keV this relation becomes of the order of unity.

Fig. 26 illustarates the dependence of β' on temperature and density

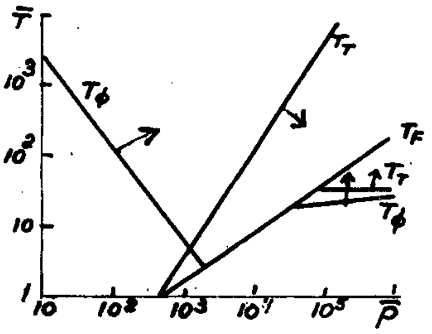

Fig.26

In fig.26 line T_F divides the regions of degenerate gas (below the line T_F) and the regions of non-degenerate gas (above T_F).Lines T_ϕ in the degenerate as well as non-degenerate regions correspond to those average temperatures and densities for which the photoneutrino luminosity equals the photon luminosity.Lines T_T in this graph correspond to the temperatures and densities for which the bremsstrahlung neutrino and photon luminosities are equal. Arrows on lines T_ϕ and T_T indicate the directions of the growth of the ratios $\frac{L_{\nu\,phot.}}{L_\gamma}$ and $\frac{L_{\nu\,brem.}}{L_\gamma}$ i.e.,the regions of temperatures and densities in which these ratios are larger than unity.

It can be seen from fig.26 that the region of astral temperatures and densities for which photoneutrino luminosity exceeds photon luminosity or is equal to it is substantially larger than the region in which bremsstrahlung neutrino luminosity is larger than photon luminosity.

Probably, the mechanism of neutrino radiation is of the greatest interest in the study of the energy balance of new stars. The values of densities close to $\rho \sim 5.10^2$ g cm^{-3} and temperatures $T \sim 10$ keV probably correspond to them.

Estimates show that in the flares of supernew stars neutron radiation attains in absolute value the largest neutrino luminosities, but in the total balance of a star's energy losses, the losses in the neutrino radiation channel probably account for a fraction of one percent of the total energy losses.

Another source~~s~~ of neutrino-antineutrino pairs[+] may be the process[103])

$$\gamma + \gamma \to \gamma + \nu + \bar{\nu}$$

The process

$$\gamma + \gamma \to \nu + \bar{\nu} .$$

proves forbidden in the now received ($V-A$) variant of weak ($e\nu$)($e\nu$)-interactions[104]). For very high temperatures

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[+] Strongly overrated estimates of the effect are given in ref.[103]) (see ref.[103']). According to ref.[103']) this process cannot be essential in neutrino astral radiation.

the process

$$e^- + e^+ \rightarrow \nu + \tilde{\nu}$$

is essential. It should be recalled once again that the neutrino radiation losses considered above imply the existence of the $(e\nu)(e\nu)$-interaction. There is not a single experimental fact as yet which would testify in favour of the existence of such an interaction.

It appears extremely important therefore to discuss various possibilities for detecting experimentally such an interaction and later undertaking concrete experimental investigations.

12. Natural Neutrino Fluxes

Celestial Bodies as Neutrino Radiation Sources

The Sun

There is a widespread opinion that the energy balance of the Sun-type stars is sustained by nuclear reactions at work in the depths of these celestial bodies. Though the hypothesis seems plausible enough, the existence of such processes in the Sun has not been confirmed experimentally and surprises with far-reaching consequences are possible. The experimental attempt to check this hypothesis and even the type of possible nuclear reactions here on Earth becomes feasible at present.

Various thermonuclear reactions suggested by many authors as possible sourses of the intra-stellar energy of the Sun-type stars have unique peculiarity: they all are accompanied by neutrino, and not antineutrino radiation. This circumstance follows from the fact that the production of heavy elements of nuclei which contain neutrons arising from hydrogen is possible only with the emission of neutrinos.

Such a property is inherent to the $C-N$ cycle proposed by Bethe[105])

$$\begin{aligned} &C^{12}+p \rightarrow N^{13} \rightarrow C^{13}+e^{+}+\nu \\ &C^{13}+p \rightarrow N^{14} \\ &N^{14}+p \rightarrow O^{15} \rightarrow N^{15}+e^{+}+\nu \\ &N^{15}+p \rightarrow C^{12}+He^{4} \end{aligned} \qquad (C-N)$$

the $H-D$ synthesis discussed by Salpeter[106])

$$\begin{aligned} &p+p \rightarrow D+e^{+}+\nu \\ &D+p \rightarrow He^{3} \\ &He^{3}+He^{3} \rightarrow He^{4}+p+p \end{aligned} \qquad (H-D)$$

very interesting possibilities indicated by Fowler[107])

$$p + p \rightarrow D + e^{+} + \nu$$

$$D + p \rightarrow He^{3}$$

$$He^{3} + He^{4} \rightarrow Be^{7} \rightarrow Li^{7} - e^{-} + \nu \qquad \text{(H-Be}$$

$$Li^{7} + p \rightarrow Be^{8} + 2He^{4}$$

and finally the reactions

$$p + p \rightarrow D + e^{+} + \gamma$$

$$D + p \rightarrow He^{3}$$

$$He^{3} + He^{4} \rightarrow Be^{7} \qquad \text{(H-B)}$$

$$Be^{7} + p \rightarrow B^{8} \rightarrow Be^{8} + e^{+} + \gamma$$

$$Be^{8} \rightarrow 2He^{4}$$

H.Tyren and P.Tove[108]) reported experimental data on the p
sible existence of an unstable isotope Li^{4} with lifetime 0.4 sec. Reeves[109]) drew attention to the importance od th
reaction for the energy balance of stars,for energy ~20 M
would be released in the decay $Li^{4}\,(e^{+}+\nu)\,He^{4}$

Evidently the latter reaction, if it exists,[+] yields neutrinos of the highest energies out of all nuclear reactions known.

Given below is a table of the Sun's neutrino activity (table VII) drawn up by V.A.Kuzmin. The third column of the table lists the maximum neutrino energies for the reactions under consideration. The maximum energies for the contemplated solar neutrinos lie within

$$0.42 \text{ MeV} < E_{\nu}^{max} < 1.75 \text{ MeV}.$$

Only in the case of the $H-B$ cycle does there arise neutrinos of energy $E_{\nu}^{max} \simeq 14.1$ MeV.

Detectors with a very low energy threshold are necessary for the registration of solar neutrinos. In this connection the reaction suggested by B.Pontecorvo[112]) is usually discussed

$$\nu + Cl^{37} \rightarrow Ar^{37} + \beta^{-}$$

The reaction threshold E_0=0.8 MeV. Unfortunately, even this reaction with its relatively low energy threshold proves

---

[+] It would be desirable to extend the reliability of this reaction. Theoretically, the existence (0.4 sec!) of Li^4 seems even less probable than the existence of, say, H^4 (Coulomb repulsion).

useles for the registration of neutrinos from the H-D and H-Be cycles.

Kuzmin has indicated a detecting reaction with a still lower threshold ($E_0 = 0.24$ MeV)

$$Ga^{71} \rightarrow Ge^{71}.$$

It is unknown, however, how "technological" this reaction is, how realistic its use is for an experiment with enormous detecting masses (1000 tons).

Table VII lists estimates of the average cross sections for the regions in which the detecting reactions apply. The average cross sections $\bar{\sigma}$ of neutrinos from the corresponding cycles are almost all close to $\sim 10^{-46} cm^2$. The H-B cycle ($1.1 \times 10^{-43} cm^2$) is a rare exception. But then in the latter case the expected neutrino flux[+] is estimated by a quantity by three orders smaller.

The estimates of the possible neutrino fluxes from stars are somewhat arbitrary. But apparently they are sufficiently reliable by the order of magnitude.

The neutrino activity of the Sun may, by various esti-

[+] It is not clear how reliable are the extrapolations for very low energies of cross sections like $Be^7 + p \rightarrow B^8$

mates, attain on the surface of the Earth the values[110])

$$10^{10} \text{ to } 10^{11} \text{ neutrinos per cm}^2 \text{ sec}^{-1}.$$

Zeldovich, Lukyanov and Smorodinsky[114]) estimate solar neutrino fluxes on the Earth's surface with an average energy 2.10^{-6} erg to contain 5.10^{10} particles per cm^2 in one second.

The number of neutrinos emitted by the Sun per sec is set down in ref.[113]) at 10^{38} particles.

The estimates of solar neutrino radiation are obtained on the basis of the following considerations.

It is assumed that thermonulear reactions essentially regulate the Sun's energy balance. All suggested reactions of this kind (table VII) reduce in the last analysis to energy release in the production of four protons in $4p \rightarrow He^4 + 2e + 2\nu$.

The energy released in this reaction (27.7 MeV) is distributed between the particles involved in the reaction and two neutrinos. The total energy lost by the Sun on radiation is divided by the energy released in the $4p \rightarrow He^4$ reaction. Thus, a rough estimate is made of the number of He nuclei originating per second and the double number of these gives the wanted number of neutrinos ($\mathcal{N}$).

A more detailed characteristic of the number of neutrinos must include the estimates of the portion of the number of neutrinos due to this or that cycle[+] (δ_i in table VII).

The Sun's neutrino activity on the Earth's surface is given by the expression

---

[+] The energy carried by neutrinos makes no contribution to the Sun's luminary activity.

Table VII

Cycle	β -process	E_{ν}^{max}, MeV	Solar neutrino flux (registered: in parens, F_1) cm^{-2}sec^{-1}	Detector	Average cross section $\bar{\sigma}$, cm^2	$F\bar{\sigma}$,sec^{-1}
H-D	$H^1(p, e^+\nu)D^2$	0.42	$5.26.10^{10}$ $(4.3x10^{10})$	$Ga^{71} \rightarrow Ge^{71}$ (E_o = 0.237MeV)	$3.5x10^{-45}$	$1.5x10^{-34}$
	$H^1(pe^-,\nu)D^2$	1.44	$\sim 3.10^8$	$Cl^{37} \rightarrow Ar^{37}$ (E_o = 0.816 MeV)	$2.4x10^{-45}$	7.10^{-37}
H-Be	$Be^7(e^-,\nu)Li^7$	0.861(87.7%)	$1.0.10^{10}$ *	$Cl^{37} \rightarrow Ar^{37}$	$4.2x10^{-46}$	$4.2x10^{-36}$
		0.383(12.3%)	$1.4x10^9$	$Ga^{71} \rightarrow Ge^{71}$	$4.6x10^{-46}$	$6.4x10^{-37}$
H-B	$B^8(e^+\nu)Be^{8*}$	14.1	$3.6x10^{7*}$	$Cl^{37} \rightarrow Ar^{37}$	$1.10x10^{-43}$	$4.0x10^{-36}$
	$N^{13}(e^+\nu)C^{13}$	1.185	$3.4x10^{10}$ δ_{CNO} ** $(1.3x10^{10})$ "		$\sim 1.3x10^{-45}$	$\sim 1.7x10^{-35}$
CNO	$O^{15}(e^+\nu)N^{15}$	1.733	$3.4x10^{10}$ " $(2.4x10^{10})$ "	$Cl^{37} \rightarrow Ar^{37}$	$\sim 3.8x10^{-45}$	$\sim 9.0x10^{-35}$
	$F^{17}(e^+\nu)O^{17}$	1.750	$\sim 1.4x10^7$ "			

* According to data of Bahcall, J. N., et al., Astrophysical J. 137(1963) 344

** δ_{CNO} is the portion of energy, released by the CNO cycle, with respect to the total energy yield.

$$n = \frac{\mathcal{N}}{4\pi R} \mathrm{cm}^{-2}\mathrm{sec}^{-1}$$

where R is the Earth-Sun distance.

The Earth

According to the estimates of G.Marx and Nora Menyhard[111]), the Earth's antineutrino activity is determined by the radioactive elements U^{238}, Th^{232} and U^{235}, their decay products in equilibrium with them and such long-living radioactive isotopes like Ka^{40}, Rb^{87}, La^{138} and Lu^{176}.

It is noteworthy that in all the above cases antineutrinos and not neutrinos, as is the case in the production of heavier elements in the possible processes inside the Sun-like stars, are emitted.

This difference is due to the fact that neutrinos are produced in all synthesis reactions, while in the above radioactive decays it is neutrons decay and radiate e^- along with antineutrinos ($n \to p + e^- + \tilde{\nu}$).

The authors[111]) estimate the antineutrino activity of the Earth's surface layer to be 1.7 x 10^6 particles per ton of substance in one sec. This number is made up of the activities listed in table VIII.

Table VIII

Antineutrino Activity of the Earth's Surface Layer

Isotope	Halflife (sec)	Maximum energy (MeV)	Concentration g/ton	Activity $\tilde{\nu}$/sec ton
U^{238}	$1.41x10^{16}$	α-radiation	3.97	-
Th^{234}	$2.08x10^{6}$	0.19		$5.0x10^{4}$
Pa^{234}	$6.96x10^{1}$	2.32	equilibr.	$4.9x10^{4}$
Pb^{214}	$1.61x10^{3}$	0.65	"	$4.5x10^{4}$
Bi^{214}	$1.18x10^{3}$	2.03	"	$4.5x10^{4}$
Tl^{210}	$7.92x10^{1}$	1.95	"	10^{-18}
Pb^{210}	$6.93x10^{8}$	0.02	"	$4.5x10^{-4}$
Bi^{210}	$4.32x10^{5}$	1.17	"	$4.5x10^{-4}$
Tl^{206}	$2.54x10^{2}$	1.65	"	0.05
Th^{232}	$4.38x10^{17}$	α-radiation	11.28	-
Ra^{228}	$2.11x10^{8}$	0.05	equilibrium	$7.4x10^{4}$
Ac^{228}	$2.21x10^{4}$	1.55	"	$7.4x10^{4}$
Pb^{212}	$3.82x10^{4}$	0.59	"	$7.0x10^{4}$
Bi^{212}	$3.63x10^{3}$	2.5	"	$6.9x10^{4}$
Tl^{208}	$1.86x10^{2}$	1.79	"	$2.3x10^{4}$
U^{235}	$2.24x10^{16}$	α-radiation	0.03	-
Th^{231}	$9.18x10^{4}$	0.20	equilibrium	$3.7x10^{4}$
Ac^{227}	$6.84x10^{8}$	0.04	"	$3.7x10^{4}$
Fr^{223}	$1.26x10^{3}$	1.2	"	$4.4x10^{-1}$
Pb^{211}	$2.17x10^{3}$	1.21	"	$3.4x10^{1}$
Tl^{207}	$2.86x10^{2}$	1.47	"	$3.3x10^{1}$
K^{40}	$4.1x10^{16}$	1.33	3.08	$7.8x10^{5}$
Rb^{87}	$1.57x10^{18}$	0.27	97.48	$3.0x10^{5}$
La^{138}	$3.15x10^{18}$	0.21	0.02	$2.0x10^{1}$
Lu^{176}	$7.6x10^{17}$	0.43	0.02	$6.0x10^{1}$

The radioactivity of the Earth's internal strata is unknown. From the assumption that table VIII reflects adequately the distribution of radioactive elements in the Earth's surface layer 15 km deep, $\mathcal{M} \approx 2.10^{19}$ tons approx., the authors obtain the following estimate of the Earth's antineutrino activity

$$I_0 = \frac{\omega \mathcal{M}}{4\pi R} = 6.7 \times 10^6 \, \tilde{\nu} \quad \mathrm{cm}^{-2}\mathrm{sec}^{-1} \quad \text{particles.}$$

Reactions with a very low energy threshold are needed for detecting the antineutrinos listed in table VIII. For the reaction

$$\tilde{\nu} + p \rightarrow n + e$$

the energy threshold $E_0 = 1.8$ MeV. In this case the number of active neutrinos decreases to 10^5 particles per cm^2 in one sec.

If it is assumed that table VIII characterizes the distribution of radioactive substances at any depths, the corresponding antineutrino activity on the Earth's surface is estimated in the form

$$I_0 = 2 \times 10^9 \ \mathrm{cm}^{-2}\mathrm{sec}^{-1}.$$

The experiment specifying the upper limit of the Earth's antineutrino activity may be expedient in terms of long-range planning [+]. This is evidently the only possibility of obtaining

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[+] According to the data of neutrino experiments near a reactor116) the upper estimate of the Earth's antineutrino radiation is $< 10^{13}$ particles cm^{-2} sec^{-1}. By the temperature conditions of the Earth the upper estimate of the Earth's antineutrino activity decreases considerably.

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the corresponding information on the composition of the substance in the depth of the Earth. It should be emphasized that the Sun's strong neutrino background does not interfere in principle with these measurements since neutrinos lead to other reactions than antineutrinos.

Evidently, the detection of the intensities of 10^{10} to 10^{11} neutrinos per cm^{2}sec in the 1 MeV energy region hovers now on the fringe of possible experiment.

The solar neutrino detection experiment is actually being discussed by many authors.

We witness the origins of experimental neutrino astrophysics. Evidently, the study of possible thermonuclear reactions in the Sun with detecting on the Earth's surface a solar neutrino flux is the first priority experimental work of the astrophysical neutrino cycle.

The attempt to establish the existence of neutrino fluxes coming from the Sun and capable of causing certain nuclear reactions with a low energy threshold will probably be undertaken within the next few years. Then[+] the existence

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[+] This sequence of the experiments is purely speculative:

registration of a smaller neutrino stream (table VII), but with energy 14.1 MeV may prove more feasible experimentally.

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in the Sun of the H-B reaction (Fowler) can be confirmed or refuted by choosing detecting reactions with a higher energy threshold, separating ~~releasing~~, for example, neutrino radiation in the region of 10 to 14 MeV. Detection of neutrinos in solar radiation in the region of energies close to 1.7 MeV would testify to the occurrence of the known C-N cycle under the solar conditions.

It should be recalled that in the region of low neutrino energies the cross sections $\nu + n \rightarrow p + e^-$ increase quadratically with neutrino energy. From this point of view detecting the neutrinos of the Li reaction ($E_\nu \sim 15$ MeV) would be 100 times more effective than detecting the neutrinos of the C-N cycle ($E_\nu = 1.7$ MeV).

It is not impossible that adequate and therefore more effective methods of detection specific for these relatively high energies can be found in the neutrino energy region of 10 to 20 MeV [+].

[+] If, for example, V.B. Beliayev's idea of the possibility of the "resonance" absorption of neutrinos in nuclei[131]) could be used.

In this sense a recent item by V-de Sabbata and C. Gualdi (Nuovo Cimento 28 (1963) 1484) is noteworthy. The reaction $\nu + Be^{9} \rightarrow p + e^{-} + Be^{8}$ is considered. The authors give the cross sections $\sigma \sim 2.10^{-47}$ cm^2 for $E_\nu = 1.7$ MeV and $\sigma \sim 2.6 \times 10^{-37}$ cm^2 for $E_\nu = 14.1$ MeV. I.e., the cross section increases by 10 orders (!). ~~True, the increase of the phase volume (3 particles in the final state)~~

~~and considerations~~131) ~~might lead to an essential growth of the cross section with energy.~~ ~~Nevertheless,~~ the results are so unexpected that independent repeated calculations of the effect are desirable, to say the least of it.

It can be supposed that space vehicles will allow neutrino experiments for more intense natural neutrino fluxes.

True, on Mercury, for example, solar neutrino radiation is only by an order more intense than on the Earth.

Moving in the Sun's orbit at a distance of ~~1,000,000~~ 10^6 km off the Sun, a space ship can be irradiated by a neutrino flux approximately 10^4 times as intense as the corresponding objects on the Earth's surface.

At high temperatures which evidently obtain in originating supernew stars ($T \sim 5.10^9$ K) the neutrino fluxes are estimated at 10^{53} particles115) per sec, neutrinos with an average energy $\sim$ 1 MeV.

At 100 light years off the source the flux is estimated to be

$$\sim 10^{13}/\text{cm}^2\text{sec}.$$

The authors115) draw attention to the fact that such neutrino fluxes are detectable and suggest that in the future the corresponding laboratories could detect the appearance of supernew stars by detecting the origin of such neutrino radiation since the rapid development of high temperatures inside such stars leads to penetrating neutrino radiation preceding a powerful flare emitted by the star's surface.

We witness the origins of neutrino astronomy.

Cosmic Rays

The estimates of possible <u>maximum</u> densities of neutrino fluxes in cosmic rays can be obtained from the experiments performed by Reines and Cowan 116) on a reactor. The Reines and Cowan installation detects antineutrinos in the spectrum section 3 to 10 MeV.

Assuming that the observed background (with the reactor shut down) is entirely due to cosmic antineutrinos, one can obtain the upper estimate 117) for the highest possible value of the antineutrino flux of cosmic rays in the given region of the energy spectrum, this estimate being approximately

$$\lesssim 10^{13} \mathrm{cm}^{-2} \mathrm{sec}^{-1}.$$

Assuming the radiation isotropic, one can obtain the maximum density of neutrino energy in the universe

$$\lesssim 10^{3} \mathrm{\ MeV/cm}^{3}.$$

This is approximately 10^5 times larger than the average energy density given by astronomical estimates and corresponds (by energy) to roughly 1 proton per cm^3.

The reaction

$$\nu + \mathrm{Cl}^{37} \rightarrow \mathrm{Ar}^{37} + e^{-}$$

was studied in the Davis 110) experiments. From his measurements it follows that

$$\int_0^\infty c\,\rho(E)\,\sigma(E)\,dE \lesssim 10^{-33} \mathrm{sec}^{-1}.$$

Here $\rho(E)$ is the cosmic neutrino density ($MeV^{-1}cm^{-3}$) and $\sigma(E)$ is the cross section of the reaction under consideration.

It should be noted that the Davis installation is not effective for detecting neutrinos of ~ 1 GeV, i.e., such neutrinos which can split the Cl nucleus. The upper limit for the density of 100 MeV neutrinos can be estimated from the Davis experiments under the assumption that the Davis detector has been irradiated by monoenergetic neutrinos of the given energy[+].

[+] For example, $E_\nu \sim 70$ MeV: the nucleon recoil does not prevent the production of Ar^{37}.

The estimates[117]) lead to the following numerical values:

$$\sim 1 \text{ MeV per cm}^3.$$

The upper estimates of neutrino fluxes with neutrino energies ~ 1 GeV can be obtained by analyzing as yet rough experiments in the underground detection of muons.

Even now it can be claimed that the neutrino energy density in the universe is in the neutrino spectrum region of 1 GeV at least by three orders less than the energy density due to the averaged nucleon density[118]). It is the data on the underground measurements of the vertical intensity of charged particles[86]) make possible this estimate. These measurements have shown that charged particles capable of passing through 5 cm of lead at depths 816, 1812, 3410, 4280 and 6380 m of water equivalent possess respectively the intensities 2.48×10^{-6}, 1.78×10^{-6}, 1.31×10^{-8}, 2.85×10^{-9} and $1.62 \times 10^{10} cm^{-2}sec^{-1}sr^{-1}$.

The above intensities practically coincide with the estimates of muon fluxes due to the decay of atmospheric pions. The upper estimate of the density of neutrinos with energies $E_\nu \geq 1$ GeV can be obtained under the assumption that all muons underground registered in ref.[86]) have originated as a result of the $\nu + n \to \mu^- + p$ and $\nu + p \to \mu^+ + n$ effects with cross sections $\sigma_\mu \sim 10^{-38} cm^2$.

From the estimates it follows that the neutrino density with $E_\nu \geq 1$ GeV is less than $10^{-8} cm^{-3}$, which corresponds to the neutrino energy density in this spectrum section less than 10^{-5} MeV cm^{-3}, which is already by three orders less than the nucleon density (10^{-2} MeV cm^{-3}).

13. Cosmological Problems

Some major problems of cosmology have proved to be connected with neutrino physics.

However, these problems are extremely speculative and often as yet reminiscent of the background of fantasy fiction.

In connection with the charge asymmetry of our world there arise ideas about the antiworlds which would ensure the charge symmetry of the universe as a whole.The local charge asymmetry of our part of the universe might have arisen as a result of fluctuation in the charge-symmetric world[117]).

It is natural to think that the fluctuation hypothesis implies ,the existence,at any rate in the past[+] ,of a strong

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[+] "In the past" means the acceptance of a model of the universe in which space curvature diminishes with time.In the "past" when the fluctuation occurred it is assumed that with the enormous energy densities of that state of the universe (the larger the energy density the greater the curvature) the neutrino-antineutrino background energy density by far exceeds the density of substance.

At present the density of thermal and photon ("symmetrical") energy can be assumed much smaller than that of the energy connected with the rest mass of the substance particles.

If it appears that at present the density of energy $\nu\tilde{\nu}$ is much less than the density of substance,this will mean that the hypothesis under discussion requires further special hypotheses on the development of the universe,the conversion of the primary symmetrical energy component into some new forms (for example,the kinetic energies of remote celestial bodies,etc.) which can be the subject of special discussions.

charge-symmetrical "background". The latter might have been produced by neutrinos and antineutrinos of the same density117)

According to the fluctuation hypothesis, the energy density of this background must be higher than the density of the energy of the charge-asymmetrical component of the world i.e., the energy density contained in substance which is estimated by astronomical data to be approximately

$$\sim 10^{-2}\ \mathrm{MeV/cm^3} \text{ or } 10^{-5} \text{ proton in } \mathrm{cm^3}.$$

It can be supposed that the energy spectrum of the symmetrical neutrino background is determined by nucleon-antinucleon annihilation which leads to the production of pions. The decay of the latter produces a symmetrical neutrino-antineutrino background with neutrino (antineutrino) energy distributed around the intensity maximum near 100 MeV.

These additional considerations on a possible spectrum region with the predominant localization of neutrino energy are not demonstrable, of course, at present. They merely focus attention on that part of the spectrum the experimental data for which (taken per se) do not as yet contradict a relatively large density of neutrino-antineutrino energy.

Somewhat more definite estimates of the neutrino field energy density maxima can be obtained in terms of certain theoretical concepts about the universe. Thus, considering the gravitation effect of the neutrino field on the expanding universe one can establish132) the upper limit for the neutrino energy density[+] as $2.10^{-28} g/cm^3 = 2.10^7$ erg/cm^3.

From this point of view the average energy density $\nu\tilde{\nu}$ is only by an order larger than the substance energy density.

For cosmology it is quite essential to know such a parameter as energy density in the universe. Should it prove that neutrinos make an overwhelming contribution to this parameter, the neutrino nature of the universe would be manifest in different aspects of cosmology.

Obviously, the detection of cosmic neutrinos in different energy spectrum regions ~~sections~~ is of considerable interest.

Considerations have been given above (sect.6) to show the fundamental importance of the experiments in the interaction of neutrinos of very high energies (10^{11} eV) with nucleons and electrons. According to ref.117), it is important to study the energy spectrum of cosmic neutrinos in the 50 to 100 MeV region. Other energy parts of the cosmic neutrino spectrum interesting from different points of view can be pointed out.

At present our knowledge of the origin and development of the universe is very poor and widely different speculations

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[+] The consideration refers in fact to the energy density due to any kinds of weakly interacting particles.

are possible as yet, and neutrino physics may play an essential role in these discussions.

The weak neutrino-substance interaction, now annoying when different attempts to detect neutrinos are contemplated, will become, with the development of experimental possibilities, the immense advantage of the neutrino as a tool for probing into the innermost workings of the universe and its evolution. The neutrino can pass through vast layers of substance without absorption. To all intents and purposes the universe is transparent for the neutrino. Indeed, the cross section for the interaction of the neutrino (antineutrino) with the nucleon in the energy spectrum region $\sim$ 1 MeV is 10^{-43} cm^2. Assuming the substance density in the universe to be 10^{-5} proton per cm^3, we obtain one antineutrino-proton interaction ($\tilde{\nu} + p \rightarrow n + e^+$) in the path of 10^{30} light years.

It is not impossible that the investigation of cosmic neutrino fluxes will furnish priceless information about the remotest areas of the universe and the earliest times of its existence.

It is supposed that the universe originated from a primary neutron cloud, the decay of neutrons (of 10^{-5} per cm^3 density) might have lead to a 10^5 cm^2 sec^{-1} antineutrino flux 111,119) in the neutrino spectrum energy region of 0.5 to 1 MeV.

This estimate gives the lower limit. It takes into account only the conversion of primary neutrons into protons and neglects the possibility during the existence of the universe of repeated neutron decay events or rather the β -decays of complex nuclei which have originated in the evolution of stellar substance.

The discussion of a cosmogonic hypothesis directly opposite to the previous one is also of interest.

In other words, it can be assumed that primary matter consisted of protons and electrons and with the origin of neutrons in subsequent times there must have arisen a neutrino flux of the same density[111]) i.e., at least 10^5 cm^2 sec^{-1}.

According to Ya.B.Zeldovich[143]), the universe at the earliest stage of its development consisted of protons, electrons and neutrinos. Zeldovich holds that neutrinos, occupying densely the corresponding energy levels make the reaction

$$p + e^- \rightarrow n + \nu$$

forbidden to all intents. Thus the production of ~~adjacent~~ complex nuclei is obstructed at this stage. Asymmtery with respect to lepton charge is intensified even more in the latest model of the universe. Without going into the comparison of different concepts of the development of the universe it can be contended that at any rate the ratio of the neutrino and antineutrino flux intensities in free cosmic space could be a parameter characterizing important information on the universe.

* * *

Several years ago M.Goldhaber[121]) proposed another fantastic mechanism for the division of the universe into worlds and antiworlds.

According to Goldhaber, at the beginning there was one particle, universon, equal in mass to the universe. This universon was charge-symmetric. At a certain moment $t = t_0$ this universon split into a particle and antiparticle, or as Goldhaber calls them a cosmon and anticosmon, with the corresponding nucleon and antinucleon charges. This spontaneous fission ~~scission~~ of the universon can be illustrated to a certain extent by an analogue in the decay of some hypothetical charge-symmetrical particle X into two particles: neutron and antineutron

$$X \rightarrow n + \tilde{n}$$

with large relative kinetic energies. The high relative speeds of the cosmon and anticosmon led to the spatial separation of particles into large relative distances. Each cosmon is converted in the prowess of evolution into the nucleon and respectively antinucleon substance of the worlds and antiworlds.

A number of fermions with masses exceeding the masses of mucleons and bosons with masses larger than those of pions has been discovered in recent years.

It is unknown whether there is any upper limit for [redacted] 50X1-HUM

the mass of the "elementary" particle[122]).Short-living states of still larger masses ("resonance states") have been discovered quite recently.Since we have entered the realm of unrestricted phantasy,we can mention the hypothesis that the production of fireballs in collisions of cosmic nucleons of tremendous energies with nucleons of substance is nothing else than the accomplished production of one or two "elementary" particles (particle and antiparticle) with relatively large masses the substance of which later degrades into pion showers[122]).Perhaps the Goldhaber cosmon is the ultimate case of such a particle.

Our concepts of the development of the universe are so speculative as yet that most unexpected possibilities are not ruled out.It is not impossible that the mechanism dividing worlds and antiworlds is not indispensable at all: for example,the production of primary "particles" like cosmons in the charge-asymmetric state is possible even from the charge-symmetric state.Elementary particle physics knows symmetrical states leading to charge-asymmetrical states. E.g.,

$$\pi^+ + \pi^- \rightarrow K^0 \quad \text{or} \quad \pi^+ + \pi^- \rightarrow \tilde{K}^0$$

True,the transition of particles into antiparticles $K^0 \rightarrow \tilde{K}^0$ proves possible with the passage of time in this case. But,perhaps,the universe turns to the antiuniverse and

[redacted] 50X1-HUM

vice versa. Or in other words, the electron and proton masses, for example, are functions varying with time?

Perhaps the worlds and antiworlds are divided to such an extent and in such a way that nucleon-antinucleon annihilation makes practically no contribution to the symmetrical energy background. Unlike our Sun, far-away anti-Suns would radiate antineutrinos in the characteristic energy interval. And sometime---

At this point we shall probably do well to stop the discussion of such possibilities if they ~~are~~ may be called so.

„Neutrino Sea" 125)

Neutrino- and antineutrino-radiating reactions are constantly at work in nature. Synthesis and decay of elements are accompanied by neutrino and antineutrino radiation. These main processes in the evolution of celestial matter supply neutrinos and antineutrinos of energies $\sim$ 1 MeV.

If the M.S and F.G weak interaction scheme is correct and the direct $(e\nu)(e\nu)$ actually exists, it is precisely by electrons that the neutrino (antineutrino) radiation of the long-wave part of the spectrum (analogue of optical, radio-radiation, etc.) is generated.

The bremsstrahlung by an electron of a neutrino-antineutrino pair in the Coulomb field of a nucleus ($e+Z \rightarrow e'+Z'+\nu+\bar{\nu}$), production of a neutrino-antineutrino pair from a γ -quantum on an electron ($\gamma + e \rightarrow e' + \nu + \bar{\nu}$) and other such effects of the ($e\nu$)($e\nu$)-interaction can cause long-wave neutrino radiation. Since there must be no direct nucleon-neutrino interaction according to the M.S. and F.G. theory, celestial bodies consisting of nucleons and electrons are not neutral with respect to neutrino-antineutrino field.

Just as an electron, moving in a closed orbit in a synchrocyclotron, must radiate γ -quanta and neutrino-antineutrino pairs, so too celestial bodies in their orbital movement with respect to the neutrino-antineutrino field constitute sources of enormous β -"charge", of the radiation of neutrino-antineutrino pairs.

All innumerable reactions in which neutrinos and antineutrinos are produced fill the universe with neutrino-antineutrino radiation. Since the neutrino (antineutrino) absorption cross sections are very small and these particles are not practically absorbed as they wander over the universe over astronomical periods (10^9 years) it can be supposed that neutrino radiation has been accumulating in the present phase of the development of the universe.

The Pauli principle restricts the maximum density of the number of neutrinos per cm^3 by energies lying between E and $E + dE$. The maximum value of this density is given by the expression

$$n(E)dE = \frac{1}{(2\pi)^2(\hbar c)^3} E^2 dE \qquad (150)$$

The maximum number of neutrinos of energies $E < E_0$ is thus restricted by

$$N_{\substack{max \\ E \leq E_0}} = \int_0^{E_0} n(E)dE = \frac{1}{(2\pi)^2(\hbar c)^3} \frac{E_0^3}{3} \qquad (151)$$

For Fermi energy ~ 1 eV, for example, the number of neutrinos per cm^3 is

$$N_{E \leq E_0} = \frac{1}{(2\pi)^2}\left(\frac{m_e c}{\hbar}\right)^3 \frac{10^{-18}}{3} = 10^{11} \qquad (152)$$

If the Earth emits, while revolving around the Sun, neutrino radiation with a wave length $\lambda \sim R$ where $R \sim 10^{13}$ cm is the radius of the Earth's orbit, the corresponding energy of these neutrinos will be

$$E_\nu \sim m_e c^2 10^{-22} \sim 10^{-22} \text{ MeV}. \qquad (153)$$

The maximum number of neutrinos with energies $E \leq E_\nu$ per cm^3 is expressed, according to eq. (151), as

$$\mathcal{N}_{E<E_\nu} \approx 10^{-36} \text{ neutrinos/cm}^3. \qquad (154)$$

While the Olbers paradox[123]) is meaningful for photons related to Newtonian cosmology in any photon energy spectrum region, neutrinos conform to the Pauli principle and, having populated all the corresponding levels with $E \leq E_0$, preclude any further processes emitting neutrinos with $E \leq E_0$. If $E_F \sim 1$ eV the number of neutrinos per cm^3 is in fact still very small—in the sense that such a neutrino background in such an energy spectrum region does not seem to be capable of showing in elementary processes like

$$\nu + n \to p + e^-$$

The energy contained in the neutrino "sea" with the Fermi energy E_F is given by the expression

$$W = \int_0^{E_0} E n(E)\, dE = \frac{1}{(2\pi)^2 (\hbar c)^3} \; \frac{E_F^4}{4} \qquad (155)$$

For $E_F \sim 1$ eV or more accurately $E_F = m_e c^2 10^{-6}$

$$W = \frac{1}{(2\pi)^2 4} \left(\frac{m_e c}{\hbar}\right)^3 \cdot 10^{-24} m_e c^2 \sim 10^5 m_e c^2 / \text{cm}^3 \sim \frac{10^5 \text{ Mev}}{\text{cm}^3}. \qquad (156)$$

That would mean that the entire matter of the universe is concentrated in neutrino radiation. The average density of matter in the universe is estimated to be 10^{-5} protons per cm^3, i.e., 10^{-2} MeV/cm^3.

Thus even when $E_F \sim 1$ eV the mass contained in neutrino radiation would be 10^7 times larger than the masses of the Galaxies whose masses could be simply neglected in the corresponding cosmological estimates.

The problem of the density of matter in the universe is important for the selection of the model of the world. The average density 124) corresponding to a flat universe (transition from the closed to open model) amounts to 5.10^{-29} g/cm^3, which is not far from what is given by the estimate of the substance of the Galaxies. Of course, a large neutrino radiation density could be a decisive factor when the model of the universe is discussed.

Developing the considerations of his paper concerned with the neutrino problems of cosmology 123) Weinberg discusses the relations between the upper limit of the Fermi energy of the filled neutrino sea (E_F) and different models of the universe 125).

According to Weinberg, in the developing universe model and the steady state cosmology the population of the neutrino levels is very low. The corresponding Fermi energy E_F is estimated as

$$E_F \sim \exp^{-10^{36}} \text{ MeV} \qquad \text{(evolutionary model)}$$

$$E_F \sim 10^{-36} \text{ or } 10^{-24} \text{ MeV} \qquad \text{(stationary model).}$$

This means that in such models celestial bodies could also radiate neutrinos in the characteristic frequency range (153).

Since the weak interaction constant is by far larger than the gravitation constant, and the radiation of gravitation waves in cosmic times can, by estimates120), amount to 0.1% of the mass of celestial bodies, it seems at first glance that the energy losses of celestial bodies via neutrino-antineutrino radiation may be catastrophic. This can even be interpreted as a certain argument in favour of the oscillating model of the universe in which the population of neutrino levels is, according to Weinberg, so large ($\sim 2.10^{-3}$eV) that the frequency range under discussion proves to be simply forbidden. However, simple analogies of the Bose fields (gravitation waves) and Fermi fields (neutrinos) are extremely risky in the region of small frequencies and large intensities since there is no classic analogue for the Fermi field.

The concrete estimates of population of neutrino levels in different models of the universe may undergo serious changes in further analyses and specifications, but the fact remains: there have resulted the idea of the neutrino sea of the universe with a certain possible Fermi energy E_F which is not so low for the oscillating model. This idea will naturally be followed by the experimental attempts to lower the upper limit for the possible value of E_F .

In his preprint Weinberg discusses experimental possibilities which are quite interesting in principle.

If the neutrino (antineutrino) levels are actually filled to $E_\nu = E_F$,characteristic deviations must in principle be observed near the upper limit of the Curie graph from its behaviour calculated without taking into account the filled neutrino levels.

If,for example,for antineutrinos there is a "background" with $E_\nu = E_F$,in β -decays all decays with electron energies higher than $E_e = W_0 - E_F$ (W_0 is the "maximum" electron energy value) will be forbidden.The Curie graph will change sharply its direction near the electron energy value $E_e = W_0 - E_F$.

The Curie graph curve near the upper limit of the electron spectrum will be such as if the antineutrino emitted in this decay had the rest mass $m_\nu = \frac{E_F}{c^2}$ (fig.27)

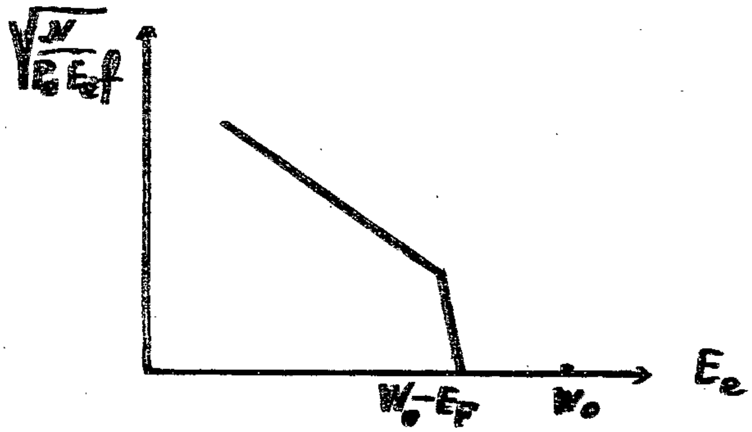

Fig.27

The electron decay energy is marked off on the X-axis of graph 27 and the quantity in the Curie graph connected with the number of decay electrons (N) on the Y-axis (f is the Coulomb factor).

If the neutrino background is filled the electron decay spectrum edge will have a characteristic continuation beyond the energy W_0 (fig.28)

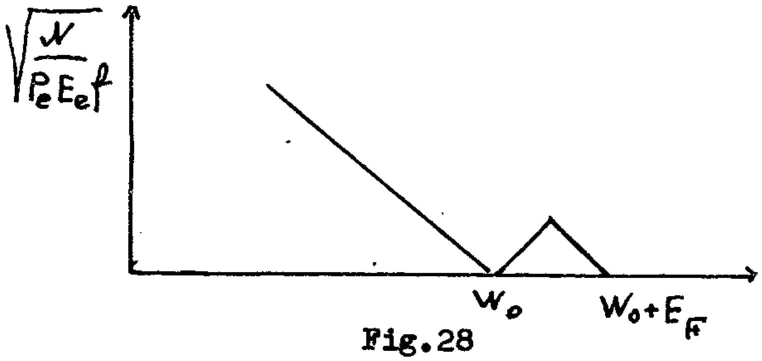

Fig.28

This means that a certain number of decay electrons originates with energies $E_e > W_0$,i.e.,with an apparent violation of conservation.

The most accurate experimental data on the electron decay energy spectrum have been obtained for tritium.The upper limit[+] they give for the antineutrino $E_F^{\tilde{\nu}}$ is

$$E_F^{\tilde{\nu}} < 200 \text{ eV}.$$

[+] It will be recalled that according to ref.^{132}) the average neutrino energy density in the universe cannot become so high.

For neutrinos (β^+ -decays) this limit is five times as high. As for muon neutrinos the upper limit $E_F^{\nu_\mu}$ for them, estimated by data on μ^+ -decays, lies still very high

$$E_F^{\nu_\mu} < 4 \text{ MeV}.$$

According to Weinberg, E_F is connected with the maximum (R_c) radius of the universe expressed in universe radius units for the present state of the universe by the relation

$$E_F \approx 5 R_c$$

Naturally, the upper limit of E_F will decrease considerably as a result of experimental attempts in the next few years. Weinberg reports about one such experiment with tritium that has been started in Glasgow.

We have one of the first examples in the history of physics when it is hoped to receive answers to questions of fundamental importance for the future theory of the universe by investigating events of the microworld. It does not take much of a profit to predict that examples of such a connection between the microworld and ultra macroworld will be more and more frequent in the future.

It should be noted that the above considerations are based on the strict observance of energy conservation law.

This applies even to the steady state cosmology in which this law is violated according to the authors of the

[redacted]

model themselves: in 1,000,000,000 years there arises approximately one electron-positron pair per 1 cm^3 of space. This number merely characterizes the scale of a possible violation[+] of the energy conservation law, but says nothing about the specific forms of the origin of such violations in interactions. Such a weak violation of the conservation law could be connected with the same weak interactions. Weak interactions may prove peculiar in this respect as well. In weak interactions the energy conservation law is checked with the same accuracy as the upper limit of the Fermi energy E_F very roughly indeed. In electromagnetic interactions the Mössbauer effect seems to afford to make considerable headway in the verification of this law.

The presence of two kinds of neutrinos change essen-

[+] Leaving aside any serious criticism of the steady state cosmology from the viewpoint of available experimental data it should be noted that the question in this model is not of an actual violation of conservation laws, but of a different form of these laws.

Ref.134) attempts at such an interpretation of conservation laws in the steady state cosmology. The production of energy connected with substance is compensated by a decrease in gravitational potential energy.

[redacted]

tially many situations in cosmological problems.

Peculiar macroscopic processes may also arise if the rest mass of (say, muon) neutrinos differs from zero. In this case non-relativistic neutrinos, subject to the purely gravitational attraction of celestial bodies will make up bound systems of macroscopic dimensions.

Indeed, for a neutrino of mass m_ν in the gravitational field of a celestial body of mass $\mathcal{M}$ the radius of the corresponding "Bohr orbit" is

$$r \sim \frac{\hbar^2}{\varkappa m_\nu^2 \mathcal{M}}$$

where $\varkappa$ is the gravitation constant.

For the neutrino mass $m_\nu = 10^{-4} m_e$ the "Bohr orbit" radius is of the order of miles if the size of the celestial body is approximately the same or larger.

The "Bohr orbit" of a neutrino of mass equal, for example, to

$$m_\nu = 10^{-12} m_e$$

must fit in within our planet. The stationary neutrino orbits inside celestial bodies is here meant.

Naturally, neutrinos with high velocities may form around celestial bodies the neutrino atmosphere of, in particular, strongly degenerate neutrino gas. In this case the interpretation of experimental results like those in figs. 27 and 28 may prove ambiguous (say, for the physicists of the generations to come).

Accumulations of purely neutrino matter may also have originated in different areas of the universe because of the reciprocal gravitational attraction of neutrinos with $m_\nu \neq 0$. Apart from the well-known alternatives of the equilibrium (electron-proton and neutron) state of large masses, it is possible in principle to discuss a purely neutrino equilibrium state, hypothesize about neutrino stars or rather neutrino celestial bodies, etc.

Though the upper limit for the muon neutrino mass is very high as yet it should be remembered that the well-known relation between the mass of degenerate non-relativistic, say, neutron gas and the size of the system contains the elementary particle mass in eighth power[135])

$$\mathcal{M} R^3 = 91{,}9 \frac{\hbar^6}{\varkappa^3 m_n^8}$$

But in general the world would be simpler and, perhaps, easier to study if the neutrino had no rest mass. Evidently, this not always very weighty ground tips the scale of scientific opinion in favour of the two-component neutrino idea.

14. Prospects of Neutrino Physics

Colliding Beams

If the Pontecorvo-Smorodinsky hypothesis is valid and in space there exist intense neutrino (antineutrino) fluxes of 100 MeV energy, electron-neutrino colliding beams are naturally produced as a result of the origin of an electron beam in any accelerator. If the intermediate meson actually exists and its mass is not larger than the nucleon mass, peculiar effects can in principle be expected in the electron beams of accelerators.

The future linear accelerator proposed by Panofsky is to yield a 4.10^{10} MeV electron beam. Electrons of such energies colliding with antineutrinos of energies $\sim$ 100 MeV may produce an intermediate meson. With the mass of the intermediate meson equal to that of the nucleon the resonance energy is $\sim 9.10^{11}$ eV in the electron rest system. Though the cross section for the intermediate meson production is large —it is $\sim 10^{-32}$ cm^2 (the case of resonance) for the observed effect (1 μ -meson per day) a very large neutrino density $\sim 10^{10}$ cm^{-3} is required. The energy density from such neutrinos would exceed 10^{14} times the average substance density in the universe (10^{-2} MeV). Regrettably, this possibility is ruled out in reality.

Nevertheless, colliding beams may have essential effect on the further development of the theory of weak interactions with which neutrino physics is linked so closely. The cross section for the production of a pair of vector mesons in the reaction with colliding electron-positron beams

$$e^- + e^+ \rightarrow W^+ + W^-$$

possesses several specific features suggesting that this effect is eminently suitable for the solution of the intermediate meson problem.

The cross section of this reaction is given[127,128] by the expression

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{32\,\mathcal{M}_W^2}\left(1 - \frac{\mathcal{M}_W^2}{\varepsilon^2}\right)^{3/2}\left[4 - \left(2 - \frac{3M_W^2}{\varepsilon^2}\right)\sin^2\theta\right] \qquad (157)$$

which approaches rapidly a limit independent of energy ($\mathcal{E}$)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathcal{E}\to\infty} = \frac{\alpha^2}{16\,M_W^2}\left(1 + \cos^2\theta\right) \qquad (158)$$

Here M_W is the intermediate boson mass. Thus, spin 1 leads, unlike spin 0 and spin 1/2, to an energy-independent cross section. The corresponding cross sections for 0 and 1/2 spin particles decrease quadratically with energy. A constant limit is attained in eq.(158) rather rapidly (when $\mathcal{E} \simeq 4\,M_W$)

and may correspond to rather appreciable cross sections. Thus, when M_W =560 MeV we have $\sigma \sim 7.10^{-32}$cm^2, which is by an order larger than the cross sections for 0 and 1/2 spin particles with the same energies.

In the production of an intermediate meson which disintegrates practically instantaneously, the effect must be registered as the production in the process of the e^+, e^- collision of a (μ, e) pair with the total energy lower than 2ε.

However, colliding lepton beams ($e^- + e^-$; $e^- + e^+$) are especially interesting because they hold out the possibility of checking electrodynamics at distances $\sim 10^{-16}$cm. A deviation from electrodynamics over these distances[+] would testify in favour of the fact that the four-fermion interaction in

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[+] A deviation from electrodynamics is possible as a result of radiation corrections and various effects of strong interactions which cannot easily be taken into account theoretically. We mean essential deviations from electrodynamics precisely in the region of lengths characteristic of weak interactions. It would be an improbable coincidence defying explanation if there existed deviations from electrodynamics as a result of, say, strong interactions for parameters $\sim 10^{-16}$cm.

its current form applies up to critical energies or up to lengths characteristic of weak interaction. Thus, the length $\sqrt{\frac{G}{\hbar c}} \sim 7.10^{-17}$cm could claim to be of fundamental importance in modern theory as its only intrinsic length, a possible determinant of the structure of our space[133]).

Thus a purely electrodynamic experiment could have a decisive effect on the development of the theory of weak interactions. As for the fundamental problem of checking experimentally the possibility of the direct $(e\nu)(e\nu)$-interaction, the same, already once tested but 10^3 times more difficult, superhuman experiment near reactors remains the most realistic undertaking. True, the enormous neutrino ~~momentum~~ intensity as a result of a thermonuclear explosion may prove more convenient experimentally. According to an estimate (evidently overrated) made by Reines[129]), a 20 kiloton explosion may yield 10 counts of the events under discussion per 1 ton of the detector.

As for detecting neutrino (antineutrino) fluxes in free space with intensities of 10^5 particles/cm^{2}sec there is no methods as yet for detecting such weak intensities. Allowances should be made of the fact that neutrino physics is still in its initial stage and perhaps experimental possibilities adequate to the problems of weak interactions have not been found so far.

On the other hand, the detection of weak low-energy neutrino (antineutrino) fluxes opens such breath-taking vistas (neutrino astronomy, antiworlds, etc.) that creative thought will inevitably keep its search for original solutions.

In a recent Dubna preprint121) V.B.Beliayev considered the possibility of accumulating optical neutrinos in closed spaces on the basis of the total inner reflection, taking into account the $(e\nu)(e\nu)$ interaction for long wave (optical) neutrinos in a fine surface film. True, the author's estimates sound too good to be true.

Actually, the surface layer is probably too thin for any appreciable accumulation of neutrinos, but a fresh angle of approach and original direction of search suggest that probably there are untrodden paths along which possibilities for detecting neutrinos of weak intensities will be found, perhaps by creating a kind of accumulator for them.

* * *

This is a hard piece of guesswork for our contemporary: the true place of the neutrino in the physics of the future. But the properties of this particle are so primary and unique as to suggest that nature has created it with some profound though not yet always clear purposes.

In this sense we can understand that well-nigh religious hymn to the neutrino expressed in J.Wheeler's "Gravitation of the Neutrino and the Universe" in terms of mathematics, this divine Latin of modern theoretical physics.

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