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*SOME NEW PROPOSALS FOR EXPERIMENTS IN THE FIELD OF NEUTRINO PHYSICS*1)

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1. INTRODUCTION

THE two-component neutrino theory is more than satisfactory. At worst it represents an astonishingly good approximation to reality. It is nevertheless not without interest to consider certain new proposals for neutrino experiments, designed to test whether the neutrino indeed possesses fully the properties which at this time are universally accepted. I shall touch on several problems, which are traditionally little discussed at conferences on high-energy physics, in order of increasing degree of remoteness. It turns out that, in principle, the questions can be answered by carrying out not too "fantastical" experiments.

2. WHAT IS THE NATURE OF "DIAGONAL" PROCESSES?

Recently Gell-Mann, Goldberger, Kroll, and Low[1] have proposed the idea that the "diagonal" and "nondiagonal" terms in the weak-interactions Hamiltonian have no relation to each other and may have an entirely different nature. While the "nondiagonal" weak processes have been rather well studied, information on the "diagonal" terms of the Hamiltonian for the weak interactions is rather scarce. First of all it refers to the nucleon part of the Hamiltonian and is based on experiments studying parity nonconservation effects in nuclear transitions[2]. Secondly, some information on the term $(\bar{e}\nu_e)(\bar{\nu}_e e)$ in the Hamiltonian is obtained from experiments with high-energy neutrinos; for the effective coupling constant G_{ν_e} one finds[3] that $G_{\nu_e}^2 < 40\ G^2$, where $G = 10^{-5}/M_p^2$—is the Fermi constant. Thirdly, as was noted more than ten years ago at the Kiev conference on high-energy physics[4], the existence of the ν-e scattering process, predicted by the universal theory, gives rise to important astrophysical consequences, the analysis of which can, in principle, test this prediction[5]. The theoretical studies of the astrophysical data[6] indicate that $G_{\nu_e}^2 = 10^{0\pm2}\ G^2$. Fourthly, there are at this time being carried out[7] and planned[8] experiments on the study of the reactions $\tilde{\nu}_e + e \rightarrow \tilde{\nu}_e + e$ utilizing as a source of $\tilde{\nu}_e$ a powerful uranium reactor. The results obtained by Reines and Gurr[7] give $G_{\nu_e}^2 < 4G^2$.

Here we would like to emphasize the possibility in principle of studying the recoil electron spectrum in $\tilde{\nu}_e$-e scattering. The point is that measurement of the spectrum is not much more difficult than the detection of the $\tilde{\nu}_e$-e scattering process itself, and the resulting information is rich. In the work of Bardin, Bilenkiĭ, and Pontecorvo[9] the $\tilde{\nu}$-e scattering process was discussed under a variety of assumptions about the neutrino-electron interaction. We consider the following possibilities:

1. The $\tilde{\nu}_e$-e scattering process is determined by the four-fermion weak interaction (V – A, V(A), S(P)).

2. The $\tilde{\nu}_e$-e scattering process is due to the "anomalous" electromagnetic interaction of the neutrino, i.e., an anomalous electromagnetic radius or anomalous magnetic moment.

The spectra of the recoil electrons in the process $\tilde{\nu}_e + e \rightarrow \tilde{\nu}_e + e$ were calculated for the known spectrum[10] of the incident $\tilde{\nu}_e$ from the uranium reactor. It was shown that the measurement of the recoil electrons spectrum under these experimentally-realistic conditions would lead to important conclusions on the

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*Report at the XV International Conference on High Energy Physics, Kiev, August 1970.

character of the “diagonal” $(\bar{e}\nu_e)(\bar{\nu}_e e)$ interaction. The spectra for the five cases (V – A, V, S, electromagnetic radius, magnetic moment) are shown in[9] in the form of a table in the recoil-electron energy regions from 1 to ~7 MeV. It is sufficient here to recall that the recoil-electron spectrum falls with increasing energy much faster for the V – A version than for the other versions of the four-fermion interaction: even a rather rough measurement of the recoil-electron spectrum in the process $\tilde{\nu}_e + e \to \tilde{\nu}_e + e$, using reactor antineutrinos, would allow us to distinguish the V – A version from the other interaction versions.

As regards the anomalous electromagnetic interaction of the neutrino, the calculations, also carried out for the spectrum of incident antineutrinos from the reactor, show that the recoil-electron spectrum in this process is substantially softer in the case when the interaction is due to the magnetic moment of the antineutrino than in the case when the interaction is due to the electromagnetic radius. The necessity for mounting experiments on the measurement of the recoil electron spectrum in the $\tilde{\nu}_e - e$ scattering process with reactor antineutrinos is obvious.

3. OTHER NEUTRINO SOURCES?

In all experiments on high energy neutrino physics it is supposed that pions and kaons are the only source of neutrinos. Correspondingly all neutrino high energy experiments are carried out by giving the pions and kaons a chance to decay in flight. It is legitimate to ask whether there exist other neutrino sources. It seems to me that as a search experiment (Stanford, Serpukhov, Batavia) one should attempt to detect neutrinos with the help of a classical high-energy neutrino detector, without giving the pions and kaons a chance to decay in flight. This means that the proton or photon (electron) beam should fall directly on the shield behind which the neutrino detector is located. For illustration one may justify the organizing such experiments in terms of a search for the intermediate meson or a search for heavy leptons, which decay “instantaneously” producing a neutrino. I have been informed that such a proposal was also made by Schwartz. Of course in these cases the intensity will be rather small, but the neutrinos should be of the electronic and muonic type in approximately equal amounts (in contrast to the neutrino of pionic nature) or belong altogether to a different type. By the way, the low intensity of neutrino production to be expected in the proposed experiment will be partly offset by a significantly better detection efficiency, due to the smaller distance between the neutrino source and detector of ν.

The organization of such experiments is of phenomenological interest independently of the justification which might be dreamed up for them.

I shall not discuss in detail the possible background in such experiments. Suffice it to say that it is due to the decay in flight “against our will” of pions and kaons, and, obviously, the length characteristic of these decays is approximately equal to the typical hadronic length (a few cm in heavy dense substances)2).

4. IS THE LEPTONIC CHARGE CONSERVED? DOES THE NEUTRINO MASS REALLY VANISH?

The question of the possible nonconservation of the leptonic charge (or leptonic charges) is quite timely. I shall discuss the trend which has been developed in the Soviet Union in recent years on this question and has not been discussed at high-energy physics conferences.

In all experiments relevant to the question of possible nonconservation of leptonic charge, one searches for the probability or cross section for some process ($\mu^+ \to e^+ + \gamma$, $\nu_\mu + p \to \mu^+ + n$, double β decay, ...), i.e., one measures the square of the amplitude for the process in question.

Even before Davis, Harmer, and Hoffman have organized the first experiment on observation of solar neutrinos[11] using as the detector the reaction $\nu_e + Cl^{37} \to Ar^{37} + e^-$[12], I called attention[13] to the fact that: 1) the problem of possible nonconservation of leptonic charge can be studied at a new level of sensitivity by methods of neutrino astronomy of the sun and 2) such a problem is of the highest priority for the astrophysical interpretation of first observations of solar neutrinos.

The sensitivity of the method is due to the large distances characteristic of the solar system and is based on the possibility of measuring the amplitude for the process, and not the square of the amplitude. As everybody knows, it is precisely such a circumstance that gave rise to the wonderful possibilities in the studies of neutral kaons. The nonconservation of leptonic charge leads to the possibility of oscillations in the vacuum between different neutrino states. Since some of the neutrino states are unobservable (for example, the low-energy ν_μ) and, moreover, the oscillations generally speaking average out, the nonconservation of leptonic charge under certain reasonably general conditions, about which we shall speak below, gives rise to the following effect: the intensity of solar neutrinos measured at the surface of the earth will be half the intensity expected for an exactly conserved leptonic charge. But how are we to estimate with sufficient accuracy the absolute value of this latter intensity? Our knowledge of the sun is insufficient to predict the number of events due to solar neutrinos to an accuracy better than a factor of two[14] (except for the case when the events are due to solar neutrinos produced in thermonuclear reactions $p + p \to d + e^+ + \nu_e$ and $e^- + p + p \to d + \nu_e$, but these neutrinos are precisely of low energy and therefore difficult to detect). Thus the absolute determination at the earth’s surface of the intensity of events due to solar neutrinos is at this time not good enough to draw the important conclusion concerning the elementary-particle-physics question of interest to us. However, this is so for the time being. In the future, astronomic measurements will provide an incomparably more sensitive method for the study of the conservation of leptonic charge than the classical methods of elementary particle physics.

In the first astronomic experiment no solar neutrinos have so far been observed. In the process it was found[11] that the number of events of the reaction $\nu_e + Cl^{37} \to Ar^{37} + e^-$, due to neutrinos, is at least two times more than expected[14]. Of course I do not believe that the discrepancy is real and due to the fact discussed above, but simply wish to call attention once more to the

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*According to the kind information of Yu. D. Prokoshkin (December, 1970) an experiment of this type is already being mounted by the Schwartz SLAC group.

fact that it is not possible today to draw a very important conclusion concerning elementary-particle physics simply owing to our insufficient knowledge of the structure of the best known star—the sun.

The description of transitions in the vacuum between different states is of interest for elementary particle physics for its own sake.

In[13], and also in the unpublished paper of I. Kobzarev and L. Okun', the possible ($\nu_e \rightleftarrows \tilde{\nu}_e$), ($\nu_\mu \rightleftarrows \tilde{\nu}_\mu$), and ($\nu_e \rightleftarrows \nu_\mu$) oscillations were discussed. As was shown in the paper of V. Gribov and B. Pontecorvo[15], the first two types of oscillations should not be considered, if it is postulated that only four types of neutrino states exist in nature. It was for this case that the conditions under which the oscillations take place were discussed in[15]. We suppose, following V. Gribov, that in zeroth approximation (V − A theory) there exist four neutrino states with zero mass, describable by two two-component spinors ν_e and ν_μ. In this approximation it is convenient to speak of two strictly conserved leptonic charges, electronic and muonic. Nonconservation of these charges gives rise to real or virtual transitions between neutrino states. All possible transitions may be described with the help of the interaction Lagrangian

$$L_{int} = m_{e\bar{e}}\bar{\nu}'_e\nu_e + m_{\mu\bar{\mu}}\bar{\nu}'_\mu\nu_\mu + m_{e\bar{\mu}}\bar{\nu}'_\mu\nu_e + \text{э. c.},$$

where $\nu' = \bar{\nu}C$ is the charge-conjugate spinor. We denote the charge-conjugate spinor by ν' rather than $\tilde{\nu}$, in order not to confuse it with $\bar{\nu}$.

For simplicity we suppose below that $m_{e\bar{e}}$, $m_{\mu\bar{\mu}}$, and $m_{e\bar{\mu}}$ are real, i.e., CP conservation is assumed. In the general case the discussion becomes somewhat more involved and we shall not stop to talk about it. The interaction is easily diagonalized. The diagonal states are given by

$$\varphi_1 = (\nu_e + \nu'_e)\cos\xi + (\nu_\mu + \nu'_\mu)\sin\xi,$$
$$\varphi_2 = (\nu_e + \nu'_e)\sin\xi - (\nu_\mu + \nu'_\mu)\cos\xi,$$

where $\tan 2\xi = \dfrac{2m_{e\bar{\mu}}}{(m_{e\bar{e}} - m_{\mu\bar{\mu}})}$. These states correspond to two Majorana neutrinos with masses m_1 and m_2 (altogether we have four states when the spin direction is taken into account):

$$m_{1,2} = \frac{1}{2}\left[m_{e\bar{e}} + m_{\mu\bar{\mu}} \pm \sqrt{(m_{e\bar{e}} - m_{\mu\bar{\mu}})^2 + 4m^2_{e\bar{\mu}}}\right].$$

(If $m_2 < 0$ then the real state with positive mass m_2 is $\varphi'_2 = \gamma_5\varphi_2$). In this case the two-component spinors ν_e and ν_μ no longer describe massless particles and should be expressed in terms of four-component Majorana spinors φ_1 and φ_2:

$$\nu_e = \frac{1}{2}(1 + \gamma_5)[\varphi_1\cos\xi + \varphi_2\sin\xi],$$
$$\nu_\mu = \frac{1}{2}(1 + \gamma_5)[\varphi_1\sin\xi - \varphi_2\cos\xi].$$

The leptonic current may in this case be written in the usual way:

$$J_\alpha = \bar{e}\gamma_\alpha\nu_e + \bar{\mu}\gamma_\alpha\nu_\mu.$$

The different masses of the Majorana neutrinos φ_1 and φ_2 give rise to $\nu_e \rightleftarrows \nu_\mu$ and $\nu'_e \rightleftarrows \nu'_\mu$ oscillations (in conventional notation $\tilde{\nu}_e \rightleftarrows \tilde{\nu}_\mu$). If at the time t = 0 an electronic neutrino was produced, then the probability of observing it at the time t has the form

$$|\nu_e(t)|^2 = |\nu_e(0)|^2\left\{\frac{m_-^2 + 2m^2_{e\bar{\mu}}}{m_-^2 + 4m^2_{e\bar{\mu}}} + \frac{2m^2_{e\bar{\mu}}}{m_-^2 + 4m^2_{e\bar{\mu}}}\cos 2\Delta t\right\}, \qquad (1)$$

where $m_- = m_{e\bar{e}} - m_{\mu\bar{\mu}}$, $\Delta = \frac{1}{2p}(m_1^2 - m_2^2) = (m_{e\bar{e}} + m_{\mu\bar{\mu}})\sqrt{m_-^2 + 4m^2_{e\bar{\mu}}}/2p$, and p is the neutrino momentum.

Let us emphasize that the oscillations take place only if $m_{e\bar{\mu}}$ and at least one of the quantities $m_{e\bar{e}}$ or $m_{\mu\bar{\mu}}$ are not zero. Physically this means that for the existence of the oscillation it is necessary that the probability of the decay $\mu \to e + \gamma$ should not vanish and that at least one of the cross sections for the processes $\tilde{\nu}_e + n \to e^- + p$ and $\nu_\mu + p \to \mu^+ + n$ should not vanish.

If the oscillations are absent, then the following two possibilities can occur. If $m_{e\bar{\mu}} = 0$ then $\xi = 0$, and we have two Majorana neutrinos (without oscillations). If $m_{e\bar{e}} = m_{\mu\bar{\mu}} = 0$ and $m_{e\bar{\mu}} \neq 0$, then it is natural to ascribe to e^- and μ^- opposite leptonic charge[16] (only one kind) and consider (in place of the degenerate states φ_1 and $\varphi'_2 = \gamma_5\varphi_2$ with mass $m = m_{e\bar{\mu}}$) the states with definite leptonic charge $\psi = \nu_e + \nu'_\mu$, $\psi' = \nu'_e + \nu_\mu$ (the four-component neutrino theory with parity nonconservation[17]). If $m_{e\bar{\mu}}$ and one of the quantities $m_{\mu\bar{\mu}}$ or $m_{e\bar{e}}$ are not zero, i.e., if the oscillations do occur, then the case when $m_{e\bar{e}}, m_{\mu\bar{\mu}} \ll m_{e\bar{\mu}}$ is particularly attractive. In that case

$$\left.\begin{aligned} \varphi_1 &\approx \frac{1}{\sqrt{2}}(\psi + \psi'),\\ \xi &\approx \frac{\pi}{4},\\ \varphi_2 &\approx \frac{1}{\sqrt{2}}(\psi - \psi'). \end{aligned}\right\} \qquad (2)$$

In that case the character of the oscillations is fully analogous to the $K^0 \rightleftarrows \tilde{K}^0$ oscillations, and φ_1 and φ_2 are analogous to K_1^0 and K_2^0. According to the expression (1), the depth of the oscillations is maximal in this case. Two spin states ν_{left} and ν_{right} approximately coincide with the observed "phenomenological" states ν_e and ν'_μ (or $\tilde{\nu}_\mu$). Analogously $\tilde{\nu}_{\text{left}} \approx \nu_\mu$ and $\tilde{\nu}_{\text{right}} \approx \nu'_e \approx \tilde{\nu}_e$. An equally simple oscillation picture, analogous to the oscillations of the neutral K mesons, occurs when $m_{e\bar{e}}$ and $m_{\mu\bar{\mu}}$ are not necessarily small in comparison with $m_{e\bar{\mu}}$, however μ − e symmetry is present, i.e., $m_{e\bar{e}} = m_{\mu\bar{\mu}}$. In that case $\xi = 4/\pi$ and the relations (2) are exact.

In[13], as well as in the unpublished work of Kobzarev and Okun', the possibility was discussed that the neutrino oscillations are due to so called milliweak interaction, which, besides PC, also violates lepton conservation. We shall mention here also the other point of view, according to which the oscillations could be due to a superweak interaction of the first kind, changing the leptonic charge by two units[18]. This interaction reminds one of the superweak interaction of Wolfenstein[19], which changes strangeness by two units and it could be closely related to it. Certain ideas on the possible values of the oscillational length 1/Δ can be found in[13], and also in[20]. Unfortunately however, nothing definite can be said about the values of $m_{e\bar{e}}$,

$m_{\mu\bar{\mu}}$, and $m_{e\bar{\mu}}$, (and, consequently on the oscillation length $1/\Delta$), even if they were to be connected with definite (milliweak, superweak) interactions, since the cut-off parameter is unknown: information on the oscillation length and hence on the value of the mass m can be obtained only by detecting solar neutrinos (see below).

Returning to neutrino astrophysics, we shall consider here only the simplest cases, when the oscillations are similar to the $K^0 \rightleftarrows \tilde{K}^0$ oscillations, say, when $m_{e\bar{e}} = m_{\mu\bar{\mu}}$.

In such a case the intensity of the observed neutrinos with momentum p at a distance R from the source will be simply

$$I(R, p) = \frac{1}{2} I_0(R, p) \left(1 + \cos \frac{4m_{e\bar{e}} m_{e\bar{\mu}} R}{p}\right), \tag{3}$$

where I_0 is the intensity which would be observed if the leptonic charge were conserved (more precisely, if $m_{e\bar{e}} m_{e\bar{\mu}} = 0$). The main effect connected with a nonvanishing value of $m_{e\bar{e}} m_{e\bar{\mu}}$, namely the decrease by a factor of two (in comparison with the expected) of the intensity of neutrino-caused events, has been already mentioned. This effect is due to averaging of the oscillations. I. Ya. Pomeranchuk noted the possibility of detecting at the earth's surface of temporal variations in the solar neutrino intensity, these variations being due to a change in the distance between the earth and the sun. This proposal is unlikely to be carried out, for owing to the smallness of the relative change in this distance ($\Delta R/R \approx 0.04$) one would require either neutrino detectors with fantastic energy resolution or extremely precise measurements of neutrino intensity.

As was noted in[15], utilizing a detector of monoenergetic neutrinos could, in principle, lead to a decrease of the observed neutrino intensity relative to the "calculated" one by even more than a factor of two. Bahcall and Frautschi[20] have discussed the detection of solar neutrino lines from the reaction $e^- + p + p \rightarrow d + \nu_e$, where it is important that the calculation of I_0 be sufficiently reliable to detect a possible discrepancy between I_0 and the absolutely measured intensity I.

Under what conditions then can one nevertheless observe the oscillating term in (3) by performing relative measurements? Clearly, the oscillations do not occur when $m_{e\bar{e}} m_{e\bar{\mu}} = 0$, and the oscillating term cannot be observed when $m_{e\bar{e}} m_{e\bar{\mu}}$ is so large (i.e., when the oscillation length $\sim p/m_{e\bar{e}} m_{e\bar{\mu}}$ for a neutrino of an arbitrary relevant momentum is so small) that the neutrino source (the sun region which effectively produces the neutrino) cannot be considered as a point source. Somewhere between these limits one may attempt to observe the oscillations: for values of $m_{e\bar{e}} m_{e\bar{\mu}}$ "uncomfortably small" ($I/I_0 \rightarrow 1$) one must detect "soft" solar neutrinos, and for values $m_{e\bar{e}} m_{e\bar{\mu}}$ "uncomfortably high" ($I/I_0 \rightarrow 1/2$) one must detect relatively "hard" solar neutrinos.

Here we would like to mention a new (albeit remote) possibility of detecting the relative effect due to the ossillating term: the measurement of the spectrum of the solar neutrinos in the high energy region with the help of electronic methods for detecting neutrino events. It can be shown that for favorable values of $m_{e\bar{e}} m_{e\bar{\mu}}$ the change in the spectrum of the observed solar neutrinos due to the oscillations as compared to the known neutrino spectrum from the decay of B^8 could be detectable3).

A neutrino detector based on electronic methods for detecting particles and appropriate for neutrino astronomy does not exist as yet, but, as was proposed in[21], it could be constructed in the future by further development of liquid counters.

What are the desirable properties for such a solar neutrino detector?

1. The setup should detect electrons from the $\nu_e - e$ scattering process or electrons from the inverse β decay with energy of the order of MeV.
2. The sensitive part of the detector should weigh no less than 10 tons.
3. The setup should give information on the direction of incidence of the detected neutrino.
4. The setup should give some information on the energy spectrum of the electrons produced by the neutrino.
5. It would be desirable for the setup to discriminate sufficiently between electrons of "neutrino nature" and background electrons.
6. It would be desirable to produce a film-less instrument, which is "always ready."

It would appear that to a large extent these requirements could be satisfied by a liquid chamber, constructed, for example, according to the principles of the Dolgoshein counter[22] (new liquid counter). By the way, a large liquid counter would probably be useful also for the detection of reactor antineutrinos.

I would now like to make more precise the assertion that the observation with the help of solar neutrinos is incomparably more sensitive than other methods for studying questions such as: is the (average) neutrino mass finite and is the leptonic charge conserved? We may express the sensitivity of a given method (study of the β spectrum of tritium, double β decay, solar neutrinos ...) in terms of the (average) neutrino mass or in terms of an upper limit for such a mass, which the given method can determine. According to formula (1), in the observation of solar neutrinos one may detect absolute or relative effects, due to oscillations, if, say

$$\frac{m_{e\bar{e}} + m_{\mu\bar{\mu}}}{p} \sqrt{(m_{e\bar{e}} - m_{\mu\bar{\mu}})^2 + 4m_{e\bar{\mu}}^2}\, R \gg 1$$

or, making the simplifying assumption on $\mu - e$ symmetry (which does not change the main conclusions), if

$$4m_{e\bar{e}} m_{e\bar{\mu}} \frac{R}{p} \gg 1.$$

For solar neutrinos of energy ~10 MeV, for example, the effects due to oscillations would be observed at the earth's surface ($R \sim 1.5 \times 10^{13}$ cm), if

$$m_{e\bar{e}} m_{e\bar{\mu}} \gg 10^{-12}\ (\text{eV})^2.$$

It is useful to recall that the masses m_1 and m_2 of the two Majorana neutrinos ν_1 and ν_2 are given in our case by the expressions

$$m_1 = m_{e\bar{e}} + m_{e\bar{\mu}}, \quad m_2 = |m_{e\bar{e}} - m_{e\bar{\mu}}|$$

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*The same proposal is also discussed by D. Kocharov and B. Ferberg, Preprint A. F. Ioffe Phys.-Tech. Inst., No. 299, Oct. 1970.

and that the mass of the "phenomenological" particles ν_e and ν_μ is given by $(m_1 + m_2)/2$. It can be seen that the sensitivity of the astronomic method is better by seven orders of magnitude than the sensitivity of the classical method[4)] involving the study of the H^3 β spectrum, which is capable of giving an upper limit of ≈ 10 eV for the ν_e mass.

5. IS THERE A NEUTRINO-NEUTRINO INTERACTION?

It is usually assumed that the sole neutrino interaction is its classical weak interaction. The question may be raised whether the neutrino possesses some other interactions. Bardin, Bilenkiĭ and Pontecorvo[23] discussed the question of a ν-ν interaction. Clearly there exists a ν-ν interaction due to second-order perturbation theory in the weak-interaction coupling constant G. We considered a new hypothetical ν-ν interaction. To our surprise it turned out that the existing experimental data are not in contradiction with the possibility of a rather strong ν-ν interaction. We have also discussed processes whose experimental study yield information on the interaction between neutrinos. After the conclusion of our work we found that already in 1964 E. Bialynicka-Birula discussed the question of neutrino-neutrino interactions[24] and made certain conclusions and proposals analogous to ours.

If a sufficiently strong neutrino-neutrino interaction exists, it is obvious that it will manifest itself in all processes involving the neutrino.

The following topics were studied:

a) new decays (see, for example, the diagram in Fig. a);

b) new processes involving a high-energy neutrino beam (see, for example, the diagram in Fig. b);

c) neutrino "form factors" (diagram in Fig. c).

The ν-ν interaction under consideration would give rise, obviously, to the appearance along with the conventional decays with the emission of a neutrino and a charged lepton, of decays with the emission of an additional neutrino-antineutrino pair. In detail the processes $\pi^+ \to e^+ + \nu_e + \nu_e + \tilde{\nu}_e$ and $K^+ \to e^+ + \nu_e + \nu_e + \tilde{\nu}_e$ were considered; for the sake of concreteness, the effective Hamiltonian describing the ν_e-ν_e interaction was chosen in the form $H_{\nu_e\nu_e} = F_{\nu_e\nu_e}(\bar{\nu}_e\gamma_\alpha\nu_e)(\bar{\nu}_e\gamma_\alpha\nu_e)$.

The electron spectrum in these decays is expressed, naturally, in terms of $F_{\nu_e\nu_e}$ and other known constants (the weak interaction constant $G = 10^{-5}/M_p^2$, the pion decay constant $|f_\pi| = 0.92 m_\pi$ or the K decay constant $|f_K| = 0.25 m_\pi$, the electron mass and the pion or kaon mass). Therefore, to obtain an upper limit on the constant $F_{\nu_e\nu_e}$, it is necessary to study the positron spectrum in π^+ or K^+ decays. The maximum number of electrons from $\pi^+ \to e^+ + \nu_e + \nu_e + \tilde{\nu}_e$ or $K^+ \to e^+ + \nu_e + \nu_e + \tilde{\nu}_e$ decays in the appropriate energy interval may be obtained from an analysis of the background in experiments on the study of $\pi^+ \to e^+ + \nu_e$[25] and $K^+ \to e^+ + \nu_e$[26] decays. An analysis of the pion and kaon decays gives respectively $F_{\nu_e\nu_e} \leq 10^7$ G and $F_{\nu_e\nu_e} \leq 2 \times 10^6$ G. This is an amazingly large number, but further searches for the $K^+ \to e^+ + \nu_e + \nu_e + \tilde{\nu}_e$ decays, aimed at improving the upper limit on $F_{\nu_e\nu_e}$, are fully possible. The observation of the process $K^+ \to \mu^+ + \nu_\mu + \nu_\mu + \nu_\mu$, aimed at information on $F_{\nu_\mu\nu_\mu}$, presents a more difficult problem[5)] owing to the large background caused by the reaction $K^+ \to \mu^+ + \nu_\mu + \gamma$ (the decays $\pi^+ \to e^+ + \nu_e + \gamma$ and $K^+ \to e^+ + \nu_e + \gamma$ are strongly suppressed for the same reason as the suppression of the decays $\pi^+ \to e^+ + \nu_e$ and $K^+ \to e^+ + \nu_e$).

Decays of muons, nucleons and hyperons are less interesting from the point of view of studying the $\nu_e - \nu_e$ or $\nu_\mu - \nu_\mu$ interaction, then the above considered decays of charged pions and kaons. We note in conclusion that the existence of a $\nu_e - \nu_e$ interaction would lead to an additional diagram of a new type in the matrix element for the conventional double β decay (with lepton charge conservation).

Decays with the emission of an additional neutrino-antineutrino pair are strongly suppressed by the smallness of the corresponding phase-space volumes. For this reason of great interest are processes involving a high-energy neutrino beam.

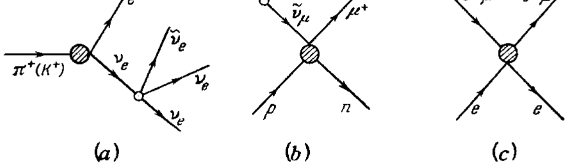
If a sufficiently strong $\nu_\mu - \nu_\mu$ interaction exists (let us emphasize that it can be entirely different from the $\nu_e - \nu_e$ interaction), then the following processes will be observed (see the diagram in Fig. b):

$$\left.\begin{array}{l} \nu_\mu + n \to \mu^- + p + \nu_\mu + \tilde{\nu}_\mu, \\ \nu_\mu + p \to \mu^+ + n + \nu_\mu + \nu_\mu \end{array}\right\} \qquad (4)$$

etc.

From the experimental point of view processes of the type (4) (in which, owing to the interaction of high energy muon neutrinos with nucleons, muons with "incorrect" sign of the charge are produced) are of greatest interest. Such processes, simulating violation of leptonic charge, are most simply identified experimentally in the case when the final state contains no charged pions.

We have calculated the cross section for the process (4) at various values of the incident neutrino energy in the interval from 0.5 GeV to 50 GeV. Here we have assumed that the $\nu_\mu - \nu_\mu$ interaction is carried by a vector particle x, whose mass m_x was set in numerical calculations equal to 1 GeV (the interaction Hamiltonian $\mathscr{H} = i\sqrt{2F_{\nu_\mu\nu_\mu}}\, m_x \bar{\nu}_\mu \gamma_\alpha \nu_\mu x_\alpha$). Let us note that this model was chosen just as a method for introduction of corresponding form factors. We have also used in the calculation nucleon form factors obtained from the analysis of data on elastic neutrino processes[27]. The results of



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*The cosmological method proposed by S. Gershteĭn and Ya. Zel'dovich (ZhETF Pis. Red. 4, 174 (1966) [JETP Lett. 4, 120 (1966)] is also less sensitive than methods of solar neutrino astronomy.

*It may be that this assertion is incorrect. I have found out recently that in Berkeley the Stining group proposed to search for the decay $K^+ \to \mu^+ + \nu_\mu + \nu_\mu + \tilde{\nu}_\mu$ using a clever experimental setup which very effectively suppresses detection of decays of the type $K^+ \to \mu^+ + \nu_\mu + \gamma$, $K^+ \to \mu^+ + \nu_\mu + \pi^0$.

Cross section for the Reaction
$\nu_\mu + p \rightarrow \mu^+ + n + \nu_\mu + \nu_\mu$

Энергия нейтрино в лаб. системе, *Гэв*	$\sigma/(m_p^2 F)^2$, in units of 10^{-40} cm^2	$\sigma_{loc}/(m_p^2 F)^2$, in units of 10^{-40} cm^2
0.5	$5.9\cdot10^{-6}$	$6.7\cdot10^{-6}$
1	$1.4\cdot10^{-4}$	$1.9\cdot10^{-4}$
2	$1.1\cdot10^{-3}$	$2.2\cdot10^{-3}$
3	$3.2\cdot10^{-3}$	$7.8\cdot10^{-3}$
5	$9.0\cdot10^{-3}$	$3.0\cdot10^{-2}$
10	$2.7\cdot10^{-2}$	$1.5\cdot10^{-1}$
20	$6.0\cdot10^{-2}$	$6.1\cdot10^{-1}$
50	$1.5\cdot10^{-1}$	3.8

In the second column the cross section σ is given for the case when the ν_μ-ν_μ interaction is carried by a vector particle x with mass $m_x = 1$ GeV (interaction Hamiltonian $\mathcal{H} = i\sqrt{2F}\, m_x \nu\gamma_\alpha \nu x_\alpha$). In the third column the cross section σ_{loc} is given for a local ν_μ-ν_μ interaction with effective constant F.

the calculations are given in the table. In the second column of the table values are given for the cross section σ, divided by the dimensionless parameter $(m_p^2 F_{\nu_\mu \nu_\mu})^2$ for the model with a vector particle.

For comparison we also give in the third column of the table the cross section for process (4) in the case of a local $\nu_\mu - \nu_\mu$ interaction.

The upper limit on the constant $F_{\nu_\mu \nu_\mu}$ may be estimated from the CERN data on possible nonconservation of leptonic charge[28]. Taking into account the spectrum of the incident neutrino beam we find $F_{\nu_\mu \nu_\mu} \leq 2 \times 10^6$ G.

It can be concluded from the table that the study of reactions of the type (4) for high energy incident neutrinos would give information on the existence of a sufficiently strong $\nu_\mu - \nu_\mu$ interaction. The experimental difficulties, connected with the admixture of antineutrino in the neutrino beam (at present[28] the admixture of $\tilde{\nu}_\mu$ in the ν_μ beam does not exceed 1%), will be substantially reduced when experiments become possible with practically monoenergetic neutrino beams. Obviously, all that has been said above applies as well to the more complex experiments with electron neutrinos of high energy, allowing the study of the $\nu_e - \nu_e$ interaction.

A strong $\nu_e - \nu_e$ ($\nu_\mu - \nu_\mu$) interaction would give rise to a modification of the $\nu_e - e$ ($\nu_\mu - \mu$)-scattering amplitude (see diagram in Fig. c). Should there exist also a sufficiently strong $\nu_e - \nu_\mu$ interaction, then the cross section for $\nu_\mu - e$ scattering could turn out to be substantially larger than the cross section calculated on the basis of the conventional V—A theory[29]. The interaction between electron and muon neutrinos would lead to processes of the type $\nu_\mu + n \rightarrow p + e^- + \tilde{\nu}_e + \nu_\mu$, simulating violation of muon charge conservation. The magnitudes given in the table referring to the high energy region apply to the cross section for this process too. Using the data of experiments[30] on the study of possible violation of muon charge conservation, we find that $F_{\nu_\mu \nu_\mu} \leq 10^6$ G. Let us note that this limit is below the upper limit for the constant $F_{\nu_\mu e \nu_\mu}$, which may be obtained from an analysis of the electron spectrum in muon decay. In the presence of a $\nu_e - \nu_\mu$ interaction the process $\nu_\mu + p \rightarrow e^+ + n + \nu_\mu + \nu_e$ also becomes possible. The study of this process may be substantially simplified experimentally by the smallness of the background due to the admixture of $\tilde{\nu}_e$ in the ν_μ beam.

In conclusion we would like to make the following remarks:

a) a strong neutrino-neutrino interaction would give rise in the case of pure leptonic processes to cut-off parameters many times smaller than the so-called unitarity limit;

b) a strong $\nu - \nu$ interaction would have important astrophysical and cosmological consequences;

c) the neutrino-neutrino interaction is the sole nonweak neutrino interaction which is not excluded by the existing experimental data; the assumption of a strong interaction between the neutrino and hadrons or charged leptons is inconsistent with experimental data.

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