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INTERROGATIVES ABOUT NEUTRINOS

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Introduction

The two-component neutrino theory is more than satisfactory, being in the worst case an extremely good approximation of reality. Nevertheless, it may be worth while to plan new types of experiments which should check whether neutrinos are really what we think they are.

I shall discuss a few questions, which by tradition are not usually dealt with at High Energy Physics Conferences, in order of increasing degree of remoteness. It will be seen that the questions can be answered, at least in principle, by performing experiments which are not too fantastic.

What is the nature of "diagonal" processes ?

Recently a paper /1/ by Gell-Mann, Golberger, Kroll and Low has been published in which it was suggested that the "diagonal" and "nondiagonal" terms in the weak interaction Hamiltonian may be of quite a different nature. While the nondiagonal weak processes are rather well studied, information on the diagonal terms is rather scarce. It relates, first, to the nucleon part of the Hamiltonian and was based upon the experimental investigation of parity nonconserving effects in nuclear transitions /2/; second, some information on the ($\bar{e}\,\nu_e$)($\bar{\nu}_e\, e$) term of the interaction Hamiltonian has been obtained from experiments on high energy neutrinos: an upper limit for the effective interaction constant $G_{\nu e}$ was found : /3/

$G_{\nu e}^2 \leq 40\ G^2$, where $G = 10^{-5}/M_p^2$ is the Fermi constant.

Third, as was noticed(4) more than ten years ago at the Kiev High Energy Conference, the universal theory prediction that there exists first order ν_e - e scattering, leads to astrophysical consequences, the analysis of which allows, in principle, to check the prediction(5). Theoretical investigations of astrophysical data show(6) that: $G^2_{\nu e} = 10^{0\pm 2}\, G^2$. Fourth, at the present time experimental studies of the $\tilde{\nu}_e + e \rightarrow \tilde{\nu}_e + e$ process are being performed(7) and planned(8) with the help of powerful reactors. The results obtained so far (7) by Reines and Gurr permit to conclude that $G^2_{\nu e} \leq 4\, G^2$.

Here I would like to stress the importance of investigating the spectrum of electron recoils from $\tilde{\nu}_e$ - e scattering. As a matter of fact the measurement of such spectrum is not much more difficult than the very observation of the $\tilde{\nu}_e$ - e scattering process, the information obtained thereby being considerably richer. In the paper by Bardin, Bilenky and Pontecorvo(9) the $\tilde{\nu}_e$ - e scattering process was investigated under the most various assumptions on the antineutrino-electron interaction. The following possibilities were considered:

1) The $\tilde{\nu}_e$ -e scattering process is due to a four-fermion weak interaction (V-A, V(A), S(P)).

2) The $\tilde{\nu}_e$ - e scattering process is due to "anomalous" electromagnetic properties of antineutrinos, that is to an anomalous electromagnetic radius or to a magnetic momentum.

The electron recoil spectra in the process $\tilde{\nu}_e + e \rightarrow \tilde{\nu}_e + e$ were calculated for the known spectrum(10) of impinging $\tilde{\nu}_e$ from an uranium reactor. We have demonstrated that measuring the recoil electron spectrum in $\tilde{\nu}_e$ - e scattering under practical conditions (that is with a reactor) would make it possible to draw important conclusions on the character of the diagonal $(\bar{e}\,\nu_e)(\bar{\nu}_e\, e)$ interaction. The calculated electron recoil spectra with energies in the region from 1 to 7 MeV are tabulated in ref.(9) for five assumptions: V-A, V, S electromagnetic radius, magnetic momentum.

Here it is sufficient to note that the recoil electron spectrum in the V-A theory decreases with increasing energy far more rapidly than in the other four-fermion theories (this is due to the fact that the $\tilde{\nu}_e - e$ scattering at 180° in the limit $m \rightarrow 0$ is forbidden for the V-A theory): even a rough measurement of the spectrum of recoil electrons from the $\tilde{\nu}_e + e \rightarrow \tilde{\nu}_e + e$ process with reactor antineutrinos would allow to distinguish the V-A interaction from the other four-fermion interactions which were considered.

As far as anomalous neutrino-electron electromagnetic interactions are concerned, the calculations(9), performed again for the spectrum of impinging $\tilde{\nu}_e$ from reactors, show that the electron recoil spectrum is essentially softer when $\tilde{\nu}_e$- e scattering is due to an antineutrino magnetic moment than in the case when the scattering is due to an electromagnetic radius. The necessity of planning measurements of the electron recoil spectrum in the $\tilde{\nu}_e + e \rightarrow \tilde{\nu}_e + e$ reaction with $\tilde{\nu}_e$ from uranium reactors is apparent.

New sources of neutrinos

In all the neutrino experiments which either have been performed or are planned in high energy Laboratories, it is assumed that the only existing neutrino sources are decaying pions and kaons. Accordingly physicists perform high energy neutrino experiments invariably giving pions and kaons the chance of decaying in flight. But the question naturally arises: are there not other, unknown, sources of neutrinos ?

It seems that in the very high energy region (Stanford, Serpukhov, Batavia) one should plan search experiments which are apt to detect neutrinos with the help of classical high energy neutrino detectors, but without allowing pions and kaons to decay in flight. This means that the proton or photon (electron) beam should directly fall upon the shield behind which the neutrino detector is placed.

As an illustration, one could justify such experiments in terms of a search for the intermediate boson or, even better, for a heavy lepton, which decaying "immediately", would produce the neutrino(s). I understand that such a proposal was made also by M.Schwartz. Of course, in such terms the neutrino intensity will be low indeed, but it is gratifying that in such experiments there should be about as many electron as muon neutrinos (this is a notable difference from experiments with neutrinos from pions). Incidentally, the presumably small neutrino production rate in the proposed experiments would be partially compensated by a much better neutrino detection efficiency, due to relatively small distances of source to detector.

However, such experiments have a phenomenological interest that is independent of the rational explanations which may be thought for them.

As for the experiment background, one can say that it is mainly due to pion and kaons decaying in flight "against our will"; the available length for their decay is obviously the typical hadron interaction length (a few cm in heavy dense materials).

Is the lepton charge conserved? Is the neutrino mass really equal to zero?

The question - are (is) lepton charges (charge) conserved exactly ? - is certainly not far-fetched from an elementary particle physics point of view. Below I will talk about some ideas on such a question, which were developed during the last few years mainly in the Soviet Union, but were not discussed previously at high energy physics conferences.

In all the well-known search experiments for possible violations of lepton charge conservation, one attempts to measure the rate or the cross section of a certain process (say, $\mu^+ \rightarrow e^+ + \gamma$, $\nu_\mu + p \rightarrow \mu^+ + n \ldots$), i.e. one is measuring the square of the amplitude of the searched for process.

A few years ago, before Davis, Harmer and Hoffman first attempted to detect solar neutrinos[II] with a detector based on the reaction $\nu_e + Cl^{37} \rightarrow e^- + A^{37}$ [I2], I pointed out[I3] that :

i) the problem of possible lepton charge violations could be investigated at a new level in a very sensitive way by methods of neutrino astronomy

ii) such a problem is of great importance for the astrophysical interpretation of observations in neutrino astronomy.

The sensitivity of the proposed method is due to the enormous distances characterizing the solar system and is based on the possibility of measuring the amplitude of a process instead of a squared amplitude. Let it be said incidentally, it is just such a circumstance which leads to remarkable possibilities in the investigation of neutral kaons. Lepton nonconservation leads to the possibility of oscillations in vacuum between different neutrino states. Because a fraction of neutrino states is "unobservable" (for example, low energy ν_μ) and because the oscillations average out, lepton charge nonconservation leads, under some conditions discussed below, to the following effect : the intensity of solar neutrinos measurable at the earth's surface is twice as small as the intensity which would be expected under exact lepton charge conservation[13]. But how is one to estimate this last intensity with sufficient accuracy ? Our knowledge of the sun is not sufficient[14], for the time being, to predict the number of (solar) neutrino induced events with an accuracy better than a factor of two (an exception is the case of events induced by solar neutrinos generated in the thermonuclear reactions $p+p\rightarrow d+e^{+}+\nu_e$, $e^{-}+p+p\rightarrow d+\nu_e$; but these neutrinos, the intensity of which can be estimated to much better accuracy, have low energy and are consequently very hard to detect). Thus, at least for the time being, absolute determinations of the solar neutrino event intensity at the earth's surface do not allow us to draw an important conclusion on the elementary particle problem at issue. But this is a question of time. In the future neutrino astronomy will give us methods of investigating the lepton conservation problem which are much more sensitive than the classical methods of nuclear and elementary particle physics. I am going to illustrate this point once more. In the first experiment in neutrino astronomy, Davis et al. were not able to detect neutrinos and found[11] that the number of neutrino induced events in the reaction $\nu_e + Cl^{37} \longrightarrow e^- + A^{37}$ is, at least, twice as small as is expected theoretically[14]. I do not think that the discrepancy is a real one and that it is due to the effect mentioned above ; but I would like to stress that the failure to draw a very important elementary particle conclusion from neutrino astronomy is due simply to a (momentary) insufficient information on the best known star, the Sun.

The description of transitions in vacuum between the various neutrino states is in itself interesting for particle physics. In ref.[13] and also in an unpublished paper of Kobzarev and Okun', possible oscillations $\nu_e \rightleftarrows \tilde{\nu}_e$, $\nu_\mu \rightleftarrows \tilde{\nu}_\mu$, $\nu_e \rightleftarrows \nu_\mu$ have been discussed. As it was pointed out in the paper by Gribov and Pontecorvo [15], the first two types of oscillations should not be considered if it is required that in nature there are only four neutrino states. In ref.[15] there are discussed the conditions under which oscillations do take place for this case.

We shall consider in the zeroth approximation (V-A theory) four neutrino states with mass zero, which are described by two two-component spinors ν_e and ν_μ. In such an approximation it is convenient to think of two exactly conserved lepton charges (muon and electron charges). Lepton nonconservation leads to virtual or real transitions between the above mentioned neutrino states. All the possible transitions may be described with the help of an interaction Lagrangian

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

+ Herm. conjug.,

where $\nu' = \bar{\nu} C$ is the charge conjugated spinor. For the charge conjugated spinors the notation ν', was adopted instead of $\tilde{\nu}$, to avoid confusion with $\bar{\nu}$.

Below, for simplicity, it will be assumed that $m_{e\bar{e}}, m_{\mu\bar{\mu}}, m_{e\bar{\mu}}$ are real values, i.e. CP-invariance is assumed. Otherwise, the formulae become somewhat more complicated and in the present note we shall not give them for the general case. The interaction can be easily diagonalized. The diagonal states are :

$$\varphi_1 = \cos\xi\,(\nu_e + \nu_e') + \sin\xi\,(\nu_\mu + \nu_\mu') ,$$

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

where

$$tg\, 2\xi = \frac{2\, m_{e\bar{\mu}}}{m_{e\bar{e}} - m_{\mu\bar{\mu}}} .$$

These states correspond to two Majorana neutrinos (i.e. four states when the spin orientation is taken into account) with the masses m_1 and m_2 ,

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

(if $m_2 < 0$, the real state with the positive mass $-m_2$ is $\varphi_2' = \gamma_5 \varphi_2$).

The two-component spinors ν_e and ν_μ are no longer describing particles with zero mass, but must be expressed in terms of four- component Majorana spinors φ_1 and φ_2 :

$$\nu_e = \frac{1}{2} (1 + \gamma_5)(\varphi_1 \cos\xi + \varphi_2 \sin\xi) ,$$

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

In this case the (V-A) lepton current, to which weak processes are due, can be written as usual ,

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

The mass difference between Majorana neutrinos described by φ_1 and φ_2 leads to the oscillations $\nu_e \rightleftarrows \nu_\mu$, $\nu'_e \rightleftarrows \nu'_\mu$ (in the usual notions $\tilde{\nu}_e \rightleftarrows \tilde{\nu}_\mu$). If at the time t=0, one electron neutrino is generated, the probability of observing it at the time t is

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

where

$$m_- = m_{e\bar{e}} - m_{\mu\bar{\mu}} ,$$

$$\Delta = \frac{1}{2P}(m_1^2 - m_2^2) = \frac{m_{e\bar{e}} + m_{\mu\bar{\mu}}}{2P}\sqrt{m_-^2 + 4m_{e\bar{\mu}}^2} ,$$

and P is the neutrino momentum.

It should be emphasized that the oscillations take place only if $m_{e\bar{\mu}}$ and at least one of the values $m_{e\bar{e}}$ and $m_{\mu\bar{\mu}}$ are different from zero. This means physically : in order that oscillations do exist it is required that the $\mu^+ \to e^+ + \gamma$ decay probability not be zero and that at least one of the cross sections for the processes, say $\tilde{\nu}_e + n \to e^- + p$, $\nu_\mu + p \to \mu^+ + n$ not be zero. In the absence of oscillations there are two possibilities. If $m_{e\bar{\mu}} = 0$, then $\{ \qquad = 0$, and there exist two Majorana neutrinos (without oscillations). If $m_{e\bar{e}} = m_{\mu\bar{\mu}} = 0$, but $m_{e\bar{\mu}} \neq 0$, it is natural to attribute an opposite sign of the lepton charge (only one !)

to charged leptons of equal electrical charge (say, e^- and μ^-)[16] and to consider (instead of the degenerate states φ_1 and $\varphi_2' = \gamma_5 \varphi_2$ with the mass $m = m_{e\bar{\mu}}$) the states with a definite lepton charge $\psi = \nu_e + \nu_\mu'$, $\psi' = \nu_e' + \nu_\mu$ (this is the four-component neutrino theory with parity nonconservation[17]).

If $m_{e\bar{\mu}}$ and one of the values $m_{e\bar{e}}, m_{\mu\bar{\mu}}$ are different from zero, i.e. if oscillations take place, a very attractive case arises when $m_{e\bar{e}}, m_{\mu\bar{\mu}} \ll m_{e\bar{\mu}}$. In such a case

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

and the oscillations are entirely similar to the $K^0 \rightleftarrows \tilde{K}^0$ oscillations, φ_1 and φ_2 being analogous to K_1^0 and K_2^0 . According to (1) the oscillation amplitude in this case is the largest possible one. The two ψ spin states, ν_{left} and ν_{right}, are approximately the same as the observable "phenomenological" particles ν_e and ν_μ' (or $\tilde{\nu}_\mu$); similarly $\tilde{\nu}_{\text{left}} \simeq \nu_\mu$ and $\tilde{\nu}_{\text{right}} \simeq \nu_e' = \tilde{\nu}_e$. A very simple picture of neutrino oscillations, similar to the $K^0 \rightleftarrows \tilde{K}^0$ oscillations, arises also if $m_{e\bar{e}}$ and $m_{\mu\bar{\mu}}$ are no longer small in comparison with $m_{e\bar{\mu}}$ but are equal ($m_{e\bar{e}} = m_{\mu\bar{\mu}}$), in other words, if there is a μ-e symmetry. In such a case $\xi = \frac{\pi}{4}$ and relations (2) are exact.

In ref.[13] and also in an unpublished work of Kobzarev and Okun', there was discussed mainly the possibility that the neutrino oscillations are due to the so-called milliweak interaction which, in addition to PC, would violate lepton charge conservation as well.

The oscillations might be also induced by a (first order) superweak interaction which changes the lepton charge by two units[18]. This interaction reminds us of the Wolfenstein[19] superweak interactions, changing the strangeness by two units and might be closely related to it. Attempts to speculate about possible values of the oscillation length $1/\Delta$ may be found in ref.[13] and also in ref.[20]. But unfortunately nothing can be really said about the mass values $m_{e\bar{e}}, m_{\mu\bar{\mu}}, m_{e\bar{\mu}}$ and about the oscillation length $1/\Delta$, even if they were connected with a definite "etiquette " (milliweak, superweak), as the cut-off energy is unknown.[x/]

Returning now to neutrino astrophysics, we are going to consider only the simple cases wherethe oscillations are similar to the oscillations in the K^0 meson beams, let us say when $m_{e\bar{e}}=m_{\mu\bar{\mu}}$. In such a case the intensity of observable neutrinos of momentum P at a distance R from their source is simply

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

where I_0 is the intensity which would be observable for lepton conservation (more exactly, for the case when $m_{e\bar{e}}m_{e\bar{\mu}}=0$). I have already spoken of the main effect which would arise from values of $m_{e\bar{e}}, m_{e\mu}\neq 0$, namely of the decrease (due to averaged out oscillations) by a factor of two in the expected intensity of neutrino induced events. Po-

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[x/] Information on the oscillation length , and hence, on the mass values m , can be obtained only by detecting solar neutrinos.

meranchuk mentioned the possibility of detecting time variations of the solar neutrino intensity at the earth's surface which are connected with the time variation ΔR of the Sun-Earth distance. This proposal can hardly be put to work because the relative variation in the Sun-Earth distance is small $(\Delta R/R \approx 0,04)$ and, consequently, a neutrino detector with fantastic energy resolution and an extremely accurate intensity measurement would be required. As was mentioned in ref.[15], the use of a detector of monoenergetic neutrinos could, in principle, result in discrepancies of the measurable intensity I from the calculated one I_0 even larger than a factor of two. In the paper of Bahcall and Frautschi[20] there was discussed the possibility of detecting the solar neutrino line from the reaction $e^- + p + p \rightarrow d + \nu_e$, the main point being that in such a case the calculation of I_0 is reliable, and real discrepancies with the absolutely measured intensity might be noticed.

But under which conditions is possible an observation, based on relative measurements, of the actual oscillating term of eq. (3) ? It is clear that oscillations do not take place when $m_{e\bar{e}}, m_{e\bar{\mu}} = 0$ and that the oscillating term is not observable when $m_{e\bar{e}}\, m_{e\bar{\mu}}$ is so large (i.e. when the oscillation length $p/m_{e\bar{e}}\, m_{e\bar{\mu}}$ for a neutrino of any relevant momentum is so small) that the neutrino source (i.e. the solar region which is effectively emitting neutrinos) is no longer a point source. Somewhere between these limits one may attempt, in principle, to observe the oscillations ; for $m_{e\bar{e}}\, m_{e\bar{\mu}}$ values " uncomfortably small " $(I/I_0 \rightarrow 1)$, it is an advantage to detect "soft" solar neutrinos and for $m_{e\bar{e}} m_{e\bar{\mu}}$ values "uncomfortably high" $(I/I_0 \to \frac{1}{2})$, it is an advantage to detect "hard" neutrinos.

Here I would like to mention a new (true, quite remote) possibility of observing relative effects connected with the oscillating term: the measuring of the solar neutrino spectrum in the high energy region,with the help of an electronic method of relatively good energy resolution.It can be shown that for favourable $m_{e\bar{e}}-m_{e\bar{\mu}}$ values the change due to oscillations in the spectrum of observable high energy neutrinos with respect to the known B^{8} spectrum might be noticed. An electronic detector suitable for solar neutrino astronomy does not exist now,but,as suggested by Pontecorvo and Zatsepin[21], could be built in the future on the basis of recent developments of liquid counters. What are the desirable properties of such a detector ?

I). It must be able to detect efficiently electrons from $\nu_e - e$ scattering or electrons from inverse β decay with an energy of ~ I MeV.

2). The weight of the sensitive part of the detector must at least be about IO tons.

3). The detector must give information on the direction of the detected neutrinos.

4). It must give some information about the spectrum of the electrons generated by neutrinos.

5). The detector must distinguish, to a sufficient extent, electrons generated by neutrinos from background electrons.

6) The detector should be of the type "always ready", without film information.

It seems that these requirements could be satisfied to a considerable degree by a large liquid chamber, designed on the basis of the Dolgoshein counters[22], liquid counters about which many of you will hear in a few days, at the International Instrumentation Conference in Dubna. Incidentally, a large liquid chamber would be also a good detector for reactor antineutrinos.

Under the assumption that there exist only four independent neutrino states, I would like now to precise the statement that solar neutrino observations are much more sensitive than other methods for the investigation of the question as to whether the (average) neutrino mass is finite and the lepton charge is violated. We may express the sensitivity of a given method (measurement of the H^3 β spectrum, double-beta decay, solar neutrinos ....) in terms of the (average) neutrino mass or in terms of the order of magnitude of the upper limit for such mass which the method is capable of establishing. According to formula 1 in solar neutrino observations one can detect absolute or relative effects due to oscillations if, say,

$$\frac{m_{e\bar{e}}+m_{\mu\bar{\mu}}}{p}\sqrt{(m_{e\bar{e}}-m_{\mu\bar{\mu}})^2+4m_{e\bar{\mu}}^2}\cdot R \gtrsim 1 \quad \text{or,}$$

making the assumption simplifying, (but not essential in any way), of μ -e symmetry, if

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

For solar neutrinos with energy $\sim$ 10 MeV, for example, oscillation effects will be observable if

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

It may be 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:

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

and that the mass of the "phenomenological" particles ν_e and ν_μ is defined as $1/2\,(m_1 + m_2)$. It is seen that the sensitivity of the solar neutrino methods is better by seven orders of magnitude than the sensitivity of the classical method of investigating the H^3 β spectrum, capable of giving an upper limit for the ν_e mass of about 10 eV.

Do neutrinos interact with neutrinos ?

It is taken for granted that the only interaction which neutrinos undergo is the classical weak interaction. Nevertheless, the question can be put as to whether the neutrino may undergo additional interactions. The work of Bardin, Bilenky and Pontecorvo[23] is concerned with a possible interaction between neutrinos. Of course, there is an interaction between neutrinos arising in the second order of the usual weak interaction, but here we shall consider a new (hypothetical) $\nu\nu$ interaction. To our surprise, it turned out that even a relatively strong $\nu\bar{\nu}$ interaction is not in contradiction with existing data. We suggest then new experiments which might give information on the $\nu\nu$ interaction. After our work was completed we found out that in a 1964 paper of Z.Bialynicka-Birula[24] the question of an interaction between neutrinos was discussed and that some conclusions and proposals similar to our own were made.

In the presence of nonweak $\nu\nu$ interactions there will appear many phenomena among which we shall consider i) some new types of decays (see, for example, Fig. 1a), ii) some new types of neutrino-induced processes at high energies

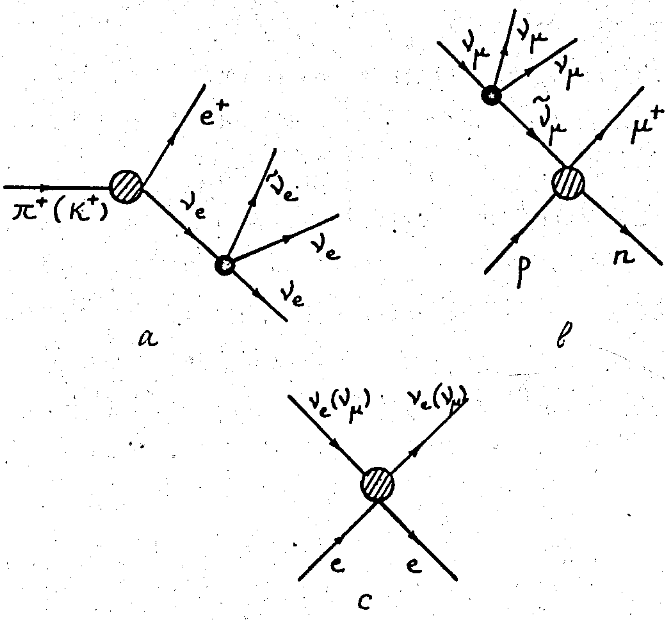

Fig. I

(see, for example, Fig.Ib), iii) neutrino "form factors" (see Fig.Ic).

In addition to the usual weak decays with emission of leptons, a $\nu\nu$ interaction clearly implies decays with the emission of an additional $\nu\tilde{\nu}$ pair. At first the processes
$\pi^+ \to e^+ + \nu_e + \nu_e + \tilde{\nu}_e$, $K^+ \to e^+ + \nu_e + \nu_e + \tilde{\nu}_e$
were considered in detail; for the sake of definitemess, an effective Hamiltonian describing the $\nu_e\nu_e$ interaction of the form $H_{\nu_e\nu_e} = F_{\nu_e\nu_e}(\bar{\nu}_e\gamma_\alpha\nu_e)(\bar{\nu}_e\gamma_\alpha\nu_e)$ was selected. Naturally, the electron spectrum in these decays is expressed through the constant $F_{\nu_e\nu_e}$ and other known constants (the weak interaction constant $G = 10^{-5}/M_p^2$, the π^-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). Thus, in order to obtain an upper limit for the constant $F_{\nu_e\nu_e}$ it is necessary to investigate the positron spectrum in the π^+ and K^+ decays. One may find the maximum number of positrons from the $\pi^+ \to e^+ + \nu_e + \nu_e + \tilde{\nu}_e$ and $K^+ \to e^+ + \nu_e + \nu_e + \tilde{\nu}_e$ decays, with energy within a suitable energy interval, by analysing the background in experiments where the $\pi^+ \to e^+ + \nu_e$ [25] and $K^+ \to e^+ + \nu_e$ [26] decays were studied. From an analysis of pion and kaon decays one gets correspondingly $F_{\nu_e\nu_e} \leq 10^7 G$ and $F_{\nu_e\nu_e} \leq 2.10^6 G$. These are surprisingly large values; a further search for the $(K^+) \to e^+ + \nu_e + \nu_e + \tilde{\nu}_e$ decay , aimed to decrease the above $F_{\nu_e\nu_e}$ upper limit, is possible as there is plenty of room for improvement. Observing the process $K^+ \to \mu^+ + \nu_\mu + \nu_\mu + \tilde{\nu}_\mu$ with the aim of getting information on $F_{\nu_\mu\nu_\mu}$ is an even more difficult task, on account of the large background due to the process $K^+ \to \mu^+ + \nu_\mu + \gamma$ (the decays $\pi^+ \to e^+ + \nu_e + \gamma$ and $K^+ \to e^+ + \nu_e + \gamma$ are strongly suppressed for the same reason that the decays $\pi^+ \to e^+ + \nu_e$ and $K^+ \to e^+ + \nu_e$ are suppressed).

Other decay processes such as decays of the nucleons, the hyperons and the muons are less interesting from the point of view of searching for a relatively strong $\nu_e \nu_e$ or $\nu_\mu \nu_\mu$ interaction. In conclusion let us remark that in the lepton conserving double beta-decay, a $\nu_e \nu_e$ interaction would imply an additional (new type) diagram.

Obviously decays with the emission of two additional neutrinos are strongly suppressed by phase space. Therefore, very high energy neutrino experiments suggest themselves ; if there exists a strong $\nu_\mu \nu_\mu$ interaction, and we stress that the interaction might be quite different from the $\nu_e \nu_e$ interaction, the processes of the following type will take place:

$$\begin{aligned} &\nu_\mu + n \to \mu^- + p + \nu_\mu + \tilde{\nu}_\mu , \\ &\nu_\mu + p \to \mu^+ + n + \nu_\mu + \nu_\mu , \end{aligned} \qquad (4)$$

etc. Processes similar to reaction (4) are the most interesting ones from the experimental point of view: in high energy events produced in ν_μ beams there will appear muons of "wrong" sign charge. These processes, simulating lepton charge violation, can be revealed especially well when there are no charged pions

Table I

Cross section for the reaction $\nu_\mu + p \to \mu^+ + n + \nu_\mu + \nu_\mu$

Neutrino energy in the lab, system (GeV)	$\sigma/(M_p^2 F)^2$ ($10^{-40}\,cm^2$)	$\sigma_{loc}/(M_p^2 F)^2$ ($10^{-40}\,cm^2$)
0.5	5.9×10^{-6}	6.7×10^{-6}
1	1.4×10^{-4}	1.9×10^{-4}
2.	1.1×10^{-3}	2.2×10^{-3}
3.	3.2×10^{-3}	7.7×10^{-3}
5	9.0×10^{-3}	3.0×10^{-2}
10	2.7×10^{-2}	1.5×10^{-1}
20	6.0×10^{-2}	6.1×10^{-1}
50	1.5×10^{-1}	3.8

In the second column the cross section σ is given for the case where the $\nu_\mu \nu_\mu$ interaction is mediated by a vector particle with the mass $m_X = 1$ GeV (Interaction Hamiltonian $H = i\sqrt{2F}\, m_X \bar{\nu}\gamma_\alpha \nu X_\alpha$). In the third column the cross section σ_{loc} is given for a local $\nu_\mu \nu_\mu$ interaction with the effective constant F.

in the final state. We choose for the calculation of the process (4) cross section a model in which the $\nu_\mu \nu_\mu$ interaction is mediated by a vector particle of mass m_X (Interaction Hamiltonian $H = i\sqrt{2F_{\nu_\mu \nu_\mu}}\; m_X \bar{\nu}_\mu \gamma_\alpha \nu_\mu X_\alpha$).
It should be noted that such a model was chosen only as a way of introducing the corresponding $\nu_\mu \nu_\mu$ form factor. As for the nucleon form factors, we used those which fit experimental elastic neutrino events[27]. In table I the cross sections for incoming neutrino energies in the interval of 0.5 - 50 GeV are given in terms of the dimensionless parameter $(M_p^2 F_{\nu_\mu \nu_\mu})^2$ for m_X = I GeV. For comparison Table I gives also cross sections for local $\nu_\mu \nu_\mu$ interaction. Our calculation, in which the CERN neutrino spectrum was taken into account, permits us to obtain an upper limit of $F_{\nu_\mu \nu_\mu}$ from CERN data on possible lepton charge nonconservation[28]: $F_{\nu_\mu \nu_\mu} \leq 2.10^6 G$.
It should be noted, however, that the energy dependence of the cross section and consequently the upper limit of $F_{\nu_\mu \nu_\mu}$ depends essentially upon the model of $\nu_\mu \nu_\mu$ interaction (at high energies in our model, $\sigma \sim E_{\nu lab}$, and in the model of local interaction, $\sigma \sim E^2_{\nu lab}$).

It may be concluded that in experiments at high energies of the type suggested here it would be possible to observe the manifestation of a $\nu_\mu \nu_\mu$ interaction of sufficient strength. Experimental difficulties connected with the contamination of $\tilde{\nu}_\mu$ in the ν_μ beam (at present amounting[28] to $\lesssim 10^{-2}$) will decrease when experiments with essentially monoenergetic neutrinos will be feasible.

It is clear that relatively strong $\nu_e \nu_e$ and $\nu_\mu \nu_\mu$ interactions imply a modification of the neutrino-lepton scattering amplitude. If a relatively strong $\nu_e \nu_\mu$ interaction also exists, in principle, there might become possible the scattering of ν_μ's by electrons with a cross section larger than the usual[29] cross section for $\nu_\mu - e$ scattering (Fig.Ic).

Other manifestations of the $\nu_e \nu_\mu$ interaction could be found in processes simulating muon charge violation of the type $\nu_\mu + n \longrightarrow e^- + p + \nu_\mu + \tilde{\nu}_e$.

Clearly, at high energies Table I refers also to this process; from CERN data[30] on possible muon charge nonconservation we obtain $F_{\nu_e \nu_\mu} \leq 10^6 G$. This upper limit is lower than the one we can deduce by a consideration of the electron spectrum in μ-decay.

Keeping in mind future experiments which are apt to reveal a $\nu_e \nu_\mu$ interaction, we would like to suggest also the reaction $\nu_\mu + p \rightarrow e^+ + n + \nu_e + \nu_\mu$ for which we might expect a very small background connected with contamination of $\tilde{\nu}_e$'s in ν_μ beams.

In conclusion we wish to make the following remarks :

i) a relatively strong interaction between neutrinos would imply cut-off values for purely leptonic processes much smaller than the so-called unitary cut-off,

ii) the interaction between neutrinos discussed above, if it exists, should have important astrophysical and cosmological consequences,

iii) the $\nu\nu$ interaction is the only strong interaction of neutrinos which is not excluded by experiment: strong interactions of neutrinos with hadrons and charged leptons are already excluded by existing data.

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