*ELECTRON AND MUON NEUTRINOS**

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The cross section for β-particle production in the collision of free neutrinos with nuclei was first evaluated in 1934 by Bethe and Peierls [1]. As is well known, the cross section for 1 MeV neutrinos was expected to be 10^{-44} cm^2. Because of this for a long time the effects induced by free neutrinos were considered unobservable. Later on, it was shown [2,3] that experimenting with free neutrinos was a real possibility and only recently some expeirments were performed in which free antineutrinos from reactor were used. These experiments, in fact, showed that free neutrino effects are observable and, thus demonstrated the «reality» of neutrinos [4]. They proved also the two-component nature [4] of neutrinos and indicated that the neutrino and the antineutrino are different particles [5].

The purpose of this paper is to emphasize the possibility of solving new problems of neutrino physics by investigating some effects induced by free neutrinos which have not yet been discussed. Such experiments may appear to be unfeasible at present, but the discussion of their planning seems to be not more premature than was at its time the discussion of experiments with antineutrinos from reactors.

Mainly attention will be drawn to the possibility of answering the question whether the neutrinos emitted in the $\pi \rightarrow \mu$-decay (ν_μ) and the neutrinos emitted in the β-decay (ν_e) are identical particles.

REACTIONS INDUCED BY NEUTRINOS

All the known slow processes are, apparently, due to the interaction between the following fermion pairs:

$$\begin{array}{llll} (e^+\nu_e), & (\mu^+\nu_\mu), & (p\tilde{n}), & (p\tilde{\Lambda}), \\ (e^-\tilde{\nu}_e), & (\mu^-\tilde{\nu}_\mu), & (\tilde{p}n), & (\tilde{p}\Lambda). \end{array} \tag{1}$$

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*Zh. Eksp. Teor. Fiz., 1959, vol.37, p.1751. This is the original text of the article published as JINR preprint, P-376, 1959.

Any pair of particles may interact with the same pair or with another one; according to the Markov–Sakata–Okun [6] scheme, strange particles other than Λ-hyperons are not included in the composition of the «strange» pair. In terms of the universal interaction theory [7,8] this scheme implies that the current j^+ entering into the weak interaction Lagrangian consists of four terms

$$j^+ = j^{e^+\nu_e} + j^{\mu^+\nu_\mu} + j^{\tilde{n}p} + j^{\tilde{\Lambda}p}, \tag{2}$$

each of which corresponds to the above-mentioned pairs.

Some processes induced by free neutrinos, if the Markov–Sakata–Okun scheme and the universal interaction theory are assumed to be valid, are listed below in the Table.

The question whether ν_e and ν_μ are identical particles is open and will be discussed in the next Section. There are no reasons for asserting that ν_e and ν_μ are identical particles. Therefore, in the Table and in the different terms of the lepton current it was written $e^+\nu_e$, $\mu^+\nu_\mu$ and not $e^+\nu$, $\mu^+\nu$ as is usually accepted.

TABLE

SOME REACTIONS INDUCED BY FREE NEUTRINOS ON REAL TARGETS

NN	Reaction	Note
1.	$\tilde{\nu}_e + p \to e^+ + n$	In investigating this process [4] free neutral leptons were first observed. The experiment supported the two-component nature of the neutrino.
2.	$\tilde{\nu}_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$	The non-observability of this process [5] proved that ν_e and $\tilde{\nu}_e$ are not identical particles.
3.	$\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$	The investigation of this process might be of interest in astrophysics, particulary, for measuring the neutrino flux from the Sun [9].
4.	$\nu_e + A \to \pi^+ + e^- + A$ $\tilde{\nu}_e + A \to \pi^- + e^+ + A$	Inverse π–e-decay in the field of a nucleus. Note that ν_e produce π^+-mesons, $\tilde{\nu}_e$ produce π^--mesons.
5.	$\tilde{\nu}_e + e^- \to \pi^- + \pi^0$	
6.	$\tilde{\nu}_e + p \to \Lambda + e^+$ $\tilde{\nu}_e + A \to \text{hyperfragments} + e^+$	Only $\tilde{\nu}$ (but not ν) may produce strange particles.
7.	$\tilde{\nu}_e + n \to \Sigma^- + e^+$	This process may occur only in nuclei.
8.	$\nu_e + A \to K^+ + e^- + A$ $\tilde{\nu}_e + A \to K^- + e^+ + A$	See 4.

NN	Reaction	Note
9.	$\tilde{\nu}_e + e^- \to K^- + K^0$	See 5.
10.	$\tilde{\nu}_e + e^- \to \tilde{\nu}_e + e^-$ $\nu_e + e^- \to \nu_e + e^-$	Scattering of neutrinos by electrons, predicted by the universal theory of weak interactions [8].
11.	$\nu_e + A \to \nu_e + e^+ + e^- + A$ $\tilde{\nu}_e + A \to \tilde{\nu}_e + e^+ + e^- + A$	Creation of a e^+e^--pair in the field of a nucleus [10]. This is the inverse process of the lepton bremsstrahlung by electrons described in [11].
12.	$\tilde{\nu}_e + e^- \to \tilde{\nu}_\mu + \mu^-$ $\nu_e + e^- \to \nu_\mu + \mu^-$	Inverse μ-decay. Forbidden, if $\nu_e \neq \nu_\mu$.
13.	$\tilde{\nu}_e + A \to \tilde{\nu}_\mu + e^+ + \mu^- + A$ $\nu_e + A \to \nu_\mu + e^- + \mu^+ + A$	Formation of a μ–e-pair in the field of a nucleus.
14.	$\tilde{\nu}_\mu + p \to \mu^+ + n$ $\tilde{\nu}_\mu + p \to e^+ + n$	Inverse μ-capture. Forbidden, if $\nu_e \neq \nu_\mu$.
15.	$\nu_\mu + A \to \pi^+ + \mu^- + A$ $\tilde{\nu}_\mu + A \to \pi^- + \mu^+ + A$	Inverse π–μ-decay in the field of a nucleus.
16.	$\tilde{\nu}_\mu + p \to \Lambda + \mu^+$ $\tilde{\nu}_\mu + p \to \Lambda + e^+$ $\tilde{\nu}_\mu + A \to \mu^+ + \text{hyperfragment}$	Forbidden, if $\nu_e \neq \nu_\mu$.
17.	$\nu_\mu + A \to \mu^- + K^+ + A$ $\tilde{\nu}_\mu + A \to \mu^+ + K^- + A$	
18.	$\nu_\mu + A \to \nu_\mu + \mu^+ + \mu^- + A$ $\tilde{\nu}_\mu + A \to \tilde{\nu}_\mu + \mu^+ + \mu^- + A$	Scattering of neutrinos by μ-mesons in the field of a nucleus.
19.	$\nu_\mu + e^- \to \nu_e + \mu^-$ $\tilde{\nu}_\mu + e^- \to \tilde{\nu}_e + \mu^-$	Inverse μ-decay. Forbidden, if $\nu_e \neq \nu_\mu$.
20.	$\nu_\mu + A \to A + \mu^- + e^+ + \nu_e$ $\tilde{\nu}_\mu + A \to A + \mu^+ + e^- + \tilde{\nu}_e$	Formation of a μ–e pair in the field of a nucleus.
21.	$\nu_\mu + e^- \to \nu_\mu + e^-$	If $\nu_e \neq \nu_\mu$, the reaction is possible only as a second order process.

Among the processes enumerated above, only the reactions 1, 2, 3, 10 had been previously discussed in the literature. For the most of the processes listed above we limit ourselves to the remarks made in the Table. Only some processes, which are related to the problem of the distinction between ν_μ and ν_e particles, are discussed in detail below.

The upper limit of the mass of neutral leptons emitted in the μ-decay, the magnitude of Michel's parameter ρ and theoretical considerations show that neutral leptons in the μ-decay have a mass equal or close to 0 and are not identical. Because of this, the μ-decay is usually described as follows: $\mu \rightarrow e + \nu + \tilde{\nu}$.

It is easy to see, however, that experimental and theoretical data require only that the two neutral leptons in the μ-decay should be not identical, but do not require that they should be necessarily a particle and an antiparticle. The possibility has already been discussed [12] that there exist two pairs of neutrinos. At first sight the question of the existence of two types of neutrinos — an electron neutrino (ν_e) and a muon neutrino (ν_μ) may be considered as an irrelevant and unnecessary complication. There are reasons, however, which make attractive the hypothesis that the electron and muon neutrinos are distinct particles. The absence in nature of some processes of the type $\mu \rightarrow 3e$, $\mu^- + p \rightarrow e^- + p$ etc. indicates that only pairs involving one charged and one neutral particle (see 1 and 2) may contribute to the currents entering into the weak interaction Lagrangian. The existence of only «charged» currents might be naturally explained [8] if in nature there would exist a charged vector boson B coupled with different fermions by an «intermediate intensity» interaction. The well-known weak interaction processes in this case would be due to an interaction of the second order with respect to the «intermediate interaction» constant. As is shown in Ref. [13], the nonlocality of the μ–*e*-decay related to the existence of the intermediate vector boson would require a transition rate for the decay $\mu \rightarrow e + \gamma$ wich contradicts the experimental data [14].

It can be easily seen, however, that even if there exists a *B*-meson the probability of the process $\mu \rightarrow e + \gamma$ would be zero* (that is entirely consistent with the experimental data), if the electron and muon neutrinos were different particles. Thus, the fact that the current in the Lagrangian of weak interaction is «charged» would be very well explainable in terms of the intermediate boson assumption only if ν_e is different from ν_μ.

Besides this reason, as it seems, the existence of two different types of neutrinos, which are not able to annihilate**, is attractive from the point of view of the symmetry and the classification of particles and might help to understand the difference in the nature of muons and electrons.

It follows from what has been said that experimental data on the question whether or not ν_e and ν_μ are identical particles would be of great interest. One possibility to get information on this point would consist in measuring the spirality of the μ-meson. If in nature there is only one neutrino-antineutrino pair the *V–A*-interaction requires a positive spirality of a μ^--meson. If in the experiment of the μ^--spirality turned out to be negative, there would be a strong evidence in favour of the existence of two types of neutrinos: the μ^+-decay, in this case, might be described by the scheme $\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$.

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*Even if there is no *B*-meson the process $\mu \rightarrow e + \gamma$ is possible in higher order approximations of the perturbation theory, if there is only one type of neutrino-antineutrino pairs, while it is absolutely forbidden if $\nu_e \neq \nu_\mu$.

**Note that if ν_μ and ν_e are different particles the muonium system (μ^+e^-) cannot go over into the antimuonium system (μ^-e^+) in any approximation.

The expeirment [16] shows, however, that the spirality of a μ^--meson is likely to be positive, as expected. Therefore, the problem whether there are two types of neutral lepton pairs in nature is open. The positive spirality of a μ^--meson indicates, however, that if in nature there are really two neutrino-antineutrino pairs the weak interaction must be described just as in (1), and the decay of a μ^+-meson must follow the scheme $\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu$. Here, as usual, ν_e is defined as the particle emitted together with a positron in β-decay. Its spirality, determined experimentally, is negative [17] (the $\tilde{\nu}_e$ spirality is, of course, positive). As for ν_μ and $\tilde{\nu}_\mu$, these particles are defined as having negative and positive spirality. Thus, the decay of a π^+-meson follows the scheme $\pi^+ \to \mu^+ + \nu_\mu$. These notations were used in the Table of the previous paragraph.

To clear up the question whether ν_e and ν_μ are different particles there remains one possibility which is discussed in the next paragraph.

DISCUSSION OF AN EXPERIMENTAL ARRANGEMENT WHICH, IN PRINCIPLE, IS APT TO ANSWER THE QUESTION AS TO WHETHER ν_e AND ν_μ ARE IDENTICAL

The method which is suggested below is essentially analogous to that used in deciding whether a neutrino and an antineutrino (in our definition ν_e and $\tilde{\nu}_e$) are identical particles [2,5] or whether K^0 and $\tilde{K}^0$-mesons are identical particles [18]. In these cases the non-identity of particles and antiparticles has been proved experimentally by the non-observability of some transitions, the matrix elements of which differ from 0 only if particles and antiparticles are identical. For example, the absence of the process $\tilde{\nu}_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$ proves that ν_e and $\tilde{\nu}_e$ are not identical since the process $\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$ must, undoubtedly, occurs.

In our case we are not concerned with the problem already solved of the non-identity of neutrinos and antineutrinos, but with that of the possible non-identity of ν_e and ν_μ (or of $\tilde{\nu}_e$ and $\tilde{\nu}_\mu$).

To solve this problem it is suggested to test experimentally whether a beam of $\tilde{\nu}_\mu$ is able to induce transitions which may be, undoubtedly, induced by $\tilde{\nu}_e$-particles. From an experimental point of view a beam of muon neutrinos is more attractive than an electron-neutrino beam for the following reasons. Usual intensive sources of electron neutrinos are radioactive isotopes. The latter ones by their nature are not capable of emitting neutrinos of high energies. On the contrary, muon neutrinos are obtained, naturally, with high energy.

On the one hand, it is of interest to use antineutrino of very high energy, say $\gtrsim 100$ MeV, since the cross section for the processes induced by these particles rapidly increases with energy. On the other hand, at very high energies the intensity of muon neutrino generation decreases due to a relativistic lengthening of the pion lifetimes. Therefore, we discuss here the arrangement of an experiment with $\tilde{\nu}_\mu$ of energy of < 100 MeV.

Consider for example the reactions (see the Table)

$$\tilde{\nu}_\mu + p \to \mu^+ + n, \tag{a}$$

$$\tilde{\nu}_\mu + p \rightarrow e^+ + n. \qquad \text{(b)}$$

The reaction (b), if ν_e and ν_μ are identical particles, was successfully observed by Reines and Cowan [4]; if $\nu_e \neq \nu_\mu$, (b) is not observable. The reaction (a) is a threshold reaction and is unobservable at energies < 100 MeV. The problem consists in determining the cross section for the reaction (b). In the energy range where the neutron from the reaction (b) may be detected with a good efficiency inside a large scintillation counter containing cadmium, Reines's and Cowan's method is quite suitable. When an event induced by the reaction (b) takes place, two impulses will appear in the scintillation counter one. One of these corresponds to the positron energy release (the neutron gets a small share of energy) and the second, which is delayed with respect to the first impulse corresponds to the photon energy released in the neutron capture by cadmium. To detect the reaction (b) a scintillation counter of the Reines and Cowan type may be bombarded by a beam of muon antineutrinos which because of their energy are not capable of inducing the reaction (a). Such $\tilde{\nu}_\mu$ beam must have a negligible small contamination of electron antineutrinos, which might induce the «trivial» reaction $\tilde{\nu}_e + p \rightarrow e^+ + n$.

In order to clear up the experimental conditions, we consider the production of neutral leptons of different types in an accelerator of protons, say, a 700 MeV accelerator.

The radioelements which are produced in the target and in other parts of the accelerator are sources of ν_e, and to a less extent, $\tilde{\nu}_e$ with a low energy ($\lesssim$ 10 MeV). These electron neutrinos do not give a dangerous background, since

a) their energy is small, and, essentially, they can be easily discriminated by analyzing the corresponding pulses from the scintillator;

b) the cross section for the reaction $\tilde{\nu}_e + p \rightarrow n + e^+$ is proportional to the square of the incident antineutrino energy, and, thus, it is relatively small at low energies. Pions of both signs will be produced in the accelerator target. They will generate neutral leptons as follows:

$$1)\ \pi^+ \rightarrow \mu^+ + \nu_\mu, \qquad 2)\ \mu^+ \rightarrow e^+ + \nu_e + \tilde{\nu}_\mu,$$

$$3)\ \pi^- \rightarrow \mu^- + \tilde{\nu}_\mu, \qquad 4)\ \mu^- \rightarrow e^- + \tilde{\nu}_e + \nu_\mu,$$

$$5)\ \mu^- + \text{nucleus} \rightarrow \nu_\mu.$$

Contaminations of ν_e and ν_μ in the beams are not harmful, since it is already known that neutrinos (both ν_e and ν_μ) cannot induce the reaction under consideration. It is easy to see that the «harmful» contamination of $\tilde{\nu}_e$ appears only from the decay (4) of μ^--mesons. However, μ^--mesons stopping in matter of high atomic number (it is not difficult to make it impossible for mesons to stop in light materials) do not practically undergo a μ^--decay. As far as a μ^--decay in flight is concerned, it may be neglected, since the decay mean free path of μ-mesons is measured in hundreds of meters whereas it is reasonable to place the detector of the reaction (b) at a distance of ~ 10 meters from the target.

Thus, it is possible to obtain a beam of $\tilde{\nu}_\mu$-particles, which practically has no contamination of $\tilde{\nu}_e$. The $\tilde{\nu}_\mu$ from reaction (2) (originating from stopped μ^+-mesons) have a mean energy of ~ 35 MeV, whereas $\tilde{\nu}_\mu$ from reaction (3) may have considerably greater energy (decay in flight), but their intensity will be in general small.

The number of $\tilde{\nu}_\mu$ produced in reaction (2) may be close to that of the π^+ produced in the target. Therefore, the number of $\tilde{\nu}_\mu$ generated in modern phasotrons may attain the value 10^{12}/sec. Models of new accelerators are being discussed now in which the intensity of the accelerated protons may be increased as much as by three orders of magnitude. Thus, one may hope that in the near future a flux φ of $10^8\ \tilde{\nu}_\mu/\text{cm}^2\cdot\text{sec}$ at a distance of 10 m from the target may become real. The cross section for the process (b) was estimated by the perturbation theory and turned out to be $2.10^{-41}\ \text{cm}^2$, if $\nu_e \neq \nu_\mu$ for $\tilde{\nu}_\mu$ of energy of 35 MeV. If we make use of a scintillation counter of the Reines and Cowan type (1-2 tons), the number of events is equal to ~ 1 per hour ($\varphi \sim 10^8/\text{cm}^2\cdot\text{sec}$), if the detection efficiency is unity and if $\nu_e = \nu_\mu$.

As Reines and Cowan [4] showed recently, the efficiency may exceed 0.5. The recording of events under consideration is less difficult technically than in Reines and Cowan's experiment, as the energy of the emitted $\tilde{\nu}_\mu$-particles is large. Thus, the reality of the experiment depends upon the magnitude of the background, which is very difficult to evaluate a priori. One may only note that unfortunately, the ratio signal to background must be considerably less than in Reines and Cowan's experiment. It is of interest to note that $\tilde{\nu}_\mu$ from reaction (2), in contrast to the neutrinos emitted in the target, are emitted isotropically. This makes it possible to decrease the difficulties which are due to the accelerator background; the detector of $\tilde{\nu}_\mu$ must be placed at an angle $\gtrsim 90°$ with respect to the direction of the protons incident on the target.

Summarizing one may say that experiments planned to test the identity of ν_e and ν_μ, though very difficult, must be seriously thought over when new intense accelerators are being designed. In particular, the problem of radiation shielding in such experiments must be considered at a very early stage of the accelerator's design.

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