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NEUTRINO EXPERIMENTS AND THE PROBLEM OF CONSERVATION OF LEPTONIC CHARGE

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The possible violations of leptonic charge conservation, which are compatible with experimental data, are large. This paper analyses various experimental setups which would be capable of detecting such hypothetical violations. It is shown that the most sensitive experiments are the search for the process $\mu \rightarrow e + \gamma$ and especially a search for oscillations of the type $\nu \rightleftarrows \bar{\nu}$ and $\nu_e \rightleftarrows \nu_\mu$. A nonvanishing neutrino mass could be related to CP-nonconservation and to an electric (and magnetic) dipole moment of the neutrino. Astronomical implications of the oscillation $\nu \rightleftarrows \bar{\nu}$ are discussed.

INTRODUCTION

DATA on lepton conservation have been obtained by different methods for the el-neutrino (ν_e) and for the mu-neutrino (ν_μ). A review of the theoretical and experimental data can be found in[1] and[2] respectively.

The conclusion that $\nu_e \neq \nu_\mu$ follows from the results of[3], from experiments involving the transition $Cl^{37} \rightarrow Ar^{37}$[4], and particularly from the recent investigations of double beta decay in Ca^{48}[5–7]. The rate of the process $Ca^{48} \rightarrow {}_{22}Ti^{48} + e^- + e^-$ turns out to be smaller than $10^{-20}\ yr^{-1}$, and the calculated probability of this process for a Majorana neutrino is $10^{-16\pm2}\ yr^{-1}$. Taking into account the theoretical difficulties in evaluating the nuclear matrix elements, as well as the experimental difficulties which are discussed in[2], I would describe the situation in the following manner: the el-neutrino and the el-antineutrino are different particles; the coupling constant F of the interaction which violates the corresponding leptonic charge conservation is smaller than one tenth of the weak interaction constant G ($F/G < 0.1$, with $G = 10^{-5}/M_p^2$, where M_p is the proton mass).

As regards the muonic leptonic charge, the most reliable information about the distinct character of the ν_μ and the $\bar{\nu}_\mu$ follows from the classical experiment of G. Bernardini et al. (cf., e. g.,[8]), where it was shown that in complex nuclei the reaction $\nu_\mu + p \rightarrow \mu^+ + n$ is at least one hundred times less likely than the reaction $\nu_\mu + n \rightarrow \mu^- + p$.

The conclusion that ν_e and ν_μ are distinct particles follows from the pioneering work of the Brookhaven group[9]. Here also essential quantitative results have been obtained by G. Bernardini et al. (cf.[8]). The cross section for the reaction $\nu_\mu + n \rightarrow e^- + p$ is not larger than a few percent of the cross section for the reaction $\nu_\mu + n \rightarrow \mu^- + p$.

Thus, in high-energy neutrino experiments the upper limit on the hypothetical interaction which violates lepton conservation is also of the order $F \sim 0.1\ G$. In experiments searching for the decay $\mu^+ \rightarrow e^+ + \gamma$ (cf. below), the upper limit is better by one order of magnitude ($F/G \leq 10^{-2}$).

These results and the totality of the available information on weak interactions put us in front of several possibilities, which can be summarized in the following manner in terms of conservation of leptonic charge.

1. There are two different additive leptonic charges, muonic and electronic.

2. There is only one additive leptonic charge, the signs of which are opposite for the μ^- and e^-[10]. There exists only one (four-component) neutrino, the left-handed components of which are associated with the electron, and the right-handed ones belong to the muon[11].

3. There is only one additive leptonic charge (equalling +1 for ν_e, ν_μ, e^-, and μ^-, and −1 for $\bar{\nu}_e$, $\bar{\nu}_\mu$, e^+, μ^+) and one multiplicative lepton number[12] (equalling +1 for ν_e, e^-, $\bar{\nu}_e$, e^+, and −1 for ν_μ, μ^-, $\bar{\nu}_\mu$, μ^+).

4. There exists one additive leptonic charge, but with different magnitudes for the pairs e^-, ν_e, and μ^-, ν_μ (e.g., +1 for e^-, ν_e and +2 for μ^-, ν_μ).

In this scheme the leptonic charge reminds us of other well-known quantum numbers, such as strangeness.

The possibilities 1 and 2 cannot be distinguished if the neutrino mass vanishes. If the neutrino mass is finite the possibility 2 is the most economical (there is only one leptonic charge). As regards the possibility 3, it is the least restrictive, since it allows, in principle, transitions muonium $\rightleftarrows$ antimuonium[13], but in my opinion it is rather artificial.

Within the framework of the schemes 1, 2, and 3 the additive leptonic charge remains unchanged (processes of the type $n \rightarrow p + e^- + \bar{\nu}_e$, $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ etc.) or changes by two units (e.g., in the hypothetical process $n \rightarrow p + e^- + \nu_e$, in the oscillations $\nu \rightleftarrows \bar{\nu}$ discussed below, etc.). It is hard to imagine a process within this framework such that the leptonic charge changes only by one unit.

According to possibility 4, the leptonic charge does not change in all observed weak processes, whereas in the process $\mu^+ \rightarrow e^+ + \gamma$ it changes by one unit, and in the other hypothetical processes which are discussed in the present paper the leptonic charge changes by more than one unit. A determination of the characteristic times for the transitions $\mu^+ \rightarrow e^+ + \gamma$ and for the oscillations $\nu \rightleftarrows \bar{\nu}$ (cf. below) will allow in principle to verify whether the alternative 4 is realized in nature.

VIOLATION OF LEPTON CONSERVATION?

In spite of their beauty, the precision of the experiments on conservation of leptonic charge leave room for rather strong violations. In addition there are no experimental data whatsoever on lepton conservation in interactions where no hadrons participate. At the present stage of development of elementary particle physics, when such quantum numbers as P, C, (and PC!) have turned out to be not quite "good," and when even the validity of the CPT-theorem is subject to some doubts, it is natural to fancy that the leptonic charge is the first pretender for the role of yet another nonconserved quantum number.

In particular the question arises (cf. e.g. [14]) whether the CP-nonconserving interaction which is responsible for the decay $K_2^0 \to 2\pi$ [15] conserves the leptonic charge?

If one assumes that the CP-nonconserving interaction also violates the conservation of leptons, one can estimate the strength of this interaction by comparing the rates for the decays $K_1^0 \to 2\pi$ and $K_2^0 \to 2\pi$. One could then naively reach the conclusion that the coupling constant F of the interaction which violates leptonic charge conservation is by three orders of magnitude smaller than the weak interaction coupling constant G.

DOUBLE BETA DECAY AND SIMILAR PROCESSES

For $F/G = 10^{-3}$ the probability of a neutrinoless double beta decay of Ca^{48} (cf. Fig. 1) caused by the F interaction would be $(F^2G^2/G^4) \times 10^{-16}\ \text{yr}^{-1} \approx 10^{-22}$ yr which is by two orders of magnitude smaller than the experimentally established [5,6] upper limit of the rate for neutrinoless double beta decay of Ca^{48}. Here the probability for neutrinoless double beta decay for a Majorana neutrino has been taken equal to $10^{-16}\ \text{yr}^{-1}$, but it should be noted that the possible error of the exponent equals ±2.

At the same time the experiment designed to search for neutrinoless double beta decay in Ca^{48} allows one to reach the conclusion that the coupling constant of the hypothetical interaction between the hadronic current and the doubly charged current e^-e^- (which yields double beta decay as a first order process) is by at least twelve orders of magnitude smaller than the Fermi constant [16].

PROCESSES OF THE TYPE $\nu_e + p \to e^+ + n$ ETC.

The search for processes of the type $\nu_e + p \to e^+ + n$, $\nu_\mu + p \to \mu^+ + n$, $\bar{\nu}_e + Cl^{37} \to e^- + Ar^{37}$ is also not suitable for the discovery of cross sections which are approximately by six orders of magnitude smaller than the usual weak interaction cross sections (cf., however, the discussion of vacuum oscillations of the type $\nu \rightleftarrows \bar{\nu}$ below).

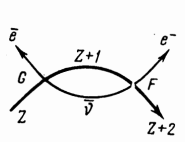

FIG. 1. Diagram for double beta decay

PROCESSES OF THE TYPE $\mu \to e + \gamma$, ETC.

Muonic charge conservation forbids processes like $\mu \to e + \gamma$, $\mu \to 3e$, $\mu^- + Z \to e^- + Z$, $\mu^+e^- \rightleftarrows \mu^-e^+$. The most suitable process for obtaining information on muonic charge conservation is the decay $\mu \to e + \gamma$. The ratio of the rates for the channels $\mu \to e + \gamma$ and $\mu \to e + \nu_e + \bar{\nu}_\mu$, assuming nonconservation of muonic charge, would be $W \approx (\alpha/2\pi)(F/G)^2$, where α is the fine structure constant. Assuming $F/G = 10^{-3}$ we see that W is $\sim 10^{-9}$. This magnitude is not so far removed from the experimentally known [17] upper limit ($W_{exp} \leq 2 \times 10^{-8}$). It is obviously necessary to perform experiments in which one could observe the process $\mu \to e + \gamma$ at a level of 10^{-9} of the principal mode, or less.

As regards the process $\nu_\mu + n \to e^- + p$, which is forbidden by muon number conservation, one can hardly hope to observe it directly, since the corresponding cross sections are a million times smaller than the cross section of the process $\nu_\mu + n \to \mu^- + p$ (however cf. below the discussion of the oscillations $\nu_\mu \rightleftarrows \nu_e$ in the vacuum).

THE PROCESS $\mu^- + Z \to (Z - 2) + e^+$

This process, which was proposed by A. I. Mukhin and L. B. Okun', reminds us of the neutrinoless double beta decay, but differs from it in one important respect: it is a "μe-process" in distinction from an "ee-process." According to one of the possibilities mentioned in the Introduction (one additive leptonic charge with opposite signs for μ^- and e^-), this process does not in principle violate lepton conservation and therefore might be less suppressed than the process $\mu^- + Z \to e^- + Z$. Therefore an investigation of the "double muon-electron process" $\mu^- + Z—(Z - 2) + e^-$ yields information differing from the one obtained from an ordinary experiment involving neutrinoless double beta decay. As we have seen, such an experiment might yield an upper limit on the coupling constant of the hypothetic interaction between the hadronic current and the doubly charged current ee, which results in double beta decay as a first order process. But such an interaction certainly does not conserve leptonic current. From this point of view an experimental investigation of the process $\mu^- + Z \to (Z - 2) + e^+$ yields information about the constant F′ of a hypothetical first order interaction, which possibly conserves leptonic charge (cf. Fig. 2 for an example of such an interaction; Δ is the well known isobar with $T = 3/2$, $J = 3/2$).

What is known about the process $\mu^- + Z \to e^+ + (Z - 2)$? The corresponding information can be obtained from an experiment designed to detect the process $\mu^- + Z \to e^- + Z$. It was found that [18]

$$R = \frac{W(\mu^- + Z \to e^- + Z)}{W(\mu^- + Z \to \nu + \ldots)} \leqslant 2.2 \cdot 10^{-7}.$$

Since in these experiments positrons were not distinguished from electrons, such a result has a direct bearing on our process. Thus we already know that

$$R' = \frac{W[(\mu^- + Z \to e^+ + (Z-2)]}{W(\mu^- + Z \to \nu + \ldots)} \leqslant 2.2 \cdot 10^{-7},$$

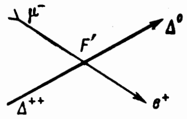

FIG. 2. A possible diagram for "double muon-electron process"

which implies that $F'/G \leq 5 \times 10^{-4}$. An improvement of this result would be of interest.

THE POSSIBILITY OF VACUUM OSCILLATIONS $\nu \rightleftarrows \bar{\nu}$, $\nu_\mu \rightleftarrows \nu_e$

If leptonic charge is not an exactly conserved quantum number (and in this case the neutrino mass would be different from zero), then oscillations of the type ($\bar{\nu} \rightleftarrows \nu$, $\nu_\mu \rightleftarrows \nu_e$), which are similar to oscillations in a beam of K^0 mesons, become possible for neutrino beams[19].

We first consider the transitions $\bar{\nu} \rightleftarrows \nu$. If such transitions exist then there exist diagonal states ν_1, ν_2 (Majorana neutrinos) which are related to ν and $\bar{\nu}$ in the same manner as the K_1^0 and K_2^0 states are related to the K^0 and $\bar{K}^0$ mesons. The situation is however quite different in the two cases. The "transition mass μ" for the process $\nu \rightleftarrows \bar{\nu}$ ($\mu = |m_{\nu_1} - m_{\nu_2}|$) could be comparable to the mass m of the neutrino, whereas the $K^0 \rightarrow \bar{K}^0$ "transition mass" ($m_{K_1} - m_{K_2}$) is negligibly small compared to the mass of the K^0 meson. We are in fact dealing with a theoretical problem in formulating the theory of neutrino oscillations which, in the author's opinion, could be of interest for theoretical physicists. One could get an idea about the difficulties by analyzing some Feynman diagrams which are possibly related to the new interaction F, and by roughly estimating their contributions to the various masses (Fig. 3).

In the formulas in Fig. 3, m_e is the electron mass, the appearance of which in the contributions of the diagrams is more or less arbitrary, and Λ is a cutoff parameter[20], which shall tentatively be set equal to 100 GeV in all cases where the interaction occurs only between leptons, and equal to the nucleon mass whenever hadrons participate in the interaction (e.g., diagram f in Fig. 3). Despite the fact that what we have just said is at best very roughly true, at worst completely false, I shall continue to speculate about neutrino oscillations. It should be added here that the method of detecting violations of lepton charge conservation based on $\bar{\nu} \rightleftarrows \nu$ oscillations is, in principle, more sensitive than the other methods. The reason for this is the fact that the period of the oscillations is inversely proportional to the first power of the transition matrix element, whereas reaction and decay rates are proportional to the square of this matrix element.

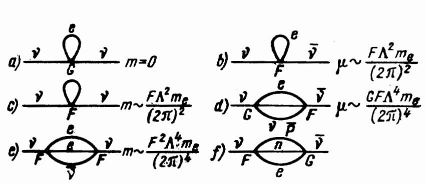

FIG. 3. Several possible diagrams and their contributions. $G = 10^{-5}/M_p^2$ is the weak interaction constant, M_p is the proton mass, F is the constant of the new interaction, m is the contribution of the given diagram to the neutrino mass, $\mu = |m_{\nu 1} - m_{\nu 2}|$ is the $\nu \rightleftarrows \nu$ transition mass, m_e is the electron mass, and Λ is the cutoff paremeter

REMARKS ON METHODS OF DETECTION FOR NEUTRINO OSCILLATIONS

The possibility of detecting the oscillations (to say nothing of the many things that will be discussed below) depends on the selection rules which operate in Nature (cf. the Introduction for the different versions of selection rules for the leptonic charge).

If there are two leptonic charges, the transitions $\nu_e \rightleftarrows \bar{\nu}_e$ and $\nu_\mu \rightleftarrows \bar{\nu}_\mu$ convert potentially active particles into particle that are, from the point of view of the ordinary weak interactions, sterile, i.e. practically unobservable, since they have the "incorrect" helicity. In this case the only method of observing the effect under consideration consists in measuring the intensity (and its temporal variation) of the original particles (e.g., neutrinos), but not of their antiparticles (say, antineutrinos). The situation is different if there is only one additive leptonic charge, with different signs for e^- and μ^-. In this case the correct notation for the four neutral objects is ν_{left}, $\bar{\nu}_{\text{left}}$, ν_{right}, $\bar{\nu}_{\text{right}}$. Then the transitions $\nu_{\text{left}} \rightleftarrows \bar{\nu}_{\text{left}}$, $\nu_{\text{right}} \rightleftarrows \bar{\nu}_{\text{right}}$ produce nonsterile particles. There will occur oscillations el-neutrino $\rightleftarrows$ mu-neutrino, which can in principle be observed not only by means of measurements of the intensity and the "time-variation" of the original particles far from their source, but also by means of detection of new particles. It is true that one cannot observe directly the transformation of a reactor neutrino into a mu-neutrino, since low energy mu-neutrinos (E smaller than the muon mass) cannot be registered. On the other hand high energy mu-neutrinos can convert into normally active el-neutrinos.

We note that the formulation of the neutrino-oscillation problem in vacuum is complicated by the existence of a large number of possibilities.

THE TIME AND LENGTH OF THE OSCILLATIONS

The oscillations $\nu \rightleftarrows \nu$, $\nu_\mu \rightleftarrows \nu_e$ are characterized by a period or length $t = l = E/\mu m$ (here E is the neutrino energy, $\hbar = c = 1$). The quantity μ is smaller than m, since ν_1, ν_2 must have positive masses, but we do not know whether $\mu \leq m$ (cf. the diagrams b and c in fig. 3) or $\mu \ll m$.

We consider typical neutrino experiments on reactors[21] and accelerators[8,9], and assume, for purposes of estimation, that $m \approx \mu$. We first assume for the magnitude of the neutrino mass the experimentally determined upper bounds (for ν_e, m = 200 eV and E = 1 MeV, for ν_μ the mass is m = 2 MeV, and E = 1 GeV). Then the characteristic oscillation lengths would respectively be equal to $l = 10^{-3}$ cm and $l = 10^{-8}$ cm. Of course, there is not the slightest reason to believe that the neutrino mass is equal to the experimental upper bound for that mass (both for the el-neutrino and for the mu-neutrino).

In the spirit of the present paper, one could obtain a less arbitrary estimate on the basis of the contributions of the diagrams in Fig. 3, e.g. the diagrams b and c. If one assumes $F/G = 10^{-3}$ and Λ = 100 GeV, these diagrams yield for m a value of ~1 eV. To such a mass value there corresponds a length of 10 cm for megavolt-neutrinos (from reactors), and 100 m for gigavolt-neutrinos (from accelerators).

Could such magnitudes be excluded already on the basis of available experiments?

Insofar as mu-neutrino experiments are concerned, the source-detector distance is of the order of 100 m, and consequently one could not exclude a comparable oscillation length, corresponding to a value $F/G \geq 10^{-3}$.

In experiments involving el-neutrinos from reactors, the existence of an oscillation length which is definitely smaller than the reactor diameter, as well as the reactor-detector distance (approximately 10 m) would lead to a decrease by a factor of two of the intensity of active particles which hit the detector, since the number of anti-el-neutrinos from a reactor and the number of sterile particles would be equal for large distances. This would lead to a cross section for the reaction $\nu_e + p \to e^+ + n$, as measured in the experiments of Nezrick and Reines[22] which is half as large as the one computed for a two-component neutrino. There is apparently no such discrepancy. Therefore we may assume that reactor experiments exclude oscillation lengths smaller than 10 cm (or they exclude the value $F/G \geq 10^{-3}$, according to diagram b in Fig. 3), although there is no complete certitude in this matter. We could then determine an upper limit on F/G from the requirement that the oscillation length l be larger than the distance between the reactor and the detector, which is, say, ten meters: $l = E(F\Lambda^2 m_e/4\pi^2)^{-2} > 10$ m. On the basis of the diagram in Fig. 3 we find $F/G \leq 10^{-4}$.

All estimates given here have only an illustrative character, and should, of course, not be taken seriously.

We do not discuss the hypothesis that hadrons participate in the interaction (cf., e.g., the diagram f in Fig. 3). It suffices to note that in the absence of other diagrams, such an interaction would admit larger oscillation lengths ($\gg 10^4$ km) even if $F/G \sim 1$.

OSCILLATIONS AND ASTRONOMY

If the oscillation length is large (> 10 km) it will be impossible to observe the transitions $\nu \rightleftarrows \bar{\nu}$, $\nu_\mu \rightleftarrows \nu_e$ in neutrino beams from reactors or accelerators. However, significant astrophysical effects might be possible.

From the point of view of detection possibilities, an ideal object is the sun. If the oscillation length is much smaller than the radius of the solar region which effectively produces neutrinos (e.g. one tenth of the solar radius $R_\odot$ or 10^5 km for neutrinos from B^8[23]) which will give the main contribution to the experiments which are being planned now (cf., e.g.,[24]), it will be impossible to detect directly oscillations of the solar neutrinos, owing to a smearing out of the effect. The only effect at the surface of the earth would consist in the fact that the flux of observable solar neutrinos would be half as large as the total flux of solar neutrinos. Unfortunately the weight of the various thermonuclear reactions in the sun, and the central temperature of the sun are insufficiently well known in order to allow a useful comparison of expected and observed solar neutrinos, from the point of view of this article[1)].

[1)]If we would know how to register the sterile particles from the transition $\nu_e \to \nu_{e\,\text{ster}}$, we could improve the limitations on F/G tremendously, since the source-detector distance is here 10^8 km, and not tens of meters.

It has been pointed out by I. Ya. Pomeranchuk that if the oscillation length of solar neutrinos is comparable to the radius of the solar region responsible for neutrino generation, or is larger than that, there might occur time variations in the intensity of solar neutrinos at the surface of the Earth. These time variations are a consequence of the variability with time of the distance between the sun and the earth. In order to observe the oscillations under discussion, it is necessary to carry out measurements over relative distances (times) comparable with the oscillation length (or period). If the oscillation length is of the order $0.1\,R_\odot = 10^5$ km, there should appear time oscillations in the intensity of solar neutrinos with a period of several days. If the oscillation length is of the order of 5×10^6 km (the difference of the semiaxes of the earth's orbit) the period of the occurring oscillations would be of the order of a hundred days.

In the not too remote future satellite experiments could become feasible.

As regards the problem of lepton conservation in the domain of high energy neutrino astronomy[25], we do not discuss it here.

CONCLUSION

Drawing the conclusions in the spirit of the present paper, we assume that the PC-nonconserving F-interaction is a very general interaction for all particles. All particles with spin, including neutrinos, will then exhibit an electric dipole moment. For the neutrino the dipole moment has roughly the magnitude

$$d \lesssim F\Lambda^2 \frac{1}{\Lambda} e \approx 10^{-20}\, e\cdot\text{cm},$$

where Λ is again the cutoff parameter characteristic for weak interactions of the four-fermion type (cf. the diagrams b and c in Fig. 3). The magnetic moment will be comparable to the electric one. If this is so, there will appear a finite neutrino mass, which makes lepton charge nonconservation likely. Of course, CP-nonconservation does not automatically require a finite value of the neutrino mass. We shall return at a later date to a discussion of the measurement of ionization produced by the electric and magnetic moments of a neutrino in matter.

I would however like to stress the fact that independently of theoretical considerations and of the extremely rough estimates given here, the importance of carrying out the experiments, in particular searches for the processes $\mu^- \to e + \gamma$, $\mu^- + Z \to e^+ + (Z-2)$, and experiments on the variation of the intensity of solar neutrinos, does not raise any doubts.

I am very grateful to I. Yu. Kobzarev and L. B. Okun' who have collaborated in carrying out this work, and to M. I. Podgoretskiĭ and A. I. Mukhin for critical remarks and useful advice.

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