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LEPTON MIXING AND THE "SOLAR NEUTRINO PUZZLE"

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Смешивание лептонов и "парадокс солнечных нейтрино"

Обсуждаются результаты известного опыта Девиса и др. по регистрации солнечных нейтрино хлор-аргонным методом. Приводятся аргументы в пользу того, что смешивание нейтрино является привлекательным с точки зрения физики элементарных частиц объяснением малости потока нейтрино по сравнению с ожидаемым потоком (так называемый "парадокс солнечных нейтрино"). Такое объяснение "парадокса" представляется более естественным, чем другие предлагавшиеся объяснения.

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Lepton Mixing and the "Solar Neutrino Puzzle"

There are discussed the results of the well known solar neutrino experiment of Davis et al., in which the Cl - Ar method is used. The result of the experiment, a too small neutrino signal (the so-called "solar neutrino puzzle"), has been tentatively accounted for in a number of quite exotic explanations. It appears that the explanation in terms of lepton mixing and neutrino sterility is quite attractive from the point of view of present day elementary particle physics and is much more natural than the other explanations of the "puzzle".

The investigation has been performed at the Laboratory of Theoretical Physics and Laboratory of Nuclear Problems, JINR.

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1. Neutrino Oscillations and Lepton Charge

The possibility of neutrino mixing and of its corollary, neutrino oscillations, was discussed qualitatively [1] a long time ago. The original motivation for considering neutrino oscillations was purely phenomenological and very simple: the oscillations give us a new very sensitive method, as interference methods usually are, of investigating experimentally possible lepton charge violations. The importance of oscillations for the interpretation of the observations in the field of neutrino astronomy (which were only being planned at the time) was recognized and a mechanism suppressing the solar neutrino signal was pointed out [1]. However, neutrino oscillations were not invented for the sake of explaining the "solar neutrino puzzle". So is called in the literature [2] the deficiency*

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*In ref. [3] there are presented the results of measurements performed from April 1970 till February 1976. In such a period the averaged rate ^{37}Ar production by solar neutrinos in the reaction $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ was found to be 1.3±0.4 SNU. (see page 4).

in the solar neutrino flux observed by Davis et al. (see ref. [3] and related references therein) in the well known experiment, based on the Cℓ–Ar method of detecting neutrinos [4].

2. Oscillations and Solar Neutrino Experiments

If there are oscillations, the suppression of the solar neutrino signal is due to the sterility [1] of a fraction of neutrinos (ν_μ in the case of two neutrino types). In such a case the intensity of ν_e with momentum p at a distance R from a source of ν_e is given [5-7] by:

$$I_{\nu_e}(R,p) = (1 - \frac{1}{2}\sin^2 2\theta + \frac{1}{2}\sin^2 2\theta \cos 2\pi \frac{R}{L(p)})\, I^{\circ}_{\nu_e}(R,p), \quad (1)$$

where $I^{\circ}_{\nu_e}$ is the ν_e intensity which would be expected in the absence of oscillations, θ is the mixing angle, $L(p) = 4\pi \frac{p}{|m_1^2 - m_2^2|}$ is the oscillation length, m_1 and m_2 are the masses of neutrinos ν_1 and ν_2 of which the usual "phenomenological" particles ν_e and ν_μ are coherent superpositions (see below). One must average the expression (1) over the Sun region in which neutrinos are effectively generated, over the momentum of detec-

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(1 SNU = 10^{-36} events/sec ^{37}Cℓ atom). The expected rate, according to the standard Solar model, is equal to 6±2 SNU (see ref. [2] and related references therein).

table neutrinos and over the Sun-Earth distance. If $L(\bar{p}) \ll R$ (the proper average over p is performed by the detector), the oscillating term in (1) turns out to be zero on averaging, so that the intensity $\bar{I}_{\nu_e}$ may be found in the interval from 1/2 $\bar{I}^{\circ}_{\nu_e}$ (when $\theta = \frac{\pi}{4}$, maximum mixing) to $\bar{I}^{\circ}_{\nu_e}$ ($\theta = 0$, no mixing) [1,5]. In the case of a number of neutrino types $N \geq 2$, the average intensity ν_e may be found in the interval between $\frac{1}{N}\bar{I}^{\circ}_{\nu_e}$ and $\bar{I}^{\circ}_{\nu_e}$ [8-10]. Let us remark here that even in the case of only two types of neutrinos the observed signal from solar neutrinos may be considerably smaller than the expected one, if the oscillation length is about equal to the Sun-Earth distance. The cosine term in (1) may then survive after averaging over the momentum of neutrinos, so that we have another possibility [5,11,12] of getting quite a low neutrino signal (this possibility, of course, is rather accidental).

Thus, under the assumption that there exist neutrino oscillations, there is nothing surprising if the solar neutrino signal turns out to be definitely smaller than the expected one the only requirement being that the mixing angle should not be small.

3. Lepton Mixing in Old and Present Days

A consistent way of introducing lepton mixing, which is similar to the quark mixing suggested in the well known papers of

Cabibbo and Glashow, Iliopoulos, Maiani[13], was first given in ref.[5]. The fields of neutrinos ν_e and ν_μ are described by orthogonal combinations

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta ,$$
$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta , \qquad (2)$$

where θ is the mixing angle, ν_1 and ν_2 are the fields of neutrinos with definite masses m_1 and m_2. The ordinary particles ν_e, ν_μ have no definite masses and are not described by stationary states (there arise oscillations $\nu_e \rightleftarrows \nu_\mu$, $\bar{\nu}_e \rightleftarrows \bar{\nu}_\mu$). In ref.[5] neutrinos are mixed but lepton mixing is not recognized in itself as a theoretically attractive feature. The last circumstance is due to the fact that i) in paper[5] ν_1 and ν_2 are Majorana particles and ii) that orthogonal combinations of the s and d quarks a la Cabibbo-Glashow had not yet been introduced.

In ref.[6,14] the fields of ν_e and ν_μ are described by orthogonal combinations identical to those of expressions (2), but ν_1 and ν_2 are Dirac fields. The motivation for lepton mixing in these papers is the assumption of a deep analogy between leptons and quarks. In other investigations there are supplementary motivations for such a mixing (see for example[10]). At the present time lepton mixing (together with its numerous consequences) is being very widely discussed, as it can be seen in ref.[15], where the list of quoted papers is in no way full.

Thus in the last two years a change in the general opinion has been taking place in the sense that lepton mixing, although not proved, is nevertheless being considered as a natural and theoretically attractive feature. One should mention also that after the growing evidence for the existence of a heavy charged lepton /16/ (together with which a new type of neutrino might be associated), the mixing of N>2 neutrinos seems today to be a natural possibility, (although it looked as a far-fetched one at the time when it was suggested /8/).

4. Neutrino Oscillations and the "Solar Neutrino Puzzle"

If really the solar neutrino flux is definitely smaller than the calculated one and if the related calculations are reliable, the solution of the "puzzle" in terms of lepton mixing is in our opinion much more natural than any other solution put forward until now. Many such suggestions are listed in the paper of Bahcall and Davis /2/, where one may find the corresponding references. They include the assumption that neutrinos decay /17/ on their way from the Sun to the Earth and the following exotic astrophysical suggestions: the Sun energy is not generated in thermo-nuclear reactions; there is a black hole inside the Sun; the Sun is not in a state of equilibrium and its apparent luminosity, due to the very slow process of diffusion of photons from the central part to the surface, is much higher than its "internal luminosity", about which information is almost instanteneously obtained in neutrino experiments; the Sun in the past has substantially increased its mass from outside, so that its internal and external regions have an entirely different composition, a circumstance which would make quite wrong the results of calculations based on homogeneous models, etc.

Thus, if we really believe that there is a solar neutrino deficiency, we have in our hands an explanation reasonable, not exotic, attractive from the point of view of today elementary particle physics, an explanation which was not invented "ad hoc" to solve the "solar neutrino puzzle": lepton mixing. Contrary to other solutions of the "solar neutrino puzzle", which were listed above, its explanation in terms of lepton mixing can be experimentally checked either directly or indirectly (see for example [7]). These experiments should include a search for solar neutrino oscillations in which different neutrino detectors are used, searches for cosmic neutrino oscillations, for oscillations of neutrinos from reactors, meson factories and high energy accelerators, searches for such processes as $\mu \to e\gamma$, $\mu \to 3e$, $\mu + N \to e + N$, etc*.

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*Such processes could be perfectly well observable [15] if there is lepton mixing and if there exist heavy leptons. Is there any connection between, say, the $\mu \to e\gamma$ process and the phenomenon of neutrino oscillations? The observation of anyone of these effects would mean that there is lepton mixing. In this general sense and only in this sense the observation of the $\mu \to e\gamma$ decay would make the existence of oscillations more likely, and conversely.

Let us note in conclusion that the solution of the "solar neutrino puzzle" in terms of lepton mixing would imply for the simplest case of two neutrino types that:
1) the neutrino mixing is substantial (θ is not far away from $\pi/4$);
2) the oscillation length is smaller than the Sun-Earth distance, from which it follows that $|m_1^2 - m_2^2|^2 \gtrsim 10^{-11}$ eV^2 *.

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* To obtain this result one must take into account that the effective neutrino momentum is ~10 MeV for neutrinos relevant in the experiment [3].

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