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EXPERIMENTAL STATUS OF THE MECHANISM OF RESONANCE ENHANCEMENT OF NEUTRINO OSCILLATIONS IN MATTER

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The present status of the mechanism of resonance enhancement of neutrino oscillations in matter has been considered by using the existent experimental data and it is concluded that this effect has no clear experimental confirmation. To prove that this mechanism is realized it is necessary to fulfil precision experiments with solar neutrinos and neutrinos which have passed through the Earth matter.

С использованием существующих экспериментальных данных изучен статус механизма резонансного усиления осцилляций нейтрино в веществе. Сделан вывод: этот эффект не имеет обоснованного подтверждения. Для строгой проверки этого эффекта необходимо с хорошей точностью провести эксперименты с солнечными нейтрино и с нейтрино, прошедшими через толщу Земли.

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INTRODUCTION

The suggestion that, in analogy with $K^0, \bar{K}^0$ oscillations, there could be neutrino–antineutrino oscillations ($\nu \to \bar{\nu}$), was made by Pontecorvo [1] in 1957. It was subsequently considered by Maki et al. [2] and Pontecorvo [3] that there could be mixings (and oscillations) of neutrinos of different flavors (i.e., $\nu_e \to \nu_\mu$ transitions).

The first experiment [4] on the solar neutrinos has shown that there is a deficit of neutrinos, i.e., the solar neutrinos flux detected in the experiment was a few times smaller than the flux computed in the framework of the Sun Standard Model [5]. The subsequent experiments and theoretical computation have confirmed the deficit of the solar neutrinos [6].

The short base reactor and accelerator experiments [7] have shown that there is no neutrino deficit. This result was interpreted as an indication that neutrino vacuum angle mixing is very small. Then the question arises: what is the deficit of the solar neutrinos related?

In 1978 the work by L. Wolfenstein [8] appeared where an equation describing neutrino passing through the matter was formulated (afterwards that equation was named Wolfenstein's). In the framework of this equation, the enhancement of neutrino oscillations in matter arises via weak interactions. This mechanism of neutrino oscillations enhancement in matter attracted attention of neutrino physicists after publications by S. Mikheyev and A. Smirnov [9],

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where it was shown that in the framework of this equation the resonance enhancement of neutrino oscillations in matter will take place. Also, it is clear that adiabatic neutrino transitions can arise in matter if effective masses of neutrinos change in matter [10]. After that an enormous number of works appeared, where the deficit of the solar neutrinos was explained by this mechanism. It is supposed that neutrino vacuum angle mixing is very small [11] and at resonance enhancement of neutrino oscillations in the solar matter this angle becomes maximal ($\pi/4$). This mechanism was recognized as the only mechanism to explain the origin of the Sun neutrino deficit. The situation changes after detection that the atmospheric neutrinos angle mixing [12] is big and close to the maximal one $\pi/4$. The $\bar{\nu}_e \to \bar{\nu}_\mu$ angle mixing obtained in KamLAND detector [13] appears to be big and near to the maximal one. Then the Day–Night effect does not obtain a confirmation [14]. Also, the Sun neutrino energy spectrum has no distortion in the energy region $E_{\nu_e} = 0.816$–13 MeV, which cannot be in the case if the resonance mechanism is realized. However, some authors insisted and continue to insist that this mechanism has already been confirmed at present time.

In the author's works [15] two remarks were done: 1) the Wolfenstein's equation is a left-right symmetrical one, while the weak interactions are left-handed interactions (then this equation has no connection with the weak interactions), 2) since the weak interactions with the charged current are the left-side ones, then these interactions cannot generate masses (masses can be generated only in the left-right symmetric interactions), then neutrino effective masses cannot change in matter and resonance conversion will be absent (the usually used χ^2 method [16] is not sufficient to prove that this resonance mechanism is actually realized).

This work is devoted to consideration of experimental status of the resonance mechanism, therefore firstly elements of the theory of resonance enhancement of neutrino oscillations in matter are given.

1. ELEMENTS OF THEORY (MECHANISM) OF RESONANCE ENHANCEMENT OF NEUTRINO OSCILLATIONS IN MATTER AND SOME CRITICAL REMARKS

Before consideration of the resonance mechanism, it is necessary to gain an understanding of the physical nature origin of this mechanism. As stressed above, at neutrino passing through matter there can be two processes — neutrino scattering and polarization of the matter by neutrino. Obviously, resonance enhancement of neutrino oscillations in matter will arise due to polarization of the matter by neutrino. If the weak interaction can generate not only neutrino scattering but also polarization of matter, then the resonance effect will exist, otherwise this effect cannot exist.

In the ultrarelativistic limit, the evolution equation for the neutrino wave function $\nu_{\rm Ph}$ in matter has the following form [8]:

$$i\frac{d\nu_{\rm Ph}}{dt} = \left(p\widehat{I} + \frac{\widehat{M}^2}{2p} + \widehat{W}\right)\nu_{\rm Ph}, \tag{1}$$

where $p, \widehat{M}^2, \widehat{W}_i$ are, respectively, the momentum, the (nondiagonal) square mass matrix in vacuum, and the matrix, taking into account neutrino interactions in matter,

$$\nu_{\mathrm{Ph}} = \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}, \qquad \widehat{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad \widehat{M}^2 = \begin{pmatrix} m^2_{\nu_e\nu_e} & m^2_{\nu_e\nu_\mu} \\ m^2_{\nu_\mu\nu_e} & m^2_{\nu_\mu\nu_\mu} \end{pmatrix}.$$

If we suppose that neutrinos in matter behave analogously to the photon in matter (i.e., the polarization at neutrino passing through matter arises) and the neutrino refraction indices are defined by the expression

$$n_i = 1 + \frac{2\pi N}{p^2} f_i(0) = 1 + 2\frac{\pi W_i}{p}, \tag{2}$$

where i is a type of neutrinos (e, μ, τ); N is density of matter; $f_i(0)$ is a real part of the forward scattering amplitude, then W_i characterizes polarization of matter by neutrinos (i.e., it is the energy of matter polarization).

The electron neutrino (ν_e) in matter interacts via $W^{\pm}, Z^0$ bosons and ν_μ, ν_τ interact only via Z^0 boson. These differences in interactions lead to the following differences in the refraction coefficients of ν_e and ν_μ, ν_τ:

$$\Delta n = \frac{2\pi N}{p^2} \Delta f(0), \quad \Delta f(0) = \sqrt{2}\frac{G_F}{2\pi} p, \tag{3}$$

where G_F is the Fermi constant.

Therefore, the velocities (or effective masses) of ν_e and ν_μ, ν_τ in matter are different. And at the suitable density of matter this difference can lead to a resonance enhancement of neutrino oscillations in matter [8, 9]

$$\sin^2 2\theta_m = \sin^2 2\theta \left[\left(\cos 2\theta - \frac{L_0}{L^0} \right)^2 + \sin^2 2\theta \right]^{-1}, \tag{4}$$

where $\sin^2 2\theta_m$ and $\sin^2 2\theta$ characterize neutrino mixings in matter and in vacuum, L_0 and L^0 are lengths of oscillations in vacuum and matter

$$L_0 = \frac{4\pi E_\nu \hbar}{\Delta m^2 c^3}, \qquad L^0 = \frac{\sqrt{2}\pi\hbar c}{G_F n_e}, \tag{5}$$

where E_ν is neutrino energy; Δm^2 — difference between squared neutrino masses; c is light velocity; $\hbar$ is Planck constant; G_F is Fermi constant and n_e is electron density of matter.

At resonance

$$\cos 2\theta \cong \frac{L_0}{L^0}, \qquad \sin^2 2\theta_m \cong 1, \qquad \theta_m \cong \frac{\pi}{4}. \tag{6}$$

It is necessary to stress that this resonance enhancement of neutrino oscillation in matter is realized when neutrino velocity is less than the light velocity in matter (i.e., $v_i < c/n_i$).

As we can see from the form of Eq. (1), this equation holds the left-right symmetric neutrinos wave function $\Psi(x) = \Psi_L(x) + \Psi_R(x)$. This equation contains term W, which arises from the weak interaction (contribution of W boson) and which contains only a left-handed interaction of neutrinos, and is substituted in the left-right symmetric Eq. (1) without indication of its left-handed origin. Then we see that Eq. (1) is an equation that includes term W which arises not from the weak interaction but from a hypothetical left-right symmetric interaction (see also works [18–20]). Therefore, this equation is not the one for neutrinos passing through real matter. The problem of neutrinos passing through real matter has been considered in [17–20].

2. WHAT IS THE SITUATION WITH EXPERIMENTAL CONFIRMATION OF THIS RESONANCE MECHANISM?

At present, the experimental data have been obtained in the accelerator, reactor, atmospheric and solar neutrinos. The data obtained in the reactor, accelerator and atmospheric neutrinos have shown that θ_{12}, θ_{23} have big values. The estimation of the value of this angle can be extracted from KamLAND [21] data:

$$\sin^2(2\theta_{12}) \cong 1.0, \quad \theta \cong \frac{\pi}{4}, \quad \Delta m^2_{12} = 6.9 \cdot 10^{-5}\,\mathrm{eV}^2, \tag{7}$$

or

$$\sin^2(2\theta_{12}) \cong 0.83, \quad \theta_{12} = 32^{\mathrm{o}}, \quad \Delta m^2_{12} = 8.3 \cdot 10^{-5}\,\mathrm{eV}^2.$$

The angle mixing for vacuum $\nu_\mu \to \nu_\tau$ transitions obtained on SuperKamiokande [22] for atmospheric neutrinos is

$$\sin^2(2\gamma_{23}) \cong 1, \quad \gamma \cong \frac{\pi}{4}, \quad \Delta m^2_{23} \simeq 2.5 \cdot 10^{-3}\,\mathrm{eV}^2. \tag{8}$$

The value of the Solar neutrinos flow measured (through elastic scattering) on SNO [23] is in good agreement with the same value measured in SuperKamiokande [24].

Ratio of ν_e flow measured on SNO (CC) to the same flow computed in the framework of SSM [25] ($E_\nu > 6.0\,\mathrm{MeV}$) is

$$\frac{\phi^{\mathrm{CC}}_{\mathrm{SNO}}}{\phi_{\mathrm{SSM2000}}} = 0.306 \pm 0.026(\mathrm{stat.}) \pm 0.024(\mathrm{syst.}). \tag{9}$$

This value is in good agreement with the same value of ν_e relative neutrinos flow measured on Homestake (CC) [26] for energy threshold $E_\nu = 0.814$ MeV:

$$\frac{\Phi^{\mathrm{exp}}}{\Phi^{\mathrm{SSM2000}}} = 0.34 \pm 0.03. \tag{10}$$

From these data we can come to a conclusion that the angle mixing for the Sun ν_e neutrinos does not depend on neutrino energy thresholds (0.8–13 MeV), and in this region the energy spectrum has no distortion.

The survival probability in different energy ranges of the solar neutrinos [27] (see also [28]) was computed taking into account the resonance effect. The profile of this effect is shown in Fig. 1 (shown are the reconstructed values of the survival probability in different energy ranges. The lines correspond to the survival probability for the LMA and LOW solutions (from [29])).

In Fig. 1 we see that the curves obtained from the computation in the framework of the resonance mechanism [27] are in clear discrepancy with the above-given experimental data (also see Fig. 4). In spite of this fact some authors come to a conclusion that this mechanism has been proved in experiments (experimental errors given in this figure many times exceed the same published errors, it is necessary to suppose that these errors were smeared for obtaining small values for χ^2 or better adjustment at smaller value of σ). The same situation takes place in the last interpretations of the solar neutrino data [16, 30]. The energy profile of the solar E_ν survival probability P_{ee} for best-fit LMA values ($\theta_{13} = 0$) is shown in Fig. 2

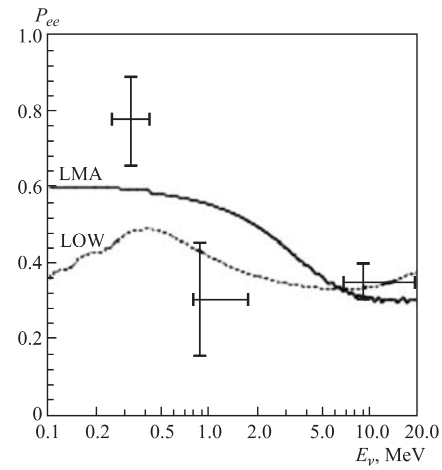

Fig. 1. The profile of the effect. Shown are the reconstructed values of the survival probability in different energy ranges. The lines correspond to the survival probability for the LMA and LOW solutions [29]

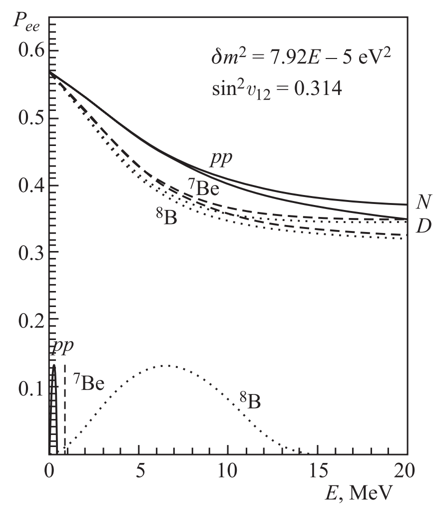

Fig. 2. The energy profile of the solar E_ν survival probability P_{ee} for best-fit LMA values and $\theta_{13} = 0$. The function $P_{ee}(E)$ shows a smooth transition from vacuum to the matter dominated regime as E increases, with some differences induced by averaging over different production regions (for ^{8}B, ^{7}Be and *pp* neutrinos) and, to a smaller extent, by nighttime (*N*) Earth effects with respect to daytime (*D*). Also, the corresponding solar neutrinos energy spectra are shown (in arbitrary vertical scale)

(experimental data see in Figs. 4 and 5, also in expressions (7)–(10)). Value for $\theta_{13} \approx 0$ was obtained from CHOOZ result analysis [31].

Is the CHOOZ result analysis trustful (i.e., is it correct that $\theta_{13} \approx 0$)? The probability of $P_{\bar{\nu}_e \bar{\nu}_e}$ transitions at three neutrino oscillations is

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(R) = 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{R}{L_{12}}\right) -$$
$$\cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\left(\frac{R}{L_{13}}\right) - \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\left(\frac{R}{L_{23}}\right), \qquad (11)$$

where $L_{12}, L_{13}, L_{23}, R$, correspondingly, are lengths of neutrino oscillations and distance from neutrino source. Since $L_{13} \approx L_{23}$, we can rewrite expression (11) in the following form:

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(R) \approx 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{R}{L_{12}}\right) - \sin^2(2\theta_{13}) \sin^2\left(\frac{R}{L_{13}}\right), \qquad (12)$$

if $L_{12} \gg R$, and taking into account that $L_{12}/L_{23} \approx 30.5$, the above expression can be rewritten in the following form:

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(R) \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{R}{L_{13}}\right), \qquad (13)$$

since $L_{12} \approx 160$ km (KamLAND), $R_{\mathrm{CHOOZ}} \approx 1$ km, then $R/L_{13} \approx 5.3, \sin^2(R/L_{13}) \approx 1/28 = 0.036$. The expression for transition probability $P_{\bar{\nu}_e \to \bar{\nu}_e}(R_{\mathrm{CHOOZ}})$ is

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(R_{\mathrm{CHOOZ}}) \approx 1 - 0.036 \sin^2(2\theta_{13}), \qquad (14)$$

and then the value of $1 - P_{\bar{\nu}_e \to \bar{\nu}_e}(R_{\mathrm{CHOOZ}})$ cannot be larger than 0.036:

$$1 - P_{\bar{\nu}_e \to \bar{\nu}_e}(R_{\mathrm{CHOOZ}}) \leqslant 0.036.$$

The precision of the CHOOZ experiment is $\approx 5\%$, i.e., 0.05. It is clear that for obtaining a limitation on $\sin^2(2\theta_{13})$ the precision of this experiment must be less than 0.036. So, we see that for this type of experiment a proper limitation on $\sin^2(2\theta_{13})$ is possible to obtain only if distances R are 3–5 km or if the precision of the experiment is very big ($\approx$ 0.4–0.5%).

Now let us return to discussion of the situation with experimental confirmation of the resonance mechanism. There is a new mechanism of enhancement of neutrino oscillation which [32] is named as MaVaN (mass-varying neutrino oscillations) mechanism. The result of computation in the framework of this mechanism together with the profile of the MSW

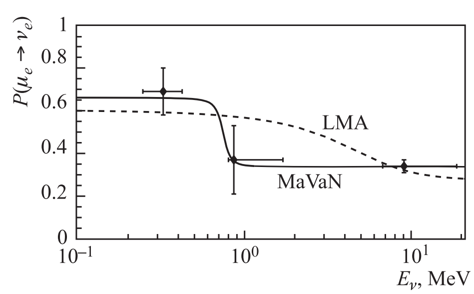

Fig. 3. $P(\mu_e \to \nu_e)$ vs E_ν for MaVaN [32] oscillations (solid curve). The dashed curve corresponds to conventional oscillations with the best-fit solution to KamLAND data

effect is given in Fig. 3. We will not discuss this mechanism since at present a direct confirmation of the dark matter existence is absent as well as its weak interactions with neutrinos.

Figure 4 gives the profile of the MSW effect (i.e., the reconstructed values of the survival probability in different energy ranges for the LMA solution from [29]). The following experimental data are also shown:

1. From the Homestake experiment in 1970–1994 [26] where the relation between the measured and calculated [25] flux data is

$$\frac{\Phi^{\rm exp}}{\Phi^{\rm SSM2000}} = 0.34 \pm 0.03. \tag{15}$$

2. From the GALLEX (GNO) [33, 35] and SAGE [34, 35] experiments where the relation between the measured and calculated BP04 [36] flux data is

$$\frac{\Phi^{\rm exp}_{\rm GALLEX}}{\Phi^{\rm BP04}} = 0.53 \pm 0.04, \tag{16}$$

$$\frac{\Phi^{\rm exp}_{\rm SAGE}}{\Phi^{\rm BP04}} = 0.51 \pm 0.04. \tag{17}$$

The data from Ga–Ge experiments are placed higher than the data of other experiments. It is necessary especially to note that the value of these experimental data decreases with statistics increasing.

3. From the SNO [23] experiment where the relation between the measured and calculated SSM2000 [25] flux data is

$$\frac{\phi^{\rm CC}_{\rm SNO}}{\phi_{\rm SSM2000}} = 0.35 \pm 0.02 \tag{18}$$

and [37]

$$\frac{\phi^{\rm CC}_{\rm SNO}}{\phi_{\rm SSM2000}} = 0.309 \pm 0.02. \tag{19}$$

4. From the SuperKamiokande [24] experiment where the relation between the measured and calculated SSM2000 [25] flux data is

$$\frac{\Phi^{\rm tot}_{^8{\rm B}}}{\rm SSM2000} = 0.465 \pm 0.005({\rm stat.}) + 0.016(-0.015)({\rm syst.}). \tag{20}$$

The data in Fig. 4 above 5 MeV were obtained by subtraction of the neutral current (Z^0 boson) deposit obtained in SNO from the SuperKamiokande data (see Fig. 5) and this difference equals to $\Delta = 0.156$ (it is the difference between the values of $\dfrac{\Phi^{\rm tot}_{^8{\rm B}}}{\rm SSM2000}$ in Eq. (20) and $\dfrac{\phi^{\rm CC}_{\rm SNO}}{\phi_{\rm SSM2000}}$ in Eq. (19)). The theoretical value of Δ is ≈ 0.155.

From Fig. 4 we see that the data obtained in SuperKamiokande, Homestake do not coincide with the computation obtained on the resonance effect in matter, i.e., the resonance effect is not confirmed. Only one point obtained in GALLEX and SAGE comes out from the other neutrino experimental data. Therefore, it is very important to study the solar neutrinos energy spectrum below 1 MeV to clarify the reason of this deviation.

The Day–Night effect is not confirmed. Usually it is claimed that this effect is very small. To avoid this argumentation it is necessary to carry out an experiment with the bigger

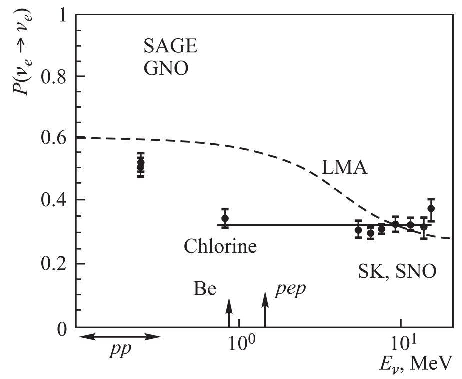

Fig. 4. The energy profile of the solar E_ν survival probability $P_{\nu_e\nu_e}$. The point and circles are SAGE, GNO, Chlorine, SNO and SuperKamiokande experimental data. The dashed curve corresponds to the profile of MSW effect [29]

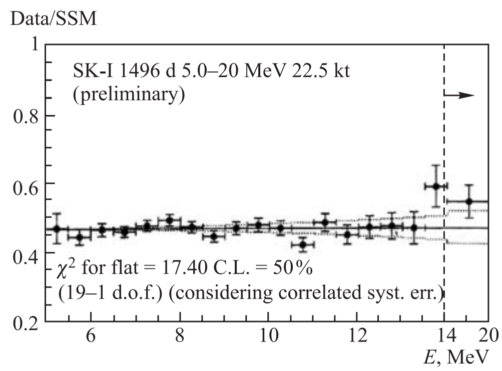

Fig. 5. The energy profile of the solar E_{ν_e} neutrinos flux from the SuperKamiokande experiment $(P_{\nu_e}(E_\nu)/P_{\mathrm{SSM2000}}(E_\nu))$

statistics (for example, in SuperKamiokande). This problem also can be solved by using neutrinos which have passed through the Earth at resonance energies for the Earth densities

$$E_{\mathrm{res}} = \frac{|\Delta m^2| \cos 2\theta_V}{2\sqrt{2} G_F n_{e,\mathrm{earth}}}, \tag{21}$$

where θ_V is the vacuum angle mixing; G_F is Fermi constant; $n_{e,\mathrm{earth}}$ is electron density of the Earth.

CONCLUSION

The present status of the mechanism of resonance enhancement of neutrino oscillations in matter by using the existent experimental data has been considered and it is concluded that this effect has no clear experimental confirmation. To prove that this mechanism is realized it is necessary to fulfil precision experiments with solar neutrinos and neutrinos which have passed through the Earth matter [38].

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