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

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Статус механизма резонансного усиления
осцилляций нейтрино в веществе

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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Status of the Mechanism of Resonance Enhancement
of Neutrino Oscillations in Matter

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.

The investigation has been performed at the Laboratory of Particle Physics, JINR.

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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 in 1957 [1]. 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 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 the matter attracted attention of neutrino physicists after publications by S. Mikheyev and A. Smirnov [9], 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 and it is supposed that the vacuum angle mixing is very small. 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 $E_{\nu_e} = 0.814 \div 13$ 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 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 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 ν_Φ in matter has the following form [8]:

$$i\frac{d\nu_{\mathrm{Ph}}}{dt} = (p\hat{I} + \frac{\hat{M}^2}{2p} + \hat{W})\nu_{\mathrm{Ph}}, \tag{1}$$

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

$$\nu_{\mathrm{Ph}} = \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}, \qquad \hat{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix},$$

$$\hat{M}^2 = \begin{pmatrix} m^2_{\nu_e\nu_e} & m^2_{\nu_e\nu_\mu} \\ m^2_{\nu_\mu\nu_e} & m^2_{\nu_\mu\nu_\mu} \end{pmatrix}.$$

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:

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

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]

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

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 the lengths of oscillations in vacuum and in 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 the neutrino energy, Δm^2 is the difference between squared neutrino masses, c is the velocity of light, $\hbar$ is the Planck constant, G_F is the Fermi constant and n_e is the 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 Eq. (1), this equation holds the left-right symmetric neutrinos wave function $\Psi(x) = \Psi_L(x) + \Psi_R(x)$. This equation contains the term W, which arises from the weak interaction (contribution of W boson) and which contains only a left-handed interaction of the neutrinos, and is substituted in the left-right symmetric Eq. (1) without indication of its left-handed origin. Then we see that equation (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 on the accelerator, reactor, atmospheric and solar neutrinos. The data obtained in the reactor, accelerator and atmospheric neutrinos have shown that the 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

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

The angle mixing for vacuum $\nu_\mu \to \nu_\tau$ transitions obtained at 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) at SNO [23] is in good agreement with the same value measured at SuperKamiokande [24].

Ratio of ν_e flow measured at 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 at Homestake (CC) [26] for energy threshold $E_\nu = 0,814\,\mathrm{MeV}$

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

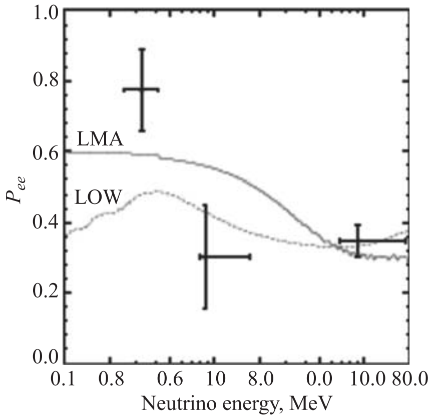

Fig. 1. The profile of the effect. Shown are the reconstructed values of the survival probability at different energy ranges. The lines correspond to the survival probability for the LMA and LOW solutions (from [29])

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 ($0.8 \div 13$ MeV), and in this region the energy spectrum has no distortion.

The survival probability at different energy ranges of the solar neutrinos [27] (see also Ref. [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 given above experimental data (see also Fig. 5). 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 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 (experimental data one can see in Figs. 4, 5 and also in expressions (7)–(10)). Value for $\theta_{13} = 0$ was obtained from CHOOZ result analysis [31].

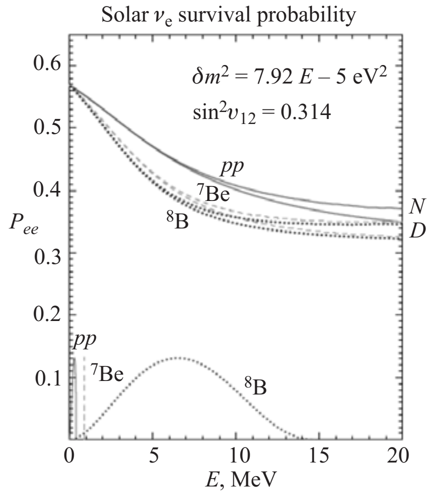

Fig. 2. The energy profile of the solar E_ν survival probability P_{ee} for best-fit LMA values and $\theta_{13} = 0$. The function P_{ee} (*E*) shows a smooth transition from vacuum to the matter dominated regime as *E* increases, with some differences induced by averaging over different production 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 shown are the corresponding solar neutrinos energy spectra (in arbitrary vertical scale)

Is the CHOOZ result analysis trustful (i. e., is it correct that $\theta_{13} = 0$)?

The probability of $P_{\bar{\nu}_e\bar{\nu}_e}$ transitions at three neutrino oscillations is

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

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

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

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:

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

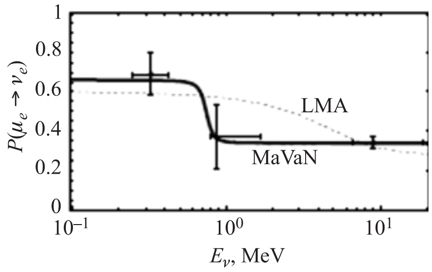

Fig. 3. $P(\mu_e \to \nu_e)$ vs. E_ν for MaVaN [32] oscillations (solid curve). The dashed curve corresponds to conventional oscillations with the best-fit solution to KamLAND data

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 $P_{\nu_e \to \nu_e}(R_{\mathrm{CHOOZ}})$ is

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

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 in this type of experiment a proper limitation on $\sin^2(2\theta_{13})$ is possible to obtain only if distances R are $3 \div 5$ km or if the precision of the experiment is very big ($\approx 0.4 \div 0.5\%$).

Now there is a new mechanism of enhancement of neutrino oscillation which is named as MaVaN (mass-varying neutrino oscillations) mechanism [32]. The result of computation in the framework of this mechanism together with the profile of the MSW effect is given in Fig. 3. We will not discuss this mechanism since at present a direct confirm of the dark matter existence is absent as well as its weak interactions with neutrinos.

Figure 5 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 [41]). 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

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

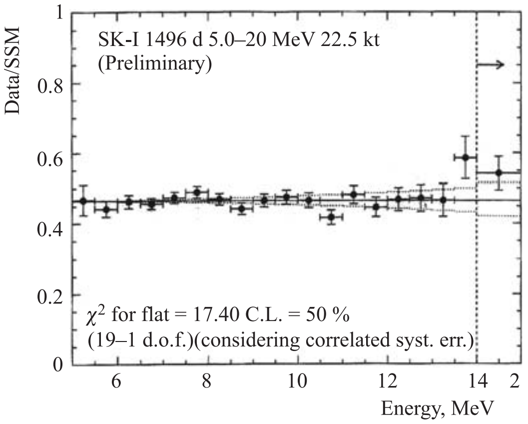

Fig. 4. The energy profile of the solar E_{ν_e} neutrinos flux from the SuperKamoikande experiment $(P_{\nu_e}(E_\nu)/P_{\mathrm{SSM2000}}(E_\nu))$

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

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

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

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

3) From the SNO [23] experiment, where the relation between the measured and calculated SSM2000 [25] flux data are

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

and [37]

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

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

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

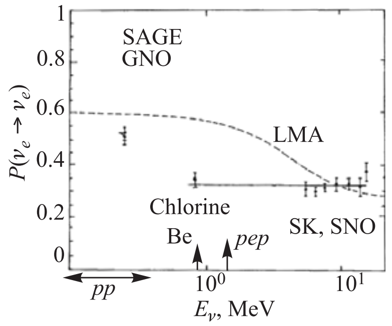

Fig. 5. The energy profile of the solar E_ν survival probability $P_{\nu_e\nu_e}$. The point and circles are SAGE, GNO, Chlorine, SNO and SuperKamiokande experimental data. The dashed curve corresponds to the profile of MSW effect [39]

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

From Fig. 5 one can see that the data obtained at SuperKamoikande, Homestake do not coincide with the computation obtained at the resonance effect in matter, i. e., the resonance effect is not confirmed. Only one point obtained at GALLEX and SAGE comes out from the other neutrino experimental data. Therefore, it is very important to study the solar neutrino energy spectra 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 statistics (for example, at SuperKamiokande). This problem can also be solved by using neutrinos passed through the Earth at resonance energies for the Earth densities

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

where θ_V is the vacuum angle mixing, G_F is the Fermi constant, $n_{e,{\rm earth}}$ 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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