ITEP--44(1987)

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NEUTRINO DECAY IN MATTER

Preprint №44

УДК 539.I2 M-I6

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We demonstrate that the matter can induce a decay of neutrino into antineutrino and light scalar particle (majoron) : $\nu \to \tilde{\nu} + \alpha$, or vice versa, $\tilde{\nu} \to \nu + \alpha$. The diagonal as well as non-diagonal transitions on neutrino types are possible. The decay probabilities depend on neutrino energies in an unusual way. Applications for 1) accelerator neutrinos passing through the earth; 2) solar neutrinos; 3) neutrino emission accompanied the gravitational collapse of stellar core are discussed.

Fig. - , ref. - 8

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It is well known that the oscillations of neutrinos in matter could be distinct compared with vacuum oscillations /1,2/. We shall demonstrate that the coherent interaction of neutrinos with matter could be important for their decay also. In particular, a transition of the left-handed neutrino into right-handed one (right neutrino in the case of Dirac neutrino or antineutrino in the case of Majorana neutrino) with the emission of massless (or sufficiently light) scalar particle can become energetically allowed even in the case of strictly massless neutrinos.

Coherent scattering could be taken into account directly into "current x current" Lagrangian which describe elastic neutrino scattering in terms of neutral currents*). In the rest frame of matter only the time components of electron, pro-ton and neutron vector currents remain nonzero after averaging over the matter, e.g. $<\bar{e}\,\gamma_\mu(1+\gamma_5)e> = \delta_{0\mu}\, n_e$. Consequently neutrino propagation in the medium is described by the Dirac equation analogous to that describing electron motion in an external field $eA_\mu = (\rho, 0)$. Therefore, for left-handed neutrino and CP conjugated right-handed antineutrino $\tilde{\nu}_R = C\,\nu_L$ energy levels we have correspondingly : $E = \sqrt{\bar{p}^2+m^2} \pm \rho$. Here $\bar{P}$ and m are ν momentum and mass

*) The charged ($\nu_e\, e$) current interactions also must be Fierz-transformed into the form $\frac{G_F}{\sqrt{2}}\ \bar{\nu}_e\,\gamma_\mu(1+\gamma_5)\nu_e\ \ \bar{e}\,\gamma_\mu(1+\gamma_5)e$.

and $\rho = \rho_e - \frac{1}{2}\rho_n$ for ν_e and $\rho = -\frac{1}{2}\rho_n$ for ν_μ and ν_τ , where $\rho_{e,n} = \sqrt{2} G_F n_{e,n}$ and n_e and n_n are electron and neutron densities correspondingly. So if there exist interaction which change neutrino chirality - for example radiation of the massless or very light scalar particle φ - the decay $\nu_L \rightarrow \tilde{\nu}_R + \varphi$ is induced in the matter (or vice versa, depending on the neutrino type and the relative neutron density of matter). We will also demonstrate that even if this scalar particle interacts diagonally with neutrino in vacuum the flavour-nondiagonal transitions would be induced in matter.

Let us illustrate the above statements within the triplet Majoron model /3/. We briefly remind this model. A triplet of scalar fields $\vec{\varphi} = (\varphi^{++}, \varphi^{+}, \varphi^{0})$ is introduced in the standard $SU(2)_L \otimes U(1)$ model of electroweak interactions without right-handed neutrino field components. The field $\vec{\varphi}$ has Yukawa couplings with the doublets $\ell_L : \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$ (for the sake of simplicity we shall discuss the case of two generations). If the Lagrangian doesn't contain couplings of the type $H \vec{\tau} \varepsilon H \vec{\varphi}$ (where H is Higgs doublet) then global U(1) symmetry could be spontaneously broken by non-zero vacuum average u of the neutral component φ^0 of triplet field. In this way neutrino acquires Majorana masses. Simultaneously massless Goldstone boson (Majoron) $\alpha = \frac{1}{\sqrt{2}} \operatorname{Im} \varphi^0$ appears in the particle spectrum. A light Higgs Boson $\varphi = \frac{1}{\sqrt{2}} \operatorname{Re} \varphi^0 - u$ with a mass $\sqrt{\lambda}\, u$ appears also (λ is an interaction constant of the field φ)*).

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*) The energy loss of "red giants" due to Majoron emission put the constraint : $u < 100$ KeV /4/. The fields φ^{++} and φ^{+} must be heavy, $M \sim M_W$.

The Lagrangian of φ° interaction has the following form :

$$\mathcal{L} = \overline{(\nu_e\ \nu_\mu)}_L\ \hat{h}\,(u + i\alpha + \varphi)\begin{pmatrix}\tilde{\nu}_e \\ \tilde{\nu}_\mu\end{pmatrix}_R \quad + \text{h.c.} \tag{1}$$

where $\widetilde{\Psi}_R \equiv C\,\Psi_L$ is antineutrino field and $\hat{h} = \begin{pmatrix} h_e & h_{e\mu} \\ h_{e\mu} & h_\mu \end{pmatrix}$ is the matrix of Yukawa coupling constants.

If one transform neutrino mass matrix into diagonal form and come to the states with definite masses m_1 and m_2 ($\nu_1 = c\,\nu_e + s\,\nu_\mu$, $\nu_2 = -s\,\nu_e + c\,\nu_\mu$, where $c = \cos\theta$, $s = \sin\theta$, $\sin^2 2\theta = 4h_{e\mu}^2/[4h_{e\mu}^2 + (h_\mu - h_e)^2]$) the Yukawa couplings (1) are diagonalized simultaneously :

$$h_{1,2} = \frac{m_{1,2}}{u} = \frac{1}{2}\left[h_e + h_\mu \mp \sqrt{4h_{e\mu}^2 + (h_\mu - h_e)^2}\right],\ \hat{h} = \begin{pmatrix} h_1 & 0 \\ 0 & h_2 \end{pmatrix} \tag{2}$$

We demonstrate that α and φ couple diagonally with ν_1 and ν_2. So the heaviest neutrino can not decay in vacuum.

The next step is to take into account effects of matter. For ultrarelativistic neutrino ($p \equiv |\vec{p}| \gg m$) the evolution of states in matter after substraction of an unessentional common phase is described by the following Schrödinger equation [1]:

$$i\,\frac{d}{dt}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix} = H\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix} \tag{3}$$

with the Hamiltonian

$$\mathcal{H} = \begin{pmatrix} \frac{m_1^2}{2p} + c^2 \rho_e - \frac{1}{2}\rho_n & c\,s\,\rho_e \\ c\,s\,\rho_e & \frac{m_2^2}{2p} + s^2 \rho_e - \frac{1}{2}\rho_n \end{pmatrix} \tag{4}$$

Eigenstates of this Hamiltonian are $\nu_1^m = c_m\,\nu_1 + s_m\,\nu_2$, $\nu_2^m = -s_m\,\nu_1 + c_m\,\nu_2$ ($c_m \equiv \cos\theta_m$, $s_m = \sin\theta_m$) where

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \xi)^2}, \tag{5}$$

and $\xi = \frac{m_2^2 - m_1^2}{2p\rho_e}$. Eigenvalues of the Hamiltonian (4) look like :

$$\lambda_{1,2} = \frac{1}{2}\left[\frac{m_1^2 + m_2^2}{2p} + \rho_e - \rho_n \mp \sqrt{\left(\frac{m_1^2 - m_2^2}{2p} + \cos 2\theta\, \rho_e\right)^2 + \sin^2 2\theta\, \rho_e^2}\, \right] \quad (6)$$

Antineutrino evolution in the same matter is described by analogous Hamiltonian with the change $\rho_{e,n} \to -\rho_{e,n}$ (when we interchange ν and $\bar{\nu}$ the zero angle scattering amplitude $f(0)$ change the sign). Eigenstates and eigenvalues for $\tilde{\nu}_R$ are given by formulae (5,6) with the change $\rho_{e,n} \to -\rho_{e,n}$ ($\tilde{c}_m = \cos\tilde{\theta}_m$, $\tilde{s}_m = \sin\tilde{\theta}_m$.

For eigenstates in a matter we obtain from (1) :

$$\mathcal{L} = \overline{(\nu_1^m\ \nu_2^m)}_L \begin{pmatrix} c_m \tilde{c}_m h_1 + s_m \tilde{s}_m h_2 & s_m \tilde{c}_m h_2 - c_m \tilde{s}_m h_1 \\ c_m \tilde{s}_m h_2 - s_m \tilde{c}_m h_1 & s_m \tilde{s}_m h_1 + c_m \tilde{c}_m h_2 \end{pmatrix} \begin{pmatrix} \tilde{\nu}_1^m \\ \tilde{\nu}_2^m \end{pmatrix} \times \quad (7)$$
$$\times (i\alpha + \varphi) + c.c.$$

Therefore, the nondiagonal $\tilde{\nu}_{1,2}^m \to \nu_{2,1}^m$ as well as diagonal $\tilde{\nu}_{1,2}^m \to \nu_{1,2}^m$ transitions are possible.

For the forthcoming statements we need an expression for the neutrino decay probabilities. We shall give a general expression from which all needed decay probabilities could easily be obtained. We shall consider a decay of Majorana neutrino ν_1 with a momentum $\vec{p}$ and mass m_1 and an interaction potential with a matter ρ_1 into a massless scalar α and Majorana neutrino ν_2 with a mass m_2 and a potential ρ_2, which is described by an amplitude $h\,\bar{\nu}_{1L}\tilde{\nu}_{2R}\,\alpha$. For the width in a reference system where matter is at rest we obtain :

$$\Gamma = \frac{h^2}{16\pi} \frac{[m_1^2 + (\rho_1 - \rho_2)\sqrt{\vec{p}^2 + m_1^2}\,]}{\sqrt{\vec{p}^2 + m_1^2}} \left\{1 - \frac{m_2^4}{[m_1^2 + (\rho_1-\rho_2)^2 + 2(\rho_1-\rho_2)\sqrt{\vec{p}^2 + m_1^2}\,]^2}\right\} \quad (8)$$

We start our analysis from the case of a dense matter (or light neutrinos) $\rho \gg \frac{m_1^2, m_2^2}{2E}$ $(\xi \ll 1)$. In this case the eigenstates of Hamiltonian (4) are directly the current ones: $\nu_1^m = \nu_e$, $\nu_2^m = \nu_\mu$. For the neutrino decay probabilities we obtain:

$$\Gamma_{\tilde{\mu}\mu} = \frac{h_\mu^2}{16\pi}\rho_n, \; \Gamma_{e\tilde{e}} = \frac{h_e^2}{16\pi}(2\rho_e - \rho_n), \; \Gamma_{\mu\tilde{e}} = \Gamma_{e\tilde{\mu}} = \frac{h_{e\mu}^2}{16\pi}(\rho_e - \rho_n) \quad (9)$$

where $\Gamma_{\tilde{\mu}\mu} \equiv \Gamma(\tilde{\nu}_\mu \to \nu_\mu)$ etc. Negative probability means that ν and $\tilde{\nu}$ must be interchanged (if $\rho_n > 2\rho_e$, then $\tilde{\nu}$ decays into ν).

Now, let us turn to the case of heavier neutrino (or low densities of matter) $\xi \gg 1$. For the diagonal transitions $\nu_{1L}^m \to \tilde{\nu}_{1R}^m$, $\nu_{2L}^m \to \tilde{\nu}_{2R}^m$ we obtain:

$$\Gamma_{1\tilde{1}} = \frac{h_1^2}{2\pi}\left(\rho_e \cos^2\theta - \tfrac{1}{2}\rho_n\right), \quad \Gamma_{2\tilde{2}} = \frac{h_2^2}{2\pi}\left(\rho_e \sin^2\theta - \tfrac{1}{2}\rho_n\right) \quad (10a)$$

Nondiagonal transitions have the following width:

$$\Gamma_{1\tilde{2}} = \Gamma_{\tilde{1}2} = \frac{h_{1\tilde{2}}^2}{16\pi|\vec{p}_1|}\,\frac{m_1^4 - m_2^4}{m_1^2}, \quad h_{1\tilde{2}} = \frac{\sin 2\theta_m}{2}(h_1 - h_2)\Big|_{\xi \gg 1} = \frac{\sin 2\theta}{2\xi}(h_1 - h_2) = \frac{h_{e\mu}}{\xi} \quad (10b)$$

which are suppressed compared with diagonal ones (10a).

The probabilities of matter-induced transitions depend on the initial neutrino energy in an unusual way. They does not depend on energy when $\xi \ll 1$ (see (9)). When $\xi \gg 1$ diagonal transitions are also energy independent. As for nondiagonal probabilities (10b), they are proportional to E/m. For ordinary vacuum decays $\Gamma = \Gamma_0\, m/E$ where Γ_0 is the decay probability in a rest frame of decaying particle.

Before we discuss some applications let us give the experimental limits on the Majoron coupling constants:

$$h_e < 2\cdot10^{-3} \text{ (} 2\beta_o \text{ decay with Majoron emission)}^{/5/} \tag{11}$$

$$h_e^2 + h_{e\mu}^2 < 4.5\cdot10^{-5} \quad /6/ \tag{12}$$
(lepton decays of π- and K-mesons)
$$h_\mu^2 + h_{e\mu}^2 < 2.4\cdot10^{-4} \tag{13}$$

1. Pass of the accelerator neutrinos through the Earth

$\tilde{\nu}_\mu$ are heavier in the matter than ν_μ. So, when a bunch of accelerator produced $\tilde{\nu}_\mu$ pass through the Earth some of them can decay into ν_μ. Charge current give a distinct signature of the effect : together with μ^+ from the readtion $\tilde{\nu}_\mu p \to n \mu^+$ μ^- from the reaction $\nu_\mu n \to \mu^- p$ appears. Let's estimate the value of the effect. For the Earth density we take 10 g/cm^3, the relative number of neutrons is given by electronic number $Y_e \equiv \frac{n_e}{n_p+n_n} \simeq 0.5$. The region $\xi >> 1$ is more profitable. With maximal value of h_μ from (10a) and (13) we obtain :

$$\tau_{\tilde{\nu}_\mu} = \frac{4\pi}{h_{\mu\mu}^2 \rho_n} \approx \frac{3\cdot10^{12}\,cm}{3\cdot10^{10}\,cm/sec} \approx 100 \text{ sec} \tag{14}$$

As the length of the Earth diameter is of the order of 10^9 cm not more than 0.03 % $\tilde{\nu}_\mu$ could transform into ν_μ .

2. Solar neutrinos

Electron neutrinos produced in a core of the Sun fall on the Earth and, in particular, are detected in Davis experiment. The deficit of ν_e in Davis experiment in comparison with standard solar model prediction can be understood if one suppose that ν_e decays inside the Sun : $\nu_e \to (\bar{\nu}_e, \bar{\nu}_\mu)\,\alpha$. Let us make an estimate for the matter induced decay. As the maximal allowed value for h_e^2 is an order of magnitude lower than then in the domain $\xi \ll 1$ neglecting ρ_n in comparison with ρ_e we obtain :

$$\Gamma_{\nu_e \to \bar{\nu}_\mu} = \frac{h^2_{e\mu}}{16\pi} \rho_e \tag{15a}$$

When $\xi \gg 1$ maximum neutrino mixing is profitable, $\theta \approx 45^\circ$. Then from (10a) we obtain :

$$\Gamma_{\nu_e \to \bar{\nu}_e, \bar{\nu}_\mu} = \frac{h^2_{e\mu}}{4\pi} \rho_e \tag{15b}$$

Taking maximally allowed value for $h^2_{e\mu}$ from (12) and using the Sun density 100 g/cm^3 at the distance $2 \cdot 10^{10}$ cm we obtain in the case (15b) :

$$N_{\bar{\nu}}/N_{\nu_e} \approx 5\ \% \tag{16}$$

which is too little to explain three times deficit of ν_e in Davis data but probably rather large to be detected in near future with new solar neutrino detectors.

3. Neutrinos from gravitational collapse of stellar core

In supernovae densities and distances are of a such value that inspite of the limits (10÷13) neutrino decays could take place. The neutrinos emitted during a collapse have a typical energy of about 10 MeV. Taking a typical density 10^{12} g/cm^3 we obtain $\rho_e \approx 10^{-1}$ eV and $\xi \ll 1$. A typical distances in supernovae are $R \sim 10^7$ cm and decays take place if $h^2 > 10^{-9}$. Relative number of electrons in supernovae Y_e varies between 0.3 at $R \sim 10^6$ cm and 0.5 at $R \sim 10^7$ cm /7/. Without taking decays into account approximately equal numbers of ν's and $\bar{\nu}$'s of different types are expected; decays change this prediction drastically. In particular at $Y = 0.3$ $\bar{\nu}_\mu$ and $\bar{\nu}_e$ decay into ν_μ and ν_e respectively and no antineutrinos fall on the Earth (let us remind that the detectors which are under operation now are sensitive only to $\bar{\nu}_e$ /8/; however, the detectors under construction will be sensitive to ν_e as well).

It is noteworthy that the effects of neutrino decay in matter can be relevant also to the case of Dirac neutrinos. Indeed, in the standard SU(2) $\otimes$ U(1) model with right-handed neutrino fields ν_R one can introduce together with standard H an additional Higgs doublet $H' = \binom{H^{0\prime}}{H^{-\prime}}$ with Yukawa couplings of the type $h\,\bar{e}_L \nu_R H'$ + h.c. and impose the global U(1) symmetry $H' \to e^{i\alpha} H'$. The breaking of this symmetry by the vacuum average of the scalar H' ($\langle H^{0\prime}\rangle \ll \langle H^0 \rangle$ = 250 GeV) leads to appearance of neutrino Dirac masses and the corresponding Goldstone boson β (Diron - by analogy with Majoron) simultaneously appears in the particle spectrum. Then the transitions $\nu_L \to \nu_R + \beta$ are possible in the matter (or vice versa, $\nu_R \to \nu_L + \beta$, depending on the neutrino type and neutron concentration). It is obvious that due to sterility of ν_R the experimental consequences of the Diron scheme substantially differ from that for the case "Majorana neutrinos + Majoron".

Let us discuss now the case of neutrino decays in vacuum. They are possible if in the Majoron scheme we incorporate also the small Dirac mass terms. Another way is the introducing of two (or more) Majoron-type global U(1) symmetries acting distinctly on the different neutrino flavours. In the vacuum only the neutrino-type nondiagonal transitions due to couplings of the type $h\,\bar{\nu}_1 \nu_2 \alpha + h.c.$ ($\nu_1 = c\,\nu_e + s\,\nu_\mu, \ldots$) are possible, e.g. $\nu_1 \to \bar{\nu}_2 + \alpha$, $\bar{\nu}_1 \to \nu_2 + \alpha$ if $m_1 > m_2$. The corresponding width in the rest frame of the neutrino source is $\Gamma = \Gamma_0 \frac{m}{E}$.

where $\Gamma_0 = \frac{\lambda^2}{16\pi}\ \frac{m_1^4 - m_2^4}{m_1^3}$.

The vacuum decays can explain the deficite of solar ν_e flux in Davis experiment in two different ways.

1. The neutrino mixing is negligible and $m_{\nu_e} > m_{\nu_\mu}$. Supposing that $\tau_{\nu_e} = \tau^0_{\nu_e} \frac{E_{\nu_e}}{m_{\nu_e}} \approx 500$ sec for $E_{\nu_e} \approx 5$ MeV we conclude that one third of emitting in the core of sun boron neutrinos decay in flight from Sun to Earth. In this scenario the flux of pp neutrinos (with energies lower than 420 KeV) is diminished in e^{10} times. This is strong (but negative) prediction for Ga-Ge detector experiments in preparation.

2. The neutrino mixing is substantial, $\nu_e = c\nu_1 + s\nu_2$, and $m_1 > m_2$. If the heavier neutrino ν_1 decay into $\bar{\nu}_2$ with life-time $\tau_{\nu_1} \ll$ 500 sec, only the component $\nu_2 = -s\nu_e + c\nu_\mu$ reaches the Earth. The magnitude of ν_e flux directly measures the neutrino mixing angle : $N_{Davis}/N_0 = \sin^4\theta$.

In conclusion we would like to emphasize that the matter induced neutrino decays are drastically distinct from vacuum decays and ν oscillations. They can take place even for strictly massless neutrinos. Experimental signatures of decays are also very distinct : neutrino changes chirality, which can not take place in a result of ν oscillations.

Numerical estimates show that in an experiment with accelerator $\bar{\nu}_\mu$ beam little part could transform into ν_μ ; a flux of ν_e from sun could contain some percent of $\bar{\nu}_e$ and $\bar{\nu}_\mu$ and a content of neutrinos and antineutrinos of different flavours coming into the Earth from stellar collapse could differ widely in number because of ν decays in dense regions of star. Finally, note that the existence of Majoron lead to the absence stages of evolution of the Universe if Yukawa constant h is greater than 10^{-5}.

We are grateful to S.I.Blinnikov, A.A.Gerasimov, A.Yu.Smirnov, M.Yu.Khlopov and V.A.Tsarev for useful discussions.

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Распад нейтрино в веществе.
Работа поступила в ОНТИ 20.01.87

Подписано к печати 12.02.87 Т05250 Формат 60х90 1/16
Офсетн.печ. Усл.-печ.л.0,75. Уч.-изд.л.0,5. Тираж 280 экз.
Заказ 44 Индекс 3624 Цена 7 коп.

Отпечатано в ИТЭФ, 117259, Москва, Б.Черемушкинская, 25

ИНДЕКС 3624

М.,ПРЕПРИНТ ИТЭФ, 1987, № 44, с.1-12