ENHANCEMENT OF THE STERILE NEUTRINOS YIELD AT HIGH MATTER DENSITY AND AT INCREASING THE MEDIUM NEUTRONIZATION

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The relative yields of active and sterile neutrinos in the matter with a high density and different degree of neutronization are calculated. A significant increase in the proportion of sterile neutrinos produced in superdense matter when approaching the medium neutronization degree to value of two is found. The results obtained can be used in the calculations of the neutrino fluxes for media with a high density and different neutronization degrees in astrophysical processes such as the formation of protoneutron core of a supernova.

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INTRODUCTION

At gravitational collapse of supernovae main part of the released energy is passed away by powerful flows of neutrino. Neutrinos of various types (flavours) are born both due to a large number of the processes with participation of nucleons and nuclei of star matter and due to processes of neutrino oscillations, i.e. to transitions of one type of neutrino to another. The feature of processes of oscillations of known types of neutrino (electron, muon and tau) in the matter is the dependence on distribution of the electron’s density. At the nonzero electron’s density the oscillation characteristics of neutrino are changed in comparison with the oscillation characteristics of neutrino in vacuum, and at certain relationships between the electron’s density, differences of squares of neutrino masses, angles of mixing and neutrino energy so-called Mikheev–Smirnov–Wolfenstein (MSW) resonances arise. In those areas of star matter, where conditions of MSW-resonances are satisfied, there is an intensification of transitions of one type of neutrino to another, even if initial vacuum mixing between different types of neutrino is insignificant.

The accounting of strengthening of transitions of one neutrino type to another due to the MSW-resonance in solar medium allowed ones to solve a problem of deficiency of the solar electron neutrino and to determine the difference of squares of neutrino masses \( \Delta m^2_{21} = m_2^2 - m_1^2 \) and the neutrino mixing angle \( \theta_{12} \). On the basis of data on oscillations of atmospheric, reactor and accelerator neutrinos other oscillation characteristics of neutrino were also determined (see Olive et al., 2014). Now most exact values of vacuum oscillation characteristics of neutrino in limits of deviations up to \( 1 \sigma \), where \( \sigma \) is standard uncertainty measurements, are obtained in a number of works. We will give the values of the oscillation characteristics from the paper of Gonzalez-Garcia et al. (2014) for the standard parametrization of a mixing matrix:

\[
\sin^2 \theta_{12} = 0.304_{-0.012}^{+0.013}, \quad (1a)
\]

\[
\sin^2 \theta_{23} = \begin{cases} 
NH : & 0.452_{-0.025}^{+0.052} \\
IH : & 0.579_{-0.037}^{+0.025} 
\end{cases}, \quad (1b)
\]

\[
\sin^2 \theta_{13} = \begin{cases} 
NH : & 0.0218_{-0.0010}^{+0.0010} \\
IH : & 0.0219_{-0.0010}^{+0.0011} 
\end{cases}, \quad (1c)
\]

\[
\Delta m^2_{21}/10^{-5} \text{eV}^2 = 7.50_{-0.17}^{+0.19}, \quad (1d)
\]

\[
\Delta m^2_{31}/10^{-3} \text{eV}^2 = \begin{cases} 
NH : & 2.457_{-0.047}^{+0.047} \\
IH : & 2.449_{-0.047}^{+0.048} 
\end{cases}. \quad (1e)
\]

As only the absolute value of oscillation characteristic \( \Delta m^2_{31} \) is known, the absolute values of neutrino masses can be ordered in two ways: a) \( m_1 < m_2 < m_3 \) and b) \( m_3 < m_1 < m_2 \), i.e. it can be realized, as the saying goes, either normal hierarchy (NH, case a), or inverted hierarchy (IH, case b) of the neutrino mass spectrum.

Along with the given values of oscillation characteristics of neutrino, for a long time there are evidences of anomalies of neutrino flows in various processes occurring on Earth, which can not be explained by oscillations of only active, i.e. electron-, muon- and tau-neutrino and antineutrino. LSND/MiniBooNE, reactor and gallium anomalies belong to such anomalies (see Abazajian et al., 2012; Kopp, et al., 2014), which could be explained by existence of one or two additional neutrinos noninteracting within the Standard Model (SM) with other particles. Such neutrinos were named as the sterile neutrinos.
The characteristic mass scale of sterile neutrinos, which is responsible for the description of the anomalies noted above is 1 eV. However, it should be noted that recently obtained observational astrophysical data pertaining to formation of galaxies and their clusters can be explained by existence of sterile neutrinos with mass of the order of 1 KeV or above, and such sterile neutrinos are the candidates for cold dark matter particles (see Dodelson and Widrow, 1994; Kusenko, 2009). More details about possible existence of sterile neutrinos and their characteristics can be found in numerous papers (see, for example, Liao, 2006; Abazajian et al., 2012; Bellini et al., 2013; Conrad et al., 2013; An et al., 2014; Kopp et al., 2014).

The great interest is represented by models with three active and three sterile neutrinos (see Bhupal Dev and Pilafsis, 2012; Duerr et al., 2013; Conrad et al., 2013; Rajpoot et al., 2013; Khruschov, 2013; Zysina et al., 2014; Khruschov and Fomichev, 2014), which can be included in the grand unification theories (GUT) keeping up the left-right symmetry. In the papers by Zysina et al. (2014) and Khruschov and Fomichev (2014) the estimates of masses of three active and three sterile neutrinos were obtained and both the appearance and survival probabilities of active and sterile neutrinos in the Sun with accounting of the MSW-resonances were calculated. However in the models with three active and three sterile neutrinos, the difficulties connected with consistency of number of the effective neutrino and the sum of their masses with the data of cosmological observations exist (see Komatsu, et al., 2011; Ade, et al., 2013). It is possible to bypass these difficulties, for example, by reducing the mixing parameters between the active and the sterile neutrinos and distorting all or some sterile neutrinos from a thermodynamic equilibrium at early stages of formation of the Universe, and also by transition to more general cosmological models.

In the current paper, the neutrino flavour composition modification due to coherent scattering of a neutrino on both electrons and neutrons of the medium is considered. The accounting of neutrons does not lead to change of oscillation characteristics, if to consider only the active neutrinos. But if to consider a contribution of the sterile neutrinos, the influence of neutron density of the matter becomes noticeable. Moreover, as is shown in the current paper, when the ratio of a number of neutrons to a number of protons is close to two, there is a considerable enhancement of the sterile neutrinos yield. Such enhancement arises at large or super-large values of density of matter (> 10^7 g/cm^3), therefore this effect can be of importance only in astrophysical conditions, for example, at formation of a protoneutron core of a supernova. In the models with participation of the sterile neutrinos this effect is additional to the MSW-effect and can lead to new consequences at supernovae explosions. In spite of the fact that influence of the sterile neutrinos on the processes in supernovae were considered in many papers (see, for example, Hidaka and Fuller, 2006 and 2007; Tamborra, et al., 2012; Wu, et al., 2014; Warren, et al., 2014), effect of enhancement of the sterile neutrinos yield at the ratio of a number of neutrons to a number of protons in the medium as \( \eta = N_n/N_p \approx 2 \) was not noticed before.

THE (3+1+2)-MODEL OF ACTIVE AND STERILE NEUTRINOS

We will give below the basic principles of the (3+1+2)-model with three active and three sterile neutrinos investigated in the papers by Zysina et al. (2014) and Khruschov and Fomichev (2014). Within the (3+1+2)-model, a neutrino of certain types of flavour \( \{ \nu_f \} \), both active and sterile, are the mix of massive neutrinos \( \{ \nu_I \} \) having a certain masses. The masses of neutrino are given by a set \( \{ m_i \} = \{ m_1, m_\nu \} \), where \( i = 1, 2, 3, i' = 1', 2', 3' \), at this the masses \( \{ m_i \} \) settle down in a direct order: \( m_1, m_2, m_3 \), and the masses \( \{ m_{i'} \} \) settle down in the return order: \( m_3', m_2', m_1' \). The full set \( \{ \nu_f \} = \{ \nu_a, \nu_s \} \) of the flavour neutrino consists of the known active neutrinos \( \{ \nu_a \} \), i.e. e-, \( \mu \)-, and \( \tau \)-neutrino, and three hypothetical sterile neutrinos \( \{ \nu_s \} \), which we will distinguish by indexes \( x, y \) and \( z \). The generalized \( 6 \times 6 \) mixing matrix \( \tilde{U} \) can be presented by means of \( 3 \times 3 \) matrices \( S, T, V \) and \( W \) as follows:

\[
\begin{pmatrix}
\nu_a \\
\nu_s
\end{pmatrix} = \tilde{U}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix} = \begin{pmatrix} S & T \\ V & W \end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}.
\]

Hereafter, the particular form of matrix \( \tilde{U} \) will be used taking into account the smallness of parameters of mixing between the active and the sterile neutrinos, and also assuming that the mixing of the sterile states \( \{ \nu_s \} \) can be neglected (\( W = 1 \)). Then, in condition of conservation of the \( CP \)-invariance in the lepton sector, the matrices \( S, T \) and \( V \) can be written down in the following form:

\[
S = U_{PMNS} + \Delta U_{PMNS}, \quad (3a)
\]
\[
T = b, \quad V = -b^T U_{PMNS}, \quad (3b)
\]

where \( U_{PMNS} \) is a mixing matrix for the active neutrinos, i.e. the Pontekorvo–Maki–Nakagawa–Sakata matrix. The contributions from the matrix elements of \( \Delta U_{PMNS} \) are actually allowed for by the experimental uncertainties of the matrix elements of \( U_{PMNS} \). In what follows we will choose the case of inverted hierarchy (IH) of the active neutrinos mass spectrum, which is preferable for the \( \nu_\mu - \nu_\tau \)-symmetry of a neutrino mass matrix, and also for the detailed description of the survival probability of the solar electron neutrinos in the energy range higher than 2 MeV (see Khruschov and Fomichev, 2014).

For the IH-case, the matrix \( b \) can be given as follows

\[
b_{IH} = \begin{pmatrix}
\gamma & \gamma' \\
\beta & \beta' \\
\alpha & \alpha'
\end{pmatrix}, \quad (4)
\]
where the parameters $\alpha, \beta, \gamma, \alpha', \beta', \gamma'$ should be in the range from zero up to 0.2 in absolute values.

The specific feature of the (3+1+2)-model is the mass spectrum of the sterile neutrinos, one of which is rather heavy and can in principle be with a mass from 0.5 eV up to several keV and above, but two others are light with masses about 2 meV (see Zysina et al., 2014). In the current paper we will use the following values of the mass parameters in addition to experimental data given above \( m \), the neutrino masses being given in eV:

\[
m_1 = 0.0496, \quad m_2 = 0.0504, \quad m_3 = 0.002, \quad (5)\]

\[
m'_1 = 0.002, \quad m'_2 = 0.0022, \quad m'_3 = 0.46, \quad (6)\]

\[
\beta = \gamma = 0.1, \quad \beta' = \gamma' = 0, \quad (7)\]

\[
\alpha = 0, \quad \alpha' = 0.15. \quad (8)\]

The value of \( m'_3 = 0.46 \) eV corresponds to the mass of the heavy sterile neutrino given in the paper by Sinev (2013). Notice that the values of parameters given above are phenomenological, i.e. they are chosen taking into account the available experimental restrictions. The choice of concrete values of parameters is necessary as for the investigation of the (3+1+2)-model and carrying out the numerical calculations, and also for the demonstration given below of new effect of enhancement of the sterile neutrino yield in the matter with high values of density and at the medium neutronization degree \( \eta = N_n/N_p \), that is the ratio of a number of neutrons to a number of protons, close or equal to two.

**ENHANCEMENT OF THE STERILE NEUTRINO YIELD**

Let us to write down the equation for the probability amplitudes of a neutrino with a certain flavours, which propagates in the medium, in the form given in the paper by Khurschov and Fonichev (2014):

\[
\begin{align*}
& i \partial_r \left( \frac{a_\alpha}{a_s} \right) = \\
& \quad \left[ \frac{\Delta_{m^2}}{2E} + \sqrt{2} G F \left( \frac{\bar{N}_e(r)}{\bar{N}_s(r)/2} \right) \right] \left( \frac{a_\alpha}{a_s} \right). \quad (9)
\end{align*}
\]

Here the matrix $\Delta_{m^2}$ is defined as $\Delta_{m^2} = \bar{U} \Delta_{m^2} \bar{U}^T$, $\Delta_{m^2} = \text{diag}\{m_1^2 - m_0^2, m_2^2 - m_0^2, m_3^2 - m_0^2, m_{\nu}^2 - m_0^2, m_{\bar{\nu}}^2 - m_0^2, m_{\bar{\nu}}^2 - m_0^2, m_{\nu}^2 - m_0^2, m_{\bar{\nu}}^2 - m_0^2, m_{\nu}^2 - m_0^2\}$, with $m_0$ the smallest neutrino mass among $m_i$ and $m_{\nu}$, and $\bar{N}_e(r)$ and $\bar{N}_s(r)$ are $3 \times 3$ matrices presented below:

\[
\bar{N}_e(r) = \begin{pmatrix} N_e(r) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad (10)
\]

FIG. 1. The behavior of the neutronization coefficient $\eta$ depending on the matter density $\rho$, which is specific for the medium of a supernova core at conditions of a gravitational collapse.

\[
\ddot{N}_n(r) = \begin{pmatrix} N_n(r) & 0 & 0 \\ 0 & N_n(r) & 0 \\ 0 & 0 & N_n(r) \end{pmatrix}, \quad (11)
\]

where $N_e(r)$ and $N_n(r)$ are the electron and neutron densities in the matter, respectively. We will find out the specific features of solutions of the equations (10) at certain values of $N_n$ and $N_e = N_p$, considering the electroneutral media. In Fig. (1) the behavior of the matter neutronization degree $\eta$ in a star at collapse is shown up to its stop, that is up to ”bounce” of the core (see Liebendörfer, 2005). Each element of the star collapses contracting and increasing the density $\rho$, herewith, passing through approximately identical states. Thus, at a collapse stage $\eta = \eta(\rho)$. As is seen from Fig. 1 the value of $\eta = 2$ corresponds to the matter density $\rho \approx 2 \times 10^{12}$ g/cm$^3$.

Fig. (2) displays the results obtained for the relative average yields of various (not electron’s) flavours of the neutrino (at a normalization of the total yield of all flavours, including electron’s one, on unity) versus the neutrino energy $E_{\nu}$ at values of density $\rho = 7 \times 10^7$ g/cm$^3$ (the left panel) and $\rho = 2 \times 10^{12}$ g/cm$^3$ (the right panel), and at the neutronization degree $\eta = 1$. This value of $\eta$ is typical for the normal (equilibrium) conditions of a matter. For the results of Fig. 2 the equation (10) was solved with a constant density on a spatial scale of the order of typical radius of the neutron star, exactly, on the scale $\Delta r = 20$ km, and for obtaining the average yields of neutrinos the solutions of this equation were averaged on the spatial scale of neutrino oscillations. As to the initial conditions, it was chosen that only electron’s neutrino are created in the very beginning. In this Figure, as expected, the relative yields of the non-electron’s neutrino flavours are small, and for neutrino energies $E_{\nu}$ more than 1 MeV they do not exceed $10^{-5}$. On the left panel in the range of $E_{\nu}$ from $10^{-2}$ MeV up to $10^{-1}$ MeV, increasing of the yields of two flavours of neu-
the matter neutronization degree as on the right panel of Fig. 2, and the results are given of the relative yields of sterile neutrinos of equation (9) was solved. In both cases a visible increase the neutrino energy at various non-electron’s flavours of neutrino depending on large matter density. Fig. 3 shows the relative yields of non-electron’s flavours are small everywhere, and for $E_\nu$-range from 10 eV up to 0.1 GeV they do not exceed $10^{-10}$. However, the picture sharply changes at approaching the matter neutronization degree $\eta$ to value of two at large matter density. Fig. 2 shows the relative yields of various non-electron’s flavours of neutrino depending on the neutrino energy at $\eta = 2$ and at the same density as on the right panel of Fig. 2 and the results are given for two different values of spatial scale $\Delta r$, where solutions of equation (9) were obtained. The yields of sterile y- and z-neutrinos practically coincide.

However, the picture sharply changes at approaching the matter neutronization degree $\eta$ to value of two at large matter density. Fig. 2 shows the relative yields of various non-electron’s flavours of neutrino depending on the neutrino energy at $\eta = 2$ and at the same density as on the right panel of Fig. 2 and the results are given for two different values of spatial scale $\Delta r$, where solutions of equation (9) were obtained. The yields of sterile y- and z-neutrinos practically coincide.

The relative yields given on the right panel for non-electron’s neutrino flavours are small everywhere, and for $E_\nu$-range from 10 eV up to 0.1 GeV they do not exceed $10^{-10}$. However, the picture sharply changes at approaching the matter neutronization degree $\eta$ to value of two at large matter density. Fig. 2 shows the relative yields of various non-electron’s flavours of neutrino depending on the neutrino energy at $\eta = 2$ and at the same density as on the right panel of Fig. 2 and the results are given for two different values of spatial scale $\Delta r$, where solutions of equation (9) were obtained. The yields of sterile y- and z-neutrinos practically coincide.

preferable owing to two factors: narrowness of the effective spatial range with $\eta \approx 2$ in a collapsing star and rather small neutrino mean free path at such density. Namely, the mean free path of neutrino in this case is equal approximately to $10 - 100$ m. To find out a nature of behaviour of the neutrino yield at approaching $\eta$ to two at large density of a matter, the relative average yields of various non-electron’s flavours of neutrino are shown in Fig. 3 (at a normalization of total yield of all neutrino flavours, including electron’s

\[ l_\nu = \frac{1}{n\sigma}, \] where $n \sim \rho/m_\nu$ is the concentration of nucleons, and interaction cross-section of neutrino is $\sigma \sim (E_\nu/m_\nu c^2)^2 \times 10^{-44}$ cm$^2$, with $m_\nu$ the electron mass, i.e., for $\rho \sim 10^{12}$ g/cm$^3$ and $E_\nu \sim 100$ MeV, $l_\nu$ is of the order of tens meters.
FIG. 4. The relative yields of various (not electron’s) flavours of the neutrino versus the neutronization degree \( \eta \) in the range of \( \eta \)-values around \( \eta = 2 \) at the density \( \rho = 2 \times 10^{12} \) g/cm\(^3\). \( E_\nu = 4 \) MeV (the left panel) and \( E_\nu = 100 \) MeV (the right panel). \( \Delta r = 100 \) m. The yields of sterile \( y \)- and \( z \)- neutrinos practically coincide.

One, to unity) in the range of values of \( \eta \) around \( \eta = 2 \), and at two values of neutrino energy. The left panel of Fig. 4 corresponds to value of density \( \rho = 2 \times 10^{12} \) g/cm\(^3\) and neutrino energy \( E_\nu = 4 \) MeV, while the right panel corresponds to the same density and neutrino energy \( E_\nu = 100 \) MeV. It is seen that at the matter density \( \rho = 2 \times 10^{12} \) g/cm\(^3\) the sharp enhancement of the relative yields of various flavours of sterile neutrinos occurs at \( \eta = 2 \), while the yields of active \( \mu \)- and \( \tau \)-neutrino only hardly change at variation of \( \eta \). Note that the latter is connected with the chosen structure of parameters of a generalized mixing matrix.

The resonance curves presented in Fig. 4 were obtained at the numerical calculations on the spatial scale \( \Delta r = 100 \) m corresponding approximately to the scale of the range of excess neutronization (closely to two) in the collapsing star (see Fig. 1), and also it corresponds to the scale of the order of the neutrino mean free path in such dense medium. By these results, it is possible to determine the relation between the width of the resonance curves over neutronization degree \( \eta \) and the range of the resonant enhancement of the sterile neutrino yield in the star.

Let us to consider a question about the width of the resonant enhancement zone of the neutrino oscillations in the star. In accordance with the calculations given above, it corresponds to a narrow zone with \( \eta \approx 2 \). The equilibrium equation in the star can be written as follows

\[
\frac{1}{\rho} \frac{dP}{dr} = -\frac{Gm}{r^2}.
\]  

(12)

where \( \rho \) and \( P \) are the density and the pressure in the star, and \( m \) and \( r \) are the mass and radial coordinates, respectively. For the pressure gradient, taking into account approximate constancy of entropy in internal areas of a star, we will obtain

\[
\frac{dP}{dr} = \frac{dP}{d\rho} \frac{d\rho}{dr} \approx \gamma \frac{P}{\rho} \frac{d\rho}{dr}.
\]  

(13)

where

\[
\gamma = \left( \frac{\partial \ln P}{\partial \ln \rho} \right)_{\text{g}}
\]  

(14)

is the medium adiabatic index. Then passing to the finite differences we obtain that

\[
\Delta r \approx \gamma \frac{P}{\rho^2} \frac{\gamma^2}{Gm} \Delta \rho = \gamma \frac{P}{\rho Gm} \frac{\gamma^2}{\Delta \rho \frac{d\rho}{dr}} [\frac{\Delta \eta}{\rho \frac{d\rho}{dr}}].
\]  

(15)

The quantity before the square brackets in equation (15) can be roughly estimated from the calculations of gravitational collapse and the equations of state of supernova matter (see, for example, Nadyozhin and Yudin 2004) by the characteristic value of \( 5 \times 10^5 \) cm. The value of derivative of neutronization degree \( \eta \) at the density \( \rho = 2 \times 10^{12} \) g/cm\(^3\) can be found from Fig. 3 \( \rho \frac{d\rho}{dr} \approx 0.22 \). Hence, the width of the resonance zone over \( r \) in a star is

\[
\Delta r \approx 2 \times 10^6 \Delta \eta \text{[cm]},
\]  

(16)

where \( \Delta \eta \) is the resonance width over the neutronization degree, which can be determined, for example, from Fig. 4. By virtue of narrowness of the resonance zone and huge magnitude of the effect (by many orders), concrete value of the width over \( \eta \) depends on its definition. We consider, for example, the case of the neutrino energy \( E_\nu = 100 \) MeV (the right panel of Fig. 4). Let us to determine the resonance width of the zone, in which the sterile \( x \)-neutrino yield falls on seven orders of magnitude from its maximum value (\( \approx 10^{-3} \)), reaching the values of the order of \( 10^{-16} \) (after that it also falls on seven orders
of magnitude, reaching the smallest values of the order of $10^{-17}$ on the ends of the inspected $\eta$-range, at $\eta = 1$ or $\eta = 3$). In this case we obtain $\Delta \eta \approx 0.003$ that corresponds to $\Delta r \approx 60$ m. All the above with the same result is applicable also to the left panel of Fig. 4 i.e. for neutrino energy $E_\nu = 4$ MeV. The estimate obtained shows the self-consistency of the carried out calculations of new neutrino resonances for sterile neutrinos in superdense medium of neutron stars.

CONCLUSION

In this paper, the effect of resonant enhancement of the sterile neutrinos yield at matter neutronization degree $\eta = 2$, which poorly depends on the neutrino energy at $E_\nu$ more than 10 eV, is presented. This effect can have a considerable impact on dynamics of gravitational collapse of a supernova star and subsequent expulsion of its envelope, that is supposed to investigate in further calculations.

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