ISSN 1561-2430 (Print)
ISSN 2524-2415 (Online)
UDC 539.12
https://doi.org/10.29235/1561-2430-2023-59-2-147-157

Received 28.02.2023
Поступила в редакцию 28.02.2023

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PREDICTION OF SOLAR FLARES USING NEUTRINO DETECTORS OF THE SECOND GENERATION

Abstract. In this paper, we propose a physics-based method of prediction high-energy solar flares (SFs) with the help of neutrino detectors utilizing coherent elastic neutrino-nucleus scattering (CEvNS). The behavior of neutrino beams passing through coupled sunspots (CSs) being the sources of future SFs is investigated. We consider the evolution of left-handed electron neutrino ν_{eL} and muon neutrino $\nu_{\mu L}$ beams formed in the convective zone after the passage of the Micheev – Smirnov – Wolfenstein resonance. It is assumed that the neutrinos possess the charge radius, the magnetic and anapole moments while the CS magnetic field is vortex, nonhomogeneous and has twisting. Estimations of the weakening of the neutrino beams after traversing the resonant layers are given. It is shown that for SFs this weakening could be registered by neutrino detectors of the second generation only when neutrinos have the Dirac nature.

Keywords: solar flares, prediction of flares, neutrino oscillations, magnetic moment, anapole moments, charge neutrino radius, neutrino detectors, coherent elastic neutrino-nucleus scattering

For citation. Boyarkin O. M., Boyarkina I. O. Prediction of solar flares using neutrino detectors of the second generation. *Vestsi Natsyyanal'nai akademii navuk Belarusi. Seryya fizika-matematychnykh navuk = Proceedings of the National Academy of Sciences of Belarus. Physics and Mathematics series*, 2023, vol. 59, no. 2, pp. 147–157. https://doi.org/10.29235/1561-2430-2023-59-2-147-157

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ПРЕДСКАЗАНИЕ СОЛНЕЧНЫХ ВСПЫШЕК С ПОМОЩЬЮ НЕЙТРИННЫХ ДЕТЕКТОРОВ ВТОРОГО ПОКОЛЕНИЯ

Аннотация. Предлагается физически обоснованный метод прогнозирования суперсолнечных вспышек с помощью нейтринных детекторов, работа которых основана на использовании когерентного упругого рассеяния нейтрино на ядрах. Исследуется поведение нейтринных пучков, проходящих через спаренные солнечные пятна, которые являются источниками будущих солнечных вспышек. Рассматривается эволюция пучка левосторонних электронных нейтрино и пучка левосторонних мюонных нейтрино, которые образовались в конвективной зоне после прохождения резонанса Михеева – Смирнова – Вольфенштейна. Предполагается, что нейтрино обладает такими мультипольными моментами, как зарядовый радиус, магнитный и анапольный моменты, в то время как магнитное поле спаренных солнечных пятен является вихревым, неоднородным и обладает скручиванием. Даются оценки ослабления нейтринных пучков после прохождения резонансных переходов. Показывается, что в случае суперсолнечных вспышек эти ослабления могут быть зарегистрированы нейтринными детекторами второго поколения только тогда, когда нейтрино имеет дираковскую природу.

Ключевые слова: солнечные вспышки, предсказания вспышек, нейтринные осцилляции, магнитный момент, анапольный момент, радиус заряда, нейтринные детекторы, упругое когерентное рассеяние нейтрино на ядрах

Для цитирования. Бояркин, О. М. Предсказание солнечных вспышек с помощью нейтринных детекторов второго поколения / О. М. Бояркин, И. О. Бояркина // Вес. Нац. акад. навук Беларусі. Сер. фіз.-мат. навук. – 2023. – Т. 59, № 2. – С. 147–157. https://doi.org/10.29235/1561-2430-2023-59-2-147-157

Introduction. Solar flares (SFs) are the most striking explosive form of solar activity. They take place in the solar atmosphere and release a wealth of energy, which could be as large as 10^{28}–10^{33} erg. Moreover, super SFs with an energy of 10^{36} erg and more are also possible in the solar conditions [1]. SFs are often (but not always) followed by coronal mass ejections, which represent eruptions of the solar coronal plasma into the interplanetary space. It is clear that high-energy SFs are very destructive when they are focussed on the Earth as it was in 1859 (the Carrington event [2]). It might be worth pointing out that flares may also occur in other Sun-like stars. Flares on these stars are also dangerous for crew members of interplanetary spaceships. Therefore, for our ever more technologically dependent society prediction of SFs is of great practical importance.

It is generally accepted that the magnetic field is the basic energy source of the SF [3, 4]. During the periods of high solar activity, the magnetic flux ~10^{24} G·cm^2 [5] is erupted from the solar center and stored on the sunspots. In so doing, big sunspots of opposite polarity could be paired forming so-called coupled sunspots (CSs). Then the accumulation of the magnetic energy starts. The more energetic the SF, the more will be the magnetic field strength of the CS. For example, in the case of super SFs B_{cs} may reach the values of 10^8 G and more. The length of the initial SF stage is extended from several to dozens of hours. Obviously, the successful SF prediction should be based on the analysis of the phenomena occurring in the CS region at the initial stage of the SF. Previous studies of forecasting the SF were carried out with the help of γ-telescopes which observe the Sun collecting particle measurements related to SFs. Further, this huge amount of observations is transferred, stored, and handled. To deal with this data, a new method of Machine Learning (ML) was created. The ML method uses such models as support vector machines [6], neural networks [7], a regression model [8], extremely randomized trees [9], and so on. It is proposed to use in the solar orbit satellites with the built-in ML capability that continuously monitors the Sun. This observatory uses the ML to calculate the probability of solar explosions from the remote sensing data. Currently the following space-borne instruments are used: Solar and Heliospheric Observatory, Solar Dynamics Observatory, Advanced Composition Explorer, Atmospheric Imaging Assembly, Large Angle Spectroscopic Coronagraph on the Solar and Heliospheric Observatory. The ML can clarify which feature is the most effective for the prediction of SFs. However, to date, it is not known which of the models used in the ML is the best.

Among the physics-based models that are used for forecasting the SF, the so-called kappa scheme proposed by a team of Japanese physicists [10] should be noted. Their model forecasts high energy SFs through a critical condition of magnetohydrodynamic instability, triggered by magnetic reconnection. The group tested the method using observations of the Sun from 2008 to 2019. In most cases, the method correctly identifies which regions will produce a high-energy SF within the next 20 hours, The method also provides the exact location where each SF will begin and limits on how powerful it will be.

The Sun is not the source of only electromagnetic radiation, it also emits a huge stream of electron neutrinos ($N_{\nu_{eL}} \simeq 6\cdot10^{10}\,\text{cm}^{-2}\text{s}^{-1}$). It is obvious that with the help of sensitive neutrino detectors it will be possible to obtain information about events occurring in the CS region. It could be done with detectors of the second generation whose work is based on coherent elastic neutrino-atomic nucleus scattering (CEνNS). This type of low-energy (anti)neutrino interaction was predicted in 1974 [11, 12] and it was discovered not long ago by COHERENT Collaboration [13]. It was shown that neutrinos and antineutrinos of all types can interact by exchanging the Z-boson with the atomic nucleus as a whole, i.e. coherently. This takes place with the neutrino energy being less than 50 MeV when the De Broglie wavelength increases to a value of the order of the nucleus charge radius $R = 1.12 \cdot (A)^{1/3}10^{-13}$ cm (here A is the number of nucleons). The cross section of the CEνNS is described by the formula

$$\sigma \simeq \text{few}\cdot10^{-45}N^2(E_\nu)^2\ \text{cm}^2,$$

where N is the number of neutrons, E_ν is the neutrino energy in MeV. Thanks to the N^2 factor, the cross section of this process is large, it is more than two orders of magnitude (for heavy nuclei) larger than the cross section of the other known processes describing the interactions of low-energy neutrinos. To satisfy the demands for a coherently enhanced interaction, neutrinos need to be have energies in the MeV-regime. As of now, the two favored neutrino sources are nuclear reactors (Connie, Conus, Ncc-1701) and π DAR sources (Coherent, Ccm, Ess). These neutrino sources taken together allow us to investigate different aspects of CEνNS at various energies and neutrino flavors.

Detectors based on the employment of CEνNS are already being used for monitoring the operation of a nuclear reactor in the on-line regime. Examples are found in the Russian Emission Detector-100 (RED-100) at a Kalininskaya nuclear power plant [14]. Installed at a distance of 19 meters from a nuclear reactor, where the reactor antineutrino flux reaches a value of $1.35 \cdot 10^{13}$ cm^{-2} c^{-1}, RED-100 should record 3300 antineutrino events per day. Moreover, in the future, it is planned to scale the detector by a factor of 10 to the mass of the sensitive volume of the order of 1 ton (RED-1000) [15]. This will make it possible to register 33,000 events per day. Therefore, for example, when RED-1000 is used for detection of solar *pp*-neutrinos, then it could detect about 2000 neutrino events per day.

The aim of our work is to investigate the possibility of prediction of high energy SF with the help of neutrino detectors utilizing CEνNS. The work represents a continuation of papers [16–18] in which the correlation between the SF and the behavior of the electron neutrino beam in the CS magnetic field during the initial stage of the SF was discussed. In contrast to the previous works, we now take into account all the neutrino multipole moments and carry out the analysis for Dirac and Majorana neutrinos. In the next Section constraining by two flavor approximation we obtain the evolution equation and find all the resonance conversions of both electron neutrinos and muon neutrinos that emerged from the MSW resonance in the convective zone of the Sun. Further we give estimations of the weakening of the neutrino beam after traversing the resonant layers and demonstrate that this quantity could be observed by the neutrino detector of the second generation. Finally, in Section 3, some conclusions are represented.

Neutrino behavior in solar matter. In the standard model (SM) the neutrino magnetic moment is determined by the expression

$$\mu_\nu = 10^{-19}\mu_B\left(\frac{m_\nu}{eV}\right). \tag{1}$$

It clear that such a small value cannot bring to any observable effects in real magnetic fields. Hence, if we use the values of neutrino MMs being close to the upper experimental limits $(10^{-10}–10^{-11})\mu_B$, then we should go beyond the SM. As an example of such a SM extension we may employ the left-right symmetric model which is based on the $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ gauge group [19–21].

In the one-photon approximation, the effective interaction Hamiltonian satisfying the demands both of the Lorentz and of the electromagnetic gauge invariance is determined by the following expression [22, 23]

$$H_{em}^{(\nu)}(x) = \sum_{i,f}\overline{\nu}_i(x)\Big\{i\sigma_{\mu\lambda}q^\lambda\left[F_M^{if}(q^2) + iF_E^{if}(q^2)\gamma_5\right] + \left(\gamma_\mu - q_\mu q^\lambda\gamma_\lambda/q^2\right)\times$$
$$\times\left[F_Q^{if}(q^2) + F_A^{if}(q^2)q^2\gamma_5\right]\Big\}\nu_f(x)A^\mu(x), \tag{2}$$

where $q_\mu = p'_\mu - p_\mu$ is the transferred 4-momentum, while $F_Q^{if}, F_M^{if}, F_E^{if}$, and F_A^{if} are the charge, dipole magnetic, dipole electric, and anapole neutrino form factors. The form-factors with $i = f\,(i \neq f)$ are named "diagonal" ("off-diagonal" or "transition") ones. In the static limit ($q^2 = 0$), $F_M^{if}(q^2)$, $F_E^{if}(q^2)$ and $F_A^{if}(q^2)$ determine the dipole magnetic, dipole electric and anapole moments, respectively. Note, the second term in the expansion of the $F_Q^{if}(q^2)$ in a series of powers of q^2 determines the neutrino charge radius

$$< r_{if}^2 >= 6\frac{dF_Q^{if}(q^2)}{dq^2}|_{q^2=0}. \tag{3}$$

We shall be interested in the magnetic moments (MM), the anapole moments (AM) and the neutrino charge radii (NCR).

The exhibiting of neutrino MMs are being searched in reactors (MUNU, TEXONO and GEMMA), accelerators (LSND), and solar (Super-Kamiokande and Borexino) experiments. The current best sensitivity limits on diagonal MMs gotten in laboratory experiments are as follows [24, 25]

$$\mu_{ee}^{\exp} \le 2.9\cdot 10^{-11}\mu_B, \qquad 90\ \%\ \text{C.L.} \quad [\text{GEMMA}],$$
$$\mu_{\mu\mu}^{\exp} \le 6.8\cdot 10^{-10}\mu_B, \qquad 90\ \%\ \text{C.L.} \quad [\text{LSND}].$$

For the τ-neutrino, the limits on $\mu_{\tau\tau}$ are less limitative (see, for example, [26]), and the current upper bound on that is $3.9\cdot 10^{-7}\ \mu_B$.

The limits on NCRs could be received from studying the elastic neutrino-electron scattering. For example, investigation of this process in the TEXONO experiment results in the following bounds on the NCR [27]

$$-2.1\cdot 10^{-32}\ \text{cm}^2 \le \left(< r_{\nu_e}^2 >\right) \le 3.3\cdot 10^{-32}\ \text{cm}^2. \tag{4}$$

The AM of the 1/2-spin Dirac particle was introduced in paper [28] for a *T*-invariant interaction which violates *P*-parity and *C*-parity, individually. Later in order to describe this kind of interaction a more general characteristic, the toroid dipole moment (TM) [29], was entered. It was shown that the TM is a general case of the AM and at the mass-shell of the viewed particle both moments coincide. The neutrino toroid interaction is manifested in the scattering of neutrinos with charged particles. In so doing, the interaction saves the neutrino helicity and gives an extra contribution, as part of radiative corrections. In this regard, the AM is similar to the NCR. Both quantities preserve the helicity in coherent neutrino collisions, but have a different nature. They define the axial-vector (AM) and the vector (NCR) contact interactions with an external electromagnetic field, respectively. From the viewpoint of determining the NCR and the AM low-energy scattering processes are of special interest (see, for example, Refs. [30, 31]). Both neutrino interactions may have very interesting consequences in different media. The possible role of the AM in studying neutrino oscillations was first specified in Ref. [32]. A point that should be also mentioned is Ref. [33] in which the existence of the AM led to changing the flux of the solar electron neutrino during the initial stage of the SF. Since the phenomenology of the AM is analogous to that of the NCR, the linkage between these quantities must exist. In the SM for a zero-mass neutrino, the value of the AM a_ν is connected with the NCR through a simple relation (see, for example, [34])

$$a'_\nu = \frac{1}{6} < r_\nu^2 > \tag{5}$$

(the dimensionality of the AM in the CGS system is “length^2 × charge”, that is to say, $a_\nu = ea'_\nu$ [28]). However, in the SM with massive neutrinos and in the case of SM extensions this relationship is violated [35].

As for CS magnetic fields, we shall assume that they are nonhomogeneous, vortex and have the geometrical phase $\Phi(z)$ (twisting)

$$B_x \pm iB_y = B_\perp e^{\pm i\Phi(z)}, \tag{6}$$

where $\Phi(z) = \arctan(B_y / B_x)$. We notice that both for the Sun and for Sun-like stars the reason of twisting is differential rotation rates of their components and the global convection of the plasma fluid. It should be recorded that configurations of the solar magnetic field implying a twisting nature have already been discussed in the astrophysical literature for a long time (see, for example [36]). In Ref. [37] the phase Φ was introduced for the solar neutrino description for the first time. Subsequently, in Ref. [38] an account of this phase was demonstrated. It should be remarked that works [39–41] were devoted to the effects on the neutrino behavior in twisting magnetic fields. For example, in Ref. [41] a neutrino beam traveling in the twisting magnetic field of the solar convective zone was considered and some new effects (change in the energy level scheme, change in the resonance location, emergence of new resonances, merger of resonances and so on) were predicted. Assuming that the magnitude of the twist frequency $\dot{\Phi}$ is determined by the curvature radius r_0 of the magnetic field lines, $\dot{\Phi} \sim 1/r_0$, while r_0 has the order of 10 % of the solar radius, the authors came to the following conclusion. To ensure that these new effects will be observed, the value of $\dot{\Phi}$ in the convective zone should have the order of 10^{-15} eV.

Inasmuch as we take into account the interaction of neutrinos with the electromagnetic field, the neutrino system under study must contain both left-handed and right-handed neutrinos. By virtue of the fact that right-handed Majorana neutrinos are not sterile and interact as right-handed Dirac antineutrinos, we shall denote them as $\overline{\nu}_{lR}$. In order to stress the sterility of right-handed Dirac neutrinos we shall use for them the notation ν_{lR}. So, in the two-flavor approximation the Majorana neutrino system will be described by the function $(\psi^M)^T = (\nu_{eL}, \nu_{\kappa L}, \overline{\nu}_{eR}, \overline{\nu}_{\kappa R})$ while for the Dirac neutrinos we shall deal with the function $(\psi^D)^T = (\nu_{eL}, \nu_{\kappa L}, \nu_{eR}, \nu_{\kappa R})$. In what follows to be specific, we shall reason $\kappa = \mu$.

To facilitate the evolution equation for the solar neutrinos we transfer to the reference frame (RF) which rotates with the same angular velocity as the transverse magnetic field. The matrix of the transition to the new RF has the view

$$S=\begin{pmatrix} e^{i\Phi/2} & 0 & 0 & 0 \\ 0 & e^{i\Phi/2} & 0 & 0 \\ 0 & 0 & e^{-i\Phi/2} & 0 \\ 0 & 0 & 0 & e^{-i\Phi/2} \end{pmatrix}. \tag{7}$$

In this RF the evolution equation for the Dirac neutrinos is given by the expression

$$\frac{d}{dz}\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{eR} \\ \nu_{\mu R} \end{pmatrix}=\left(H_0^D+H_{\text{int}}^D\right)\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{eR} \\ \nu_{\mu R} \end{pmatrix}, \tag{8}$$

where

$$V'_{eL}=V_{eL}+V_{ee}^{\tilde{\delta}}, \qquad V_{eL}=\sqrt{2}G_F(n_e-n_n/2), \qquad V_{\mu L}=-\sqrt{2}G_F n_n/2,$$

$$\Delta^{12}=\frac{\Delta m^2}{4E}=\frac{m_1^2-m_2^2}{4E}, \qquad A_{ll'}^{DL}=\left\{e\frac{<r^2_{\nu_{lL}\nu_{l'L}}>}{6}+a_{\nu_{lL}\nu_{l'L}}\right\}[\text{rot}H(z)]_z,$$

$$\cos 2\theta=c_{2\theta}, \qquad \sin 2\theta=s_{2\theta}, \qquad m_1=m_{\nu_e}\cos\theta-m_{\nu_\mu}\sin\theta, \qquad m_2=-m_{\nu_e}\sin\theta+m_{\nu_\mu}\cos\theta,$$

V_{eL} ($V_{\mu L}$) is the matter potential caused by the interaction of the ν_{eL} ($\nu_{\mu L}$) neutrinos with the gauge bosons W^- and Z, $V_{ee}^{\tilde{\delta}}$ is the contribution to the matter potential produced by the singly charged Higgs boson $\tilde{\delta}^-$, θ is the neutrino mixing angle in a vacuum, m_1 and m_2 are the mass eigenstates, $\dot{\Phi}$ is the twisting frequency, n_n (n_e) is the neutron (electron) density, and the free Hamiltonian

$$H_0^D=\begin{pmatrix} -\Delta^{12}c_{2\theta} & \Delta^{12}s_{2\theta} & 0 & 0 \\ \Delta^{12}s_{2\theta} & \Delta^{12}c_{2\theta} & 0 & 0 \\ 0 & 0 & -\Delta^{12}c_{2\theta} & \Delta^{12}s_{2\theta} \\ 0 & 0 & \Delta^{12}s_{2\theta} & \Delta^{12}c_{2\theta} \end{pmatrix} \tag{9}$$

describes oscillations in a vacuum, while the interaction Hamiltonian

$$H_{\text{int}}^D=\begin{pmatrix} V_{eL}+A_{ee}^{DL}-\dot{\Phi}/2 & A_{e\mu}^{DL} & \mu_{ee}B_\perp & \mu_{e\mu}B_\perp \\ A_{\mu e}^{DL} & V_{\mu L}+A_{\mu\mu}^{DL}-\dot{\Phi}/2 & \mu_{e\mu}B_\perp & \mu_{\mu\mu}B_\perp \\ \mu_{ee}B_\perp & \mu_{e\mu}B_\perp & \dot{\Phi}/2 & 0 \\ \mu_{e\mu}B_\perp & \mu_{\mu\mu}B_\perp & 0 & \dot{\Phi}/2 \end{pmatrix} \tag{10}$$

covers the interaction with the medium. When writing H_{int}^D we take into consideration that the toroid interaction does not equal to zero in the external inhomogeneous vortex magnetic field. In a concrete experimental situation this field may be realized according to Maxwell's equations as the displacement and conduction currents. The universally adopted model of the SF is the magnetic reconnection model [4]. Owing to it, a variable electric field induced by variation of the CS magnetic field appears at the SF initial phase. This field causes the conduction current which takes on the appearance of a current layer aimed at the limiting strength line which is common for both CSs. So, in this case the neutrinos are influenced by both the displacement current and the conduction current.

For the Majorana neutrino case the evolution equation will look like the following

$$i\frac{d}{dz}\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \overline{\nu}_{eR} \\ \overline{\nu}_{\mu R} \end{pmatrix}=\left(H_0^M+H_{\text{int}}^M\right)\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \overline{\nu}_{eR} \\ \overline{\nu}_{\mu R} \end{pmatrix}, \tag{11}$$

where

$$H_0^M = H_0^D,$$

$$H_{\text{int}}^M = \begin{pmatrix} V'_{eL} + A_{ee}^L - \dot{\Phi}/2 & A_{e\mu}^L & 0 & \mu_{e\mu} B_\perp \\ A_{\mu e}^L & V_{\mu L} + A_{\mu\mu}^L - \dot{\Phi}/2 & -\mu_{e\mu} B_\perp & 0 \\ 0 & -\mu_{e\mu} B_\perp & -V'_{eL} + A_{ee}^R + \dot{\Phi}/2 & A_{e\mu}^R \\ \mu_{e\mu} B_\perp & 0 & A_{\mu e}^R & -V_{\mu L} + A_{\mu\mu}^R + \dot{\Phi}/2 \end{pmatrix}, \qquad (12)$$

$$A_{ll'}^L = \left\{ e[1-\delta_{ll'}] \frac{< r^2_{\nu_{lL}\nu_{l'L}} >}{6} + a_{\nu_{lL}\nu_{l'L}} \right\} [\text{rot}\, H(z)]_z,$$

$$A_{ll'}^R = \left\{ e[1-\delta_{ll'}] \frac{< r^2_{\nu_{lR}\bar{\nu}_{l'R}} >}{6} - a_{\bar{\nu}_{lR}\bar{\nu}_{l'R}} \right\} [\text{rot}\, H(z)]_z.$$

In order to find the exact expressions for the resonance conversion probabilities we should specify the coordinate dependence of the quantities n_e, n_n, $B_\perp$, $\dot{\Phi}$ and solve the evolution equation. Then, with the help of the found functions $\nu_l(z)$, we could determine all resonance conversion probabilities. Of course we shall be dealing with a numerical solution and, as a result, the physical meaning will be far from transparent. Moreover, in the most general case some of the resonance transitions may be forbidden. Therefore, first we must establish which of these transitions are allowed and which of them are forbidden. Remember that for the resonance transition to occur, the following requirements must be met: (i) the resonance condition must be carried out; (ii) the width of the resonance transition must be nonzero; (iii) the neutrinos must pass a distance comparable with the oscillation length.

So, we shall follow the generally accepted scheme (see, for example, [41]), namely, we shall believe that all resonance regions are well separated, which allows us to put these resonances independent. As far as the twisting is concerned, amongst the existing twisting models we choose the simple model

$$\Phi(z) = \frac{\alpha}{L_{mf}} z, \qquad (13)$$

where α is a constant and L_{mf} is the distance on which the magnetic field exists.

We begin with the resonant transitions of the ν_{eL} neutrinos in the Dirac neutrino case. Here the ν_{eL} may experience three resonance transitions. The first one is the $\nu_{eL} \to \nu_{\mu L}$ (Micheev – Smirnov – Wolfenstein – MSW) resonance transition. The requirement of the resonance existence, the width of the transition and the oscillation length are given by the expressions

$$\Sigma_{\nu_{eL}\nu_{\mu L}} = -2\Delta^{12} c_{2\theta} + V'_{eL} - V_{\mu L} + A_{ee}^{DL} - A_{\mu\mu}^{DL} = 0, \qquad (14)$$

$$\Gamma_{\nu_{eL}\nu_{\mu L}} \simeq \frac{\sqrt{2}\left(\Delta^{12} s_{2\theta} + A_{e\mu}^{DL}\right)}{G_F}, \qquad (15)$$

$$L_{\nu_{eL}\nu_{\mu L}} = \frac{2\pi}{\sqrt{\Sigma^2_{\nu_{eL}\nu_{\mu L}} + \left(\Delta^{12} s_{2\theta} + A_{e\mu}^{DL}\right)^2}}. \qquad (16)$$

From Eqs. (14) and (15) it follows that the oscillation length reaches its maximum value at the resonance

$$(\Gamma_{\nu_{eL}\nu_{\mu L}})_{\max} = \frac{2\sqrt{2}\pi}{G_F [L_{\nu_{eL}\nu_{\mu L}}]_{\max}}. \qquad (17)$$

By virtue of the fact that $(\Gamma_{\nu_{eL}\nu_{\mu L}})_{\max} \simeq 3.5 \cdot 10^7$ cm, this resonance transition is realized before the convective zone. Therefore, it is unrelated to the SFs which occur in the solar atmosphere. That, in turn, means that under the MSW resonance the quantities A_{ee}^{DL}, $A_{\mu\mu}^{DL}$ and $A_{e\mu}^{DL}$ play no part. Estimation of the transition probability at the MSW resonance could be fulfilled with the help of the Landau – Zener formulae which in the case of the linear dependence of density on distance is given by the expression

$$P_{LZ} = \exp\left\{\frac{-\pi\Delta m^2 \sin^2 2\theta}{4E\cos 2\theta \,|\, d(\ln n_e)/dr \,|_{\text{res}}}\right\}.$$

Then using P_{LZ} it can be shown that the neutrino flux passing through the region of this resonance must be reduced by about a factor of two, as it was verified by the experiments.

Further we cross to treating the resonances of the ν_{eL} neutrinos traversing the CS magnetic field. In that case the ν_{eL} neutrinos may experience the following resonance transitions

$$\nu_{eL} \to \nu_{eR}, \qquad \nu_{eL} \to \nu_{\mu R}.$$

The quantities characterizing the $\nu_{eL} \to \nu_{eR}$ resonance transition are the following

$$\Sigma_{\nu_{eL}\nu_{eR}}^{D} = V_{eL} + A_{ee}^{DL} - \dot{\Phi} = 0, \tag{18}$$

$$(L_{\nu_{eL}\nu_{eR}})_{\max} \simeq \frac{2\pi}{\mu_{ee} B_{\perp}}. \tag{19}$$

The case when the term A_{ee}^{DL} is negligible compared to $\dot{\Phi}$ and the resonance condition amounts to

$$V_{eL} \simeq \dot{\Phi}, \tag{20}$$

is unreal. Genuinely, in order for Eq. (18) to be satisfied, it is necessary that the twisting magnetic field exists at a distance greater than the solar radius. On the other hand, the currents producing the inhomogeneous vortex magnetic field could reach the value of 10^{-1} A/cm^2. Then, for the CSs the quantity $(a_{\nu_{eL}\nu_{eL}})[\text{rot } H(z)]_z$ will have the order of 10^{-30} eV and being negative it could compensate the term of V_{eL} in Eq. (18). In doing so, the $\nu_{eL} \to \nu_{eR}$ resonance may take place only in the corona.

We are coming now to the $\nu_{eL} \to \nu_{\mu R}$ resonance. The pertinent expressions for this resonance will look like

$$\Sigma_{\nu_{eL}\nu_{\mu R}}^{D} = -2\Delta^{12} c_{2\theta} + V_{eL} + A_{ee}^{DL} - \dot{\Phi} = 0, \tag{21}$$

$$(L_{\nu_{eL}\nu_{\mu R}})_{\max} \simeq \frac{2\pi}{\mu_{e\mu} B_{\perp}}. \tag{22}$$

In the solar atmosphere, the term V_{eL} in Eq. (21) is much less than $\Delta^{12} c_{2\theta}$ and plays no role. Analogously the quantity $(a_{\nu_{eL}\nu_{eL}})[\text{rot } H(z)]_z$ appears to be also small compared with $\Delta^{12} c_{2\theta}$. Hence, the $\nu_{eL} \to \nu_{\mu R}$ resonance may take place only owing to the twisting, that is, when the relation

$$\Sigma_{\nu_{eL}\nu_{\mu R}} = 2\Delta^{12} c_{2\theta} + \dot{\Phi} \simeq 0 \tag{23}$$

is realized.

Let us determine the values of the parameter α which provide the fulfilment of Eq. (23) for different solar neutrinos. Assuming $\mu_{e\mu} = \mu_{ee}$, $B_{\perp} = 10^5$ G and using for μ_{ee} its upper limit $2.9 \cdot 10^{-11}\ \mu_B$ we obtain

$$-\alpha = \begin{cases} 10^4, & \text{for } E_\nu = 0.1 \text{ MeV } (pp\text{-neutrinos}), \\ 10^2, & \text{for } E_\nu = 10 \text{ MeV } (^8B\text{-neutrinos}). \end{cases} \tag{24}$$

If the CS magnetic field increases to the value of 10^8 G (as it may be for the super flare case [1]), the above mentioned values of $|\alpha|$ are decreased by a factor of 10^3. Thus it becomes obvious that under certain conditions the $\nu_{eL} \to \nu_{\mu R}$ resonance transition may be observed. The resonance condition (23) does not contain n_e and n_n and, as a consequence, the $\nu_{eL} \to \nu_{\mu R}$ resonance may occur both in the corona and in the chromosphere.

Now we introduce the quantity which characterizes the weakening of the electron neutrino beam after traversing the resonant layer

$$\eta_{\nu_{eL}\nu_{\mu R}} = \frac{N_i - N_f}{N_i},$$

where N_i and N_f are the numbers of the ν_{eL} neutrinos before and after the passage of the $\nu_{eL} \to \nu_{\mu R}$ resonance, respectively. Again, to find the exact value of $\eta_{\nu_{eL}\nu_{\mu R}}$ we should concretize the dependence on distance of the quantities n_e, n_n, $B_\perp$ and solve Eq. (8). However, to roughly estimate this quantity, it will suffice to compare the resonance widths $\Gamma_{\nu_{eL}\nu_{\mu L}}$ and $\Gamma_{\nu_{eL}\nu_{\mu R}}$, while taking into account the value of $\eta_{\nu_{eL}\nu_{\mu L}}$. Calculations result in

$$\eta_{\nu_{eL}\nu_{\mu R}} \simeq \begin{cases} 2\cdot 10^{-4}, & \text{if } \mu_{e\mu} = (\mu_{ee})_{\text{upper}} = 2.9\cdot 10^{-11}\mu_B, \quad B_\perp = 10^5 \text{ G}, \\ 0.12, & \text{if } \mu_{e\mu} = (\mu_{\mu\mu})_{\text{upper}} = 6.8\cdot 10^{-10}\mu_B, \quad B_\perp = 10^7 \text{ G}. \end{cases} \tag{25}$$

It should be noted that all the magnetic-induced resonances have the resonance widths which are completely determined by the quantity $\mu_{\nu_l \nu_{l'}} B_\perp$. So, the foregoing estimations remain valid for such resonance conversions. Then it becomes evident that the second generation detectors utilizing the CEνNS could display the weakening of the ν_{eL} beam already at $B_\perp \geq 10^7$ G.

Let us assume that the ν_{eL} beam passes through the MSW resonance before entering the CS magnetic field. To put it another way, we shall deal with the beam which has been weakened at the cost of the $\nu_{eL} \to \nu_{\mu L}$ resonance. Therefore, the oscillations picture will be incomplete, if we do not take into consideration the oscillation transitions of the $\nu_{\mu L}$ neutrinos produced due to the MSW resonance. In the CS magnetic field these neutrinos may experience $\nu_{\mu L} \to \nu_{eR}$ and $\nu_{\mu L} \to \nu_{\mu R}$ resonance conversions. The corresponding resonance conditions will look like as follows

$$\Sigma^D_{\nu_{\mu L}\nu_{eR}} = 2\Delta^{12} c_{2\theta} + V_{\mu L} + A^{DL}_{\mu\mu} - \dot{\Phi} = 0, \tag{26}$$

$$\Sigma^D_{\nu_{\mu L}\nu_{\mu R}} = V_{\mu L} + A^{DL}_{\mu\mu} - \dot{\Phi} = 0. \tag{27}$$

From Eq. (27) it follows that the $\nu_{\mu L} \to \nu_{\mu R}$ resonance appears to be allowed when

$$\dot{\Phi} < |V_{\mu L}|, |A^{DL}_{\mu\mu}|, \qquad V_{\mu L} + A^{DL}_{\mu\mu} \simeq 0. \tag{28}$$

Note that in the conditions of the $\nu_{\mu L} \to \nu_{eR}$ and $\nu_{eL} \to \nu_{\mu R}$ resonances a large value of $\Delta^{12} c_{2\theta}$ could be compensated only by $\dot{\Phi}$. However, the fulfillment of condition (26) requires that $\dot{\Phi}$ is positive, while condition (21) will be satisfied only if $\dot{\Phi}$ is negative.

So, the survival probabilities of the electron and muon neutrinos are defined by the expressions

$$P_{\nu_{eL}\nu_{eL}} = 1 - (P_{\nu_{eL}\nu_{eR}} + P_{\nu_{eL}\nu_{\mu R}}), \qquad P_{\nu_{\mu L}\nu_{\mu L}} = 1 - (P_{\nu_{\mu L}\nu_{eR}} + P_{\nu_{\mu L}\nu_{\mu R}}), \tag{29}$$

where the contribution of the MSW-resonance was eliminated for the reasons expounded above. From the foregoing expressions it follows that the AM and/or the NCR must be taken into account for the Dirac neutrino case.

In what follows we shall discuss the oscillation picture for the Majorana neutrinos. Here for ν_{eL} we shall deal with the $\nu_{eL} \to \overline{\nu}_{\mu R}$ resonance transition only. The relations being pertinent to this transition are as follows

$$\Sigma_{\nu_{eL}\overline{\nu}_{\mu R}} = -2\Delta^{12} c_{2\theta} + V'_{eL} + V_{\mu L} + A^L_{ee} - A^R_{\mu\mu} - \dot{\Phi} = 0, \tag{30}$$

$$\Gamma_{\nu_{eL}\overline{\nu}_{\mu R}} \simeq \frac{\sqrt{2}(\mu_{e\mu} B_\perp)}{G_F}, \tag{31}$$

$$L_{\nu_{eL}\overline{\nu}_{\mu R}} \simeq \frac{2\pi}{\sqrt{\Sigma^2_{\nu_{eL}\overline{\nu}_{\mu R}} + (\mu_{e\mu} B_\perp)^2}}. \tag{32}$$

In the solar atmosphere, the terms V'_{eL}, $V_{\mu L}$ and $(a_{\nu_{eL}\nu_{eL}} + a_{\bar{\nu}_{\mu R}\bar{\nu}_{\mu R}})[\text{rot } H(z)]_z$ appear to be small compared with $\Delta^{12}c_{2\theta}$. Therefore, the $\nu_{eL} \to \bar{\nu}_{\mu R}$ resonance may take place only as a consequence of the twisting, that is, when the relation

$$\Sigma_{\nu_{eL}\bar{\nu}_{\mu R}} = 2\Delta^{12}c_{2\theta} + \dot{\Phi} = 0 \quad (33)$$

is realized.

We should take into account the resonant transitions of the $\nu_{\mu L}$ neutrinos produced in the MSW resonance. In the CS magnetic field these neutrinos may have the $\nu_{\mu L} \to \bar{\nu}_{eR}$ resonance conversion. The corresponding resonance condition will look like

$$\Sigma_{\nu_{\mu L}\bar{\nu}_{eR}} = 2\Delta^{12}c_{2\theta} - \dot{\Phi} = 0. \quad (34)$$

From comparing of the obtained expression with $\Sigma_{\nu_{eL}\bar{\nu}_{\mu R}}$ it follows that when the $\nu_{eL} \to \bar{\nu}_{\mu R}$ resonance is forbidden then the $\nu_{\mu L} \to \bar{\nu}_{eR}$ resonance is allowed, and vice versa. In that case the survival probabilities for the ν_{eL} and the $\nu_{\mu L}$ beams will be given by the expressions

$$P_{\nu_{eL}\nu_{eL}} = 1 - P_{\nu_{eL}\bar{\nu}_{\mu R}}, \qquad P_{\nu_{\mu L}\nu_{\mu L}} = 1 - P_{\nu_{\mu L}\bar{\nu}_{eR}}. \quad (35)$$

It should be also noted that from the obtained equations it follows that the contributions coming from the AM and the CNR can be safely neglected when the neutrino is the Majorana particle.

Conclusion. It was shown that in the Majorana neutrino case the decreasing of the electron neutrino numbers is caused by the $\nu_{eL} \to \bar{\nu}_{\mu R}$ resonance while decreasing the muon neutrino numbers is connected with the $\nu_{\mu L} \to \bar{\nu}_{eR}$ resonance. Both these resonances may exist only when the CS magnetic field possesses twisting. It should be stressed that under the fulfillment of the $\nu_{eL} \to \bar{\nu}_{\mu R}$ resonance condition the appearance of the $\nu_{\mu L} \to \bar{\nu}_{eR}$ resonance is excluded, and conversely. Also note, that for the Majorana neutrino the AM and the NCF do not exert any influence on the values of the oscillation parameters under the conditions of the Sun. In the Majorana theory right-handed neutrinos $\bar{\nu}_{\mu R}$ and $\bar{\nu}_{eR}$ are physical particles whereas detectors based on CEνNC are flavor-blind (at least with the existing experimental technique). Then, since the total neutrino flux is kept constant after traveling the resonances, the detectors will not feel the change in the flavor composition of the neutrino beam.

In the Dirac neutrino case the oscillation picture is richer. Here we have the following resonances

$$\nu_{eL} \to \nu_{eR}, \qquad \nu_{eL} \to \nu_{\mu R}$$

for electron neutrinos, and

$$\nu_{\mu L} \to \nu_{\mu R}, \qquad \nu_{\mu L} \to \nu_{eR}$$

for muon neutrinos. It should be stressed that in this case the ν_{eR} and $\nu_{\mu R}$ are sterile particles and they cannot be recorded by detectors based on CEνNC. The $\nu_{eL} \to \nu_{\mu R}$ and $\nu_{\mu L} \to \nu_{eR}$ – resonances could be realized only in the magnetic twisting field, while the existence of the $\nu_{eL} \to \nu_{eR}$ and $\nu_{\mu L} \to \nu_{\mu \mathrm{R}}$ – resonances is possible only if either or both the AM and the NCR have the values close to their experimental bounds. For all the magnetic-induced resonances the oscillation width depends on the quantity $\mu_{ll'}B_{\perp}$ which, in its turn, determines the weakening of the neutrino beams passing the CS magnetic field. In this time, one should expect that the decrease of the electron neutrino beam will be less than the decrease of the muon neutrino beam, since the upper bound on $\mu_{\mu\mu}$ is bigger than that on μ_{ee}. Then, for example, using the upper bound on $\mu_{\mu\mu}$ and assuming $B_{\perp} = 10^8\,\mathrm{G}$ we shall get the weakening of the $\nu_{\mu L}$ beam being equal to 1.2. It is obvious that second-generation detectors could observe such a weakening of the neutrino flux. Note that the sensitivity of the measurement could be significantly improved when detectors with different element compositions are employed. Then the systematic errors associated with the inaccuracy in determining the intensity of the neutrino beam are mutually excluded.

So, the detectors based on CEνNC could be utilized for forecasting high-energy SFs only when the neutrino has the Dirac nature. This also allows us to state that the observation of the neutrino beams passing through the magnetic fields of the CSs, which are the sources of the SF, will allow us to determine the neutrino nature.

Flares could occur in Sun-like stars too. In that case high-energy flares exhibit a serious danger to the crew of the spacecraft. Consequently, the problem of forecasting the flare is topical for cosmic flights as well. Obviously those terrestrial neutrino detectors will be of no avail when flying outside the solar system. It is hoped that the problem could find its solution with the help of neutrino detectors similar in design to the RED-100 installed on a spacecraft.

Acknowledgements. The work was partially supported by the Ministry of Education of the Republic of Belarus (grant no. 20211660).

Благодарности. Работа частично поддержана Министерством образования Республики Беларусь (грант № 20211660).

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