Solar neutrinos as indicators of the Sun's activity

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Abstract

Opportunity of the solar flares (SF's) prediction observing the solar neutrino fluxes is investigated. In three neutrino generations the evolution of the neutrino flux traveling the coupled sunspots (CS's) which are the SF source is considered. It is assumed that the neutrinos possess both the dipole magnetic moment and the anapole moment while the magnetic field above the CS's may reach the values $10^5 - 10^6$ Gs, displays the twisting nature and has the nonpotential character. The possible resonance conversions of the solar neutrino flux are examined. Since the $\nu_{eL} \to \nu_{\mu L}$ resonance takes place before the convective zone, its existence can in no way be connected with the SF. However, when the solar neutrino flux moves through the CS's in the preflare period, then it may undergo the additional resonance conversions and, as a result, depleting the electron neutrinos flux may be observed.

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1 Introduction

At certain conditions the evolution of active regions on the Sun may lead to the appearance of solar flares (SF's) that occur in the solar atmosphere and release enormous amounts of energy, over the entire electromagnetic spectrum. The energy generated during the SF

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is about of $10^{28} - 10^{33}$ erg. Moreover, as it was shown in Ref. [1], the super-SF's with energy as large as 10^{36} erg are also possible. This gigantic energy is released on the Sun in a few minutes and corresponds to an average power of few $\times 10^{29}$ erg/s. However, this is less than hundredths portion of a percent of the total solar radiation power in the optical range which is equal to 4×10^{33} erg/s.

The SF's are quite prominent in X-rays, UV, and optical lines and they are often (but not always) followed by eruptions that throw out solar coronal plasma into the interplanetary space (coronal mass ejections - CME's). In relation to their peak X-ray intensity, as recorded by the National Oceanic and Atmospheric Administration's Geostationary Operational Environmental Satellite system, flares are separated into classes, the strongest and most important being X, M and C (in decreasing order). Flare classification is logarithmic, with a base of 10, and is complemented by decimal sub-classes (e.g. M5.0, C3.2 etc.).

It should be noted that flare events also occur in other first-generation stars. Remember, first generation stars consist of only from ingredients provided directly by the big bang, namely, essentially from hydrogen and helium. Therefore, the study of the SF's sheds light on the structure and evolution of the Universe. Our comprehension of the SF's has been greatly enhanced in recent times, both from a theoretical and observational viewpoint [2]. These achievements have been supplemented by a great deal of data from the Kepler mission [3], which surveyed $\sim 10^5$ stars of M-, K-, and G-types and produced detailed statistics concerning the frequency of large flares with energies of order 10^{33} erg.

The high-power SF's can be especially destructive when they are aimed towards the direction of the Earth. They cause problems with power grids, radio blackouts on Earth, mutations in DNA, destruction of ecosystems, breakdowns of different instruments on the satellites and so on.

The strongest observed SF and accompanying CME was the Carrington event that took place in 1859. It was about twice as big as the strongest events observed during the space era. The SF which has occurred at 4 August 1972 led to the triggering of magnetic detonators of American underwater mines in the vietnamese port Hon La. The SF's and their accompanying CME's which have taken place between mid-October to early November 2003 peaking around 28 and 29 October (so called Halloween solar storms) even caused failure to the power supply of the Japanese Earth-resource satellite, the Advanced Earth Observation Satellite-II "Midori II", and made it inoperative, while the effects of the Halloween solar storms extended beyond the Earth to Mars and caused the Mars Odyssey spacecraft to go into deep safe-mode [4].

Therefore, for our increasingly technologically dependent society it is of great practical significance to predict when and how large the SF's will be. Previous studies on predicting solar eruptive phenomena mainly employed measurements of the active region (AR) magnetic field in the solar photosphere to calculate the physical indices of the AR's and connect these indices to the occurrences of the SF's and CME's [5]. These SF prediction is mainly fulfilled by using space-borne instruments such as the Atmospheric Imaging Assembly, the Helioseismic and Magnetic Imager on the Solar Dynamics Observatory, the

Large Angle Spectroscopic Coronagraph on the Solar and Heliospheric Observatory, and Geostationary Operational Environmental Satellite series. However, it does not mean that the ground-based telescopes are no longer useful for the SF's prediction. There are several observational methods from the ground such as a coronagraph, a magnetogram, a continuum light observation, and a H-alpha observation. For example, at Hida Observatory in Kyoto University, there is a powerful instrument observing the Sun in a H-alpha line and its wings called Solar Dynamics Doppler Imager installed on Solar Magnetic Activity Research Telescope [6].

The γ-telescopes observing the Sun continuously collect electromagnetic and particle measurements related to SF's, CMEs and this huge amount of observations must be transferred, stored, and handled. To deal with these large amount of solar observation data, a new method of Big Data Mining, also called Machine Learning (ML) has been developed. The ML method has been using different models, such as support vector machines [7], neural networks [8], a regression model [9], an extremely randomized trees [10] and so on. An introduction to ML research can be found in several textbooks (see, for example, [11]). The ML can clarify which feature is most effective for predicting the SF's. However, it is still not clear which model is the best for prediction in an operational setting.

However, the Sun radiates not only photons by which we could define its state, the Sun is also a powerful source of neutrinos. In the result of thermonuclear fusion reactions in the Sun's core the total electron neutrino flux falling on a terrestrial surface could be as large as $\Phi_\nu \simeq 6 \times 10^{10}$ cm^{-2}s^{-1}. For the first time a correlation of a neutrino flux with the SF's was predicted in Ref's. [12, 13]. Later this hypothesis has received support through experiments which have demonstrated decreasing the β-decay rate of some elements of the periodic table during the SF's [14, 15, 16, 17, 18]. Early result was presented by Jenkins and Fischbach [14] who have detected this decreasing for ^{54}Mn at the level of $\sim 7\sigma$ before the large SF which was at 2006 Dec.13. They have connected this changeability with depletion of the electron neutrino flux passing through the SF region (hypothesis of the ν_e-induced β-decays). In Ref. [19] one was supposed that this depletion may be bound by the neutrino oscillations in the solar matter and solar magnetic field. However, the analysis of that work has been fulfilled within two flavor approximation. It might be well to point out that changing the decay rate has been observed only for $\beta^\pm$ decay and electron capture processes.

Neutrino oscillations in magnetic fields also allows to explain the deficit of high-energetic muon neutrinos arising at long Gamma-ray bursts (GRBs) which are probably connected with the gravitational collapse of very massive stars. A black hole produced during the collapse ejects two relativistic jets whose magnetic fields could reach 10^8 Gs. Besides producing electromagnetic emission the GRBs could also be sources of cosmic rays, neutrinos, and gravitational waves. In so doing the neutrino energy could be as large as 10^{18} eV. There are a lot of works devoted to studying the neutrino production in different scenarios of GRBs. However, the upper limit on the high energy muon neutrino flux obtained from the data collected with the 59-string configuration of IceCube is 3.7

times below existing theoretical predictions. It is not inconceivable that this decreasing may be caused by neutrino resonance transitions as well [20].

In the present work we shall continue investigation about behavior of the solar neutrino flux which travels the region of the SF in the preflare period. The investigation is carried out within the context of three neutrino generations. The purpose of our work is to answer the question whether it is possible to predict the SF's observing the solar neutrino flux. In the next section we give a brief sketch of the magnetic reconnection model which describes the SF mechanism. The neutrino electromagnetic properties are discussed in section 3. In section 4 we find the evolution equation and define the possible resonance conversions of the neutrino flux in the Sun's matter and magnetic field. Our treatment of the problem carries rather general character, namely, it holds for any standard model extensions in which neutrinos have masses and possess both the magnetic dipole and anapole moments. Section 5 is devoted to our conclusions. The natural system of units ($\hbar = c = 1$) is used.

2   Magnetic reconnection model

It is believed that the magnetic field is the main energy source of the SF's. Note that one could only observe the magnetic activity at the surface of the Sun and infer the magnetic field inside. Therefore configuration and strength of the solar interior magnetic field are not quite clear. However one may claim that in the central part of the Sun's core, the magnetic field must not exceed the value $B_c = 5 \times 10^7$ Gs. Otherwise, as calculation show, at $B > B_c$ this magnetic field would be lost by the Sun due to the effect of "floating to the surface" during its existence. Both in the center core and in the radiative zone the fields do not display the time dependence. In the convective zone the magnetic field module has a 11.2-yr cycle and in its bottom the field could reach the value of 10^5 Gs while its value at the surface totaly depends on the existence of the AR's. During the years of the active Sun, the magnetic flux $\sim 10^{24}$ Gs $\cdot$ cm^2 [21] erupts from the solar interior and accumulates to form the AR's. The flux collects within the AR's giving rise to the stored magnetic field B_s. In those places of the AR's where the magnetic field value reaches 500 Gs the process of producing sunspots begins. A typical size of sunspots has the order of the Earth's radius ($R_\oplus = 6.37 \times 10^8$ cm) in diameter and its hight may reach the corona level. One could estimate the magnetic field strength of sunspots which will be, for example, the source of the super-SF's. If we assume that the magnetic field of such a sunspot extends to the distance $h \simeq 10^7$ cm and that the magnetic energy stored with the volume $V = \pi R_\oplus^2 h$ is equal to 10^{36} erg, then we get $B_s \simeq$ few $\times 10^6$ Gs. In fact, the value of B_s must be greater, since only a small portion of the total energy of a sunspot can be used, that is, a large amount of energy is unavailable because it is distributed as the potential field energy.

The magnetic field in the convective zone is characterized by the geometrical phase $\Phi(z)$ defined by the relation

$$B_x \pm iB_y = B_\perp e^{\pm i\Phi(z)} \tag{1}$$

and its first derivative on z, $\dot{\Phi}(z)$, in another way, the magnetic field exhibits the twisting nature and has the twist frequency. Nonzero values of $\Phi(z)$ and $\dot{\Phi}(z)$ also exist in the photosphere and the chromosphere in regions above sunspots. The magnetic field above and under sunspots has the nonpotential character

$$(\text{rot } \mathbf{B})_z = 4\pi j_z, \tag{2}$$

where j_z is the electric current density. The data concerning centimeter radiation above a spot is indicative of a gas heating up to the temperatures of a coronal order. For example, at the height $\sim 2 \cdot 10^2$ km the temperature could be as large as 10^6 K, that leads to a great value of solar plasma conductivity ($\sigma \sim T^{3/2}$). That permits to assume, that the longitudinal electric current J_z might be large enough in a region above sunspots. In Ref. [22] it was shown that when the magnetic field of newly emerged sunspot takes the value 2000 Gs, J_z can reach $(0.7 - 4) \times 10^{12}$ A. Then, for the sunspot with $R_s = 10^8$ cm the electric current density ranges between $(0.7 - 4) \times 10^{-1}$ mA/cm^2.

The commonly accepted model of the SF production is the magnetic reconnection model (MRM) which is based on breaking and reconnection of magnetic field strength lines of neighboring sunspots. This mechanism suggested in Ref. [23] further on was developed in details in Refs. [24, 25]. According to the MRM the process of the SF evolution is as follows. The SF formation starts from the integration of group of big sunspots in pairs of opposite polarity (in what follows we shall call them *coupled sunspots*). Then changing the magnetic field configuration could result in the appearance of a limiting strength line being common for the coupled sunspots. Throughout this line which rises from photosphere to the corona the redistribution of magnetic fluxes incoming from the solar interior got under way. From the moment of appearance of the limiting strength line, an electric field induced by magnetic field variations causes current along this line. By virtue of the interaction with a magnetic field this current takes the form of a current layer (CL). Because the CL prevents from the magnetic fluxes redistribution, the process of magnetic energy storage of the CL begins. In so doing the magnetic field of the coupled sunspots acquires the magnetic energy excess of the CL. The greater the magnetic field of the coupled sunspots was, the powerfuler the SF will be. The duration of the formation period of the CL (the SF initial phase) varies from several to dozens of hours. At this phase the magnetic field value for coupled sunspots B could be increased from $\sim 10^4$ Gs up to $\sim 10^5$ Gs and upwards. The second SF stage (the explosion phase) at which the CL is broken has a time interval of 1-3 minutes. The cause for the rupture of the CL is thermal instability, which leads to the chain of kinetic phenomena: (i) the rapid heating of plasma electrons; (ii) the excitation of a plasma instability; and (iii) the transition of the CL to a turbulent state. In that case the electric resistance of the CL increases sharply. The appearance in a certain part of the CL of a region of high or anomalous resistance leads to the rapid current dissipation and, accordingly, to the penetration of the magnetic fields through the CL. The latter phenomenon is accompanied by a reconnection of the magnetic field lines, which is why it has been called the magnetic reconnection. A strong magnetic field arises across the CL, which creates a magnetic force that tends to break

the CL. Under the action of this force, the plasma is ejected from the region of the CL at high speed. The magnetic energy of coupled sunspots is transformed into kinetic energy of matter emission (at a speed of the order of 10^6 m/s), energy of hard electromagnetic radiation, and fluxes of solar cosmic rays which consist of protons, nuclei with charges $2 \leq Z \leq 28$, and electrons. The produced photons reach the Earth by approximately 8.5 minutes after the explosion phase of the SF. Further during some tens of minutes powerful flux of charged particles attains terrestrial surface. As far as the plasma clouds are concerned, they reach our planet within two-three days only. The most powerful flux falling onto the Earth's surface may reach $\sim 4500\%$ in comparison to the background flux of cosmic particles. The concluding SF stage (the hot phase) could continue for several hours. It is exemplified by the existence of a high temperature coronal region which consists of dense hot plasma cloud. One of the characteristic features of flares is their isomorphism, that is, the repetition in one and the same place with the same field configuration. A small flare may repeat up to 10 times per day while a large one may take place the next day and even several times during the active region lifetime.

Note, there are some kinds of models which predict different values for the magnetic reconnection rates at the explosion phase of the SF. For discussing of this problem see, for example, Ref. [26]. However, in this work our interest is in the investigation of the SF initial phase only.

3   Neutrino multipole moments

In this section we shall discuss the neutrino electromagnetic properties. Neutrinos are neutral particles and their total Lagrangian does not contain any electromagnetic multipole moments (MM's). These moments are caused by the radiative corrections (RC's). The results of the RC's are usually reported in terms of the effective Lagrangian

$$\mathcal{L}_{em} = \frac{i}{2}\mu_{ll'}\overline{\nu}_l(x)\sigma^{\mu\lambda}(1-\gamma_5)\nu_{l'}(x)F_{\lambda\mu}(x) + \frac{i}{2}a_{ll'}\overline{\nu}_l(x)(\partial^\mu\gamma^\lambda - \partial^\lambda\gamma^\mu)(1-\gamma_5)\nu_{l'}(x)F_{\lambda\mu}(x) =$$

$$= \frac{i}{2}\mu_{ab}\overline{\nu}_a(x)\sigma^{\mu\lambda}(1-\gamma_5)\nu_b(x)F_{\lambda\mu}(x) + \frac{i}{2}a_{ab}\overline{\nu}_a(x)(\partial^\mu\gamma^\lambda - \partial^\lambda\gamma^\mu)(1-\gamma_5)\nu_b(x)F_{\lambda\mu}(x) + \text{conj.},$$
(3)

where the indexes l, l' refer to the flavor basis ($l, l' = e, \mu, \tau$) while the indexes a and b refer to the mass eigenstate basis ($a, b = 1, 2, 3$), μ_{ab} (a_{ab}) are the dipole magnetic (anapole) moments of the mass eigenstates, and $F_{\lambda\mu} = \partial_\lambda A_\mu - \partial_\mu A_\lambda$.

For a Majorana neutrino from the CPT invariance it is evident that all the diagonal MM's, except the anapole one, are identically equal to zero. As regards non-diagonal elements, the situation depends on the fact whether CP-parity is conserved or not. For the CP non-variant case all MM's are nonzero. When CP invariance takes place and the $\nu_{initial}$ and ν_{final} states have identical (opposite) CP-parities, then a_{ab} (μ_{ab}) are different from zero.

Further we address the experimental bounds on the dipole magnetic and anapole neutrino moments. Let us start with the Dirac neutrinos. The Borexino experiments give the limits on the DMM's of the form [27, 28]

$$\mu_{\nu_e\nu_e} \leq 2.9 \times 10^{-11}\mu_B, \qquad \mu_{\nu_\mu\nu_\mu} \leq 1.5 \times 10^{-10}\mu_B, \qquad \mu_{\nu_\tau\nu_\tau} \leq 1.9 \times 10^{-10}\mu_B, \qquad (4)$$

where μ_B is the Bohr magneton. As far as the bounds on transit DMMs are concerned, they will be obtained only under observation of processes proceeding with the partial lepton flavor violation. In the case of Majorana neutrinos the global fit of the reactor and solar neutrino data result in the following bounds for transition DMMs [29]

$$\mu_{12}, \mu_{13}, \mu_{23} \leq 1.8 \times 10^{-10}\mu_B. \qquad (5)$$

The value of the anapole moment is connected with the charge radius through the relation (see, for example, [30])

$$a_{\nu_i} = \frac{1}{6} < r^2(\nu_i) > . \qquad (6)$$

The relation (6) is obtained within the SM and it is model dependent. Moreover, even in the SM, this relation is valid only for massless neutrinos. It should be also recorded that, by now, calculation of the anapole moment has been fulfilled only within the SM in the case of both massless and massive Dirac neutrinos. Therefore, it is not improbable that in the SM extension the anapole moment value appears to be much bigger than that predicted by the SM, as happened with the DMM's. Remember, the DMM values in the SM are given by the expression [31]

$$\mu_{\nu_l\nu_l} = 10^{-19} \, \mu_B \left(\frac{m_{\nu_l}}{\text{eV}}\right), \qquad (7)$$

while in models containing right-handed charged currents and/or charged Higgs bosons $\mu_{\nu_l\nu_l}$ is proportional to the charged lepton mass m_l and proves to be on 7-8 orders of magnitude bigger (see, for example, Ref. [32]).

One should remember that the right dimensionality of the anapole moment in CGS system is "length^2 × charge" [33]). So, to turn from the natural system of units to CGS system the a_{ν_i} value must be multiplied by $\sqrt{\hbar c}$.

Measuring the elastic neutrino-electron scattering at the TEXONO experiment leads to the following bounds on the electron neutrino charge radius (ENCR) [34]

$$-2.1 \times 10^{-32} \text{ cm}^2 \leq < r_{\nu_e}^2 > \leq 3.3 \times 10^{-32} \text{ cm}^2. \qquad (8)$$

There are other limits on the ENCR as well. They are derived from neutrino neutral-current reactions [35]

$$-2.74 \times 10^{-32}\text{cm}^2 \leq < r_{\nu_e}^2 > \leq 4.88 \times 10^{-32} \text{ cm}^2. \qquad (9)$$

Calculations carried out within the SM [36] lead to the conclusion that the charge radiuses of $\nu_{eL}, \nu_{\mu L}$ and $\nu_{\tau L}$ have the same order, namely, few $\times 10^{-32}$ cm^2. However, it must be emphasized that the boundaries (8) and (9) were obtained under comparison of experimental results with the theoretical expressions for the corresponding cross sections obtained within the SM. Since similar analysis was not completed with alternative models, we have to use the above mentioned boundaries for the ENCR.

Further, making numerical estimates, we shall take the following values for the MM's neutrino

$$\mu_{\nu_l \nu_{l'}} = 10^{-10} \ \mu_B, \qquad |a_{\nu_l \nu_{l'}}| = 3 \times 10^{-40} \ \text{esu} \cdot \text{cm}^2,$$

where esu (electrostatic unit) is the unit of measurement of electricity in the CGS system. As for the magnetic field of the coupled sunspots, we shall assume that $B_s \geq 10^5$ Gs.

4 Solar neutrino flux

We are coming now to the analysis of the evolution equation of the neutrino flux traveling the SF region. We shall work within the three neutrino generations. In so doing we are going to allow for interaction not only with solar matter, but with solar magnetic field as well. Therefore, the system under study must include both the left-handed and right-handed neutrinos, that is, its wave function must be as follows $\psi^T = (\nu_{eL}, \nu_{\mu L}, \nu_{\tau L}, \nu_{eR}, \nu_{\mu R}, \nu_{\tau R})$. For the magnetic field of coupled sunspots we shall adopt a simple model in which

$$\Phi(z) = \frac{\alpha \pi}{L_{mf}} z, \tag{10}$$

that is, the magnetic field exists over a distance L_{mf} and twists by an angle $\alpha \pi$ ($\alpha \pi / L_{mf}$ is the twist frequency).

The current values of oscillation parameters we are interested in are as follows [37]

$$\left. \begin{array}{ll} \Delta m^2_{31(23)} \simeq 2.56 \times 10^{-3} \ \text{eV}^2, \quad \Delta m^2_{21} \simeq 7.87 \times 10^{-5} \ \text{eV}^2, \quad \sin^2 \theta_{12} \simeq 0.297, \\ \sin^2 \theta_{13} \ (\Delta m_{31(32)} > 0) \simeq 0.0215, \qquad \sin^2 \theta_{13} \ (\Delta m_{31(32)} < 0) \simeq 0.0216, \\ \sin^2 \theta_{23} \ (\Delta m_{31(32)} > 0) \simeq 0.425, \qquad \sin^2 \theta_{23} \ (\Delta m_{31(32)} < 0) \simeq 0.589. \end{array} \right\} \tag{11}$$

In order to get the evolution equation we shall use the standard technique of obtaining the similar equations (see, for example, the books [38, 39]). The basic idea of this approach consists in the reduction of the totality of the neutrino interactions in matter and magnetic field to the motion in a field with a potential energy. As this takes place, to find the matter potential one should first consider the neutrino interactions with single electron, neutron, proton and then fulfill averaging over all matter particles. Taking into account Eg.(3) and

assuming the Dirac neutrino nature we obtain the required equation

$$
i\frac{d}{dz}\begin{pmatrix}\nu_{eL}\\ \nu_{\mu L}\\ \nu_{\tau L}\\ \nu_{eR}\\ \nu_{\mu R}\\ \nu_{\tau R}\end{pmatrix}=\mathcal{H}\begin{pmatrix}\nu_{eL}\\ \nu_{\mu L}\\ \nu_{\tau L}\\ \nu_{eR}\\ \nu_{\mu R}\\ \nu_{\tau R}\end{pmatrix},
\tag{12}
$$

where

$$
\mathcal{H}=\mathcal{U}\begin{pmatrix}
E_1 & 0 & 0 & \mu_{11}B_\perp e^{i\Phi} & \mu_{12}B_\perp e^{i\Phi} & \mu_{13}B_\perp e^{i\Phi}\\
0 & E_2 & 0 & \mu_{21}B_\perp e^{i\Phi} & \mu_{22}B_\perp e^{i\Phi} & \mu_{23}B_\perp e^{i\Phi}\\
0 & 0 & E_3 & \mu_{31}B_\perp e^{i\Phi} & \mu_{32}B_\perp e^{i\Phi} & \mu_{33}B_\perp e^{i\Phi}e^{i\Phi}\\
\mu_{11}B_\perp e^{-i\Phi} & \mu_{12}B_\perp e^{-i\Phi} & \mu_{13}B_\perp e^{-i\Phi} & E_1 & 0 & 0\\
\mu_{21}B_\perp e^{-i\Phi} & \mu_{22}B_\perp e^{-i\Phi} & \mu_{23}B_\perp e^{-i\Phi} & 0 & E_2 & 0\\
\mu_{31}B_\perp e^{-i\Phi} & \mu_{32}B_\perp e^{-i\Phi} & \mu_{33}B_\perp e^{-i\Phi} & 0 & 0 & E_3
\end{pmatrix}\mathcal{U}^{-1}+
$$

$$
+\begin{pmatrix}
V_{eL}+d_{\nu_{eL}\nu_{eL}} & 0 & 0 & 0 & 0 & 0\\
0 & V_{\mu L}+d_{\nu_{\mu L}\nu_{\mu L}} & 0 & 0 & 0 & 0\\
0 & 0 & V_{\tau L}+d_{\nu_{\tau L}\nu_{\tau L}} & 0 & 0 & 0\\
0 & 0 & 0 & -d_{\nu_{eR}\nu_{eR}} & 0 & 0\\
0 & 0 & 0 & 0 & -d_{\nu_{\mu R}\nu_{\mu R}} & 0\\
0 & 0 & 0 & 0 & 0 & -d_{\nu_{\tau R}\nu_{\tau R}}
\end{pmatrix},
$$

$$
\mathcal{U}=\begin{pmatrix}\mathcal{D} & 0\\ 0 & \mathcal{D}\end{pmatrix},
$$

$$
\mathcal{D}=\exp(i\lambda_7\psi)\exp(i\lambda_5\phi)\exp(i\lambda_2\omega)=\begin{pmatrix}
c_\omega c_\phi & s_\omega c_\phi & s_\phi\\
-s_\omega c_\psi-c_\omega s_\psi s_\phi & c_\omega c_\psi-s_\omega s_\psi s_\phi & s_\psi c_\phi\\
s_\omega s_\psi-c_\omega c_\psi s_\phi & -c_\omega s_\psi-s_\omega c_\psi s_\phi & c_\psi c_\phi
\end{pmatrix},
$$

$\psi=\theta_{23}$, $\phi=\theta_{13}$, $\omega=\theta_{12}$, $s_\psi=\sin\psi, c_\psi=\cos\psi, s_\phi=\sin\phi, c_\phi=\cos\phi, s_\omega=\sin\omega, c_\omega=\cos\omega$, the λ's are Gell-Mann matrices corresponding to the spin-one matrices of the $SO(3)$ group, V_{eL} ($V_{\mu L}$) is a matter potential describing interaction of the ν_{eL} ($\nu_{\mu L},\nu_{\tau L}$) neutrinos with a solar matter,

$$
V_{eL}=\sqrt{2}G_F(n_e-n_n/2),\qquad V_{\mu L}=V_{\tau L}=-\sqrt{2}G_F n_n/2,
$$

n_e and n_n are electron and neutron densities, respectively,

$$
d_{\nu_{lL}\nu_{lL}}=4\pi a_{\nu_{lL}\nu_{lL}}j_z,\qquad d_{\nu_{lR}\nu_{lR}}=4\pi a_{\nu_{lR}\nu_{lR}}j_z,
$$

$a_{\nu_l\nu_{l'}}$ ($\mu_{\nu_l\nu_{l'}}$) is an anapole (dipole magnetic) moment between ν_l and $\nu_{l'}$ states, and, for the sake of simplicity, we have assumed that the nondiagonal neutrino anapole moments are equal to zero.

In Eq.(12) one should get rid of imaginary part in Hamiltonian. It is achieved by transformation to reference frame (RF), rotating at the same angle speed as a magnetic field [40]. The matrix of transition to the new RF will look like

$$S = \mathrm{diag}(\lambda, \lambda, \lambda, -\lambda, -\lambda, -\lambda), \tag{13}$$

where $\lambda = \exp\left(i\Phi/2\right)$. The Hamiltonian in this RF follows from the initial one by a replacement

$$e^{\pm i\Phi} \longrightarrow 1, \qquad 4\pi a_{\nu_{lL}\nu_{lL}} j_z \to 4\pi a_{\nu_{lL}\nu_{lL}} j_z - \dot{\Phi}/2, \qquad 4\pi a_{\nu_{lR}\nu_{lR}} j_z \to 4\pi a_{\nu_{lR}\nu_{lR}} j_z - \dot{\Phi}/2. \tag{14}$$

In general, the evolution equation (12) could be solved numerically or with appropriate approximations. In our case to define all possible electron neutrino resonance conversions in the system under study and make the results physically more transparent, one may proceed in the following manner. We shall search for such a basis in which, on the one hand, physical implications will be evident, and, on the other hand, one of the states will be predominantly the ν_{eL} state. Taking into account smallness of the mixing angle ϕ we find the required transformation

$$\begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \\ \nu_{1R} \\ \nu_{2R} \\ \nu_{3R} \end{pmatrix} = \mathcal{U}' \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \\ \nu_{eR} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix}, \tag{15}$$

where

$$\mathcal{U}' = \begin{pmatrix} \mathcal{D}' & 0 \\ 0 & \mathcal{D}' \end{pmatrix}, \qquad \mathcal{D}' = \exp(-i\lambda_5\phi)\exp(-i\lambda_7\psi) = \begin{pmatrix} c_\phi & 0 & s_\phi \\ -s_\phi s_\psi & c_\psi & c_\phi s_\psi \\ -s_\phi c_\psi & -s_\psi & c_\phi c_\psi \end{pmatrix}. \tag{16}$$

From (15) it follows that the ν_{1L} (ν_{3L}) state is predominately the ν_{eL} ($\nu_{\tau L}$) flavor state while the ν_{2L} state represents the mixing of the $\nu_{\mu L}$ and $\nu_{\tau L}$ flavor states. The same is true for their corresponding right-handed partners.

The transformed Hamiltonian acquires the form

$$\mathcal{H}' = \mathcal{U}' \, \mathcal{H} \, \mathcal{U}'^{-1} = \begin{pmatrix} \mathcal{B}_v + \Lambda & \mathcal{M} \\ \mathcal{M} & \mathcal{B}_v + \tilde{\Lambda} \end{pmatrix}, \tag{17}$$

where

$$\mathcal{B}_v = \begin{pmatrix} -\delta^{12}c_{2\omega} & \delta^{12}s_{2\omega} & 0 \\ \delta^{12}s_{2\omega} & \delta^{12}c_{2\omega} & 0 \\ 0 & 0 & \delta^{31}+\delta^{32} \end{pmatrix}, \qquad \Lambda = \begin{pmatrix} V_{eL}^{eff}c_\phi^2 & 0 & V_{eL}^{eff}s_{2\phi}/2 \\ 0 & 0 & 0 \\ V_{eL}^{eff}s_{2\phi}/2 & 0 & V_{eL}^{eff}s_\phi^2 \end{pmatrix},$$

$$\tilde{\Lambda} = \begin{pmatrix} \mathcal{A}_{\nu_{lR}\nu_{lR}} - \mathcal{A}_{\nu_{lL}\nu_{lL}} - V_{\mu L} & 0 & 0 \\ 0 & \mathcal{A}_{\nu_{lR}\nu_{lR}} - \mathcal{A}_{\nu_{lL}\nu_{lL}} - V_{\mu L} & 0 \\ 0 & 0 & \mathcal{A}_{\nu_{lR}\nu_{lR}} - \mathcal{A}_{\nu_{lL}\nu_{lL}} - V_{\mu L} \end{pmatrix},$$

$$\mathcal{M} = \begin{pmatrix} (\mu_0 + \mu_{12}s_{2\omega})B_\perp & \mu_{12}c_{2\omega}B_\perp & (\mu_{13}c_\omega + \mu_{23}s_\omega)B_\perp \\ \mu_{12}c_{2\omega}B_\perp & \mu_{12}c_{2\omega}B_\perp & (\mu_{13}c_\omega + \mu_{23}s_\omega)B_\perp \\ 0 & 0 & \mu_{33}B_\perp \end{pmatrix},$$

$$\delta^{ik} = \frac{m_i^2 - m_k^2}{4E}, \qquad \mu_{11} = \mu_{22} = \mu_0/2, \qquad V_{eL}^{eff} = \sqrt{2}G_F n_e,$$

$$\mathcal{A}_{\nu_{lL}\nu_{lL}} = 4\pi a_{\nu_{lL}\nu_{lL}} j_z - \dot{\Phi}/2, \qquad \mathcal{A}_{\nu_{lR}\nu_{lR}} = -4\pi a_{\nu_{lR}\nu_{lR}} j_z + \dot{\Phi}/2,$$

and, for the sake of simplicity, we have set

$$a_{\nu_{eL}\nu_{eL}} = a_{\nu_{\mu L}\nu_{\mu L}} = a_{\nu_{\tau L}\nu_{\tau L}} = a_{\nu_{lL}\nu_{lL}}, \qquad a_{\nu_{eR}\nu_{eR}} = a_{\nu_{\mu R}\nu_{\mu R}} = a_{\nu_{\tau R}\nu_{\tau R}} = a_{\nu_{lR}\nu_{lR}}.$$

Now, using the expression for $\mathcal{H}'$, we can establish all possible resonance conversions. We shall assume that the resonance localization places are situated rather far from one another. That allows us to consider them as independent ones. We shall also be constrained by consideration of the resonance transitions with the participation of the ν_{1L} neutrino only.

Let us start with the $\nu_{1L} \to \nu_{2L}$ transition. Equating the corresponding diagonal elements of the Hamiltonian $\mathcal{H}'$ we obtain the conditions of the resonance existence (in what follows we shall use the term "resonance condition")

$$-2\delta^{12}c_{2\omega} + V_{eL}^{eff}c_\phi^2 = 0. \tag{18}$$

To deeper realize consequences of neutrino behavior we proceed as follows. We infer that the matter density is constant. Then the expression for the transition probability of the neutrino system consisting only from ν_{1L} and ν_{2L} will look like

$$P_{\nu_{1L}\to\nu_{2L}}(z) \simeq \sin^2 2\theta_m \sin^2\left(\frac{z}{L_{\nu_{1L}\nu_{2L}}}\right), \tag{19}$$

where $L_{\nu_{1L}\nu_{2L}}$ is the oscillation length of the $\nu_{1L} \to \nu_{2L}$ resonance

$$L_{\nu_{1L}\nu_{2L}} = \frac{2\pi}{\sqrt{[2\delta^{12}c_{2\omega} - V_{eL}^{eff}c_\phi^2]^2 + (2\delta^{12}s_{2\omega})^2}}, \tag{20}$$

θ_m is a mixing angle in a matter

$$\tan 2\theta_m = \frac{2\mathcal{H}'_{\nu_{1L}\nu_{2L}}}{\mathcal{H}'_{\nu_{2L}\nu_{2L}} - \mathcal{H}'_{\nu_{1L}\nu_{1L}}} \simeq \frac{2\delta^{12}s_{2\omega}}{2\delta^{12}c_{2\omega} - V_{eL}^{eff}c_\phi^2}. \tag{21}$$

The behavior character of the mixing angle θ_m becomes more evident when we rewrite the relation (21) in the form

$$\sin^2 2\theta_m = \frac{(2\delta^{12}s_{2\omega})^2}{[2\delta^{12}c_{2\omega} - V^{eff}c_\phi^2]^2 + (2\delta^{12}s_{2\omega})^2}. \tag{22}$$

From Eq.(22) it immediately follows, in a solar matter with a variable electron density the dependence of the mixing angle θ_m on n_e has a resonance character. When the condition (18) is fulfilled θ_m reaches its maximum value $\pi/4$. However, from Eq.(19) it follows that for oscillations to be appeared a neutrino beam must pass a distance comparable with oscillation length. Note the oscillation length reaches its maximal value at the resonance.

One more important characteristic of the resonance represents the transition width. If it is equal to zero the resonance transition will be forbidden, even though the resonance condition is satisfied. For the $\nu_{1L} \to \nu_{2L}$ resonance it is given by the expression

$$\Gamma(\nu_{1L} \to \nu_{2L}) \simeq \frac{\sqrt{2}\delta^{12}s_{2\omega}}{G_F}. \tag{23}$$

Note that the expressions (19) - (23) coincide with the corresponding ones describing the $\nu_{eL} \to \nu_{\mu L}$ resonance in two flavor approximation (so called Micheev-Smirnov-Wolfenstein — MSW resonance) under substitution

$$n_e \to n_e c_\Phi^2. \tag{24}$$

When we set

$$E = 10 \text{ MeV}, \qquad \Delta m^2 = 7.37 \times 10^{-5} \text{ eV}^2, \qquad \sin^2 \theta_{12} = 0.297, \tag{25}$$

then the maximum oscillation length takes the value $\simeq 3.5 \times 10^7$ cm and, as a result, this resonance occurs before the convective zone. Therefore it happens whether the SF being at work or not. Since the expressions (18) - (22) depend on the neutrino energy then only electron neutrinos with the energy of order of few MeV take part in this resonance transition.

If one assumes that not only the matter density is a constant, but the quantities $B_\perp$ and j_z are constants as well, then, for the well-separated resonances the transition probabilities will be given by the expressions being analogous to (19) with corresponding values of the oscillation length and the mixing angle. It is obvious that in the real case, when we deal with the variable matter density and variable magnetic field, the occurrence of a resonance will be also dependent on values of such characteristics as the resonance condition, the resonance width and the distance traveled by the neutrino beam. By these reasons when discussing the resonances we shall be limited by the analysis of these characteristics only.

We now turn to the discussion of the helicity flip resonance transitions. For the first time within one-flavor approximation the existence of $\nu_{lL} \to \nu_{lR}$ resonance in a magnetic field was indicated in the work [41]. In the literature, this helicity flip transition (HFT) is often referred to as the Voloshin-Vysotskii-Okun effect. Later the HFT's of the neutrino systems traveling in magnetic fields were generalized to the case of two flavor approximations (see, for example, [42, 43, 12, 44]). We start our consideration with the $\nu_{1L} \to \nu_{2R}$ resonance. It may be realized at the condition

$$-2\delta^{12}c_{2\omega} + V_{eL}c_\phi^2 + 4\pi(a_{\nu_{lL}\nu_{lL}} + a_{\nu_{lR}\nu_{lR}})j_z - \dot{\Phi} = 0. \tag{26}$$

The corresponding expressions for the transition width and the maximum oscillation length are as follows

$$\Gamma(\nu_{1L} \to \nu_{2R}) \simeq \frac{\sqrt{2}\mu_{12}c_{2\omega}B_\perp}{G_F}, \tag{27}$$

$$(L_{\nu_{1L}\to\nu_{2R}})_{max} \simeq \frac{2\pi}{\mu_{12}c_{2\omega}B_\perp}. \tag{28}$$

It should be pointed out that the sunspots occur not only at the surface of the Sun, but at the convective zone as well. Thanks to the Wilson depression [45] they could lie below the photosphere on $L_W \sim 500 - 700$ km where the matter potential V_{eL} is nothing more than few $\times 10^{-17}$ eV. One may assume that the preflare pairing of the Wilson's sunspots takes place as well. Then the $\nu_{1L} \to \nu_{2R}$ resonance may occur when the neutrino beam passes through the magnetic field of these coupled sunspots. However, we shall not consider the case of Wilson's sunspots and assume that we deal with the coupled sunspots positioned on the solar atmosphere.

For the solar neutrinos $(\delta^{12})_{min} \simeq 10^{-12}$ eV which is much more bigger than the matter potential even in photosphere $(V_{ph} \simeq 10^{-20}$ eV$)$. Therefore, in the Sun's conditions the resonance $\nu_{1L} \to \nu_{2R}$ may occur only at the cost of magnetic field, that is, when the sum

$$2\delta^{12}c_{2\omega} + \dot{\Phi} - 4\pi(a_{\nu_{lL}\nu_{lL}} + a_{\nu_{lR}\nu_{lR}})j_z \tag{29}$$

has the same order as $V_{eL}c_\phi^2$. So, we may say that this resonance falls to the kind of the magnetic-induced resonances. It should be emphasized that the magnetic field must be twisted and/or has a nonpotential character.

Since the resonance condition (26) does not contain the value of $B_\perp$, it may seem that the $\nu_{1L} \to \nu_{2R}$ resonance can also occur when $B_\perp = 0$. However, it is not the case. Indeed, the resonance condition is valid also for tiny values of $B_\perp$ and $\theta_m \to \pi/4$ for any value of $B_\perp$. However, the oscillation length tends to infinity in the limit of $B_\perp \to 0$ making the transition impractical.

Comparing the expressions (26) - (28) with the corresponding ones describing the $\nu_{eL} \to \nu_{\mu R}$ resonance in two flavor approximation (FA) [19] one could be convinced that the formulas for three neutrino generations are evident from those of two FA under substitutions

$$n_e \to n_e c_\Phi^2, \tag{30}$$

$$\mu_{\nu_{eL}\nu_{\mu R}} \to \mu_{12}c_{2\omega}. \tag{31}$$

Using $B = 10^5$ Gs we get $(L_{\nu_{1L}\to\nu_{2R}})_{max} \simeq 7 \times 10^8$ cm. Then the resonance condition and the equality $L_{mf} = (L_{\nu_{1L}\to\nu_{2R}})_{max}$ will be fulfilled provided the twist frequency $\dot{\Phi}$ is equal to $-10\pi/L$, where we have assumed that

$$\dot{\Phi} \gg 4\pi(a_{\nu_{lL}\nu_{lL}} + a_{\nu_{lR}\nu_{lR}})j_z.$$

On the other hand when the magnetic field reaches the value of 10^6 Gs what will be possible for the super-SF's, the fulfillment above mentioned requirements will be effected

at the twist frequency being equal to $-\pi$ and $L_{mf} = 7 \times 10^7$ cm. So, we see that under the specific conditions the $\nu_{1L} \to \nu_{2R}$ resonance may be in existence.

The next resonance conversion is $\nu_{1L} \to \nu_{1R}$. The corresponding formulas will look like

$$V_{eL}^{eff} c_\phi^2 + 4\pi(a_{\nu_{lL}\nu_{lL}} + a_{\nu_{lR}\nu_{lR}})j_z - \dot{\Phi} = 0, \tag{32}$$

$$\Gamma(\nu_{1L} \to \nu_{1R}) \simeq \frac{\sqrt{2}(\mu_{11} + \mu_{12}s_{2\omega})B_\perp}{G_F}, \tag{33}$$

$$(L_{\nu_{1L}\to\nu_{1R}})_{max} \simeq \frac{2\pi}{(\mu_{11} + \mu_{12}s_{2\omega})B_\perp}. \tag{34}$$

It is clear that the situation when $V_{eL}^{eff} c_\phi^2 = \dot{\Phi}$ is excluded, since in this case the twisting magnetic field must exist over the distance which is much more even the solar radius. So, only when the requirements

$$\dot{\Phi} \ll V_{eL}^{eff}, \qquad \text{but} \qquad V_{eL}^{eff} c_\phi^2 \simeq -4\pi(a_{\nu_{lL}\nu_{lL}} + a_{\nu_{lR}\nu_{lR}})j_z \tag{35)}$$

will be fulfilled the $\nu_{1L} \to \nu_{1R}$ resonance may be observed. Calculations demonstrate that all the expressions which govern the $\nu_{1L} \to \nu_{1R}$ resonance conversion may be deduced from the expressions for $\nu_{eL} \to \nu_{eR}$ resonance obtained in two FA [19] provided the replacement

$$n_e \to n_e c_\Phi^2, \tag{36}$$

$$\mu_{\nu_{eL}\nu_{eR}} \to \mu_{11} + \mu_{12}s_{2\omega}. \tag{37}$$

We see that, in point of fact, the resonance condition (32) is the distance function. On the other hand, since both the resonance condition and the transition width do not display the dependence on the neutrino energy, then all the electron neutrinos produced in the center of the Sun (pp-, ^{13}N-,...and hep-neutrinos) may undergo $\nu_{1L} \to \nu_{1R}$ resonance transition.

Let us estimate the value of j_z which is needed to realize the $\nu_{1L} \to \nu_{1R}$ resonance in the chromosphere (corona). Taking into account $n_n \simeq n_e/6$ we obtain the following value for the matter potential $\sim 10^{-27}$ eV ($\sim 10^{-30}$ eV). Further, assuming $a_{\nu_{lL}\nu_{lL}} = a_{\nu_{lR}\nu_{lR}}$, we see that the resonance condition (32) will be fulfilled provided

$$j_z \simeq 6 \text{ A/cm}^2 \qquad (j_z \simeq 0.06 \text{ A/cm}^2). \tag{38}$$

In what follows we are coming to consideration of the resonance conversions which are absent in two FA, namely, to the $\nu_{1L} \to \nu_{3L}$ and $\nu_{1L} \to \nu_{3R}$ transitions. For the Sun conditions the relation

$$V_{eL}^{eff}, \Delta m_{12}^2 \ll \Delta m_{23}^2, \Delta m_{13}^2 \tag{39}$$

holds. The quantity proportional to $\Sigma = \delta^{31} + \delta^{32}$ is the dominant term in the Hamiltonian (17) and this leads to the decoupling of ν_{3L} from the remaining states apart from the ν_{3R} one. This means that the oscillation $\nu_{1L} \to \nu_{3L}$ which is driven by the Σ term can be simply averaged out in the final survival probability of electron neutrinos at the Earth.

As far as the $\nu_{1L} \to \nu_{3R}$ resonance is concerned, the situation here is not so obvious and requires a more detailed analysis. The resonance condition, the transition width and maximum oscillation length are given by the expressions

$$V_{eL}^{eff}c_\Phi^2 + V_{\mu L} + 4\pi(a_{\nu_{lL}\nu_{lL}} + a_{\nu_{lR}\nu_{lR}})j_z - \delta^{12}c_{2\omega} - \Sigma - \dot{\Phi} = 0, \tag{40}$$

$$\Gamma(\nu_{1L} \to \nu_{3R}) \simeq \frac{\sqrt{2}(\mu_{13}c_\omega + \mu_{23}s_\omega)B_\perp}{G_F}, \tag{41}$$

$$(L_{\nu_{1L} \to \nu_{3R}})_{max} \simeq \frac{2\pi}{(\mu_{13}c_\omega + \mu_{23}s_\omega)B_\perp}. \tag{42}$$

At the first glance it would seem that the quantities $\dot{\Phi}$ and $4\pi(a_{\nu_{lL}\nu_{lL}} + a_{\nu_{lR}\nu_{lR}})j_z$ could cancel the big value of Σ. However, such is not the case. So, for example, requiring the fulfillment $\dot{\Phi} \simeq \Sigma$, even when $B_\perp = 10^6$ Gs, we get

$$L_{mf} \ll (L_{\nu_{1L} \to \nu_{3R}})_{max}.$$

Therefore, in the Sun conditions the $\nu_{1L} \to \nu_{3R}$ resonance proves to be forbidden.

With a knowledge of the transition probabilities $\mathcal{P}(\nu_{1L} \to \nu_{2L})$, $\mathcal{P}(\nu_{1L} \to \nu_{1R})$, $\mathcal{P}(\nu_{1L} \to \nu_{2R})$ and taking into consideration the flavor contents of the ν_{lL} and ν_{lR} states, we could find the electron neutrino survival probability

$$\mathcal{P}(\nu_{eL} \to \nu_{eL}) = 1 - c_\phi^2 \Big[\mathcal{P}(\nu_{1L} \to \nu_{2L}) + \mathcal{P}(\nu_{1L} \to \nu_{1R}) + \mathcal{P}(\nu_{1L} \to \nu_{2R}) \Big] +$$

$$+ s_\phi^4 s_\psi^2 \mathcal{P}(\nu_{1L} \to \nu_{2R}). \tag{43}$$

Further we assume that the transition probabilities depend only on the mixing angles and the oscillation lengths, as happens with the constant values of n_e, j_z and $\dot{\Phi}$. When in (43) we make any allowance for the connection between μ_{ab} and $\mu_{ll'}$ (see Eqs. (31) and (37), put ϕ and ψ equal to zero, then, as would be expected, the expression (43) converts to the survival probability for the electron neutrino in two FA.

Note that the majority of resonances have an energy range in which neutrino conversion occurs. Since any given experiment is only sensitive to a small, finite range of energies, it will generally overlap only one of the transition regions.

It should be stressed that since the transition width of the MSW resonance does not depend on the DMM then it proves to be allowed within the SM. As far as the remaining magnetic-induced resonances are concerned, their realization is possible only in the model with nonzero DMM.

5   Conclusions

The goal of this work was to investigate the influence of the solar flares (SF's) on behavior of solar neutrino fluxes. Within three neutrino generations the evolution of the neutrino

flux traveling the coupled sunspots (CS's) being the SF source has been studied. One was assumed that the neutrinos possess both the dipole magnetic moment and the anapole moment while the magnetic field above the CS's has the twisting nature and displays the nonpotential character. We also inferred that in the process of magnetic energy storage the strength of this field may reach the values of $10^5 - 10^6$ Gs. For the analysis of the evolution equation we have transferred to the new basis in which one of the states ν_{1L} was predominantly the ν_{eL} state ($\nu_{eL} = \nu_{1L}|_{\phi=0}$). This permits to connect the evolution of the electron neutrino beam with the behavior of the ν_{1L} state. The possible resonance conversions with the participation of the ν_{1L} neutrino have been examined.

Since the $\nu_{eL} \to \nu_\mu$ resonance (MSW resonance) occurs before the convective zone, its existence can in no way be connected with the SF. After escaping the Sun, the neutrino flux flies 1.5×10^8 km in a vacuum before it will attain a terrestrial observer. In so doing reduction of the electron neutrino flux is caused by the vacuum oscillations which brings about $\nu_{eL} \to \nu_{\mu L}$ transitions only. Therefore, when the SF is absent, the neutrino telescopes detect the electron neutrino flux weakened at the expense both of vacuum oscillations and of the MSW resonance. However, when the electron neutrino flux travels the magnetic field of the CS's then it may be further weakened because of additional resonance conversions, apart from the above-listed. In the case of Dirac neutrinos the following resonances $\nu_{eL} \to \nu_{eR}$, $\nu_{eL} \to \nu_{\mu R}$ and $\nu_{eL} \to \nu_{\tau R}$ could take place.

The conditions of the resonances existence and the transition widths (TW's) have been found. It is worth noting that since for the $\nu_{eL} \to \nu_{eR}$ resonance both the resonance condition and the TW do not depend on the neutrino energy then all electron neutrino born in the Sun's center may go through the $\nu_{eL} \to \nu_{eR}$-resonance. The TW's of the resonances $\nu_{eL} \to \nu_{eR}$, $\nu_{eL} \to \nu_{\mu R}$, and $\nu_{eL} \to \nu_{\tau R}$ proves to be proportional to the neutrino dipole magnetic moment (DMM). Since the standard model (SM) predicts the neutrino DMM value close to zero, then from the SM point of view these resonances are forbidden.

So, under passage of the electron neutrino flux through the region of the SF one may observe the depletion of the electron neutrino flux. If the hypothesis of the ν_{eL}-induced β-decays is valid then observation of changeability of the β-decay rates of some elements during the SF's may be viewed as experimental confirmation of decreasing the solar neutrino flux. Needles to say the existence of such depletion must be confirmed by other experiments. It could be done at the neutrino telescopes of the next generation in which the events statistics will be increased on several orders of magnitude (for example, at the Fermi Lab Liquid ARgon experiment — FLARE).

In summary, we emphasize that the conditions for emergence of the $\nu_{eL} \to \nu_{eR}$, $\nu_{eL} \to \nu_{\mu R}$, $\nu_{eL} \to \nu_{\tau R}$ resonances contains two uncertainties, namely, the value of the magnetic field above the CS's providing the SF source, and the values of the neutrino multipole moments. Therefore, knowledge of these parameters will allow us to give the ultimate answer, whether it is possible or not to predict the SF's by observing solar neutrino fluxes.

Acknowledgments

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