Solar flares and their associated processes

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Abstract

Consideration is being given to the neutrino system governed by the wave function $\Psi^T = (\nu_{eL}, \nu_{XL}, \bar{\nu}_{eL}, \bar{\nu}_{XL})$ traveling in the region of the solar flare (SF). Our treatment of the problem holds for any standard model (SM) extensions in which massive neutrinos possess nonzero dipole magnetic and anapole moments. The possible resonance conversions of the electron neutrinos are examined. Since the $\nu_{eL} \rightarrow \nu_{XL}$ and $\nu_{eL} \rightarrow \bar{\nu}_{XL}$-resonances take place in the convective zone, their existence can in no way be connected with the SF. However, when the solar neutrino flux moves through the SF region in the preflare period, then it undergoes the additional resonance conversions resulting in appearance of the $\bar{\nu}_{eL}$ and $\bar{\nu}_{XL}$ neutrinos. On the other hand, according to the hypothesis of the $\nu_e$-induced $\beta$-decays weakening the electron neutrinos flux leads to the decrease of the $\beta$-decay rate for some elements. So, under passage of the electron neutrino flux through the region of the SF, the following four phenomena could be detected: (i) decreasing the number of the electron neutrinos; (ii) appearance of the $\bar{\nu}_{eL}$ neutrinos; (iii) increasing the amount of the $\bar{\nu}_{XL}$-neutrinos; (iv) reduction of the $\beta$-decay rate for some elements of the periodic table.

The possible influence of the electron antineutrino flux produced in the superflares on the regime of the hypothetical georeactor is considered.

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1 Introduction

At certain conditions the evolution of active regions (ARs) on the Sun may lead to the appearance of solar flares (SFs), which represent the most powerful events of the solar activity. The energy generated in the process of the SF is about $10^{28} - 10^{32}$ erg. However, as it was shown in Ref. [1], the superflares whose energy could be as large as $10^{36}$ are also possible. It is believed that just the magnetic field provides a main energy source of the SF’s. The commonly accepted model of the SF production is the magnetic reconnection model which is based on breaking and reconnection of magnetic field strength lines of neighboring spots. According to it the process of the SF evolution is as follows [2]. The SF formation starts from integrating sunspots of fairly opposite polarity. Then changing the magnetic field configuration could result in the appearance of a limiting strength line (LSL) being common for whole group. Throughout the LSL which rises from photosphere to the corona the redistribution of magnetic fluxes happens. From the moment of the LSL appearance 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 a 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. Duration of the formation period of the CL (the initial SF phase) varies from several to dozens of hours. The second stage (an explosion phase of the SF) has a time interval of 1-3 minutes. It starts from the appearance of a high-resistance region in some part of the CL that results in a current dissipation. Then, due to penetration of the magnetic field through the CL a strong magnetic field appears perpendicular to it. An arising magnetic force breaks the CL and throws out a plasma at a great speed. The magnetic energy of 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. Produced photons reach the Earth by approximately 8.5 minutes after 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 flux falling on the Earth’s surface for the most powerful the SF may reach $\sim 4500\%$ in comparison to the background flux of cosmic particles. The concluding stage (the hot phase of the SF) is characterized by the existence of a high temperature coronal region and can continue for several hours. One of the characteristic futures 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.

It is clear that the high-power SF’s can be especially destructive when they proves to be aimed at the Earth. They are dangerous for satellites, astronauts, pilots, power grids and so on. Moreover, intensive fluxes of the electron antineutrinos produced during the SF could influence on the work of a georeactor. It is obvious that forecasting the SF at the initial phase is a very important task.
In this work we are going to investigate the phenomena which are connected with the SF’s. In the next section we consider the evolution of the neutrino flux in the solar 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 with the values being close to the current experimental bounds. We find all possible the resonance conversions of the electron neutrino flux which travels the region of the SF in preflare phase. Section 3 is devoted to our conclusions.

2 Solar neutrino flux

Our goal is to obtain an evolution of the neutrino system traveling through the region of the SF. So, we have to discuss both the neutrino electromagnetic properties and characteristics of the solar magnetic field.

Let us start with the neutrino multipole moments (MM’s). Neutrinos are neutral particles and their total Lagrangian does not contains any MM’s. These moments are caused by the radiative corrections. The most general form of the matrix element for the conserved neutrino electromagnetic current $J_{\mu}^{em}$ could be obtained from the demands of the relativistic and gauge invariance. It is easy to show that for a Dirac neutrino ($J_{\mu}$) if must have the form

$$<\nu_D^i(p')|J_{\mu}^{em}\nu_D^j(p)> = <\nu_D^i(p')|i\sigma_{\mu\lambda}q^\lambda[F_M(q^2) + F_E(q^2)\gamma_5]+$$

$$(q^2\gamma_\mu - q_\mu q)[F_V(q^2) + F_A(q^2)\gamma_5]|\nu_D^j(p)>,$$

where $q = p' - p$, $F_M(q^2)$, $F_E(q^2)$, $F_A(q^2)$ and $F_V(q^2)$ are magnetic, electric, anapole and reduced Dirac formfactors. In static limit ($q^2 = 0$) $F_M(0)$ and $F_E(0)$ define dipole magnetic moment (DMM) $\mu_{ij}$ and dipole electric moment $d_{ij}$, respectively. At $i = j$, $F_A(0)$ represents the anapole moment (AM).

For a Majorana neutrino from the CPT invariance it is evident that all the formfactors, except the axial one $F_A$, 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 the four formfactors are nonzero. When $CP$ invariance takes place and the $|\nu_i^M>$ and $|\nu_j^M>$ states have identical (opposite) $CP$-parities, then $(F_E)_{ij}$ and $(F_A)_{ij}$ ($F_M)_{ij}$ and $(F_V)_{ij}$) are different from zero.

Now we address the recent experimental bounds on the neutrino DMM and AM. The world best limit on electron neutrino DMM was derived from the GEMMA experiment at the Kalinin nuclear power plant [3]

$$\mu_{\nu_e} \leq 2.9 \times 10^{-11} \mu_B \quad \text{at 90\% C.L.}$$

A search for the solar neutrino effective magnetic moment has been performed using data from 1291.5 days exposure during the second phase of the Borexino experiment. The
obtained bound is as follows \[4\]

\[\mu_{\nu}^{\text{eff}} \leq 2.8 \times 10^{-11} \mu_B \quad \text{at 90\% C.L.} \quad (3)\]

Note that the minimally extended SM (the SM with the massive neutrinos — MESM) predicts that the values of the neutrino DMMs are negligibly small and are of no physical interest \[5\]. Further we remember that at neutrino mass neglecting the AM is associated with a neutrino charge radius by the relation

\[a_{\nu} = \frac{1}{6} < r_{\nu}^2 > \quad (4)\]

Measuring the neutral-current coherent elastic neutrino-nucleus scattering at the TEXONO experiment leads to the following bounds \[6\]

\[\mu_{\nu_e} \leq 0.83 \times 10^{-10} \mu_B, \quad -0.17 \times 10^{-32} \text{ cm}^2 \leq < r_{\nu_e}^2 > \leq 0.17 \times 10^{-32} \text{ cm}^2. \quad (5)\]

On the other hand, using the lowest-energy solar neutrino data of pp,\(^7\)Be and pep spectra from phase-I and phase-II runs of Borexino experiment results in \[7\]

\[\mu_{\nu} \leq 8.75 \times 10^{-12} \mu_B, \quad -0.82 \times 10^{-32} \text{ cm}^2 \leq < r_{\nu}^2 > \leq 1.27 \times 10^{-32} \text{ cm}^2. \quad (6)\]

Proceeding to the solar magnetic field we note that the field strength \(B\) of a big sunspots \((d \sim 2 \times 10^5 \text{ km})\) could reach \(10^4\) Gs while their geometrical depth \(h\) is approximately 300 km. In this case a magnetic field above sunspots is characterized by geometrical phase \(\Phi(z)\)

\[B_x \pm iB_y = B_\perp e^{\pm i\Phi(z)} \quad (7)\]

and has non-potential character

\[(\text{rot } B)_z = 4\pi j_z. \quad (8)\]

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 density of longitudinal electric current might be large enough in a region above a spot. For example, in Ref. \[8\] it was shown that AR’s current could reach the values of \((0.7 - 4) \times 10^{12}\) A.

In our consideration we shall be limited by two generations. Therefore, the subject of our consideration will be a neutrino system consisting of \(\nu_{\nu_L}, \nu_{\nu_X}\) and their anti-particles \((\nu_{\nu_L})^c, (\nu_{\nu_X})^c\) \((c\) means an operation of charge conjugation, and \(X = \mu, \tau)\). It should be stressed that at a switching on of weak interaction the Majorana neutrino does not represent an eigenstate of a charge conjugation operator. Then, by virtue of the fact that \((\nu_{\nu_L})^c\) and \((\nu_{\nu_X})^c\) are right-handed neutrinos, we shall employ for them both in Majorana and Dirac cases following designations \(\overline{\nu}_{\nu_L}\) and \(\overline{\nu}_{\nu_X}\) respectively.
For the system of the Dirac neutrinos the evolution equation will look like

$$\frac{i}{\hbar} \frac{d}{dz} \begin{pmatrix} \nu_{eL} \\ \nu_{XL} \\ \nu_{eL}' \\ \nu_{XL}' \end{pmatrix} = \mathcal{H} \begin{pmatrix} \nu_{eL} \\ \nu_{XL} \\ \nu_{eL}' \\ \nu_{XL}' \end{pmatrix}, \quad (9)$$

where

$$\mathcal{H} = \begin{pmatrix} -\delta_{c}^{12} + V_{eL} + 4\pi a_{\nu_{e}\nu_{e}} j_{z} & \delta_{s}^{12} + 4\pi a_{\nu_{e}\nu_{X}} j_{z} & \mu_{\nu_{e}} \mu_{X} e_{L} e_{L} e_{L} e_{L} & \mu_{\nu_{e}} \mu_{X} e_{L} e_{L} e_{L} e_{L} \\ \delta_{s}^{12} + 4\pi a_{\nu_{e}\nu_{X}} j_{z} & -\delta_{c}^{12} + V_{XL} + 4\pi a_{\nu_{X}\nu_{X}} j_{z} & \mu_{\nu_{e}} \mu_{X} e_{L} e_{L} e_{L} e_{L} & \mu_{\nu_{e}} \mu_{X} e_{L} e_{L} e_{L} e_{L} \\ \mu_{\nu_{e}} \mu_{X} e_{L} e_{L} e_{L} e_{L} & \mu_{\nu_{e}} \mu_{X} e_{L} e_{L} e_{L} e_{L} & -\delta_{s}^{12} - 4\pi a_{\nu_{X}\nu_{e}} j_{z} & \delta_{s}^{12} - 4\pi a_{\nu_{X}\nu_{X}} j_{z} \\ \mu_{\nu_{e}} \mu_{X} e_{L} e_{L} e_{L} e_{L} & \mu_{\nu_{e}} \mu_{X} e_{L} e_{L} e_{L} e_{L} & \delta_{s}^{12} - 4\pi a_{\nu_{X}\nu_{e}} j_{z} & -\delta_{s}^{12} - 4\pi a_{\nu_{X}\nu_{X}} j_{z} \end{pmatrix}, \quad (9)$$

$$\delta_{c}^{12} = \frac{m_{2}^{2} - m_{3}^{2}}{4E} \cos 2\theta_{\nu}(\sin 2\theta_{\nu}), \quad V_{eL} = \sqrt{2}G_{F}(n_{e} - n_{n}/2), \quad V_{XL} = -\sqrt{2}G_{F}n_{n}/2,$$

$n_{e}$ and $n_{n}$ are electron and neutron densities, respectively, $\theta_{\nu}$ is a mixing angle in vacuum between mass eigenstates $\nu_{1}$ and $\nu_{2}$. $V_{eL}$ ($V_{XL}$) is a matter potential describing interaction of the $\nu_{eL}$ ($\nu_{XL}$) neutrino with a solar matter, and $a_{\nu_{l}\nu_{l}'}$ is an anapole moment between $\nu_{l}$ and $\nu_{l'}$ states.

When the neutrino has a Majorana nature, we must set

$$\mu_{\nu_{e}} \mu_{X} = \mu_{\nu_{X}} \mu_{e} = 0, \quad (10)$$

and replace $-4\pi a_{\nu_{e}\nu_{e}} j_{z}$ ($l = e, X$) on $4\pi a_{\nu_{e\nu}} j_{z} - V_{l}$.

Having carried out a phase rotation

$$\begin{pmatrix} \nu_{eL}' \\ \nu_{XL}' \\ \nu_{eL}' \end{pmatrix} = S \begin{pmatrix} \nu_{eL} \\ \nu_{XL} \\ \nu_{eL}' \end{pmatrix}, \quad (11)$$

where

$$S = \begin{pmatrix} e^{i\phi/2} & 0 & 0 & 0 \\ 0 & e^{i\phi/2} & 0 & 0 \\ 0 & 0 & e^{-i\phi/2} & 0 \\ 0 & 0 & 0 & e^{-i\phi/2} \end{pmatrix},$$

and $\Psi' = (\nu_{eL}', \nu_{XL}', \nu_{eL}', \nu_{XL}')$ is the vector state of neutrino system in the reference frame rotating with the same angular velocity as the transverse magnetic field. The expression for the transformed Hamiltonian $\mathcal{H}' = S\mathcal{H}S^{-1}$ follows from the old one by the substitutions

$$e^{\pm i\phi} \rightarrow 1, \quad \mathcal{H}_{11}' \rightarrow \mathcal{H}_{11} - \hat{\phi}/2, \quad \mathcal{H}_{22}' \rightarrow \mathcal{H}_{22} - \hat{\phi}/2, \quad \mathcal{H}_{33}' \rightarrow \mathcal{H}_{33} + \hat{\phi}/2, \quad \mathcal{H}_{44}' \rightarrow \mathcal{H}_{44} + \hat{\phi}/2 \quad (12)$$
By virtue of the fact that $|\Psi'|^2 = |\Psi|^2$ we shall drop the prime sign in what follows.

Further we shall concentrate on the resonance conversions of the electron neutrinos. When the neutrinos are the Dirac particles there are three resonance conversions. The $\nu_{eL} \rightarrow \nu_{XL}$ (Micheev-Smirnov-Wolfenstein — MSW) resonance is the first. It is realized when

$$\Sigma_{\nu_{eL} \rightarrow \nu_{XL}} = -2\delta^1_{e} + V_{eL} - V_{XL} + 4\pi(a_{\nu_e\nu_e} - a_{\nu_X\nu_X})j_z = 0. \tag{13}$$

while the transition width is as follows

$$\Gamma(\nu_{eL} \rightarrow \nu_{XL}) \simeq \frac{\sqrt{2}(\delta^1_{e} + 4\pi a_{\nu_e\nu_X}j_z)}{G_F}. \tag{14}$$

Attention is drawn to the fact that both $\Sigma_{\nu_{eL} \rightarrow \nu_{XL}}$ and $\Gamma(\nu_{eL} \rightarrow \nu_{XL})$ depend on the neutrino energy. As a result in this resonance only electron neutrinos with the energy of order of few MeV take part. It is also believed to be well established that the MSW resonance may occur before the convective zone, that is, it takes place whether the SF happens or not.

The second one is the $\nu_{eL} \rightarrow \bar{\nu}_{XL}$ resonance happening with flavor and spin flipping. It occurs at the condition

$$\Sigma_{\nu_{eL} \rightarrow \bar{\nu}_{XL}} = -2\delta^1_{c} + V_{eL} - V_{XL} + 4\pi(a_{\nu_e\nu_e} + a_{\nu_X\nu_X})j_z - \dot{\Phi} = 0. \tag{15}$$

Corresponding expressions for the transition width will look like

$$\Gamma(\nu_{eL} \rightarrow \bar{\nu}_{XL}) \simeq \frac{\sqrt{2}\mu_{\nu_e\nu_X}B_{\perp}}{G_F}. \tag{16}$$

Comparing Eqs.(13) and (15) we see that the $\nu_{eL} \rightarrow \bar{\nu}_{XL}$ resonance occurs at a higher density than the MSW one. 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 $\nu_{eL} \rightarrow \bar{\nu}_{XL}$ resonance is concerned, then its realization is possible only in the model with nonzero DMM. The $\nu_{eL} \rightarrow \bar{\nu}_{XL}$ resonance may occur not only in the convective zone, but also in the chromosphere where the neutrino MM’s may play an important role. However, in the latter case this resonance could take place only when $\dot{\Phi} \sim 10^{-7}$ cm$^{-1}$ what is improbable. This seemingly circumstance leads to the conclusion that in the solar neutrino flux which travels the SF region at the preflare period the amount of $\bar{\nu}_{XL}$ neutrinos appearing under $\nu_{eL} \rightarrow \bar{\nu}_{XL}$ resonance transition will not be changed. However it is not the case. The $\nu_{XL}$ neutrinos produced under the MSW resonance could undergo the resonance transition $\nu_{XL} \rightarrow \bar{\nu}_{XL}$ that takes place when the condition

$$\Sigma_{\nu_{XL} \rightarrow \bar{\nu}_{XL}} = V_{XL} + 4\pi(a_{\nu_X\nu_X} + a_{\nu_{X}\bar{\nu}_X})j_z - \dot{\Phi} = 0 \tag{17}$$

is realized. The corresponding transition width is defined as

$$\Gamma(\nu_{XL} \rightarrow \bar{\nu}_{XL}) \simeq \frac{\sqrt{2}\mu_{\nu_X\nu_X}B_{\perp}}{G_F}. \tag{18}$$
We note, that notwithstanding the fact, that both $\Sigma_{\nu_{XL} \to \bar{\nu}_{XL}}$ and $\Gamma(\nu_{XL} \to \bar{\nu}_{XL})$ do not depend on the energy, only neutrinos having energy of order of few MeV exhibit this resonance conversion.

The third resonance conversion is $\nu_{eL} \to \bar{\nu}_{eL}$. It will proceed when the condition

$$\Sigma_{\nu_{eL} \to \bar{\nu}_{eL}} = V_{eL} + 4\pi(a_{\nu_{e}\nu_{e}} + a_{\nu_{e}\bar{\nu}_{e}})j_{z} = 0$$

is carried out. In this case the transition width has the view

$$\Gamma(\nu_{eL} \to \bar{\nu}_{eL}) \simeq \sqrt{2}\mu_{\nu_{e}\nu_{e}}B_{\perp}\frac{G_{F}}{s}.$$  

As we see both $\Sigma_{\nu_{eL} \to \bar{\nu}_{eL}}$ and $\Gamma(\nu_{eL} \to \bar{\nu}_{eL})$ do not display the dependence on the neutrino energy. This, in its turn, means that all electron neutrinos produced in the center of the Sun (pp-, $^{13}$N-,...and hep-neutrinos) may undergo $\nu_{eL} \to \bar{\nu}_{eL}$ resonance transitions. We note if $B_{\perp}\mu_{\nu_{e}\nu_{e}} \simeq 4\pi\delta_{12}$, then the transition width of this resonance will have the same order of magnitude as the MSW one. Since the transition time in the level-crossing region is proportional to the transition width, then we can expect that approximately half electron neutrinos are subjected to the $\nu_{eL} \to \bar{\nu}_{eL}$ conversion. For example, in that case the flux of the antineutrinos with the energy up to 0.5 MeV could be as large as $10^{11}$ cm$^{-2}$s$^{-1}$.

Further we assume that $\nu_{eL} \to \bar{\nu}_{eL}$-resonance take place in chromosphere. Then from Eq. (19) it follows this resonance will be allowed in two simplest cases: (i)

$$\dot{\Phi} \ll V_{eL} \quad \text{but} \quad -4\pi(a_{\nu_{e}\nu_{e}} + a_{\bar{\nu}_{e}\bar{\nu}_{e}})j_{z} = V_{eL},$$

or (ii)

$$-4\pi(a_{\nu_{e}\nu_{e}} + a_{\bar{\nu}_{e}\bar{\nu}_{e}})j_{z} \ll V_{eL} \quad \text{but} \quad \dot{\Phi} = V_{eL}.$$  

To realize requirements (21) the AM’s sum $(a_{\nu_{e}\nu_{e}} + a_{\bar{\nu}_{e}\bar{\nu}_{e}})$ must have negative sign and the value of $j_{z}$ must have the order of $10^{-6}$ A/cm$^{2}$ (where we have used the lower bound on the AM and the value of the matter potential in chromosphere $V_{\text{cr}} \sim 10^{-26}$ eV). On the other hand, for fulfillment of (22) we need to demand $\dot{\Phi} \sim 10^{-21}$ cm$^{-1}$.

In the case of Majorana neutrinos only the resonances $\nu_{eL} \to \nu_{XL}$ and $\nu_{eL} \to \bar{\nu}_{XL}$ are allowed. The resonance transitions $\nu_{eL} \to \bar{\nu}_{eL}$ and $\nu_{XL} \to \bar{\nu}_{XL}$ are absent by reason of zeroth DMM.

In recent years a number of articles, presenting evidence that some $\beta$-decay rates are variable, have been published (see, for up-to-date review, Ref. 9). First result was presented in Ref. [10]. It was observed that the $\beta$-decay rate of $^{54}$Mn decreased slightly beginning 39 hours before the large SF of 2006 Dec.13. Later the hypothesis was offered [9] that this changeability may be connected with decreasing the solar neutrino flux (hypothesis of the $\nu_{e}$-induced $\beta$-decays — $\text{H} \nu_{e}$ID) when it passes through the region of the SF. Another way of putting it is that some elements we belief that they are natural radioactive, in reality, are artificial radioactive because of the solar neutrino flux bombardment. It should be recalled that for the first time the idea about correlation of a neutrino flux with the SF’s has been suggested in the works [11].
It is not inconceivable that the solar electron antineutrinos flux produced in a super powerful flare could influence on the operating conditions of a georeactor. For the first time the georeactor concept was proposed by J.M. Herndon [12]. There are several reasons for its existence. We enumerate the basic ones. The first reason is connected with the Earth’s magnetic field. It is known that this field varies in intensity and irregularly reverses polarity with an average interval between reversals of about $2 \times 10^5$ years. To ensure that some variable or intermittent energy source is required. This source is understood as georeactor, i.e., as naturally varying self-sustaining nuclear chain reaction burning at the center of the Earth. The second reason is associated with the attempt of explanation of increasing the relation $^{3}\text{He}/^{4}\text{He}$ as the distance is varied from the surface to the bottom mantle of the Earth [13].

In the georeactor $^{239}\text{Pu}$ is formed by neutron capture in $^{238}\text{U}$ followed by two short-lived beta decays: $^{238}\text{U}(n,\gamma) \rightarrow ^{239}\text{U}(\beta^-) \rightarrow ^{239}\text{Np}(\beta^-) \rightarrow ^{239}\text{Pu}$. The neutron flux in the reactor is extremely low and, in contrast with man-made high flux power reactors, $^{239}\text{Pu}$ does not contribute to the fission power and decays in $^{235}\text{U}$: $^{239}\text{Pu}(\alpha, T_{1/2} = 2.4 \times 10^4 \text{y}) \rightarrow ^{235}\text{U}$. Thus the georeactor operates in a breeder regime and reproduces $^{235}\text{U}$ through $^{238}\text{U} \rightarrow ^{239}\text{Pu} \rightarrow ^{235}\text{U}$ cycle. Variations of georeactor power originate from self-poisoning due to accumulation of fission products and subsequent removal of these products by diffusion or some other mechanism. The reactors of such a type are referred to as the traveling wave reactor. Georeactor numerical simulations indicate that the georeactor would function as a fast neutron breeder reactor capable of operating for at least as long as Earth has existed. Nuclear fission chain reaction can occur in nature. In 1972 such a natural nuclear fission reactor were actually found in the mine at Oklo in the Republic of Gabon in Africa [14].

At present the searches for the antineutrino flux produced by the georeactor are carried out in Borexino and KamLAND. Like investigations will be fulfilled at the following neutrino telescopes (NT’s): SNO+ (Sudbury Neutrino Observatory+) [15], BNO (Baksan Neutrino Observatory) [16], HanoHano [17] and LENA (Low Energy Neutrino Astronomy) [18] which will be placed into operation in the nearest future.

It should be stressed that one of the main problems of the georeactor is connected with the mechanism of the nuclear burning start-up, that is, with the appearance of the neutron-dividing wave (see, for example, [19]). One of the possible explanations is as follows. Let us assume that in the far past the super solar flare (SSF) has been happened. The ultra high energy protons injected downwards from the coronal acceleration region will interact with dense plasma in the lower solar atmosphere producing mesons which subsequently decay, resulting in, so called postflare neutrinos with O(MeV-GeV) energies

$$p + p \text{ or } p + \alpha \rightarrow \begin{cases} \pi^+ + X, & \pi^+ \rightarrow \mu^+ + \nu_\mu, \\
\pi^- + X, & \pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \\
\end{cases} \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Further one could speculate that the emerged electron antineutrino flux passing the Earth’s thickness faces the region which is enriched by protons. In this case due to the reaction of the inverse $\beta^-$ decay the neutrons flux will be born. Then, these neutrons
with the energy $E_n \geq 1$ MeV bombarding $^{238}$U could cause the nuclear burning start-up of the georeactor.

3 Conclusions

In two flavor approximation the evolution of the solar neutrino flux traveling the region of the solar flare (SF) has been investigated. One was assumed that the neutrinos possess both the dipole magnetic moment (DMM) and the anapole moment. The cases of the Dirac and Majorana nature of neutrinos have been considered. The possible resonance conversions of the electron neutrinos have been examined.

The MSW- and $\nu_{eL} \rightarrow \bar{\nu}_{XL}$-resonances take place in the convective zone, therefore, their existence can in no way be connected with the SF. However, when the electron neutrinos pass the SF region in preflare period they are subjected to additional resonance conversions. In the case of the Majorana neutrino we may have only the conversion $\nu_{eL} \rightarrow \bar{\nu}_{XL}$ while for Dirac neutrino apart from that we deal with one more conversion $\nu_{eL} \rightarrow \bar{\nu}_{eL}$. The conditions of the resonances existence and the transition widths (TW’s) have been found. The TW’s of the resonances $\nu_{eL} \rightarrow \bar{\nu}_{XL}$, $\nu_{eL} \rightarrow \bar{\nu}_{eL}$, and $\nu_{XL} \rightarrow \bar{\nu}_{XL}$ proves to be proportional to the DMM. However, the MESM predicts the DMM value close to zero. Therefore, in the MESM these resonances have the TW’s being equal to zero and, as a result, they must not be observed from the point of view of this model.

After leaving from the Sun the neutrino flux flies $1.5 \times 10^8$ km in a vacuum before it will reach the Earth. As this takes place, reduction of the electron neutrino flux is caused by the vacuum oscillations which lead solely to $\nu_{eL} \rightarrow \nu_{XL}$ transitions. Therefore, when the SF is absent, the NT records the electron neutrino flux weakened at the expense of vacuum oscillations, of the MSW resonance, and $\nu_{eL} \rightarrow \bar{\nu}_{XL}$-resonance. However, when the electron neutrino flux passes the SF region in preflare period then it is further weakened because of additional resonance conversions, apart from the above-listed. As the analysis showed the most probable scenario is the existence of the $\nu_{eL} \rightarrow \bar{\nu}_{eL}$- and $\nu_{XL} \rightarrow \bar{\nu}_{XL}$-resonances which are allowed for the Dirac neutrino only. It is worth noting that since both $\Sigma_{\nu_{eL} \rightarrow \bar{\nu}_{eL}}$ and $\Gamma(\nu_{eL} \rightarrow \bar{\nu}_{eL})$ do not depend on the neutrino energy then all electron neutrino born in the Sun center may go through the $\nu_{eL} \rightarrow \bar{\nu}_{eL}$ resonance. Having regard to appearing the $\bar{\nu}_{XL}$ neutrinos in $\nu_{eL} \rightarrow \bar{\nu}_{XL}$ transition as well, one may argue, when the solar neutrino flux moves through the SF region in the preflare period, the $\nu_{eL}$ neutrinos will be appeared while the amounts of $\bar{\nu}_{XL}$ neutrinos will be increased.

Then, terrestrial detectors could record these phenomena with the help of the reactions

$$\bar{\nu}_{eL} + p \rightarrow n + e^+ \quad (24)$$

$$\bar{\nu}_{\mu L} + p \rightarrow n + \mu^+. \quad (25)$$

Note, the reaction (24) is at the heart of the antineutrino detectors that are used for nuclear reactor monitoring in the on-line regime. Since the energy threshold of the reaction (24) is $\sim 1.8$ MeV then the antineutrinos produced from $^{13}N$, $^{15}O$ and more
energetic electron neutrinos could initiate this reaction. As a result, the value of the electron antineutrinos flux falling on the proton target of the detector could be as large as $10^8 \text{ cm}^{-2}\text{s}^{-1}$.

The hypothesis of the $\nu_e$-induced $\beta$-decays has been considered as well. According to it the reduction of the $\beta$-decay rate for some elements in the preflare period is caused by decreasing the electron neutrinos flux.

So, under passage of the electron neutrino flux through the region of the SF, the following four phenomena could be detected: (i) decreasing the number of the electron neutrinos; (ii) appearance of the $\overline{\nu}_{eL}$ neutrinos; (iii) increasing the amount of the $\overline{\nu}_{XL}$-neutrinos; (iv) reduction of the $\beta$-decay rate for some elements of the periodic table. It should be stressed that all these phenomena will be not only forerunners of the SF, but they also will be the convincing arguments in favour both of the Physics beyond the SM and of the Dirac neutrino nature.

We have also pointed to the possible influence of the electron antineutrino flux produced in the superflares on the regime of the hypothetical georeactor.

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