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μ_ν (Review talk at the workshop 'Search for Dark Matter and Neutrino Magnetic Moment", ITEP, 11.12.2001): Preprint ITEP 17-02/
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The present situation and hopes on bounding (founding) neutrino magnetic moment in future are reviewed.

μ_ν (Обзорный доклад на рабочем совещании "Поиск темной материи и магнитный момент нейтрино", ИТЭФ, 11.12.2001)
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Обзор современной ситуации и надежды на получение более строгого ограничения (либо обнаружения) магнитного момента электронного нейтрино в будущем.

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1. Motivation: Solar neutrinos

The reviewed story starts from the solar neutrino deficit and apparent anticorrelation of the Homestake data on the solar ν_e flux with the Sun magnetic activity [1]. To explain this anticorrelation the hypothesis of a large neutrino magnetic moment was suggested in [2]. According to it the left-handed electron neutrinos, produced in thermonuclear reaction in the Sun core, are (partly) transformed to the right-handed neutrinos when they pass the toroidal magnetic field generated in a solar convective zone in the years of active Sun. (It was noted in [3] that the electric dipole moment of ultrarelativistic neutrino would lead to the same effect.) This field manifests itself as the Sun spots – low temperature regions on the Sun surface where a toroidal field goes out from (or comes inside) the Sun. The number of the left-handed neutrinos which survive is given by the following formula:

$$N_L = N_0 \cos^2[\mu_\nu \int H_\perp dx] \ , \tag{1}$$

where N_0 is the initial flux, $H_\perp$ is the component of the magnetic field normal to the neutrino trajectory and the integral goes along a straightforward neutrino trajectory. For the toroidal field $H_\perp \gg H_\parallel$, that is why formula (1) is valid. It is convenient to measure μ_ν in Bohr magnetons, $\mu_B = e/2m_e \approx 3 \cdot 10^{-4} \frac{1}{\text{G}\cdot\text{cm}}$. The width of the solar convective zone L equals approximately $2 \cdot 10^{10}$ cm. The magnitude of the toroidal magnetic field is not known. At the Sun spots it varies between 2 and 4 kG and in some solar models the toroidal field grows at inner regions of the Sun. There exists the upper bound: the magnetic field inside the Sun can not exceed ~ 100 kGauss. That is why in order to have considerable reduction of the active electron neutrino flux μ_ν should be bounded from below by at least

$$\mu_\nu > 10^{-12} \mu_B \ . \tag{2}$$

The toroidal field depends on the time with the 22 years period reaching the maximum values each 11 years, at the periods of the active Sun.

At the years of the quiet Sun the toroidal field transforms to poloidal; the field configuration is that of a dipole. The magnitude of the poloidal field is several orders less than that of a toroidal field. The directions of the toroidal field are opposite at the northern and southern solar hemispheres. That is why in the vicinity of a solar equator the toroidal field vanishes even when the Sun is active. Due to the inclination of the Sun's rotation axis to the ecliptic we come to the prediction of a half-a-year period of the electron neutrino flux in the years of the active Sun [4]. The traces of this periodicity were found in Homestake data [5]. Finally, in paper [6] the damping of the spin flip due to a neutrino interaction with the matter was considered. We note also in that paper that the existence of a sterile right-handed neutrino is not necessary for the phenomenon to occur because the muon (or tau) antineutrinos could play its role in case of the so-called Majorana magnetic moment (see also [7]).

Our papers were not the first where the influence of the solar magnetic field on the flux of neutrinos from the Sun was analyzed. In paper [8] it was found that for the solar magnetic field of the order of 10^6 Gauss the flux of active neutrinos would be reduced for $\mu_\nu > 10^{-13}\mu_B$. However, the time variation of a solar neutrino flux was not considered in [8].

The azimuthal angle distribution of electrons on which the solar neutrinos scatter could help to reveal the neutrino spin rotation inside the Sun [9].

2. Bounds on μ_{ν_e}

They arrive from the astrophysical considerations and experiments with reactor $\bar{\nu}_e$. The first are more stringent while the second ones – more reliable.

The most restrictable bound has come from the consideration of a supernova explosion. Trapped in a supernova interior, the active neutrinos diffuse to the star shell approximately 10 seconds and this time interval coincides with the duration of a neutrino signal observed at the moment of SN 1987A explosion by Kamiokanda and IMB detectors. Trapping occurs due to the weak interactions of neutrinos. If neutrino has a nonzero magnetic moment, then the scattering due to the photon exchange between a neutrino and a charged particle in plasma leads to the neutrino spin flip. If a produced particle is a right-handed neutrino sterile in a weak interaction, it leaves SN without further interactions. This pattern contradicts to the observed neutrino signal of SN 1987A. The energy released in SN implosion is taken away by sterile neutrinos. Due to this no energy is left for the envelope explosion. To avoid these difficulties according to [10], the neutrino magnetic moment should be bounded from above:

$$\mu_\nu^{SN} \lesssim\sim 10^{-12}\mu_B \ . \tag{3}$$

The simplest way to avoid this bound is to use Majorana neutrino magnetic moment which transfers a left-handed neutrino to an anti-left-handed neutrino of another flavour. Both participate in weak interactions and are trapped in supernova. Esthetically this kind of a magnetic moment is much more appealing: we avoid introduction of right-handed neutrinos, needed only for solution of one particular problem. This scenario works with solar neutrinos if the mass difference of two states mixed by the magnetic field is bound from above [6]:

$$\frac{\Delta m^2}{2E} \lesssim \mu H \ . \tag{4}$$

For $\mu = 10^{-11}\mu_B$, $H = 10^4$ G and $E = 10$ MeV we obtain $\Delta m^2 \lesssim 10^{-8}$ eV^2.

However, even the case of Dirac neutrino could work: the magnetic field inside supernova can flip neutrino spin back transforming them into active left-handed particles. This mechanism could help to transfer the energy to star envelope solving the problem of supernova explosion [11].

The next set of bounds comes from an additional star cooling mechanism due to a plasmon decay into a neutrino pair. Such a mechanism would essentially change the time evolution of stars. This contradicts the observed temperature dependence of the star population unless μ_ν is small enough [12]:

$$\mu_\nu^{\text{star cooling}} \lesssim\sim 10^{-11}\mu_B \ . \qquad (5)$$

This bound follows from the analysis of white dwarfs, red giants and helium burning stars. Unlike the case of supernova, the neutrinos leave these stars without scattering, so the only way to avoid bound (5) is to make the neutrino mass larger than the plasma frequency, in this way making neutrino production in plasmon decay kinematically forbidden. Since the plasma frequency is of the order of keV, the electron neutrinos produced in the Sun are definitely lighter and bound (5) applies to the phenomena in which solar neutrinos participate.

Finally, we come to the bounds from the experiments with the reactor neutrinos. If they have a nonzero magnetic moment, then in addition to scattering due to W- and Z-boson exchanges, one should take into account the photon exchange. The weak and electromagnetic scatterings do not interfere as far as neutrino mass can be neglected. For the differential cross section of the electron antineutrino scattering on the electron we obtain:

$$\frac{d\sigma}{dT} = \left(\frac{\mu_\nu}{\mu_B}\right)^2 \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right) + \frac{2G_F^2 m_e}{\pi}\left[(1-\frac{T}{E_\nu})^2 g_L^2 + \right.$$

$$\left. + g_R^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right] \ , \ g_R = s_W^2 \ , \ g_L = \frac{1}{2} + s_W^2 \ , \qquad (6)$$

where the first term is due to the photon exchange, the second one is due to the weak interactions; E_ν is the energy of the initial neutrino, T – the kinetic energy of recoil electron, $G_F \approx 10^{-5}/m_p^2$ – the Fermi constant, $s_W^2 \approx 0.23$ – the electroweak mixing angle. We see that the relative contribution of the photon exchange grows with diminishing of neutrino energy, that is why one should look for the sources of soft neutrinos in order to bound μ_ν most effectively. Two dedicated reactor experiments lead to the following bounds:

$$\mu_\nu^{\text{reactor}} < 2.4 \cdot 10^{-10}\mu_B \ \text{at 90\% C.L. Krasnoyarsk [13]}$$

$$\mu_\nu^{\rm reactor} < 1.9 \cdot 10^{-10} \mu_B \ \text{ at 95\% C.L. Rovno [14]} \ , \qquad (7)$$

for review see [15].

Results of MUNU collaboration were recently announced. 60% of data are analyzed leading to the following bound:

$$\mu_\nu^{\rm reactor} < 1.3 \cdot 10^{-10} \mu_B \ \text{ at 90\% C.L. Grenoble [16]} \ .$$

One more reactor experiment with low threshold germanium detector is running now [17].

In conclusion, comparing (2) and (7), we see that to clarify if spin flip occurs when neutrinos cross the solar magnetic field, the earth-based experiment which is sensitive to the value of μ_ν being two orders of magnitude smaller than the existing reactor bound is highly desirable. The artificial sources of low-energy neutrinos could provide radical progress in this direction. Great expectations are connected with the experiment with a tritium source since the neutrino energies are very low, $E_\nu < 18$ keV, and a powerful source might be available [18].

3. Models

The neutrino magnetic moments are zero in Standard Model with three flavors of massless left-handed neutrinos. Dirac moments are zero since there are no right-handed components while Majorana moments are zero because the lepton quantum numbers are conserved. If neutrino is a massive Dirac particle, then loop diagrams with W exchange lead to nonzero μ_ν:

$$\mu_\nu = \frac{eg^2}{16\pi^2}\frac{m_\nu}{M_W^2}\frac{3}{4} \approx 3 \cdot 10^{-10}\frac{m_\nu}{m_p}\mu_B \ , \qquad (8)$$

where g is $SU(2)_L$ gauge coupling constant and m_p – the proton mass. From the investigation of a tritium beta spectrum, we know that $m_{\nu_e} < 1$ eV, that is why μ_ν described by eq. (8) is many orders of magnitude smaller than the one interesting for the solar neutrino. The proportionality of μ_ν

to the neutrino mass originates from left-handedness of weak interactions. W-boson interacts only with the left-handed fermions, that is why spin flip should occur on a neutrino line.

In the left-right symmetric extensions of $SU(2)_L \times U(1)$ theory or in a model with charged scalar interacting with leptons, spin-flip can occur on a charged fermion line and substituting mass of charged lepton (e, μ or τ) instead of m_ν in eq. (8) we get the value of μ_ν which can lead to spin flip of neutrinos in the Sun [19]. However, all such models have naturality problem. The point is that the same loop diagrams which generate a neutrino magnetic moment contribute to neutrino mass when an external photon line is eliminated. This contribution is logarithmically divergent. However, the coefficient in front of the logarithm is:

$$\Delta m_\nu \sim \frac{\mu_\nu}{e} M^2 \approx 10^{-11} \frac{M}{m_e} M \sim 100 \text{ keV} \ , \tag{9}$$

and at least five orders of magnitude should be fine tuned in order to get $m_\nu < 1$ eV (we substituted $\mu_\nu = 10^{-11}\mu_B$ and the mass of a heavy charged particle $M \approx 100$ GeV which is a lower bound from the absence of this particle in LEP II experiments).

In paper [20] it was pointed out that the naturality problem could be avoided by an $SU(2)$ symmetry that would forbid neutrino masses but allow the nonzero magnetic moment. The beautiful realization of this idea was suggested in [21], where horizontal $SU(2)_H$ symmetry between leptons of the first two generations was used. The operator of Majorana magnetic moment, being antisymmetric with respect to the permutations of ν_e^L and ν_μ^L, is $SU(2)_H$ singlet, while Majorana mass terms are components of $SU(2)_H$ triplet. That is why $SU(2)_H$ forbids Majorana neutrino masses while the magnetic moment is allowed. In [21] it is generated by the diagrams with a heavy charged scalar propagated in the loop. $SU(2)_H$ is not an exact symmetry since it is violated by the difference of the electron and muon masses. This difference is tiny; multiplying the right-hand side of equation (9) by $(m_\mu - m_e)/M_W$, we avoid the naturality problem.

The $SU(2)$ custodial symmetry which helps to avoid generation of a too big neutrino mass in the models with large μ_ν was not the last word in model building. The generation of the magnetic moment at a two-loop level was suggested in [22]. One loop generates $\gamma W S^+$ vertex, where S^+ is a charged scalar particle. S^+ and W are absorbed at a fermion line, leading to Majorana neutrino magnetic moment. Removing a photon, we get a two-loop contribution to the neutrino mass. The S^+W vertex should be proportional to momentum k_μ which, acting on $We\nu$ vertex, converts into the charged lepton mass. We obtain that the right-hand side of an estimate (9) should be multiplied by the factor $(m_e/M_W)^2$ removing in this way the naturality problem (proportionality to the second power of lepton mass follows from the well-known fact that changing a sign of fermion mass we should get the same expressions for the observables).

Concluding this part, we should say that a large number of extensions of the Standard Model were suggested which lead to the value of the neutrino magnetic moment, interesting from the point of view of neutrino propagation in the Sun. As a rule, these models contain heavy charged scalars which interact with leptons.

4. Solar neutrinos: sixteen years later

A considerable progress in detecting solar neutrinos was achieved after 1986. Together with Homestake experiment Kamiokanda, SAGE, GALLEX, Superkamiokanda, GNO and, finally, SNO experiments were and are running. All of them, measuring the solar neutrino fluxes in the different energy intervals, detect the neutrino deficit in comparison to the standard solar model predictions. The routine explanation of this deficit has become neutrino oscillation considered many years ago by B. Pontecorvo [23]. In this section we shall analyze if the hypothesis of the neutrino magnetic moment remains an alternative explanation of the neutrino deficit. To do this let us look at the relevant papers, which appeared during the last 16 years.

In paper [24] the Homestake data obtained during the years 1970 – 1991 were analyzed. This period covers two eleven-years cycles of the solar activity. The authors studied the anticorrelation of a neutrino flux with the solar surface magnetic field. According to [24], the effect is very strong when the magnetic field is taken in the vicinity of a solar equator, where the neutrinos, which are detected on the Earth, pass. It diminishes when the field at higher latitudes is taken into account. Also Kamiokanda data from the period 1987 – 1990 were analyzed. At this period the Sun magnetic activity was rising while no change in the neutrino flux was found in [25]. The authors of [24] noted that there is approximately one year delay in growing of the magnetic field at the low Sun latitudes which could explain Kamiokanda result. Also we should note that Majorana magnetic moment transforms electron neutrinos to muon or tau antineutrinos which are sterile for Davies experiment (as well as SAGE and GALLEX (GNO)) but scatter on electrons due to Z exchange being active at Kamiokanda detector.

It was noted in paper [26] that the solar magnetic field is highly inhomogeneous and that some components of this field last for several or even many Sun rotations. In view of this, the authors look for periodicity in GALLEX-GNO data. The discovered periodicity coincides with the rotation frequency of an equatorial part of a convective zone confirming in this way the hypothesis of neutrino flip by the magnetic field.

In a number of recent papers [27] the data from all solar neutrino detectors were analyzed in the framework of the neutrino magnetic moment hypothesis. The general conclusion is that the fit of the data of the same quality as that of using the neutrino oscillations can be achieved. In the framework of μ_ν scenario the energy dependence of neutrino suppression is achieved when $\Delta m_\nu^2/E_\nu$ term in the neutrino Hamiltonian is taken into account. Since the solar magnetic field varies along the neutrino trajectory, resonance spin flip could occur (the so-called Resonance Spin Flavor Precession [28]; the neutrino flavor is changed simultaneously with spin in case of Majorana magnetic moments).

There is a general consensus in the literature that in order to have observable effects on solar neutrinos the magnetic moment of ν_e should be larger than $10^{-12}\mu_B$. In view of this the laboratory experiment sensitive to $\mu_{\nu_e} \sim (10^{-11} \div 10^{-12})\mu_B$ is very actual. Projected experiment with a powerful tritium source has been one of the topics of the present workshop.

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