L.B. Okun, M.B. Voloshin, M.I. Vysotsky

ELECTROMAGNETIC PROPERTIES OF NEUTRINO AND POSSIBLE SEMIANNUAL VARIATION CYCLE OF THE SOLAR NEUTRINO FLUX

MOSCOW (1986)
Abstract

The existence of neutrino magnetic moment $\mu_\nu$ or/and electric dipole moment $\varepsilon_\nu$ of the order of $10^{-10} \mu_B$ would give rise to variations of the observed solar neutrino flux correlated with the magnetic activity of the Sun. In this case besides the overall 11-year period there should also exist in the years of maximal activity a semiannual variation cycle of the observed flux of boron neutrinos. The latter variations are caused by the existence of the equatorial "slit" in the toroidal magnetic field of the Sun and by inclination of the ecliptic to the solar equator. We also discuss neutrino flavor changing electromagnetic moments of the type of $\mu_\nu$ and $\varepsilon_\nu$ and possibilities of studying them with a large liquid argon $\nu e$ - scattering detector.
If a neutrino has a magnetic moment $\mu$ or an electric dipole moment $e\nu$ then traversing a magnetic field a left-handed neutrino would be partly converted into a right-handed one due to helicity rotation. The present limit for the combination $\mu = (\mu_\mu^2 + e^2 \nu^2)^{1/2}$ is $\mu \leq 10^{-10}$ (in units of the Bohr magneton $\mu_\text{Bohr} = e/(2m_e)$; hereafter we call $\mu$ electromagnetic moment)*. The fraction of right-handed neutrinos which appears after

*)From the analysis of the $\beta\gamma$ scattering data of Reines et al.11 the bound $\mu < 2 \times 10^{-10}$ was derived12. There are also astrophysical bounds which are obtained from the limits on energy leakage from stars due to the decay $\gamma \rightarrow \mu\nu$. The limit from the Sun is $\mu < 5 \times 10^{-10}$13, however it is argued14 that a value $5 \times 10^{-10} < \mu < 2 \times 10^{-8}$ would not require an essential modification of the model of the Sun interior. A somewhat lower limit follows15 from the same considerations for the white dwarfs, $\mu < 6 \times 10^{-10}$. It can be also noted that a value $\mu \sim 10^{-10}$ is not ruled out by models of the electroweak interaction, and such values can be accommodated in e.g. left-right symmetric models16,17.
the initially left-handed neutrinos pass a distance $L$ through a magnetic field is given by $\sin^2(\mu HL)$, where $H$ is the component of the field orthogonal to the neutrino momentum. In appropriate units $\mu = 10^{-10}$ corresponds to $\mu = 3 \times 10^{-14} \, [\text{G}\cdot\text{cm}]^{-1}$, which means that a sizable deficiency of the left-handed neutrinos occurs at $HL \gtrsim 3 \times 10^{13} \, \text{G}\cdot\text{cm}$. This value is very far beyond possibilities of laboratory technology. However it was noticed (7) that the effect could take place for neutrinos with a magnetic moment $\mu_\nu \approx (0.3 - 1) \times 10^{-10}$ in the magnetic field of the convective zone of the Sun. The thickness of the zone is $L \approx 2 \times 10^{10} \, \text{cm}$ and the toroidal magnetic field in the zone reaches in the peak of the solar activity a value $H \approx (1 - 5) \times 10^3 \, \text{G}$. In this case the deficiency of the left-handed solar neutrinos ($N_L \propto \cos^2(\mu HL)$) in the years of maximal activity would result in a lower counting rate in the experiment of Davis et al. (8) since the right-handed neutrinos are sterile in this experiment. Possible indications to an (anti)correlation of the observed flux with the solar activity are discussed in the literature (9, 10). In the case discussed in ref. (7) there should be one or few beats of the measured solar neutrino flux during the 11-year cycle if the product $\mu HL$ is large enough.

In this note we would like to point out that besides the overall 11-year variation of the solar neutrino flux, the measured boron neutrino flux should also undergo a semiannual variation, which is caused by weakening of the toroidal magnetic field near the solar equator and by the $7^\circ 15'$ inclination of the Earth's orbit to this equator.
The point is that the toroidal field \( H \) changes sign on the solar equator (on which it is thus vanishing). The characteristic size \( 1/11 \) of the transition region of the field is \( \pm 7^\circ \) of latitude which corresponds to the linear size of the "slit" in the magnetic field \( \pm 8.5 \times 10^9 \text{cm} \). On the other hand the radius of the region in which the high-energy boron neutrinos are produced (only to which the Davis detector is sensitive) is about \( 3 \times 10^9 \text{cm}/12/ \). (The total radius of the active zone in which 90% of solar energy is generated is about \( R_6/4 \approx 1.7 \times 10^{10} \text{cm} \). However in this region mainly the soft pp neutrinos are produced, for which the semiannual variations of the measured flux should be rather weak since the region from which they are emitted is larger than the size of the equatorial slit in the magnetic field. On the contrary, the high-energy boron neutrinos are generated in the hot innermost part of the active zone because of the very sharp temperature dependence of the corresponding reactions.) Thus when the Earth is near one of the nodes of the solar equator, i.e. near one of the intersections of its orbit with the plane of the solar equator, the active zone in which the boron neutrinos are produced is viewed through the equatorial non-magnetic slit and the observed flux of the left-handed neutrinos is not attenuated by the helicity-flip in the magnetic field. (The longitude of the ascending node of the solar equator is about 76°, therefore the Earth passes the equatorial plane in the beginning of June and in the beginning
of December.) As the Earth moves towards the maximal distance from the plane of the solar equator (in the beginning of September and in the beginning of March) the neutrinos coming on Earth traverse the strong toroidal magnetic field and the flux measured in a Davis-type experiment should vary. Naturally the strongest semiannual modulation of the flux should occur in the peak of magnetic activity of the Sun, and the effect should vanish during the period of quiet Sun.

Unfortunately, it is rather difficult to decide on the existence of the semiannual cycle from the data available so far, because the data are accumulated over irregular and rather long runs. The statistical errors of the data are also large. However the data of the years 1979-1982 which correspond to the active Sun suggest an indication to existence of the semiannual cycle. The mean counting rate in the runs containing March and September is by 3 standard deviations lower than the average counting rate in the rest runs.

The same effect of helicity-flip can also occur due to electric dipole moment of neutrino\[^{13}\]. In fact, for relativistic neutrinos it is impossible to resolve between \(\mu\) and \(\bar{\epsilon}\), since the corresponding terms in the interaction with the electromagnetic field \(F_{\mu\nu}\)

\[
\langle \mu_{\nu} + i\bar{\epsilon}_{\nu} \rangle \frac{\partial}{\partial \nu} \sigma_{\mu\nu} F_{\mu\nu} \frac{\bar{\nu}_{L}}{} + h. c. \quad (1)
\]

differ only by phase. In the massless limit the phases of \(\frac{\bar{\nu}_{L}}{}\) and \(\bar{\nu}_{L}\) are independent and by a corresponding phase rotation the coefficient in eq. (1) is reduced to the quantity \(\mu = (\mu^2 + \bar{\epsilon}^2)^{1/2}\) which was introduced in the
beginning of this paper. It can be also noted that beyond
the minimal SU(2)\(_L\) \(\times\) U(1) electroweak theory in which \(\mu\)
is proportional to the neutrino mass\(^6\) there is in gene-
ral no relation between the mass and the electromagnetic
moment of neutrino. In particular one can discuss an elec-
 tromagnetic moment of a massless neutrino, though this situa-
tion may seem somewhat unnatural.

We would also like to mention that for an interaction
of the type (1) it is not necessary to introduce additional
right-handed neutrinos \(\nu^c\) since their role can be played
by right-handed antineutrinos of a different flavor. For
example, the interaction can convert left-handed electron
neutrino to the right-handed muon antineutrino:

\[
\frac{1}{\sqrt{2}} \sigma_{\mu\nu} F^\mu_{\nu} \nu^c \nu
\]  

(a diagonal in flavor expression of this type is vanishing
identically). Of course this is a lepton number violating
interaction. It should be emphasized however that the mag-
netic field-induced oscillations between neutrinos of dif-
ferent flavor, occur only if the mass difference \(\Delta m\) of
the neutrinos is small enough. Namely the length of the
field-induced oscillations should be shorter than that of
the usual oscillations in the vacuum which implies the
condition \(\mu H \gg \Delta m^2/E_\nu\). For \(\mu = 10^{-10}\), \(H = 10^3\)G
and the neutrino energy \(E_\nu = 5\) MeV this bounds the
mass difference as follows: \(\Delta m^2 \ll 3 \times 10^{-9}\) eV\(^2\).

An introduction of the interaction of the type (2)
enables to avoid doubling of degrees of freedom of neutrino-
nes which otherwise might cause difficulties with explana-
tion of the primordial helium abundance created in the cosmological nucleosynthesis\cite{14}.

If the neutrino helicity indeed flips in the convective zone of the Sun the interaction of the type (2) can be distinguished from that in eq.(1) by a detector sensitive to the $\nu e$ -scattering of solar neutrinos. If $\nu_e$ oscillates in the magnetic field into $\tilde{\nu}_e$ (or $\tilde{\nu}_\mu$) as described by eq.(2), the muon (or $\tau^-$) antineutrinos would still scatter on electrons due to the neutral currents. On the other hand in the case of oscillation into the $SU(2)_L$ singlet $\nu_\mu^R$, these right-handed neutrinos would scatter on electrons only electromagnetically due to the interaction (1) which results in the characteristic $E^{-1}$ spectrum of the recoil electron\cite{2}.

Electronic detectors for detecting $\nu e$ -scattering of energetic solar neutrinos are being discussed at present. According to private communication from C.Rubbia and D.Cline a liquid argon detector is discussed which would contain 1000 tones of argon and about $10^5$ sensitive wires which collect electrons produced by an ionizing particle. In connection with the discussion presented above it would be very helpful if such a detector were available by the beginning of 1990's, when the next peak of solar activity is expected.

In conclusion we summarize once again the main points of this paper. The existence of a neutrino electromagnetic moment $\mu \sim 10^{-10} \mu_B$ should give rise to time variation of the neutrino flux from the Sun. For the rather soft pp neutrinos the 11-year cycle should be observed in anticorrelation with the magnetic activity of the Sun (we recall that by the end of 1980's Ga-Ge detectors are expected to
start taking data with a threshold sufficiently low for detecting the pp neutrinos). For the boron neutrinos besides the 11-year cycle there should also exist the semiannual cycle of the flux caused by the Earth's motion with respect to the plane of the solar equator. It would be very interesting to look for such variations during the next peak of solar activity in 1989-1991.

If the semiannual cycle is not confirmed by forthcoming experiments this will mean that the neutrino electromagnetic moment is substantially smaller than the present upper limit or that the magnetic field in the convective zone is lower than is estimated in the literature.

We are thankful to S.I. Blinnikov and A.A. Ruzmaikin for useful discussions and also to E.A. Gavryucheva and G.T. Zatsepin for providing us with detailed data of the experiment of Davis et al.
References

Л.Б. Окунь и др.
Об электромагнитных свойствах нейтрино и возможных полугодовых вариациях потока нейтрино от Солнца.
Работа поступила в ОНТИ 1.02.86