Neutrino electrodynamics and possible consequences for solar neutrinos

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The neutrino electromagnetic moment matrix and the possibility that some of the elements of this matrix are of the order of $10^{-11}$ to $10^{-10}$ of the Bohr magneton are discussed. Flavor oscillations and spin precession are examined for a neutrino in a magnetic field in the presence of matter. The interaction between solar neutrinos and the magnetic field in the interior of the convective zone of the Sun can lead, in this case, to the 11-year and semiannual variations in the neutrino flux, shown experimentally to be correlated with the magnetic activity of the Sun.

1. INTRODUCTION

There has been continuing interest in the mass matrix that determines the masses of neutrinos, in neutrino oscillations, and, when Majorana terms are present, in the probability of double-$\beta$-decay without the emission of a neutrino. In this paper, we discuss a further class of static characteristics of neutrinos, namely, the electromagnetic moment (EMM) matrix $\mu$ that appears in the Lagrangian for the interaction between a neutrino and the electromagnetic field $F_{\mu\nu}$:

$$L_{\text{int}} = \frac{i}{2} \mu_0 (\vec{\gamma}_\mu F_{\mu\nu}(\nu_i) + \vec{\gamma}_\nu F_{\mu\nu}(\nu_i)) \cdot \vec{p} + \text{h.c.}$$

(1)

The subscripts $L$ and $R$ indicate left- and right-handed fields, the subscripts $i, j$ label the current states of the neutrinos, $i = e, \mu, \tau, \ldots$ (this will be referred to as the flavor basis), and $a, b$ refer to the eigenstate basis of the neutrinos. The matrix $\mu$ is diagonal, with the diagonal elements $\mu_a = \ldots$ that contain the magnetic (electric) dipole moments of the mass state $a = \ldots$ (with masses $m_1 < m_2 < m_3$), and the off-diagonal elements of $\mu$ describe the decay of neutrinos into lighter neutrinos and $\gamma$-rays, e.g., $\nu_e \rightarrow \nu_\mu \gamma$.

We shall examine the possibility that some of the elements of the matrix $\mu$ may be of the order of $10^{-11} - 10^{-10}$ of the Bohr magneton, which may already have been seen experimentally in the form of the very specific variations in the solar neutrino flux recorded by the Davis group. This question has been examined in our previous brief communications. Here, we would like to give a more complete and closed presentation of the possible manifestations of the EMM in solar-neutrino experiments.

Briefly, the effect is that the EMM ensures that the helicity of the neutrinos is partially modified during their passage through the toroidal magnetic field $H$ in the convective zone of the Sun, and the observed solar activity is ascribed to processes in this zone. This results in a reduction in the flux of left-handed neutrinos, as detected by the Cl-Ar method. The quantity $H$ and, consequently, the reduction in the flux reach their respective maxima at the maximum of the 11-year cycle of solar activity. Moreover, $H$ changes sign at the solar equator, so that, because of the inclination of the Earth’s orbit to this equator, there should also be semianual variation in the recorded neutrino flux.

In Section 2, we shall discuss electroweak interaction models, in which EMM values of the order of $10^{-11} - 10^{-10}$ of the Bohr magneton can be obtained, and we summarize experimental and astrophysical limits on the matrix $\mu$. In Section 3, we consider the behavior of the neutrino helicity when the EMM interact with the magnetic field in the presence of matter, which may be very significant for neutrino propagation in the solar interior. In Section 4, we give a brief review of aspects of the theory of the Sun that are relevant to this question, and estimate the time variation in the recorded neutrino flux. Finally, in Section 5, we discuss possible further studies of this effect, using the new solar-neutrino detectors that are being built at present.

2. THE NEUTRINO EMM MATRIX

I. In standard $SU(2) \times U(1)$ theory, if the right-handed neutrino $\nu_R$ is an $SU(2)$ singlet, the matrix $\mu$ can be found from the diagrams shown in Fig. 1, and turns out to be proportional to the neutrinos mass matrix $m$ (Refs. 5, 6):

$$\mu = \frac{3G}{8\pi^2} m = \frac{3G}{8\pi^2} \mu_0 m \approx 3 \times 10^{-10} m$$

(2)

where $G$ is the Fermi constant and $m_\nu$ the nucleon mass.

The EMM described by this formula are exceedingly small, e.g., $\mu_{\nu_e} \sim 10^{-17} \mu_0$ for $m_{\nu_e} = 30$ eV. The reason for the fact that $\mu$ and $m$ are mutually proportional (and, hence, $\mu$ is small) in this scheme is that the $W^-$ boson in the diagrams of Fig. 1 interacts only with left-handed currents. This means that the change in helicity demanded by such an interaction is 1) must occur on the external neutrino line, $\nu_i \rightarrow \nu_j \gamma$, and 2) is proportional to $m_{\nu_i}$. Hence, it is clear that the neutrino EMM can be substantially increased if the theory contains right-handed currents. The change in helicity can then occur on the charged fermion line, so that the matrix $\mu$ will contain the charged lepton masses instead of the neutrino masses.

FIG. 1. Diagrams describing the origin of the neutrino EMM.
2. As an example of a model with right-handed currents, let us examine the widely discussed scheme with left-right symmetry $SU(2)_{L} \times SU(2)_{R} \times U(1)$ (see, for example, Ref. 7). The mediator of the usual weak interaction in this scheme is the charged boson $W_{\tau}^{\pm}$, containing a small admixture of the right-handed boson $W_{4}$. 

$$W_{\tau}^{\pm} = W_{\tau} \cos \theta + W_{4} \sin \theta.$$ 

The neutrino EMM matrix is determined in this model by the masses of the charged leptons and the matrices $U$ and $P$ that mix the neutrinos in the left-handed ($U$) and right-handed ($P$) currents:

$$g_{\nu_{e}} = \frac{G_{F}}{\sqrt{2}} \mu_{\nu_{e}} \sin 2 \theta_{13} U_{e3} P_{3R},$$

(3)

where the sum is evaluated over the types of charged leptons. In the minimum model of this kind with the flavor basis we have $U = F = 1$, so that $\mu_{ij}$ is diagonal:

$$g_{\nu_{e}} = 3.6 \times 10^{-14} \mu_{e} \sin 2 \theta_{13} (m_{e}/m_{\tau}).$$

(4)

In this scheme, the maximum EMM has a neutrino current state that appears in the doublet with the heaviest charged lepton. In the case of three generations, this is the $\nu_{\tau}$, for which the magnitude of $\mu$ corresponding to the maximum value $\sin 2\theta = 0.1$ allowed by the experimental limit is $\mu_{\nu_{\tau}} = 0.01 \times 10^{-14} \mu_{e}$.

(5)

For the mass states of the neutrinos, the EMM values in this case are obviously proportional to the fraction of the $\nu_{\tau}$ present in them. We note that the matrix $\mu_{\nu_{\tau}}$ is nondiagonal in the mass basis, i.e., decays of the form $\nu_{\tau} \rightarrow \nu_{\tau}^{\pm}$ should occur. It is also clear that, if there is a fourth generation, the neutrino appearing in this generation will have the highest EMM.

It is clear from the above example that matrix elements of the order of $10^{-17} \mu_{e}$ can be obtained in schemes involving an admixture of right-handed currents allowed by the corresponding experimental limits. Of course, the mechanism for the appearance of the neutrino EMM may be quite different, and the structure of the matrix $\mu$ may be significantly different from that described by (3) and (4). In particular, in supersymmetric models, the appearance of fairly large EMM (including $g_{\nu_{e}} = 10^{-17} \mu_{e}$) seems quite possible because these schemes include heavy fermions (winos and higgsinos), whose masses effectively turn over the helicity in graphs similar to those shown in Fig. 2.

We emphasize that, strictly speaking, the EMM are not necessarily related to the masses of the neutrinos themselves. In principle, it is possible to consider the EMM of massless neutrinos without introducing contradictions although, from the point of view of the natural condition $\mu \neq 0$ for $m = 0$, this seems strange and requires special compensation by counterterms in the neutrino mass diagrams.

3. Let us now consider the limits on the matrix $\mu$ that follow from reactor experiments and astrophysical estimates. The interaction (1) produces an additional contribution to the neutrino-electron scattering cross section described by the graph of Fig. 2. The differential cross section for $\nu_{e}$ scattering due to this mechanism is the same for $\nu_{e}$ and $\nu_{\tau}$, and is given by:

$$\frac{d\sigma}{dT} = \frac{\sigma_{\nu_{e}}}{4\pi} \left( \sum_{i} |\mu_{\nu_{i}}|^{2} \right) \frac{1}{m_{\nu_{i}}^{2}} \left( 1 - \frac{T^{2}}{E_{\nu_{e}}^{2}} \right).$$

(6)

where $E_{\nu_{e}}$ is the energy of the incident neutrino and $T$ the kinetic energy of the recoil electron, which is actually the quantity recorded experimentally.

The sum over the neutrino current states in (6) corresponds to summation over the different final states of the neutrinos in the reaction $\nu_{e} \rightarrow \nu_{e} e$. Let us compare (6) with the well-known expression for the $\nu_{e}$ cross section due to the weak interaction (see, for example, Ref. 11):

$$\frac{d\sigma}{dT} = \frac{\sigma_{\nu_{e}}}{2\pi} \left( 1 - \frac{T^{2}}{E_{\nu_{e}}^{2}} \right)^{2} \left( 1 + 2 \sin^{2} \theta_{W} \right) \sin^{2} \theta_{W} \left( 1 - \frac{T^{2}}{E_{\nu_{e}}^{2}} \right).$$

(7)

where $\theta_{W}$ is the Weinberg angle. The electromagnetic and weak amplitudes do not interfere, so that the total cross section is obtained by combining the expressions given by (6) and (7). When $T < E_{\nu_{e}}$, the cross section given by (7) becomes constant, while that in (6) behaves as $T^{-1}$, and when $\sin^{2} \theta_{W} = 0.22$, it becomes comparable with the weak cross section for $T = 0.3$ MeV if $\mu_{\nu_{e}} \approx (2 \times 10^{-14}) \mu_{e}$. Thus, the problem of reducing the experimental limit for $\mu_{\nu_{e}}$ involves, above all, a reduction of the threshold for the detection of recoil electrons, which is complicated by the higher background at low electron energies. The experimental data reported in Ref. 12 have been used to show $\mu_{\nu_{e}} \leq 10^{-16} \mu_{e}$. The best limitation on the matrix $\mu$ is obtained by considering the cooling of young white dwarfs due to the decay of plasmons $Y_{\pm} \rightarrow \nu_{e} \nu_{e}$ pairs. The decay width due to the EMM is

$$\Gamma_{\nu_{e}}(Y_{\pm} \rightarrow \nu_{e} \nu_{e}) = \frac{\sum_{i} |\mu_{\nu_{i}}|^{2} \sin^{2} \theta_{i}}{24m_{\nu_{i}}},$$

(8)

where $n_{\nu_{i}}$ is the plasma frequency in the star. Analysis of astrophysical data gives the following limit:

$$\sum_{i} |\mu_{\nu_{i}}|^{2} \leq 0.7 \times 10^{-14} \mu_{e},$$

(9)

which is actually the upper limit for the norm of the matrix $\mu$.
According to Okun' [16], the fact that (8) contains precisely this quantity is due to the summation over all the types of neutrino pairs. This summation and the neglect of the neutrino masses, is justifiable if the masses are substantially smaller than $\alpha_\mu/2$. For young white dwarfs, for which (9) was obtained, $\alpha_\mu = 30 - 40$ keV, so that the last assumption seems fully acceptable. It would be interesting to repeat the analysis given in Ref. 15 with more recent astrophysical data, and deduce the upper limit for $|\mu|$, which may well turn out to be more stringent than (9).

4. To conclude this section, let us consider a further aspect of the neutrino magnetic moment. The introduction of right-handed neutrinos $v_\mu$ increases the number of neutrino degrees of freedom by a factor of two, which may give rise to difficulties in explaining the primordial abundance of $^4\text{He}$ (see, for example, the review in Ref. 16 and the book by Okun' [16]). Leaving to one side the question of how serious these difficulties really are, we note that, if we allow the non-conservation of lepton number, we can avoid the introduction of the right-handed neutrino field and, instead, use the antineutrino field. The analog of (1) then assumes the "Majorana" form:

$$L_{\nu\nu}=\left|\mu_\nu\right|^2\nu_\mu^\dagger\nu_\nu^*+\text{h.c.}$$

(10)

The matrix $\mu_\nu$ should then be antisymmetric because the part of the lepton operator in (10) that is symmetric in the neutrino types will then vanish. In other words, only the off-diagonal matrix moments are possible in this case. We shall not consider specific models leading to interactions such as (10), but it is not difficult to foresee that, in such models, the condition for the experimental absence of a double $\beta$-decay without the emission of neutrinos will be a very stringent limitation.

3. SPIN PRECESSION AND NEUTRINO OSCILLATIONS IN A MAGNETIC FIELD, INCLUDING THE EFFECT OF MATTER

1. We begin by considering the motion of a neutrino with energy $E \gg m$ in a vacuum, taking oscillations into account. The standard description of these oscillations follows from the fact that the momentum $p$ in the neutrino wave function $\psi_\nu = \exp(-iEz + ip\xi)\phi_\nu$ is a matrix in the space of the neutrino types, and is related to the mass matrix by

$$p = (E^2 - m^2)^{1/2}E = m^22E$$

(11)

(we shall choose the phases of the $v_L$ and $v_\nu$ so that the matrix $m$ is Hermitian). Let us extract the unimportant phase factor $\exp\left(iE(2z - t)\right)$:

$$\psi = \exp\left[iE(2z - t)\right]v(z).$$

According to (11), we then have $v = \exp(-im^2z/(2E))v_\nu$, so that $v(z)$ satisfies the evolution equation.

$$i\frac{dv}{dz} = \frac{m^2}{2E}v.$$  

(12)

This implies that $v$ is a vector (column vector) in the space of the elements of the column is a spinor:

$$\left(\begin{array}{c} v_L \\ v_\nu \end{array}\right).$$

(13)

(the direction of motion of the neutrino is taken to be the spin quantization axis).

2. When the electromagnetic field $F_{\mu\nu}$ is present, the interaction (1) leads to the following modification of (12):

$$i\frac{dv}{dz} = \mathcal{H}v,$$

(14)

where the "Hamiltonian" $\mathcal{H}$ is

$$\mathcal{H} = m^2 - \mu_\nu \sigma(\mathbf{H} - (E)\mathbf{P}_- - \mu_\nu \sigma(\mathbf{H} + (E)\mathbf{P}_+),$$

and $P_\pm = (1 \pm \sigma_3)/2$ are projectors onto the $v_L$ and $v_\nu$ states. We note that, since $P_\pm \sigma_2 P_\mp = 0$, the longitudinal components of $\mathbf{H}$ and $\mathbf{E}$ do not appear in $\mathcal{H}$. This is readily understood because the longitudinal field components remain unaltered under the transformation to the neutrino rest system, whereas the lateral components contain the factor $\gamma = E/m > 1$. The derivation of the Hamiltonian (15) assumes that the field $F_{\mu\nu}$ changes little over the length $E^{-1}$. It is also assumed that the neutrino is not deflected by field gradients, which is valid with high precision in all realistic situations.

We note that we deliberately retained the difference between $\mu$ and $\mu_\nu$ in (15) because the phases of the mass matrix were fixed. If it were possible to observe the phase difference between neutrinos oscillations in the presence and absence of the field, it would be possible to find the relative phases of the elements of the matrices $m$ and $\mu$. Nonzero values of these phases would correspond to $CP$ violation in the neutrino sector.

It is immediately clear from (14) and (15) that, for the mass states $v_L$ in a transverse magnetic field $\mathbf{H}$, there are oscillations between left- and right-handed components (spin precession) with frequency $\omega(z) = [\mu_\nu(\mathbf{H}(z))$. If the region in which $\mathbf{H}$ is present (its direction is independent of $z$) intercepts a beam of the $v_L$, the numbers of the $v_L$ and $v_\nu$ are given by

$$N_L(z) = N_L \cos\left[\int \omega(z) dz\right], \quad N_\nu = N_\nu \sin\left[\int \omega(z) dz\right].$$

(16)

In the case of Dirac masses that we are considering, precession will occur in an arbitrarily weak transverse field because the left- and right-handed neutrinos are degenerate in energy. Oscillations between the mass states $\nu_L \leftrightarrow \nu_\nu$ are possible because of the diagonal terms in $\mu_\nu$. However, these oscillations have appreciable amplitudes only when the mixing element $|\mu_{\nu\nu}| = |H_{11}|$ is comparable with the difference between the diagonal elements of the Hamiltonian (19):

$$|\mu_{\nu\nu}| \geq \frac{m_{11}^2 - m_{22}^2}{2E}.$$ 

(17)

To estimate the order of magnitude of the various quantities in this expression, we note that $\Delta m^2 \lesssim 10^{-3} eV^2$ for $|H_{11}| = 10^7 G$, $|\mu_{\nu\nu}| = 10^{-10} \mu_B$, and $E = 10$ MeV.

Finally, let us consider the general case where the

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neutrino propagates in matter, it is precisely this case that is interesting from the point of view of solar neutrinos. Only the coherent interaction between the neutrinos and matter is significant because the noncoherent neutrino interaction cross section is exceedingly small. Coherent effects are conveniently examined directly at the level of the Lagrangian. The rate interaction neutrino Lagrangian is

\[
L_{\nu} = \frac{G}{\sqrt{2}} \left[ \bar{\nu}_\tau (1 + \gamma_5) \nu (1 + \gamma_5) \right] + \frac{2G}{\sqrt{2}} \sum_i \bar{\nu}_i (1 + \gamma_5) \nu_i, \\
- \frac{4G}{\sqrt{2}} \sum_i \bar{T}_i \gamma_5 (1 - \gamma_5) \nu_i \nu_i.
\]

(18)

The first term is due to the inelastic effects of the electron-neutrino and the electron, and the second due to the interaction with the neutrino strain current

\[
J^\nu = J^\nu_e - \sin^2 \theta \nu J^m
\]

(19)

\((J^m)\) is the electromagnetic current and \(J^\nu\) is the current of the third component of weak isospin. Finally, the third term in (18) occurs when the third component of weak isospin of right-handed neutrinos, \(T^\nu\), is not zero. The next step is to average the Lagrangian (18) over matter. For matter at rest, which does not have a macroscopic spin magnetic moment, only the average of the time component of the vector part of the current is nonzero. We thus have

\[
\langle T_\mu (1 + \gamma_5) \rangle = \rho_n n_\mu
\]

(20)

where \(n_\mu\) is the electron density. For electrically neutral matter, (19) shows that current elastic collisions cancel out for protons and electrons, and only neutrinos provide a contribution to \(J^\nu\):

\[
J^\nu = -i \rho_n n_\mu.
\]

(21)

As a result, the neutrino equation of motion, obtained by averaging the Lagrangian over matter, corresponds to the following Hamiltonian in the flavor basis:

\[
\begin{align*}
\tilde{H}_{\nu} - 
\frac{\rho_n}{2v}(\bar{\nu}_\tau (1 + \gamma_5) \nu (1 + \gamma_5) + \bar{\nu}_i (1 + \gamma_5) \nu_i + \bar{T}_i \gamma_5 (1 - \gamma_5) \nu_i \nu_i).
\end{align*}
\]

(23)

4. Let us begin by considering the case where there is no electromagnetic field, so that the helicities are not reversed. The matrix \(C_\tau\) then describes the effect of matter on the oscillations of left-handed neutrinos, first considered by Wolfenstein. The contribution of neutrinos to \(C_\tau\) is then the same for all neutrino types, and is unimportant for oscillations, whereas the contribution of electrons leads to a striking and potentially exceedingly important effect, discovered by Mikheev and Smirnov, which can be summarized as follows. Let us suppose that \((m^2)_{\nu_e} < (m^2)_{\nu_\mu}\) or \((m^2)_{\nu_\tau}\), to be specific, we shall consider \(n_e\) and \(n_{\nu_e}\). If the density \(n_e(\tau)\) is such that

\[
\tilde{H}_{\nu} = \left[(m^2)_{\nu_\mu} - (m^2)_{\nu_e}\right]/2E,
\]

(24)

the difference \(\tilde{H}_{\nu} - \tilde{H}_{\nu_e}\) between the diagonal matrix elements is then zero. This corresponds to "level crossing," well-known in quantum mechanics. If \(n_e(\tau)\) varies sufficiently slowly and passes through the value given by (24), and if there is slight mixing \((\tilde{H}_{\nu},\tilde{H}_{\nu_e})\), neutrinos of a given type will adiabatically transform into neutrinos of the other type. In our example, \(v_{\nu_e} = v_{\nu_\mu}\) will transform to \(v_{\nu_\mu} = v_{\nu_e}\). The adiabatic condition then requires that the characteristic length \(L\) for a change in \(n_e\) must satisfy the condition

\[
L > 2E/(m^2)_{\nu_e}.
\]

(25)

Mikheev and Smirnov have analyzed numerically the solution of the neutrino evolution equation and found that the mechanism they have discovered is effective for solar neutrinos in a very wide range of values of \(m^2\) and mixing angles. (Typical intervals for \(E=10^6\) MeV are \(10^{-6} eV^2 < \Delta m^2 < 10^{-4} eV^2, \sin^2 2\theta < 10^{-3}\).)

5. When spin precession in a magnetic field is considered, the difference between \(C_\tau\) and \(C_{\mu}\) becomes significant because it lifts the degeneracy of the left- and right-handed components. Let us consider the simplest case of one neutrino type in a uniform magnetic field \(H|_{z}=H=\text{const}\) in constant-density matter, so that \(\Delta C = C_\tau - C_{\mu}\) = const. Discarding the unimportant phase factor, the solution of (14) can then be written in the form

\[
\psi(z) = \psi(0) \exp [(i\mu H_{\tilde{C}} - \Delta C)z/2] v_{\nu_e} = [\cos \alpha + i(\mu H_{\tilde{C}} - \Delta C)z/2] \sin \alpha \nu_{\nu_e},
\]

(26)

where \(\alpha = [(\mu H_{\tilde{C}}^2 + (\Delta C/2)^2)]^{1/2}\). If the initial state \(v(0)\) is a pure left-handed state, the number of left- and right-handed neutrinos at the point \(z\) is then, respectively, given by

\[
N_{L} = \cos^2 \alpha + \sin^2 \alpha \nu_{\nu_e}, \quad N_{R} = \sin^2 \alpha \nu_{\nu_e},
\]

(27)

where \(\tan 2\theta_{\nu_e} = 2\mu H / \Delta C\). These two expressions correspond to the usual picture of the oscillations with mixing angle \(\theta_{\nu_e}\). It is clear that the mixing angle is a maximum \((|\theta_{\nu_e}| = \pi/4)\) for \(\Delta C = 0\), and that this angle is always less than \(\pi/4\) for \(\Delta C \neq 0\). The necessary condition for effective modulation of the left-handed neutrino flux is therefore

\[
2\mu H > \Delta C.
\]

(28)

When \(\mu = 10^{-11} \mu_B\) and \(H = 10^3 G\), this condition demands that the electron density must be less than \(10^{-23} \text{cm}^{-3}\) in the case of the electron-neutrino, and \(\Delta C\) is due to the interaction between charged currents. For the other neutrino types, the limit on the neutrino density for \(T^\nu = 0\) is \(n_{\nu_\mu} \lesssim 2 \times 10^{10} \text{cm}^{-3}\). If, on the other hand, \(T^\nu = 1\), the left- and right-handed nonelectron neutrinos are degenerate even in the presence of matter of any density.

In the opposite limit from (28), i.e.,
spin precession is strongly suppressed, and the beam consists mostly of the $v_L$.

4. THE SUN AND POSSIBLE CONSEQUENCES FOR SOLAR NEUTRINOS

1. Neutrino spin precession cannot be observed under terrestrial laboratory conditions because, when $\mu = 10^{-10} \mu_B$, the field $H$ necessary to turn the spin through an angle of unity over a path length $L$ is given by

$$HL = 1.8 \times 10^9 \text{ G cm.}$$

2. The solar radius $R_s$ is about $7 \times 10^{10}$ cm. The core, in which the nuclear reactions providing the Sun with its energy take place, accounts for about a quarter of the radius. We note, however, that neutrino generation occurs in this region mostly as a result of the reaction $pp - d + e^+ + v_e$, in which the maximum energy of the $v_e$ is 0.42 MeV, and is below the detection threshold of the Cl–Ar method.¹ High-energy neutrinos from $^3He$ and $^8B$, recorded in Ref. 1, originate from the central, hottest part of the core, whose radius amounts to only $3 \times 10^{10}$ cm (see Ref. 19 for the flux calculations). The radiative transfer zone (so called because of the way in which heat is transferred by turbulent convection. This zone contains the currents responsible for global magnetic fields with the 22-year (quasi) periodicity, and the modulus of the magnetic field has an 11-year cycle. During solar-active years, the magnetic field in the convective zone has a toroidal structure (it points in the azimuthal direction). The strength of this field can be judged from the sunspot field²⁰ ($H = 2 \times 10^7 - 4 \times 10^8$ G). The sunspots are regions in which the lines of force of the $B$ field that has “floated up” to the surface either leave or enter the Sun. It is therefore very likely that, during the years of solar activity maximum, the magnetic field in the convective zone is of the order of a few kG. The field $H$ may increase to some extent between the surface and the bottom of the convective zone. The 22-year component of the field cannot penetrate the radiative heat-transfer zone because of the jump in the magnetic permeability ($\sim 1$ in the radiative transfer zone and $\sim 10^{-5}$ in the convective zone).²¹ While the Sun remains quiet at the minimum of the 11-year cycle, the field in the convective zone decreases by at least an order of magnitude.²² (A more detailed account of the structure of the Sun and its magnetic field can be found in the literature.)²³

2. Thus, the product of the average (within the convective zone) field $H$ and the depth $L$ of the zone may reach $HL = 3 \times 10^{15} - 10^{14}$ G cm. The estimate given by (30), therefore suggests that, for $\mu = 10^{-10} \mu_B$, the flux of left-handed neutrinos measured in Ref. 1 was effectively modulated during the 11-year cycle. If the product $\mu HL$ does not reach $1/2$, the flux recorded for the active Sun should be a minimum; the maximum flux should, at any rate, be reached at the activity minimum. The possibility of this type of anticorrelation first emerged as a result of the analysis of experimental data²⁴ in Ref. 22 (see Ref. 23 for a discussion of possible time variations in the data of the Davis group with other periods). Figure 3 shows a graph taken from Ref. 1, in which the neutrino flux data are compared with the number of sunspots characterizing the solar activity. There is a clear reduction in the neutrino flux during the solar activity maximum in 1979–1980. However, the experimental uncertainties are very large and the statistical significance of the anticorrelation effect is still not clear.

Another possible effect requiring a shorter time of observation is the seasonal (semianual) variation in the recorded flux of high-energy neutrinos. This effect is due to the fact that the sign of the magnetic field in the convective zone is different in the Northern and Southern Hemispheres, and is therefore zero at the equator. The transition region covers the latitude interval $\pm (5° - 7°)$, which corresponds to distances of $\pm 6 \times 10^7 - 8 \times 10^7$ cm from the equator. (The reduction in the field near the equator is reflected in the fact that there are no sunspots at these latitudes.) On the other hand, the plane of the Earth’s orbit (the plane of the ecliptic) makes an angle of $71.5°$ with the plane of the solar equator. This means that, when the Earth lies in the plane of the solar equator (at the beginning of June and the beginning of December), the central part of the core, whose diameter is $3 \times 10^7$ cm and in which the boron and beryllium neutrinos originate, is seen from the Earth through the equatorial “slit” in the magnetic field, and the flux of left-handed neutrinos should be maximum. Conversely, at the beginning of March and the beginning of September (maximum distance from the plane of the solar equator), the strong-field region will lie in the field of view of the terrestrial neutrino detector during the years of the active Sun, and the recorded flux should change because the neutrino helicity is reversed. (When $\mu HL \leq 2$, the minimum current should occur at the beginning of March and of September.) Seasonal variations should become weaker as the solar activity falls, and may disappear altogether during the years of the quiet Sun.

We emphasize that the last effect is not well-defined for $p p$-neutrinos because the size of the region in which these

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FIG. 3. Graph taken from Ref. 1 and showing the rate of production of $^{37}$Ar as a function of time (annual averages are reproduced) and the number of sunspots (right-hand scale).

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neutrinos originate ($R_{\odot}/\ell \simeq 1.7 \times 10^{10}$ cm) is greater than the size of the equatorial gap in the magnetic field.

Figure 4 shows the semianual phase diagrams for the solar active years 1979–1980 (solid line) and for 1975–1978 and 1983–1984 (dashed line). Arrow 1 shows the time of maximum distance of the Earth from the plane of the solar equator and arrow 2 shows the time when the Earth crosses this plane.

The flux observed by the Davis group is so low as compared with the theoretical calculations sometimes explained by supposing that the solar core contains a frozen-in (primal) magnetic field of the order of $10^4$ G, and that $v_{\nu}$ has an EMM of about $10^{-13} \mu_B$, so that the neutrinos are completely depolarized by the magnetic field (and the flux of left-handed neutrinos is reduced by a factor of two). The estimates given in Section 3 inequalities (28) and (29) show that the interaction between $v_{\nu}$ and matter then excludes depolarization even for $p \leq 10^{10} \mu_B$, the condition for the absence of depolarization by the frozen-in field is more stringent (but can be satisfied). Actually, the random primeval field in the solar interior should be $H_{\ell} \sim r^{1/3}$ (the condition for the frozen-in flux in matter). Hence, to satisfy condition (3), it is sufficient to satisfy the inequality given by (33) for the lowest density, i.e., on the surface of the radiative transfer zone (where, we recall, $\rho \simeq 0.2 \text{g/cm}^3$). If we take into account the estimates given above, this leads us to an upper limit for the frozen-in primeval field immediate-
ly under the surface of the radiative transfer zone: $H_{p} \leq 10^{6}$ G for $v_{e}$ and $H_{p} \leq 10^{5}$ G for $v_{\mu}$ and $v_{\tau}$. If $H_{p} \approx 10^{6}$ G, the corresponding limits on the frozen-in field near the solar center are $H_{p} \leq 10^{5}$ G and $H_{p} \leq 10^{5}$ G. As far as we know, there is no evidence against these limits for $H_{p}$.

5. MAGNETIC MOMENT AND DETECTORS OF SOLAR NEUTRINOS

It is clear from the foregoing discussion that, because the neutrino mass and electromagnetic matrices are not adequately known, there is a range of possibilities, and a choice must be made between them by using different detectors with different energy thresholds. For example, if the $v_{e}$ has an EMM $< 10^{-10}$ $\mu$B, and oscillations are unimportant, the boron and beryllium neutrinos detected with the Cl-Ar detectors26 are the only two possible variations for $v_{e}$. For $v_{\mu}$ and $v_{\tau}$, there are only the 11-year variations and the semiannual variations should be weak. If oscillations and the Mikheev-Smirnov effect are significant, the corresponding limits on the frozen-in field near the solar center are $H_{\rho} \leq 10^{5}$ G and $H_{\rho} \leq 10^{5}$ G. For $v_{\mu}$ and $v_{\tau}$, the oscillation-independent limits on the electromagnetic parameters of these neutrinos are being built for these neutrinos and superconducting indium detectors are being developed27, there are only the 11-year variations and the semiannual variations should be weak. If oscillations and the Mikheev-Smirnov effect are significant, the 11-year variations in the flux during this period should be particular interesting. In this respect, it is very interesting to consider the establishment of the electromagnetic properties of these neutrinos during the forthcoming solar activity maximum in the 1980s because the next solar activity maximum (the 1979-1980 peak was strong, judging by the number of sunspots). In this respect, it is very interesting to consider the possibility of solving the converse problem, i.e., the problem of monitoring the magnetic field in the interior of the Sun by using the neutrino flux. If it were possible to establish independently the electromagnetic parameters of the neutrino (e.g., by measuring the EMM of the $v_{e}$ in reactor experiments), this would enable us to perform quantitative studies of magnetic fields in the solar interior. At any rate, the time variation in the flux of solar neutrinos, regarded as a manifestation of the electromagnetic properties of these neutrinos, appears to us to deserve further theoretical and experimental study.

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21. I. Valukhovitch, Ya. B. Zel'dovich, and A. A. Raevska, Turkv calculated on the Sun (Turkish Dynamics in Astrophysics), Nauka, Moscow, 1980.
27. We are grateful to A. A. Raevska and P. V. Suzorov for a discussion of the structure of the solar magnetic field.
28. We are indebted to S. I. Blinnikov, A. A. Raevska, A. V. Turukov and L. R. Uyng"{u}f"{o}n for a discussion of the density distribution and isotropic composition in the Sun.

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