# Dynamics of electron neutrinos in a supernova and limitations on the magnetic moment of $\nu_e$

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If an electron neutrino has a magnetic moment $\mu \approx 10^{-11}\mu_B$, its helicity can undergo a complete resonant flip in that shell of the interior of a supernova where the density is $\rho \approx 10^{-12}$ g/cm$^3$. Consequently, and in contrast with assertions in the literature, such a value of $\mu$ not only does not contradict neutrino data on SN1987A but also can explain the mechanism for the ejection of supernova envelopes.

It was suggested some time ago that the temporal variations in the flux of solar neutrinos, which the data of the experiment of Davis *et al.*[1] seem to imply, might be explained on the basis of a rotation of the spin of the neutrinos in the magnetic field in the solar convection zone. This rotation would occur because the electron neutrinos would have a magnetic moment $\mu \approx (1\text{–}10)\times 10^{-11}\mu_B$ (Refs. 2 and 3); ($\mu_B = e/2m_e$ is the Bohr magneton; and we are using a system of units with $\hbar = c = 1$). This value of $\mu$ is many orders of magnitude higher than that predicted by the minimal standard electroweak model. Confirmation of this value would be definite evidence for the existence of new particles and/or new interactions.

In a paper written by Dar[4] before the observation of the supernova SN1987A, similar values of $\mu$ were invoked to explain the mechanism for the ejection of supernova envelopes. Dar's mechanism[4] can be summarized as follows: Left-hand electron neutrinos $\nu_L$ produced in the hot ($T\sim 50$ MeV) central core of the supernova convert into right-hand neutrinos $\nu_R$ by virtue of their magnetic moment as they are scattered by electrons and protons. This conversion occurs in a time shorter than the time required for the neutrinos to diffuse out of the interior ($\sim 10$ s). The mean free path of right-hand neutrinos is far greater than the size of the interior, and these neutrinos carry energy out of it. According to Dar,[4] the neutrinos then become depolarized in the magnetic field in the envelope (with $\rho \sim 10^6$ g/cm$^3$). As a result of the weak scattering, the $\nu_L$s transfer some of their energy to the envelope, causing it to be ejected. In this mechanism, the energy spectrum of the neutrinos emitted by a star corresponds to the initial temperature of the central core, corrected for the gravitational redshift. It is harder than that in the standard analysis[5] of cooling with $\mu = 0$. Consequently, the observation of neutrinos from SN1987A with a spectrum in semiquantitative agreement with the standard spectrum (with a temperature $T\sim 3$ MeV) has recently been used[6–8] to find upper limits on $\mu$: $(10^{-14}\text{–}10^{-12})\mu_B$.

In Dar's paper[4] and also in some subsequent papers, however, the mechanism of the adiabatic resonant conversion[1] $\nu_R \rightarrow \nu_L$ was disregarded and was not mentioned. As we will show below, it is extremely probable that this conversion occurs at

$\mu \approx 10^{-11}\mu_B$ in a shell with a density $\rho_0 \approx 10^{12}$ g/cm$^3$. At this density, the matter of the interior would still be completely opaque to left-hand neutrinos, so the diffusion of the $\nu_L$s would subsequently establish a neutrinosphere with a temperature close to the standard temperature ($T \sim 3$ MeV), and no contradiction of the neutrino data on SN1987A would arise. At this value of $\mu$, the original ejection of the $\nu_R$s from the core would occur in a time of[4,8] $10^{-2}$ s, and the rapid energy transport into a layer with a density $\rho_0$ should give rise to a shock wave, which would propagate away from the center and which could be responsible for the ejection of the supernova envelope.

In our estimates we are thinking of a value $\mu \approx 10^{-11}\mu_B$, since (on the one hand) such a value is permitted by the latest limitations based on an analysis of white dwarfs[11,12] and helium stars,[13] while (on the other) it might be sufficient[14] to explain the variations in the flux of solar neutrinos.

The evolution equations for the helicity of electron neutrinos along the radius in a medium with a magnetic field $B$ transverse with respect to $\mathbf{r}$ are[3]

$$i d\nu_L/dr = C_L(r)\nu_L + \mu B(r)\nu_R\,, \qquad i d\nu_R/dr = \mu B(r)\nu_L\,. \tag{1}$$

The amplitude $C_L(r)$ is due to a coherent weak interaction of left-hand neutrinos with the medium, and for $\nu_e$ it is given by $C_L = \sqrt{2G}\,(n_e - n_n/2)$, where $G$ is Fermi's constant, and $n_e$ and $n_n$ are the densities of electrons and neutrons, respectively. For definiteness, we are ignoring both a possible mixing of the neutrinos and a mass, which would be unimportant for the processes under consideration here. Writing $C_L$ in terms of the (number) abundance $Y$ and the density $\rho$, we have

$$C_L = \frac{G\rho}{\sqrt{2}\,m_p}\,(3Y_e - 1)\,. \tag{2}$$

Here we have used $Y_e = Y_p$ and $Y_n + Y_p = 1$. The quantities $Y_n$ and $Y_p$ also incorporate the neutrons and protons bound in nuclei. It can be seen from (2) that in a shell with $Y_e = 1/3$ the amplitude $C_L(r)$ crosses zero, and there is a resonance in the precession of the neutrino spin. Estimates (Refs. 15 and 16, for example) yield values of $Y_e$ at the center which are no greater than 0.3 immediately after the formation of a central core with a density $\rho_c \sim 8\times10^{14}$ g/cm$^3$, while in the outer layers with $\rho \sim 10^9$ g/cm$^3$ the value of $Y_e$ would be typical of iron, $Y_e \approx 0.46$. Consequently, $Y_e$ definitely passes through the value of 1/3. According to detailed calculations,[16] this event occurs at a density $\rho = \rho_0 \approx 10^{12}$ g/cm$^3$, near which, over the interval from $(1/3)\rho_0$ to $3\rho_0$, the behavior can be parametrized approximately as $Y_e - 1/3 \approx -0.02\ln(\rho/\rho_0)$.

Adopting the simplest model,[5] in which the density of the core outside the central core—i.e., at $r > R_c \approx 10$ km—is parametrized in the form $\rho(r) \sim \rho_c(R_c/r)^3$, we find that this resonance occurs at a radius $R_0 \approx 10\,R_c \approx 100$ km, and the adiabatic condition,[9] which in this case becomes a condition on the magnetic field $B$ which would be required at this radius, takes the form

$$\mu B(R_0) \gtrsim \left(0{,}02\,\frac{9G\rho_0}{\sqrt{2}\,m_p R_0}\right)^{1/2} \approx 6\times10^{-3}\,\mathrm{cm}^{-1}. \tag{3}$$

(Strictly speaking, the adiabatic condition requires a strong inequality, but in practice, even in the case of the equality, only about 1% of the neutrinos will fail to undergo a conversion as they cross the resonance.) From (3) with $\mu \approx 10^{-11}\ \mu_B$ we find $B(R_0) \gtrsim 2\times 10^{12}$ G. The assumption of a field of this magnitude at the density $\rho_0$ is by no means extreme (cf. Refs. 4 and 6).

The length parameter in estimate (3) is $l \approx 1.5$ m. [Therefore, in particular, Eqs. (1) ignore the imaginary part of $C_L$, since the range of the $\nu_L$s with a characteristic energy of 100 MeV at $\rho \approx \rho_0$ is $\lambda \sim 100\ \text{m} \gg l$.] A complete conversion of the helicity of the neutrinos occurs over a distance on the order of $\pi l$. Nowhere outside this thin shell could there be a precession of the neutrino spin, because it would be blocked by the amplitude[3] $C_L$, provided that the magnetic field was not several orders of magnitude greater than the value corresponding to estimate (3) with the law $B \propto \rho^{2/3}$. Finally, we note that, in contrast with the Mikheev-Smirnov-Wolfenstein effect, the condition for this resonance and the adiabatic condition do not depend on the energy of the neutrinos.

These estimates are of course based on models, and the models themselves ignore the mechanism which we have been discussing for a rapid energy transport away from the center of the interior to the periphery. At best, this approach could be legitimate for only the first ejection of $\nu_R$s from the center, i.e., during the first $10^{-2}$ s. A detailed numerical analysis would be required for a self-consistent incorporation of this mechanism in the overall dynamics of the supernovae.

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[1)] A complete conversion of neutrinos in an adiabatic resonant regime of oscillations has attracted widespread interest in connection with the Mikheev-Smirnov-Wolfenstein effect.[9] A possible resonant precession of the spin of neutrinos in the case of a flavor—nondiagonal magnetic moment has been discussed by Akhmedov.[10]

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