Limit on the Magnetic Moment of the Neutrino from Supernova 1987A Observations

Riccardo Barbieri
Dipartimento di Fisica, Università di Pisa, Pisa, Italy, and
Sezione di Fisica, Istituto Nazionale di Fisica Nucleare, Pisa, Italy

and

Rabindra N. Mohapatra
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
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We consider the possible emission of right-handed neutrinos ν_R from SN1987A by neutrino-magnetic-moment interactions. By imposing a bound on the ν_R luminosity, we get a limit on the neutrino magnetic moment, $\mu_\nu < (0.2\text{–}0.8)\times 10^{-11}\mu_B$, depending on the core temperature. It appears that consideration of the number of high-energy ($E\simeq 100\text{–}200$ MeV) neutrino events that should have been observed in the underground detectors, after $\nu_R \rightarrow \nu_L$ rotation in the galactic magnetic field, may lead to a stronger bound, $\mu_\nu < (10^{-13}\text{–}10^{-12})\mu_B$, under specific assumptions.

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In recent years, a nonvanishing magnetic moment of the neutrino[1] has been suggested as a possible solution to the solar neutrino puzzle.[2] If we express the neutrino magnetic moment μ_ν as $\mu_\nu = \mu_{10}\times 10^{-10}\,\mu_B \equiv \mu\mu_B$, where μ_B is the Bohr magneton ($\mu_B = e\hbar/2m_e c$), solution of the solar neutrino puzzle requires[1-3] $\mu_{10}\simeq 1$. With such a large magnetic moment, a significant fraction of the neutrinos emitted by the sun will be rotated by the magnetic field in the sun to right-handed neutrinos, which are sterile with respect to observation of weak interactions and will therefore escape detection. This mechanism has the interesting and testable feature that the intensity of solar neutrinos on Earth should be correlated with the eleven-year sunspot cycle[2] and, further, a semiannual variation of the solar flux should be expected. On the theoretical side, it would provide us with solid hints regarding new physics beyond the standard model. It is, therefore, of a great deal of interest to study the implications of such a large value of μ_ν in other cosmological as well as astrophysical settings. It was pointed out by Morgan[4] sometime ago that unless $\mu_{10}\lesssim \frac{1}{10}$, the conventional big-bang nucleosynthesis will be disrupted by the excitation of the additional right-handed neutrino degree of freedom. It has also been pointed out that[5] a large μ_ν would lead, via rapid plasmon decay $\gamma^* \rightarrow \nu\bar{\nu}$ in stars, to rapid stellar cooling unless $\mu_{10}\leq 0.7$. A recent examination[6] of the energy loss of helium stars has led to an improvement of the above constraints to the level of $\mu_{10}\leq 0.08$, which is already perhaps too small to account for the solar neutrino deficit.

In this Letter, we consider the impact of a nonzero μ_ν on the supernova SN1987A. Our basic observations can be summarized as follows. Immediately after collapse, in the superdense, hot core ($\rho\simeq 8\times 10^{14}$ g/cm^3, $T = 30\text{–}70$ MeV)[7,8] right-handed neutrinos[9] can be produced predominantly via $\nu_L e^- \rightarrow \nu_R e^-$ and $\nu_L p \rightarrow \nu_R p$ scattering. The large mean free path of the ν_R's, as compared to the core radius ($R\simeq 10^6$ cm), allows them to escape, at least for $\mu_{10}\lesssim 1$. In order that ν_R emission, not too rapidly, cool the hot neutron star in a time $\lesssim 1$ s, we require that the ν_R luminosity Q_{ν_R} be less than 10^{53} ergs/s. {We have arrived at this number by assuming that the integrated luminosity implied by IMB (Irvine-Michigan-Brookhaven) and Kamiokande observations account for almost all the binding energy [$\sim(2\text{–}4)\times 10^{53}$ ergs] released in the core collapse. Therefore, the integrated luminosity allowed for ν_R's can at most be $\leq 10^{53}$ ergs. Using the fact that ν_R's are emitted over 10 s, we expect $Q_{\nu_R}\leq 10^{52}$ ergs/s. To be on the safe side, we have assumed $Q_{\nu_R}\leq 10^{53}$ ergs/s.} In this way, mainly depending on the value chosen for the core temperature, we can set a bound on the magnetic moment,

$$\mu_\nu \lesssim (0.2\text{–}0.8)\times 10^{-11}\mu_B, \tag{1}$$

comparable to the one obtained from the cooling of helium stars.[6] Right-handed neutrino production by plasmon decay is shown to be negligible in the case of the supernova.

A better limit can be obtained by our considering the possibility that ν_R ($\bar{\nu}_R$) are turned back into ν_L ($\bar{\nu}_L$) by flipping their spins in the galactic magnetic field, $B_g \gtrsim 10^{-6}$ G.[10] Since for a traveled distance D the flipping phase is

$$\phi \simeq \mu_\nu B_g D, \tag{2}$$

the condition $\phi\gtrsim 1$ is met for $D=50$ kpc ($\simeq$the distance to SN1987A) provided $\mu_\nu \gtrsim 10^{-14}\mu_B$. The point now is that these reflipped neutrinos, although being less copious than the standard low-energy neutrinos ($E\simeq 10\text{–}20$ MeV) emitted from the neutrinosphere, have a considerably larger mean energy, $E\simeq 200\text{–}300$ MeV. As such, through their ν_L component, they would have given rise to a large number of unobserved (high energy) neutrino events, by interacting with underground detectors via the charged-current neutrino-oxygen cross section growing as E^2. By our computing the number of expected ν_L events with an energy $E \gtrsim 60$ MeV, a limit can be set on the neutrino magnetic moment,

$$\mu_\nu \lesssim (0.1\text{–}1)\times 10^{-12}\mu_B. \tag{3}$$

This limit, although showing an even stronger core-temperature dependence than in Eq. (1), is about 2 orders of magnitude better. Notice that the limit in Eq. (3) is not restricted by the flipping condition, Eq. (2), but rather by the number of unobserved neutrino events. Notice also that the flipping of the spin inside the star is unlikely to occur, because of the large density, which gives rise to a large coherent forward-scattering amplitude of ν_L ($\bar\nu_L$) and blocks[3] the helicity flip by the magnetic field inside the star.[11]

In view of the various uncertainties, we shall take, following Ref. 8, a simplified picture of the inner core immediately after collapse, with approximate constant density $\rho \simeq 8\times 10^{14}$ g/cm^3, temperature $T=30$–70 MeV, and volume $V \simeq 4\times 10^{18}$ cm^3. Furthermore, for $t \lesssim 0.5$–1 s we shall take constant electron, proton, and neutrino relative density numbers $Y_e \simeq 0.3 \simeq Y_p$ and $Y_\nu \simeq 0.04$.[7] This corresponds to degenerate electrons and ν_L's with respective chemical potentials (for $T=60$ MeV)

$$\tilde\mu_e \simeq 280 \text{ MeV}, \quad \mu_\nu \simeq 160 \text{ MeV}. \tag{4}$$

For comparison we shall also consider the case of an almost completely deleptonized star, with $\tilde\mu_e = \tilde\mu_\nu = 0$. As we said, ν_R production in the stellar core is dominated by $\nu_L e^- \to \nu_R e^-$ and $\nu_L p \to \nu_R p$, with all other reactions ($\nu_L e^+ \to \nu_R e^+$, $\bar\nu_L e^\pm \to \bar\nu_R e^\pm$, $e^+e^- \to \bar\nu_L \nu_R$) being less important, because of either the initial particle phase spaces or lower cross section. On the other hand, the mean free path for the inverse process $\nu_R e^- \to \nu_L e^-$ and $\nu_R p \to \nu_L p$ is always longer than the core radius for $\mu_\nu \lesssim 5\times 10^{-11}\ \mu_B$. In this case the luminosity of the supernova core for ν_R emission is given by

$$Q_{\nu_R} = Q^e_{\nu_R} + Q^p_{\nu_R},$$

where

$$Q^e_{\nu_R} = V\left(\prod_{i=1}^{4}\int \frac{d^3p_i}{2E_i(2\pi)^3}\right) E_4 n_e(E_1) n_\nu(E_2)[1-n_e(E_3)]\,|M_e|^2 (2\pi)^4 \delta^{(4)}(p_1+p_2-p_3-p_4). \tag{5a}$$

Here $n_e(E)$, $n_\nu(E)$ are the usual Fermi functions corresponding to the chemical potentials (4), while the factor $1-n_e(E_3)$ accounts for the Pauli blocking of the final electron. A similar expression holds for $Q^p_{\nu_R}$ with the difference that the Pauli blocking is not important in this case, i.e., $1-n_p \simeq 1$. Finally the squared matrix element $|M_a|^2$, for scattering off electrons ($a=e$) and protons ($a=p$), summed over spins is given by

$$|M_a|^2 = \frac{2e^4}{m_e^2}\mu^2 \frac{t(s-m_a^2)(u-m_a^2)}{(t-m_D^2)^2}, \tag{5b}$$

where s, t, u are the usual Mandelstam variables and m_D is the Debye mass, which, for a highly relativistic, degenerate electron plasma, is $m_D = \omega_p \approx (4\alpha/3\pi)^{1/2}\tilde\mu_e$.[12] In order to compute the total ν_R luminosity, we first note that the contribution of both the protons and the electrons is the same and we get

$$Q_{\nu_R} = V\frac{\pi\alpha^2}{m_e^2}\mu^2 Y_e Y_\nu \frac{\rho^2}{m_p^2} T F\left(\frac{\tilde\mu_e}{T}, \frac{\tilde\mu_\nu}{T}, \frac{m_D}{T}\right), \tag{6}$$

and the dimensionless function F can be computed numerically. For T ranging from 30 to 60 MeV we find

$$Q_{\nu_R} = (4-40)\times 10^{55}\mu_{10}^2 \text{ ergs/s}. \tag{7}$$

With the limit $Q_{\nu_R} \lesssim 10^{53}$ ergs/s, Eq. (7) can be converted into the limit given in Eq. (1). The violation of this bound would lead to too rapid a cooling of the supernova core and thereby quench the emission of the thermal neutrinos observed in various underground detectors.[13]

We note that the lepton degeneracy, present in the supernova core at least for $t \lesssim 1$ s, is determinant in getting the result of Eq. (7). Had we computed the ν_R luminosity for $\tilde\mu_e = \tilde\mu_\nu = 0$, we would have obtained a value of Q_{ν_R} always smaller than (7) by 1 order of magnitude at least even at the highest T.

As observed previously, ν_R emission can also occur by plasmon decay, which turns out in part to be a most dangerous process in helium stars. This is not the case in the supernova core. From Refs. 5 and 6 one gets (for nondegenerate neutrinos)

$$Q^{\text{plasmon}}_{\nu_R} \simeq V\frac{\alpha\mu^2}{16\pi^2 m_e^2} m_D^4 T^3 \tag{8}$$

which, for $m_D \simeq (4\alpha/3\pi)^{1/2}\tilde\mu_e \simeq 15$ MeV, is always negligible compared to Eq. (7). If neutrinos are degenerate, $Q^{\text{plasmon}}_{\nu_R}$ is further suppressed.

We turn now to the spectrum of the emitted right-handed neutrinos. We are interested in their interactions with the large-volume water Cherenkov detectors after helicity flip by the galactic magnetic field. At the energies of interest, $E \approx 200$ MeV, far above threshold, the cross section for $\nu_L + \text{O} \to e^- + \text{F}$ becomes comparable to that for $\bar\nu_L p \to e^+ n$,[14] which dominates at lower energies, $E \approx 10$ MeV. On the other hand, the neutrino degeneracy suppresses the $\bar\nu_R$ production compared to the ν_R production by about 1 order of magnitude. Therefore, after the helicity precession in the galactic magnetic field (i.e., $\nu_R \to \nu_L$) it is the nuclear cross section $\nu_L + \mathrm{O} \to e^- + \mathrm{F}$ which is relevant in the calculation of the number of induced neutrino events. For this cross section in the energy range of interest, we shall take[14]

$$\sigma(\nu_L + \mathrm{O} \to e^- + \mathrm{F}) = \sigma_0 E^2,$$

where

$$\sigma_0 = 10^{-43}\,\mathrm{cm}^2\,\mathrm{MeV}^{-2}. \tag{9}$$

The number n of ν_R produced per unit time and unit energy is given by the same expression as Eq. (5) with the factor E_4 replaced by $\delta(E_4 - E)$. We are not directly interested in this differential flux but rather in the number of events produced by the interaction of these neutrinos, assuming about half of them get their helicity flipped while crossing the galactic magnetic field, with a larger-volume (mass M) water Cherenkov detector via Eq. (9).[15] The number $dN(E > E_0)/dt$ of these events for neutrinos of energy $E > E_0$ is

$$\frac{dN(E>E_0)}{dt} = \frac{1}{2}\,\frac{1}{18}\,\frac{M}{m_p}\,\frac{\sigma_0}{4\pi D^2}\int_{E_0}^{\infty} E^2 dE \frac{dn}{dE\,dt}$$

$$= \frac{1}{2}\,\frac{1}{18}\,\frac{M}{m_p}\,\frac{\sigma_0}{4\pi D^2} V \frac{\pi\alpha^2}{m_e^2}\mu^2 Y_e Y_n \left(\frac{\rho}{m_p}\right)^2 T^2 G\left(\frac{\tilde{\mu}_e}{T}, \frac{\tilde{\mu}_\nu}{T}, \frac{m_{\mathrm{D}}}{T}, \frac{E_0}{T}\right), \tag{10}$$

where again the dimensionless function G can be computed numerically. Because of the predominance of higer-energy neutrinos G shows weak dependence on E_0 for $E_0 \lesssim 60$ MeV. For the $M = 5$ kiloton IMB detector we find, for $T = 30$ to 60 MeV,

$$\frac{dN}{dt}(E \gtrsim 60\ \mathrm{MeV}) = (0.2\text{–}20) \times 10^5 \mu_{10}^2\,\mathrm{s}^{-1}. \tag{11}$$

Since in the IMB data sample[13] all neutrinos have an energy lower than 60 MeV, the limit given in Eq. (3) can be inferred. It is, of course, conceivable, though rather unlikely, that the phase shift is exactly 2π so that the emitted ν_R's appear at the earth as ν_R's. If such were to be the case, the bound in Eq. (3) would not hold. It is also conceivable that there are new interactions that are strong enough to cause trapping of ν_R's in the supernova core. In this case, one can avoid both the bounds in Eq. (1) and (3).

In conclusion we find that presently known information about the supernova SN1987A enables us to set a significant bound on the magnetic moment of the neutrino. Although plagued by the uncertainties of the models of the supernova core, this limit would perhaps rule out a magnetic-moment effect as a possible solution of the solar neutrino problem. If, however, only the bound in Eq. (1) is taken seriously, it is only a factor of 3 lower than what is required to solve the solar neutrino puzzle.[1]

Finally, we wish to comment on the phase-flipping condition in Eq. (2). In deriving Eq. (2), we assumed a uniform magnetic field of 10^{-6} G throughout the flight path of the ν_R's. It is, however, believed that a typical distance scale over which we expect that field B to be coherent is 100 pc and there are roughly 500 such coherent regions. It is, therefore, more appropriate to use a random-walk approximation,[16] which implies that we replace the distance D in Eq. (2) by $D_{\mathrm{eff}} \simeq (\sqrt{500}) \times 100$ pc $\simeq 2.2 \times 10^3$ pc. The condition $\phi \gtrsim 1$ is then satisfied for $\mu_\nu \gtrsim 0.3 \times 10^{-13} \mu_e$. This leaves our final conclusion in Eq. (3) unaffected.

After completion of this paper we recieved a paper by Lattimer and Cooperstein[17] dealing with the same matter. Based on rough estimates of the supernova energetic this paper claims a limit $\mu \lesssim 10^{-12}$. This paper also observes the possibility of the rotation of the neutrino helicity in the galactic magnetic field. We think that our work contains complementary information.

The same matter was also briefly considered by Nussinov and Rephaeli,[18] who suggest a limit $\mu < 10^{-14}$, by assuming a rotation of ν_L into ν_R in the supernova magnetic field, and barring the doubling of the original ν_L flux consequently required to explain observations. As mentioned, the flipping condition in the supernova is unlikely to be met. Furthermore, in view of the various uncertainties, a doubling of the original neutrino flux does not appear excluded at the present level of knowledge. (This same remark applies as well to the work of Lattimer and Cooperstein.) Making reference to an unpublished work by Dar, Nussinov and Rephaeli also suggest a limit in the range $10^{-12} < \mu < 4 \times 10^{-10}$ from the nonobservation of high energy ν_L's, after reflipping ν_R into ν_L in the magnetic field of the core. We have discussed quantitatively this effect, which is expected from the rotation in the galactic magnetic field, as explained.

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