Implications of the Supernova SN1987A Neutrino Signals

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The neutrino events from the supernova SN1987A observed by the Kamiokande II and Irvine-Michigan-Brookhaven detectors are used to suggest constraints on neutrino physics. In particular, bounds on the value of the electron neutrino magnetic moment $\mu_{\nu_e} \lesssim (10^{-12}\text{-}10^{-13})\mu_B$ are suggested.

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The duration, spectra, and intensities of the SN1987A neutrino pulses[1,2] are, within the limited statistics and ambiguities of the analysis, in accord with the standard collapse scenario.[3-5] The large propagation distance suggested the possibility of a (mild) improvement of the terrestrial bounds on m_{ν_e}.[6-8] The strong magnetic field likely to be present around the collapsing core and the fairly high values of the total energy emitted via neutrinos, inferred by most authors, suggest the very strong bound $\mu_{\nu_e} \lesssim (10^{-13}/B_{12}^{-1}R_6^{-1})\mu_B$ with μ_B the (electron) Bohr magneton, $B_{12}=B/(10^{12}\text{ G})$, and $R_6=R/(10^6\text{ cm})$, where B and R are the surface magnetic field and radius of the neutrinosphere, respectively. The ~5-10-s duration of the detected neutrino burst and the absence of very energetic ($E > 100$ MeV) events imply a weaker but less model-dependent bound, $\mu_{\nu_e} \lesssim 10^{-12}\mu_B$. These bounds are far smaller than the experimental upper bound[9] $\mu_{\nu_e} \leqq 2\times10^{-10}\mu_B$ and the value $\mu_{\nu_e} \sim 10^{-10}\mu_B$ suggested[10] as a possible explanation for solar neutrino puzzle.

We present next the arguments for these bounds and the (interesting) scenarios in which the stronger one can be avoided.

Neutrino energetics.—The estimated values of $W_\nu = W_{\nu_e} + W_{\bar\nu_e} + \cdots + W_{\bar\nu_\tau}$, the total energy emitted via neutrinos, depend on the distance to SN1987A and on the modeling of the neutrino spectra and time structure, the neutrino-water interactions, and the core collapse itself. The original estimate of Hirata *et al.* [Kamiokande (KII) collaboration],[1] $W_{\bar\nu_e} \sim 8\times10^{52}$ ergs, yields, when multiplied by a factor 7-8.3,[4] accounting for the energy in the other species, $W_\nu = (5.6\text{-}6.6)\times10^{53}$ ergs. This value is only marginally consistent with a standard collapse yielding a residual neutron star. The total (gravitational plus nuclear) binding of a "canonical" $M \simeq 1.4M_\odot$ neutron star is $\simeq 3\times10^{53}$ ergs and the maximal binding [for $M \simeq (1.8\text{-}2)M_\odot$] is $(6\text{-}7)\times10^{53}$ ergs, depending on the nuclear-matter equation of state.[11-15] The Bionta *et al.* [Irvine-Michigan-Brookhaven (IMB)] data[2] give a lower $W_{\bar\nu_e}$; however, recently the IMB collaboration[16] estimated it to be $\simeq 6\times10^{52}$ ergs, close to the above KII estimate. Subsequent estimates,[17-21] which often incorporated the IMB data—with a much higher energy threshold and different experimental systematics—obtain W_ν values in the range $(3\text{-}7)\times10^{53}$ ergs.

It is worth noting that numerical simulations yield neutrino energy spectra which deviate from a thermal distribution,[21,22] implying higher estimates for the neutrino luminosity than those obtained by the assumption of a thermal spectrum. In particular, the fit of a thermal spectrum to the IMB data, which correspond to the high-energy wing of the spectrum, overestimates the effective temperature and underestimates the total energy. Also, the recent analysis[23] of the five Baksan events, which occurred in coincidence with the KII and IMB events, implied W_ν which is $\simeq 2\text{-}3$ times larger than that of the KII experiment. While the statistical significance is not high, this also supports the higher range of the energy estimates.

Duration of the neutrino burst.—The standard scenario predicts a neutrino burst of ~5-10-s duration, corresponding to the diffusion time of the thermal neutrinos trapped inside the core.[5,24] The duration of the detected neutrino burst from SN1987A is consistent with the above prediction.

Effects of nonzero ν_e magnetic moment.—A nonvanishing ν_e magnetic moment can lead to $\nu_e^L \to \nu_e^R$ (or $\bar\nu_e^R \to \bar\nu_e^L$) flips via ν_e-e scatterings in the dense core, to $L \leftrightarrow R$ precessions in the strong magnetic field outside the neutrinosphere, and to $L \leftrightarrow R$ precessions in the galactic magnetic field. The observed neutrino events reflect the compound effect of all these processes.

(i) *The range* $10^{-10}\mu_B \gtrsim \mu_{\nu_e} \gtrsim 10^{-12}\mu_B$.—Values of μ_{ν_e} in the range $10^{-10}\text{-}10^{-11}\mu_B$ were previously suggested[10] to explain the suppression of solar neutrino counts and also its apparent correlation with the solar-flare cycle. For the range[25] $10^{-10}\mu_B \gtrsim \mu_{\nu_e} \gtrsim 10^{-12}\mu_B$ the scattering $\nu_e^L + e \to \nu_e^R + e$ flips the spin of the ν_e which in the standard picture ($\mu_{\nu_e}=0$) would have been trapped in the core for a few seconds. The "sterile" ν_e^R escape from the core before a thermal equilibrium of all neutrino species is established and will cool the core very efficiently, on a time scale $\lesssim 1$ s. This implies that the observed pulse duration should be far shorter than that predicted by the standard model. The ~5-10-s duration of the events observed in the KII and IMB detectors is consistent with the standard model of neutrino trapping, and thus a bound $\mu_{\nu_e} \lesssim 10^{-12}\mu_B$ follows.

Unless the escaping sterile neutrinos are later converted into "active" ones, the total detected neutrino energy should also be drastically reduced. Thus, the primary energy output required to produce the observed total energy far exceeds the binding energy of a neutron star. An appreciable transformation of sterile into active neutrinos by a precession either in the magnetic field outside the core[25] or in the galactic magnetic field implies a nonthermal component of very energetic neutrinos ($E \gtrsim 100$ MeV). The detected average ν_e energies are much lower ($\simeq 15$ MeV). Thus neither alternative, regeneration or no regeneration, is acceptable. This provides additional support to the above bound, $\mu_{\nu_e} \lesssim 10^{-12}\mu_B$.

(ii) *The range* $\mu_{\nu_e} \lesssim 10^{-12}\mu_B$.—Could a more stringent limit on μ_{ν_e} be drawn from the data? Let us consider the precession of $\nu_e^L \rightarrow \nu_e^R$ due to the presence of a magnetic field. In order for the precession not to be quenched by ν_L scatterings it is required[25] that $\mu_{\nu_e} B \gtrsim 2^{-1/2} G_F n_e$, where G_F is the Fermi coupling constant and n_e is the electron number density. This implies a condition on the matter density:

$$\rho \lesssim 1.5 \times 10^5 \chi_{-13} B_{12} (Y_e/0.1)^{-1} \text{ g cm}^3,$$

where $B_{12} = B/(10^{12}\text{ G})$, $\chi_{-13} = 10^{13}\mu_{\nu_e}/\mu_B$, and Y_e is the electron fraction. Note that surface fields exceeding 10^{13} G were estimated for neutron stars in pulsars.[3,26] These field strengths correspond to "aged" neutron stars and since the field is expected to decay in time, it may well be that the initial field is even higher (flux freezing during collapse yield up to $\simeq 10^{15}$ G). In particular, if the collapsing core is fast rotating the field can be amplified because of winding up of field lines.[27,28]

The above condition for nonquenching cannot be satisfied inside the neutrinosphere, where $\rho > 10^{11}$ g cm^{-3}, unless χ_{-13} is orders of magnitudes larger than 1; could it be satisfied outside the neutrinosphere? The answer depends on whether a prompt or delayed explosion took place in SN1987A. The prompt explosion mechanism[29] that operates (marginally) for small cores ($M \lesssim 1.3 M_\odot$) produces just outside the neutrinosphere densities of $\simeq 10^{10}$ g cm^{-3} which quench the B precession for the μ_{ν_e} values of interest here.

In the delayed-explosion scenario of Wilson *et al.*,[24] an extremely sharp density drop develops at the neutrinosphere for $t \gtrsim 0.5$ s so that just outside the neutrinosphere $\rho \sim 10^5$ g cm^{-3}; thus quenching is avoided so long as $\chi_{-13} B_{12} \gtrsim 1$. This results in a precession angle $\alpha \gtrsim 10 \chi_{-13} B_{12} R_6 \gtrsim 10$. Since different neutrinos sample the magnetic field at different locations this will yield on the average $\langle \cos^2\alpha \rangle \sim \frac{1}{2}$, reducing by a factor of ~ 2 the number of detectable neutrinos emitted after $\simeq 0.5$ s. Since $\simeq 80\%$ of the total neutrino energy is emitted at times later than $\simeq 0.5$ s, the estimates of W_ν should be multiplied by a factor of ~ 1.8. So only the lowest estimates of W_ν mentioned above could be consistent with a neutron-star formation. If a neutron star indeed forms then the bound $\mu_{\nu_e} \lesssim 10^{-13} B_{12}^{-1} \mu_B$ is suggested.

Although it was also suggested otherwise,[30] there are indications that indeed the delayed-explosion scenario is the one relevant for SN1987A. First, the apparent 0.1-0.3-s oscillations in the timing of the neutrino events are in accord with the predictions of this scenario.[20] Also, the high main-sequence mass of the progenitor of SN1987A [$(20\text{-}25) M_\odot$] leads to cores too massive for the prompt mechanism to take place.[24] Such masses produce a neutrino light curve[21] which is consistent with that of SN1987A. Moreover, W_ν for main-sequence masses of $(20\text{-}25) M_\odot$[21,31] is consistent with the apparent high estimate of W_ν from the KII experiment.[1]

It should be noted that the stronger bound obtained here is more model dependent than $\mu_{\nu_e} \lesssim 10^{-12}\mu_B$ obtained above. It relies on reasonable but not directly testable assumptions concerning the values of the magnetic field and the matter density outside the neutrinosphere, in the first seconds following core collapse.

(iii) *Precession in the galactic magnetic field.*—The galactic magnetic field ($B \sim 10^{-6}$ G on scales of order kiloparsecs) will yield a precession angle $\alpha \sim 1$ for $\mu_{\nu_e} \gtrsim 10^{-12}\mu_B$; however, unlike in the vicinity of the neutron star this precession is the same for all the neutrinos and thus it imparts an unknown amount of equal precession. This precession would not change an equal mixture of active and sterile neutrinos but otherwise can either reduce or enhance the detected signal. To see this point, consider a case in which the fractions of active ($\nu_e^L, \bar{\nu}_e^R$) and sterile ($\nu_e^R, \bar{\nu}_e^L$) neutrinos emitted from the supernova are f_A, f_S, respectively ($f_A + f_S = 1$). For a precession angle α caused by the galactic magnetic field one gets at the detector the fractions $f_A' = \cos^2\alpha f_A + \sin^2\alpha f_S$, $f_S' = \cos^2\alpha f_S + \sin^2\alpha f_A$. Thus if $f_A = f_S = \frac{1}{2}$ then indeed $f_A' = f_S' = \frac{1}{2}$ but otherwise one can get f_A' larger or smaller than $\frac{1}{2}$. Consider the case in which $\mu_{\nu_e} \gtrsim 10^{-12}\mu_B$ and $f_A \ll f_S \sim 1$ as a result of $\nu_A e \rightarrow \nu_S e$ scattering in the core which because of the quenching effect is unaccompanied by the reverse ($\nu_S \rightarrow \nu_A$) magnetic precession outside the neutrinosphere. One cannot conclude that the detected signal will be strongly suppressed since if $\sin^2\alpha \sim 1$ then one gets $f_A' \sim 1$ and the active component is fully revived. A value of $\sin^2\alpha > 0.9$, which has a 10% probability to occur, will cause a 90% revival.

(iv) *Effects of off-diagonal* $\mu_{\nu_e\nu_\mu}\ldots$ and $\mu_{\nu_\mu\nu_\mu}\ldots$.—So far, we have discussed only effects of a diagonal magnetic moment $\mu_{\nu_e\nu_e}$. In most particle-physics models it is quite difficult[32] to obtain "large" values of $\sim(10^{-10}\text{-}10^{-13})\mu_B$. The models that do allow such values[33] typically invoke large flavor mixing and hence one cannot avoid also effects of nonvanishing $\mu_{\nu_e\nu_\mu}$, $\mu_{\nu_\mu\nu_\mu}$, etc. If $\mu_{\nu_\mu\nu_\mu} \sim 10^{-9}\mu_B$, $\mu_{\nu_e\nu_\mu} \sim 10^{-10} M_B$, and $\mu_{\nu_e\nu_e} \sim 10^{-12}\mu_B$ the time structure of the detected neutrinos could be modified.[34] This results from the fact that the generated ν_e^R can flip back inside the core into ν_μ^L before escaping; thus the ν_μ^L and ν_μ^R equilibrate and stay trapped in the core for a few seconds. The full discussion of such effects is, however, beyond the scope of the present paper.

The black hole possibility.— Numerical simulations[24] indicate that progenitors with masses $\gtrsim 25M_\odot$ produce a massive iron core ($\sim 2M_\odot$) which collapses to form a "hot" neutron star. The latter cools via neutrino emission over a time scale of a few seconds while it accretes matter and eventually a black hole forms.[24] In this case one can obtain "high" values of $W_{\bar{\nu}_e}\sim 11\times 10^{52}$ ergs. The high value $W_{\bar{\nu}_e}=8\times 10^{52}$ ergs of the original Kamiokande II estimate could motivate the possibility of a black hole formation.[35] The many subsequent estimates of W_ν, which are lower than $W_\nu\sim(6\text{-}7)10^{53}$ ergs, weaken the motivation for this scenario.

If a black hole forms, the bound on the magnetic moment derived in (i) above stays but we lose the stronger μ_{ν_e} bound derived in (ii) above. This would be a small "price" in consideration of the importance of such a potential discovery. The "collapse pursuit and plunge"[36] multicore collapse scenarios, suggested[37,38] in order to explain the Kamiokande "seven second gap," could lead to a black hole.

The nature of the collapsed object formed in SN1987A could be eventually decided by future radio, optical, and x-ray observations. If it is a neutron star, then detection of a thermal x-ray emission from its surface could possibly also restrict its radius and mass, tightening the estimate of the theoretically expected W_ν and putting the μ_{ν_e} bound on a firmer basis.

Decaying neutrinos.— If ν_μ and ν_τ are heavier than ν_e, then the invisible decays of the heavy neutrino $\nu_H \rightarrow \nu_e+X^0$, with X^0 an axion or majoron, could occur. For a dimensionless $\nu_H\nu_e X^0$ coupling g, heavy-neutrino mass $m_{\nu_H}\equiv m \gg m_{\nu_e}$, and energy E_ν, we can show[39] that a decay ν_e will be delayed by $\Delta t\sim 4\pi/g^2E_\nu$ with respect to a simultaneously emitted "direct" ν_e. For $E_\nu\sim 10$ MeV we find that $\Delta t\lesssim 1$ s, provided that $g^2\gtrsim 10^{-20}$. In this case, the decay neutrinos are indistinguishable from the direct ν_e ($\bar{\nu}_e$) and will simply add up and enhance the ν_e ($\bar{\nu}_e$) signal.

Since $\sigma_{\bar{\nu}_e}\sim E_\nu^2$, neutrinos of higher energies are more easily detected. The energy sharing between the decay products of $\nu_H\rightarrow \nu_e+X^0$ is partially compensated by the higher energies expected for ν_μ and ν_τ.[5,21] The net effect of the decays will be to enhance the observed ν_e ($\bar{\nu}_e$) signal by factors 2-3. If such a decay, which is of interest on its own right, occurs, it could compensate for the decrease in W_ν due to $\mu_{\nu_e}\neq 0$.

We find it very intriguing that an interplay of particle physics and astrophysics can suggest the bound $\mu_{\nu_e}\lesssim 10^{-13}\mu_B$. It is worth pointing out that the large values $10^{-11}\mu_B\lesssim\mu_{\nu_e}\lesssim 10^{-10}\mu_B$, though motivated by the systematics of the solar neutrino counting, are almost unattainable in any "standard" extension of the present weak plus electromagnetic gauge models.[32] This is not the case for $\mu_{\nu_e}\lesssim 10^{-13}\mu_B$ and the bound suggested here is therefore a useful probe to new physics.

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[1] K. Hirata *et al.* (Kamiokande II Collaboration), Phys. Rev. Lett. **58**, 1490 (1987).

[2] R. M. Bionta *et al.* (IMB Collaboration), Phys. Rev. Lett. **58**, 1494 (1987).

[3] S. L. Shapiro and S. A. Teukolsky, *Black Holes, White Dwarfs and Neutron Stars* (Wiley, New York, 1983).

[4] J. N. Bahcall, A. Dar, and T. Piran, Nature (London) **326**, 135 (1987).

[5] A. Burrows, J. M. Lattimer, Astrophys. J. **307**, 178 (1986); S. E. Woosley and T. A. Weaver, Annu. Rev. Astron. Astrophys. **24**, 205 (1986).

[6] J. N. Bahcall and S. L. Glashow, Nature (London) **326**, 476 (1987).

[7] D. Arnett and J. Rosner, Phys. Rev. Lett. **58**, 1906 (1987).

[8] E. W. Kolb, J. Stebbins, and M. S. Turner, Phys. Rev. D **35**, 3598 (1987).

[9] See, e.g., A. Cline, to be published.

[10] L. B. Okun, M. B. Voloshin, and M. I. Vysotsky, Zh. Eksp. Teor. Fiz. **91**, 754 (1986) [Sov. Phys. JETP **64**, 446 (1986)].

[11] W. D. Arnett and R. L. Bowers, Astrophys. J. Suppl. Ser. **33**, 415 (1977).

[12] V. Canuto, B. Datta, and G. Kalman, Astrophys. J. **221**, 274 (1978).

[13] N. K. Glendenning, Astrophys. J. Lett. **293**, L170 (1985).

[14] J. L. Friedman, J. R. Isper, and L. Parker, Astrophys. J. **304**, 115 (1986).

[15] C. Alcock, E. Farhi, and A. Olinto, Astrophys. J. **310**, 261 (1986).

[16] R. Svoboda *et al.* (IMB Collaboration), in Proceedings of the European Space Organization Workshop on the Supernova 1987A, edited by I. J. Danziger (to be published), p. 229.

[17] D. N. Spergel, T. Piran, A. Loeb, J. Goodman, and J. N. Bahcall, Science **237**, 1471 (1987).

[18] A. Borrows and J. Lattimer, Astrophys. J. Lett. **318**, L63 (1987).

[19] J. Arafune and Fukugita, Phys. Rev. Lett. **59**, 367 (1987).

[20] K. Sato and H. Suzuki, Phys. Rev. Lett. **58**, 2722 (1987).

[21] R. Mayle, J. R. Wilson, and D. Schramm, Astrophys. J. **318**, 288 (1987).

[22] H. T. Janka, in *Nuclear Astrophysics,* edited by W. Hillebrandt *et al.* (Springer-Verlag, New York, 1987).

[23] E. N. Alexeyev, L. N. Alexeyeva, I. V. Krivosheina, and V. I. Volchenko, in Ref. 16, p. 237.

[24] J. R. Wilson, R. Mayle, S. E. Woosley, and T. A. Weaver, Ann. NY Acad. Sci. **470**, 207 (1986).

[25] A. Dar, to be published. It has been suggested by Dar, prior to SN1987A, that the escaping "sterile" neutrinos could undergo a precession in the magnetic field outside the core, $\nu_e^R\rightarrow\nu_e^L$, transforming $\simeq$50% of the sterile ν_e^R into "active"

energetic ν_e^L, whose large nuclear cross section could help the supernova explosion.

[26] R. Narayan, Astrophys. J. **319**, 162 (1987).

[27] G. S. Bisnovatyi-Kogan, Astron. Zh. **47**, 813 (1970) [Sov. Astron. **14**, 652 (1970)].

[28] W. Kundt, Nature (London) **261**, 673 (1976).

[29] Woosley and Weaver, Ref. 5.

[30] E. Baron, H. A. Bethe, G. E. Brown, J. Cooperstein, and S. Kahana, Phys. Rev. Lett. **59**, 736 (1987).

[31] S. E. Woosley, J. R. Wilson, and R. Mayle, Astrophys. J. **302**, 19 (1986).

[32] M. S. Duncan, J. A. Grifols, A. Mendes, and S. Uma-Sankar, Phys. Lett. B **191**, 304 (1987).

[33] M. Fukugita and T. Yanagida, Phys. Rev. Lett. **58**, 1807 (1987).

[34] S. Nussinov and Y. Rephaeli, Phys. Rev. D **36**, 2278 (1987).

[35] S. Nussinov, I. Goldman, G. Alexander, and Y. Aharanov, Nature (London) **329**, 134 (1987).

[36] R. Ruffini and J. A. Wheeler, in Proceedings of the European Space Research Organization Conference on Space Physics, Paris (to be published), p.45.

[37] T. Nakamura and M. Fukugita, in Ref. 16, p. 355.

[38] I. Kovner, to be published.

[39] The intrinsic laboratory decay times are given by $\tau(\nu_H \to \nu_L + X^0) = 8\pi g^2 m$ and $\tau_{\text{lab}}(\nu_H \to \nu_L + X^0) = \gamma\tau = 8\pi E/g^2 m^2$. The time delay due to the initial slower propagation of ν_H is on the average $\Delta t = (m^2/2E^2)\tau_{\text{lab}} = 4\pi/g^2 E = g^{-2} \times 10^{-22}$ s. The same time delay occurs when the initial ν_H emerges at an angle α with respect to the supernova-earth direction and is then redirected to earth by the decay $\nu_H \to \nu_L + X^0$. The laboratory decay angle is $\theta \sim \alpha \sim m/E$ and the additional length of the initial ν_H tilted path is again $c\tau_{\text{lab}}\theta^2/2 = (c\tau_{\text{lab}}/2(m/E^2)^{-2}$.