Bounds on Exotic-Particle Interactions from SN1987A

Georg Raffelt

Astronomy Department, University of California, Berkeley, California 94720, and
Institute for Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, Livermore, California 94550

and

David Seckel

Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, Santa Cruz, California 95064
(Received 26 October 1987)

The observation of a neutrino pulse from the supernova SN1987A constrains the production of light exotic particles in the proto neutron star. We derive a new bound on the axion decay constant, $f_a \gtrsim 10^{10}$ GeV. If right-handed (RH) neutrinos exist, the "RH Fermi constant" is $G_{\rm RH} \lesssim 10^{-4} G_{\rm F}$, 2 orders of magnitude below laboratory bounds. The Dirac mass of ν_μ can be constrained below laboratory limits.

PACS numbers: 97.60.Bw, 14.60.Gh, 14.80.Gt, 97.60.Jd

The recent supernova SN1987A in the Large Magellanic Cloud has triggered much excitement among particle physicists because the very first observation[1] of the neutrino pulse from a collapsing star allows one to use this astronomical event as a particle-physics laboratory.[2] The main effort has been directed toward extraction of information on neutrino masses, mixing parameters, and decay properties from the energy and time structure of the observed pulse. Furthermore, the measured neutrino pulse severely constrains the operation of an "exotic" cooling mechanism of the supernova (SN) core.[3] Therefore various species of light exotic particles (LEP's) cannot have been "overproduced" in the hot interior of the proto neutron star that has formed after collapse and so bounds on their interaction strengths can be derived. We shall use this argument to derive new and very restrictive limits on the axion decay constant, on right-handed weak currents, and on the Dirac masses of neutrinos.

To illustrate this argument we consider a LEP with a coupling strength g_x to ordinary matter. In Fig. 1 we show schematically how the luminosity in exotics, L_x, of the proto neutron star depends upon g_x. For small g_x, all LEP's freely escape so that L_x is proportional to g_x^2 and to a volume integral over the star. Therefore L_x increases with increasing g_x. However, the absorption cross sections also grow as g_x^2 until the star becomes "optically thick" for LEP's. In this situation the particles essentially emerge from the "LEP sphere" at a radius r_x, corresponding to an optical depth equal to unity. Then L_x may be approximated by blackbody emission from the LEP sphere so that $L_x \propto r_x^2 T^4(r_x)$. For the proto neutron star, $r^2 T^4(r)$ is a rapidly decreasing function of r so that L_x now *decreases* as g_x increases.

An application of these arguments to neutrinos shows that their coupling is on the "strong-interaction" side of Fig. 1, i.e., they are "trapped." Hence there will be a window of coupling strengths, $g_{\min} < g_x < g_{\max}$, where we may expect $L_x > L_\nu$. If g_x were to lie in this window, the gravitational binding energy, $E_{\rm tot}$, of the neutron star would be emitted primarily in LEP's. However, the neutrino pulse from SN1987A has been observed[1] and its characteristics agree well with theoretical expectations,[2] leaving little room for LEP emission, so that coupling strengths in this window may be excluded. We are mostly interested in determining $g_{\min}$ because, in many cases, other astrophysical arguments or laboratory data exclude couplings as strong as $g_{\max}$. Before we move on to a case-by-case study, we discuss how the energy lost to LEP's will change the neutrino signal and then consider

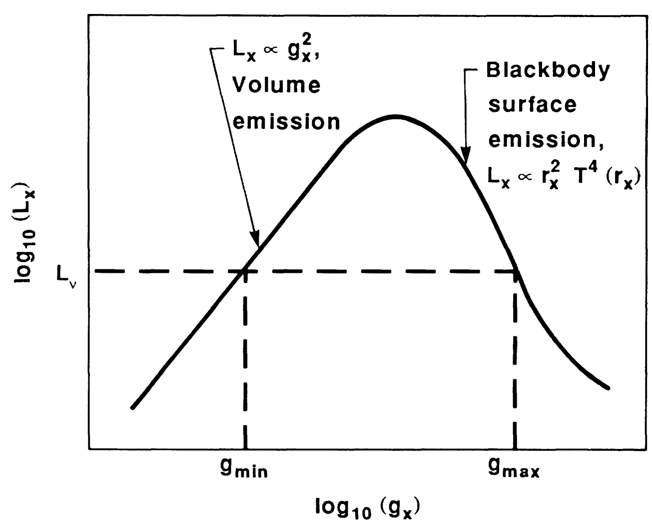

FIG. 1. Schematic dependence of L_x on the coupling strength g_x. The horizontal line denotes the neutrino luminosity L_ν. In the range $g_{\min} < g < g_{\max}$ the LEP emission L_x would exceed L_ν.

some general features of the emission rates.

The neutrino pulse observed from SN1987A implies $E_{\rm tot}=(1\text{-}4)\times10^{53}$ erg in neutrinos and continuous emission for at least[4] 5 s. This long time scale suggests that the remnant of the collapse was a neutron star[5] (not a black hole), implying an upper limit to the binding energy, $E_{\rm tot}<6\times10^{53}$ erg, and we shall assume that this is, indeed, the case. Examining the numerical models in detail one finds that roughly half the energy is emitted in the first second. We interpret this emission as due to energy deposited in the outer core by the formation and passage of the shock wave responsible for the SN explosion. It is difficult for LEP's to compete with this luminosity. The later neutrino signal, however, is interpreted as being due to the diffusive energy transfer from the core to the neutrino sphere and it is this part of the signal which is most susceptible to modification by LEP emission from the core. Therefore we believe that the most powerful way to constrain the LEP luminosity is the resulting cutoff of neutrino emission at late times rather than simple considerations of total energetics.

To estimate the time at which the neutrino signal is cut off for a given value of g_x we make use of a specific model provided to us by Mayle and Wilson.[6] It allows us to calculate $L_x(t)$ from the properties of the unperturbed model. We take into account the "back reaction" of the LEP emission on the star by lowering the momentary temperature profile by an overall factor $f(t)$, while all other physical parameters are left unchanged. We keep track of the energy emitted in LEP's, $E_x(t)=\int_0^t L_x(t')dt'$, and in neutrinos, $E_\nu(t)=\int_0^t L_\nu(t')dt'$ where $L_\nu(t)$ is taken to be the same as in the unperturbed model. Since the thermal energy density is dominated by the T^2 dependence for degenerate nucleons we set $f^2(t)=1-E_x(t)/[E_{\rm tot}-E_\nu(t)]$ where $E_{\rm tot}$ is the energy budget of the model. This procedure cuts off LEP emission at late times and keeps our "perturbed model" consistent with the requirement of energy conservation. Our modified neutron luminosity is then identical to the original luminosity, with a cutoff at the time when $E_x(t)+E_\nu(t)$ exceeds $E_{\rm tot}$. Our nominal bound on g_x is obtained by the requirement that this cutoff occurs at 5 s after collapse. Had we used 12 s instead,[4] the axion bound, for example, would have improved by a factor of about 2.

The model we have integrated has a core mass of $1.64M_\odot$ with a soft equation of state as described by Mayle and Wilson.[6] This model has $E_{\rm tot}=4.1\times10^{53}$ erg and a peak core temperature of $T_{\rm core}\approx75$ MeV. This large $T_{\rm core}$ results in large values for L_x. Nonetheless, we do not think that our constraints on g_x are unduly restrictive. Lower values for $T_{\rm core}$ would decrease L_x, but it would also imply a smaller core and/or a harder equation of state, either of which reduces $E_{\rm tot}$ and the time scale of neutrino emission. Such models have difficulties accounting for the observed neutrino signal even in the absence of LEP's. Increasing $E_{\rm tot}$, on the other hand, necessarily increases $T_{\rm core}$ and therefore L_x. In addition to this model uncertainty, there is some uncertainty associated with the use of L_ν from the "unperturbed" model. Doubtless, the real L_ν would be lower, but it is not clear how this would affect our bounds. Use of a lower L_ν would allow emission over a longer period and imply a weaker bound on g_x. However, the more realistic L_ν would have a lower mean energy per emitted neutrino which would result in an *observable* flux that may cut off even before 5 s. We do not believe that the uncertainties associated with our use of a single SN model and the unperturbed L_ν exceeds an order of magnitude. It would be desirable, of course, to corroborate our results by detailed numerical studies where the LEP emission is included self-consistently in a variety of SN models.

From our general argument, it is the SN *core* that dominates LEP emission. Therefore, we have to focus on processes involving nucleons because they are more abundant than leptons or photons. Moreover, the nucleons are less degenerate than the leptons so that the phase space available for nucleon reactions is larger. This requires a calculation of reaction rates at supernuclear densities, a state-of-the-art problem in nuclear physics. Instead, we have chosen to use several approximations. We ignore spatial correlations between nucleons, use one-pion exchange for nuclear interactions, and take the nucleon effective mass to be 0.8 GeV. We work in a nonrelativistic approximation and assume that degenerate fermions participating in an emission process lie on their Fermi surfaces. These assumptions allow us to concentrate on the LEP properties. At the same time they give us a handle on the nuclear-physics uncertainties which have been discussed by previous authors[7-9] using a similar set of approximations for their "lowest-order" calculations. From this previous work we conclude that such effects as nucleon correlation might reduce the emission rates by as much as an order of magnitude.

Thus, there are two major sources of uncertainty for our results. We cannot make our calculation of the LEP-emission rate more precise than an order of magnitude because of the difficult nuclear physics involved. Another order-of-magnitude uncertainty should be associated with our treatment of L_ν and choice of SN model. Thus, our limiting value for E_x is uncertain by as much as 2 orders of magnitude, which translates into a 1 order of magnitude uncertainty in our limiting value for g_x. This means that our actual *bound* on g_x is correspondingly weaker than our nominal result, while at the same time it means the LEP emission could have a significant effect on SN dynamics for g_x values much smaller than our limiting value.

Axions have been proposed as a solution to the *CP* problem of strong interactions[10] and they are among the most widely discussed hypothetical light particles. Their CP-invariant coupling to fermions j can be written as[11]

$$\mathcal{L}_{\rm int} = (c_j/2f_a)\bar{\psi}_j \gamma_\mu \gamma_5 \psi_j \partial^\mu a, \tag{1}$$

where a is the pseudoscalar axion field, f_a is the axion decay constant, and c_j is a model-dependent coefficient typically of order unity. We shall focus on "invisible" axion models where $f_a \gg f_{\rm weak} \approx 250$ GeV. From white-dwarf cooling times and from the observed evolution of red giants one infers[12,13] $f_a \gtrsim c_e \times 2\times 10^9$ GeV. In "hadronic" axion models, however, $c_e = 0$ so that no meaningful bound can be extracted. All models have an axion-photon coupling $\mathcal{L}_{a\gamma\gamma} = (c_\gamma a/4f_a)F_{\mu\nu}\tilde{F}^{\mu\nu}a$, and the lifetime of helium-burning red giants implies[14] $f_a \gtrsim c_\gamma \times 0.7 \times 10^7$ GeV. Moreover, in all models axions couple to nucleons through a mixing with the π^0, even if they have no direct coupling to the u and d quarks, so that bounds on the axion-nucleon coupling can be translated into robust bounds on f_a. Iwamoto[7] and later Tsuruta and Nomoto[15] have shown that axion cooling of neutron stars is in conflict with the observed surface temperatures of some pulsars of known age unless $f_a \gtrsim c_n \times 3\times 10^9$ GeV, with considerable uncertainty, however, because the emission rate is strongly suppressed if nucleon superfluidity occurs.

We have reevaluated[16] the axion emission rate from nucleon bremsstrahlung. For $n+n \to n+n+a$, our result is smaller by a factor of $\frac{1}{2}$ than Iwamoto's emission rate.[7] However, $n+p \to n+p+a$ is larger by a factor of about 2 if $c_p = 0$, and even more important otherwise. Following the procedure discussed earlier, we find the axion luminosity shown in Fig. 2. We conclude that, indeed, L_a is very small at first and cannot affect the onset of the neutrino signal, while axion emission will cut off L_ν at later times. Using the criterion discussed earlier, we find the nominal bounds $f_a > c_n \times 3\times 10^{10}$ GeV for $c_p = 0$ and a similar result with $c_p \leftrightarrow c_n$. For $c_p = c_n \equiv c_N$, we find $f_a > c_N \times 5\times 10^{10}$ GeV. Our constraints are more restrictive than all other lower bounds on f_a, even if we allow for the 1 order of magnitude uncertainty discussed above.

Light, right-handed (RH) neutrinos, i.e., $SU_L(2)$ singlets, could also play the role of LEP's. If RH weak currents exist, and if their structure is analogous to the left-handed (LH) interactions, we can scale the production rates for LH states with $\epsilon^2 = (G_{\rm RH}/G_{\rm F})^2$ to obtain the emissivity in RH neutrinos. $G_{\rm RH}$ is the "RH Fermi constant." The relevant processes are nucleon bremsstrahlung of $\nu\bar{\nu}$ pairs involving neutral currents (NC) to constrain $\epsilon_{\rm NC}$ and the Urca processes involving charged currents (CC), which give us a handle on $\epsilon_{\rm CC}$. The laboratory limit[17] is $\epsilon_{\rm CC} < 0.03$. Big-bang-nucleosynthesis constraints on the effective number of neutrino species yield[18] $\epsilon_{\rm NC} \lesssim 10^{-3}$. We stress that the SN is *simultaneously* sensitive to both types of RH currents. We have reevaluated the emission rates[16] and find them to be a factor of $\frac{1}{2}$ smaller than the results of Friman and Maxwell.[8] As with our axion calculation we find that np bremsstrahlung dominates over nn by about a factor of 3. Using the procedure discussed earlier, we find the nominal bounds $\epsilon_{\rm CC} < 3\times 10^{-5}$ for $\epsilon_{\rm NC} = 0$ and $\epsilon_{\rm NC} < 7\times 10^{-5}$ for $\epsilon_{\rm CC} = 0$. For NC we have used only one flavor so that for three flavors with equal $\epsilon_{\rm NC}$ our bound improves by a factor of $\sqrt{3}$.

Another possibility to produce RH neutrinos occurs through the helicity flip by a mass term. The dominant production process is elastic scattering of thermal neutrinos on nucleons where RH states emerge with a relative probability of $(E_\nu - |\mathbf{p}_\nu|)/(E_\nu + |\mathbf{p}_\nu|) \approx (m_\nu/2E_\nu)^2$. Our method yields a nominal bound on the Dirac mass $m_\nu < 20$ keV, which is more resitrictive than the laboratory bounds $m_{\nu_\mu} < 250$ keV and $m_{\nu_\tau} < 70$ MeV. For ν_τ we are confronted with a situation where the "strong interaction" side of Fig. 1 is not excluded by other evidence. We estimate that m_{ν_τ} above a few megaelectronvolts is still allowed.

We have shown that the observed neutrino pulse from SN1987A allows one to constrain such exotic-particle properties as the axion decay constant, the strength of RH weak currents, and the Dirac mass of neutrinos. Our effort has been directed toward extraction of reasonably safe bounds on the LEP properties, but we believe that there remains a 1 order of magnitude uncertainty in our results. A more detailed treatment of the nuclear-physics uncertainties, a self-consistent incorporation of

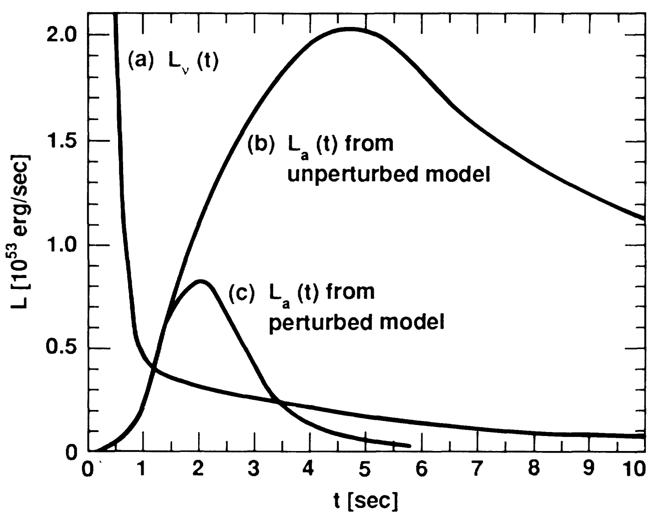

FIG. 2. Particle emission from the SN for the $1.64M_\odot$ model of Mayle and Wilson (Ref. 6). Curve a is the unperturbed neutrino luminosity $L_\nu(t)$. In this model, the prompt neutrino pulse is emitted at about 0.3 s. Curve b is the axion luminosity $L_a(t)$ from the unperturbed model for $f_a = 3.5\times 10^{10}$ GeV, $c_n = 1$, and $c_p = 0$. Curve c is $L_a(t)$ for the same parameters with the temperature adjustment described in the text. The luminosity given by curves $a+c$ exhausts the total-energy budget at about 5 s.

LEP emission in a SN code, a better knowledge of the electron-neutrino mass, and statistically more significant data from future supernovae would each allow one to improve the accuracy of these bounds. We imagine that our arguments would lead to new constraints for other cases such as anomalous neutrino magnetic dipole moments and scalar-quark masses in theories with light photinos.

While this work was in progress, we learned that similar conclusions concerning the axion bounds have been independently reached by other authors[19] who have employed somewhat different criteria to arrive at their results.

We thank T. Banks, A. Burrows, R. Sawyer, and S. Woosley for very helpful discussions and comments. We are particularly indebted to R. Mayle for providing us with numerical data of SN models[6] and for answering many questions on SN physics. At Berkeley and Livermore, this research was supported, in part, by grants from NASA and U.S. Department of Energy. At Santa Cruz, this research was supported by National Science Foundation Grant No. NSF-PHY-8415444.

[1]K. Hirata *et al.*, Phys. Rev. Lett. **58**, 1490 (1987); R. Bionta *et al.*, Phys. Rev. Lett. **58**, 1494 (1987).

[2]D. Schramm, Comments Nucl. Part. Phys. **17**, 239 (1987).

[3]J. Ellis and K. Olive, Phys. Lett. B **193**, 525 (1987).

[4]At Kamioka, neutrinos have been *observed* as late as 12 s, but it is not certain that these late events would not be due to such effects as dispersion of the pulse because of a nonzero m_{ν_e}. Thus it is not certain that neutrino *emission* from the SN lasted that long. For the last events in the Irvine-Michigan-Brooklyn (IMB) detector at 5 s, this caveat is much less severe because of their high energy which precludes a simple interpretation as a time-of-flight delay after emission.

[5]A. Burrows, private communication; R. Mayle, private communication.

[6]R. Mayle and J. Wilson, unpublished.

[7]N. Iwamoto, Phys. Rev. Lett. **53**, 1198 (1984).

[8]B. Friman and O. Maxwell, Astrophys. J. **232**, 541 (1979).

[9]P. Haensel and A. J. Jerzak, unpublished.

[10]For reviews see D. Kaplan, Nucl. Phys. **B260**, 215 (1985); M. Srednicki, Nucl. Phys. **B260**, 689 (1985).

[11]See Kaplan, Ref. 10. The seemingly equivalent use of $\mathcal{L}_{\rm int}=i(c_j m_j/f_a)\bar{\psi}_j\gamma_5\psi_j a$ may lead to incorrect cross sections unless one includes a dimension-5 term proportional to $\bar{\psi}_j\psi_j a\pi$ where π is the pion field. If we use the derivative axion coupling, Eq. (1), we reproduce the results of Iwamoto (Ref. 7), independently of whether we use a pseudoscalar or derivative structure for the pion-nucleon vertex. However, if we use a pseudoscalar form for both the axion-nucleon and pion-nucleon couplings and if we omit the dimension-5 term, we reproduce the results of A. Pantziris and K. Kang, Phys. Rev. D **33**, 3509 (1986). Thus, Iwamoto's result appears to be the correct emission rate in the one-pion exchange approximation.

[12]D. Dearborn, D. Schramm, and G. Steigman, Phys. Rev. Lett. **56**, 26 (1986); G. Raffelt, Phys. Lett. **166B**, 402 (1986).

[13]In Ref. 3, a more restrictive bound on c_e/f_a is derived from the neutrino pulse of SN1987A. We believe that this result is incorrect because of an overestimate of the emission rates by many orders of magnitude.

[14]G. Raffelt and D. Dearborn, Phys. Rev. D **36**, 2211 (1987).

[15]S. Tsuruta and K. Nomoto, in the Proceedings of the International Astronomical Union Symposium No. 124 on Observational Cosmology, Beijing, China, 1986 (to be published).

[16]Seckel and Raffelt, Ref. 11.

[17]See, e.g., A. Jodidio *et al.*, Phys. Rev. D **34**, 1967 (1986), and **37**, 237(E) (1988).

[18]See, e.g., K. Olive, D. Schramm, and G. Steigman, Nucl. Phys. **B180**, 497 (1981); J. Ellis *et al.*, Phys. Lett. **167B**, 457 (1986).

[19]M. Turner, following Letter [Phys. Rev. Lett. **60**, 1797 (1988)]; R. Mayle, J. Wilson, J. Ellis, K. Olive, D. N. Schramm, and G. Steigman, Phys. Lett. B (to be published).