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Massive Dirac Neutrinos and SN 1987A

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Abstract. The wrong-helicity states of a Dirac neutrino can provide an important cooling mechanism for young neutron stars. Based on numerical models of the early cooling of the neutron star associated with SN 1987A which self consistently incorporate wrong-helicity neutrino emission, we argue that a Dirac neutrino of mass greater than 30 keV (25 keV if it is degenerate) leads to shortening of the neutrino burst that is inconsistent with the IMB and KII data. If pions are as abundant as nucleons in the cores of neutron stars, our limit improves to 15 keV.

Introduction. The detection of antineutrinos from SN 1987A by the Kamiokande II (KII) [1] and Irvine-Michigan-Brookhaven (IMB) [2] detectors confirmed the standard model of core-collapse (type II) supernovae [3] and provided a "laboratory" to study the properties of neutrinos [4-7] and exotic particles such as axions [8]. In particular, previous work suggests that the KII and IMB data exclude a Dirac neutrino more massive than somewhere between 1 keV and 50 keV [5-7]. Evidence for a 17 keV neutrino eigenstate that mixes with the electron neutrino at the 1% level [9] motivates us to take a more careful look at the bound. (The absence of $\beta\beta0\nu$ decay in several isotopes suggests that such a neutrino is a Dirac or pseudo-Dirac fermion [10].) In this *Letter* we clarify the situation by presenting a bound that is based upon numerical cooling models that incorporate all relevant microphysics.

So far as neutron-star cooling goes it is the "wrong-helicity" states of a Dirac neutrino, ν_+ and $\bar{\nu}_-$, that are important. Were it not for the "mismatch" of helicity and chirality for a massive neutrino, they would be inert. Because of this mismatch ν_+ ($\bar{\nu}_-$) has a small projection, $\mathcal{O}(m_\nu/2E_\nu)$, onto ν_L ($\bar{\nu}_R$), and therefore can be produced by ordinary weak interactions through "helicity-flip" processes such as $\nu_-(\bar{\nu}_+) + N \to \nu_+(\bar{\nu}_-) + N$, $N + N \to N + N + \nu_+\bar{\nu}_+(\nu_-\bar{\nu}_-)$, or $\pi + N \to N + \nu_+\bar{\nu}_+(\nu_-\bar{\nu}_-)$ (N is a nucleon), with rates that are suppressed by a factor $\mathcal{O}(m_\nu^2/4E_\nu^2)$ relative to the nonflip processes. Since wrong-helicity neutrinos are practically inert, once produced they simply escape [11]; in contrast, proper-helicity neutrinos are "trapped" in the core and must diffuse out [3]. Because of this, wrong-helicity neutrinos can efficiently carry away energy and accelerate the cooling of young neutron stars. If their cooling effect were significant, it would have shortened the neutrino bursts from SN 1987A. The duration of the observed bursts (about 12 sec in KII and about 6 sec in IMB) is consistent with expectations in the "standard" cooling scenario, and previous mass limits [4-7] were based upon this "timing argument." However, no one of these studies is definitive; for example, the most detailed study [6], which used numerical cooling models, incorporated only the neutrino-nucleon spin-flip production process and did not consider the possibility that the Dirac species was degenerate.

The Model. Our strategy is to carefully model the neutrino signal expected in the KII and IMB detectors from the early cooling of the neutron star associated with SN 1987A with numerical cooling models that incorporate the standard cooling mechanism, thermal neutrino emission, and the additional cooling provided by wrong-helicity neutrinos. (A crucial feature of our work is taking account of the "back reaction" of wrong-helicity neutrino emission on the cooling of the neutron star and further wrong-helicity emission.) By comparing the neutrino bursts predicted by our "exotic" cooling models with those actually recorded we set a mass limit: Dirac masses greater than the limit lead to bursts that are too short to be consistent with those observed. (We refer the reader interested in more details to earlier analogous work constraining the mass of the axion [12].)

We begin with the Burrows-Lattimer numerical models of the cooling of a hot neutron star just after its formation [13-15]. In the standard scenario, the bulk of the binding energy of the neutron star ($\sim 3 \times 10^{53}$ erg) is released by intense thermal neutrino emission from a "neutrinosphere" ($T \sim 5\,\mathrm{MeV}$, $\rho \sim 10^{11}\,\mathrm{g\,cm^{-3}}$) over about 10 sec. Neutrino emission is divided into two phases: (1) The first second or so, powered by thermal energy in the outer part of the nascent neutron star, during which about half the binding energy is radiated (the source of the thermal energy is the release of gravitational binding energy as the nascent neutron star contracts and slow accretion continues); and (2) the bulk of the 10 sec, powered by thermal energy deep in the core, during which the other half of the binding energy is radiated. The timescale for the second phase—which determines the duration of the neutrino burst—is set by neutrino diffusion from the core to the neutrinosphere.

We have supplemented the Burrows-Lattimer models with the additional cooling provided by wrong-helicity neutrino emission [7]:

$$N + \nu_-(\bar{\nu}_+) \to N + \nu_+(\bar{\nu}_-); \tag{1a}$$

$$N + N \to N + N + \nu_+\bar{\nu}_+(\nu_-\bar{\nu}_-); \tag{1b}$$

$$p + \pi^- \to n + \nu_+\bar{\nu}_+(\nu_-\bar{\nu}_-). \tag{1c}$$

The volume emission rates ($\mathrm{erg\,cm^{-3}\,sec^{-1}}$) for these processes were calculated for arbitrary nucleon and neutrino degeneracy, assuming nonrelativistic nucleons. All three processes are "spin-flip" reactions, and so their rates are proportional to the neutrino mass squared. The rate for the pion process is very uncertain because it depends upon the number of pions in the core of the neutron star: Since neutron stars are on the verge of pion condensation this number could be very large, $n_\pi \gtrsim n_N$, or insignificant, $n_\pi \ll n_N$. Finally, the (proper-helicity) neutrino flux from our "exotic" cooling models along with the response functions for the KII and IMB detectors [1,2] are used to predict the characteristics of the detected neutrino bursts. In all cases we follow the cooling for 20 sec.

One final physics issue bears discussion: neutrino degeneracy. The post-collapse core has a significant lepton number, about 0.35/nucleon, which resides in electrons and electron neutrinos, and deep in the core both these species have a large chemical potential, $\mu_e \sim \mu_\nu \sim 100\,\mathrm{MeV} - 300\,\mathrm{MeV}$; the chemical potentials of the other leptons (ν_μ, ν_τ, μ) are zero. If the Dirac neutrino species mixes sufficiently with the electron neutrino, $\sin^2\theta \gtrsim 10^{-2}(\mathrm{keV}/m_\nu)^4$ (θ is the vacuum mixing angle between the Dirac neutrino and the electron neutrino), it will rapidly ($\ll 0.1$ sec) become degenerate due to ν-ν_e mixing. This significantly increases the energy density of the massive neutrino, in turn increasing wrong-helicity neutrino emission through the neutrino-nucleon scattering process [7].

Results. We begin with the nondegenerate case, $\sin^2\theta \lesssim 10^{-2}(\mathrm{keV}/m_\nu)^4$, as it corresponds most closely to previous work [6]. The wrong-helicity emission processes are very temperature dependent, $\varepsilon \propto T^4$ (spin-flip scattering) and $\varepsilon \propto T^{3.5}$ (bremsstrahlung), and thus emission is most important deep in the core. The emission of wrong-helicity neutrinos from deep in the core cannot directly affect neutrino emission from the neutrinosphere;

rather, its effect is to deplete the heat that powers the second phase of neutrino emission. The result of this depletion is clearly seen in Figs. 1a,b where we show the expected burst duration vs. neutrino mass for both detectors. *The length of the expected burst in the IMB detector is reduced to less than half of that of the detected burst for a neutrino mass of* 30 keV; *we take this to be our mass constraint.* Even for the largest masses, the length of the burst remains at about 1 sec as wrong-helicity emission hardly affects the first phase of neutrino emission. (Because of its lower energy threshold the KII detector is more "immune" to wrong-helicity neutrinos robbing the core of its heat.)

In Fig. 2 we show the amount of energy carried off by wrong-helicity neutrinos as a function of neutrino mass. For small masses the energy carried away by wrong-helicity neutrinos is negligible, and the energy scales as the neutrino mass squared (just as the emission rates); when the amount of energy emitted becomes significant back reaction is important: The cooling effect of wrong-helicity neutrino emission suppresses further emission, and the total energy radiated no longer increases as fast as m_ν^2. While the scattering and bremsstrahlung processes were expected to be of comparable importance [7], the scattering process is about eight times more important. This is explained by the fact that in our models nucleons are mildly degenerate, and Pauli blocking suppresses the bremsstrahlung process by about a factor of ten.

If the massive neutrino species is degenerate, $\sin^2\theta \gtrsim 10^{-2}(\,\mathrm{keV}/m_\nu)^4$, the situation changes. (We treat this regime by assuming that the chemical potential of the massive neutrino species is always equal to that of the electron neutrino.) Degeneracy has two direct effects on wrong-helicity neutrino emission. First, the energy density of the massive neutrino is increased:

$$\frac{\rho_{\nu\bar{\nu}}(\mu_\nu \neq 0)}{\rho_{\nu\bar{\nu}}(\mu_\nu = 0)} = \frac{15}{7\pi^4}\left(\frac{\mu_\nu}{T}\right)^4 + \frac{30}{7\pi^2}\left(\frac{\mu_\nu}{T}\right)^2 + 1; \tag{2}$$

this enhances spin-flip-scattering emission which is proportional to the total energy density in massive neutrinos (for the relevant conditions, a factor of $10-100$). Second, due to Pauli blocking, the bremsstrahlung processes with the $\nu_-\bar{\nu}_-$ final state are suppressed, reducing emission due to bremsstrahlung by up to a factor of two.

Because wrong-helicity neutrino emission is enhanced, one might expect the mass constraint to be more stringent. However, wrong-helicity neutrino emission also depletes the lepton number, reducing μ_ν—eventually to zero—and thereby quenching the enhanced emission. (Even in the absence of wrong-helicity emission the lepton number is reduced on a timescale of a few sec.) *In addition, wrong-helicity neutrino emission from a degenerate sea actually heats the core:* The average energy carried off by a wrong-helicity neutrino is $3\mu_\nu/4$. and the radiated neutrino is replaced by a neutrino from the Fermi surface (energy μ_ν), a heat release of $\mu_\nu/4$; in sum this amounts to close to 10^{53} erg. In the standard scenario, the heat release from the degenerate lepton sea is smaller because the lepton chemical potential varies smoothly from the interior of the star outward: see [14]. (More precisely, the local change in entropy density

$$\dot{s} = \mu_\nu \dot{n}_\nu - \dot{\varepsilon} \propto \frac{7\pi^4}{60} + \frac{\pi^2}{6}\left(\frac{\mu_\nu}{T}\right)^2 - \frac{1}{12}\left(\frac{\mu_\nu}{T}\right)^4; \tag{3}$$

where n_ν is the net number density of neutrinos and $\dot{\varepsilon}$ is the rate ($\mathrm{erg\,cm^{-3}\,sec^{-1}}$) at which wrong-helicity neutrinos carry away energy.)

In the end, the effect of degeneracy is not dramatic (see Figs. 1, 2). The total energy carried off by wrong helicity neutrinos increases by less than a factor of two; and using the same criterion as before, the mass constraint improves from 30 keV to 25 keV. The small effect of degeneracy traces to several factors: (i) μ_ν is big for at most a few sec (for $m_\nu = 30\,\mathrm{keV}$ the lepton number is radiated in about 0.3 sec); (ii) μ_ν is large in only about 40% of the core; and (iii) wrong-helicity emission heats the core slightly.

Finally, consider the pion emission processes, $p + \pi^- \to n + \nu_+ \bar{\nu}_+ (\nu_- \bar{\nu}_-)$. The rate for these processes depends upon the abundance of pions in the core which is very uncertain; *if* the pion abundance is comparable to the nucleon abundance, pion processes are expected to be much more important than spin-flip scattering or bremsstrahlung [7]. The thermal abundance of π^-'s relative to nucleons is

$$\frac{n_\pi}{n_N} = \frac{\zeta(3)T^3}{\pi^2 n_N} \simeq 7.2 \times 10^{-3} \frac{(T/30\,\mathrm{MeV})^3}{\rho/10^{14}\,\mathrm{g\,cm^{-3}}}; \tag{4}$$

where we have assumed that $\mu_\pi \ll T, m_\pi$ and that pions are ultrarelativistic, i.e., $T \gg m_\pi$ (since $T \not\gg m_\pi$, there will be Boltzmann suppression). Under these assumptions pions are too scarce to make the pion processes competitive. On the other hand, it is thought that the cores of neutron stars are on the verge of pion condensation ($\mu_\pi \sim m_\pi$). While the uncertainties are great, for illustrative purposes we have run cooling models that incorporate the pion processes, taking $n_\pi/n_N = 1$. In the nondegenerate case the pion process is about five times more important than spin-flip scattering, while in the degenerate case it is comparable. The mass constraint improves significantly, to about 15 keV in either case. If n_π/n_N is larger, the constraint is even more stringent.

Discussion. The mass limits derived only strictly apply to a pure Dirac neutrino. Suppose that the massive neutrino is not a pure Dirac, but also has a small Majorana mass: $m_M \ll m_\nu$; in this case ν_+-$\bar{\nu}_+$ ($\bar{\nu}_-$-ν_-) oscillations occur, with mixing angle in matter, $\sin 2\theta_m \simeq 2 \times 10^{-9}(m_M m_\nu/\mathrm{eV}^2)$. Such oscillations lead to wrong-helicity neutrinos "behaving" as proper-helicity antineutrinos a fraction $\frac{1}{2}\sin^2 2\theta_m$ of the time, which can lead to their trapping. A rough estimate of their mean free path is $2\sin^{-2} 2\theta_m$ times that of a proper-helicity neutrino (about 1 m). We assumed that once emitted wrong-helicity neutrinos simply escape, and so self consistency requires that their mean free path be larger than the core (about 10^6 cm), which occurs provided that $\sin 2\theta_m \lesssim 10^{-2}$. It follows that our constraints also apply to a Dirac neutrino with a small Majorana mass provided $m_M m_\nu \lesssim 6 \times 10^6\,\mathrm{eV}^2$—a condition met for any neutrino species that satisfies the primordial nucleosynthesis bound to the number of neutrino degrees of freedom [16].

Finally, let us address the uncertainties in our mass constraints. By their very nature astrophysical and cosmological bounds have irreducible uncertainties that are not easily quantified. Residual uncertainties here include our cooling models and finite-density effects. There is a certain degree of latitude in our cooling models; e.g., equation of state and residual accretion onto the neutron star. We have explored a variety of models that result in a neutrino signal that is consistent with those recorded in KII and IMB (without wrong-helicity neutrino emission), and the mass limits derived for these different models vary by about 10 keV. *We have based all out bounds on the cooling model that gave the least stringent mass limits* [15].

Since densities reach several times nuclear density in the cores of neutron stars, finite-density effects may be significant. For example, the effective nucleon mass can be reduced by a factor of order two: The spin-flip scattering process is insensitive to the nucleon mass, and the bremsstrahlung process actually increases with decreasing nucleon mass [7]. It has been suggested that the large nucleon-nucleon scattering rate leads to a significant suppression of the bremsstrahlung emission process [17]; while we are not convinced of the validity of this calculation, it leads to only a modest suppression of the bremsstrahlung process, about 10%. Last but not least, if pions are very abundant in the cores of neutron stars (as some calculations indicate; see [18]), wrong-helicity neutrino emission is significantly increased and the mass constraint improves.

In sum, we believe that a very *conservative* SN 1987A Dirac-neutrino mass limit is 30 keV if it is nondegenerate, i.e., $\sin^2\theta \lesssim 10^{-2}(\,\mathrm{keV}/m_\nu)^4$, 25 keV if it is degenerate, and 15 keV if pions are as abundant as nucleons in the cores of neutron stars. We estimate an irreducible uncertainty in these limits of order 10 keV. While our work does not definitively settle the issue of whether or not a 17 keV Dirac neutrino is ruled out by SN 1987A, it indicates that such a neutrino lives on the ragged edge of this important constraint.

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[10] There are models where the 17 keV is a Majorana neutrino, and masses and mixings are "tuned" to avoid $\beta\beta 0\nu$ bounds. There are also models where a "pseudo-Dirac" neutrino is constructed from ν_μ and $\bar{\nu}_\tau$; in this case, the wrong-helicity states have ordinary weak interactions and are "trapped" so that our limits are not applicable. For discussion, see e.g., G. Gelmini, S. Nussinov, and R.D. Peccei, *Intl. J. Mod. Phys. A*, in press (1992).

[11] Because of the helicity/chirality mismatch a wrong-helicity neutrino has a scattering cross-section of order $G_F^2 m_\nu^2/\pi$; for $m_\nu \gtrsim 300$ keV its mean free path is smaller than the size of the core, and even wrong-helicity neutrinos become trapped. Thus our analysis is not strictly valid for $m_\nu \gtrsim 300$ keV.

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[15] The cooling models here are "more conservative" than those used in [6] to obtain a limit of 28 keV (and those used in [12]). The central densities reach $1-2\times 10^{15}\,\mathrm{g\,cm^{-3}}$ and the maximum temperatures 30 MeV $-$ 40 MeV. They correspond to model 55 in Ref. [14]; the initial core mass is $1.3M_\odot$, which increases through accretion to $1.5M_\odot$. In addition, to obtain our conservative bounds we have *increased* the neutrino opacities at supranuclear densities by a factor of two (which is within the physically acceptable range); this has the effect of increasing the neutrino burst duration (by increasing the neutrino diffusion time). In the case of a degenerate Dirac neutrino the post-collapse (initial cooling) model is different than one where the Dirac species is nondegenerate (less degenerate-electron pressure since the lepton number is spread out among more species); this explains why for $m_\nu = 0.1$ keV the predicted burst duration differs in the degenerate and nondegenerate cases, in spite of the fact that the energy carried off by wrong-helicity neutrinos is "small."

[16] See e.g., J.M. Cline, McGill Univ. preprint 91-38 (1991) and references therein [sub-

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Figure Captions

Figure 1: Duration of the expected neutrino burst vs. Dirac-neutrino mass for: (a) KII detector and (b) IMB detector. Broken curves indicate models that included the pion processes (with $n_\pi/n_N = 1$), solid curves indicate models that do not (lower solid curves are for a degenerate Dirac neutrino). The duration, $\Delta t_{90\%}$, is defined as the time it takes for 90% of the total number of events to accumulate.

Figure 2: The energy radiated in wrong-helicity neutrinos vs. Dirac-neutrino mass. The solid curves are for the pion emission process (upper for nondegenerate Dirac neutrino); the heavy solid curves are for the spin-flip scattering process (upper for degenerate Dirac neutrino); and the broken curves are for the bremsstrahlung process (upper for nondegenerate Dirac neutrino).

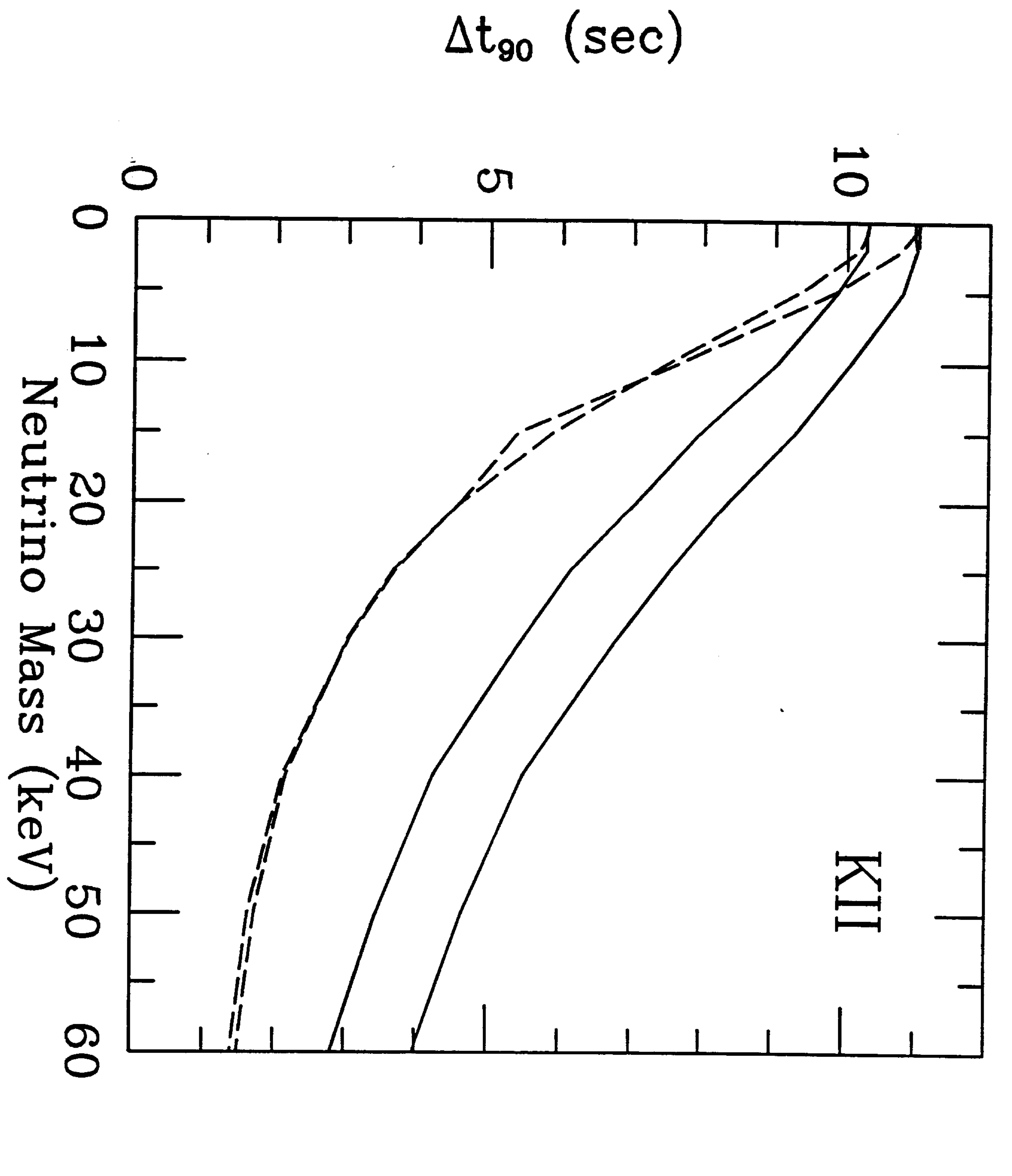

Figure 1a

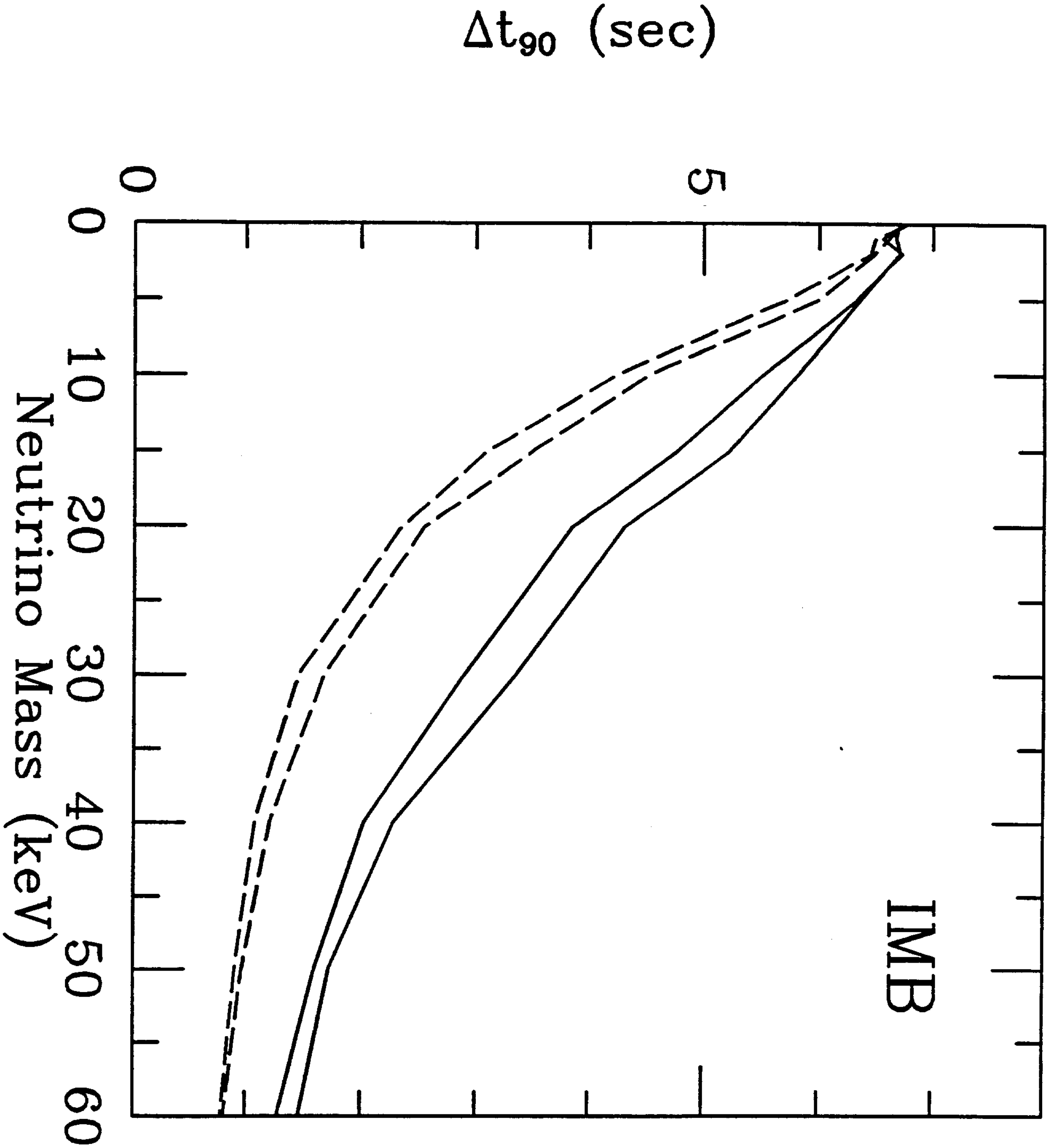

Figure 1b

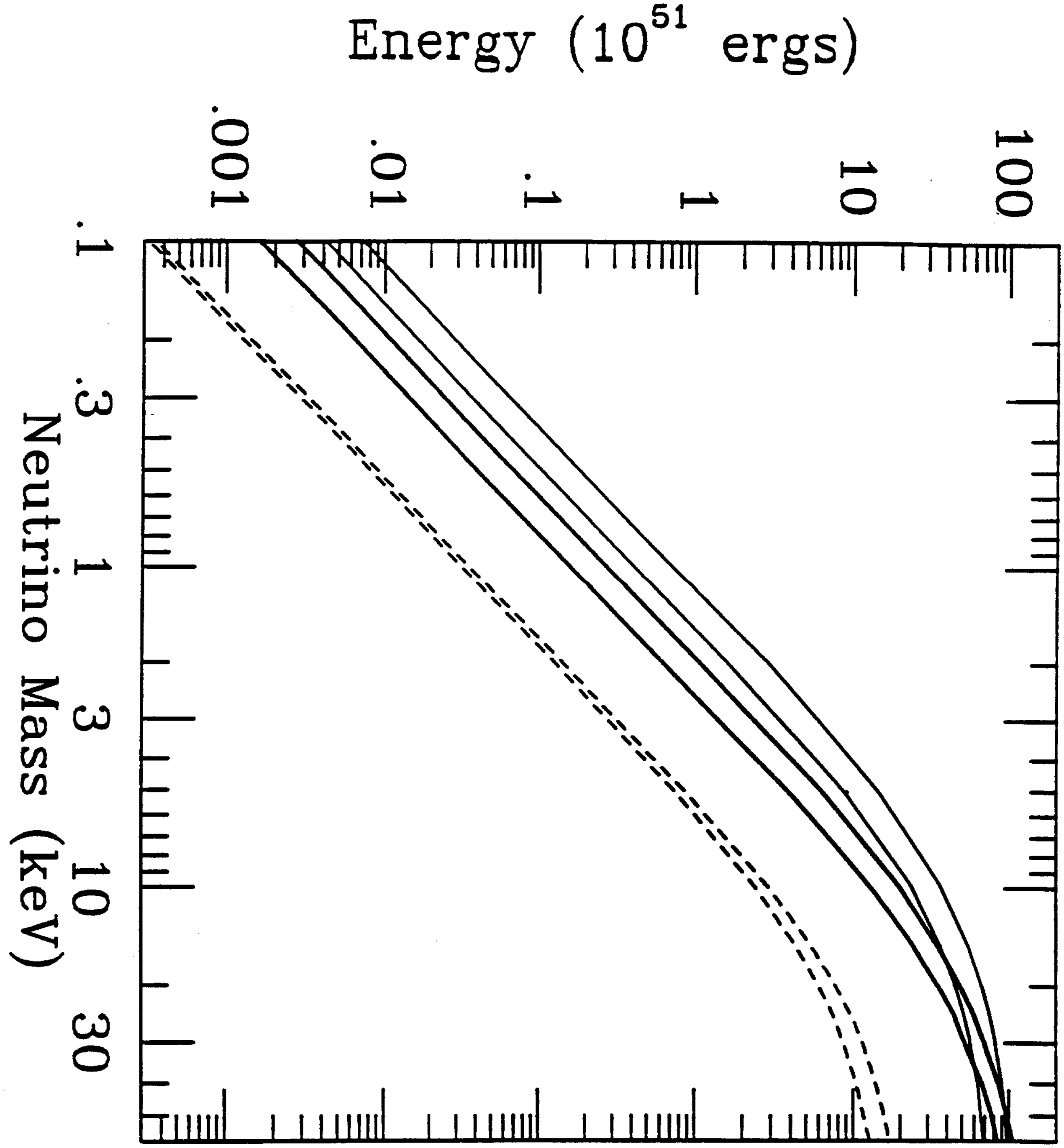

Figure 2