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Lower Bound on e^+e^- Decay of Massive Neutrinos

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ABSTRACT

Astronomical observations of SN1987A, such as the light curve, spectral intensities of lines, the X-ray emission etc., constrain the lifetime for the decay of a heavy neutrino $1MeV \lesssim m_{\nu_H} \leq 50MeV$ through $\nu_H \to \nu_1 + e^+ + e^-$ exceeds $4 \cdot 10^{15} exp(-m_{\nu_H}/5MeV)$ seconds. Otherwise, resulting ionization energy deposits and stronger x-ray emission would have been observed. This coupled with traditional cosmological considerations argues that the lifetime of τ-neutrinos probably exceeds the age of the universe. This in turn would imply the standard cosmological mass bound does apply to ν_τ, namely $m_{\nu_\tau} \lesssim 100h^2 eV$ (where h is the Hubble constant in units of 100 km/sec/mpc). The only significant loophole for these latter arguments would be if ν_τ primarily decays rapidly into particles having very weak interactions.

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The standard model of weak interactions demands that individual lepton numbers be conserved. On the other hand almost every extention of the model envisages the possibility of the nonconservation of lepton numbers, thereby allowing neutrinos of one type to decay into others. It has been recognized, for more than a decade now, that astrophysical and cosmological considerations can provide rather stringent bounds on the decay rates of neutrinos through various channels[2,3]. Among these the most stringently constrained mode is the radiative one: $\nu_H \rightarrow \nu_1 + \gamma$. However, theoretically, this channel is expected to be suppressed[4]. Alternative modes of decay are those with scalars, pseudo scalars, Nambu-Goldstone bosons or e^+e^- pairs in the final state[1]. Since the decay products are directly observable the last of these modes is of particular interest, especially for the τ neutrino whose mass is constrained by laboratory measurements to be $m_{\nu_\tau} < 35\ MeV$, thus allowing in principle, for above the threshold decay into e^+e^- pairs. The supernova 1987A which exploded in the LMC provides a sensitive and direct way of looking for decays of neutrinos without the uncertainties caused by assumptions about the cosmological density parameter and the supernova rate which go into the earlier discussions. Previous examinations (cf. ref. 5,6) have focused on lifetime limits from the pure radiative mode implied by the lack of observed γ-coincidences with the ν-burst. In this letter we derive the constraints placed by the observations in the vicinity of SN1987A on the decay $\nu_H \rightarrow \nu_1 + e^+ + e^-$.

The idea on which these discussions are based is that the electrons and positrons that emerge from the decay will lead to observable effects through their interaction with the supernova debris and the circumstellar material. These effects are listed below:

1. Deposition of energy in the material through coulomb interactions.
2. Ionization.
3. Generation of X-rays through bremsstrahlung.
4. Generation of X-rays through annihilation of the positrons.
5. Acceleration of the material by the gradients in the pressure of electrons and positrons.

Limits on neutrinos come from the fact that in gravitational collapse the neutron star binding energy, $\sim 3 \times 10^{53} ergs$, is radiated in neutrinos. Via neutral currents, all

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species of neutrinos are radiated. The arguments below will apply to all neutrinos with $m_\nu \gtrsim 1.1\ MeV$ so that e^+e^- pairs can be produced.

In calculating the bounds we make several simplifying assumptions; more exact calculations will not qualitatively alter the limits presented here. These assumptions are the following:

1. The total energy radiated per neutrino species (neutrino plus antineutrino) is independent of its flavor[7] and is given by

$$\begin{aligned} Q &\sim 10^{53} ergs \approx 6\times 10^{58} MeV \text{ for } m_\nu \leqq kT_\nu \sim 5\ MeV \\ &\approx 10^{53}(\frac{m_\nu}{kT_\nu}) exp - (\frac{m_\nu}{kT_\nu}) \text{ for } m_\nu \gg kT_\nu \end{aligned}$$

   [A temperature of 5 MeV is a conservative estimate for μ and τ neutrinos. Mayle etal.[7] find $kT_{\nu_\mu} \sim 6\ MeV$. Only ν_e and $\overline{\nu_e}$ have lower temperatures, due to their charged current interactions altering the radii of their respective neutrino spheres[7].]

2. The kinematics of the three body decay are not included in the calculations but it is assumed that about a third of the energy of the neutrino is carried away by each of the decay products.

3. We assume that the electrons and positrons that arise in the decay have negligible spatial diffusion. In the Large Magellanic Cloud, with its high density of interstellar gas, the magnetic fields are expected to be somewhat higher than the 3μ Gauss fields of our Galaxy, say $\sim 5\mu$ Gauss; the circumstellar fields may even be larger. In any case the gyroradii of the electrons and positrons with typical energies of $\sim 5\ MeV$ in such fields is $\lesssim 10^{10} cm$. Since the scattering meanfree path of particles in a magnetised plasma is about the same as their gyroradii the spatial diffusion can be neglected over the length scales of interest here.

With these assumptions we now proceed to calculate the effects. The energy radiated in neutrinos is given by

$$\begin{aligned} Q &= 10^{53}\ f(m)\ erg \\ f(m) &= 1 \text{ for } m \leqq kT \\ f(m) &= (m/kT) exp - (m/kT) \text{ for } m \gg kT. \end{aligned} \quad (1)$$

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The number of neutrinos emitted in the supernova is given by

$$N \sim \frac{Q}{< E_\nu >} \sim 4 \times 10^{57} e^{-m/kT} \tag{2}$$

where $< E_\nu > \approx 3kT$ for $m \lesssim kT \sim 6\ MeV$ and $< E_\nu > \approx m$ for $m \gg kT$. The number of positrons or electrons generated per unit volume at a distance r is given by

$$n(r) \approx \frac{N}{4\pi r^2 \gamma \beta c\tau} \approx \frac{N}{4\pi r^2 c\tau} \approx \frac{N}{kT 4\pi r^2 c\tau} \tag{3}$$

where τ is the lifetime for the neutrino decay. Since we are considering neutrinos of mass above the decay-threshold of $\sim 1.1\ MeV$, setting $\gamma \approx 1$ and $\beta \approx 1$ in eq. 3 does not lead to serious error in our estimates.

Each electron and positron arising from the decay will have an energy of several MeV in the laboratory frame and will deposit energy in the surrounding material at the rate of $\xi \approx 4\ MeV\ g^{-1} cm^2 \approx 4.10^{-6}\ erg\ g^{-1}\ cm^2$. This will heat up the debris and will contribute to the luminosity of the supernova in a manner quite similar to the energy deposited there by ^{56}Co decay, for example. The contribution to the luminosity due to this process is given by

$$L = \int 2nc\xi\rho\ d^3r = \int \frac{2Q}{3kT\tau}\xi\rho\ dr = \frac{2Q\xi\tau_o}{3kT\tau} \approx \frac{4 \cdot 10^{53} e^{-m/kT}}{\tau} erg\ s^{-1} \tag{4}$$

Here $\tau_o \approx 10\ gcm^{-2}$ is the optical depth of the matter surrounding the supernova at present. Now, the present luminosity of the supernova is $\sim 10^{39.5} erg\ s^{-1}$ and the light-curve fits a ^{56}Co decay lifetime of 114 days excellently[7]. Study of the light curve shows that an additional contribution from any hypothetical process cannot exceed $\sim 2.5\%$ or $\leqq 10^{38} erg\ s^{-1}$. Substituting this in eq. (4) we get

$$\tau > 4 \cdot 10^{15} e^{-m/kT} s \tag{5}$$

Note that even for $m_\nu > kT_\nu \sim 5\ MeV$ this still yields a restrictive limit.

A sizable fraction of the energy transferred to the debris through Coulomb interactions of the electrons and positrons goes into ionization of the hydrogenic material. At larger distances ($10^{16.5-17} cm$) the particle densities are sufficiently low and the velocities are sufficiently large, that Lyman-α photons escape relatively freely from the material. Under these circumstances a fraction of about 30 % of the ionization energy is converted into Lyman-α photons. Thus the luminosity in Ly-α is about a

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third of the energy transfer rate given in eq. 4

$$L_\alpha \approx \frac{2Q\xi\tau_o}{9kT\tau} \approx \frac{10^{53}e^{-m/kT}}{\tau} erg\ s^{-1} \tag{6}$$

Noting that a luminosity of $\sim 2.10^{38}$ in Lyman-α would have been detected, even if interstellar absorption is taken into account, one gets as before the limit

$$\tau > 10^{15}e^{-m/kT}\ s \tag{7}$$

The limits obtained from the rest of the considerations 3-5 are less stringent; we therefore discuss them only briefly. The X-ray luminosity of the supernova is less than $\sim 10^{39} erg\ s^{-1}$ now[8]. The expected X-ray flux is estimated simply by assuming that the electrons and positrons radiate e^{-1} of their energy within a radiation length $\lambda_{rad} \approx 100 gcm^{-2}$.

$$L_{X-ray} \approx \frac{Q\tau_o}{\tau\lambda_{rad}} f(m) \lessapprox 10^{39} erg\ s^{-1} \tag{8}$$

The inequality (8) translates into $\tau > 10^{13}$ f(m) s. The gamma-ray data has been obtained with telescopes with very large angular response and yield far less stringent limits. The dynamical effects of the electrons and positrons on the debris could be used to preclude very short decay times for the massive neutrinos by noting that the kinetic energy in the debris is a small fraction of the energy emitted in neutrinos. The dynamical effects for relatively large τ are subtle and need further study.

It is interesting to consider the implications of the limits derived here. Among these the most stringent is the one derived from the observations of the light curve in eq. 5. Let us focus on discussions on the τ-neutrinos whose mass is constrained by laboratory studies[9] to be less than 35 MeV and thus may be in a regime where these limits are relevant. Depending on the actual value of its mass the lifetime for the decay into electrons and positrons the τ must satisfy the following set of conditions

$$\left.\begin{array}{rl} \tau > 4\cdot 10^{15} s \text{ for } 1.1 < & m \lessapprox 5MeV \\ \tau > 4\cdot 10^{15} s \text{ for } & m \approx 10MeV \\ \tau > 4\cdot 10^{13} s \text{ for } & m \approx 35MeV \end{array}\right\} \tag{9}$$

This means that the τ-neutrinos generated in the big bang will survive without substantial decay up to redshifts $(1 + z_d) \approx (\tau_u/\tau)^{2/3}$ i.e. up to redshifts of 100 to 1000 depending upon their mass. That is the decay will occur *after* the decoupling of the cosmological background radiation. And, if their decay lifetime should be as short as indicated by the limits then there would be several important cosmological consequences[3], distortion of the relic microwave background and the effect on the cosmological expansion, to name only two of them. The latter effect is discussed in detail by Dicus, Kolb and Teplitz who derive the constraint

$$m(\tau/\tau_u)^{1/2} < 100\ h^2\ eV \tag{10}$$

From equation (10) one can see that either the mass of the τ-neutrino is below the 1.1 MeV threshold for $\nu e^{\pm}$ decay or that its lifetime is longer than the age of the universe. Keeping in mind the theoretical and experimental constraints on radiative decays this long lived option would mean that the τ-neutrino is also very light and should satisfy the constraint

$$\Sigma m_{\nu_i} < 100\ h^2\ eV \tag{11}$$

unless, of course, it can decay rapidly into particles having only very weak interactions with matter.

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