Neutrino masses and lifetimes from supernova observations

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Observations of the arrival times and energies of neutrinos from a supernova can provide information on the masses and lifetimes of ν_μ and ν_τ for masses above 100 eV. Cosmological arguments suggest that for masses above 10 keV the neutrinos from a supernova at 10 kpc should decay before reaching Earth. If this is true the maximum median time delay for any mass is less than a day and so all masses up to 1 MeV can be detected if the lifetime is not too short. Time and energy distributions are presented.

I. INTRODUCTION

The laboratory limits on the masses of the neutrinos ν_μ and ν_τ are given by

$$m(\nu_\mu) < 250 \text{ keV}, \quad m(\nu_\tau) < 35 \text{ MeV} . \tag{1}$$

While it may be possible to reduce the limit on ν_τ by an order of magnitude with a great deal of effort, there exists a large range of masses that cannot be explored in the laboratory. On the other hand, it was pointed out a long time ago[1] that the measurement of the delay times of supernova neutrinos provides a unique way of exploring a large range of masses. The proposal for the Sudbury Neutrino Observatory[2] (SNO) states that masses of ν_μ or ν_τ in the range of 50 eV to 100 keV "could be measured readily" by detection of delayed neutral-current events. Their analysis indicates that masses above 100 keV could not be detected since the delays would be greater than several months for a supernova at the center of the galaxy.

Most discussions such as that of SNO are based on the assumption that the neutrinos do not decay on the way to Earth. However, neutrinos with masses greater than 50 eV or so must not be perfectly stable or else they will provide too large an energy density for the Universe.[3] Assuming that the products of neutrino decay are massless, one obtains the condition on the lifetime[4]

$$\tau < 7\times 10^6 \text{ yr}(1 \text{ keV}/m_\nu)^2 . \tag{2}$$

These numbers correspond to the requirement that the lifetime of the Universe is greater than 10^{10} yr and the Hubble constant H_0 is greater than 50. It follows that a neutrino with an energy of 20 MeV, coming from a supernova at a distance of 10 kpc, will probably decay before reaching Earth if $m_\nu > 200$ keV.

However, there are strong reasons to believe that decay times are much shorter than the upper limit in Eq. (2). The equality in Eq. (2) corresponds to the situation in which the Universe has been "radiation dominated" by the massless decay products even since the decay. The formation of structure under such circumstances seems very difficult. These considerations have led Steigman and Turner[5] to suggest the much more restrictive bound

$$\tau < 10^3 \text{ yr}(1 \text{ keV}/m_\nu)^2 \tag{3}$$

for values of m_ν above 2 keV. In this case 20-MeV neutrinos will probably decay before reaching Earth if $m_\nu > 10$ keV. As a result the *maximum* characteristic delay of an arriving neutrino, either the original neutrino or the decay product, will be less than *one day* for all possible values of $m(\nu_\mu)$ or $m(\nu_\tau)$.

In this paper we discuss the neutrino signal to be expected from the products of decaying neutrinos. We concentrate on the decay[6]

$$\nu_x \to \nu_d + J , \tag{4}$$

where ν_x is either ν_μ or ν_τ, ν_d is the detected neutrino assumed to be effectively massless, and J is a massless Goldstone boson such as the Majoron or familon. Our results which are purely kinematic also hold for the decay $\nu_x \to \nu_d + \gamma$, but in this case severe constraints arise from the search for the final gamma ray.[7]

The decay (4) is highly suppressed[8] in the simplest Majoron models.[9] However, there exist other Majoron models[10] or familon models[11] that allow decays as fast as indicated by Eq. (3). It would also be possible to consider the decays $\nu_x \to 3\nu$, although it is difficult to find theories where this decay occurs with the required rate.

II. TIME AND ENERGY DISTRIBUTIONS

The neutrinos ν_x (ν_μ or ν_τ) emerge from the supernova over a very short time interval of a few seconds with an energy distribution approximately given by a Fermi distribution characterized by the temperature T. Since we are interested in observations indicating a significant delay time, we shall approximate this original time distribution as a delta function so that the observed time of arrival t directly measures the delay time. If we assume that the mass m of the original neutrino ν_x is much less than its energy E_0 the delay time t is given by

$$t = \frac{1}{2}\left[\frac{m}{E}\right] t_0[1-\lambda(1-E/E_0)] ,$$
$$\lambda = c t_0 \left[\frac{E_0}{m}\right] / D_s . \tag{5}$$

Here t_0 is the time to decay measured in the ν_x rest frame, E is the energy of the outgoing neutrino ν_d (in the supernova rest frame), and D_s is the distance to the supernova. The quantity λ, assumed to be less than unity, represents the distance traveled by ν_x as a fraction of D_s. If we assume $\lambda \ll 1$ our results will be independent of D_s and

$$t=\frac{1}{2}\left[\frac{m}{E}\right]t_0 . \quad (6)$$

In the usual descriptions of supernova neutrinos one expects identical fluxes of ν_μ and $\bar{\nu}_\mu$ (or ν_τ and $\bar{\nu}_\tau$) where ν_μ and $\bar{\nu}_\mu$ have opposite helicities. Since we are assuming that ν_x is a Majorana neutrino, the resulting ν_x ensemble consists of ν_μ plus $\bar{\nu}_\mu$ and is thus unpolarized. Another way to get this answer is to note that the neutral current coupling of a Majorana neutrino to the Z^0 is parity conserving and so the neutrinos resulting from annihilation have no preferred helicity. It follows that the decay angular distribution in the ν_x rest frame is isotropic, independent of the helicity of the outgoing ν_d. This results in a distribution of the energy E of ν_d in the laboratory frame given by $E_0^{-1}\theta(E_0-E)$ as is very familiar from other two-body decays.

We can obtain simple but quite accurate analytical results if we use Eq. (6) and in addition approximate the Fermi distribution by

$$dF(E_0)=\tfrac{1}{2}T^{-3}E_0^2\exp(-E_0/T)dE_0 . \quad (7)$$

The final time-energy distribution of ν_d is then given in terms of T and the lifetime τ and mass m of ν_x by

$$\frac{dN(E,t)}{dEdt}=\tfrac{1}{2}\int\int dE_0 dt_0 T^{-3}\tau^{-1}E_0 e^{-E_0/T} \times e^{-t_0/\tau}\theta(E_0-E)\delta\left[t-\frac{1}{2}\frac{m}{E}t_0\right]$$

$$=(m\tau)^{-1}\frac{E}{T}\left[1+\frac{E}{T}\right]e^{-\xi} , \quad (8)$$

where

$$\xi=(E/T)(1+t/t_c) , \quad (9a)$$

$$t_c=m\tau/2T . \quad (9b)$$

The spectra for different values of the time t are shown in Fig. 1. For any time t the average energy is

$$\langle E\rangle=\frac{2T(4+t/t_c)}{(1+t/t_c)(3+t/t_c)} .$$

Integrating over time, we find that the energy distribution of ν_d is given by

$$\frac{dN}{dE}=\frac{1}{2T}\left[1+\frac{E}{T}\right]e^{-E/T} . \quad (10)$$

This spectrum is considerably softer than the primary ν_x spectrum and the average energy is given by

$$\langle E\rangle=\tfrac{3}{2}T .$$

If we integrate Eq. (8) over all energies above a cutoff energy E_c we obtain the time distribution shown in Fig. 2. For $E_c=0$ the distribution is given by

$$\frac{dN}{dt}=\frac{1}{2t_c}\left[1+\frac{t}{t_c}\right]^{-2}\left[1+2\left[1+\frac{t}{t_c}\right]^{-1}\right] . \quad (11)$$

The median of this distribution is $\frac{1}{2}(5^{1/2}-1)t_c$.

The main effect of the approximation [Eq. (7)] used for the Fermi distribution is to soften the final spectrum of ν_d. The maximum error in Eq. (8) which occurs only for the extreme energies is 10%. Since the Fermi distribution is not expected to give a completely accurate picture of the ν_x spectrum we believe that this approximation is satisfactory. For values of $E>\frac{1}{2}T$ which probably includes all energies that can be detected, our neglect of

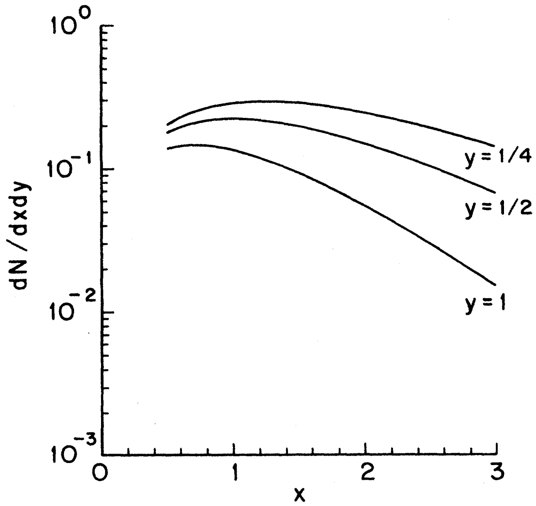

FIG. 1. Energy distribution of ν_d (Eq. 8) for different delay times. Here $x=E/T$ and $y=t/t_c$.

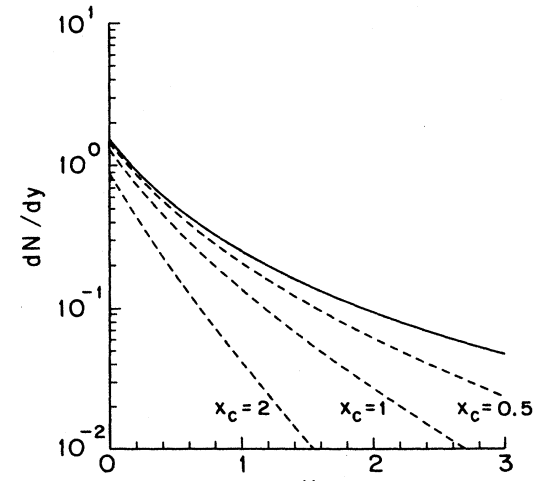

FIG. 2. Time distribution of ν_d. The solid curve corresponds to all ν_d while the dashed curves correspond to energies greater than $E_c=x_cT$. $y=t/t_c$.

corrections of order $(m/E_0)^2$ is an excellent approximation for $m<2$ MeV and our results should remain qualitatively correct at least up to 5 MeV. We have omitted in Fig. 1 the very small values of x for which the approximation might fail.

Assuming we are looking at ν_d the energy distribution can be used to determine T and the time distribution to determine t_c. The question necessarily arises, however, as to whether one is really observing the decay product ν_d rather than the original ν_x. The ideal situation would be that in which the delayed neutrinos are ν_e or $\bar{\nu}_e$ since in this case the energy can be determined from inverse beta decay detection. One can check the decay hypothesis by seeing if all the data fits Eq. (8). One can check if one is detecting ν_x since in this case there is a one-to-one correlation between delay and energy in contrast with Fig. 1.

The more difficult situation is that in which ν_d is ν_μ (ν_τ) and ν_x is ν_τ (ν_μ). In this case only the time distribution will be known with perhaps a rough indication of energy from electron scattering events. With sufficient data one can distinguish the case in which one is observing ν_x with no decay from the case of observing ν_d by the time distribution alone. The time distribution of ν_x with no decay is given by

$$\frac{dN}{dt}=\frac{1}{4t_d}(t_d/t)^{5/2}e^{-(t_d/t)^{1/2}}\,, \qquad t_d=(m^2/2T^2)(D_s/c)\,. \tag{12}$$

This distribution is compared to that of ν_d [Eq. (11)] in Fig. 3. It is seen that the two cases can be distinguished because the decay distribution falls monotonically. The possibility that some of the neutrinos ν_x reach the detector without decaying while some do decay may be more difficult to distinguish. The detected neutral-current events would be a mixture of both ν_x and ν_d. An example of the time distribution of the sum of the nondecayed ν_x plus the decay product ν_d when one-half of the neutrinos decay is also shown in Fig. 3. In obtaining the curves we have used Eq. (5) for the delay time and not the approximate form of Eq. (6).

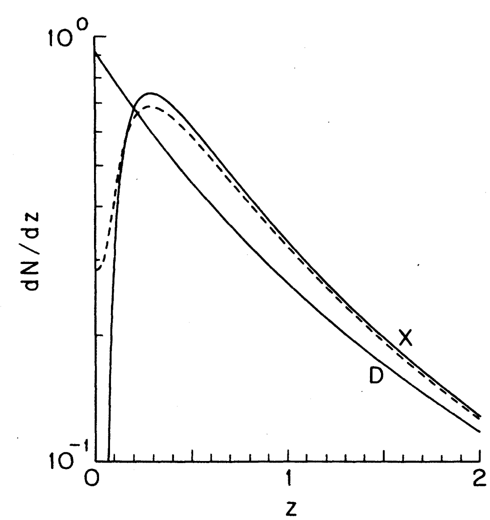

FIG. 3. Time distribution of ν_x plus ν_d. Curve D is the case $t_d \gg t_c$ and only ν_d are detected. Curve X is the case $t_d \ll t_c$ and only ν_x are detected. The dashed curve is for the case $t_d=1.7t_c$ for which half of the ν_x decay. $z=t/t_m$ where t_m is the median value of t for each curve.

III. DISCUSSION

Our results may be summarized on the m_ν-τ plot of Fig. 4. The solid line A indicates $t_d/t_c=1.7$ for which 50% of the ν_x will decay before reaching Earth. We assume here a distance D_s to the supernova of 10 kpc and a temperature T of 10 MeV. Lines of constant median delay time are shown. We have been mainly concerned with the region to the left of A where the decay product ν_d is detected. In this region, except in the neighborhood of A, the results depend solely on the combination $m\tau$. Close to A the results depend on t_d and t_c and, therefore, on m and τ independently. For any median delay time there is a minimum value for the mass.

In order for the neutrino delay to be detected it must be long enough that the signal can be distinguished from the spread of the initial pulse in a model-independent way. For the case of the observation of the decay product ν_d this probably requires a median time delay t_m greater than 5 sec. The line $A1$ on Fig. 4 shows the region excluded by this requirement. Similarly the delay time must not be too long so that the signal can be distinguished from the background. The line $A2$ shows the region excluded if we require $t_m<6$ months. Note that in this case 15% of the ν_d arrive with less than one month delay. The main analysis of this paper concerns the region to the left of A bounded by $A1$ and $A2$. The dashed curves show the cosmological bound of Eq. (2) and the more restrictive Turner-Steigman bound of Eq. (3). If anything like the second bound is valid there is no concern about delay times being too long but the real lim-

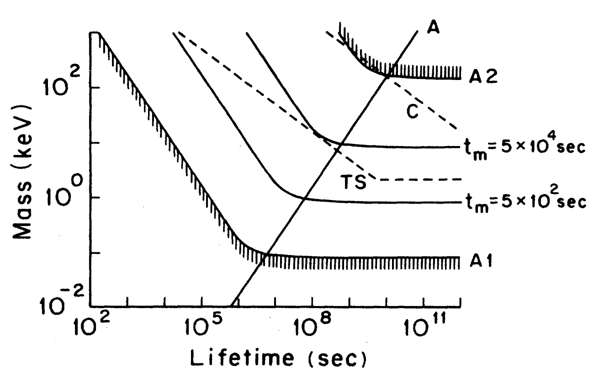

FIG. 4. Region to be explored in the mass-lifetime plane. Solid curves show fixed values of the median time delay t_m with $A2$ corresponding to $t_m=6$ months and $A1$ to $t_m=5$ sec. The analysis in this paper relates mainly to the region to the left of A when the neutrino ν_d is detected. The dashed line C corresponds to the cosmological limit of Eq. (2) while the line TS is the limit from Ref. 5.

itation comes from the possibility that delay times may be too short. The region to the right of A and between $A1$ and $A2$ can be explored by detecting ν_μ or ν_τ that have not decayed. Except in the neighborhood of A the result determines the mass m and a lower limit on τ.

So far we have considered two types of neutrinos ν_x and ν_d. With specific assumptions we can apply the results to the world with three neutrino types. The following are some possibilities.

(A) Only $m(\nu_\tau)$ is greater than 100 eV. The masses of ν_e and ν_μ are very small. The simplest assumption is $\nu_\tau \rightarrow \nu_\mu + J$ and our results are to be applied to the delayed neutral-current events due to ν_μ. It is also possible that the decays go to both ν_μ and ν_e so that some delayed events with a similar time distribution would also be seen in the charged-current sample.

(B) $m(\nu_\tau) \gg m(\nu_\mu) \gg m(\nu_e)$. Both ν_τ and ν_μ have masses greater than 100 eV. The decays are $\nu_\tau \rightarrow \nu_\mu + J$, $\nu_\mu \rightarrow \nu_e + J$. In this case our results can be directly applied to ν_e from the original ν_μ, but there will be some lower energy ν_e from the cascade decay. An alternative is that only the ν_τ decays with ν_μ reaching the detector without decaying. Then the neutral-current signal will contain a distribution of the form of Eq. (12) with m corresponding to $m(\nu_\mu)$ but there will be a second distribution at later times from the ν_μ arising from ν_τ. This second distribution would have the form of Eq. (11) if $t_c(\nu_\tau)$ is much larger than $t_d(\nu_\mu)$, but in general could be more complicated.

So far we have not considered any effects of neutrino oscillations. Assuming mixing angles are small, as required for the large mass differences we are considering, the only oscillations of interest are those induced by matter. For values of the heavy neutrino less than a few hundred eV, one expects matter oscillations outside the neutrinosphere unless the mixing angle is extremely small. Assuming the usual hierarchy this would mean that the ν_τ flux (but not the $\bar{\nu}_\tau$) leaving the star would be that of the ν_e leaving the neutrinosphere.[12] This would lead to some modification of the results presented. For larger masses matter oscillations take place within the neutrinosphere, these may affect supernova dynamics but probably do not alter the general considerations given here.

One could try to apply this analysis to the Kamiokande data[13] on SN 1987A with emphasis on the three late events. For example, one might characterize these $\bar{\nu}_e$ events as three decay product ν_d observed in the carefully chosen time interval 6.5–13 sec. Optimally choosing t_c as about 25 sec, one finds that these three events constitute only about 20% of all ν_d and that most of the early events must also be attributed to ν_d. Furthermore given the expected time distribution of Fig. 1 there is no real explanation of the time gap in the data. Since the data are very limited one cannot probably rule out the value $t_c = 25$ seconds (or any other similar value) but neither can one claim any evidence in favor of neutrino decay. On the other hand analysis of the data between 13 sec and a few thousand seconds might provide some evidence relative to values of t_c of the order of hundreds of seconds.

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