Supernova Neutrinos and the Neutrino Masses

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Core-collapse supernovae emit of order $10^{58}$ neutrinos and antineutrinos of all flavors over several seconds, with average energies of $10-25$ MeV. In the Sudbury Neutrino Observatory (SNO), a future Galactic supernova at a distance of 10 kpc would cause several hundred events. The $\nu_\mu$ and $\nu_\tau$ neutrinos and antineutrinos are of particular interest, as a test of the supernova mechanism. In addition, it is possible to measure or limit their masses by their delay (determined from neutral-current events) relative to the $\bar{\nu}_e$ neutrinos (determined from charged-current events). Numerical results are presented for such a future supernova as seen in SNO. Under reasonable assumptions, and in the presence of the expected counting statistics, a $\nu_\mu$ or $\nu_\tau$ mass down to about 30 eV can be simply and robustly determined. This seems to be the best technique for direct measurement of these masses.

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I. INTRODUCTION

Whether or not neutrinos have mass and are mixed are subjects of great current interest. Many experiments are now or will soon be searching for neutrino flavor mixing in a variety of circumstances. The strongest evidence for mixing (which implies mass) so far comes from the atmospheric neutrino experiments. However, all of these experiments by their nature are only sensitive to the differences of neutrino masses, and not the mass scale.

The absolute scale of the neutrino masses is an important probe of physics beyond the standard model of particle physics. In addition, if the neutrinos have masses of order a few eV or more, they may be an important part of the dark matter in the universe. Direct mass measurements from decay kinematics do not place very stringent limits: $m_{\nu_e} \leq 5$ eV [1], $m_{\nu_\mu} < 170$ keV [2], and $m_{\nu_\tau} < 18$ MeV [2]. It will be very difficult to significantly improve these limits with terrestrial experiments.

A core-collapse supernova is a tremendous source of neutrinos and antineutrinos of all flavors. Since the current limit on the $\nu_e$ mass is comparatively low, the $\nu_\mu$ and $\nu_\tau$ masses could be measured by their time-of-flight delay relative to the $\nu_e$ and $\bar{\nu}_e$. Since they have energies only of order 25 MeV, the $\nu_\mu$ and $\nu_\tau$ can be detected only by their neutral-current interactions. While they also have neutral-current interactions, the $\nu_e$ and $\bar{\nu}_e$ will be detected primarily by their charged-current interactions.

Even a tiny mass will make the velocity slightly less than for a massless neutrino, and over the large distance to a supernova will cause a measurable delay in the arrival time. A neutrino with a mass $m$ (in eV) and energy $E$ (in MeV) will experience an energy-dependent delay (in s) relative to a massless neutrino in traveling over a distance $D$ (in 10 kpc, approximately the distance to the Galactic center) of

$$\Delta t(E) = 0.515 \left( \frac{m}{E} \right)^2 D,$$

where only the lowest order in the small mass has been kept.

If the neutrino mass is nonzero, lower-energy neutrinos will arrive later, leading to a correlation between neutrino energy and arrival time. Using this idea, Ref. [3] has shown that the next supernova will allow sensitivity to a $\nu_e$ mass down to about 3 eV, comparable to the terrestrial limit. Since the neutrino energy is not measured in neutral-current interactions a similar technique cannot be used for the $\nu_\tau$ mass. (The incoming neutrino energy is not determined since a complete kinematic reconstruction of the reaction products is typically not possible.)

Instead, the strategy for measuring the $\nu_\tau$ mass is to look at the difference in time-of-flight between the neutral-current events (mostly $\nu_\mu, \nu_\tau, \bar{\nu}_\mu$, and $\bar{\nu}_\tau$) and the charged-current events (just $\nu_e$ and $\bar{\nu}_e$). We assume that the $\nu_\mu$ is massless and will ask what limit can be placed on the $\nu_\tau$ mass. There are three major complications to a simple application of Eq. (1): (i) The neutrino energies are not fixed, but are characterized by spectra; (ii) The neutrino pulse has a long intrinsic duration of about 10 s, as observed for SN1987A; and (iii) The statistics are finite.
One possible neutral-current signal is the excitation of $^{16}\text{O}$, followed by detectable gamma emission. In SuperKamiokande (SK), which has a target volume of 32 kton of light water, this would cause about 710 events. This signal would allow sensitivity to a $\nu_e$ mass as low as about 45 eV.

Another possible neutral-current signal is deuteron breakup, followed by neutron detection. In the Sudbury Neutrino Observatory (SNO), which has a target volume of 1 kton of heavy water, this would cause about 485 events. (This detector also has a light-water target with an active volume of about 1.4 kton). While the statistics are somewhat lower than for SK, the energy dependence of the cross section is less steep and emphasizes lower energies and hence longer delays, leading to a sensitivity to a $\nu_e$ mass down to about 30 eV.

Since one expects a type-II supernova about every 30 years in our Galaxy, there is a good chance that these mass limits can be dramatically improved in the near future.

II. PRODUCTION AND DETECTION OF SUPERNOVA NEUTRINOS

When the core of a large star ($M \geq 8M_{\odot}$) runs out of nuclear fuel, it collapses to proto-neutron star. About 99% of the gravitational binding energy change, about $3 \times 10^{53}$ ergs, is carried away by neutrinos. Because of the high density, they diffuse outward over a timescale of several seconds. When they are within about one mean free path of the edge, they escape freely, with a thermal spectrum (approximately Fermi-Dirac) characteristic of the surface of last scattering. Because different flavors have different interactions with the matter, the temperatures are different. The $\nu_\mu$ and $\nu_\tau$ neutrinos and their antiparticles have a temperature of about 8 MeV (or $\langle E \rangle \simeq 25$ MeV). The $\bar{\nu}_e$ neutrinos have a temperature of about 5 MeV ($\langle E \rangle \simeq 16$ MeV), and the $\nu_\tau$ neutrinos have a temperature of about 3.5 MeV ($\langle E \rangle \simeq 11$ MeV). The luminosities of the different neutrino flavors are approximately equal at all times. The neutrino luminosity rises quickly over a time of order 0.1 s, and then falls over a time of order several seconds, roughly like an exponential with a time constant $\tau = 3$ s. The detailed form of the neutrino luminosity used below is less important than the general shape features and their characteristic durations.

For thermal spectra which are constant in time, and for equal luminosities among the different flavors, the scattering rate for a given reaction can be written as:

$$\frac{dN_{sc}}{dt} = C \int dE f(E) \left[ \frac{\sigma(E)}{10^{-42}\text{cm}^2} \right] \left[ \frac{L(t - \Delta t(E))}{E_B/6} \right],$$

where $f(E)$ is the neutrino energy spectrum, $\sigma(E)$ the cross section, and $L(t)$ the luminosity. For a massless neutrino (i.e., the charged-current events), $\Delta t(E) = 0$, and the time dependence of the scattering rate is simply the time dependence of the luminosity. For a massive neutrino (i.e., the neutral-current $\nu_e$ events), the time dependence of the scattering rate is additionally dependent on the mass effects, as written. The overall constant is

$$C = 8.28 \left[ \frac{E_B}{10^{53}\text{ ergs}} \right] \left[ \frac{1 \text{ MeV}}{T} \right] \left[ \frac{10 \text{ kpc}}{D} \right]^2 \left[ \frac{\text{det. mass}}{1 \text{ kton}} \right] n,$$

where $E_B$ is the total binding energy release, $T$ is the spectrum temperature, $D$ is the distance to the supernova, and $n$ is the number of targets per molecule for the given reaction. For a light-water detector, the initial coefficient in $C$ is 9.21 instead of 8.28.

The Sudbury Neutrino Observatory, though primarily intended for solar neutrinos, also makes an excellent detector for supernova neutrinos. Electrons and positrons will be detected by their Čerenkov radiation, and gammas via secondary electrons and positrons. Neutrinos will be detected by one of three possible modes, depending on the detector configuration. The key neutral-current reaction is deuteron breakup: $\nu + d \rightarrow \nu + p + n$ and $\bar{\nu} + d \rightarrow \bar{\nu} + p + n$, with thresholds of 2.22 MeV. Some other relevant reactions are given in Table I.

III. SIGNATURE OF A SMALL NEUTRINO MASS

A. General description of the data

As noted, for a massless neutrino ($\nu_e$ or $\bar{\nu}_e$) the time dependence of the scattering rate is simply the time dependence of the luminosity. For a massive neutrino ($\nu_e$), the time dependence of the scattering rate additionally depends on the delaying effects of a mass. To search for these effects, we define two rates: a Reference $R(t)$ containing only massless events, and a Signal $S(t)$ containing some fraction of massive events (along with some massless events which cannot be separated).
The Reference $R(t)$ can be formed in various ways, for example from the charged-current reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ in the light water of either SK or SNO (the former with a much better precision).

The primary component of the Signal $S(t)$ in SNO is the 485 neutral-current events on deuterons. With the hierarchy of temperatures assumed here, these events are 18% ($\nu_e + \bar{\nu}_e$), 41% ($\nu_\mu + \bar{\nu}_\mu$), and 41% ($\nu_\tau + \bar{\nu}_\tau$). The flavors of the neutral-current events of course cannot be distinguished. Under our assumption that only $\nu_\tau$ is massive, there is already some unavoidable dilution of $S(t)$.

In Figure 1, $S(t)$ is shown under different assumptions about the $\nu_\tau$ mass. The shape of $R(t)$ is exactly that of $S(t)$ when $m_{\nu_\tau} = 0$, though the number of events in $R(t)$ will be different. The rates $R(t)$ and $S(t)$ will be measured with finite statistics, so it is possible for statistical fluctuations to obscure the effects of a mass when there is one, or to fake the effects when there is not. We determine the mass sensitivity in the presence of the statistical fluctuations by Monte Carlo modeling. We use the Monte Carlo to generate representative statistical instances of the theoretical forms of $R(t)$ and $S(t)$, so that each run represents one supernova as seen in SNO. The best test of a $\nu_\tau$ mass seems to be a test of the average arrival time $\langle t \rangle$. Any massive component in $S(t)$ will always increase $\langle t \rangle$, up to statistical fluctuations.

B. $\langle t \rangle$ analysis

Given the Reference $R(t)$ (i.e., the charged-current events), the average arrival time is defined as

$$\langle t \rangle_R = \frac{\sum_k t_k}{\sum_k 1},$$

where the sum is over events in the Reference. The effect of the finite number of counts $N_R$ in $R(t)$ is to give $\langle t \rangle_R$ a statistical error:

$$\delta(\langle t \rangle_R) = \frac{\sqrt{\langle t^2 \rangle_R - \langle t \rangle_R^2}}{\sqrt{N_R}}.$$  (5)

For a purely exponential luminosity, $\langle t \rangle_R = \sqrt{\langle t^2 \rangle_R - \langle t \rangle_R^2} = \tau$.

For the Signal $S(t)$ (i.e., the neutral-current events), the average arrival time $\langle t \rangle_S$ and its error $\delta(\langle t \rangle_S)$ are defined similarly. The widths of $R(t)$ and $S(t)$ are similar, each of order $\tau = 3$ s (the mass increases the width of $S(t)$ only slightly for small masses.) The signal of a mass is that the measured value of $\langle t \rangle_S - \langle t \rangle_R$ is greater than zero with statistical significance.

Using the Monte Carlo, we analyzed $10^4$ simulated supernova data sets for a range of $\nu_\tau$ masses. For each data set, $\langle t \rangle_S - \langle t \rangle_R$ was calculated and its value histogrammed. These histograms are shown in the upper panel of Fig. 2 for a few representative masses. (Note that the number of Monte Carlo runs only affects how smoothly these histograms are filled out, and not their width or placement.) These distributions are characterized by their central point and their width, using the 10%, 50%, and 90% confidence levels. That is, for each mass we determined the values of $\langle t \rangle_S - \langle t \rangle_R$ such that a given percentage of the Monte Carlo runs yielded a value of $\langle t \rangle_S - \langle t \rangle_R$ less than that value. With these three numbers, we can characterize the results of complete runs with many masses much more compactly, as shown in the lower panel of Fig. 2. Given an experimentally determined value of $\langle t \rangle_S - \langle t \rangle_R$, one can read off the range of masses that would have been likely (at these confidence levels) to have given such a value of $\langle t \rangle_S - \langle t \rangle_R$ in one experiment. From the lower panel of Fig. 2, we see that SNO is sensitive to a $\nu_\tau$ mass down to about 30 eV if the SK $R(t)$ is used, and down to about 35 eV if the SNO $R(t)$ is used.

We also investigated the dispersion of the event rate in time as a measure of the mass. A mass alone causes a delay, but a mass and an energy spectrum also cause dispersion. We defined the dispersion as the change in the width $\sqrt{\langle t^2 \rangle_S - \langle t \rangle_S^2} - \sqrt{\langle t^2 \rangle_R - \langle t \rangle_R^2}$. We found that the dispersion was not statistically significant until the mass was of order 80 eV or so; however, for such a large mass the statistical significance of $\langle t \rangle_S - \langle t \rangle_R$ cannot be missed. This means that the average delay is well-characterized by a single energy, which for SNO is $E_e \simeq 32$ MeV.

IV. CONCLUSIONS AND DISCUSSION

One of the key points of our technique is that the abundant $\bar{\nu}_e$ events can be used to calibrate the neutrino luminosity of the supernova and to define a clock by which to measure the delay of the $\nu_\tau$ neutrinos. The internal calibration substantially reduces the model dependence of our results, and allows us to be sensitive to rather small masses. Our calculations indicate that a significant delay can be seen for $m = 30$ eV with the SNO data, corresponding to a delay
in the average arrival time of about 0.15 s. Even though the duration of the pulse is expected to be of order 10 s, such a small average delay can be seen because several hundred events are expected. Without such a clock, one cannot determine a mass limit with the \((t)_{S} - (t)_{R}\) technique advocated here, since the absolute delay would be unknown. Instead, one would have to constrain the mass from the observed dispersion of the events; only for a mass of \(m = 150\) eV or greater would the pulse become significantly broader than expected from theory.

Moreover, the technique used here allows accurate analytic estimates of the results, so that it is easy to see how the conclusions would change if different input parameters were used. If the \(\nu_{\tau}\) mass is very small, and only a limit is placed, then this scales as \(m_{\text{limit}} \sim T^{3/4} \sqrt{\tau}\), where \(T\) is the \(\nu_{\mu}\) and \(\nu_{\tau}\) temperature and \(\tau\) is the luminosity timescale \([6]\). Thus the final result is relatively insensitive to the supernova parameters in their expected ranges. Additionally, this is independent of the distance \(D\). Because of obscuration by dust, it may be difficult to observe the light from a future Galactic supernova. It is therefore rather important that this does not affect the ability to place a limit on the \(\nu_{\tau}\) mass. In Ref. \([6]\), we have discussed how a supernova could be located by its neutrinos, perhaps in advance or independently of the light.

The observation of the neutrino signal of a future Galactic supernova will be extremely significant test of the physics involved. It will allow, among other things, determination of the imprecisely-known supernova neutrino emission parameters. In addition, we hope to be able to use the same data to determine or constrain neutrino properties. In Refs. \([5,6]\), we discuss how both of these goals can be achieved simultaneously, with or without the additional complication of neutrino oscillations.

Despite the long intrinsic duration of the supernova neutrino pulse and the spectra of neutrino energies, it is in fact possible to discern even a small \(\nu_{\tau}\) mass by a time-of-flight measurement. The results are that SK and SNO are sensitive to a \(\nu_{\tau}\) mass as low as about 45 eV and 30 eV, respectively. In the above, we considered that the \(\nu_{\mu}\) is massless and the \(\nu_{\tau}\) is massive. Since they cannot be distinguished experimentally, the limit in fact applies to both \(\nu_{\mu}\) and \(\nu_{\tau}\). These results include the effects of the finite statistics, and are relatively insensitive to uncertainties in some of the key supernova parameters. When the next Galactic supernova is observed, the \(\nu_{\tau}\) mass limit will be improved by nearly 6 orders of magnitude. The importance of this result is highlighted by its significance to both cosmology and particle physics. So that the universe is not overclosed, the sum of the stable neutrino masses must be less than about 100 eV. Some seesaw models of the neutrino masses predict a \(\nu_{\tau}\) mass as large as about 30 eV \([8]\). As noted, this seems to be the best technique for direct measurement of the \(\nu_{\mu}\) and \(\nu_{\tau}\) masses.

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TABLE I. Calculated numbers of events expected in SNO for a supernova at 10 kpc. In rows with two reactions listed, the number of events is the total for both. The notation $\nu$ indicates the sum of $\nu_e$, $\nu_\mu$, and $\nu_\tau$, though they do not contribute equally to a given reaction, and $X$ indicates either $n$+\textsuperscript{15}O or $p$+\textsuperscript{15}N.

| Reaction | Events in 1 kton D\textsubscript{2}O |
|----------|-------------------------------------|
| $\nu + d \rightarrow \nu + p + n$ | 485 |
| $\bar{\nu} + d \rightarrow \bar{\nu} + p + n$ | 160 |
| $\nu_e + d \rightarrow e^- + p + p$ | 160 |
| $\bar{\nu}_e + d \rightarrow e^+ + n + n$ | 20 |
| $\nu + ^{16}\text{O} \rightarrow \nu + \gamma + X$ | 20 |
| $\bar{\nu} + ^{16}\text{O} \rightarrow \bar{\nu} + \gamma + X$ | 15 |
| $\nu + ^{16}\text{O} \rightarrow \nu + n + ^{15}\text{O}$ | 15 |
| $\bar{\nu} + ^{16}\text{O} \rightarrow \bar{\nu} + n + ^{15}\text{O}$ | 10 |
| $\nu + e^- \rightarrow \nu + e^-$ | |
| $\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$ | |

| Reaction | Events in 1.4 kton H\textsubscript{2}O |
|----------|-------------------------------------|
| $\bar{\nu}_e + p \rightarrow e^+ + n$ | 365 |
| $\nu + ^{16}\text{O} \rightarrow \nu + \gamma + X$ | 30 |
| $\bar{\nu} + ^{16}\text{O} \rightarrow \bar{\nu} + \gamma + X$ | 15 |
| $\nu + e^- \rightarrow \nu + e^-$ | |
| $\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$ | |
Figure Captions

FIG. 1. The expected event rate for the Signal $S(t)$ at SNO in the absence of fluctuations for different $\nu_\tau$ masses, as follows: solid line, 0 eV; dashed lines, in order of decreasing height: 20, 40, 60, 80, 100 eV. Of 535 total events, 100 are massless ($\nu_e + \bar{\nu}_e$), 217.5 are massless ($\nu_\mu + \bar{\nu}_\mu$), and 217.5 are massive ($\nu_\tau + \bar{\nu}_\tau$). These totals count events at all times; in the figure, only those with $t \leq 9$ s are shown.

FIG. 2. The results of the $\langle t \rangle$ analysis for a massive $\nu_\tau$, using the Signal $S(t)$ from SNO defined in the text. In the upper panel, the relative frequencies of various $\langle t \rangle_S - \langle t \rangle_R$ values are shown for a few example masses. The solid line is for the results using the SK Reference $R(t)$, and the dotted line for the results using the SNO $R(t)$. In the lower panel, the range of masses corresponding to a given $\langle t \rangle_S - \langle t \rangle_R$ is shown. The dashed line is the 50% confidence level. The upper and lower solid lines are the 10% and 90% confidence levels, respectively, for the results with the SK $R(t)$. The dotted lines are the same for the results with the SNO $R(t)$. 

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Figure 1
Figure 2