Prospects for detection of a cosmologically significant neutrino mass from a galactic supernova neutrino burst using a neutral-current-based detector

D. B. Cline,[1] G. M. Fuller,[2] W. P. Hong,[1,*] B. Meyer,[3] and J. Wilson[4]

[1]*Department of Physics & Astronomy, University of California, Los Angeles, California 90024*

[2]*Department of Physics, University of California at San Diego, La Jolla, California 92093*

[3]*Department of Physics & Astronomy, Clemson University, Clemson, South Carolina 29634*

[4]*Lawrence Livermore National Laboratory, Box 808 L-413, Livermore, California 94550*

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We discuss how proposed supernova neutrino detectors could measure masses for ν_μ or ν_τ neutrinos in the range of 15 to 50 eV. The range for measurable masses might be extended down to 5 eV, depending on our confidence in some of the predicted features of the supernova-neutrino-burst signal. We discuss the expected characteristics of supernova neutrino signals in proposed neutral-current-based detectors.

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I. INTRODUCTION

The issue of whether or not neutrinos have masses is important for astrophysics and cosmology. Unfortunately, terrestrial experimental probes of neutrino mass, especially the ν_μ and ν_τ masses, remain problematic. Astrophysical considerations may represent the best hope for inferring neutrino masses and mixings. In this paper we examine how proposed neutral-current-based supernova neutrino burst detectors, in conjunction with the next generation water Čerenkov detectors, could use a galactic supernova event to either measure or place constraints on ν_μ and/or ν_τ masses in excess of 5 eV. Such measurements would have important implications for our understanding of particle physics, cosmology, and the solar neutrino problem, and would be complementary to proposed laboratory vacuum oscillation experiments.

A light neutrino mass between 1 eV and 100 eV would be highly significant for cosmology [1]. In fact if a neutrino contributes a fraction Ω_ν of the closure density of the Universe it must have a mass $m_\nu \approx 92\Omega_\nu h^2$ eV, where h is the Hubble parameter in units of 100 $\text{km}^{-1}\,\text{sec}^{-1}\,\text{Mpc}^{-1}$. Reasonable ranges for Ω_ν and h then give 1 eV to 92 eV as a cosmologically significant range. A neutrino with a mass is the higher end of this range, i.e., $10 \lesssim m_\nu \lesssim 92$ eV, could contribute significantly to the closure density of the Universe. The Cosmic Background Explorer (COBE) observation of anisotropy in the microwave background [2], combined with observations at smaller scales [3], and the distribution of galaxy streaming velocities, have been interpreted as implying that there are two components of dark matter: i.e., hot and cold dark matter components $\Omega_{\text{CDM}} \sim 0.6$ and $\Omega_{\text{HDM}} \sim 0.3$. The hot dark matter (HDM) component could be provided by a neutrino with a mass of about 7 eV [4].

Calculations of the standard solar model ν_e flux [5] are not easily reconciled with the results of recent experiments [6]. This constitutes the solar neutrino problem. Matter-enhanced neutrino flavor transformation remains an attractive mechanism to solve this problem. This mechanism is referred to as the Mikheyev-Smirnov-Wolfenstein (MSW) solution [7]. The favored MSW solution implies that the $\nu_e\nu_\mu$ (or $\nu_e\nu_\tau$) mixing angle is confined to two small regions: the so-called large angle region with $\sin^2 2\theta \approx 0.1$ and another region with $\sin^2 2\theta \approx 10^{-2}$. In either case the difference in the squares of the neutrino mass eigenvalues must be about $\delta m^2 \approx m_1^2 - m_2^2 \simeq 10^{-5}-10^{-6}$ eV^2. This suggests that the mass of either the ν_μ or ν_τ neutrino needs to be of order $m_{\nu_{\mu(\tau)}} \approx 2-3\times 10^{-3}$. The "seesaw" mechanism [8] for generating a muon neutrino mass in this range also would suggest that the ν_τ mass lies in the cosmologically significant range.

Despite the cosmological and particle physics interest in massive neutrinos there are very few terrestrial experimental means for measuring neutrino masses. The electron neutrino mass is constrained by the tritium end point experiments [9] to be less than about 7.2 eV. It is conceivable that $\nu_\mu\nu_\tau$ accelerator neutrino oscillation experiments, such as the NOMAD [10] and CHORUS [11] experiments at CERN, could be used to infer a mass in the cosmologically interesting range for ν_μ or ν_τ. This would depend on there being a fairly large vacuum mixing between these neutrino flavors. Nucleosynthesis from supernovas could possibly provide a signature for neutrinos with these masses [12].

Perhaps the most straightforward and obvious signature of a massive neutrino would come from the lengthening in flight time from a distant supernova. For example, the flight time difference between ν_τ and $\nu_e(\bar{\nu}_e)$ in seconds is

$$\delta t \approx 0.514 R_{10\ \text{kpc}} \left[\left[\frac{m_{\nu_\tau}}{E_{\nu_\tau}} \right]^2 - \left[\frac{m_{\bar{\nu}_e}}{E_{\bar{\nu}_e}} \right]^2 \right] , \quad (1)$$

where m_{ν_τ} is in eV, E_{ν_τ} is the neutrino energy in MeV, and $R_{10\ \text{kpc}}$ is the distance to the supernova in units of 10 kpc. A finite neutrino mass would alter the neutrino

*Author to whom correspondence should be addressed. Electronic address: hong@UCLA15.physics.UCLA.edu

spectra in characteristic ways which could result in broadening and flattening of the observed signal [15,16].

Thus neutrino masses might be obtained by comparing the observed neutrino signal with the signal expected from supernova models. However the paucity of observed neutrino events (19 events) detected by the Kamiokande II (KII) [13] and the Irvine-Michigan-Brookhaven (IMB) [14] Collaboration for the SN 1987A explosion does not allow us to obtain a clear signature for a massive $\bar{\nu}_e$. Since detectors such as Super-Kamiokande (SK) and IMB are relatively insensitive to ν_μ and ν_τ, they are unlikely to measure cosmologically significant neutrino masses for these flavors. One of the neutral-current-based detectors being built at present, the Sudbury Neutrino Observatory (SNO) [17], seems to have some capabilities to detect ν_τ events (see Tables II and IV of Ref. [16]) but it would not be likely to give clean massive neutrino signatures [18].

The proposed Supernova Neutrino Burst Observatory (SNBO [21]), working in conjunction with SK, could give clear signatures for ν_μ and/or ν_τ when the masses of these species are in the cosmologically significant range. As we will discuss however, this will be dependent on having small mixings with ν_e.

This conclusion is in contrast with previous pessimistic conclusions [19] regarding detection of such neutrino masses. The pessimistic conclusions of the study in Ref. [19] are largely based on the limitation in size of a massive detector and intrinsic backgrounds. In Sec. II, we review two methods for measurement of neutrino masses utilizing charged and neutral current detectors. We also discuss all existing and proposed detectors' characteristics and capabilities. In Sec. III, we calculate inelastic neutrino-nucleus interaction cross sections and estimate the expected supernova neutrino burst signal in large SNBO-like neutral-current-based detectors. We consider the analysis of expected supernova neutrino burst signals in Sec. IV.

II. REVIEW OF NEUTRINO TIME-OF-FLIGHT MASS DETERMINATION FROM SN: TWO TECHNIQUES

In principle there are two basic methods for neutrino mass determination using finite time delay from a distant supernova. The first method is to analyze the total observed neutrino signal using parametrized supernova models. The neutrino mass is estimated from the model signal which gives the greatest likelihood for agreement with the observed signal. The Supernova 1987A data from the Kamiokande and the IMB detectors, which use the charged current reaction ($\bar{\nu}_e+p$), at best put an upper bond on the ν_e neutrino mass (<9.3 eV (95% C.L.) [20]). Note that the signal dispersion due to time-of-flight effects in a water Čerenkov detector is given as

$$(\delta t)_{\text{dispersion}}=0.514\times R_{10\text{ kpc}}\frac{\int_0^\infty\left[\frac{m_{\nu_e}}{\epsilon}\right]^2\epsilon^2 D_e(\epsilon)\exp(-\epsilon/T_{\nu_e})d\epsilon}{\int_0^\infty D(\epsilon)\epsilon^2\exp(-\epsilon/T_{\nu_e})d\epsilon}\simeq(0.03\text{ sec})R_{10\text{ kpc}}(m_{\nu_e}/T_{\nu_e})^2\ , \tag{2}$$

where $D_e(\epsilon)$ is the detector efficiency multiplied by the cross section for a water Čerenkov reaction, m_{ν_e} is the ν_e neutrino mass in eV, and T_{ν_e} is the temperature of the blackbody neutrino spectrum in MeV. The major difficulty in deconvolving a clear massive ν_e ($\bar{\nu}_e$) signal from the measured spectrum is that the electron neutrino has a time-of-flight dispersion for a galactic supernova of $(\delta t)_{\text{dispersion}}\simeq 0.3$ sec for $R_{10\text{ kpc}}=10$, $m_{\nu_e}=10$ eV, and $T_{\nu_e}=3$ MeV. This mass-induced dispersion is comparable to the intrinsic signal dispersion.

Fortunately, when the Super-Kamiokande Large Volume Detector (LVD) and SNO are on line for a supernova watch in the future, high statistics measurements during the first second of the signal may show the characteristic increase in rise time for massive ν_e ($\bar{\nu}_e$). For example, a 50-msec rise to maximum in KII and LVD at zero mass becomes a 300-msec rise time for a neutrino with a mass of 10 eV [16]. Thus high statistics measurements are the key for measuring ν_e ($\bar{\nu}_e$) masses in the cosmologically significant range. This method of neutrino mass measurement cannot be extended to ν_μ or ν_τ unless a neutral-current-based detector is employed.

μ or τ neutrino masses could be inferred for a supernova burst event by employing the combined signals from different kinds of detectors. In this method, information from water Čerenkov detectors sensitive to $\bar{\nu}_e$ (for example, Super-Kamiokande) is used to give the time of a stellar collapse. The time shift in the onset of the ν_μ or ν_τ signal in a *pure neutral-current-based* detector such as the SNBO [21] is then used to infer or constrain the ν_μ or ν_τ mass. The ν_μ and ν_τ luminosities rise very rapidly after stellar core bounce. Figure 1 shows neutrino luminosities as a function of time for a typical supernova event. This figure shows luminosity histories for $\bar{\nu}_e$, ν_e, and ν_μ (ν_τ). Signal time shifts of the order of ~ 0.1 sec are detectable, so that collapse events in our Galaxy ($R_{\text{kpc}}\approx 10-20$) are far enough away to give measurable shifts for ν_μ or ν_τ with cosmologically significant masses.

It is plausible that the detection of gravitational waves could be used as the initial time mark for a pure neutral current detector, since the gravity wave signal would be generated within ~ 0.001 sec of the stellar core bounce. The energy output in gravity waves in stellar collapse is estimated to be rather low, but very high sensitivity gravitational wave [22] detectors should be operating for supernova watch in the future.

Several reactions can be employed for supernova neutrino burst detection. Table I (also see Burrows *et al.* [16]) summarizes these reactions, and possible detection schemes employing them, for several detectors in the operation or construction stage. There are three possible reactions which can be used to detect ν_x ($\bar{\nu}_x$) neutrinos ($x=\mu,\tau$):

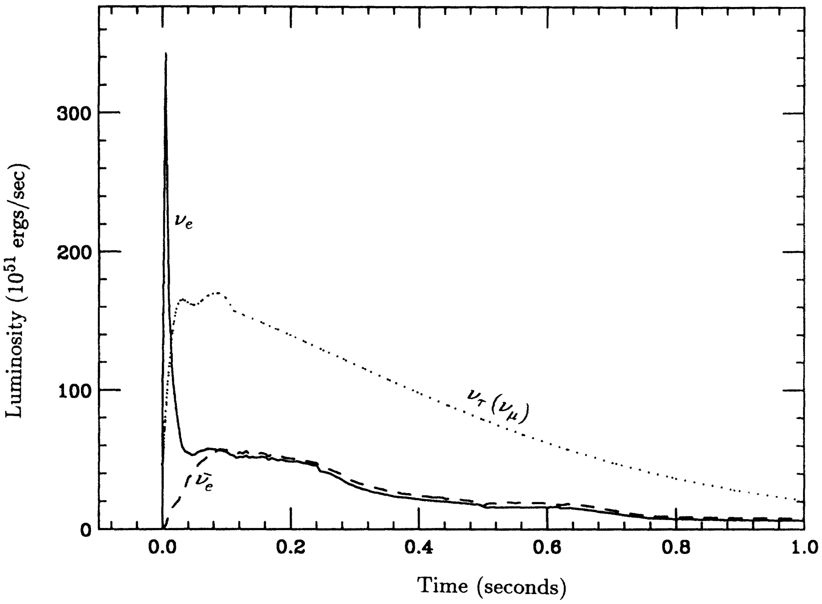

FIG. 1. Time evolution of luminosities for three neutrino flavors. Notice that the luminosities coincide with each other at very early times.

$$\begin{cases} \overset{(-)}{\nu}_x + e \rightarrow \overset{(-)}{\nu}_x + e : \text{ elastic scattering on electrons ,} \\ \overset{(-)}{\nu}_x + N \rightarrow \overset{(-)}{\nu}_x + N : \text{ elastic scattering on nucleons or nuclei ,} \\ \overset{(-)}{\nu}_x + N \rightarrow \overset{(-)}{\nu}_x + N^* : \text{ inelastic scattering on nuclei ,} \end{cases} \tag{3}$$

where N^* is an excited nuclear state that results in the production of a proton, a neutron, or a hard photon that is subsequently detected. In all cases the major sources of possible confusion with ν_e ($\overset{(-)}{\nu}_e$) induced events come from the reactions

$$\begin{cases} \overset{(-)}{\nu}_e + p \rightarrow e^+ + n \text{ ,} \\ \overset{(-)}{\nu}_e + e \rightarrow \overset{(-)}{\nu}_e + e \text{ ,} \\ \overset{(-)}{\nu}_e + N \rightarrow \overset{(-)}{\nu}_e + N \text{ ,} \\ \overset{(-)}{\nu}_e + N \rightarrow \overset{(-)}{\nu}_e + N^* \\ \rightarrow p, \ n, \text{ or } \gamma \text{ .} \end{cases} \tag{4}$$

Table II lists the approximate event rates for various reaction channels for supernova detection in the 1990s and beyond (for a detailed review see Burrows *et al.* [16]). The primary conditions for successful supernova neutrino burst detection are that the detector be large in effective volume and be composed of inexpensive material with high neutrino interaction cross section. Most detectors in operation now or proposed for the future rely on large ($\bar{\nu}_e$) cross section, $\bar{\nu}_e + p \rightarrow n + e^+$ [KII,SK,IMB,LVD, Monopole, Astrophysics and Cosmic Ray Observatory (MACRO)]. The Imaging of Cosmic and Rare Underground Signals (ICARUS) [24] detector is in the construction stage and will provide some important information regarding the ν_e burst resulting from the shock breakout phase of neutrino emission from the supernova core. Unfortunately, the ICARUS detector is not optimized for detecting ν_μ and ν_τ. At present, the most promising neutral current detector actually being constructed is the SNO [17], which utilizes the neutral-current breakup reaction of deuterium: $\nu_x + d \rightarrow n + p + \nu_x$, where $x = e, \mu, \tau$. However the charged current reactions $\nu_e + d \rightarrow p + p + e^-$ and $\bar{\nu}_e + d \rightarrow n + n + e^+$ may contaminate the massive ν_μ or ν_τ signals (Burrow *et al.* [16] discusses this point). The most useful neutral current based galactic supernova detector may be the SNBO. This detector sited in a low radioactive background would give a large number of $\nu_\tau(\nu_\mu)$ events—about 10 000 depending on detector geometry and the detector medium (see Sec. III).

III. NEUTRINO MASS DETERMINATION

A. Neutrino detection employing neutrino-nucleus inelastic scattering

A promising technique for neutrino detection involves neutral current inelastic neutrino-nucleus scattering. If

TABLE I. Supernova neutrino detection methods in the 1990s.

Reactions	$\bar{\nu}_e p \rightarrow e^+ n$	$\nu_x e \rightarrow \nu_x e$	$\nu_x N \rightarrow \nu_x N$	$\nu_z N \rightarrow \nu_z N^* \rightarrow n$
Parameters				
Cross section	Large (KII,SK,IMB,LVD)	Small $\sim E_\nu^2$ (ICARUS)	Large for coherent process	Large at high E_{ν_x} SNO/SNBO
Neutrino energy estimate	Yes $\sim E_e$	Partial $E_{\nu_e} \sim f(E_e)$	No	No Threshold may set E_{ν_x}
ν direction	No	Yes	No	No
Time information	Yes	Yes	Yes	Yes
Down time speculation	$\gtrsim 10\%$	$\sim 30\%$	?	Could be small
Maximum detector size	2×10^5 ton (H_2O) LENA $\gtrsim 10^4$ ton liq. scint. (LVD)	$\sim 2\times10^5$ ton (H_2O) or $\sim 10^3$ ton Cryogenic (ICARUS)	? Kilograms No detector proposed	$\sim 10^5$–10^7 ton of NaCl (SNBO) or $\sim 10^3$ ton D_2O (SNO)
Backgrounds	Small if e^+ and n capture detected; OK for H_2O galactic signal	Small if directionally used to reject background	?	Depends on radioactivity of material

this reaction is endothermic (neutrino scatters to a lower energy state) then the nucleus may be left in a particle-unstable exited state:

$$\nu_x + A(Z,N) \rightarrow A(Z,N-1) + n + \nu_x' \ , \qquad (5)$$

where the nucleus has mass number $A = Z + N$, and contains Z protons and N neutrons. In the process shown in Eq. (5) the exited nucleus decays by neutron emission. In this expression ν_x is either a ν_e, ν_μ, ν_τ, or their antiparticles. Recent studies have shown that the cross section for this process can be very large by nuclear weak interaction standards, approaching $\sigma_n \approx 10^{-42}$ cm^2 per nucleon for the energetic ν_μ and ν_τ neutrinos expected from stellar collapse [25,26].

In fact the cross section for the interaction in Eq. (5) is quite energy dependent, so that the ν_μ and ν_τ neutrinos dominate the neutron yield. In effect then, a detector based on this inelastic process filters out low energy neutrinos. We expect that the average energies for the neutrino species satisfy $\bar{\epsilon}_{\nu_{\mu(\tau)}} > \bar{\epsilon}_{\bar{\nu}_e} > \bar{\epsilon}_{\nu_e}$. Typical values for these quantities after 1 sec are $\bar{\epsilon}_{\nu_{\mu(\tau)}} \approx 25$ MeV, $\bar{\epsilon}_{\bar{\nu}_e} \approx 16$ MeV, $\bar{\epsilon}_{\nu_e} \approx 11$ MeV. In the absence of significant neutrino flavor mixing between $\bar{\nu}_{\tau(\mu)}$ and $\bar{\nu}_e$, we an conclude that the detectors utilizing reaction (5) operate as flavor filters, effectively detecting only $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ induced events.

We follow Ref. [26] and compute the total average neutrino-nucleus inelastic scattering cross section as

$$\sigma_{\rm FD}(T_\nu) = \frac{\sigma_0 \int_0^\infty F_\nu(E_\nu) dE_\nu \int_0^{E_\nu} dE_\nu' E_\nu'^2 \beta(E_\nu - E_\nu')}{\int_0^\infty F_\nu(E_\nu) dE_\nu} \ , \qquad (6)$$

where $\sigma_0 \approx 2.583\times10^{-44}$ cm^2 MeV^{-2}, and E_ν and E_ν' are the incident and scattered neutrino energies, respec-

TABLE II. Events expected from a galactic supernova in further supernova ν detectors at 10 kpc.

Comparison of future supernova ν detectors						
Process	$\bar{\nu}_e p \rightarrow e^+ n$ $\bar{\nu}_e d \rightarrow ppe^-$	$\bar{\nu}_e e \rightarrow \bar{\nu}_e e$	$\bar{\nu}_x e \rightarrow \bar{\nu}_x e$ $x = \mu,\tau$	$\nu_e N \rightarrow N^* \nu_e$ $\rightarrow n$	$\nu_x NN \rightarrow N^* n_x$ $\rightarrow n$	ν_e prompt
Detectors						
ICARUS		~ 140	25			4[a]
SNO (1.6 kT):	~ 435	3	21	~ 117	~ 200	5[a]
($D_2O + H_2O$)	(H_2O shield $+D_2O$)					5-20
LVD (1.8 kT): scint	~ 342					
MACRO (1 kT): scint	~ 220					
Kamiokande II (3 kT)	~ 355	~ 1				
Super Kam (40 kT) H_2O	~ 5310	~ 17				~ 5[a]
SNBO (100 kT)	100s			~ 100s	10000	
Comments	Measure t_ν, $E_\nu \sim E_e$ No direction	t_ν E_ν estimated from E_e Θ_ν measured		t_ν only No E_ν! No Θ_ν		$\Delta r \simeq 10$ ms

[a]Depends on energy spectrum of prompt ν_e and detector threshold.

tively. In this equation we present a neutrino-flux-averaged cross section, where $F_\nu\ (E_\nu, T_\nu)$ is the neutrino flux at energy E_ν. The weak nuclear strength function is $\beta\ (E_\nu - E'_\nu)$, and $(E_\nu - E'_\nu)$ is the neutrino energy transfer to the nucleus. Shell model fits for this strength function can be found in Ref. [26].

Figure 2 shows the total flux-averaged neutrino-nucleus inelastic scattering cross sections *per nucleon* for ^{28}Si and ^{23}Na as functions of T_ν. In this figure we have assumed that each nucleus is in an exited state with an excitation energy of $\langle E \rangle \approx 20$ MeV. In fact, for inelastic neutrino-nucleus scattering in the endothermic channel there is very little dependence of the cross section on nuclear excitation energy, so that the results shown in Fig. 1 would be essentially unchanged for $\langle E \rangle = 0$. Obviously the $\langle E \rangle = 0$ case is the one relevant for terrestrial detectors. The neutrino flux $F_\nu(E_\nu, T_\nu)$ used for the results in Fig. 2 was taken to be a blackbody Fermi-Dirac distribution with zero chemical potential.

We can use these techniques to make estimates of the neutron production cross sections per nucleon for various materials which might serve as a detection medium for a neutral-current-based supernova neutrino burst detector. We have computed these cross sections for three different "rocks" composed of NaCl, $CaCO_3$, and SiO_2. We sum the cross section for each nucleus, weighting each by the appropriate frequency of occurrence in each molecule. A terrestrial detector has nuclear excitation energy $\langle E \rangle = 0$, and the appropriate weak strength function is $\beta(E_\nu - E'_\nu)$. The neutron production cross section is then

$$\sigma_n^i(E_\nu) = \alpha_i \sigma_0 \int_0^{E_\nu} dE'_\nu E'^2_\nu \beta_i(E_\nu - E'_u)\ , \tag{7}$$

where the index i refers to a specific nucleus and α_i is the efficiency for neutron emission.

In Fig. 3 we show the neutron emission cross section per nucleon as a function of incident neutrino average energy for detector material composed of NaCl, $CaCO_3$, and SiO_2 (dashed, dotted, and dot-dashed curves, respectively). In these calculations we employ a neutron emission efficiency of $\alpha \approx 20\%$ for al nuclear species. Shown for comparison purposes is the cross section for $\bar{\nu}_e$ absorption on protons, $\bar{\nu}_e + p \rightarrow n + e^+$. It is apparent from this figure that the neutron production cross sections will dominate the $\bar{\nu}_e + p \rightarrow n + e^+$ cross section when the incident neutrino energy is in excess of 25 MeV. Given the average neutrino energy hierarchy discussed above it is clear that $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_\tau$ neutrinos will dominate neuron production in neutral current based detectors. This conclusion is true, however, only when $\overset{(-)}{\nu}_{\mu(\tau} \rightarrow \overset{(-)}{\nu}_e$ interconversion in negligible.

B. Expected performance for a neutral-current-based neutrino detector

In gauging the prospects for time-of-flight delay measurement for ν_μ or ν_τ mass from a galactic supernova event it is useful to consider the characteristics of a plausible neutral current based detector. As described above, such a detector is sensitive primarily to high energy neutrinos and, therefore, acts as a neutrino flavor filter in the absence of matter enhanced oscillations. The proposed Supernova Neutrino Burst Observatory (SNBO) (see Refs. [21] and [23]) would use NaCl in a salt deposit as a detector medium. The high threshold energy ($E_{\rm th} \gtrsim 12$ MeV) for neutron production in ^{23}Na enhances the flavor-filter aspects of the detector. The SNBO detector would use BF_3 neutron counters, which detect neutrons from neutrino-nucleus spallation events via the reaction

$$n + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Li} + {}^{4}\mathrm{He}\ . \tag{8}$$

Clearly, the feasibility of such a detector depends on having low neutron backgrounds. At least one site has

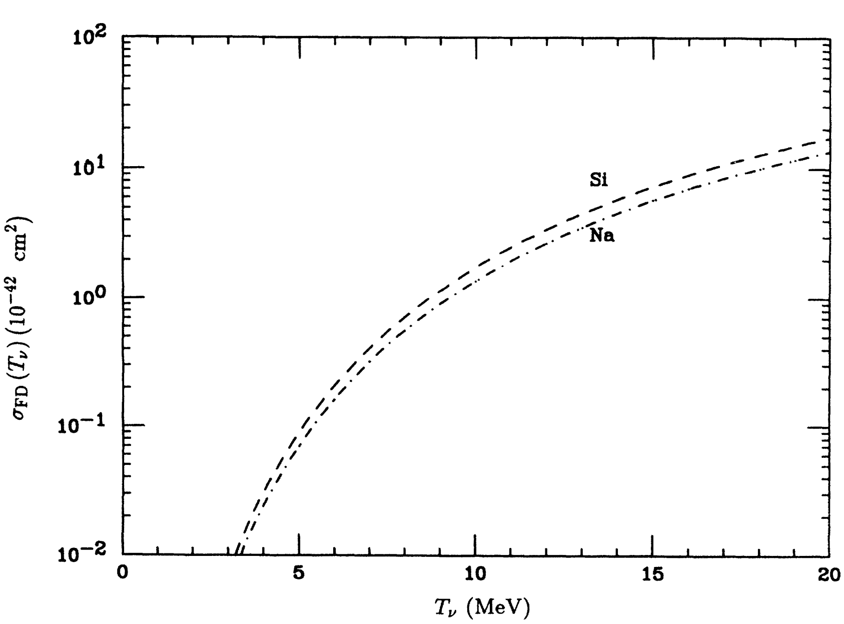

FIG. 2. $\nu + A(N,Z)$ inelastic scattering cross section averaged over a blackbody Fermi-Dirac distribution of neutrinos. We show results for ^{28}Si and ^{23}Na as indicated.

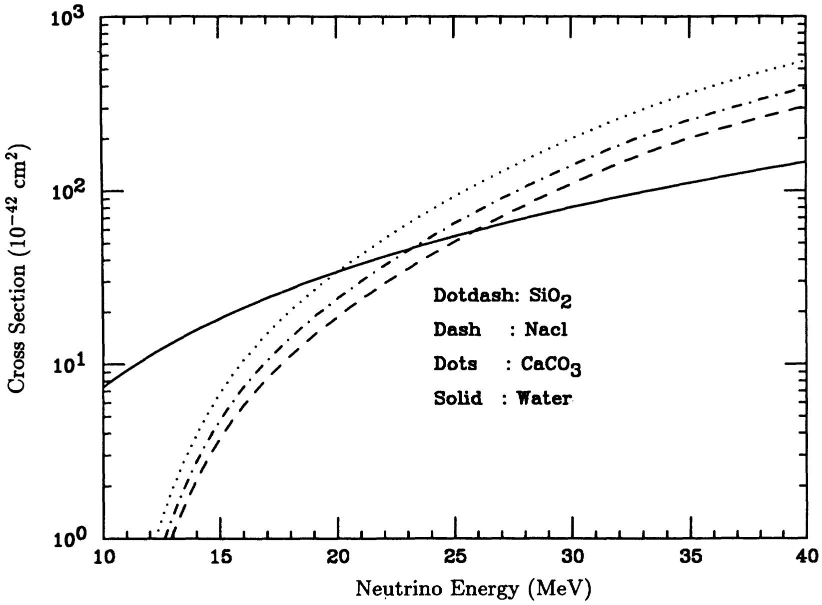

FIG. 3. Neutron production cross sections for three different rocks. The cross sections for each rock are obtained by summing the individual nuclear cross sections weighted according to their frequency of occurrence. The $\bar{\nu}_e + p \rightarrow n + e^+$ cross section is compared with neutron production cross sections. Above $E_{\nu_\tau} \sim 20$ MeV, the NaCl, $CaCO_3$, SiO_2 cross sections are greater than the dominant water Čerenkov detector interaction.

been suggested where the background is measured to be low enough that the detector would provide a large number of counts from a galactic supernova. This is the WIPP site (Waste Isolation Plot Plant [23]) where the neutron background has been measured to be about six counts per hour for a 2-m-long neutrino counter (see [28]).

A detector such as the SNBO is envisaged to consist of a tunnel several thousand feet under ground (to reduce cosmic-ray background). This tunnel would be about 1 km long and 5 m in diameter. The tunnel would be lined with BF_3 counters. Detailed Monte Carlo calculations of neutron transport combined with a proper account of the efficiency for neutron detection indicate that of order 10^4 high-energy-neutrino-induced events would be expected from a supernova at 10 kpc distance (i.e., a galactic supernova).

A low neutron background is essential for massive neutrino time-of-flight delay measurements for yet another reason. These measurements would require time correlation between neutron detection and the neutrino burst. Monte Carlo calculations show that 90% of the neutrons counted come in the first millisecond after emission from the excited nuclei. The neutrino signals are expected to have durations of about 10 sec, with peak luminosities occurring within the first few hundreds of milliseconds.

C. Expected supernova signals and analysis

We briefly discuss some essential features of neutrino emission from supernova and how these features relate to time-of-flight delay measurement. The numerical work of Wilson [30], Wilson and Mayle [31], Bruenn [32], Myra and Burrows [33], and Burrows [34] show that there are two short pulses of neutrinos followed by a much longer pulse in a type-II supernova neutrino burst. As shown in Fig. 1, electron neutrinos (ν_e), emitted predominantly during the infall and when the shock reaches the neutrino sphere, carry away an energy of a few times 10^{51} ergs. The "neutronization pulse" comes when the shock passes through the neutrino sphere. Subsequently, the long thermal neutrino pulse is characterized by all six neutrino species carrying away almost all the gravitational binding energy ($\sim 10^{53}$ ergs) of the newborn neutron star. The cooling and deleptonization of the proton-neutron star occurs largely during this phase.

The flight time shift method is somewhat dependent on the particular collapse model. The computer model developed by Wilson and Mayle [31] has given good agreement with the observation of SN 1987A. The calculations give the correct neutrino spectrum and time distribution as well as the observed total explosion energy. A key property which we require from these calculations is the rise time of the $\bar{\nu}_e$ emission relative to the $\nu_{\mu,\tau}$ emission. The $\bar{\nu}_e$ production and emission is suppressed until the core becomes hot enough that degeneracy is decreased. Similarly, the $\nu_{\mu,\tau}$ emission is initially limited by the temperature since the $\nu_{\mu,\tau}$ production rate is proportional to T^9. A temperature of about 9 MeV is needed to produce enough $\nu_{\mu,\tau}$ so that the luminosity, $L_{\mu,\tau}$ is diffusion limited. This temperature is also about the same as that needed to relieve the degeneracy suppression of the $\bar{\nu}_e$. Thus, the coincidence of the rise time of the $\bar{\nu}_e$ and $\nu_{\mu,\tau}$ is not strongly model dependent. Note that the $\bar{\nu}_e$ and $\nu_{\mu,\tau}$ signals rise abruptly to their peak in about 0.1 sec (see Fig. 1). The model calculations of Myra and Burrows [33] also shows the narrow peak in the $\bar{\nu}_e$ and $\nu_{\mu,\tau}$ spectrum in the first 0.1–0.2 s after core bounce [16,33].

Following the above outline we can estimate the expected count rate from a supernova burst for various detector materials (or "rocks"). Considering the signal delay from finite neutrino masses, the count rates are estimated as

$$C(t)_{\rm rock}=\frac{N_T}{4\pi R^2_{10\ \rm kpc}}\frac{\int_{\epsilon_{\rm cut}}^{\infty}\sigma_n(\epsilon_{\nu_\tau},\epsilon_{\rm cut})\epsilon^2_{\nu_\tau}\exp[-\epsilon_{\nu_\tau}/T_{\nu_\tau}(t_e)]N_{\nu_\tau}(t_e)d\epsilon_{\nu_\tau}}{\int_{\epsilon_{\rm cut}}^{\infty}\epsilon^2_{\nu_\tau}\exp[-\epsilon_{\nu_\tau}/T_{\nu_\tau}(t_e)]d\epsilon_{\nu_\tau}}\ , \tag{9}$$

where

$$t_e=t-0.514R_{10\ \rm kpc}\left[\frac{m_{\nu_\tau}}{\epsilon_{\nu_\tau}}\right]^2 \sec\ , \tag{10}$$

where N_T is the total number of target nucleons in various rocks, σ_n $(\epsilon_{\nu_\tau},\epsilon_{\rm cut})$ is the neutron production cross sections per nucleon (see Fig. 3), and where the cut-off energy is $\epsilon_{\rm cut}\simeq 20$ MeV. Figure 4 shows average neutrino energies for $\bar{\nu}_e$, ν_e, and ν_μ (ν_τ) as functions of time. The core temperature is taken as $T_{\nu_\tau}(t_e)=\bar{\epsilon}_{\nu_\tau}/3$ and the total number of incident neutrinos $N_{\nu_\tau}(t_e)=L_{\nu_\tau}/\bar{\epsilon}_{\nu_\tau}$ is fitted to the computer model (see Figs. 3 and 4), where $\bar{\epsilon}_{\nu_\tau}$ is the average τ neutrino energy.

Depending on the detector medium we can normalize the total number of events by

$$N_{\rm rock}=\int C_{\rm rock}(t)dt$$
$$=\frac{\rm events}{\rm effective\ detector\ mass}\ . \tag{11}$$

For different rocks consisting of NaCl, $CaCO_3$, and SiO_2, we have calculated the expected neutron count rates for the SNBO-type configuration for a supernova at 10 kpc. Figure 5(a) shows results of these computations for total neutron production cross sections for three different rocks (Fig. 3). These calculations assume zero neutrino mass for all species. These signal "history" curves show all the essential characteristics outlined as expected in a stellar collapse model: rapid rise to the maximum count rate within 150 msec, and a long time scale decay after the peak. Clearly, the event rates depends on the rock composition.

Figure 5(b) shows the effect of finite ν_μ or ν_τ masses on the expected signal count rate for a NaCl detector medium. These signal count rate curves show the characteristic massive neutrino effects such as flattening, smoothing, broadening and a slower time decrease in the signal. Figure 5(b) indicates that a cosmologically significant τ neutrino mass may be easily discernible. This is because for $m_{\nu_\tau}=10$ eV the rise time of the signal in the SNBO detector is delayed at least ~ 0.1 sec for a galactic supernova neutrino burst. As we mentioned in the Introduction, the $\bar{\nu}_e$ signal from the Super-Kamiokande detector should allow a good timing mark for the events.

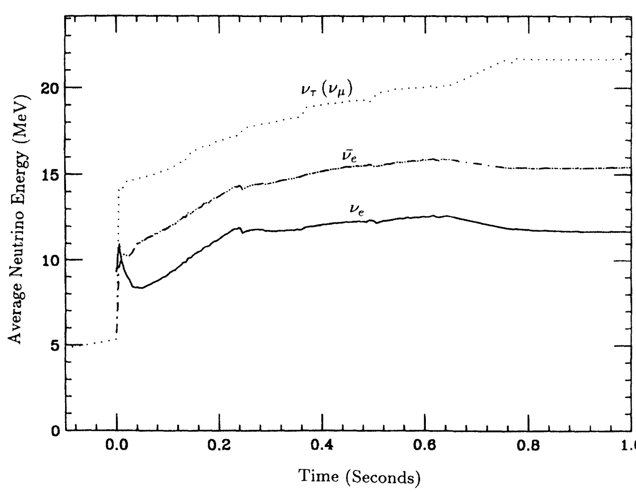

FIG. 4. Time evolution of average energies for three neutrino flavors are shown. In these calculations we fit the curves by polynomials to obtain smooth functions.

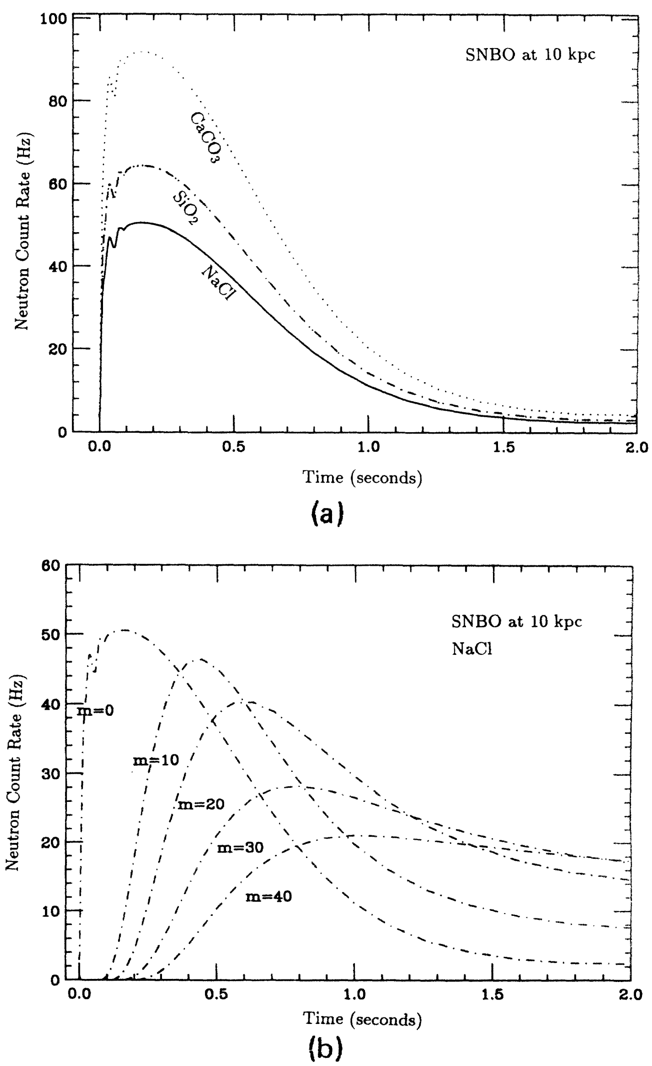

FIG. 5. (a) Signal count rates for three rocks. (b) Effects of a massive μ or τ neutrino (7, 10, 20, 40 eV) on the signal count rates for NaCl medium.

Our analysis assumes that neutrino masses are less than the cosmological limit, 92 eV. If the ν_μ or ν_τ are heavier than a few hundred eV, then their signal will be so spread out as to be difficult to interpret and pick out, due to detector background. For the low background indicated for the WIPP site, time-of-flight mass determination for ν_μ or ν_τ should be feasible for neutrino masses between about 90 eV and 15 eV. The lower limit might conceivably be extendable down to of order 5 eV, depending on the reliability of our predicted supernova model.

Neutrino flavor mixing represents a complicating aspect for the time-of-flight decay measurement for ν_μ and ν_τ masses outlined above. In particular, if the massive high energy ν_μ or ν_τ undergoes a matter-enhanced level crossing anywhere in the supernova about the neutrino sphere, then the detector may not be capable of resolving the expected time-of-flight decay. For example if $m_{\nu_\tau} \gtrsim 15$ eV, and somewhere in the supernova ν_τ is efficiently converted to ν_e, then approximately one quarter of the neutron events induced by neutral current interactions will come from the resulting high energy ν_e. Furthermore, in this case only one-quarter of the neutrinos ($\bar{\nu}_\tau$) responsible for the neutron events would propagate from the supernova to the detector in the high-mass, time-of-flight-delayed eigenstate. This is to be contrasted with the case with no flavor mixing where fully one-half the neutron events are caused by time-of-flight-delayed neutrinos (i.e., both ν_τ and $\bar{\nu}_\tau$). Estimates for SNBO show that mass determination is unlikely when only 1/4 of the events are time delayed.

Neutrino flavor interconversion depends not only on the neutrino energy and mass and the supernova density profile (these quantities determine the radius of a neutrino mass level crossing), but also on the vacuum mixing angle between $\nu_{\mu(\tau)}$ and ν_e. Matter-enhanced neutrino flavor oscillations in supernovas are discussed in Refs. [12,29]. Reference [12] shows that the nucleosynthesis consideration mitigates against efficient ν_μ or $\nu_\tau \rightarrow \nu_e$ flavor conversion for ν_μ or ν_τ with cosmologically significant masses. Reference [29] shows how efficient $\nu_{\mu(\tau)} \rightarrow \nu_e$ conversion for any $\nu_{\mu(\tau)}$ mass will have a readily discernible signature in a large water-detectorlike SK. This signature is due to the $^{16}O\,(\nu_e, e^-)\,^{16}F$ neutrino capture reaction, which has an effective ν_e-energy threshold of 35 MeV or so, and produces a backward peaked electron [35]. Observation of this feature is a dead giveaway that efficient $\nu_{\tau(\mu)} \leftrightarrow \nu_e$ interconversion has occurred in the supernova. Note that such an observation does not tell us what the neutrino mass scales are. For example, $\delta m^2 \approx 10^{-6}$ eV^2 with the small mixing angle value for the preferred MSW solution of the solar neutrino problem would give efficient $\nu_\tau(\mu) \rightarrow \nu_e$ conversion in the envelope of the supernova [29], and should give a clear oxygen signal in SK.

Clearly our interpretation of the neutral-current-based detector data for a supernova burst event in the Galaxy will depend on whether an oxygen ν-conversion signal is seen in a concurrently operating water-detectorlike SK. Table III shows the interpretation of possible outcomes for neutrino burst detection in SK and SNBO. For example, if we both observe a time-of-flight-delay signal in SNBO and an $\nu_{\tau(\mu)} \rightarrow \nu_e$ mixing signal in SK, then we know there is a massive ν_τ or ν_μ ($m_{\nu_{\tau(\mu)}} > 5$ eV) and that there is a matter-enhanced level crossing. This could be consistent with the MSW mechanism in the Sun if the ν_τ is the heavy neutrino and the matter-enhanced level crossing in the supernova is $\nu_\nu \rightarrow \nu_e$ with $m_{\nu_\mu} \simeq 10^{-3}$ eV.

On the other hand if *no* time-of-flight delay is observed in SNBO, but a ν-mixing signal is observed in SK, then it still might be that ν_μ or ν_τ has a mass $m_{\nu_{\tau(\mu)}} > 5$ eV. In this case, the high energy ν_μ or ν_τ neutrino may have propagated to Earth in the ν_e state because of efficient $\nu_{\tau(\mu)} \rightarrow \nu_e$ conversion in the supernova. Such signals could be consistent with the MSW solution in the sun.

If a time-of-flight signal is seen in SNBO, but is not accompanied by a mixing signal in SK, then we conclude that there is a massive ν_μ or ν_τ, but mixing between these species and ν_e is negligible. In particular, MSW is not the solution for the solar neutrino problem. The case where no time-of-flight signal is observed in SNBO *and* no mixing signal is observed in SK is similar: the MSW

TABLE III. Interpretation of future neutrino burst detection.

SNBO	Super-Kamiokande	Interpretation
Observe time-of-flight signature?	Observe $\nu_e \leftrightarrow \nu_{\tau(\mu)}$ oxygen signal?	
Yes	Yes	Consistent with ν_e-ν_μ solar ν mixing solution for solar ν problem plus a massive ν_τ ($m_{\nu_\tau} > 5$ eV)
No	Yes	Conclude there are high energy ν_e's from $\nu_e \leftrightarrow \nu_{\tau(\mu)}$, could still have $m_{\nu_{\tau(\mu)}} > 5$ eV Could be consistent wtih solar ν mixing solution
Yes	No	There is a massive $\nu_{\tau(\mu)}(m_{\nu_\mu(\nu_\tau)}) > 5$ eV but $\nu_e \leftrightarrow \nu_{\tau(\mu)}$ mixing negligible. Neutrino mixing is *not* the solution for solar ν problem
No	No	Upper limits on $m_{\nu_{\tau(\mu)}}$. No solar ν mixing $\nu_e \leftrightarrow \nu_{\tau(\mu)}$ mixing very small

solution cannot be the solution of the solar neutrino problem; but we do place upper limits on the ν_μ and ν_τ masses which are far better than current experimental limits.

IV. CONCLUSIONS

We have discussed the feasibility of detecting cosmologically significant neutrino masses using the time-of-flight-delay technique for a neutral current based detector. Inelastic neutrino-nuclei scattering and neutron detection provides an attractive technique for supernova neutrino detection. The inherent cutoff energy in such a detector will imply preferred sensitivity to ν_μ and ν_τ. We have shown that such a detector operating in conjunction with a water Čerenkov detector such as SK can give valuable, and otherwise unobtainable, constraints on neutrino masses and mixings. We conclude that reliable limits on cosmologically significant ν_μ and/or ν_τ masses derived from galactic supernova burst events are feasible. Obtaining these limits depends on having neutral-current-based detectors operating in conjunction with the next generation of water Čerenkov detectors.

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