Electron Neutrino Mass Measurement by Supernova Neutrino Bursts and Implications for Hot Dark Matter

Tomonori Totani*
Department of Physics, School of Science, The University of Tokyo, Tokyo 113, Japan
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We present a new strategy for measuring the electron neutrino mass (m_{ν_e}) by future detection of a Galactic supernova in large underground detectors such as Super-Kamiokande. This method is nearly model independent, and one can get a mass constraint in a straightforward way from experimental data without specifying any model parameters for profiles of supernova neutrinos. We have tested this method using virtual data. It is shown that the method is sensitive to m_{ν_e} of $\sim$3 eV for a Galactic supernova, and this range is as low as the prediction of the cold+hot dark matter scenario with a nearly degenerate mass hierarchy of neutrinos. [S0031-9007(98)05434-9]

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It is well known that detection of a neutrino burst from a collapse-driven supernova by large underground detectors gives us some constraints on neutrino masses, due to the delay of arrival times depending on the neutrino energy as $\Delta t = 5.15(D/10\text{ kpc})(m_\nu/1\text{ eV})^2(\varepsilon_\nu/10\text{ MeV})^{-2}$ msec, where D is a distance to the supernova, m_ν the neutrino mass, and ε_ν the neutrino energy [1]. Some upper bounds on the electron neutrino mass (m_{ν_e}), ranging in 10–20 eV, have already been derived by a number of papers using the historical data of SN 1987A [2]. On the other hand, given the status of tritium β-decay experiments, experimental upper limits on m_{ν_e} are also considered to be $\sim$10–15 eV [3]. Therefore the next Galactic supernova expected in the near future and its detection by the currently emerging international network of second-generation neutrino detectors, such as the Super-Kamiokande (SK) [4] or Sudbury Neutrino Observatory [5], would give an important opportunity of setting a more stringent constraint on m_{ν_e} than the current astrophysical or experimental limits. Especially, the normal water Čerenkov detectors are the most sensitive to electron antineutrinos ($\bar{\nu}_e$'s), and an enormous number of $\bar{\nu}_e p \to e^+ n$ events expected in the SK ($\sim$5000–10 000 events) for a supernova at the Galactic center ($D = 10$ kpc) would give much better statistics than that of SN 1987A.

However, the electron neutrino mass measurement by supernova neutrinos generally suffers significant uncertainties related to the original profiles of supernova neutrino emission, i.e., neutrino luminosity curve and energy spectrum. The analyses on SN 1987A data were based on the luminosity decay during the cooling phase of hot neutron stars, during which the majority of $\bar{\nu}_e$'s is emitted. Because the decay time scale in this phase is $O(10)$ seconds, it is difficult to probe the arrival time delay shorter than this scale. This is why we could not probe the mass scale smaller than $\sim$10 eV for SN 1987A ($D = 50$ kpc). Therefore it is clear that we have to devise a different strategy which maximally utilizes the much larger number of expected events in the SK. Although the cooling phase is $\sim$10 sec long, the time scale of initial rise of neutrino luminosity is much shorter: a recent numerical simulation of gravitational collapse and neutrino emission [6] shows that this scale for $\bar{\nu}_e$'s is 1–10 msec. The prediction of this time scale by the current theory of collapse-driven supernovae is robust because this is determined by the time scale for the shock wave generated by the core bounce to cross the neutrino sphere [7]. This suggests that we can probe the neutrino mass of $\sim$1 eV, at least in principle, by using a sufficient number of events around the initial steep rise of neutrino luminosity. In the following, we propose a new strategy to set a constraint on m_{ν_e} from the initial rise of $\bar{\nu}_e p$ events assuming a detection by the SK. We then test this method by virtual data of neutrino events detected by the SK, which are produced by realistic Monte Carlo simulations (MCs) with a numerical model of supernova neutrino emission [8]. We find that m_{ν_e} of $\sim$3 eV can be probed by a future galactic supernova.

Getting constraints on the electron neutrino mass.— Strong $\bar{\nu}_e$ emission suddenly breaks out when the shock wave passes the neutrino sphere with a time scale of 1–10 msec, and after this breakout the time variability of neutrino luminosity or energy spectrum is on a scale of $\sim$1 sec [6–8]. The signature of a finite neutrino mass which we try to detect is the earlier arrival of high energy neutrinos in the breakout. Since events from the $\bar{\nu}_e p \to e^+ n$ reaction are dominant, we treat all events as this reaction, and the validity of this approximation will be checked later. Suppose that we get a sequence of arrival time and detection energy of positrons as $(t_1, \varepsilon_1), (t_2, \varepsilon_2), \ldots, (t_N, \varepsilon_N)$, where N is the observed number of events, and order of events is defined as $t_k < t_{k+1}$. Consider a transformation of detection time of events ($t_k \to t'_k$) for a given value of m_{ν_e}, which subtracts the arrival time delay due to the assumed neutrino mass, as

$$t'_k = t_k - \frac{D m_{\nu_e}^2}{2c(\varepsilon_k + \Delta_{np})^2}, \qquad (1)$$

where Δ_{np} is the neutron-proton mass difference ($= 1.3$ MeV). Let ε'_k be the sequence of detection energy in increasing order of t'_k. Since the neutrino spectrum is roughly constant after the breakout on a time scale of $\sim$1 sec, it is expected that the distribution of ε'_k is random without any correlation to t'_k, if the assumed value of m_{ν_e} is correct. Here we define a measure of correlation between t'_k and ε'_k in the first $N_{\rm cut}$ events as follows:

$$S^2(m_{\nu_e}) \equiv \sum_{k=2}^{N_{\rm cut}} \frac{\{N_k(\varepsilon'_k) - (k-1)f(\varepsilon'_k)\}^2}{(k-1)f(\varepsilon'_k)}, \qquad (2)$$

where $N_k(\varepsilon'_k)$ is the number of events detected earlier than t'_k with energy greater than ε'_k, and $f(\varepsilon)$ is the fraction of expected events with energy greater than ε. We can calculate $f(\varepsilon)$ from $\bar{\nu}_e$ spectrum, the cross section of $\bar{\nu}_e p$ reaction, and detection efficiency of the SK. If we use the Ferm-Dirac (FD) distribution with zero chemical potential as the spectrum of neutrinos, we can straightforwardly calculate S^2 as a function of m_{ν_e}, FD temperature $T_{\bar{\nu}_e}$, and $N_{\rm cut}$ from a given experimental data set of (t_k, ε_k). It is known that the real energy spectrum of supernova neutrinos is slightly different from the pure black body radiation because of energy-dependent opacity of neutrinos. However, we note that we are paying attention to how random the ε'_k distribution is, and a detailed shape of the spectrum is not important in our analysis. This will be checked later. Now let us consider the physical meaning of $S^2(m_{\nu_e}, T_{\bar{\nu}_e}, N_{\rm cut})$. If we approximately regard the Poisson distribution as the Gaussian distribution, the distribution of S^2 is the χ^2 statistics with $N_{\rm cut} - 1$ ($\sim N_{\rm cut}$) degrees of freedom, and hence it is expected that S^2 obeys the χ^2 distribution if the assumed m_{ν_e} is correct. On the other hand, if the assumed m_{ν_e} is significantly different from the true value, only high- or low-energy neutrinos will arrive earlier and S^2 will become larger than the expectation from the χ^2 distribution. Similarly, incorrect values of $T_{\bar{\nu}_e}$ will lead to unexpectedly large S^2. Therefore S^2 is expected to take the minimum at the correct values of m_{ν_e} and $T_{\bar{\nu}_e}$. Hereafter we always take a value of $T_{\bar{\nu}_e}$ which minimizes S^2. Then we get a constraint on m_{ν_e} with n sigma confidence level, for a given value of $N_{\rm cut}$ as

$$S^2(m_{\nu_e}, N_{\rm cut}) < \min_{m_{\nu_e}} S^2(m_{\nu_e}, N_{\rm cut}) + n\sqrt{2N_{\rm cut}}, \qquad (3)$$

with the best-fit value of $m_{\nu_e}^{\rm fit}(N_{\rm cut})$ which minimizes S^2, where $2N_{\rm cut}$ is the variance of the χ^2 distribution with $N_{\rm cut}$ degrees of freedom. We stress that this strategy does not require any specification of model parameters, and constraints on m_{ν_e} can be calculated in a straightforward way from experimental data. It should also be noted that we have implicitly assumed in the above argument that the distance to a supernova is known, although in a future detection it may be unknown. In such a case the above strategy is still applicable but we can only get constraint on $Dm_{\nu_e}^2$.

Test for the strategy by Monte Carlo simulations.— In the following, we give a test about the reliability of this strategy, by using neutrino emission profiles of a one-dimensional numerical model of supernova explosion which does not assume any particular energy distribution of neutrinos [6]. This is a model of SN 1987A with a main-sequence mass of $\sim 20 M_\odot$. We have made virtual data sets of (t_k, ε_k) by Monte Carlo simulations of the SK detector supposing a supernova at a distance of $D = 10$ kpc. The MC simulation is described in Ref. [8] which takes account of the SK detection efficiency, energy resolution, and reaction modes of $\bar{\nu}_e p$ absorption, νe scatterings, and charged-current $\nu_e(\bar{\nu}_e)$ absorptions into oxygen. Therefore we can check the validity of the approximations in the proposed method, i.e., assuming the FD distribution and regarding all events as $\bar{\nu}_e p$ events. We have made four MC realizations with simulated neutrino masses ($m_{\nu_e}^{\rm MC}$) of 0, 3, 5, and 7 eV, and applied the method to these data varying the value of $N_{\rm cut}$. We have used events with detection energy greater than 10 MeV to avoid the background noise of $(\nu, \nu' p\gamma)$ and $(\nu, \nu' n\gamma)$ reactions on ^{16}O [9]. The obtained best-fit $m_{\nu_e}^{\rm fit}$ and 2 sigma (95% C.L.) lower and upper limits ($m_{\nu_e}^l$ and $m_{\nu_e}^u$) are shown in Fig. 1 as functions of $N_{\rm cut}$. If the strategy correctly detects the signature of a finite neutrino mass, the best-fit $m_{\nu_e}^{\rm fit}$ should not vary with $N_{\rm cut}$. In other words, the constancy of $m_{\nu_e}^{\rm fit}$ against $N_{\rm cut}$ gives an important consistency check of this analysis.

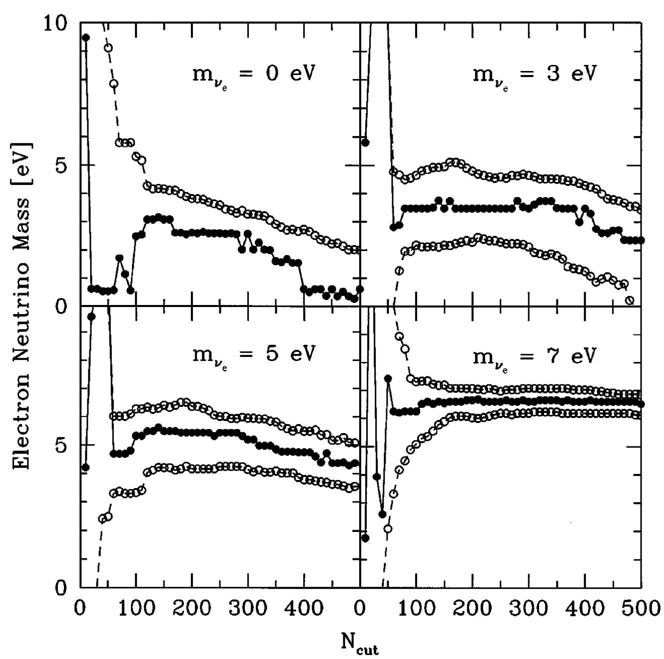

FIG. 1. The result of the proposed strategy of measuring m_{ν_e} applied to four Monte Carlo realizations of the SK detection of a supernova at the Galactic center ($D = 10$ kpc) with simulated values of $m_{\nu_e}^{\rm MC} = 0$, 3, 5, and 7 eV. Best fit m_{ν_e} (filled circles) and 95% C.L. lower and upper limits (open circles) are shown as functions of $N_{\rm cut}$.

The figure shows that, for $m_{\nu_e}^{\rm MC} = 3$, 5, and 7 eV, $m_{\nu_e}^{\rm fit}$ is almost constant at the simulated values in $N_{\rm cut} \sim 100-300$, suggesting that this method correctly detects a finite neutrino mass if we use neutrinos of the first 200–300 events, i.e., during 60–80 msec after the core bounce. One can see a slight systematic decrease of $m_{\nu_e}^{\rm fit}$ in $N_{\rm cut} \gtrsim 300$, and this is an effect of spectral hardening of $\bar{\nu}_e$'s, which begins from ~100 msec after the core bounce as a signature of the delayed explosion mechanism [7,8]. It should be noted that, in the prompt explosion scenario, stellar envelope is expelled in a very short time scale of 1–10 msec which is the same as that of the shock breakout, and neutrino spectrum is rather constant after the breakout. Therefore the proposed strategy would work even better in prompt explosions. The optimal value of $N_{\rm cut}$ depends on the distance and profiles of neutrino emission, and it should be determined by the constancy in the $m_{\nu_e}^{\rm fit}$-$N_{\rm cut}$ diagram produced from real data detected in the future.

We next estimate the sensitivity of the proposed strategy by statistical average of many MC realizations. One hundred MC realizations are generated from the supernova model with $D = 10$ kpc for each of three values of $m_{\nu_e}^{\rm MC} = 0$, 3, and 5 eV, and the proposed method is applied to these data with $N_{\rm cut} = 200$. The average of $m_{\nu_e}^{\rm fit}$, $m_{\nu_e}^{l}$, and $m_{\nu_e}^{u}$ for the 100 MCs are shown in Table I with 1σ statistical fluctuations. In order to check the validity of estimated confidence levels, the probability that this method gives incorrect results (i.e., $m_{\nu_e}^{l} > m_{\nu_e}^{\rm MC}$ or $m_{\nu_e}^{u} < m_{\nu_e}^{\rm MC}$) is also shown in this table, as well as the probability of detecting finite m_{ν_e} (i.e., $m_{\nu_e}^{l} > 0$). These results suggest that the estimated confidence levels are roughly valid for $m_{\nu_e}^{\rm MC} = 0$ and 3 eV. For $m_{\nu_e}^{\rm MC} = 5$ eV, $m_{\nu_e}^{\rm fit}$ is systematically smaller than $m_{\nu_e}^{\rm MC}$ and 28 trials out of 100 MCs give incorrect results of $m_{\nu_e}^{u} < 5$ eV. However, this systematic error is not greater than 1 eV, and we can detect finite m_{ν_e} with a probability of 99% if $m_{\nu_e} = 5$ eV. The origin of this systematic error is difficult to understand clearly, but it is probably the gradual hardening of the neutrino spectrum. The probability of detecting finite mass is about 50% for $m_{\nu_e} = 3$ eV, and we can conclude that this method is marginally sensitive to the electron neutrino mass of 3 eV, and can easily detect m_{ν_e} of 5 eV. This strategy also gives a fit of neutrino effective temperature $T_{\bar{\nu}_e}^{\rm fit}$, and the average of $T_{\bar{\nu}_e}^{\rm fit}$ is also given in the table. This $T_{\bar{\nu}_e}^{\rm fit}$ agrees well with the true neutrino spectrum, considering that average $\bar{\nu}_e$ energy is $3.15T_{\bar{\nu}_e}$ in FD distribution and that of the numerical supernova model in this early phase is about 10–12 MeV. (FD-fit average energy is a little lower than the true value because of the deviation of the true spectrum from the FD distribution. See Fig. 9 of Ref. [8].)

Now let us consider the dependence of the proposed strategy on the distance to a supernova. There are two competing effects: The available number of events becomes smaller with increasing distance, while the time delay due to the finite mass increases. In order to see which is more effective, we have tested the proposed method against supernovae at $D = 5$ and 20 kpc, with $m_{\nu_e}^{\rm MC} = 0$ eV. Statistical average of $m_{\nu_e}^{u}$ for 100 MC simulations is 2.4 ± 0.6 and 3.1 ± 0.7 eV for $D = 5$ and 20 kpc cases, respectively (Table I). Here we have used 400 and 100 as the values of $N_{\rm cut}$, which are found to be appropriate from $m_{\nu_e}^{\rm fit}$-$N_{\rm cut}$ diagrams. Combined with the fact that the average of $m_{\nu_e}^{u}$ for $D = 10$ kpc case is 2.8 ± 0.7 eV, the sensitivity becomes slightly better with decreasing distance, but the dependence is very weak and smaller than statistical dispersion. Therefore we conclude that the sensitivity of the proposed method is roughly the same for any collapse-driven supernova in our Galaxy. In the above estimate, we have abandoned low-energy events below 10 MeV, to avoid γ-ray events induced by neutral current reactions of ν_μ (or ν_τ) with ^{16}O which are expected to be roughly the same number with $\bar{\nu}_e p$ events in 5–10 MeV [9]. If we could somehow remove or effectively subtract these noises and apply the method to all events with detection energy greater than 5 MeV (threshold of the SK), then the average of $m_{\nu_e}^{u}$ could be as low as 1.5 ± 0.4 eV for a supernova at $D = 10$ kpc (Table I).

Finally, we discuss some implications of the reported sensitivity of supernova neutrinos to the electron neutrino mass. Currently there are some hints on nonzero neutrino masses in astrophysical and cosmological observations,

TABLE I. The results of application of the proposed method for measuring m_{ν_e} to virtual data of supernova neutrinos produced by 100 Monte Carlo simulations of the SK detection, where D is the distance to a supernova, $N_{\rm cut}$ the number of events used, $\varepsilon_{\rm th}$ the threshold energy in the analysis, and $m_{\nu_e}^{\rm fit}$ and $m_{\nu_e}^{l}$ ($m_{\nu_e}^{u}$) are the best-fit mass and 95% C.L. lower (upper) limits, respectively.

				Average of 100 MCs				Probability [%]		
D [kpc]	$m_{\nu_e}^{\rm MC}$ [eV]	$N_{\rm cut}$	$\varepsilon_{\rm th}$ [MeV]	$m_{\nu_e}^{l}$ [eV]	$m_{\nu_e}^{\rm fit}$ [eV]	$m_{\nu_e}^{u}$ [eV]	$T_{\bar{\nu}_e}^{\rm fit}$ [MeV]	$m_{\nu_e}^{l} > 0$	$m_{\nu_e}^{l} > m_{\nu_e}^{\rm MC}$	$m_{\nu_e}^{u} < m_{\nu_e}^{\rm MC}$
10	0	200	10	0.0 ± 0.0	0.81 ± 0.78	2.8 ± 0.7	2.7 ± 0.1	0	0	0
10	3	200	10	0.77 ± 0.95	2.7 ± 0.9	3.9 ± 0.6	2.8 ± 0.2	47	3	5
10	5	200	10	3.2 ± 0.7	4.4 ± 0.5	5.3 ± 0.5	2.8 ± 0.2	99	1	28
5	0	400	10	0.04 ± 0.22	0.74 ± 0.85	2.4 ± 0.6	2.6 ± 0.1	5	5	0
20	0	100	10	0.05 ± 0.05	0.92 ± 0.91	3.1 ± 0.7	2.7 ± 0.2	1	1	0
10	0	200	5	0.0 ± 0.0	0.35 ± 0.40	1.5 ± 0.4	2.8 ± 0.1	0	0	0

and here we consider the following three: The solar and atmospheric neutrino anomalies and hot dark matter in the Universe. The standard cold dark matter model of structure formation normalized by the COBE data with $\Omega_0 = 1$ is known to be inconsistent with the clustering properties of galaxies or clusters of galaxies, and the cold+hot dark matter model with $\Omega_\nu \sim 0.2$–0.3 is one of some possibilities to resolve this discrepancy, where Ω_ν is the fraction of hot dark matter in the critical density of the Universe (e.g., Ref. [10]). The most promising solution for the solar neutrino problem is the Mikheyer-Smirnov-Wolfenstein (MSW) solutions with $\Delta m^2 \sim 10^{-5}$ eV^2 [11], and the atmospheric neutrino anomaly can be explained by the neutrino oscillation with $\Delta m^2 \sim 10^{-3}$–10^{-1} eV^2 [12]. The only way to combine these hits without sterile neutrinos is an almost degenerate mass hierarchy of neutrinos [13], with $m_\nu = 4.6(h/0.7)^2(\Omega_\nu/0.3)$ eV for all three generations of neutrinos, where h is the Hubble constant $H_0/[100\ (\mathrm{km/s})/\mathrm{Mpc}]$. Oscillations between $\nu_e \leftrightarrow \nu_\mu$ and $\nu_\mu \leftrightarrow \nu_\tau$ give the solutions for the solar and atmospheric neutrino problems, respectively. The proposed method to constrain m_{ν_e} from supernova neutrino bursts can probe m_{ν_e} as low as this scale and might detect a finite m_{ν_e} if the mass hierarchy of neutrinos was actually degenerate.

Let us briefly discuss effects of possible neutrino oscillations. If the mixing angle between ν_e and others is order unity, the observed $\bar{\nu}_e$ spectrum would be a mixture of original $\bar{\nu}_e$ and $\bar{\nu}_\mu$ (or $\bar{\nu}_\tau$) due to the vacuum oscillation. (The MSW matter oscillation in supernovae is not effective for antineutrinos unless the mass hierarchy is inverse.) If the hierarchy of neutrino masses is not degenerate, i.e., $m_1 \ll m_2 \ll m_3$ as observed in charged leptons, the mixture of light neutrinos with negligible time delay and heavy neutrinos with significant delay would make the proposed method inapplicable to measurement of m_{ν_e}. However, in case of the almost degenerate hierarchy, the effect of oscillation is only deformation of observed $\bar{\nu}_e$ spectrum due to contamination of original $\bar{\nu}_\mu$'s (or ν_τ's), and the proposed method is still applicable because a detailed shape of $\bar{\nu}_e$ spectrum is not important in this method.

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*Electronic address: totani@utaphp2.phys.s.u-tokyo.ac.jp

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