Getting the Most from Detection of Galactic Supernova Neutrinos in Future Large Liquid-Scintillator Detectors postprint

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Abstract

Future large liquid-scintillator detectors can be implemented to observe neutrinos from a core-collapse supernova (SN) in our galaxy in various reaction channels: (1) The inverse beta decay ¯¯¯e+p→n+e+; (2) The elastic neutrino-proton scattering +p→ +p; (3) The elastic neutrino-electron scattering +e−→ +e−; (4) The charged-current e interaction e+12C→e−+12N; (5) The charged-current ¯¯¯e interaction ¯¯¯e+12C→e++12B; (6) The neutral-current interaction +12C→ +12C∗. The less abundant 13C atoms in the liquid scintillator are also considered as a target, and both the charged-current interaction e+13C→e−+13N and the neutral-current interaction +13C→ +13C∗ are taken into account. In this work, we show for the first time that a global analysis of all these channels at a single {liquid-}scintillator detector, such as Jiangmen Underground Neutrino Observatory (JUNO), is very important to test the average-energy hierarchy of SN neutrinos and how the total energy is partitioned among neutrino flavors. In addition, the dominant channels for reconstructing neutrino spectra and the impact of other channels are discussed in great detail.

Full Text

Preamble

Getting the Most from Detection of Galactic Supernova Neutrinos in Future Large Liquid-Scintillator Detectors

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Abstract

Future large liquid-scintillator detectors can be implemented to observe neutrinos from a core-collapse supernova (SN) in our galaxy through various reaction channels: (1) inverse beta decay $\bar{\nu}_e + p \to n + e^+$; (2) elastic neutrino-proton scattering $\nu + p \to \nu + p$; (3) elastic neutrino-electron scattering $\nu + e^- \to \nu + e^-$; (4) charged-current ν_e interaction $\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$; (5) charged-current $\bar{\nu}_e$ interaction $\bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$; and (6) neutral-current interaction $\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$. The less abundant ${}^{13}\mathrm{C}$ atoms in the liquid scintillator are also considered as a target, and both the charged-current interaction $\nu_e + {}^{13}\mathrm{C} \to e^- + {}^{13}\mathrm{N}$ and the neutral-current interaction $\nu + {}^{13}\mathrm{C} \to \nu + {}^{13}\mathrm{C}^*$ are taken into account.

In this work, we show for the first time that a global analysis of all these channels at a single liquid-scintillator detector, such as the Jiangmen Underground Neutrino Observatory (JUNO), is very important for testing the average-energy hierarchy of SN neutrinos and determining how the total energy is partitioned among neutrino flavors. In addition, we discuss in great detail the dominant channels for reconstructing neutrino spectra and the impact of other channels.

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Introduction

How massive stars eventually end their lives remains an open question in astrophysics and astronomy. In particular, a star with mass above approximately eight solar masses is expected to experience core collapse under its own gravity, followed by a violent explosion [1]. In the paradigm of neutrino-driven explosions, neutrinos carry away most of the gravitational binding energy released in the core collapse and deposit part of it to the surroundings, reviving the halted shock wave and leading to a successful explosion [2, 3]. Therefore, the detection of neutrino signals and reconstruction of neutrino energy spectra are crucial for verifying the neutrino-driven paradigm and ultimately revealing the true mechanism of core-collapse supernova explosions [4].

Interest in supernova neutrino detection has recently been stimulated by great progress in neutrino oscillation experiments, for which large water-Cherenkov and liquid-scintillator detectors are under construction or will be built in the near future. For a galactic core-collapse supernova at a typical distance of 10 kpc, the Super-Kamiokande detector (SK) can collect about 10^4 neutrino events mainly through the inverse beta decay channel $\bar{\nu}_e + p \to n + e^+$ (IBD). In Ref. [5], it has been demonstrated that SK with a gadolinium-loaded water Cherenkov detector opens the possibility to determine, with 20% precision, the total and average energy of $\bar{\nu}_e$ via elastic neutrino-electron scattering $\nu + e^- \to \nu + e^-$ (eES). This precision could be further improved by a factor of five in the future Hyper-Kamiokande with dissolved gadolinium [5]. In addition, the JUNO experiment is designed to determine the neutrino mass ordering by precisely measuring the spectrum of reactor antineutrinos with a 20 kiloton liquid-scintillator detector [6, 7]. Undoubtedly, JUNO will also serve as a powerful detector for galactic supernova neutrinos. For instance, we found in Ref. [8] that JUNO is even better than SK in constraining absolute neutrino masses through time-delay effects. See Ref. [9] for a study of a future liquid-argon detector.

Future large liquid-scintillator detectors, such as JUNO [7], RENO-50 [10], and LENA [11], will have several advantages for detecting supernova neutrinos. First, the threshold of visible energy in a liquid-scintillator detector can be rather low, limited only by the intrinsic radioactive backgrounds of the liquid scintillator itself. If the abundance of ^{14}C can be controlled at the level already achieved in the Borexino experiment, the energy threshold will be as low as 0.2 MeV [12]. In this case, elastic neutrino-proton scattering $\nu + p \rightarrow \nu + p$ (pES) becomes very important, giving rise to a large number of events in a channel other than IBD. Second, the carbon nuclei in the liquid scintillator serve as an invaluable target for supernova neutrino detection. In particular, SN ν_e is detectable via the charged-current interaction $\nu_e + {}^{12}\text{C} \rightarrow e^- + {}^{12}\text{N}$ (^{12}N-CC) in addition to elastic scattering off electrons and protons. Although the natural abundance of ^{13}C on Earth is small (about 1.1%), the charged-current interaction $\nu_e + {}^{13}\text{C} \rightarrow e^- + {}^{13}\text{N}$ (^{13}N-CC) and the neutral-current interaction $\nu + {}^{13}\text{C} \rightarrow \nu + {}^{13}\text{C}^*$ (^{13}C-NC) have been proposed as promising channels to detect solar ^{8}B neutrinos [13–16]. These two processes may be important in a massive liquid-scintillator detector and are relevant for supernova neutrino detection. Third, it is in principle possible to distinguish between protons and photons/electrons/positrons in a liquid-scintillator detector using pulse shape discrimination, implying remarkable background reduction in each channel. Therefore, liquid-scintillator detectors can provide more information about neutrino flavors and energy spectra. The event spectra of supernova neutrinos in highly pure liquid-scintillator detectors have been studied in the literature [7, 17]. In Ref. [18], a combined analysis of the two dominant channels eES and ^{12}N-CC was carried out to probe the total and average energies of ν_e, as a counterpart to the SK study in Ref. [5].

In this paper, we perform for the first time a global analysis of the main detection channels of supernova neutrinos at a large liquid-scintillator detector. We examine the prospects for SN $\bar{\nu}_e$, ν_e, and ν_x detection through quantitative analyses, where ν_x collectively stands for ν_μ, ν_τ, or their antiparticles. We explore the experimental sensitivities to the total and average energies of each neutrino flavor. First, we ignore neutrino flavor oscillations and concentrate on how well the average and total energies of each neutrino flavor can be determined. Then, we take into account neutrino oscillations with matter effects in the supernova envelope and the impact of neutrino mass ordering. We proceed to reconstruct the total and average neutrino energy from the global analysis and further test how the energy is distributed among neutrino flavors. The hypothesis of energy equipartition, which has been taken for granted in previous studies of supernova neutrinos, is critically examined.

The remainder of our paper is organized as follows. Section II summarizes supernova neutrino fluxes and detection channels in future large liquid-scintillator detectors. In Section III, we carry out numerical simulations for the JUNO detector to determine the total energies ($E^{\rm tot}_{\nu_e}$, $E^{\rm tot}_{\bar{\nu}_e}$, $E^{\rm tot}_{\nu_x}$) and average energies ($\langle E_{\nu_\alpha} \rangle$) of supernova neutrinos for the three species ν_e, $\bar{\nu}_e$, and ν_x. To clearly see the experimental sensitivities, we temporarily ignore flavor conversions of supernova neutrinos and concentrate on the impact of combining different signal channels. In Section IV, we test the energy-equipartition hypothesis in the realistic case by including flavor conversions for both neutrino mass orderings. Finally, we summarize our main conclusions in Section V, and provide details of the χ^2 functions used in our calculations in the Appendix.

II. Supernova Neutrinos at Liquid-Scintillator Detectors

A. Neutrino Spectra

For a core-collapse supernova, the total gravitational binding energy is about 3×10^{53} erg, which is mostly carried away by neutrinos and antineutrinos of all three flavors over approximately ten seconds. According to detailed Monte Carlo studies of neutrino spectra formation, the time-integrated neutrino spectrum can be well described by three parameters: the total energy $E^{\rm tot}_\alpha$, the average energy $\langle E_{\nu_\alpha} \rangle$, and the spectral index γ_α. In this parametrization, the neutrino fluences are given by [19]

$$\Phi_\alpha(E) = \frac{(1+\gamma_\alpha)^{1+\gamma_\alpha}}{\Gamma(1+\gamma_\alpha)} \frac{E^{\rm tot}_\alpha}{\langle E_{\nu_\alpha} \rangle^2} \left(\frac{E}{\langle E_{\nu_\alpha} \rangle} \right)^{\gamma_\alpha} \exp\left[-(1+\gamma_\alpha) \frac{E}{\langle E_{\nu_\alpha} \rangle} \right] ,$$

where α stands for ν_e, $\bar{\nu}_e$, and ν_x, and r denotes the radius where the neutrino fluxes are evaluated. Usually the total energy is assumed to be equally distributed among all neutrinos and antineutrinos, namely $E^{\rm tot}_{\nu_e} = E^{\rm tot}_{\bar{\nu}_e} = E^{\rm tot}_{\nu_x} = 5 \times 10^{52}$ erg. In our discussions, we also consider situations where this assumption is relaxed.

B. Detection Channels

In a liquid-scintillator detector, various possibilities exist for probing supernova neutrinos. For concreteness, we consider the JUNO detector [6, 7]. The detector comprises 20 kilotons of LAB-based liquid scintillator, for which the fraction of free protons is 12%. We employ a detector energy resolution of $3\%/\sqrt{E/\mathrm{MeV}}$, where E is the visible energy of prompt event signals (i.e., $E = E_{e^+} + m_e$). We also assume a detector threshold of 0.2 MeV for the visible energies of recoiled protons and electrons. For a galactic supernova at a distance of 10 kpc, the numbers of neutrino events in six primary channels at JUNO are presented in Table I, where the supernova neutrino fluences are given by Eq. (1) under the assumption of energy equipartition $E^{\rm tot}_{\nu_e} = E^{\rm tot}_{\bar{\nu}_e} = E^{\rm tot}_{\nu_x} = 5 \times 10^{52}$ erg. In addition, the average neutrino energies are $\langle E_{\nu_e} \rangle = 12$ MeV, $\langle E_{\bar{\nu}_e} \rangle = 14$ MeV, and

$\langle E_{\nu_x} \rangle = 16$ MeV, while the spectral index $\gamma_\alpha = 3$ is assumed to be universal for all neutrino flavors. Note that $\gamma_\alpha = 2$ corresponds to a Maxwell-Boltzmann distribution, and numerical simulations indicate that the actual value $2 < \gamma_\alpha < 4$ is time-dependent [19]. Hence, $\gamma_\alpha = 3$ can be regarded as an effective description of the time-integrated energy spectra of supernova neutrinos.

The corresponding event spectra of prompt neutrino signals are shown in Fig. 1. Below we summarize the main features of the detection channels [7]:

1. **Inverse Beta Decay (IBD)**: This is the most important channel for detecting supernova $\bar{\nu}_e$ in liquid-scintillator detectors, where a huge number of free protons are available. In this reaction, the neutrino energy threshold is $E_{\rm th} \simeq \Delta + m_e \approx 1.8$ MeV, where $\Delta = 1.293$ MeV is the neutron-proton mass difference. The energy of the incident neutrino can be fully reconstructed from the positron energy via $E_\nu \approx E_{e^+} + \Delta$, as the recoil energies of nucleons are negligible. The annihilation of positrons and capture of neutrons on free protons lead to prompt and delayed gamma-ray signals, respectively. Hence, the time coincidence within 200 µs between prompt and delayed signals greatly increases the tagging power. In this work, we take the default selection efficiency of IBD events to be 95%, implying that 5% of IBD events are detected without tagged neutrons. The latter could constitute an important background for other channels, such as eES, as can be observed from Fig. 1. To investigate the impact of IBD efficiency on the determination of total and average energies of ν_e and ν_x, we also consider two cases with lower and higher values, i.e., 90% and 99%. Since the statistics of IBD events are already quite high, a slight reduction in efficiency should not alter the experimental sensitivities to $E^{\rm tot}_{\bar{\nu}_e}$ and $\langle E_{\bar{\nu}_e} \rangle$ much. The IBD cross section has been precisely calculated in Refs. [20, 21] and applied to supernova neutrino detection. In general, the angular distribution of positrons is nearly isotropic, making it difficult to extract directional information about neutrinos. However, the angular distribution of neutrons may be used to further reduce backgrounds and locate the neutrino source [20, 22, 23].

2. **Proton Elastic Scattering (pES)**: This channel is crucial for detecting supernova neutrinos of heavy-lepton flavors [24, 25]. Although the total cross section of pES is about four times smaller than that of IBD, all neutrinos and antineutrinos of three flavors contribute, thus compensating for the reduction in cross section. In this channel, the recoil energy of the proton $T_p \leq 2E_\nu^2/m_p$ is highly suppressed by the nucleon mass and will be further quenched in the scintillator material. Therefore, precise determination of the quenching factor for protons and a low energy threshold are required to reconstruct neutrino energy and accumulate sufficient statistics. In our calculations, Birks' law for the quenching effects of protons is implemented with a Birks' constant $k_B = 0.0098 \pm 0.0003$ cm/MeV, where the uncertainty is also included [26]. The quench effects of positrons or electrons [27] are neglected in the current study. The pES cross section

was first calculated in Ref. [28] and has been recently simplified for low-energy neutrinos [24]. However, the cross section receives its dominant contribution from the axial form factor of the proton, which is currently known with 30% uncertainty if the strange-quark contribution to nucleon spin is taken into account [29]. In the present work, a 20% uncertainty on the cross section is considered for illustration. Low-energy neutrinos from pion decays at rest can be used to probe proton strangeness and reduce the uncertainty of the axial charge by an order of magnitude in an underground laboratory with a kiloton liquid-scintillator detector [30].

3. **Electron Elastic Scattering (eES)**: In this channel, the scattered electrons carry directional information about incident neutrinos and can thus be used to locate the supernova. This will be an extremely important approach in addition to observation through infrared light if a supernova is hidden in galactic gas and dust clouds and the optical signal is obscured. The eES reaction is most sensitive to ν_e because of its largest cross section, which is particularly useful for detecting the prompt ν_e burst in the early stage of a supernova explosion. However, it is difficult to determine the direction of a scattered electron in a liquid-scintillator detector after multiple scattering. At this point, large water-Cherenkov detectors such as SK and its upgraded version Hyper-Kamiokande are necessary and complementary to liquid-scintillator detectors. The cross sections of neutrino- and antineutrino-electron elastic scattering have been computed and summarized in Ref. [34], where electroweak radiative corrections are also included.

4. **Neutral-Current Interaction on** ^{12}C: This is crucial for probing neutrinos of heavy-lepton flavors, i.e., $\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$ (denoted as ^{12}C-NC), where ν collectively denotes neutrinos and antineutrinos of all three flavors. A 15.11-MeV gamma from the de-excitation of $^{12}\mathrm{C}^*$ to its ground state is a clear signal of supernova neutrinos. The cross section can be found in Refs. [31, 32] and has also been measured in the LSND experiment [33]. Since ν_x has a higher average energy, the ^{12}C-NC channel is most sensitive to ν_x, offering a possibility to pin down the flavor content of supernova neutrinos. However, the kinetic energy of ^{12}C is heavily quenched in liquid scintillator and thus invisible to current detectors, making it impossible to reconstruct neutrino energy on an event-by-event basis in this channel. In this sense, the pES channel is more important. Note that neutral-current processes are not affected by neutrino flavor oscillations.

5. **Charged-Current Interaction on** ^{12}C: As an advantage of liquid-scintillator detectors, the charged-current interaction on ^{12}C occurs for both ν_e and $\bar{\nu}_e$ via $\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$ and $\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$, which we denote as ^{12}N-CC and ^{12}B-CC, respectively. The energy threshold is 17.34 MeV for ν_e and 14.39 MeV for $\bar{\nu}_e$. The subsequent beta decays of ^{12}B and ^{12}N with half-lives of 20.2 ms and 11 ms, respectively, lead to prompt-delayed coincident signals. Hence, the charged-current reac-

tions provide another possibility to separately detect ν_e and $\bar{\nu}_e$. However, discriminating between electrons and positrons is difficult in large liquid-scintillator detectors, and we may only have time and energy distributions to statistically separate the ^{12}N-CC and ^{12}B-CC processes. Therefore, we conservatively combine these two processes into a single detection channel, ^{12}C-CC, in our current study. The cross section for neutrino interaction on ^{12}C has been calculated in Ref. [31] using a direct evaluation of nuclear matrix elements from experimental data at that time. Recent calculations based on the nuclear shell model and random-phase approximation can be found in Ref. [32]. The cross section has been measured in the LSND experiment, and the result is well compatible with theoretical calculations [33].

6. ^{13}C **Interactions**: The ^{13}C atoms in the liquid scintillator can also be used to capture supernova neutrinos, although the natural abundance of ^{13}C is only about 1.1%. Similar to the case of ^{12}C, both charged-current and neutral-current interactions of neutrinos and antineutrinos should be considered. The numbers of neutrino events are generally small in the ^{13}C case, so we include the corresponding reactions in the determination of ν_e and ν_x properties.

For the charged-current interaction, we consider $\nu_e + {}^{13}\mathrm{C} \to e^- + {}^{13}\mathrm{N}$, where the final state ^{13}N can be either the ground state $1/2^-$ or the excited state $3/2^-$. The energy threshold in the ground-state case is $E_{\mathrm{th}} = 2.2$ MeV, while the excitation energy of $^{13}\mathrm{N}^*(3/2^-)$ is about 3.51 MeV. Cross sections for higher excited states are suppressed [14, 15], so those reactions can be safely ignored. Since the de-excitation of $^{13}\mathrm{N}^*(3/2^-)$ to the ground state is extremely rapid and the beta-decay lifetime of ^{13}N is about ten minutes, it is impossible to distinguish between ^{13}N-CC and eES signals. Therefore, we combine these two channels and denote them as eES+^{13}N-CC.

For the neutral-current reaction $\nu + {}^{13}\mathrm{C} \to \nu + {}^{13}\mathrm{C}^*$, we account for two excited states, $3/2^-$ and $5/2^-$, of ^{13}C, whose excitation energies are 3.685 MeV and 7.547 MeV, respectively. For supernova neutrinos, the cross sections for these two states dominate over those for higher excited states [14, 15]. The signals for this reaction, ^{13}C-NC, are the same as those for ^{12}C-NC but with de-excitation photons of different energies.

C. Flavor Conversions

The flavor conversions of supernova neutrinos are complicated by the dense matter and neutrino background. In the supernova core, the matter density is so high that lepton flavors are approximately conserved due to frequent scattering of neutrinos with background particles [35]. From the neutrinosphere up to one thousand kilometers, neutrino-neutrino refraction may lead to spectral splits of supernova neutrinos [36]. However, it remains to be clarified whether nonlinear collective neutrino oscillations actually occur in a real supernova environment. For simplicity, we temporarily set aside collective neutrino oscillations but keep in mind that they may have an important impact on supernova neutrino detection [4]. Even farther from the supernova core, the Mikheyev-Smirnov-Wolfenstein (MSW) matter effects [37-39] come into play and reprocess neutrino spectra [40].

According to the latest neutrino oscillation data [41], two neutrino mass-squared differences $\Delta m^2_{21} \approx 7.5 \times 10^{-5}$ eV^2 and $|\Delta m^2_{31}| \approx 2.5 \times 10^{-3}$ eV^2 are precisely measured, and the reactor neutrino mixing angle θ_{13} is found to be relatively large (i.e., $\sin^2\theta_{13} \approx 0.024$). The resonant flavor conversions corresponding to the two neutrino mass-squared differences in the outer layer of a supernova are perfectly adiabatic for the observed mixing angles, i.e., $\sin^2\theta_{12} \approx 0.303$ and $\sin^2\theta_{13} \approx 0.024$ [40]. After flavor conversions, the neutrino fluxes leaving the supernova are related to the initial ones as

$$F_{\nu_e} = \cos^2\theta_{12} F^0_{\nu_e} + \sin^2\theta_{12} F^0_{\nu_x},$$

$$F_{\bar{\nu}_e} = \sin^2\theta_{12} F^0_{\bar{\nu}_e} + \cos^2\theta_{12} F^0_{\nu_x},$$

$$F_{\nu_x} = \frac{1}{2}\sin^2\theta_{12} F^0_{\nu_e} + \frac{1}{2}\sin^2\theta_{12} F^0_{\bar{\nu}_e} + \cos^2\theta_{12} F^0_{\nu_x},$$

for the normal neutrino mass ordering with $\Delta m^2_{31} > 0$ (NO); and

$$F_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x},$$

$$F_{\bar{\nu}_e} = \cos^2\theta_{12} F^0_{\bar{\nu}_e} + \sin^2\theta_{12} F^0_{\nu_x},$$

$$F_{\nu_x} = \frac{1}{2}\cos^2\theta_{12} F^0_{\nu_e} + \frac{1}{2}\cos^2\theta_{12} F^0_{\bar{\nu}_e} + \sin^2\theta_{12} F^0_{\nu_x},$$

for the inverted neutrino mass ordering with $\Delta m^2_{31} < 0$ (IO). Note that the fluxes F_α at distance D should be scaled by a factor of r^2/D^2, where the initial fluxes F^0_α are evaluated at radius r from the supernova core.

To investigate the experimental sensitivity to the average energy and total energy of each flavor, we first assume in Section III that there are no flavor oscillations. In this case, the neutrino spectrum for a given flavor is parameterized by the average energy $\langle E_{\nu_\alpha} \rangle$ and total energy $E^{\rm tot}_\alpha$. In the presence of flavor conversions, the neutrino spectra at Earth are no longer thermal, as seen in Eqs. (6) and (7). Therefore, we turn to the realistic case where neutrino flavor conversions are included and test the hypothesis of energy equipartition at future large liquid-scintillator detectors in Section IV. We also provide an Appendix with details of the χ^2 functions and corresponding efficiencies, backgrounds, and systematics used in our calculations.

III. Different Neutrino Flavors

A. The $\bar{\nu}_e$ Spectrum

The $\bar{\nu}_e$ flavor is detected through the IBD and ^{12}C-CC processes, which according to Table I have event statistics of around 5000 and 100, respectively. Therefore, the parameters of the $\bar{\nu}_e$ flavor are determined predominantly by the IBD channel, as shown in the left panel of Fig. 2 [Figure 2: see original paper]. The precision of the luminosity (i.e., $E^{\text{tot}}_{\bar{\nu}_e}$) and average energy (i.e., $\langle E_{\bar{\nu}_e}\rangle$) at the 90% confidence level (C.L.) in the IBD channel are 5.4% and 1.4%, respectively. In the right panel of Fig. 2, we illustrate the global fitting regions of the IBD and ^{12}C-CC processes at 90% C.L. with different IBD selection efficiencies, which are shown to have negligible effects on $E^{\text{tot}}_{\bar{\nu}_e}$ and $\langle E_{\bar{\nu}_e}\rangle$. This is mainly because the statistical uncertainty is much smaller than the corresponding systematic uncertainty in the $\bar{\nu}_e$ and IBD detection channel.

B. The ν_e Spectrum

The ν_e flavor contributes to the eES, ^{12}C-CC, ^{12}C-NC, ^{13}N-CC, and ^{13}C-NC processes, and is correspondingly constrained by measurements in these channels. In Fig. 3 [Figure 3: see original paper], we show the allowed regions of the luminosity ($E^{\text{tot}}_{\nu_e}$) and average energy ($\langle E_{\nu_e}\rangle$) of ν_e at 90% C.L. in both individual (left panel) and global (right panel) fitting of the eES, ^{12}C-CC, and ^{13}N-CC processes. To illustrate the impact of ^{13}N-CC, we present separate contours for the case with only eES (pink dashed curve) and the combined case of eES+^{13}N-CC (red solid curve). One can observe that including ^{13}N-CC events indeed improves the results. The left panel uses an IBD efficiency of 95%, while variations of IBD efficiency are applied in the right panel.

In the left panel, we see that both the eES and ^{12}C-CC processes are sensitive to the ν_e energy spectrum, providing an excellent measurement of the ν_e average energy. On the other hand, because the event number of the eES (plus ^{13}N-CC) process is much larger than that of the ^{12}C-CC process, the eES channel has better sensitivity to the ν_e luminosity, achieving 27% precision at 90% C.L. The ^{12}C-NC and ^{13}C-NC processes only measure the total rate of neutrino fluxes, so we expect the allowed region to display an anti-correlation between the luminosity and average energy of ν_e. However, the main contributions to these signals actually come from ν_x, as shown in Table I. Therefore, they set very poor constraints on the average energy and luminosity of ν_e. Combining three dominant channels, we obtain the global fitting results in the right panel of Fig. 3. The accuracies of $E^{\text{tot}}_{\nu_e}$ and $\langle E_{\nu_e}\rangle$ at 90% C.L. are 24% and 12%, respectively. With decreasing IBD efficiencies, backgrounds from increasing untagged positrons from IBD samples would have a sizeable effect on measurements of the luminosity and average energy of ν_e.

C. The ν_x Spectrum

The ν_x flavor is measured in the neutral-current interaction channels: eES+^{13}N-CC, pES, ^{12}C-NC, and ^{13}C-NC. In Fig. 4 [Figure 4: see original paper], we illustrate the allowed regions of the luminosity ($E_{\nu_x}^{\rm tot}$) and average energy ($\langle E_{\nu_x}\rangle$) at 90% C.L. in both individual (left panel) and global (right panel) fitting of the eES+^{13}N-CC, pES, ^{12}C-NC, and ^{13}C-NC processes. The left panel uses an IBD efficiency of 95%, while variations are applied in the right panel. The pES channel in Table I contains around 1500 events above the 0.2 MeV energy threshold, offering the most precise measurement of the ν_x average energy, with precision of 5.2% at 90% C.L. However, for the luminosity, pES is not the best probe because a 20% uncertainty in the cross-section normalization is included. On the other hand, the eES process, which has the smallest normalization uncertainty, provides the most accurate measurement of the luminosity. The pES gives a comparable precision for the lower limit of $E_{\nu_x}^{\rm tot}$, but the upper limit is much worse. The ^{13}C-NC channel offers slightly better constraint compared to ^{12}C-NC, since the former contains spectral information from two distinct peaks. Combining these complementary processes, we obtain the global fitting results in the right panel of Fig. 4, where the precision levels of the luminosity and average energy at 90% C.L. are 27% and 4.6%, respectively. We also observe that variations in IBD efficiency have negligible impact on the precision of $E_{\nu_x}^{\rm tot}$, which is predominantly determined from the pES process, and small visible effects on $\langle E_{\nu_x}\rangle$, which is constrained from all three channels.

Before concluding this section, we comment on the adopted energy threshold of 0.2 MeV for single events and on the impact of liquid-scintillator detector sizes. First, although such a low threshold is achieved in Borexino, the currently largest liquid-scintillator detector KamLAND reaches only 0.7 MeV. KamLAND' s primary goal is detecting reactor antineutrinos, for which the threshold for prompt energy of IBD events is around 1.0 MeV, so a cutoff at 0.7 MeV is sufficient to cover all antineutrino events. If this cutoff is also applied to JUNO, the number of pES events will be reduced from 1500 to 250, implying that the precisions of ν_x average energy and luminosity will worsen by a factor of $\sqrt{6} \approx 2.4$ if only statistical error is considered. If an intermediate energy threshold of 0.5 MeV is achieved, the pES event number will be around 400, and the parameter precision will be reduced by a factor of $\sqrt{3.5} \approx 1.9$. Second, since the target mass of the proposed RENO-50 experiment is 18 kilotons, our results for JUNO are also applicable to RENO-50. For the LENA detector, the target mass will be larger by a factor of 2.5, so we expect precision enhanced by a factor of $\sqrt{2.5} \approx 1.6$ for channels where statistical error dominates. This is the case for SN ν_e and ν_x, but systematic uncertainty may be important for $\bar{\nu}_e$ due to the huge number of IBD events.

IV. Hypothesis of Energy Equipartition

After exploring the experimental capability to determine the average energy and luminosity of supernova neutrinos for each flavor, we proceed to consider the potential of future large liquid-scintillator detectors to test fundamental assumptions in supernova physics. One of the most important assumptions is that the gravitational binding energy of 3×10^{53} erg is equally distributed among all neutrino species (i.e., ν_e, ν_μ, ν_τ, and their antiparticles), known as the hypothesis of energy equipartition, which has been taken for granted in most works related to supernova neutrinos. Since ν_μ and $\bar{\nu}_\mu$ interact almost identically with matter and are produced in pairs via neutral-current interactions, and likewise for ν_τ and $\bar{\nu}_\tau$, it is reasonable to assume their energies are equal. However, for ν_e and $\bar{\nu}_e$, which possess charged-current interactions and are produced in different ways, it is not well justified that they should have the same energy as neutrinos of heavy flavors.

To test the energy-equipartition hypothesis, we allow $E^{\rm tot}_{\nu_e}$, $E^{\rm tot}_{\bar{\nu}_e}$, and $E^{\rm tot}_{\nu_x}$ to be different and define the total energy of all flavor neutrinos as $E_{\rm tot} = E^{\rm tot}_{\nu_e} + E^{\rm tot}_{\bar{\nu}_e} + 4E^{\rm tot}_{\nu_x}$ and the energy ratio of flavor neutrino ν_α as

$$R_{\nu_\alpha} = \frac{E^{\rm tot}_{\nu_\alpha}}{E_{\rm tot}}.$$

In this section, we take the same assumptions as in previous numerical calculations with $E_{\rm tot} = 3 \times 10^{53}$ erg and $(R_{\nu_e}, R_{\bar{\nu}_e}, R_{\nu_x}) = (1/3, 1/3, 1/3)$. Unlike Section III, we employ realistic neutrino flavor conversions as shown in Eqs. (6) and (7) for this study.

Assuming the ^{12}N-CC and ^{12}B-CC processes are indistinguishable, and combining eES and ^{13}N-CC into eES+^{13}N-CC, we consider the global fitting of all detection channels with proper correlation of detection systematic uncertainties. The statistical fitting results for the energy ratios are presented in Fig. 5 [Figure 5: see original paper] as ternary plots, showing the allowed regions of R_{ν_e}, $R_{\bar{\nu}_e}$, and R_{ν_x} at 1σ, 2σ, and 3σ C.L. for both NO (upper panel) and IO (lower panel) cases. Note that the value of R_{ν_α} should be read according to the ticks along the corresponding side of the triangle. The 1σ ranges for R_{ν_e}, $R_{\bar{\nu}_e}$, and R_{ν_x} are respectively $[0, 0.60]$, $[0.23, 0.49]$, and $[0.17, 0.57]$ in the NO case, while $[0.01, 0.63]$, $[0, 0.78]$, and $[0.20, 0.48]$ in the IO case. Comparing the upper and lower panels, the orientation of allowed regions is completely different for the two cases. The NO case provides the best measurement of R_{ν_e}, whereas the most accurate measurement of R_{ν_x} is obtained in the IO case. This property can be understood from Eqs. (4) and (5), where one notices that 70% (100%) of the initial $\bar{\nu}_e$ (ν_x) fluxes are measured in the IBD process. On the other hand, we can only obtain upper bounds for R_{ν_e} in the NO case and for $R_{\bar{\nu}_e}$ in the IO case. Because of neutrino flavor conversions, the initial ν_e flavor in the NO case and the initial $\bar{\nu}_e$ flavor in the IO case are both recognized as ν_x in the neutral-current interaction processes. Therefore, their contributions can be compensated by fluctuations of other initial neutrino flavors (i.e., $\bar{\nu}_e$ and ν_x in the NO case and ν_e and ν_x in the IO case).

Besides testing the energy-equipartition hypothesis, it is also interesting to constrain the total energy of all flavor neutrinos $E_{\rm tot}$ in global-fitting scenarios. In Fig. 6 [Figure 6: see original paper], we illustrate the $\Delta\chi^2$ distributions of $E_{\rm tot}$ for both NO (upper panel) and IO (lower panel) cases. The solid, short-dashed, dotted, and dash-dotted lines correspond to cases using all detection processes, without the pES process, without the eES process, and without both eES and pES processes, respectively. From the figure, we observe sudden turns and asymmetries in the $\Delta\chi^2$ distributions of $E_{\rm tot}$. These behaviors can be qualitatively explained by the boundary effect of $E^{\rm tot}_{\nu_\alpha}$, which is considered non-negative in the physical range. When the deviation of $E_{\rm tot}$ from its true value (i.e., 3×10^{53} erg) becomes larger, the best-fit values of R_{ν_e} in the NO case and of $R_{\bar{\nu}_e}$ in the IO case become zero in the marginalization process, resulting in sudden turns in the $\Delta\chi^2$ distributions of $E_{\rm tot}$. Moreover, when fitting with a smaller $E_{\rm tot}$, the scanned ranges of $E^{\rm tot}_{\nu_\alpha}$ accordingly become smaller to meet non-negative requirements. If a larger $E_{\rm tot}$ is fitted, one has a wider range of $E^{\rm tot}_{\nu_\alpha}$ to minimize the χ^2 function. This asymmetric fitting process explains the observed asymmetries in the $\Delta\chi^2$ distributions. For both NO and IO cases, the total energy $E_{\rm tot}$ can be determined to be $(3.0^{+0.42}_{-0.37}) \times 10^{53}$ erg and $(3.0^{+0.74}_{-0.33}) \times 10^{53}$ erg at 1σ C.L., respectively. The precision ranges from 15% to 28% depending on different combinations of detection processes.

V. Concluding Remarks

In this work, we have discussed the detection prospects of a galactic supernova neutrino burst in future large liquid-scintillator detectors. Taking the JUNO experiment as an example, we have shown that a global analysis of different detection channels is important and complementary for constraining the spectral parameters of each neutrino species, testing the average-energy hierarchy of supernova neutrinos, and determining how the total energy is partitioned among neutrino flavors. When combined with observations from large water- and ice-Cherenkov detectors, the multi-channel detection of galactic supernova neutrinos in liquid-scintillator detectors will be particularly important for verifying the neutrino-driven explosion mechanism of core-collapse supernovae.

First, ignoring neutrino flavor conversions, we investigated how well the average and total energies for each neutrino species—namely $\bar{\nu}_e$, ν_e, and ν_x—can be determined at the JUNO detector. Assuming a total gravitational binding energy of 3×10^{53} erg equally distributed among all six neutrino and antineutrino flavors, we further took the flavor-dependent spectra in Eq. (1), where the time-integrated neutrino energy spectra are parametrized by the average energies $(\langle E_{\nu_e}\rangle, \langle E_{\bar{\nu}_e}\rangle, \langle E_{\nu_x}\rangle) = (12, 14, 16)$ MeV and a universal spectral index $\gamma_\alpha = 3$. For a galactic supernova at $D = 10$ kpc, the numbers and energy distributions of neutrino events in different detection channels have been summarized in Table I and Fig. 1, based on the JUNO nominal setup. Through statistical analysis, we reached the following conclusions:

For $\bar{\nu}_e$, the precisions for the average energy and total energy $E^{\rm tot}_{\bar{\nu}_e}$ reach 1.4% and 5.4%, respectively, at 90% C.L. Although the ^{12}B-CC channel also contributes, the precisions are dominated by the IBD channel due to its large number of events. Variation of the IBD detection efficiency from 90% to 99% does not change the results much, but it affects other channels without coincident signals.

For ν_e, the average energy is mainly determined from the eES+^{13}N-CC and ^{12}C-CC channels, with precision of 12% at 90% C.L. On the other hand, precision of about 27% for the total energy $E^{\rm tot}_{\nu_e}$ can be reached using only the eES-like signal, but this improves to 24% at the same C.L. when the constraint from ^{12}C-CC is included.

For ν_x, the pES, eES+^{13}N-CC, ^{12}C-NC, and ^{13}C-NC are the most important channels. Regarding the average energy, precision is dominated by the large number of pES events, reaching 5.2% at 90% C.L. However, the total energy $E^{\rm tot}_{\nu_x}$ is most constrained by eES, as a 20% uncertainty in the pES cross section is assumed. The combined analysis of all relevant channels yields precision of 27% for $E^{\rm tot}_{\nu_x}$ and 4.6% for $\langle E_{\nu_x}\rangle$ at the same C.L.

It is worth mentioning that these conclusions depend on the assumption of a mild hierarchy among neutrino average energies. If higher average energies for ν_e and ν_x are taken, e.g., $(\langle E_{\nu_e}\rangle, \langle E_{\bar{\nu}_e}\rangle, \langle E_{\nu_x}\rangle) = (12, 15, 18)$ MeV, the precisions will be improved [18].

Second, motivated by JUNO’ s capabilities for detecting supernova neutrinos of different flavors, we propose to test the hypothesis of energy equilibration, namely $R_{\nu_e} = R_{\bar{\nu}_e} = R_{\nu_x} = 1/3$, where the energy ratio for each neutrino species is defined in Eq. (9). Taking into account MSW matter effects in the supernova envelope, we find at the 1σ level that $0 < R_{\nu_e} < 0.60$, $0.23 < R_{\bar{\nu}_e} < 0.49$, and $0.17 < R_{\nu_x} < 0.57$ in the NO case, while $0.01 < R_{\nu_e} < 0.63$, $0 < R_{\bar{\nu}_e} < 0.78$, and $0.20 < R_{\nu_x} < 0.48$ in the IO case. The total gravitational binding energy can be determined to be $(3.0^{+0.42}_{-0.37}) \times 10^{53}$ erg with 13% precision for NO, and $(3.0^{+0.74}_{-0.33}) \times 10^{53}$ erg with 18% precision for IO.

Therefore, future large liquid-scintillator detectors—JUNO, RENO-50, and LENA—will offer a great opportunity to detect galactic supernova neutrinos through many different channels, which can be used to reconstruct average neutrino energies and the total gravitational binding energy. In addition, real-time measurements in both liquid-scintillator and water-Cherenkov detectors will hopefully be able to distinguish neutrino emission during three distinct stages: the prompt ν_e burst, accretion phase, and cooling phase. All this information is indispensable for understanding the dynamics of core-collapse supernovae.

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Appendix: Statistical Analysis Details

In this appendix, we present a detailed description of our statistical analyses. To analyze detection capabilities for different neutrino flavors, we assume efficiencies of 95%, 99%, and 99% for the IBD, pES, and eES processes, respectively, and 90% for the ^{12}N-CC and ^{12}B-CC processes. We assume 100% efficiency for other processes for simplicity. Different detection efficiencies for the IBD process are also considered to illustrate their quantitative effects. Moreover, the ^{12}N-CC and ^{12}B-CC processes in Eqs. (2) and (3) are taken to be completely indistinguishable and thus combined into a single detection channel denoted as ^{12}C-CC. Similarly, we do not distinguish electrons between the eES and ^{13}N-CC processes and denote their combination as eES+^{13}N-CC.

Next we discuss possible backgrounds for different channels. Untagged IBD events constitute backgrounds for the eES+^{13}N-CC, ^{12}C-NC, and ^{13}C-NC processes. In addition, we consider proton and electron discrimination using pulse shape techniques and assume a 1% misidentification probability, which contributes additional backgrounds for the eES+^{13}N-CC and pES processes. In this study, uncertainties on signal efficiencies and backgrounds are neglected. A detailed simulation analysis of detection efficiencies, backgrounds, and corresponding uncertainties will be presented elsewhere.

For systematics, we employ a 2% detection uncertainty for all channels and an additional 20% cross-section uncertainty for the pES, ^{12}C-NC, ^{13}N-CC, and ^{13}C-NC processes. Besides these normalization uncertainties, an energy-related uncertainty is included in the pES case by taking a 3% relative uncertainty on Birks' constant k_B of the proton quenching effect, where the central value of k_B is taken as 9.8×10^{-3} cm/MeV [26]. The quench effects of positrons or electrons [27] are neglected in the current study.

We now construct the least-squares functions for our statistical analyses. For a particular detection process, we employ a Poisson-type χ^2 distribution with proper pull terms accounting for experimental systematic factors:

$$\chi_i^2 = \sum_{j=1}^{N_{\text{bin}}^i} 2\left(T_{ij} - O_{ij} + O_{ij}\ln\frac{O_{ij}}{T_{ij}}\right) + \sum_k \frac{\epsilon_k^2}{\sigma_k^2},$$

where i denotes the reaction channel index, N_{bin}^i is the number of bins, O_{ij} is the number of observed events in the j-th bin of the i-th channel, and T_{ij} is the expected number of events. In practice, both observed and expected events are divided into signals s_{ij} and backgrounds b_{ij}, while the signals in the expected number of events are corrected as $\hat{s}_{ij} = s_{ij}(1+\sum_k \alpha_{ik}\epsilon_k)$ by taking into account possible systematic uncertainties. Here σ_k is the k-th systematic uncertainty, ϵ_k is the corresponding nuisance parameter, and α_{ik} is the fraction of neutrino event contribution in the i-th energy bin for the k-th nuisance parameter.

In detecting $\bar{\nu}_e$ flavor neutrinos, we perform statistical analysis of the IBD and ^{12}C-CC processes as shown in the left panel of Fig. 2. For ν_e flavor neutrinos, the eES+^{13}N-CC and ^{12}C-CC processes are considered the main detection channels, as shown in the left panel of Fig. 3. Finally, the main detection channels for ν_x flavor neutrinos in the left panel of Fig. 4 include the pES, eES+^{13}N-CC, ^{12}C-NC, and ^{13}C-NC processes. The efficiencies, backgrounds, and systematics of different detection channels in constructing all the above χ^2 functions are summarized in Table II.

When performing global fitting of different reaction channels, we sum their respective χ^2 functions by considering the full correlation of detection systematic uncertainties and marginalize all nuisance parameters in Table II. In the global analyses of Section IV, we also marginalize other relevant supernova neutrino flux parameters, i.e., $E^{\rm tot}_{\nu_\alpha}$ and R_{ν_α} in Fig. 5, and $E_{\rm tot}$ in Fig. 6.

TABLE II: Summary of efficiencies, backgrounds, and systematics of detection channels considered in this work, where ^{12}C-CC denotes a combination of the ^{12}N-CC and ^{12}B-CC processes. We also combine the eES and ^{13}N-CC processes together and denote them as eES+^{13}N-CC.

Note: Figure translations are in progress. See original paper for figures.

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