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Presupernova neutrino signals as potential probes of neutrino mass hierarchy

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ABSTRACT

We assess the potential of using presupernova neutrino signals at the Jiangmen Underground Neutrino Observatory (JUNO) to probe the yet-unknown neutrino mass hierarchy. Using models for stars of 12, 15, 20, and 25 $M_\odot$, we find that if the $\bar{\nu}_e$ signals from such a star can be predicted precisely and the star is within $\approx$ 440–880 pc, the number of $\bar{\nu}_e + p \to n + e^+$ events detected within one day of its explosion allows to determine the hierarchy at the $\gtrsim$ 95% confidence level. For determination at this level using such signals from Betelgeuse, which is at a distance of $\approx$ 222 pc, the uncertainty in the predicted number of signals needs to be $\lesssim$ 14–30%. In view of more realistic uncertainties, we discuss and advocate a model-independent determination using both ν_e and $\bar{\nu}_e$ signals from Betelgeuse. This method is feasible if the cosmogenic background for ν-e scattering events can be reduced by a factor of $\sim$ 2.5–10 from the current estimate. Such reduction might be achieved by using coincidence of the background events, the exploration of which for JUNO is highly desirable.

1. Introduction

Stars are profuse sources of neutrinos. For massive stars of $\gtrsim 8M_\odot$, as their central temperature and density increase dramatically during later evolution stages, $\nu_a\bar{\nu}_a$ $(a = e, \mu, \tau)$ pair production by photo-neutrino emission, plasmon decay, and $e^\pm$ pair annihilation becomes the dominant mechanism of energy loss (e.g., [1,2]). Likewise, ν_e and $\bar{\nu}_e$ production by weak nuclear processes, including $e^\pm$ capture and $\beta^\pm$ decay, becomes more and more significant as such stars evolve. These neutrinos not only play essential roles in cooling the interiors of massive stars, but also serve as potential signatures of their evolution, which leads to the eventual core collapse and supernova (SN) explosion. With the next generation of detectors such as the Jiangmen Underground Neutrino Observatory (JUNO) [3] and the Deep Underground Neutrino Experiment (DUNE) [4] under construction, there is growing interest in detecting pre-SN neutrinos. Previous studies [5–12] showed that it is plausible to detect the pre-SN $\bar{\nu}_e$ from a star within a few kpc a few days before its explosion, thereby providing an advance warning. A promising candidate is Betelgeuse with an estimated mass of $20^{+5}_{-3}\,M_\odot$ [13] and at a distance of 222^{+48}_{-34} pc [14].

In this paper we focus on the possibility of using pre-SN neutrinos to determine the yet-unknown neutrino mass hierarchy (νMH). As these neutrinos propagate through the stellar interior, they undergo flavor transformation due to the Mikheyev-Smirnov-Wolfenstein (MSW) effect [15]. This effect depends on the electron number density profile of the star and the vacuum neutrino mixing parameters, especially on whether the νMH is normal (NH) or inverted (IH) [16]. Because the survival probability of $\bar{\nu}_e$ for the NH is much higher than that for the IH, the rate of $\bar{\nu}_e + p \to n + e^+$ (inverse β-decay, IBD) events in a detector is correspondingly higher for the NH [7,8,10]. Unaware of any detailed analysis, here we quantitatively assess the potential of using pre-SN neutrino signals as probes of the νMH.

Based on the typical energies and fluxes of pre-SN neutrinos, we focus on JUNO as the detector, whose best capability is to detect $\bar{\nu}_e$ above $\approx$ 1.8 MeV through IBD. The key input to determine the νMH from pre-SN $\bar{\nu}_e$ signals is the theoretical model for the stellar source. We adopt representative models [17] for stars of 12, 15, 20, and 25 $M_\odot$. For each model, we determine the limiting distance within which the NH or IH can be distinguished assuming that the predicted number of IBD signals is precise. We further estimate the maximum uncertainty permitted in the prediction so

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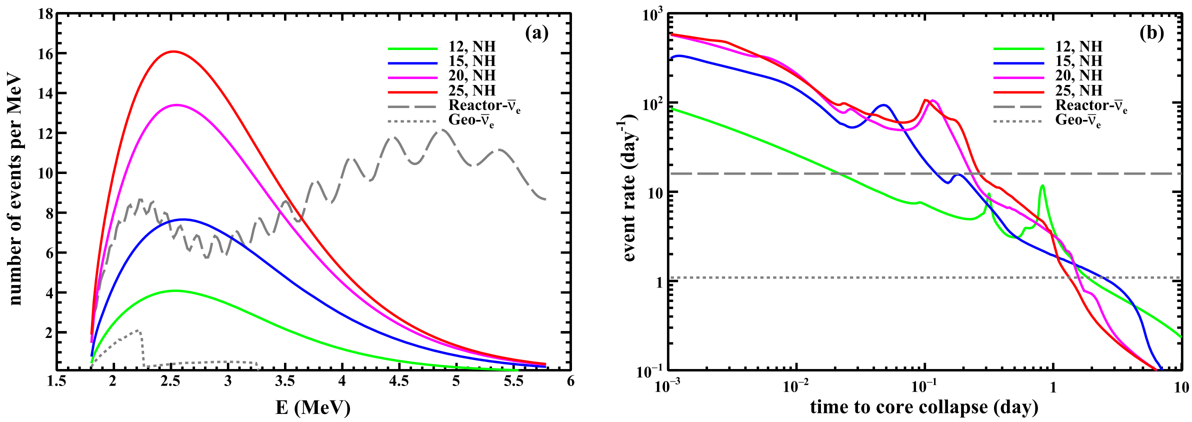

Fig. 1. Expected spectra (a) and time evolution of rates (b) for IBD events at JUNO for stars of 12, 15, 20, and 25 $M_\odot$ at $d = 1$ kpc. The spectra are integrated over the last day before core collapse and the rates are for the $\bar{\nu}_e$ energy window of $1.8 \le E \le 4$ MeV. Both these results are shown for the NH and should be reduced by a factor of ≈ 3.4 for the IH. The backgrounds from reactor $\bar{\nu}_e$ and geo-$\bar{\nu}_e$ are also shown for comparison.

that such signals from Betelgeuse can be used to determine the νMH. In view of realistic uncertainties, we finally discuss a model-independent determination using both IBD and ν-e scattering (ES) events at JUNO.

2. Analyses with IBD events only

Pre-SN $\bar{\nu}_e$ signals mostly occur a few days prior to core collapse and are predominantly produced by $e^\pm$ pair annihilation in a star. Weak nuclear processes contribute significantly to these signals within ~ 1 hour of the core collapse [6], but account for $\lesssim 10\%$ of the total pre-SN $\bar{\nu}_e$ signals [10–12]. Below we only consider the signals from $e^\pm$ pair annihilation.

Without neutrino oscillations, the energy-differential pre-SN $\bar{\nu}_a$ flux from a star is

$$F^{(0)}_{\bar{\nu}_a}(E,t) = \frac{1}{4\pi d^2}\int j_{\bar{\nu}_a}(E,T,n_e,t)dV, \quad (1)$$

where E is the $\bar{\nu}_a$ energy, t is time, d is the distance to the star, $j_{\bar{\nu}_a}$ is the energy-differential rate of $\bar{\nu}_a$ production by $e^\pm$ pair annihilation per unit stellar volume, and dV is the differential volume element. The calculation of $j_{\bar{\nu}_a}$ requires the temperature, T, and the net electron number density, n_e, both of which vary with the radius inside the star and with time.

Pre-SN $\bar{\nu}_a$ undergo flavor transformation due to the MSW effect [15]. Inspection of the stellar n_e profiles shows that flavor evolution of pre-SN $\bar{\nu}_a$ with $1 \lesssim E \lesssim 10$ MeV is highly adiabatic. Therefore, the $F_{\bar{\nu}_e}(E,t)$ at JUNO is

$$F_{\bar{\nu}_e}(E,t) = \bar{p}F^{(0)}_{\bar{\nu}_e}(E,t) + (1-\bar{p})F^{(0)}_{\bar{\nu}_x}(E,t), \quad (2)$$

where $\bar{\nu}_x$ is equivalent to $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$, $\bar{p} = \cos^2\theta_{12}\cos^2\theta_{13} \approx 0.681$ for the NH, and $\bar{p} = \sin^2\theta_{13} \approx 0.022$ for the IH [16,18,19]. For the time window and $\bar{\nu}_a$ energy relevant for detection, we find that $F^0_{\bar{\nu}_x}(E,t)/F^0_{\bar{\nu}_e}(E,t) \approx 0.2$. Consequently, $F_{\bar{\nu}_e}(E,t)$ for the NH is ≈ 3.4 times higher than that for the IH. We use detailed stellar models [17] to calculate $F_{\bar{\nu}_e}(E,t)$.

The energy spectrum of pre-SN IBD events integrated over a time window $[t_1,t_2]$ is

$$\frac{dN_{\rm IBD}}{dE} = N_p\int_{t_1}^{t_2} F_{\bar{\nu}_e}(E,t)\sigma_{\rm IBD}(E)\epsilon(E)dt, \quad (3)$$

where N_p is the total number of protons in JUNO (20 kton liquid scintillator with a proton mass fraction of $\approx 12\%$), $\sigma_{\rm IBD}(E)$ is the IBD cross section, and $\epsilon(E) \approx 0.73$ is the detection efficiency [3]. In Fig. 1a, we show the $dN_{\rm IBD}/dE$ over the last day prior to the core collapse at $d = 1$ kpc for four stellar models [17] and the NH. For comparison, we also show the expected background, which is predominantly from the two closest reactors with negligible contributions from geo-$\bar{\nu}_e$ [20]. As shown in Fig. 1a, pre-SN IBD spectra peak at ~ 2.5 MeV and decrease rapidly above ~ 4 MeV, where the reactor $\bar{\nu}_e$ background dominates. For all the results on the IBD signals presented below, we adopt the $\bar{\nu}_e$ energy window of $1.8 \le E \le 4$ MeV, where the lower value corresponds to the IBD threshold. We find that this choice is close to optimal for analyzing these signals. Within this energy window and over the last day prior to the core collapse at $d = 1$ kpc, we expect 6.1 (1.9), 12.0 (3.6), 20.5 (5.9) and 24.5 (7.0) IBD signals in JUNO for the NH (IH) using stellar models [17] of 12, 15, 20 and 25 $M_\odot$, respectively. For comparison, 15.7 and 1.1 events are expected from reactor $\bar{\nu}_e$ and geo-$\bar{\nu}_e$, respectively. The corresponding rates are shown as functions of time in Fig. 1b.

We now estimate the limiting distance $d_{\rm lim}$ within which pre-SN IBD signals might allow a determination of the νMH. For each of our adopted stellar models, we calculate the predicted number, $N_{\rm IBD}$, of IBD events with $1.8 \le E \le 4$ MeV and over the time window $[t_1,t_2]$ as a function of d and $\Delta = t_2 - t_1$, where t_2 always corresponds to the onset of core collapse. We then determine how likely the cases of the NH and IH can be distinguished considering the background, statistical fluctuations, and uncertainty in $N_{\rm IBD}$.

We assume that the relative uncertainty α of $N_{\rm IBD}$ follows a Gaussian distribution $G(\alpha) \propto \exp[-\alpha^2/(2\sigma_\alpha^2)]$ normalized over $-1 \le \alpha < \infty$, and that the expected number, $N_b^{\rm IBD}$, of background events is well measured. Under these assumptions, the observed number of events, N, follows the distribution

$$P(N, N_b^{\rm IBD}, N_{\rm IBD}, \sigma_\alpha) = \int_{-1}^{\infty} \frac{G(\alpha)[N_{\rm IBD}(1+\alpha) + N_b^{\rm IBD}]^N}{N!\exp[N_{\rm IBD}(1+\alpha) + N_b^{\rm IBD}]}d\alpha. \quad (4)$$

For a fixed set of $N_b^{\rm IBD}$, $N_{\rm IBD}^{\rm NH}$, $N_{\rm IBD}^{\rm IH}$, and σ_α, the distributions $P(N, N_b^{\rm IBD}, N_{\rm IBD}^{\rm NH}, \sigma_\alpha)$ and $P(N, N_b^{\rm IBD}, N_{\rm IBD}^{\rm IH}, \sigma_\alpha)$ cross at $N = N_0$, where $N_{\rm IBD}^{\rm NH}$ and $N_{\rm IBD}^{\rm IH}$ are the predicted numbers of signals for the NH and IH, respectively. If the NH is true, then the probability of observing more than N_0 events is

$$P_{\rm NH}^{\rm IBD} = \sum_{N=N_0+1}^{\infty} P(N, N_b^{\rm IBD}, N_{\rm IBD}^{\rm NH}, \sigma_\alpha). \quad (5)$$

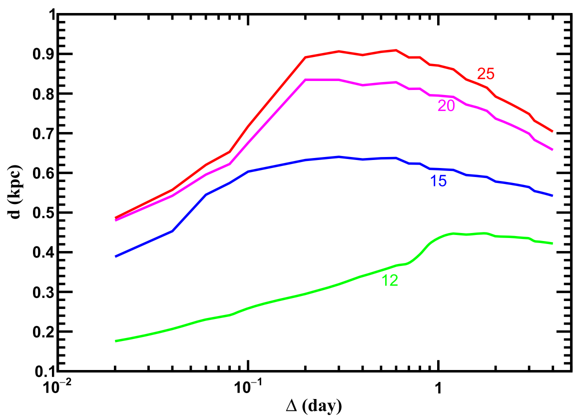

Fig. 2. Combinations of d and Δ for which the νMH can be determined at the 95% CL in the ideal case with precisely-predicted numbers of pre-SN IBD signals from stars of 12, 15, 20, and 25 $M_\odot$.

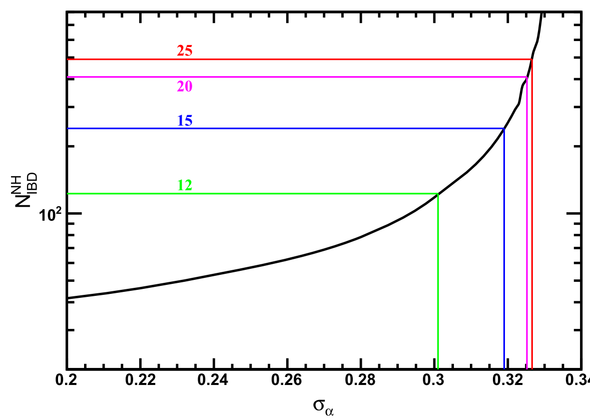

Fig. 3. Combinations of $N_{\rm IBD}^{\rm NH}$ and σ_α required to determine the νMH at the 95% CL. The horizontal solid lines indicate the predicted $N_{\rm IBD}^{\rm NH}$ over the last day before the core collapse of Betelgeuse at $d = 222$ pc for an assumed mass of 12, 15, 20, or 25 $M_\odot$.

Given that $N_{\rm IBD}^{\rm NH} \approx 3.4 N_{\rm IBD}^{\rm IH}$, the above outcome can be distinguished from the case of the IH at a confidence level (CL) of

$$P_{\rm IH}^{\rm IBD} = \sum_{N=0}^{N_0} P(N, N_b^{\rm IBD}, N_{\rm IBD}^{\rm IH}, \sigma_\alpha). \tag{6}$$

Consequently, we have a probability of $P_{\rm NH}^{\rm IBD}$ to exclude the IH at a CL of $P_{\rm IH}^{\rm IBD}$ if the NH is true. Likewise, if the IH is true, we have a probability of $P_{\rm IH}^{\rm IBD}$ to exclude the NH at a CL of $P_{\rm NH}^{\rm IBD}$. We take $P_{\rm NH}^{\rm IBD} = P_{\rm IH}^{\rm IBD} = 95\%$ and refer to fulfillment of this criterion as determining the νMH at the 95% CL.

To precisely predict $N_{\rm IBD}$, we must know with high accuracy the distance d to the source and its stellar model for pre-SN neutrino emission. Assuming that d is known exactly, we consider an ideal case of precisely predicted $N_{\rm IBD}$ by taking $\sigma_\alpha = 10\%$ for the uncertainty in the stellar model. For this case, we show in Fig. 2 combinations of d and Δ for which the νMH can be determined at the 95% CL for each of the adopted stellar models. It can be seen that the largest d values correspond to $\Delta \sim 1$–4, 0.1–1, 0.2–1, and 0.2–1 day for stars of 12, 15, 20, and 25 $M_\odot$, respectively. Taking $\Delta = 1$ day, we obtain $d_{\rm lim} \approx 0.44$, 0.6, 0.8, and 0.88 kpc, respectively, as the limiting distance within which the νMH can be determined at the $\gtrsim 95\%$ CL for the ideal case. We find that $\Delta = 1$ day is not only optimal for all of our stellar models in this case, but also for $\sigma_\alpha \gg 10\%$. We take $\Delta = 1$ day for all the analyses below.

For a specific source, $N_{\rm IBD}^{\rm NH}$ and $N_{\rm IBD}^{\rm IH}$ are related by a fixed factor and have the same relative uncertainty σ_α. Using Eqs. (4), (5), and (6), we show in Fig. 3 the combinations of $N_{\rm IBD}^{\rm NH}$ and σ_α that are required to determine the νMH at the 95% CL. As an example of using this figure, we assume that one of our stellar models provides a good description of Betelgeuse as a potential source. We take $d = 222$ pc and show the $N_{\rm IBD}^{\rm NH}$ predicted by our models in Fig. 3. It can be seen that if one of these models fits Betelgeuse, the uncertainty in the predicted $N_{\rm IBD}^{\rm NH}$ is required to be $\sigma_\alpha \lesssim 30\%$ so that its pre-SN IBD signals can be used to determine the νMH at the $\gtrsim 95\%$ CL. With the current measurement of $d = 222^{+48}_{-34}$ pc for Betelgeuse [14], the error in d already contributes $\sim 30\%$ to σ_α, which leaves little room for error in stellar models. An uncertainty of $\sim 30\%$ in the model prediction is permitted, however, if a precise distance measurement, e.g., at the $\sim 1\%$ level becomes available.

It is unclear which of our stellar models fits Betelgeuse. This uncertainty greatly increases the error in predicting its pre-SN IBD signals. Consistent with the mass estimate of Ref. [13], we assume that our 15 and 25 $M_\odot$ models represent the limiting cases for Betelgeuse. Under this assumption, we estimate the restriction on σ_α so that the case of a 15 $M_\odot$ star and the NH can be distinguished from that of a 25 $M_\odot$ star and the IH. Using $N_{\rm IBD}^{\rm NH}$ for a 15 $M_\odot$ star in Eq. (5) and $N_{\rm IBD}^{\rm IH}$ for a 25 $M_\odot$ star in Eq. (6) and assuming the same σ_α for both these numbers, we find that $\sigma_\alpha \lesssim 14\%$ is required to distinguish the two cases at the $\gtrsim 95\%$ CL. This requirement is unlikely to be fulfilled by stellar models even if the distance to Betelgeuse can be measured precisely. Clearly, a model-independent determination of the νMH is highly desirable. Below we discuss such a determination using both the pre-SN IBD and ES events at JUNO.

3. Model-independent analyses

All neutrino species contribute to the ES events. Subsequent to flavor evolution in the stellar interior, the pre-SN neutrino fluxes at JUNO for species other than $\bar\nu_e$ are

$$F_{\bar\nu_\mu+\bar\nu_\tau}(E,t) = (1-\bar p)F_{\bar\nu_e}^{(0)}(E,t) + (1+\bar p)F_{\bar\nu_x}^{(0)}(E,t), \tag{7}$$

$$F_{\nu_e}(E,t) = pF_{\nu_e}^{(0)}(E,t) + (1-p)F_{\nu_x}^{(0)}(E,t), \tag{8}$$

$$F_{\nu_\mu+\nu_\tau}(E,t) = (1-p)F_{\nu_e}^{(0)}(E,t) + (1+p)F_{\nu_x}^{(0)}(E,t), \tag{9}$$

where $p = \sin^2\theta_{13} \approx 0.022$ for the NH, and $p = \sin^2\theta_{12}\cos^2\theta_{13} \approx 0.291$ for the IH [16,18,19]. Considering recoil electrons with kinetic energy $T_{e,1} \le T_e \le T_{e,2}$ and assuming 100% detection efficiency, we estimate the expected number, $N_{\rm ES}$, of ES events as

$$N_{\rm ES} = N_e \int_{t_1}^{t_2} dt \int_{E_1}^{\infty} dE \int_{T_{e,1}}^{T_{e,u}} \sum_\nu F_\nu(E,t)\frac{d\sigma_{\nu e}(E,T_e)}{dT_e} dT_e, \tag{10}$$

where N_e is the total number of electrons in JUNO, $T_{e,u} = \min\{T_{e,2}, T_e^{\max}\}$, $T_e^{\max} = E/[1+(2m_e/E)]$, m_e is the electron rest mass, E_1 corresponds to $T_e^{\max} = T_{e,1}$, and $d\sigma_\nu(E,T_e)/dT_e$ is the differential cross section for ν-e scattering [21]. In Eq. (10), the sum runs over F_{ν_e}, $F_{\bar\nu_e}$, $F_{\nu_\mu+\nu_\tau}$, and $F_{\bar\nu_\mu+\bar\nu_\tau}$, with the last two fluxes multiplied by $d\sigma_{\nu_x e}/dT_e$ and $d\sigma_{\bar\nu_x e}/dT_e$, respectively.

The pre-SN ES signals mostly occur at $T_e \le 2.5$ MeV, but solar neutrinos present a high background at $T_e < 0.8$ MeV. Taking $T_{e,1} = 0.8$ MeV and $T_{e,2} = 2.5$ MeV, we obtain $N_{\rm ES}^{\rm IH}/N_{\rm ES}^{\rm NH} \approx 1.23$ for all the stellar models considered. This ratio is insensitive to the energy and time windows. For our adopted windows, we find $N_{\rm ES}^{\rm NH}/N_{\rm IBD}^{\rm NH} \approx 0.91$ for all of our stellar models. In contrast, the above ratios along with $N^{NH}_{IBD}/N^{IH}_{IBD} \approx 3.42$ give $N^{IH}_{ES}/N^{IH}_{IBD} \approx 3.8$, which greatly exceeds N^{NH}_{ES}/N^{NH}_{IBD}. This large difference in N_{ES}/N_{IBD} between the NH and IH, along with the associated insensitivity to stellar models, provides the basis for a model-independent determination of the νMH by combining the IBD and ES signals.

Unlike the IBD events, which can be identified by coincidence, ES causes single hits in the detector and suffers from high background. For our adopted energy window of $0.8 \le T_e \le 2.5$ MeV, the dominant background at JUNO is β^+ decay of the cosmogenic ^{11}C, with an estimated level of $\sim 2 \times 10^4$ events per day [3]. For comparison, the predicted number, N_{ES}, of pre-SN ES signals from Betelgeuse over the last day is 117.2 (143.5), 212.9 (259.0), 380.9 (467.1), or 479.8 (592.1) for the NH (IH) and a mass of 12, 15, 20, or 25 $M_\odot$, respectively. Therefore, the above model-independent method to determine the νMH is practical only when the high ES background can be suppressed. Because ^{11}C is mainly produced by (γ, n) spallation following the shower initiated by cosmic muons, a three-fold coincidence of the muon, neutron, and ^{11}C decay products can be used to suppress the background [22,3]. With this possible experimental improvement in mind, we calculate the maximum allowed number, N^{ES}_b, of ES background events so that the model-independent method can be used to determine the νMH at the 95% CL with the pre-SN signals from Betelgeuse.

We define

$$R \equiv \frac{N' - N^{ES}_b}{N - N^{IBD}_b}, \tag{11}$$

where N' and N, respectively, are the observed numbers of ES and IBD events including the associated background. The expected number, N^{IBD}_b, of IBD background events is the same as in Section 2 and assumed to be well measured. The expected number, N^{ES}_b, of ES background events is to be constrained but is also assumed to be well measured. Similarly to the analyses in Section 2, N' and N follow the corresponding Poisson distributions. To allow for large uncertainties in the predicted numbers of signals in view of the poorly-known stellar model of Betelgeuse, we calculate the expected numbers, $\tilde{N}^{NH(IH)}_{ES}$ and $\tilde{N}^{NH(IH)}_{IBD}$, of ES and IBD signals, respectively, for the NH (IH) as follows. We treat the predicted number, N^{NH}_{IBD}, of IBD signals as a parameter. For each predicted N^{NH}_{IBD}, we consider that the expected $\tilde{N}^{NH}_{IBD}$ is uniformly distributed over $[0.5, 2]N^{NH}_{IBD}$ as a conservative estimate. For each $\tilde{N}^{NH}_{IBD}$, we generate $\tilde{N}^{IH}_{IBD}$, $\tilde{N}^{NH}_{ES}$, and $\tilde{N}^{IH}_{ES}$ by sampling Gaussian distributions for the ratios $\tilde{N}^{NH}_{IBD}/\tilde{N}^{IH}_{IBD}$, $\tilde{N}^{NH}_{ES}/\tilde{N}^{NH}_{IBD}$, and $\tilde{N}^{IH}_{ES}/\tilde{N}^{NH}_{ES}$. Based on our stellar models, we adopt central values of 3.42, 0.91, and 1.23, respectively, for these distributions, with a common 1σ relative uncertainty of 5% (including the $\sim$ 1–2% variations of the above ratios due to uncertainties in the vacuum neutrino mixing parameters [19]).

For each N^{NH}_{IBD}, we generate 10^6 sets of $N'_{NH(IH)}$ and $N_{NH(IH)}$ to calculate the distribution $P_{NH(IH)}$ of $R_{NH(IH)}$, which peaks at $R_{NH(IH)} \approx N^{NH(IH)}_{ES}/N^{NH(IH)}_{IBD} \approx 0.91$ (3.8). The distributions P_{NH} and P_{IH} cross at $R_{NH} = R_{IH} = R_0$. Similarly to the analyses with IBD events only, we consider that the νMH can be determined at the 95% CL when

$$\int_{-\infty}^{R_0} P_{NH} dR_{NH} = \int_{R_0}^{\infty} P_{IH} dR_{IH} = 0.95. \tag{12}$$

The combinations of N^{NH}_{IBD} and N^{ES}_b corresponding to the above criterion are shown as the solid curve in Fig. 4, where the predicted values of N^{NH}_{IBD} for our stellar models are also indicated. It is reasonable to assume that our 15 and 25 $M_\odot$ models provide the limiting cases for Betelgeuse, especially when the results shown in Fig. 4 allow for a factor of 2 uncertainty in the model prediction. Accordingly, we conclude that the pre-SN IBD and ES signals from Betelgeuse over the last day can be used to determine the νMH at the 95% CL in a model-independent manner if the ES background in JUNO can be reduced from $N^{ES}_b \sim 2 \times 10^4$ by a factor of ~ 2.5. If our 12 $M_\odot$ model fits Betelgeuse better, the reduction needs to be by a factor of ~ 10.

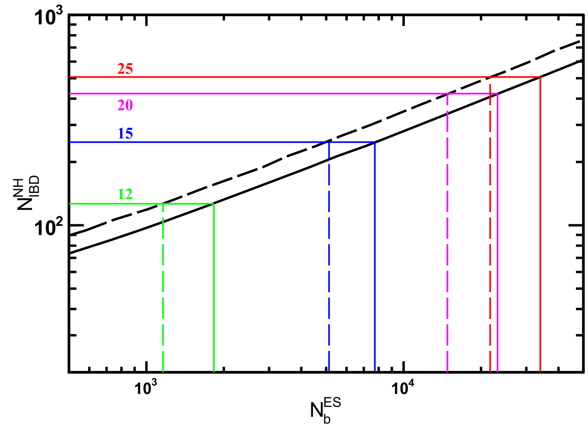

Fig. 4. Combinations of N^{NH}_{IBD} and N^{ES}_b required to determine the νMH at the 95% CL. The horizontal solid lines indicate the predicted N^{NH}_{IBD} over the last day before the core collapse of Betelgeuse at $d = 222$ pc for an assumed mass of 12, 15, 20, or 25 $M_\odot$. The solid curve ignores the pre-SN ν_e produced by weak nuclear processes, whereas the dashed curve represents an estimate of their maximum effect.

So far we have ignored the pre-SN ν_e produced by weak nuclear processes in stars. In view of the theoretical uncertainties associated with these ν_e, we estimate their maximum effect by treating their contribution to the ES signals as additional uncertainties in the ratios N^{NH}_{ES}/N^{NH}_{IBD} and N^{IH}_{ES}/N^{NH}_{ES}. For a generous estimate, we consider that these ν_e are up to $\sim 50\%$ of those produced by $e^\pm$ pair annihilation in the relevant energy window [12]. As increasing $F^{(0)}_{\nu_e}$ by $\sim 50\%$ increases N^{NH}_{ES}/N^{NH}_{IBD} and N^{IH}_{ES}/N^{NH}_{ES} by $\sim 15\%$ and $\sim 8\%$, respectively, we adopt larger 1σ relative uncertainties of 20% and 10% for the Gaussian distributions of N^{NH}_{ES}/N^{NH}_{IBD} and N^{IH}_{ES}/N^{NH}_{ES}, respectively, and repeat the calculations described above. The results are shown as the dashed curve in Fig. 4. It can be seen that the maximum effect of the pre-SN ν_e produced by weak nuclear processes is to require a further reduction of the ES background by a factor of ~ 1.5 for a model-independent determination of the νMH with pre-SN neutrinos from Betelgeuse.

4. Discussion and conclusions

We have presented quantitative analyses of pre-SN neutrino signals at JUNO as potential probes of the νMH. Using the IBD events alone, we have considered three cases, for all of which determination of the νMH requires accurate stellar models of pre-SN neutrino emission. In the ideal case where the distance to the source is known exactly and the uncertainty in the predicted number, N_{IBD}, of IBD events is 10%, the νMH can be determined at $\gtrsim$ 95% CL with pre-SN IBD signals over the last day from stars of 12, 15, 20, and 25 $M_\odot$ within ≈ 0.44, 0.6, 0.8, and 0.88 kpc, respectively. In the case where the stellar model for the nearby Betelgeuse is known, determination at this level requires an uncertainty of $\lesssim 30\%$ in the predicted N_{IBD}. In the more realistic case where our 15 and 25 $M_\odot$ models provide the limiting cases for Betelgeuse, this uncertainty is restricted to $\lesssim 14\%$. With the current measurement of $d = 222^{+48}_{-34}$ pc for the distance to Betelgeuse [14], the error in d already gives a $\sim 30\%$ uncertainty in the predicted N_{IBD}. Even if this distance can be measured precisely, the required uncertainty of $\lesssim 14$–30% in the prediction is difficult to achieve for stellar models.

We advocate a model-independent determination of the νMH using both the pre-SN IBD and ES events at JUNO. This determination relies on the large difference in $N_{\mathrm{ES}}/N_{\mathrm{IBD}}$ between the NH and IH, as well as the insensitivity of this ratio to stellar models. The key issue here is the ES background in the adopted energy window of $0.8 \leq T_e \leq 2.5$ MeV, which is dominated by β^+ decay of the cosmogenic ^{11}C. Our analyses show that if our 15 and 25 $M_\odot$ models provide the limiting cases for Betelgeuse, using its pre-SN IBD and ES signals to determine the νMH at the $\gtrsim 95\%$ CL requires this background to be $\lesssim 8 \times 10^3$ events per day. With the background currently estimated to be $\lesssim 2 \times 10^4$ events per day, the required reduction by a factor of ~ 2.5 is possible by using coincidence of the background events [22,3]. Even if our 12 $M_\odot$ model fits Betelgeuse better, the required reduction by a factor of ~ 10 might still be feasible. In any case, however, a further reduction by a factor of ~ 1.5 might be required when uncertainties associated with the pre-SN ν_e produced by weak nuclear processes are taken into account. On the other hand, measuring solar neutrinos at JUNO precisely may allow us to use the ES signals with $T_e < 0.8$ MeV, which would increase the pre-SN signals significantly, thereby relaxing the requirement of the cosmogenic background reduction.

The pre-SN ν_e of ~ 5–10 MeV from weak nuclear processes produce signals in both charged-current and neutral-current channels at DUNE. These signals can, in principle, provide a model-independent determination of the νMH, which merits a quantitative assessment. We note, however, that the relevant event rates are low and have significant theoretical uncertainties.

A large number of neutrino events can be detected from a Galactic SN (e.g., [23,24,3,25]). Flavor evolution of SN neutrinos, however, is complicated by details of their emission, SN dynamics, and collective oscillations (e.g., [26,27]), which may make it difficult to determine the νMH with these neutrinos. Therefore, pre-SN neutrinos are not only precursors to their SN counterpart, but also complementary probes of neutrino physics. We consider it an exciting possibility to determine the νMH with pre-SN neutrinos from Betelgeuse and urge that background reduction at JUNO be explored for the model-independent determination presented here.

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