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Estimation of γ-Ray Production from Neutral-Current Neutrino-Carbon and -Oxygen Inelastic Reactions Induced by Supernova Neutrinos

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We estimate the number of events of γ-ray production from ^{12}C and ^{16}O(ν, ν') neutral-current (NC) inelastic reactions induced by neutrinos from supernova explosion which can be observed by neutrino detectors in the Earth. The feature of this work is to use our new measurements of γ-ray emission probability from giant resonance of ^{12}C and ^{16}O, and combine it with the NC cross sections of ^{12}C and ^{16}O(ν, ν') calculated with the latest shell-model calculation. We also use the supernova neutrino flux spectra used by previous publications as well as the latest flux calculations. We present the estimation of those numbers of NC events for JUNO detector (20 kton, liquid scintillator) and Super-K detector (32kton, water) which are two typical supernova detectors.

KEYWORDS: supernova, neutrinos, giant resonance, neutral-current neutrino-nucleus interaction

1. Introduction

The first neutrinos outside the solar system were detected from SN 1987A by the Kamiokande-II, IMB, and Baksan experiments [1–3]. Even tens of neutrinos detected have provided new understanding of the physics of supernova (SN) explosion and the properties of neutrinos. The vast number of neutrinos, with a total energy of about 10^{53} erg, are produced from an SN core in 10 s and their mean energies are 10-20 MeV. While ν_e (and their antiparticle $\overline{\nu}_e$) can interact by both charged-current (CC) and neutral-current (NC) reactions in the SN core and in the neutrino detectors in the Earth, ν_μ and ν_τ (and their antiparticles) can only interact by NC reactions, since they have too low energy to produce muons and tau-leptons through CC reactions. In the next SN explosion in our Galaxy, it is important to measure all flavors of neutrinos and their spectra to obtain better understanding of the SN explosion mechanism and neutrino oscillations [4].

Experimentally, the NC reactions in a few tens of MeV were observed in ^{12}C(ν, ν')^{12}C*(15.1MeV, $J^P = 1^+$) by KARMEN experiment [5] and recently in coherent ν-CsI(Na) scattering by COHERENT Collaboration [6]. Kolbe et al. [7] proposed to measure γ rays for the detection of NC inelastic events by ^{12}C and ^{16}O(ν, ν') reactions induced by SN neutrinos, and Beacom and Vogel [8, 9] estmated the number of NC events for a water Cherenkov detector. Beacom, Farr, and Vogel [10] proposed to measure neutrino-proton elastic scattering ($\nu + p \rightarrow \nu + p$) in scintillator detectors [12] [1].

In this presentation, we focus on the evaluation of the number of the γ-ray production from ^{12}C and ^{16}O(ν, ν') NC inelastic reactions induced by neutrinos from SN explosion which can be observed by the neutrino detectors in the Earth. We used the latest theoretical estimation of the SN neutrino flux, the NC cross sections and a new experimental measurement of the γ-ray emission probability from the giant resonance in the excitation energy 16 MeV< E_x <32 MeV. The number of the NC signals containing γ rays from the hadronic decay of giant resonances of ^{12}C and ^{16}O, which we call "NC γ events" for short, can be calculated as

$$N_{\gamma}^{NC} = \int_{E_x=16\text{ MeV}}^{E_x=32\text{ MeV}} dE_x \left[n_{tar} \int_0^{E_\nu^{max}} dE_\nu F(E_\nu) \cdot \frac{d\sigma(E_\nu)}{dE_x} \right] \cdot R_\gamma(E_x), \quad (1)$$

where n_{tar} is the number of targets (^{12}C or ^{16}O) in the neutrino detectors, $F(E_\nu)$ is the neutrino flux which is generated by SN and observed by a detector, $d\sigma(E_\nu)/dE_x$ is the differential cross section for the giant resonance (E_x) at the incident neutrino energy E_ν, and $R_\gamma(E_x)$ is the γ-ray emission probability at E_x. We will present the estimation of the number of NC γ events for JUNO (20 kton, liquid scintillator) [13] and Super-K (32kton, water) [14] for the case of the core-collapse SN, including the case of a blackhole formation, at a distance of 10 kpc.

The estimation of the number of NC γ events by neutrinos from SN explosion has been done by several groups for water-Cherenkov detectors [7, 8]. The study of NC events in liquid scintillator detectors has been performed for ^{12}C(ν, ν')^{12}C*(15.1MeV, $J^P = 1^+$) [11, 13] and for neutrino-proton elastic scattering ($\nu + p \rightarrow \nu + p$) [11–13], since the event rate of NC γ events was expected to be much smaller and the rate estimation was uncertain. The νe elastic scattering reaction in a water-Cherenkov detector has been studied by Super-K Collaboration [14], but this reaction is contributed to by both NC and CC interactions. The feature of this presentation is to use the γ-ray emission probability $R_\gamma(E_x)$ from the giant resonances of ^{12}C and ^{16}O which we measured for the first time experimentally [15], instead of using the statistical model calculation based on the Hauser-Feshbach method [31]. Our measurement $R_\gamma(E_x)$ from the giant resonance shows that the statistical model calculation predicts a higher decay probability to the excited states by 30-40% than the measured values in the energy region where giant resonances dominate. In addition, we use the latest NC cross sections of ^{12}C and ^{16}O(ν, ν') based on the shell-model calculations [16–18].

This report is organized as follows. In Section 2, we explain the two neutrino flux spectra: one is used conventionally before and another is the one tabulated by Nakazato et al. [19]. In Section 3, we show the NC cross section calculations. In Section 4, we show our new measurement of γ-ray emission probability $R_\gamma(E_x)$ from giant resonace of ^{12}C and ^{16}O. In Section 5, we combine the results of Sections 2-4 and discuss over the estimation of NC γ events from SN neutrinos.

2. Neutrino Flux from Supernova Explosion

We first start with the neutrino flux spectra described conventionally as the Fermi-Dirac (FD) and the modified Maxwell-Boltzmann (mMB) distributions in order to compare with the previous publications [7–10, 12–14, 25]. They are given as

$$f_{FD}(E_\nu) = 0.555 \frac{E_\nu^2}{T^3} \frac{1}{1 + exp(E_\nu/T)}, \text{ and } f_{mMB}(E_\nu) = \frac{128 E_\nu^3}{3\langle E_\nu \rangle^4} exp\Big(- \frac{4E_\nu}{\langle E_\nu \rangle} \Big), \quad (2)$$

respectively. The FD spectra for ν_e, $\overline{\nu}_e$ and ν_x ($x = \mu$ and τ) are plotted in Fig. 1(a) using the equilibrium temperature T= 3.5 MeV, 5 MeV, and 8 MeV, respectively. For the FD spectra, the average

The JUNO collaboration studied the detection of this NC neutrino-proton elastic scattering in a liquid scintillator in details in the proposal of the JUNO experiment under construction [13].

energy $\langle E_\nu \rangle$ is related to the equilibrium temperature by $\langle E_\nu \rangle \approx 3.15\ T$. The spectra $f_{FD}(E_\nu)$ and $f_{mMB}(E_\nu)$ are normalized to unity. It is known that a FD spectrum give higher energy neutrinos than a mMB spectrum even with the same average energy $\langle E_\nu \rangle$. The time-integrated neutrino flux from SN explosion at a detector is given as

$$F(E_\nu) = \frac{1}{4\pi d^2} \frac{E_\nu^{tot}}{\langle E_\nu \rangle} f(E_\nu), \tag{3}$$

where E_ν^{tot} is the total energy carried away by one neutrino flavor, $\langle E_\nu \rangle$ is the average energy carried by a single neutrino and d is the distance from a detector to the SN. The spectrum $f(E_\nu)$ stands for either FD, mMB or a numerical distribution, normalized to unity.

According to the latest SN flux calculations taking into account the $NN \to NN\nu\bar{\nu}$, $e^+e^-\nu\bar{\nu}$ and $\nu_e\bar{\nu}_e \to \nu_x\bar{\nu}_x$, (x=$\mu$ and τ) [20–22], the energy spectra of ν_x and $\bar{\nu}_x$ ($x = \mu$ and τ) become softer and more similar to the spectra of ν_e and $\bar{\nu}_e$ than previously expected [23]. Thus, recently, the SN event rates are calculated at various average energies which are flavor independent [13, 24]. Hereafter, ν_x stands for one of ν_μ, ν_τ, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$. We choose two sets of the SN neutrino spectra from the Supernova Neutrino Database [19]: one is the model with (M,Z) = (20M$_\odot$, 0.02) and a shock revival time of 200 ms, which is chosen as an ordinary SN neutrino model consistent with SN1987A, and the other is the model with (M,Z) = (30M$_\odot$, 0.004), which is a model of neutrino emission from a blackhole-forming collapse. M, M$_\odot$ and Z stand for a progenitor mass, a solar mass and the metalicity, respectively. We consider only the time-integrated spectra, whose average and total energies are listed in Table I. We name the former spectra NK1 and the latter spectra NK2 in this report. We also give the SN rates assuming a mMB distribution with $\langle E_\nu \rangle$=12 MeV for all neutrino flavors. The average energy $\langle E_\nu \rangle$ and the total energy E_ν^{tot} of various SN neutrino fluxes which we use in this report are summarized in Table I. We note that those SN fluxes are arranged roughly in order of their average value $\langle E_{\nu_x} \rangle$ for later discussion. Those spectra (NK1) using the numerical table of Ref. [19] are shown in Fig. 1(b); the average energies of neutrino and antineutrino flavors are not very different with NK1 in the figure. Note that, while supernova simulations with more sophisticated neutrino interaction rates and multidimensional effects have been performed recently, differences in the emergent neutrino spectra are not drastic [26–28].

ν flux Model	$\langle E_{\nu_e} \rangle$ (MeV)	$\langle E_{\bar{\nu}_e} \rangle$ (MeV)	$\langle E_{\nu_x} \rangle$ (MeV)	$E_{\nu_e}^{tot}$ (10^{52} erg)	$E_{\bar{\nu}_e}^{tot}$ (10^{52} erg)	$E_{\nu_x}^{tot}$ (10^{52} erg)
mMB	12.0	12..0	12.0	5.0	5.0	5.0
Ordinary SN (NK1)	9.32	11.1	11.9	3.30	2.82	3.27
Fermi-Dirac	11.0	16.0	25.0	5.0	5.0	5.0
Blackhole (NK2)	17.5	21.7	23.4	9.49	8.10	4.00

Table I. Average energy, $\langle E_\nu \rangle$, and total energy, E_ν^{tot}, of the SN neutrino spectrum for one of neutrinos and antineutrinos (ν_e, $\bar{\nu}_e$, ν_x and $\bar{\nu}_x$ ($x = \mu$ and τ)). The neutrino spectra of the ordinary SN (NK1) and the case of a blackhole formation (NK2) are taken from Ref. [19, 25].

3. Cross Sections of ^{12}C and ^{16}O(ν, ν') Neutral-Current Reactions

Neutrinos produced by SN explosion with energies of tens of MeV interact with protons, ^{12}C and ^{16}O in the detectors through weak interactions. $\bar{\nu}_e$ has the largest cross section with protons through the inverse β decay reaction (IBD) $\bar{\nu}_e + p \to e^+ + n$, while ν_e does not have the corresponding interaction, since there are no bare neutrons in a detector in the Earth. ν_e and $\bar{\nu}_e$ interact with electrons in a

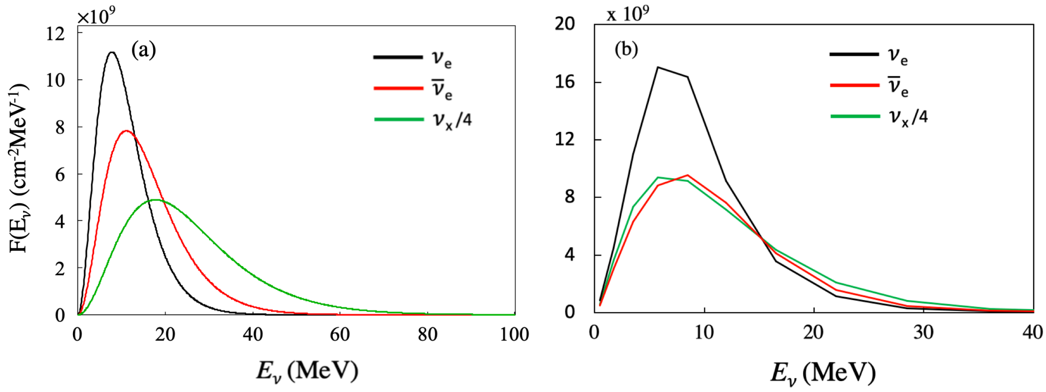

Fig. 1. (a) Fermi-Dirac spectra for ν_e, $\overline{\nu}_e$ and ν_x ($x = \mu$ and τ) using the equilibrium temperature T= 3.5 MeV, 5 MeV, and 8 MeV, respectively. (b) SN neutrino spectrum (NK1) calculated for different neutrino flavors by Nakazato et al. [19].

detector, but their cross sections are smaller by about 2 orders of magnitude than those with nucleons like IBD. We use the calculation for IBD cross section of Ref. [29]. ν_e and $\overline{\nu}_e$ interact with proton and neutron in nucleus (C and O) through CC interactions, but their cross sections are much smaller due to the high energy threshold (Q value). ν_x and $\overline{\nu}_x$ ($x = \mu$ and τ) cannot have CC reaction to produce μ- and τ-leptons in this energy region. In order to understand the explosion mechanism, we must detect all types of neutrinos (ν_e, ν_μ, ν_τ and their antineutrinos), especially because there are effects of neutrino oscillations, matter oscillations and collective effects due to ν-ν forward scattering [4, 30].

We used neutrino-nucleus cross sections on ^{12}C which was evaluated with a new p-shell Hamiltonian [16, 17]. This calculation can reproduce the GT transition strength of ^{12}C and also reproduce both the exclusive and inclusive neutrino-^{12}C CC reaction cross sections induced by decay-at-rest neutrinos. We also used the neutrino-^{16}O cross sections from Ref. [16, 18]. Dominant contributions come from spin-dipole transitions, where p-shell nucleons are excited into sd-shell. This model reproduces the rate of the muon capture on ^{16}O within 10% accuracy, in which the quenching factor was set to $g_A^{eff}/g_A = 0.95$ for both ^{12}C and ^{16}O. Excited states up to E_x =50 MeV are taken into account for both ^{12}C and ^{16}O.

First, we show the NC cross section $d\sigma/dE_x$ at $E_\nu = 50$ MeV in Fig. 2. For ^{12}C, the dominant cotribution is the $M1$ transition to ^{12}C*(15.11 MeV, J$^{\rm P}$ = 1$^+$, T=1) and above E_x >16MeV, the multipoles via spin-dipole transitions (J$^{\rm P}$ = 1$^-$, 2$^-$, T =1) contribute. For ^{16}O, only the multipoles via the spin-dipole transitions (J$^{\rm P}$ = 1$^-$, 2$^-$ and 0$^-$, T=1) are dominant. The contribution from 1$^+$ is negligible. We show NC inelastic cross sections of ^{12}C(ν, ν') and ^{16}O(ν, ν') reactions for 16 MeV < E_x < 32MeV as functions of E_ν in Fig. 3. For ^{12}C, the cross section of 15.11 MeV (J$^{\rm P}$ = 1$^+$, T=1) is not included in this plot.

4. Measurement of γ-Ray Emission Probability $R_\gamma(E_x)$ from Giant Resonace of ^{12}C and ^{16}O

We measured both the differential cross section ($\sigma_{p,p'} = d^2\sigma/d\Omega dE_x$) and the γ-ray emission probability $R_\gamma(E_x)$ (=$\sigma_{p,p'\gamma}/\sigma_{p,p'}$) from the giant resonances excited by ^{12}C(p,p') reaction at 392 MeV and 0°, using a magnetic spectrometer and an array of NaI(Tl) counters [15]. We show the cross section ($\sigma_{p,p'} = d^2\sigma/d\Omega dE_x$) in Fig. 4 and the γ-ray emission probability $R_\gamma(E_x)$ in Fig. 5. In Fig. 4, the excitation energies E_x, spin-parities J^π, and isospin T of the known resonances are indicated. We note that the absolute values of the γ-ray emission probability $R_\gamma(E_x)$ were verified by using in-situ γ

rays (15.1 and 6.9 MeV) with an accuracy of ±5% during the experiment. This calibration procedure made it possible to measure $R_\gamma(E_x)$ reliably as a function of the excitation energy of ^{12}C and ^{16}O in the energy range E_x = 16-32 MeV.

For ^{12}C, $R_\gamma(E_x)$ starts from zero at E_x=16 MeV, increases to a maximum of 53.3±0.4±3.9% at E_x=27 MeV and then decreases. As shown in Fig. 5(a), the statistical model calculations (red dashed line) predicted a higher decay probability to the excited states by 30-40% as compared to the measured values in the energy region E_x=20-24 MeV, where giant resonance dominates [15]. For ^{16}O, $R_\gamma(E_x)$ starts from 20% at E_x=16 MeV and increases to 25% at E_x=20 MeV. In this region, we observe 4.4 MeV γ rays from the first excited state of ^{12}C, which is from the α decay of the excited states of ^{16}O* (T=0). It then increases to a maximum of ∼60% at E_x=24 MeV and then decreases.

5. Estimation of γ-Ray Production from Neutral-Current Neutrino-Carbon and -Oxygen Inelastic Reactions Induced by Supernova Neutrinos

When we evaluate the number of NC γ events given in Eq.(1), we first calculate the number of NC events $N^{NC}(E_x)$ for each E_x, which is the quantity in the parenthesis [] in Eq.(1). We show $N^{NC}(E_x)$ for ^{16}O using various SN fluxes in Fig. 6. Then, we multiply $N^{NC}(E_x)$ by $R_\gamma(E_x)$ for each E_x and integrate over the giant resonance region to obtain the number of NC γ events in Eq.(1). Note that $R_\gamma(E_x)$ is the γ-ray emission probability at each E_x and it depends soly on the excited state at E_x. The values $R_\gamma(E_x)$ at E_x should not depend on the values of the cross section for excited states in (p,p') and (ν,ν') reactions, as long as the same T=1 multipoles (1^-, 2^-) appear in E_x. Since we identify those γ rays from the daughter nuclei which are decay products from the giant resonances ($J^P = 1^-, 2^-, T=1$) contributing to the (ν,ν') reactions in the analysis [15], we re-evaluate the γ-ray emission probability $\tilde{R}_\gamma(E_x)$ by excluding the contribution of T=0 states. For ^{16}O case, we considered γ rays with energy greater than 5 MeV (E_γ >5 MeV) in order to exclude the contribution (4.4 MeV γ ray) from the T=0 states. Cross sections of the ^{12}C$(\nu,\nu'\gamma)$ and ^{16}O$(\nu,\nu'\gamma)$ reactions for 16 MeV< E_x <32 MeV are also shown in Fig. 3. We used the re-evaluated γ-ray emission probability $\tilde{R}_\gamma(E_x)$ in Eq.(1) and Fig. 3. Thus, we summarize the number of SN event rates including our NC γ events for ^{12}C and ^{16}O in Tables II and III. Our estimation and that of Ref. [25] assumes the 100% detection efficiency. The more details of the calculation will be reported elsewhere.

First, we look at the rates in Table II. Our calculation of IBD and NC 15.1 MeV γ-ray production is consistent with that estimated by the JUNO Collaboration [13], where both used mMB spectra with $\langle E_\nu \rangle$=12 MeV for all neutrino flavors. We find that the rate of NC γ events is much smaller than the rate of 15.1 MeV γ-ray production in general. However, the rate of NC γ events is very sensitive to the high energy component of the neutrino spectra. The rate of NC γ events becomes comparable to that of 15.1 MeV if the energy spectrum is as hard as FD spectra with $\langle E_{\nu_x} \rangle$=25 MeV; it becomes negligle if the spectrum is as soft as mMB with $\langle E_\nu \rangle$=12 MeV.

Next, we look at the rate for ^{16}O in Table III. We estimated the rate using the FD spectra for ν_e, $\overline{\nu}_e$ and ν_x ($x = \mu$ and τ) using the equilibrium temperature T= 3.5 MeV, 5 MeV, and 8 MeV, respectively, to compare with the previous publication using the same parameters [8]. We note that we reproduce almost the same number of NC γ events if we employ their NC cross section and the simple statistical calculation for $R_\gamma(E_x)$. The electron spectra from the CC neutrino-^{16}O reactions in a large water Cherenkov detector were studied in Ref. [25] for SN neutrinos. We include their estimations for comparison, along with the rate of neutrino-electron elastic scattering [25] in Table III. Those expected numbers of NC γ events are comparable to those of neutrino-electron scattering and CC O(ν,e) reactions, depending on the still unknown SN neutrino spectra.

Finally, we give a remark again on the feature of the NC γ rates for SN neutrinos which can be understood clearly in Fig. 3 by paying attention to the energy dependence of the NC ^{12}C and ^{16}O cross sections. The $(\nu,\nu'\gamma)$ cross sections increase rapidly above E_ν=16 MeV, namely the threshold of the giant resonances shown in Fig. 3. We understand that the NC γ rates increase rapidly with $\langle E_{\nu_x} \rangle$ as the SN energy spectrum contains the higher energy component above 16 MeV and and that the rate of the blackhole model (NK2) becomes even larger due to the large $E^{tot}_{\nu_x}$ value. The feature is also clearly seen in Fig. 6. If the SN neutrino spectra contain higher energy component, the NC γ rates become larger.

6. Summary

We have evaluated the number of events of γ-ray production from ^{12}C and ^{16}O(ν, ν') NC inelastic reactions induced by neutrinos from SN explosion including a blackhole forming case, which can be observed by neutrino detectors in the Earth. We used our new measurement of γ-ray emission probability from giant resonance of ^{12}C and ^{16}O and combine it with the NC cross sections of ^{12}C and ^{16}O(ν, ν') calculated with the latest shell-model calculation and various SN neutrino fluxes.

The number of the NC γ events may become comparable to those of neutrino-electron scattering and CC O(ν, e) reactions, if the neutrino spectra contain higher energy component. Since the neutrino spectrum from SN explosion was only measured for $\overline{\nu}_e$ at SN1987A and the neutrino spectra for other neutrino flavors are not known, it is important to estimate and measure as many NC reactions with good accuracy for the better understanding of core-collapse supernova.

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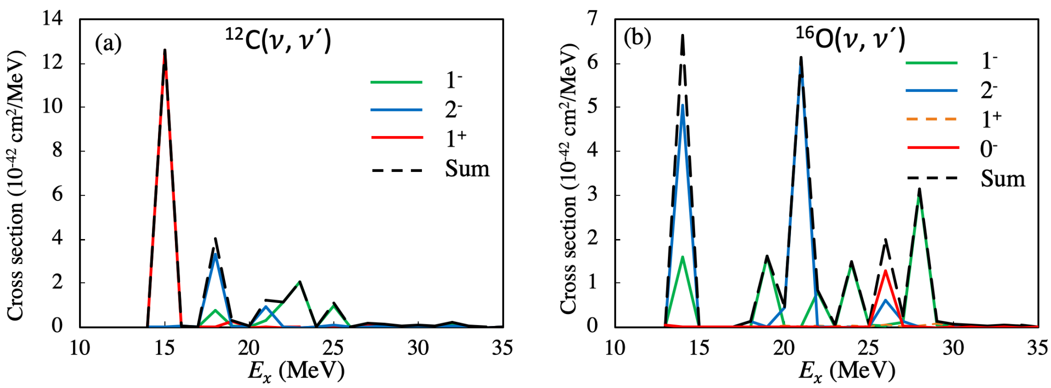

Fig. 2. The inelastic cross sections $d\sigma/dE_x$ (10^{-42} cm^2/MeV) as a function of excitation energy E_x at the neutrino energy E_ν=50 MeV. (a) ^{12}C(ν,ν')^{12}C* (left) and ^{16}O(ν,ν')^{16}O* (right). For ^{16}O, excitations 1^-, 2^- and 0^- are strong. For ^{12}C, the transition strength to 15.1 MeV (1^+, T=1) is the strongest.

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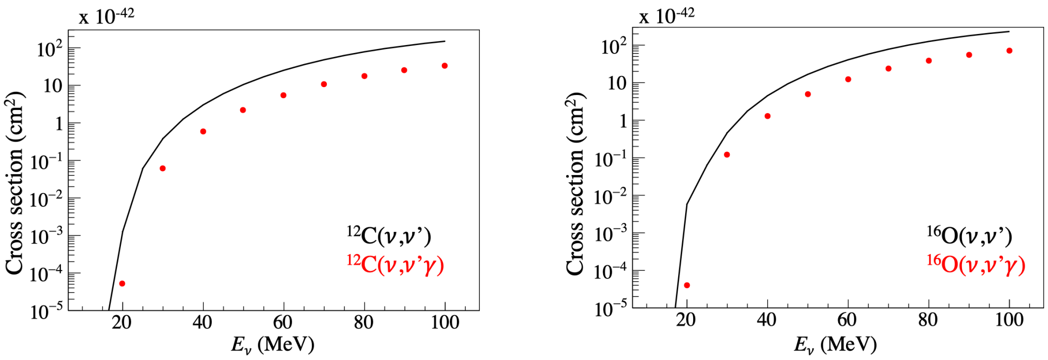

Fig. 3. (a) The inelastic cross sections for ^{12}C(ν,ν') (black) and ^{12}C$(\nu,\nu'\gamma)$ (red) as a function of neutrino energy (E_ν). (b) ^{16}O$(\nu,\nu')^{16}$O* (black) and ^{16}O$(\nu,\nu'\gamma)$X (red) as a function of neutrino energy (E_ν). Only excitations for E_x >16 MeV are considered.

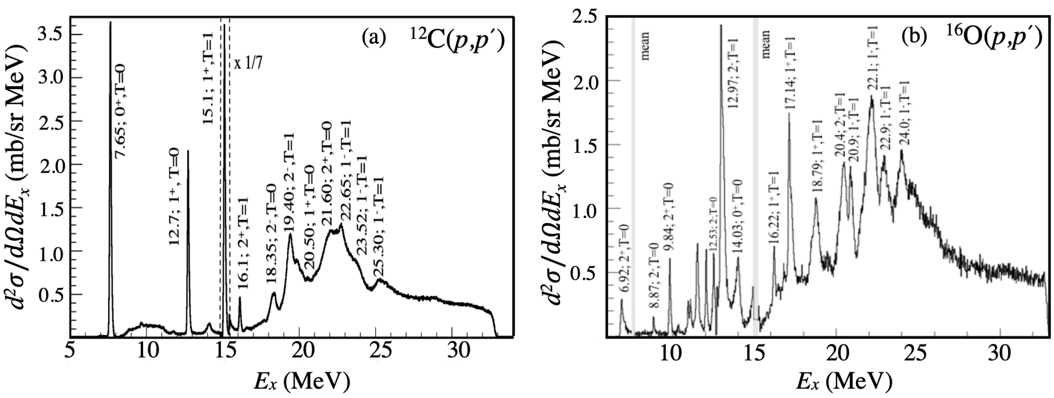

Fig. 4. The measured inelastic cross sections of (a) ^{12}C(p,p') and (b) ^{16}O(p,p') as a function of the excitation energy E_x at the incident proton energy of 392 MeV.

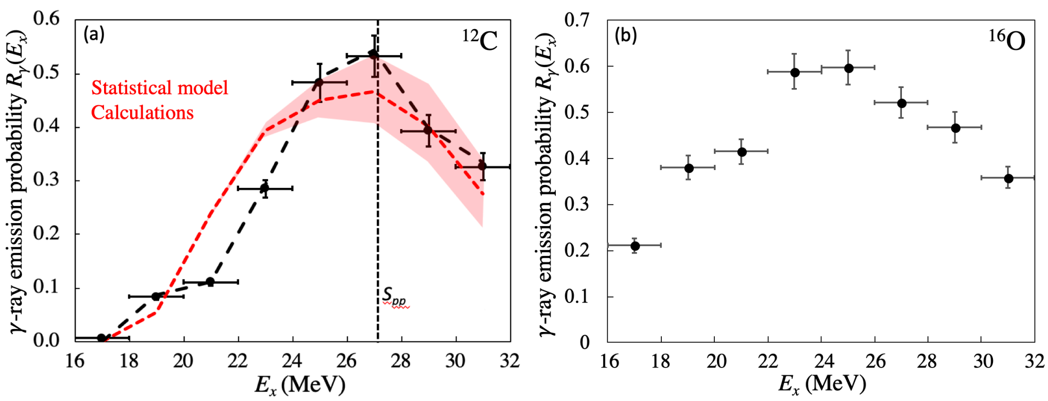

Fig. 5. Total γ-ray emission probability (R_γ) as a function of E_x, compared with the statistical model prediction (red dashed line) [31]. The error bars on data points include both statitstical and systematic uncertainties. The red band shows the uncertainty in calculation due to the error in quasifree process.

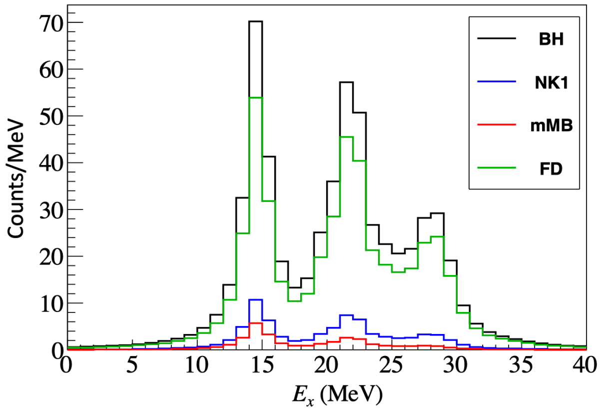

Fig. 6. The number of NC ν^{16}O events $N^{NC}(E_x)$ for various SN fluxes.

Reaction	Present work				JUNO Collab. [13]
	mMB	NK1	FD	NK2	mMB
$p(\bar{\nu}_e, e^+)n$	4140	2310	6950	12820	4300
NC ^{12}C$(\nu,\nu')^{12}$C*(15.1 MeV)	150	170	1030	840	170
NC ^{12}C$(\nu,\nu')^{12}$C*(E_x >16 MeV)	5	21	190	230	-

Table II. Expected number of neutrino events from a core-collapse supernova at 10 kpc to be detected at JUNO(20 kton). For mMB spectra, $\langle E_\nu \rangle$=12 MeV is used for all neutrino flavors.

Reaction	Present work				Beacom-Vogel [8]
	mMB	NK1	FD	NK2	FD
$p(\bar{\nu}_e, e^+)n$	5900	3290	7960	18290	8300
NC ^{16}O$(\nu,\nu')^{16}$O*(E_γ >5 MeV)	12	62	500	980	710
Cf. CC ^{16}O$(\nu_e, e^-)+^{16}$O$(\bar{\nu}_e, e^+)$(E_e > 5 MeV) [25]	-	77	-	3831	-
νe elastic scattering [25]	-	140	-	514	-

Table III. Expected number of neutrino events from a core-collapse supernova at 10 kpc to be detected at Super-K (32kton).

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