Detection of supernova neutrinos at spallation neutron sources*

Ming-Yang Huang(黄明阳)\(^1{,2,1}\) Xin-Heng Guo(郭新恒)\(^3,2\) Bing-Lin Young(杨炳麟)\(^4,5,3\)

\(^1\) Institute of High Energy Physics (IHEP), Chinese Academy of Sciences (CAS), Beijing 100049, China
\(^2\) Dongguan Institute of Neutron Science (DINS), Dongguan 523808, China
\(^3\) College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China
\(^4\) Department of Physics and Astronomy, Iowa State University, Ames, Iowa 5001, USA
\(^5\) Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China

Abstract: After considering supernova shock effects, Mikheyev-Smirnov-Wolfenstein effects, neutrino collective effects, and Earth matter effects, the detection of supernova neutrinos at the China Spallation Neutron Source is studied and the expected numbers of different flavor supernova neutrinos observed through various reaction channels are calculated with the neutrino energy spectra described by the Fermi-Dirac distribution and the “beta fit” distribution respectively. Furthermore, the numerical calculation method of supernova neutrino detection on Earth is applied to some other spallation neutron sources, and the total expected numbers of supernova neutrinos observed through different reactions channels are given.

Keywords: neutron source, supernova neutrinos, neutrino effects, number

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1 Introduction

Supernovas (SNs) are the extremely powerful explosions with which the lives of stars more massive than eight solar masses (\(>8\) \(M_\odot\)) terminate, leaving behind compact remnants such as neutron stars or black holes. SN explosions are one of the most spectacular cosmic events and a source of new physics ideas [1]. A broad area of fundamental physics can be studied by the observation of SNs [2]. Detection of SN neutrinos on Earth [3], such as from SN1987A [4, 5], has been a subject of intense investigation in astroparticle physics. Some information about the SN explosion mechanism and neutrino mixing parameters can be obtained by detecting SN neutrinos on Earth [2, 6].

The China Spallation Neutron Source (CSNS) [7] is a high power accelerator-based facility. It consists of an 80 MeV H\(^-\) linac, a 1.6 GeV Rapid Cycling Synchrotron (RCS), a solid tungsten target station, and instruments for spallation neutron applications [8]. The accelerator operates at 25 Hz repetition rate with an initial design beam power of 100 kW, upgradeable to 500 kW [9, 10]. As the only spallation neutron source in a developing country, CSNS will be among the top four such facilities in the world when it is completed.

![](accelerator_neutrino_energy_spectra.png) ![](supernova_neutrino_energy_spectra.png)

Fig. 1. (color online) Neutrino energy spectra. (a) accelerator neutrinos at CSNS (from Ref. [11]); (b) SN neutrinos on Earth. \(N(I)\) corresponds to the normal (inverted) mass hierarchy, and \(x = \mu, \tau\).

In previous work, using the code FLUKA, the processes of accelerator neutrino production from the proton beam hitting the tungsten target at CSNS were simulated, and the energy spectra of accelerator neutrinos

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1) E-mail: huangmy@ihep.ac.cn
2) E-mail: xhguo@bnu.edu.cn
3) E-mail: young@iastate.edu

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were obtained [11], as shown in Fig. 1(a). While considering SN shock effects [12–15], Mikheyev-Smirnov-Wolfenstein (MSW) effects [16–19], neutrino collective effects [20–22], and Earth matter effects [23–25], the detection of SN neutrinos on Earth was studied [26]. Then, the energy spectra of SN neutrinos can be calculated, as shown in Fig. 1(b). Comparing the energy spectra of accelerator neutrinos with those of SN neutrinos, it is clear that the energy spectrum ranges of SN neutrinos are very close to those of accelerator neutrinos. Therefore, by using the accelerator neutrino detector at spallation neutron sources, different flavor neutrinos from a SN explosion can also be detected, thus serving as a SN Early Warning System [27].

Different from our previous work [26], in this paper, we study the detection of SN neutrinos on Earth by accelerator neutrino detectors at some current GeV-range spallation neutron sources, and the expected numbers of different flavor SN neutrinos observed through various reaction channels are calculated. In addition, the SN neutrino energy spectra described by the Fermi-Dirac distribution [28] and the “beta fit” distribution [29] are studied at the same time, and the numerical results are compared. Furthermore, the backgrounds of SN neutrino detection at spallation neutron sources are studied detail and the efficiencies of different detectors are also considered in our calculations.

The paper is organized as follows. In Section 2, we study the SN neutrino detection by the accelerator neutrino detector at CSNS. In Section 3, the numerical calculation method for SN neutrino detection on Earth is applied to some other GeV-range spallation neutron sources. In Section 4, a summary and discussion are given.

2 SN neutrino detection at CSNS

In SN core collapse, a vast number of neutrinos are produced in two bursts [30, 31]. When SN neutrinos of each flavor are produced, they are approximately the effective mass eigenstates due to the extremely high matter density environment. While the neutrinos propagate outward to the surface of the SN, they could be subjected to SN shock effects, MSW effects, and neutrino collective effects. Then, after travelling the cosmic distance to reach Earth, they go through a part of the Earth and are subjected to Earth matter effects. Figure 2 shows the path of SN neutrinos reaching a detector in the Earth.

When all effects are taken into account, including SN shock effects, MSW effects, neutrino collective effects, and Earth matter effects, the SN neutrino fluxes at the detector can be written as [26]

\[ F_{\nu_e}^D = p F_{\nu_e}^{(0)} + (1 - p) F_{\bar{\nu}_e}^{(0)}, \]
\[ F_{\bar{\nu}_e}^D = \bar{p} F_{\nu_e}^{(0)} + (1 - \bar{p}) F_{\bar{\nu}_e}^{(0)}, \]

where \( p = P_{2e} [P_{1\bar{e}} P_{\nu
u} + (1 - P_{1\bar{e}}) (1 - P_{\nu
u})] \), \( \bar{p} = (1 - P_{2e}) P_{\nu
u} \),

for the normal mass hierarchy and

\[ p = P_{2e} P_{\nu
u}, \]
\[ \bar{p} = (1 - P_{2e}) [P_{1\bar{e}} P_{\nu
u} + (1 - P_{1\bar{e}}) (1 - P_{\nu
u})], \]

for the inverted mass hierarchy. In Eqs. (2) and (3), \( P_{2e} (\bar{P}_{2e}) \) is the probability that a (anti)neutrino mass eigenstate \( \nu_2 (\bar{\nu}_2) \) enters the surface of the Earth and arrives at the detector as an electron (anti)neutrino \( \nu_e (\bar{\nu}_e) \), \( P_{\nu
u} (\bar{P}_{\nu
u}) \) is the probability that the (anti)neutrino \( \nu (\bar{\nu}) \) remains as \( \nu (\bar{\nu}) \) after the collective effects, and \( P_{1\bar{e}} (\bar{P}_{1\bar{e}}) \) is the crossing probability for (anti)neutrinos to jump from one eigenstate to another at the high resonance layer [26].

We assume a “standard” SN explosion at a distance \( D = 10 \) kpc from the Earth, releasing a total energy \( E_0 = 3 \times 10^{53} \) erg (similar to SN1987A [4, 5]). For the SN neutrino of flavor \( \alpha (\alpha = e, \mu, \tau) \), the luminosity flux is distributed in time as

\[ L_\alpha(t) = \frac{E_0}{18} \exp(-t/3). \]

In general simulations, the time-integrated neutrino energy spectra can be described by the Fermi-Dirac distribution (the “Livermore” model) [28] or the “beta fit” distribution (the “Garching” model) [29]:

(1) Fermi-Dirac distribution

\[ F^{(0)}_{\alpha}(E) = \frac{L_\alpha(t)}{F^{(0)}_{\alpha}T_{\alpha}^2} \exp\left(E/T_{\alpha} - \eta_\alpha\right) + 1, \]
where $E$ is the neutrino energy, $T_\alpha$ is the temperature of neutrino $\alpha$, $n_\alpha$ is the dimensionless pinching parameter of the spectrum, and $F_{\alpha j}$ is defined by

$$F_{\alpha j} = \int_0^\infty \frac{x^j}{\exp(x - n_\alpha) + 1} \, dx,$$

where $j$ is an integer. The spectra obtained from numerical simulations can be well fitted by \cite{32, 33}

$$T_{\nu_e} = 3 - 4 \text{ MeV, } n_{\nu_e} \approx 3 - 5,$$
$$T_{\nu_x} = 5 - 6 \text{ MeV, } n_{\nu_x} \approx 2.0 - 2.5,$$
$$T_{\nu_\tau} = T_{\nu_x} = 7 - 9 \text{ MeV, } n_{\nu_\tau} = n_{\nu_x} \approx 0 - 2.$$

(6) “Beta fit” distribution

$$F_{\alpha j}^{(0)}(E) = \frac{L_\alpha(t)}{\langle E_{\nu} \rangle^2} \frac{\beta_{\alpha}^{j+1}}{\Gamma(\beta_{\alpha})} \left( \frac{E_{\nu}}{\langle E_{\nu} \rangle} \right)^{\beta_{\alpha} - 1} \times \exp \left( -\beta_{\alpha} \frac{E_{\nu}}{\langle E_{\nu} \rangle} \right),$$

(7)

where $\langle E_{\nu} \rangle$ is the neutrino average energy and $\beta_{\alpha}$ is the dimensionless pinching parameter. The spectra obtained from numerical simulations can be well fitted by \cite{2, 34}

$$\langle E_{\nu_e} \rangle = \langle E_{\nu_x} \rangle = 12 - 15 \text{ MeV},$$
$$\langle E_{\nu_\tau} \rangle = \langle E_{\nu_x} \rangle = 15 - 18 \text{ MeV}, \quad \beta_{\alpha} = 3.5 - 6.$$

Therefore, the numbers $N(i)$ of SN neutrinos observed through various reaction channels “i” can be calculated by

$$N(i) = N_T \int dE \cdot \frac{\sigma(i)}{\langle E_{\nu} \rangle} \cdot \frac{1}{4\pi D^2} \cdot F_{\alpha}^D,$$

(9)

where $N_T$ is the number of target particles, $\sigma(i)$ is the cross section of the given reaction channel, and $D$ is the distance between the SN and the Earth.

For CSNS \cite{11}, a medium scale detector will be placed just below the ground surface about 50 - 60 meters from the spallation target. A spherical 803-ton fiducial mass of mineral oil ($\text{CH}_2$, density 0.845 $\text{g/cm}^3$) has a fiducial radius of 6.1 m, occupying a volume of 950 m$^3$. Then the total numbers of target protons, electrons, and $^{12}\text{C}$ nuclei are

$$N_T^{(p)} = 6.90 \times 10^{31}, \quad N_T^{(e)} = 2.76 \times 10^{32},$$
$$N_T^{(C)} = 3.45 \times 10^{31}.$$

It is clear that there are three reaction channels which can be used to detect SN neutrinos: inverse beta decay, neutrino-electron reactions, and neutrino-carbon reactions. Table 1 shows the reaction thresholds, number of target particles, and effective cross sections for the three kinds of reactions \cite{35-38}. It can be seen that, for the inverse beta decay, the neutrino events can be identified by the detection of both the $e^+$ and the 2.2 MeV $\gamma$ from the reaction $n + p \rightarrow d + \gamma$ with a mean capture time $\tau = 250 \mu s$ \cite{39, 40}; for the neutrino-electron reactions, the neutrino events can be identified by the signal of recoil electrons which are strongly peaked along the neutrino direction (this forward peaking is usually used to distinguish electron elastic scattering from neutrino reactions on nuclei \cite{41, 42}); for the neutrino reactions on $^{12}\text{C}$, there are two charged-current and six neutral-current reactions as follows:

- **Charged-current capture of $\nu_e$:**

  $$\nu_e + ^{12}\text{C} \rightarrow ^{12}\text{N} + e^-, \quad E_{th} = 17.34 \text{ MeV},$$
  $$^{12}\text{N} \rightarrow ^{12}\text{C} + e^+ + \nu_e, \quad \tau_{1/2} = 11.00 \text{ ms}.$$

- **Charged-current capture of $\bar{\nu}_e$:**

  $$\bar{\nu}_e + ^{12}\text{C} \rightarrow ^{12}\text{B} + e^+, \quad E_{th} = 14.39 \text{ MeV},$$
  $$^{12}\text{B} \rightarrow ^{12}\text{C} + e^- + \bar{\nu}_e, \quad \tau_{1/2} = 20.20 \text{ ms}.$$

Neutral-current inelastic scattering of $\nu_\alpha$ or $\bar{\nu}_\alpha$ ($\alpha = e, \mu, \tau$):

$$\nu_\alpha (\bar{\nu}_\alpha) + ^{12}\text{C} \rightarrow ^{12}\text{C}^* + \nu_\alpha' (\bar{\nu}_\alpha'), \quad E_{th} = 15.11 \text{ MeV},$$
$$^{12}\text{C}^* \rightarrow ^{12}\text{C} + \gamma.$$

The charged-current events have the delayed coincidence of a $\beta$ decay following the interaction. The neutral-current events have a monoenergetic $\gamma$ ray at 15.11 MeV. Therefore, the charged-current and neutral-current reactions on carbon can be tagged and observed by the neutrino detector \cite{35, 43}.

In Table 1, for the neutrino-carbon reactions, the effective cross sections of the charged-current interaction are given for SN neutrinos without oscillations. When neutrino oscillations are taken into account, the oscillations of higher energy $\nu_i$ into $\nu_e$ result in an increasing event rate since the expected $\nu_e$ energies are just at or below the reaction threshold. This leads to an increase by a factor of 35 for the efficiency cross section ($\sigma(\nu_C^e, e^-)_{12}^N$). Similarly, the efficiency cross section ($\sigma(\nu_C^e, e^+)_{12}^B$) increases by a factor of 5.

Since the energy spectrum ranges of accelerator neutrinos and reactor neutrinos are close to those of SN neutrinos, the background due to accelerator neutrinos from CSNS and reactor neutrinos from the Daya Bay reactor needs to be estimated while observing SN neutrinos. After careful calculation and analysis \cite{11}, with the neutrino detector at CSNS, the event rate of accelerator neutrinos which can be observed is about $10^{-3}$ to $10^{-4}$ per second. The neutrino luminosity of the Daya Bay reactor is very large \cite{44}, but due to the long distance from the Daya Bay reactor to CSNS (about 70 km), detailed calculation gives the event rate of reactor neutrinos observed at CSNS to be about $10^{-3}$ to $10^{-4}$ per second. A SN explosion lasts for only about 20 seconds. Therefore, the number of accelerator neutrinos and reactor neutrinos during that time will be very low and can be ignored during the detection of SN neutrinos at CSNS.

| Reaction Channel | Thresholds | Cross Section |
|------------------|------------|---------------|
| | | |
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SN relic neutrinos, also known as the diffuse SN neutrino background, are of intense interest in neutrino astronomy and neutrino physics [45]. With the neutrino detector at CSNS, the event rate of SN relic neutrinos can be observed [46] is about $10^{27}$ to $10^{28}$ per second. Due to the very short time of SN explosions, the background from SN relic neutrinos can also be neglected.

In general, there is no serious background, because of the characteristics of the SN neutrino events, which are concentrated in a short 20 second interval with energies no more than 30 MeV. This has been confirmed in the Kamiokande [4] and IMB [5] neutrino events of SN1987A.

In order to calculate the number of SN neutrinos more accurately, the energy resolution and event selection need to be studied, and then the detector efficiency can be obtained. For the proposed CSNS detector, we choose to use the detector efficiency $\varepsilon_{PC}$ for the inverse beta decay, $\varepsilon_{EC}$ for the neutrino-electron reactions, and $\varepsilon_{CC}$ for the neutrino-carbon reactions, respectively, during the calculation of the SN neutrino numbers [47].

Using the latest experimental results for neutrino oscillations [48, 49], the neutrino mixing parameters are taken as:

$$\Delta m^2_{21} = 7.5 \times 10^{-3} \text{eV}^2, \quad |\Delta m^2_{32}| = 2.4 \times 10^{-3} \text{eV}^2,$$

$$\sin^2 \theta_{12} = 0.308, \quad \sin^2 \theta_{23} = 0.446, \quad \sin^2 \theta_{13} = 0.0237.$$
Using Eqs. (1)–(9), the number of SN neutrinos detected on Earth can be calculated. The numerical results calculated with the neutrino energy spectra described by the Fermi-Dirac distribution and the “beta fit” distribution are both shown in Table 2. In the table, the ranges of number of events are given for different flavor neutrinos observed through various reaction channels: inverse beta decay, neutrino-electron reactions, and neutrino-carbon reactions. It is found that:

(i) If $\varepsilon_{\nu_e} \approx \varepsilon_{\nu_x} \approx \varepsilon_{\nu_{\beta}}$, the total number of different flavor neutrinos observed through the neutrino-electron reaction channels is much smaller than through the inverse beta decay and neutrino-carbon reaction channels;

(ii) If $\varepsilon_{\nu_e} \approx \varepsilon_{\nu_{\beta}} \approx \varepsilon_{\nu_{\beta}}$, the number of $\nu_e$ observed through the inverse beta decay channel is much larger than through the neutrino-electron and neutrino-carbon reaction channels;

(iii) For the inverse beta decay, the number of $\nu_e$ calculated with the neutrino energy spectra described by the Fermi-Dirac distribution is larger than that calculated by the “beta fit” distribution; however, for the neutrino-carbon reactions, the numbers of different flavor neutrinos calculated with the neutrino energy spectra described by the Fermi-Dirac distribution are all smaller than those calculated by the “beta fit” distribution;

(iv) For the neutrino-electron and neutrino-carbon reactions, the numbers of $\nu_e$ and $\nu_x$ are larger than those of $\nu_x$ and $\nu_x$;

(v) More precise values of $T_\alpha$ and $\eta_\alpha$ ($\langle E_\alpha \rangle$ and $\beta_\alpha$) will help obtain more reliable ranges of SN neutrino numbers [1, 50];

(vi) When the CSNS neutrino detector design is completed, the detector efficiency will be available and more accurate ranges of SN neutrino numbers can be obtained.

In the next section, the numerical calculation method for SN neutrino detection on Earth will be applied to some other GeV-range spallation neutron sources.

3 SN neutrino detection at other spallation neutron sources

In the history of neutrino research, there are many famous neutrino experiments which were based on spallation neutron sources and made important achievements [51], including the Liquid Scintillator Neutrino Detector (LSND) [52] at the Los Alamos Meson Physics Facility (LAMPF), the Karlsruhe Rutherford Medium Energy Neutrino experiment (KARMEN) [53, 54] at the Spallation Neutron Source of Rutherford Appleton Laboratory (ISIS) [55] and so on. Since the beginning of the 21st century, some new spallation neutron sources have been built or are under construction, and may be used for accelerator neutrino experiments in the future. These include the Spallation Neutron Source at Oak Ridge National Laboratory (SNS) [56], CSNS (under construction) [7], the European Spallation Neutron Source (ESS) (under construction) [57] and so on. In Table 3, we list the liquid scintillator material, detector masses, underground depth of the detectors, and number of target particles of the proposed neutrino detectors at some of these GeV-range spallation neutron sources. Similar to the proposed CSNS neutrino detector discussed in the preceding section, these neutrino detectors could also be used for observing SN neutrinos, and information about the neutrino mixing parameters and explosion mechanism of SNs may be gained.

| detector   | material | mass /kton | depth /km | number of target particles |
|------------|----------|------------|-----------|---------------------------|
| vSNS [58]  | CH$_2$   | 0.886      | 0.006     | $N_p$: $7.62 \times 10^{41}$ |
|            |          |            |           | $N_e$: $3.05 \times 10^{42}$ |
|            |          |            |           | $N_O$: $3.81 \times 10^{41}$ |
| vESS [59]  | H$_2$O   | 500        | 1.0       | $N_p$: $3.35 \times 10^{44}$ |
|            |          |            |           | $N_e$: $1.67 \times 10^{45}$ |
|            |          |            |           | $N_O$: $1.67 \times 10^{44}$ |

For the neutrino detector at SNS, there are three reaction channels which can be used to detect SN neutrinos: inverse beta decay, neutrino-electron reactions, and neutrino-carbon reactions. Their effective cross sections are given in Table 1. For the neutrino detector at ESS, there are also three reaction channels which can be used to detect SN neutrinos: inverse beta decay, neutrino-electron reactions, and neutrino-oxygen reactions. The effective cross sections for the inverse beta decay and neutrino-electron reactions are given in Table 1, and the total effective cross sections for the neutrino-oxygen reactions are given as follows [60–62]:

$$
\langle \sigma (^{16}O(\nu_e, e^-)^{16}F^-) \rangle = 1.91 \times 10^{-43} \text{ cm}^2,
\langle \sigma (^{16}O(\bar{\nu}_e, e^+)^{16}N^+) \rangle = 1.05 \times 10^{-42} \text{ cm}^2,
\langle \sigma (^{16}O(\nu_x, \nu_x)^{16}O) \rangle = 5.90 \times 10^{-42} \text{ cm}^2,
(10)
\langle \sigma (^{16}O(\bar{\nu}_x, \bar{\nu}_x)^{16}O^+) \rangle = 4.48 \times 10^{-42} \text{ cm}^2.
$$

The effective cross sections of the charged-current interaction in Eq. (10) are given for SN neutrinos without oscillations. When neutrino oscillations are taken into account, the oscillations of higher energy $\nu_x$ into $\nu_x$ result in an increased event rate since the expected $\nu_x$ energies are just at or below the reaction threshold. This leads to an increase by a factor of 71.7 for the efficiency cross section $\langle \sigma (^{16}O(\nu_e, e^-)^{16}F) \rangle$. Similarly, the efficiency cross section $\langle \sigma (^{16}O(\bar{\nu}_e, e^+)^{16}N) \rangle$ is growing by a factor of 9.2.
Similar to the CSNS detector, in order to calculate the numbers of SN neutrinos more accurately, for the SNS detector, we choose to use the detector efficiency \( \varepsilon_{ps} \) for the inverse beta decay, \( \varepsilon_{cs} \) for the neutrino-electron reactions, and \( \varepsilon_{es} \) for the neutrino-carbon reactions, respectively; for the ESS detector, we choose to use the detector efficiency \( \varepsilon_{pe} \) for the inverse beta decay, \( \varepsilon_{ec} \) for the neutrino-electron reactions, and \( \varepsilon_{oe} \) for the neutrino-oxygen reactions, respectively.

By using Eqs. (1)-(9), the numbers of SN neutrinos detected at SNS and ESS can be calculated. The numerical results calculated with the neutrino energy spectra described by the Fermi-Dirac distribution and the “beta fit” distribution are both shown in Table 4. In the table, the total ranges are given for numbers of SN neutrinos observed through the various reaction channels. It is found that:

(i) If the efficiencies of different detectors are similar, then the total number of SN neutrinos detected at ESS is much larger than at CSNS and SNS;

(ii) The total number of SN neutrinos detected in the case of inverted hierarchy is larger than for the normal hierarchy;

(iii) If the detector efficiencies of different reaction channels are similar, then the total number of SN neutrinos observed through the neutrino-electron reaction channels is much smaller than through the inverse beta decay, neutrino-carbon, and neutrino-oxygen reaction channels;

(iv) For the inverse beta decay, the total number of SN neutrinos calculated with the neutrino energy spectra described by the Fermi-Dirac distribution is larger than that calculated by the “beta fit” distribution. However, for the neutrino-carbon and neutrino-oxygen reactions, the total numbers of SN neutrinos calculated with the neutrino energy spectra described by the Fermi-Dirac distribution are both smaller than those calculated by the “beta fit” distribution.

Table 4. Summary of the total numbers of SN neutrinos detected in various reactions at SNS and ESS. “range (FD)” and “range (BF)” stand for the ranges of number of SN neutrinos calculated using the Fermi-Dirac and “beta fit” distributions respectively. \([x, y]_{\varepsilon}^{\varepsilon} \) stands for the range satisfying \( \varepsilon \times x \leq N \leq y \times \varepsilon \) where \( \varepsilon \) is the detector efficiency.

| detector | hierarchy | reaction | range (FD) | range (BF) |
|----------|-----------|----------|------------|------------|
| SNS      | normal    | \( \nu_e p \) | \([410.21, 566.67]_{\varepsilon_{ps}}\) | \([244.33, 350.02]_{\varepsilon_{ps}}\) |
|          |           | \( \nu_e \) | \([14.88, 15.25]_{\varepsilon_{es}}\) | \([15.15, 15.26]_{\varepsilon_{es}}\) |
|          |           | \( \nu^{12} C \) | \([79.13, 118.26]_{\varepsilon_{cs}}\) | \([142.95, 174.88]_{\varepsilon_{cs}}\) |
|          | inverted  | \( \nu_e p \) | \([493.13, 707.65]_{\varepsilon_{ps}}\) | \([281.85, 394.62]_{\varepsilon_{ps}}\) |
|          |           | \( \nu_e \) | \([15.39, 15.71]_{\varepsilon_{es}}\) | \([15.44, 15.58]_{\varepsilon_{es}}\) |
|          |           | \( \nu^{12} C \) | \([97.02, 141.01]_{\varepsilon_{cs}}\) | \([170.92, 205.36]_{\varepsilon_{cs}}\) |
| ESS      | normal    | \( \nu_e p \) | \([1.80 \times 10^4, 2.49 \times 10^4]_{\varepsilon_{pe}}\) | \([1.07 \times 10^5, 1.54 \times 10^5]_{\varepsilon_{pe}}\) |
|          |           | \( \nu_e \) | \([8.15 \times 10^3, 8.35 \times 10^3]_{\varepsilon_{oe}}\) | \([8.30 \times 10^3, 8.53 \times 10^3]_{\varepsilon_{oe}}\) |
|          |           | \( \nu^{16} O \) | \([4.73 \times 10^4, 7.18 \times 10^4]_{\varepsilon_{oe}}\) | \([8.72 \times 10^4, 1.07 \times 10^5]_{\varepsilon_{oe}}\) |
|          | inverted  | \( \nu_e p \) | \([2.17 \times 10^5, 3.11 \times 10^5]_{\varepsilon_{pe}}\) | \([1.24 \times 10^6, 1.72 \times 10^6]_{\varepsilon_{pe}}\) |
|          |           | \( \nu_e \) | \([8.43 \times 10^3, 8.61 \times 10^3]_{\varepsilon_{oe}}\) | \([8.45 \times 10^3, 8.53 \times 10^3]_{\varepsilon_{oe}}\) |
|          |           | \( \nu^{16} O \) | \([5.89 \times 10^4, 8.56 \times 10^4]_{\varepsilon_{oe}}\) | \([1.04 \times 10^5, 1.25 \times 10^5]_{\varepsilon_{oe}}\) |

4 Summary and discussion

In this paper, SN neutrino detection on Earth was studied while considering all relevant effects: SN shock effects, MSW effects, neutrino collective effects, and Earth matter effects. Then, the number of different flavor SN neutrinos expected for various reaction channels at CSNS, including inverse beta decay, neutrino-electron reactions and neutrino-carbon reactions, were calculated with the neutrino energy spectra described by the Fermi-Dirac distribution and the “beta fit” distributions respectively.

The numerical calculation method of SN neutrino detection on Earth was then applied to some other spallation neutron sources in the GeV energy range (SNS and ESS). The total number ranges of SN neutrinos detected in different reactions channels (SNS: inverse beta decay, neutrino-electron reactions, neutrino-carbon reactions; ESS: inverse beta decay, neutrino-electron reactions, neutrino-oxygen reactions) were calculated.

In future, after completion of the design of neutrino detectors at these spallation neutron sources, the detector efficiencies will be available and more accurate ranges of SN neutrino numbers can be obtained. Furthermore, more precise values of \( T_A \) and \( \eta_A \) (\( E_A \) and \( \beta_A \)) will give more reliable ranges of SN neutrino numbers.

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