Supernova Neutrinos Detection On Earth *

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Abstract In this paper, we first discuss the detection of supernova neutrino on Earth. Then we propose a possible method to acquire information about $\theta_{13}$ smaller than $1.5^\circ$ by detecting the ratio of the event numbers of different flavor supernova neutrinos. Such an sensitivity cannot yet be achieved by the Daya Bay reactor neutrino experiment.

Key words supernova, neutrino, collective effects, MSW effects, Earth matter effects, Daya Bay

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1 Introduction

The supernova (SN) explosion is one of the most spectacular cosmic events and a source of new physics ideas[1, 2, 28, 29, 30]. Observable effects of SN neutrinos in underground detectors have been a subject of intense investigation in astroparticle physics, both on general grounds and in relation to the SN event like 1987A. In particular, flavor oscillation in the SN may shed light on the problem of neutrino masses and mixing by means of the associated matter effects. Several neutrino laboratories, including the Daya Bay reactor neutrino underground laboratory[3] which is under construction, can be used to detect possible neutrino events from an SN explosion and serve as the SN Earth Warning System. Hence theoretical prediction for the detection of SN neutrinos in the Daya Bay and other neutrino experiments is very desirable.

In the realistic case, when we detect neutrinos from a type II SN explosion at Daya Bay, there are three effects (the collective effects arising from neutrino-neutrino interactions[4, 5, 6, 7, 8, 9, 10, 11, 12], the well-known Mikheyev-Smirnov-Wolfenstein (MSW) effects[13, 14, 15, 16], and Earth matter effects[17, 18, 19]) need to be considered. Using the Landau-Zener formula[20, 21], the expression of the crossing probability, $P_H$, which is the neutrino jump probability from mass eigenstate $\nu_1$ to $\nu_3$ at the high resonance region inside the SN, can be calculated[22, 23, 24]. With the relation between $P_H$ and the mixing angle $\theta_{13}$, we can predict the SN neutrino event numbers $N$ as a function of $\theta_{13}$. Therefore, we can propose a possible method to acquire information about small $\theta_{13}$ through the detection of SN neutrinos[25].

2 Detection of SN neutrinos on Earth

SN are extremely powerful explosions in the universe which terminate the life of some stars[1, 25, 26, 27]. They make the catastrophic end of stars more massive than 8 solar masses leaving behind compact remnants such as neutron stars or black holes which may be observed. For historical reasons, SN are divided into two wide categories (type I and type II) characterized by the absence or presence of hydrogen lines. However, the most important physical characteristics is the mechanism that produces the SN, which distinguishes SN of type Ia from SN of type Ib, Ic, and II. This difference becomes noticeable in the light spectrum some months after maximum luminosity, when the ejecta become optically thin and the innermost regions become visible: the spectrum of SN Ia is dominated by Fe emission lines, while SN Ib, Ic, and II show O and C emission lines. From the point of view of neutrino physics, type Ib, Ic, and II SN are much more important than type Ia SN, simply because they

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produce a huge flux of neutrinos and antineutrinos of all flavors.

The type II SN is thought to be generated by the core collapse of red (or blue as SN1987A) giant star with a mass between about 8-9 and 40-60 solar masses. The total energy release (about $3 \times 10^{53}$) is approximately the gravitational binding energy of the core. It generates intensive neutrinos which take away about 99% of this total energy. The explosion itself consumes about 1% of this total energy. The vast amount of neutrinos are produced in two bursts. In the first burst which lasts for only a few milliseconds, electron neutrinos are generated via the electron capture by nuclei $e^- + N(Z,A) \rightarrow N(Z-1,A) + \nu_e$ and the inverse beta-decay $e^- + p \rightarrow n + \nu_e$. In the second burst which lasts longer, neutrinos of all flavors ($\nu_e$, $\nu_\mu$, $\nu_\tau$) are produced through the electron-positron pair annihilation $e^- + e^+ \rightarrow \nu_e + \bar{\nu}_e$, electron-nucleon bremsstrahlung $e^\pm + N \rightarrow e^\pm + N + \nu_e + \bar{\nu}_e$, nucleon-nucleon bremsstrahlung $N + N \rightarrow N + N + \nu_e + \bar{\nu}_e$, plasmon decay $\gamma \rightarrow \nu_e + \bar{\nu}_e$, and photoannihilation $\gamma + e^\pm \rightarrow e^\pm + \nu_e + \bar{\nu}_e$. When SN neutrinos of a definite flavor are produced they are approximately in an effective mass eigenstate due to the extremely high matter density environment. While they propagate outward to the surface of the SN they could experience collective effects[13, 14, 15, 16] and MSW effects[13, 14, 15, 16]. After travelling the cosmic distance to reach Earth, the arriving neutrinos are mass eigenstates, which then oscillate in flavors while going through Earth matter. Therefore, we also have to consider Earth matter effects[17, 18, 19] when we compute the event numbers of the various flavors of neutrinos.

Let $P_{\nu\nu}$ represent the collective effects of 3 neutrino-neutrino interactions which is a stepwise flavor conversion probability of neutrinos at a critical energy $E_C$. In order to obtain a simple expression for $P_{\nu\nu}$ for the neutrino and $\bar{P}_{\nu\nu}$ for the antineutrino, we take a constant matter density and box-spectra for both the neutrino and antineutrino[20, 21, 22]. An analysis of the collective effects in the case of three flavors has been made in Ref. [11], and it allows us to characterize the collective oscillation effects and to write down the flavor spectra of the neutrino and antineutrino arriving at Earth. Following Ref. [11], we have $P_{\nu\nu} = \bar{P}_{\nu\nu} = 1$ for the normal hierarchy; and $P_{\nu\nu} = 1$, while

$$P_{\nu\nu} = \begin{cases} 1 & (E < E_C), \\ 0 & (E > E_C), \end{cases}$$

(1)

for the inverted hierarchy, where $E_C = 7MeV[21, 22]$.

There are two MSW resonance regions: the high resonance region and the low resonance region. Let us denote the probability that the neutrinos jump from one mass eigenstate to another at the high (low) resonance layer by $P_H$ ($P_L$). Using the Landau-Zener formula[22, 23], one can obtain that

$$P_H = \frac{\exp(-\frac{\pi}{2} F) - \exp[-\frac{\pi}{2} \gamma(\frac{E}{\sin \theta_{13}})]}{1 - \exp[-\frac{\pi}{2} \gamma(\frac{E}{\sin \theta_{13}})]},$$

(2)

$$\gamma = \frac{|\Delta m^2_{13}| \sin^2 2\theta_{13}}{2E} \cos 2\theta_{13} \frac{d \ln N_e/d \gamma}{\text{res}},$$

where $N_e$ is the electron density and $F$ can be calculated by Landau’s method[22]. Using the SN matter density profile $\rho \approx C \cdot (10^7 cm/r)^3 \cdot 10^{10} g/cm^3$ where $C$ is a structure constant between 1 and 15[24, 25, 26] and $F \approx 1$ ($\theta_{13}$), we can obtain an simple expression of $P_H$ that[21, 22, 23, 24]

$$P_H = \exp\left\{-\frac{\pi}{12} \frac{10^9 MeV}{E} \left(\frac{\sin^3 2\theta_{13}}{\cos 2\theta_{13}}\right) \times \left(\frac{\Delta m^2_{13}}{1eV^2}\right)^{2/3}\right\},$$

(3)

where $|\Delta m^2_{13}| = 2.6 \times 10^{-3}eV^2$. Similarity, we can calculate the expression of the crossing probability at the low resonance region inside the SN, $P_L$. However, due to the large angle solution of the neutrino mixing, $P_L \approx 0$.

Suppose a neutrino reaches the detector underground in Earth. $D$ is the location of the detector, $\theta$ is the incident angle of the neutrino, $O$ is the center of Earth, $L$ is the distance the neutrino travels through Earth, and $x$ is the distance of the neutrino to the center of Earth.

$$L = (-R_E + h) \cos \theta + \sqrt{R_E^2 - (R_E - h)^2 \sin^2 \theta},$$

(4)

Fig. 1. Illustration of the path of the SN neutrino reaching the detector underground in Earth. $D$ is the location of the detector, $\theta$ is the incident angle of the neutrino, $O$ is the center of Earth, $L$ is the distance the neutrino travels through Earth, and $x$ is the distance of the neutrino to the center of Earth.
where $h \approx 0.4\text{km}$ for the Daya Bay experiment) is the depth of the detector in and $R_E = 6400$ km is the radius of Earth. Let $x$ be the distance that the neutrino travels into Earth, then the distance of the neutrino to the center of Earth, $\tilde{x}$, is given by

$$\tilde{x} = \sqrt{(-R_E + h)^2 + (L-x)^2 + 2(R_E-h)(L-x)\cos \theta}.$$ 

Let $P_{\nu_e}$ be the probability that a neutrino mass eigenstate $\nu_e$ enters the surface of Earth and arrives at the detector as an electron neutrino $\nu_e$, one obtains

$$P_{\nu_e} = \sin^2 \theta_{12} + \frac{1}{2} \sin^2 2\theta_{12} \int_{x_0}^{x_f} dx V(x) \sin \phi_{\nu_e}^m,$$

where $x_{12} = 32.5^\circ$, the potential $V(x)$ that the electron neutrino experiences in Earth is $\sqrt{2}G_F \rho(x)/(m_p + m_n)$ and $\phi_{\nu_e}^m$ is defined as

$$\phi_{\nu_e}^m = \int_a^b dx \Delta m^2(x),$$

$$\Delta m^2(x) = \frac{\sqrt{2}E}{2\pi D} \sqrt{\cos^2 2\theta_{12} - \varepsilon(x)^2 + \sin^2 2\theta_{12}},$$

where $\varepsilon(x) = 2EV(x)/\Delta m^2_{12}$ and $\rho(x)$ is the matter mass density inside Earth.

In the following, we calculate the event numbers $N(i)$ of SN neutrinos that can be observed through various reaction channels $i$. This is done by integrating over the neutrino energy $E$ of the product of the target number $N_T$, the cross section of each channel $\sigma(i)$, and the neutrino flux function at the detector $F_{\alpha}^i(E)/4\pi D^2$,

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

where $\alpha$ stands for the neutrino or antineutrino of a given flavor, and $D$ (10 $\text{km}$ in the present discussion) is the distance between the SN and Earth. After a straightforward calculation, the fluxes at the detector can be obtained

$$F_{\nu_e}^{i(N)} = P_{\nu_e} P_H F_{\nu_e}^{(0)} + (1 - P_{\nu_e} P_H) F_{\bar{\nu}_e}^{(0)} + (1 - P_{\nu_e} P_H) F_{\nu_e}^{(0)} + (1 + P_{\nu_e} P_H) F_{\bar{\nu}_e}^{(0)},$$

$$F_{\bar{\nu}_e}^{i(N)} = (1 - P_{\bar{\nu}_e} P_H) F_{\nu_e}^{(0)} + P_{\bar{\nu}_e} P_H F_{\bar{\nu}_e}^{(0)},$$

$$2F_{\nu_e}^{i(N)} = P_{\nu_e} F_{\nu_e}^{(0)} + (2 - P_{\nu_e}) F_{\bar{\nu}_e}^{(0)},$$

$$2F_{\bar{\nu}_e}^{i(N)} = P_{\bar{\nu}_e} F_{\nu_e}^{(0)} + (2 - P_{\bar{\nu}_e}) F_{\bar{\nu}_e}^{(0)}.$$ 

for the normal hierarchy ($\Delta m^2_{31} > 0$), and

$$F_{\nu_e}^{i(1)} = \begin{cases} 2P_{\nu_e} F_{\nu_e}^{(0)} + (1 - P_{\nu_e}) F_{\nu_e}^{(0)}, & (E < E_C) \\ F_{\nu_e}^{(0)}, & (E > E_C) \end{cases},$$

$$F_{\bar{\nu}_e}^{i(1)} = \begin{cases} 2P_{\bar{\nu}_e} F_{\nu_e}^{(0)} + (1 - P_{\bar{\nu}_e}) F_{\bar{\nu}_e}^{(0)}, & (E < E_C) \\ F_{\bar{\nu}_e}^{(0)}, & (E > E_C) \end{cases},$$

$$2F_{\nu_e}^{i(1)} = \begin{cases} (1 - P_{\nu_e}) F_{\nu_e}^{(0)} + (1 + P_{\nu_e}) F_{\nu_e}^{(0)}, & (E < E_C) \\ F_{\nu_e}^{(0)} + F_{\nu_e}^{(0)}, & (E > E_C) \end{cases},$$

$$2F_{\bar{\nu}_e}^{i(1)} = \begin{cases} (1 + P_{\bar{\nu}_e}) F_{\nu_e}^{(0)} + (1 - P_{\bar{\nu}_e}) F_{\bar{\nu}_e}^{(0)}, & (E < E_C) \\ (1 + P_{\bar{\nu}_e}) F_{\nu_e}^{(0)} + (1 - P_{\bar{\nu}_e}) F_{\bar{\nu}_e}^{(0)} & (E > E_C). \end{cases}$$

for the inverted hierarchy ($\Delta m^2_{31} < 0$). In Eqs. (7) and (8), $F_{\nu_{\alpha}}^{(0)}$ is the time-integrated neutrino energy spectrum of flavor $\alpha$ in vacuum which can be described by the Fermi-Dirac distribution

$$F_{\alpha}^{(0)}(E) = \frac{L_{\alpha}^{(0)}}{F_{\alpha3} T_{\alpha}} \exp \left( \frac{E^2}{T_{\alpha}} - \eta_{\alpha} \right) + 1,$$

where $T_{\alpha}$ is the temperature of the neutrino.

$$T_{\nu_e} = 3 - 4 MeV, \quad T_{\bar{\nu}_e} = 5 - 6 MeV, \quad T_{\nu_x} = 7 - 9 MeV,$$

$$\eta_{\alpha} = \text{the pinching parameter of the spectra to represent the deviation from being exactly thermal.}$$

$$T_{\alpha} \approx 3 - 5, \quad \eta_{\alpha} \approx 2.0 - 2.5, \quad \eta_{\alpha} \approx 0 - 2,$$

$L_{\alpha}^{(0)}$ is the the luminosity, and $F_{\alpha j}$ is defined by

$$F_{\alpha j} = \int_0^{\infty} \frac{x^j}{\exp(x - \eta_{\alpha})} dx.$$

In the next section, using the relation between the event number of SN neutrinos detected at Daya Bay, $N$, and the mixing angle $\theta_{13}$, we will propose a possible method to acquire information about $\theta_{13}$ smaller than $1.5^\circ$.

### 3 Acquire information about $\theta_{13}$ smaller than $1.5^\circ$ at Daya Bay

It can be seen from the above section that, using Eqs. (1), (3), (5), (6), (7), and (8), we can obtain the relation between the event number of different flavor SN neutrinos, $N$, and the mixing angle $\theta_{13}$. Let $R$ be the ratio of the event number of $\nu_e$ over that of $\bar{\nu}_e$, one can obtain $R$ as a function of $\theta_{13}$. Therefore, we can propose a possible method to acquire some information about the mixing angle $\theta_{13}$ by detecting SN neutrinos. In this section, we will just consider the process of the neutrino-carbon reactions, since our method is not suitable for the inverse beta-decay and the neutrino-electron reactions in the Daya Bay experiment. The details are discussed at length in Ref. [19].

The Daya Bay Collaboration uses LAB as the main part of the liquid scintillator and the total detector mass is about 300 tons. LAB has a chemical composition including C and H. In our calculation, the ratio of the numbers of C and H, $N_C/N_H$, is about 0.6. Therefore, the total numbers of target
protons $\lambda_C^{(N)} = 1.32 \times 10^{31}$. For the neutrino-neutrino reactions, the effective cross sections are as follows:\(^{34}\):

$$\langle \sigma^{(12)}(C(\nu_e,e^-)^{12}N) \rangle = 1.85 \times 10^{-43} \text{cm}^2,$$

$$\langle \sigma^{(12)}(C(\bar{\nu}_e,e^+)^{12}B) \rangle = 1.87 \times 10^{-42} \text{cm}^2, \quad (12)$$

for the charged-current capture, and

$$\langle \sigma^{(12)}(C) \rangle = 1.33 \times 10^{-43} \text{cm}^2,$$

$$\langle \sigma^{(12)}(C) \rangle = 6.88 \times 10^{-43} \text{cm}^2,$$

$$\langle \sigma^{(12)}(C) \rangle = 3.73 \times 10^{-42} \text{cm}^2, \quad x = \mu, \tau,$$

for the neutral-current capture. Using Eqs. (1), (3), (4), (5), (6), (7), (8), (12) and (13), we plot the ratio $R$ of the event number of $\nu_e$ over that of $\bar{\nu}_e$, which can be detected at Daya Bay as a function of the mixing angle $\theta_{13}$. The result is shown in Fig. 2.

![Graph showing the ratio $R$ of the event number of $\nu_e$ to that of $\bar{\nu}_e$, $R$, as a function of the mixing angle $\theta_{13}$ (in units of degrees) for different values of $\theta_{13}$: $\theta = 30^\circ$, $\theta = 90^\circ$, $\theta = 93^\circ$, $\theta = 150^\circ$.](image)

Fig. 2. The ratio of the event number of $\nu_e$ to that of $\bar{\nu}_e$, $R$, as a function of the mixing angle $\theta_{13}$ in the channel of neutrino-carbon reactions at the Daya Bay experiment. The incident angle is (a) $\theta = 30^\circ$; (b) $\theta = 90^\circ$; (c) $\theta = 93^\circ$; (d) $\theta = 150^\circ$. The solid curves correspond to the normal hierarchy (max), the dashed curves correspond to the inverted hierarchy (max), the dot-dashed curves correspond to the normal hierarchy (min), the dotted curves correspond to the inverted hierarchy (min), where “max” (“min”) corresponds to the maximum (minimum) values of $T_\alpha$ and $\eta_\nu$.

It can be seen from Fig. 2 that the uncertainties of $R$ due to $T_\alpha$ and $\eta_\nu$ are not large. For $\theta_{13} \leq 1.5^\circ$, $R$ is very sensitive to $\theta_{13}$. However, while $\theta_{13} > 1.5^\circ$, $R$ is nearly independent of $\theta_{13}$. Therefore, when $\theta_{13}$ is smaller than $1.5^\circ$, we may restrict the mixing angle $\theta_{13}$ in a small range and get information about mass hierarchy by detecting the ratio of event numbers of SN neutrinos even though there are still some uncertainties due to the incident angle $\theta$, the mass hierarchy $\Delta m^2_{31}$, and the structure coefficient $C$ of the SN density function.

At the Daya Bay experiment, the sensitivity of $\sin^22\theta_{13}$ will reach 0.01, i.e., to determine $\theta_{13}$ down to about $3^\circ$. Therefore, if the actual value of $\theta_{13}$ is smaller than $3^\circ$, the Daya Bay experiment can only provide an upper limit for $\theta_{13}$. However, if an SN explosion takes place during the operation of Daya Bay, roughly within the cosmic distance considered here, it is possible to reach a much smaller value of $\theta_{13}$ through the ratio of the event numbers of different flavor SN neutrinos in the channel of neutrino-carbon reactions as discussed above. It is interesting to note that because of the multi detectors set up, experiments such as the Daya Bay have an internal coincidence check for SN neutrino events.

### 4 Summary and discussion

In this paper, we first discuss the detection of SN neutrinos on Earth. Since neutrino flavor conversions inside the SN depend on the neutrino mixing angle $\theta_{13}$, we give a possible method to acquire information about $\theta_{13}$ smaller than $1.5^\circ$ by detecting SN neutrinos at Daya Bay.

We let the parameters in the neutrino energy spectra (the temperatures and the pinching parameters) vary in some reasonable ranges. In fact, the simulations from the two leading groups, the Livermore group\(^{36,37}\) and the Garching group\(^{36,37}\), led to parameters which agree within about 20-30%. However, their central values of SN parameters are different.

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