NEUTRINO EVENTS FROM SN1987A REVISITED* **

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The e^- and e^+ energy spectra from the SN1987A Supernova neutrino burst interactions are calculated and compared to the observed spectra in Kamiokande-II and IMB experiments. Neutrino oscillations in Supernova and regeneration effects in the Earth, for four combinations of neutrino mass hierarchy (Direct/Inverted) and the value of the mixing angle θ_{13} (Large/Small), are taken into account. The influence of the (anti)neutrino production spectra in Supernova on the observed, in Kamiokande-II and IMB detectors, e^-/e^+ spectra is shown.

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1. Introduction

When a thermal pressure of the heat, resulting from the sequence of nuclear fusion reactions taking place in a star, cannot longer balance the gravitational attraction, the last stage of a massive star evolution begins. For sufficiently massive stars (mass $> 10M_{\odot}$), the collapse of their iron core with a mass exceeding the Chandrasekhar limit creates a type II Supernova (SN), which explosion is an intense source of neutrinos. It is estimated that, about $\sim$99% of the SN type II binding energy (about $\sim 10^{53}$ erg) is radiated as (anti)neutrinos of all flavors. The SN neutrino flux is so enormous,

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that even (anti)neutrino signals from SN explosions outside our Galaxy can be detected on the Earth. Up to now, there was only one case of a detection of extra-solar system neutrinos, namely neutrinos from the SN1987A, which had exploded in the Large Magellanic Cloud. Two terrestrial detectors, Kamiokande-II [1] and IMB [2], were able to observe 20 events of the SN1987A neutrino interactions in total. This observation confirms the main features of the mechanism of the stellar evolution.

2. The Supernova 1987A signal

The number of observed neutrino events, in the terrestrial detectors, and their energy spectrum depend on:

(1) the assumed neutrino production fluxes,

(2) the changes in neutrino fluxes due to the neutrino flavor mixing (oscillations) in both, the Supernova and in the Earth, and

(3) the detector properties — including detection efficiency and the dead time.

All these effects were taken into account in our calculations of the electron and positron energy spectra from the SN1987A neutrino interactions in Kamiokande-II and IMB detectors (these detectors were not able to distinguish between electrons and positrons), presented in this paper.

For the purpose of our simulations, we assume that the distance between the SN1987A and the Earth is 52kpc and that the total energy emitted in the core collapse of the star in form of (anti)neutrinos is $L_{\rm tot} \simeq 3 \times 10^{53}$ergs.

2.1. Primary spectra

We focus on the spectral characteristics of the time-integrated (anti)neutrinos fluxes. The detailed spectral shape of the production fluences is not well known. Such fluxes are often expressed in the form of Fermi–Dirac distributions with the chemical potential equal to zero (see also [3]),

$$F^0_\alpha(E) = \frac{120}{7\pi^4}\,\frac{L_\alpha}{T^4_\alpha}\,\frac{E^2}{e^{E/T\alpha}+1}\,,$$

where $\alpha = \nu_e\,,\ \nu_\mu\,,\ \nu_\tau\,,\ \bar{\nu}_e,\ \bar{\nu}_\mu\,,\ \bar{\nu}_\tau$ and E represents the energy of (anti)neutrinos. The L_α is the total energy released in various flavors of (anti)neutrinos ($L_\alpha \simeq L_{\rm tot}/6$, where an equipartition of the energy emitted in different species is assumed), the T_α is the temperature of the ν_α

gas in the (anti)neutrino sphere. In our calculations, we assume the following, "standard", hierarchy of temperatures: $T_{\nu_e} = 3.5$ MeV, $T_{\bar{\nu}_e} = 5$ MeV, $T_{\nu_x,\bar{\nu}_x} = 8$ MeV, where ν_x and $\bar{\nu}_x$ mean ν_μ, ν_τ and $\bar{\nu}_\mu$, $\bar{\nu}_\tau$, respectively. These temperatures corresponds to the following, approximate average values of the neutrino energies: $E_{\nu_e} = 11$ MeV, $E_{\bar{\nu}_e} = 16$ MeV, $E_{\nu_x,\bar{\nu}_x} = 25$ MeV.

Using a nominal Fermi–Dirac distribution to approximate the spectrum is physically motivated because a truly thermal neutrino flux would follow this behavior. Numerical simulations of the Supernova explosion suggest, however, that the production fluences can be "pinched", meaning that their low- and high-energy parts are suppressed relative to the Fermi–Dirac spectrum of the same average energy. Therefore, we consider also an alternative "Analytic Fit Function" [4] for which analytic simplicity is the main motivation,

$$F_\alpha^0(E) = \frac{L_\alpha}{E_\alpha^2} \frac{(\beta_\alpha + 1)^{\beta\alpha+1}}{\Gamma(\beta_\alpha + 1)} \left(\frac{E}{E_\alpha}\right)^{\beta\alpha} e^{-(\beta\alpha+1)E/E\alpha} ,$$

where E is the energy of (anti)neutrinos, L_α is the total energy released, E_α is the average energy and β_α is the amount of spectral pinching.

In our analysis, we sum up the spectra coming from the two phases of the Supernova explosion, the "accretion" phase in which (about) 10% of the total $L_{\rm tot}$ is released, and the "cooling" phase in which the remaining 90% of the $L_{\rm tot}$ is released. The values of parameters, that we use, were extracted from the Garching group paper [5] and are given in Table I.

TABLE I

The values of the parameters, of the "Analytic Fit Functions", used in this paper. For details see text and [5].

	E_{ν_e}	$E_{\bar{\nu}_e}$	$E_{\nu_x,\bar{\nu}_x}$	β_{ν_e}	$\beta_{\bar{\nu}_e}$	$\beta_{\nu_x,\bar{\nu}_x}$	$\frac{L\nu_e}{L\nu_x,\bar{\nu}_x}$	$\frac{L\bar{\nu}_e}{L\nu_x,\bar{\nu}_x}$
Accretion	11.0	13.5	15.0	4.0	4.5	3.0	1.4	1.4
Cooling	13.5	16.5	18.0	2.7	2.7	2.7	0.7	0.7

2.2. Modifications by oscillations

The details of our approach can be found in [3], so here we only recall the main features: (1) neutrino oscillations in SN are expressed in terms of *flip probabilities* describing their transitions in two resonance layers [6], (2) due to the large distance from the Supernova, they reach the Earth surface in form of incoherent mass eigenstates, (3) for the neutrino regeneration in the Earth, the realistic PREM I [8] Earth density profile is used.

We consider two neutrino mass hierarchies — the Direct (Normal, $m_1 < m_2 \ll m_3$) and Inverted ($m_3 \ll m_1 < m_2$) ones, and two values of Θ_{13} (called "Large" and "Small", see also [3]). The following values of the neutrino mixing parameters were used ([7], the Dirac's phase $\delta = 0$):

$$\begin{aligned} \Delta m^2_{21} &= 7.92 \times 10^{-5}\mathrm{eV}^2 \\ \Delta m^2_{32} &= 2.4 \times 10^{-3}\mathrm{eV}^2 \\ \sin^2\Theta_{12} &= 0.314 \\ \sin^2\Theta_{23} &= 0.44 \\ \sin^2\Theta_{13} &= 0.9 \times 10^{-2} \qquad Large\ \Theta_{13} \\ \sin^2\Theta_{13} &= 1.0 \times 10^{-7} \qquad Small\ \Theta_{13} \end{aligned}$$

2.3. Kamiokande-II and IMB detectors

Both these detectors are water Čerenkov detectors. For the description of the Kamiokande-II detector we use [1] (2.14ktons of water, the efficiency extracted from the Fig. 3 in there, dead time negligible), while for the description of the IMB detector we use [2] (6.8ktons of water, the efficiency extracted from the Fig. 1 in there, 13% dead time correction).

The Charge Current (CC) (anti)neutrino interactions with water, which are considered in our calculations (together with their calculated percentage contributions to the total number of interactions in these detectors), are given in Table II (the cross sections for all processes come from [9]).

TABLE II

The main CC (anti)neutrino interactions with water, together with their calculated percentage contributions to the total number of interactions (given ranges correspond to different combinations of neutrino mass hierarchy and Θ_{13} value).

	Fermi–Dirac	Analytic Fit Function
$\bar{\nu}_e + p \to n + e^+$	76%–80%	87%–89.5%
$\nu_e + O \to F + e^-$	6%–10%	2%–3.5%
$\bar{\nu}_e + O \to N + e^+$	2.5%–10%	1.5%–2%

The Fig.1 shows the sketch of the positions of Kamiokande-II and IMB detectors at the time of the arrival of SN1987A neutrinos. We assume the following distances traveled by (anti)neutrinos in the Earth during the SN1987A neutrino burst (see also [10]): 4363km for Kamiokande-II and 8535km for IMB.

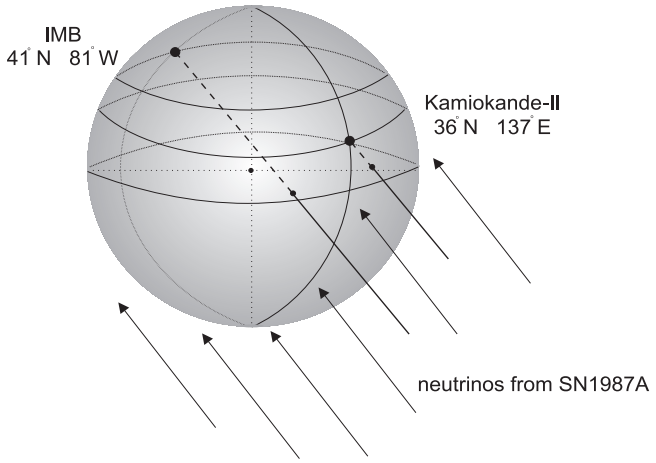


Fig. 1. The sketch of the positions of Kamiokande-II and IMB detectors at the time of the arrival of SN1987A neutrinos.

3. Results and discussion

The predicted e^+ and e^- energy spectra, from the SN1987A neutrino interactions, in Kamiokande-II and IMB detectors are presented in Figs. 2 and 3, respectively, for the Fermi–Dirac and the "Analytic Fit Functions" describing the Supernova neutrino production spectra.

The lines correspond to the four combinations of neutrino mass hierarchy and Θ_{13} value, namely DL — Direct mass hierarchy and *Large* Θ_{13}, IL — Inverted mass hierarchy and *Large* Θ_{13}, DS — Direct mass hierarchy and *Small* Θ_{13}, IS — Inverted mass hierarchy and *Small* Θ_{13}. The shaded areas show the histograms of the observed SN1987A neutrino events, respectively, 12 and 8, in the Kamiokande-II and IMB detectors.

The predicted total numbers of registered events, in both detectors, are given in Table III. The numbers in parenthesis give the predicted total numbers of neutrino interactions N in these detectors (all possible reactions taken into account, no detector efficiency and no dead time considered, see also [3]).

It can be seen that none of the simulated spectra, obtained with any of the considered neutrino production energy spectra, and any of the mass hierarchy and Θ_{13} combinations, agrees satisfactorily with the measured distributions. The agreement is slightly better for the IMB spectra, especially for the "Analytic Fit Function" neutrino production spectra.

Moreover, with the current neutrino mixing parameters, the different Earth matter effects (*i.e.* the different distances traveled by neutrinos in

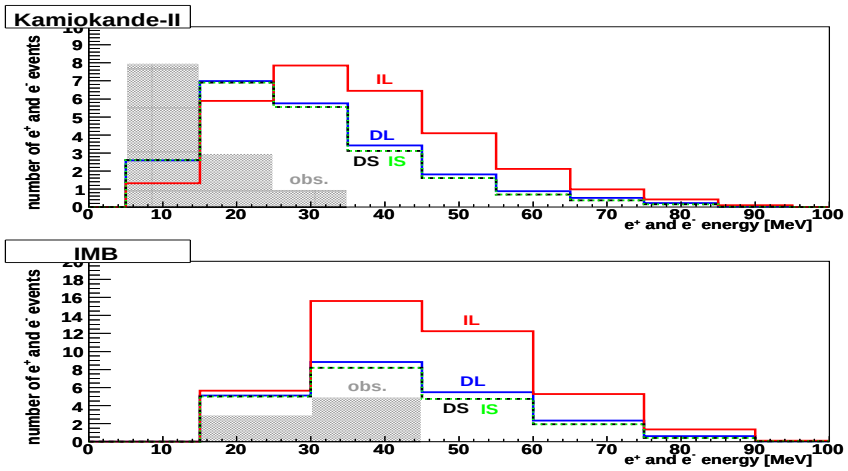


Fig. 2. The predicted e^+ and e^- energy spectra, in case the SN1987A production spectra are described by the thermal Fermi–Dirac functions, for different combinations of mass hierarchy and Θ_{13} (DL — Direct mass hierarchy and *Large* Θ_{13}, IL — Inverted mass hierarchy and *Large* Θ_{13}, DS — Direct mass hierarchy and *Small* Θ_{13}, IS — Inverted mass hierarchy and *Small* Θ_{13}). The shaded areas show the histograms of observed SN1987A events. For details see the description in text.

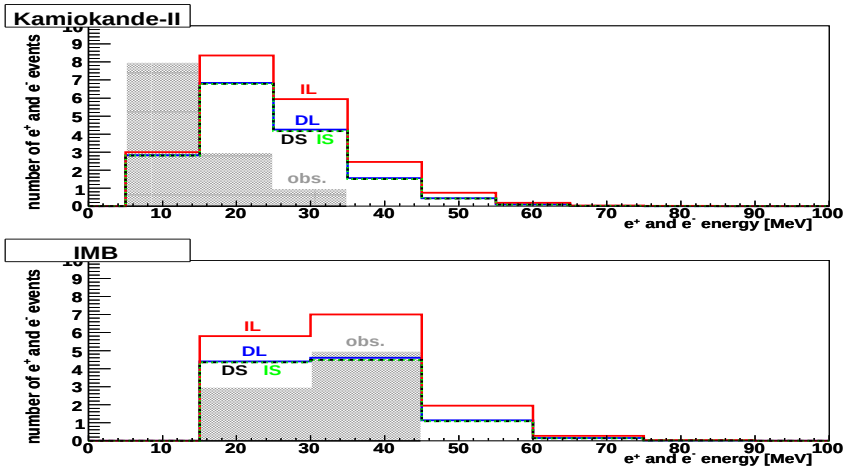


Fig. 3. The predicted e^+ and e^- energy spectra, in case the SN1987A production spectra are described by the "Analytic Fit Functions", for different combinations of mass hierarchy and Θ_{13}. For details see the description in Fig.2 and in text.

TABLE III

The predicted total numbers of registered neutrino events in Kamiokande-II and IMB detectors. The numbers in parenthesis give the predicted total numbers of neutrino interactions N in these detectors. For details see text.

	DL	DS	IL	IS
	Fermi–Dirac			
Kamiokande-II	22.2 (30.1)	21.0 (29.4)	29.3 (36.5)	21.0 (29.4)
IMB	22.4 (95.6)	20.3 (93.3)	40.2 (116.1)	20.3 (93.3)
	Analytic Fit Function			
Kamiokande-II	16.0 (21.0)	15.8 (20.8)	20.7 (25.9)	15.8 (20.8)
IMB	10.3 (66.8)	10.1 (66.1)	15.0 (82.5)	10.1 (66.1)

the Earth) cannot also explain the qualitative differences in the observed Kamiokande-II and IMB spectra. In fact, as we have already noticed in [3], the Earth matter effects have almost no influence on the expected total number of neutrino interactions N in detectors, nor on the predicted event spectra, except on distances below about 2500km, where some variations within 3.5% (1.5%), for the Fermi–Dirac ("Analytic Fit Function") neutrino production spectrum exist (one gets the highest numbers of events when neutrinos do not cross the Earth at all).

The shape of all four (DL, IL, DS and IS) simulated e^+ and e^- energy spectra is very similar. However, the number of the expected events is considerably higher (and the spectrum is harder) for the IL case than for the remaining three, for which the distributions are practically identical (note also that, all these numbers scale linearly with the assumed total energy $L_{\rm tot}$ released in form of (anti)neutrinos, and are inversely proportional to the square of the assumed distance to the Supernova).

The next generations of neutrino experiments, with much bigger detectors, and improved detection techniques, should be able to observe future Supernova neutrino bursts, and not only confirm the main features of the SN mechanism, but also to allow for more precise tests of SN models.

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