Search for High-Energy Neutrinos from SN1987A: First Six Months

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Upward-going muons with energy greater than 1.7 GeV produced in the nearby rock by neutrinos from SN1987A were searched for in a 2140-ton underground water Cherenkov detector, Kamiokande II. No upward-going muons from the direction of SN1987A were found from 23 February 1987 to 1 September 1987; the 90%-confidence-level flux limit is 1.2×10^{-13} cm^{-2} s^{-1} for an energy threshold of 1.7 GeV. For neutrino energy greater than 1.7 GeV, limits on the SN1987A neutrino flux and luminosity are 2.4×10^{-5} cm^{-2} s^{-1} and 1.6×10^{41} erg s^{-1} for cutoff energy $E_c=10^{15}$ eV and spectral index $\gamma=2.1$, and 2.3×10^{-3} cm^{-2} s^{-1} and 4.6×10^{42} erg s^{-1} for $E_c=10^{12}$ eV and $\gamma=2.7$.

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Supernovae are considered as a primary source of ultrahigh-energy cosmic rays. Several acceleration mechanisms have been proposed, in which the rotational energy of a strongly magnetized neutron star is efficiently converted to particle energies,[1] or in which a shock wave with a magnetic field emanating from the collapse provides the statistical Fermi acceleration.[2] Actually, x rays produced as synchrotron radiation from high-energy electrons which were accelerated by a supernova were detected in the Crab nebula and the Cas A supernova remnant. On the other hand, accelerated protons would produce high-energy neutrinos and γ rays in the following way.[3,4] Protons and heavier ions accelerated inside the expanding supernova would collide with a sufficiently thick gas which initially comprised the envelope of the progenitor and later became diffused at the supernova explosion. Pions and kaons produced in the collisions would decay into neutrinos and γ rays. Thus, the observation of high-energy neutrinos or γ rays from a supernova would be a direct confirmation of nuclear active particle acceleration to high energies actually taking place in supernovae. The recent supernova, SN1987A, provides an excellent opportunity to search for such processes experimentally.[5-7]

We report here the Kamiokande II result of a search for neutrino-induced upward-going muons from the direction of SN1987A during the observation period between 23 February and 1 September 1987. Kamiokande II is a water Cherenkov detector located 2700 m of water equivalent underground in the Kamioka mine, about 300 km west of Tokyo (36.42°N, 137.31°E). 2140 tons of water in a cylindrical steel tank is viewed by 948 20-in. photomultiplier tubes covering 20% of the tank surface. This inner detector is surrounded by a 4π water anticounter layer at least 1.5 m thick, viewed by 123 20-in. photomultiplier tubes. A more detailed description of Kamiokande II is given by Hirata *et al.*[8]

High-energy muon neutrinos from SN1987A, if emitted, would interact in the rock surrounding the detector and produce muons. Because Kamiokande II is located in the northern hemisphere, these muons would be observed as penetrating muons traveling upward in the detector and be easily distinguished from the downward-going muons generated by cosmic-ray interactions in the upper atmosphere. Upward-going muons are also produced by atmospheric neutrinos from the opposite side of the earth, but the flux of these muons is smaller by 5 orders of magnitude than the corresponding downward-going flux and does not constitute a significant background. Although low-energy muons would be produced by neutrino interactions in the detector or by escaping from the nearby rock and stopping in the detector, the expected number of these muons is small in comparison with that of the penetrating muons for the spectral indices considered in this paper (see later). Moreover, the angular correlation between muon and parent low-energy neutrino is less sharply peaked. Therefore, we do not consider such low-energy muons in the present paper.

Data from the time period between 23 February and 1 September 1987 are analyzed. They correspond to 129 d of "weekday data," which is fully efficient for upward-going muons, and 31 d of "holiday data," in which approximately 10% of upward-going muons are not recorded. Two independent algorithms are used to select upward-going muons. One uses the event charge information, and the other mainly timing information. 97% of the upward-going muons are selected by at least one or both of the two algorithms. After selection, 11 800 events survive, almost all of which are downward-going muons traveling horizontally or multiple muons. These events are scanned visually and reconstructed manually by two physicists working independently. A total of 24 upward-going muons (zenith angle larger than 90°, path length >7 m, corresponding to an energy threshold of 1.7 GeV) are finally selected from the nominal detection area of 150 m^2. Figure 1 shows the celestial distribution of the 24 muons together with the position of SN1987A.

The flux of the upward-going muons is determined to be $(1.92\pm0.39)\times10^{-13}$ cm^{-2} s^{-1} sr^{-1}, which is consistent with the value[9] of 2.38×10^{-13} cm^{-2} s^{-1} sr^{-1} expected from the atmospheric (cosmic-ray) neutrino background flux. More detailed comparisons with the expected atmospheric neutrino flux will be discussed in a separate paper.

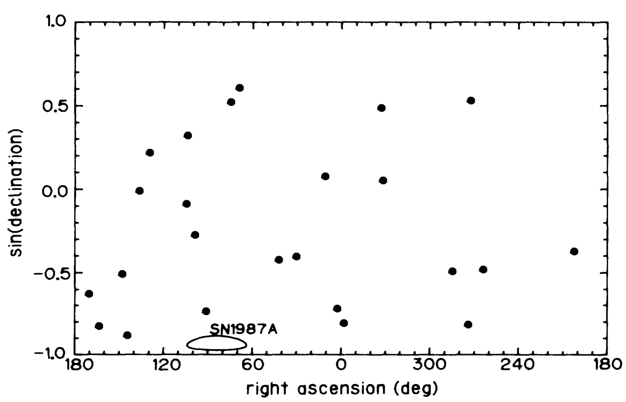

FIG. 1. Arrival direction of 24 upward-going muon events (circles) in the celestial coordinate. The 7° window around SN1987A is also shown.

The angular difference between the reconstructed muon and the parent neutrino, $\Delta\theta$, is written as

$$\Delta\theta=(\Delta\theta_1^2+\Delta\theta_2^2+\Delta\theta_3^2)^{1/2},$$

where $\Delta\theta_1$ is the error coming from manual reconstruction, $\Delta\theta_2$ is the scattering angle between the produced muon and the parent neutrino, and $\Delta\theta_3$ is the uncertainty in angle caused mainly by multiple Coulomb scattering of muons traversing the rock. $\Delta\theta_1$ is studied with use of Monte Carlo events and found to be 2.1°. $\Delta\theta_2$ and $\Delta\theta_3$ depend on the energy spectrum and the cutoff energies of the parent neutrinos. $(\Delta\theta_2^2+\Delta\theta_3^2)^{1/2}$ is calculated by a computer simulation based on cutoff energies between 10^{12} and 10^{15} eV and various spectral indices, i.e., the exponent γ of the energy spectrum assumed as $E^{-\gamma}$ where E is the energy of the parent neutrino. The results of the calculation are summarized in Table I. In consideration of these angular resolutions, an angular window with a radius of 7° is taken which is safe enough to pick up more than 95% of muons from the direction of SN1987A.

No muon event is observed from the direction of SN1987A for the product of area and live time of 62.1 m^2 yr. The 90%-confidence-level upper limit of the muon flux from SN1987A with an energy greater than 1.7 GeV is calculated to be 1.2×10^{-13} cm^{-2} s^{-1}. The corresponding 90%-confidence-level upper limit of the muon-neutrino flux and of the muon-neutrino luminosity of SN1987A can be calculated for various spectral indices and cutoff energies. The probability $P(E)$ that a neutrino of energy E interacts in the rock outside the detector and produces a muon which passes through the detector is given by Quigg, Keng, and Walker.[10] $f(E)$ is defined as the probability that a neutrino of energy E coming from SN1987A survives after passing through the earth, which was calculated by Honda and Mori.[11] The muon flux in the detector, Φ_μ, is given in terms of

TABLE I. Monte Carlo simulation of one standard deviation of the angles between the direction of the parent neutrino and that of the produced muon when the muon arrives at the detector with an energy greater than 1.7 GeV. The results are presented as a function of spectral indices in the range of 2.1 to 2.7 and cutoff energies (E_c) from 10^{12} to 10^{15} eV. The unit is degree.

E_c (eV)	Spectral index 2.1	2.4	2.7
10^{12}	1.70	2.00	2.77
10^{13}	0.49	0.70	1.29
10^{14}	0.17	0.23	0.46
10^{15}	0.05	0.07	0.17

TABLE II. The 90%-confidence-level upper limit for the muon-neutrino flux from the direction of SN1987A (top, in per square centimeter per second) and the corresponding muon-neutrino luminosity ($E_{\rm th} < E < E_c$) of SN1987A (bottom, in ergs per second). It is assumed that neutrinos have an energy spectrum given by the power law $E^{-\gamma}$. The flux limit is calculated for spectral indices of 2.1 to 2.7 and cutoff energies E_c of 10^{12} to 10^{15} eV. The energy threshold $E_{\rm th}$ is 1.7 GeV. The distance to SN1987A is taken as 50 kpc.

E_c (eV)	Spectral index 2.1	2.4	2.7
10^{12}	2.1×10^{-4}	7.4×10^{-4}	2.3×10^{-3}
	8.6×10^{41}	1.9×10^{42}	4.6×10^{42}
10^{13}	4.6×10^{-5}	2.8×10^{-4}	1.4×10^{-3}
	2.4×10^{41}	7.7×10^{41}	2.8×10^{42}
10^{14}	2.8×10^{-5}	2.2×10^{-4}	1.3×10^{-3}
	1.7×10^{41}	6.1×10^{41}	2.5×10^{42}
10^{15}	2.4×10^{-5}	2.1×10^{-4}	1.2×10^{-3}
	1.6×10^{41}	5.9×10^{41}	2.5×10^{42}

the neutrino spectrum $d\Phi_\nu/dE$ and the probabilities $P(E)$ and $f(E)$:

$$\Phi_\mu = \int_{E_{\rm th}}^{E_c} P(E) f(E) \frac{d\Phi_\nu}{dE}\, dE,$$

where E_c is the cutoff energy and $E_{\rm th}$ the minimum muon energy ($E_{\rm th} = 1.7$ GeV). If $d\Phi_\nu/dE$ is assumed to be $AE^{-\gamma}$, the neutrino flux Φ_ν is calculated by

$$\Phi_\nu = \int_{E_{\rm th}}^{E_c} AE^{-\gamma} dE.$$

The results are presented in Table II, together with the neutrino luminosity L ($E_{\rm th} < E < E_c$) at SN1987A, which is obtained by the formula

$$L = 4\pi R^2 \int_{E_{\rm th}}^{E_c} AE^{-\gamma} E\, dE,$$

where $R = 50$ kpc. The fluxes and luminosities ($E_{\rm th} < E < E_c$) range from 2.4×10^{-5} to 2.3×10^{-3} $\rm cm^{-2}\,s^{-1}$ and 1.6×10^{41} to 4.6×10^{42} erg $\rm s^{-1}$ for $\gamma = 2.1$, $E_c = 10^{15}$ eV, and $\gamma = 2.7$, $E_c = 10^{12}$ eV, respectively. This result sets a severe limit on the SN1987A neutrino luminosity and already rules out some naive models[5-7] which predict more than 10^{43} erg $\rm s^{-1}$ for accelerated protons with flat spectrum index.

The upper limit on the high-energy γ-ray flux is roughly estimated with use of Ref. 11 and Gaisser, Harding, and Stanev.[12] Our result with $\gamma = 2.1$ and $E_c = 10^{15}$ eV corresponds to upper limits on the γ-ray flux of 1×10^{-8} and 1×10^{-10} $\rm cm^{-2}\,s^{-1}$ for γ-ray energy larger than 10^{12} and 10^{14} eV, respectively. The former limit is applicable for an air Cherenkov technique and the latter limit for a high-altitude surface air-shower–array observation. These results may place some restrictions on ultrahigh-energy γ-ray observations which are to be done in the southern hemisphere.

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