Evidence of High-energy Neutrinos from SN1987A by Kamiokande-II and IMB

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ABSTRACT

High-energy neutrinos from SN1987A were searched for using upward-going muons recorded by the Kamiokande-II experiment and the IMB experiment. Between August 11 and October 20, 1987, and from an angular window of 10° radius, two upward-going muon events were recorded by Kamiokande-II, and also two events were recorded by IMB. The probability that these upward-going muons were explained by a chance coincidence of atmospheric neutrinos was calculated to be 0.27%. This shows a possible evidence of high-energy neutrinos from SN1987A.

1. INTRODUCTION

Supernovae are considered as a primary source of ultrahigh-energy cosmic-ray protons and heavier ions (Gunn et al. 1969; Goldreich et al. 1969; Scott et al. 1975; Colgate et al. 1960; Blandfold et al. 1980). High-energy (> GeV) neutrinos can be generated from supernova remnants immediately after the explosion. In this scenario, protons accelerated by newly born neutron stars collide with a sufficiently thick gas that initially comprised the envelope of the progenitor and subsequently diffused due to supernova explosion. Charged pions and kaons produced in the collisions decayed into high-energy neutrinos. Observations of high-energy neutrinos from a supernova remnant will confirm the existence of an acceleration mechanism of ultrahigh-energy protons (Berezinsky et al. 1978; Sato 1977).

The supernova SN1987A (RA=83.9°, δ=−69.3°) (Hirata et al. 1987, 1988; Bionta et al. 1987) provided an excellent opportunity to search for such processes experimentally. High-energy neutrinos can be observed as upward-going muons in underground detectors. The expected number of upward-going muon events from SN1987A and their time structures were previously reported (Gaisser et al. 1987; Sato 1987). Although they are model-dependent, 10–100 upward-going muon events could be observed by ~100 m² detectors within one year from the explosion.

2. THE DATA

After the SN1987A explosion, underground detectors, including Kamiokande-II and IMB, searched for upward-going muon events from SN1987A. The results from Kamiokande-II were published until 191 days after the explosion (Oyama et al. 1987). The results until 385 days from the explosion were also reported (Oyama 1989). One upward through going muon event was detected on the 209th day (September 19, 1987) within a 7.0° angular window. However, it was not statistically significant because the expected atmospheric neutrino background was approximately 0.4 (Oyama 1989).

In addition, the Kamiokande-II experiment observed 2 upward stopping muon events on October 18. At that time, a systematic analysis of upward stopping muons was not performed owing to their small event number and poor angular correlations with parent neutrinos. However, some upward stopping muons were found during a visual scan in the upward through going muon selection because of a similarity of the event topologies. The results were not published officially because the collaboration concluded that even if upward stopping muons are combined with the through-going muon candidate detected on September 19, the statistical significance is still poor to claim as evidence.

The IMB experiment accumulated upward-going muon events throughout the entire experimental period. A total of 666 through-going events between September 1982 and December 1990, and 34 stopping events between May 1986 and February 1990 were recorded. Upward-going muon events from the direction of SN1987A were examined, and three possible candidates were found. However, they also concluded that the statistical significance was not satisfactory for a publication.
### Table 1

A list of upward-going muon events from the direction of SN1987A detected by Kamiokande-II and IMB. The date and time of the events, their celestial positions, angular deviation from SN1987A, and the event categories are listed. “thru” indicates upward through-going muons and “stop” indicates upward stopping muons. In the last column, the events from the 10.0° angular window between August 11 and October 20, 1987 are indicated by open circles.

| Date/Time (UT) | (RA, δ)     | Δθ_{SN} | cos Δθ_{SN} | category selected |
|---------------|-------------|---------|-------------|------------------|
| 1987-08-12 05:08:27 | (97.1°, -67.5°) | 5.2°     | 0.996       | IMB-thru         |
| 1987-09-19 11:39:10 | (67.2°, -67.9°) | 6.2°     | 0.994       | Kam-thru         |
| 1987-10-16 10:17:49 | (60.0°, -73.9°) | 8.7°     | 0.988       | IMB-thru         |
| 1987-10-18 16:16:47 | (18.8°, -63.5°) | 25.4°    | 0.903       | Kam-stop         |
| 1987-10-18 18:15:00 | (95.9°, -61.2°) | 9.5°     | 0.987       | Kam-stop         |
| 1988-01-13 03:23:27 | (67.4°, -64.0°) | 8.4°     | 0.989       | IMB-stop         |

**Figure 1.** Celestial map of upward-going muon events observed by Kamiokande-II and IMB between August 11 and October 20, 1987. The 10.0° angular window around SN1987A is also shown.

Recently, it was ascertained that two experiments both independently obtained statistically insufficient results, of which neither were published. However, the combined results seemed more publication worthy. Therefore, in this study, the results of the combined analysis are presented.

Details of the analysis can be found in the original papers (Oyama et al. 1987, 1989; Svoboda et al. 1987) and are not discussed here. A list of three possible candidates from each experiment are given in Table 1.

### 3. THE STATISTICAL SIGNIFICANCE AND DISCUSSION

For statistical significance calculations, the time and angular window were assumed as follows.

1. The time period was 71 days between August 11, 1987 and October 20, 1987.

2. Angular difference from SN1987A was less than 10.0°.

Four events were selected according to these criteria, as shown in Table 1. The celestial map of all upward-going muon events recorded in this time period is shown in Figure 1 together with the 10.0° angular window around SN1987A.

The probability that these four events can be explained by atmospheric neutrinos was calculated as follows. Table 2 lists the number of candidates and the number of expected atmospheric neutrino backgrounds from the time/angular window. Atmospheric neutrino backgrounds were estimated based on the publications from the experiments (Oyama et al. 1987, 1989; Hara 1993; Svoboda et al. 1987). When atmospheric neutrino background from SN1987A was not specified in the papers, the background for LMC X-4 (RA=83.2°, δ=−66.4°), whose celestial position is only 2.9° away
Table 2. Number of upward-going muon events detected by Kamiokande-II and IMB. The first column is the event category. The second column indicates number of candidates in each category. The third column shows the expected atmospheric neutrino background from the time/angular window. The calculation and the results of the probability $N \geq N_{\text{cand}}$ are shown in the final two columns. During calculation, the Poisson distribution function $\text{Poi}(N|\lambda) = \frac{e^{-\lambda} \lambda^N}{N!}$ was used.

| Event Category | Number of candidates ($N_{\text{cand}}$) | Expected atmospheric $\nu$ background ($\lambda$) | Calculation | Probability of $N \geq N_{\text{cand}}$ |
|----------------|-----------------------------------------|-----------------------------------------------|-------------|----------------------------------------|
| Kam-thru       | 1                                       | 0.127                                         | $1 - \text{Poi}(0|0.127)$ | 0.119                                   |
| Kam-stop       | 1                                       | 0.026                                         | $1 - \text{Poi}(0|0.026)$ | 0.026                                   |
| IMB-thru       | 2                                       | 0.315                                         | $1 - \text{Poi}(0|0.315) - \text{Poi}(1|0.315)$ | 0.040                                   |
| IMB-stop       | 0                                       | 0.029                                         | —            | —                                      |

Therefore, the analysis using data until the 385th day reasonably covers the expected neutrino period. However, for the completeness of the analysis, all data after SN1987A was also examined. Figure 2 shows an angular correlation between upward-going muons and SN1987A between the SN1987A explosion and the end of experiments. Obviously, no event cluster from the direction of SN1987A can be found after one year from the explosion.

Figure 2. Angular correlation between upward-going muons and SN1987A between the SN1987A explosion and the end of experiments. The last upward-going muon events were recorded on April 8, 1990 (Kamiokande-II) and December 14, 1990 (IMB). They correspond to the 1140th day and the 1390th day after the explosion, respectively. The time/angular window between August 11 and October 20, 1987, and $10.0^\circ$ from SN1987A is also shown.
To examine the probability of the chance coincidence more carefully, a “fake event” analysis was employed. Most of the upward-going muons are produced from atmospheric neutrinos generated at the opposite side of the Earth. Their times and directions are denoted by $(t_i, (\Theta_i, \Phi_i))$, where $t_i$ is the time of the event, and $(\Theta_i, \Phi_i)$ is the zenith angle and azimuth angle of the event in the horizontal coordinate. From 252 upward through going muons by Kamiokande-II and 666 upward through going muons by IMB, fake event sets were produced by shuffling the combination of the time $t_i$ and the direction $(\Theta_i, \Phi_i)$ using random numbers. For upward stopping muons, the shuffling method was not used because of small number of real events. Instead, fake event sets were produced based on the zenith angle distribution of the upward-going muon flux. A hundred thousand sets of fake upward-going muon events were produced, and the similar analysis as for the real data were applied. Among 100,000 event sets, only 243 event sets showed similar event cluster between the SN1987A explosion and the 385th day. This result well agrees with the probability of the chance coincidence 0.27% obtained for the real data.

It could be argued that the angular window $10^\circ$ is too large for an analysis of directional coincidence; a $7.0^\circ$ window was employed in the previous analysis (Oyama 1989). However, if the nominal neutrino energy is much lower than the theoretical expectations, around $\sim 10$ GeV for example, the scattering angle by the neutrino interactions can be larger. The angular correlation between parent neutrinos and daughter muons in the $< 100$ GeV energy range can be written (Berezenskii et al. 1985) as

$$\Delta \theta_{\nu\mu} \sim 2.6^\circ \sqrt{100 \text{GeV}/E_\nu}.$$  

For $E_\nu = 10$ GeV, $\Delta \theta_{\nu\mu} \sim 8.2^\circ$. Noted that the angular deviation due to multiple scattering of daughter muons during their travel and the angular resolutions of the detectors should be also considered. The existence of one upward stopping muon candidate supports this “low energy” hypothesis because $\sim 10$ GeV neutrinos can be detected as upward stopping muons with high probability. The “low energy” hypothesis implicitly suggests that the nominal proton energy accelerated by SN1987A might be $\sim 100$ GeV.

4. SUMMARY

In summary, 2 upward-going muons by Kamiokande-II and 2 upward-going muons by IMB are observed between August 11 and October 20, 1987 within $10.0^\circ$ angular window around SN1987A. The probability that these events can be explained by a chance coincidence of atmospheric neutrinos was calculated as 0.27%. These events might be the first evidence of high-energy neutrinos from a supernova explosion.

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The author proposed to publish this result as a joint publication from the Kamiokande-II collaboration and the IMB collaboration. However, remaining members of both collaborations suggested that very few members remain active and making a decision as collaboration is difficult. It was also suggested that the old data are free for use, and the results can be published with an author’s responsibility. The author gratefully acknowledges all members of both collaborations.

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