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Angular distribution of events from SN1987A

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The energy and trigger response of the Irvine-Michigan-Brookhaven detector at the time of supernova SN1987A has been studied further since the detection of a burst of neutrinos on 23 February 1987. Here we present improved measurements of the event energies and energy uncertainties, relative times, triggering efficiencies, and angles from the presumed source. The detector is found to have no significant directional bias against tracks moving in the direction toward the supernova. The statistical significance of the observed excess of events pointing away from the Large Magellanic Cloud is discussed.

Since our initial report[1] of detection of a neutrino burst from SN1987A (Ref. 2), we have done further studies to refine all aspects of the measurement. In this paper, we will concentrate on determination of the detector's triggering efficiency as a function of direction and energy. In addition, we have reevaluated the energies of all eight events, cross-checked possible systematic effects, and assigned statistical errors on an event-by-event basis. Finally, we have refit the directions of the observed tracks and estimated the uncertainties in the polar angles from the supernova direction due to multiple scattering and reconstruction resolution.

At the time the neutrino pulse arrived on 23 February 1987, $\gtrsim 20$ photomultiplier tubes (PMT's) firing within ~ 55 ns were required to trigger our detector. This corresponds to a threshold of 15–25 MeV for showering particles, depending on the event geometry. Some two and a half hours before the burst, one of our high-voltage power supplies failed and shut off power to 25% of the detector's 2048 PMT's, almost all the affected PMT's being located on the detector's south and top faces. The quantitative extent of any triggering bias against tracks moving in the direction of these PMT's (which could not contribute in forming the trigger) was unknown at the time of our initial publication.[1]

We have since used a laser-driven source which emits light in a conelike pattern mimicking that of a Cherenkov-radiating track to verify the 20-PMT trigger criterion and to calibrate a computer simulation of the detector trigger. To account for any directional triggering bias against tracks illuminating tubes which could not participate in the trigger, these PMT's were ignored by the simulations. Simulated neutrino scattering events at various energies were generated uniformly throughout the detector volume and randomly in direction, and subjected to the trigger criterion.

Figure 1 shows the resulting mean trigger efficiency versus energy for positrons produced isotropically

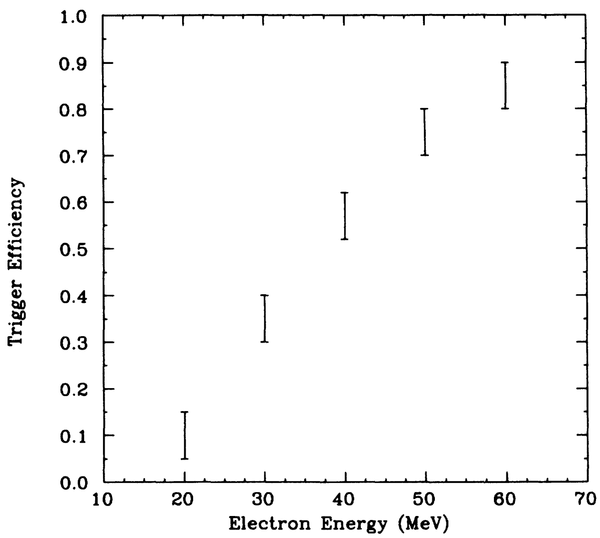

FIG. 1. Trigger efficiency vs electron (or positron) energy averaged over an isotropic distribution in the full 6800-m^3 volume of the detector. Error bars represent systematic uncertainty in efficiency (see text).

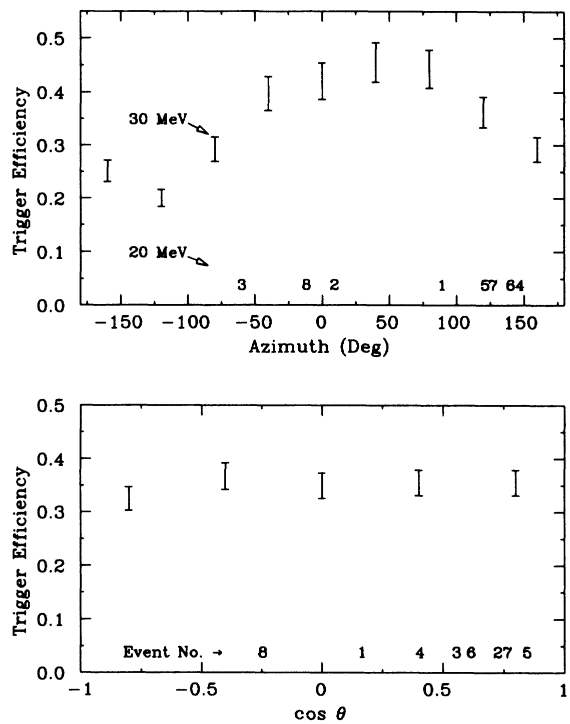

FIG. 2. Angular dependence of the trigger efficiency, as in Fig. 1, for 30-MeV electrons (solid line) and for 20-MeV electrons (dotted lines). Angles are measured with respect to the direction away from the supernova (see text). Error bars represent systematic uncertainty in angular dependence. Similar fractional errors apply to the 20-MeV curves. An additional overall systematic uncertainty applies (see Fig. 1). The angles of the eight events listed in Table I are indicated by the numerals.

throughout the entire 6800-m^3 volume inside the detector's phototube planes. The previously published[1] efficiencies for a 5000-m^3 central volume are slightly higher, since the detector's sensitivity falls off near the edges. However, since the efficiency is not zero even at the detector walls, we now believe it is more appropriate to calculate efficiencies based on the 6800-m^3 total volume. The error bars in Fig. 1 show the estimated uncertainty in the efficiency measurement. The energy scale has an additional systematic uncertainty of $\pm 10\%$.

The dependence of the trigger efficiency on angle at two typical electron energies (20 and 30 MeV) is shown in Fig. 2. The polar angle θ is measured with respect to a Z axis in the direction away from the supernova (which was 42° below the horizon and 28° west of south at the time of the neutrino burst). The azimuthal angle is measured from an X axis which points below the horizon to a Y axis which is chosen horizontal. Only a $\sim 10\%$ inefficiency exists for tracks in the backward direction ($\theta > 90°$), while there is a large drop in efficiency around $-120°$ azimuth angle, in the general direction of the phototubes affected by the malfunctioning power supply. Hence, although the inoperative phototubes should modulate the distribution of events in solid angle, it appears that the polar-angle distribution is relatively insensitive to this effect when events are generated within the

TABLE I. Energies and angles of the eight events from supernova SN1987A. (a) Absolute UT is accurate to ±50 ms. Relative times are accurate to the nearest millisecond. (b) Additional systematic error in energy scale estimated to be ±10%. (c) Angle with respect to direction away from SN1987A. Angle errors include multiple scattering and event reconstruction. (d) assumes events are due to $\bar{\nu}+p \rightarrow e^{+}+n$ on free protons.

Event	(a) Time (UT) 23 Feb. 1987	(b) Measured energy (MeV)	(c) Polar angle (deg)	(d) Antineutrino energy (MeV)
1	7:35:41.374	38±7	80±10	41±7
2	7:35:41.786	37±7	44±15	39±7
3	7:35:42.024	28±6	56±20	30±6
4	7:35:42.515	39±7	65±20	42±7
5	7:35:42.936	36±9	33±15	38±9
6	7:35:44.058	36±6	52±10	38±6
7	7:35:46.384	19±5	42±20	21±5
8	7:35:46.956	22±5	104±20	24±5

entire detector volume.

The angles of the eight data events are indicated on Fig. 2 by the numerals listed in Table I. The polar angles appear peaked in the forward direction in a way inconsistent with either a roughly isotropic distribution (expected from inverse β decay) or a strongly forward-peaked one (expected from scattering off electrons). A Monte Carlo calculation using the Smirnov–Cramer–Von Mises statistic gives a 1.5% probability that a fluctuation as large as this could result from a flat parent distribution. However, the inverse-β-decay differential cross section actually has the approximate form $1+A\cos\theta$ with $A\sim0.13$ at the typical energies of our events (30 MeV). If we increase A to 0.23 to account for (conservatively) our polar-angle efficiency (Fig. 2), this increases the fluctuation probability to 4.5%. On the other hand, we note that the four events above 20 MeV simultaneously observed by the Kamiokande-II group[3] also have polar angles in the range 15°–50°. Thus the angular distribution of both data samples must be considered somewhat puzzling.

The energies of the events have been recalculated, using two independent methods, and are listed in Table I. One method uses through-going cosmic-ray muons to calibrate the detector's energy response, while the other uses electrons from muons which stop and decay inside the detector. Based on the close agreement between these two methods, the systematic error in the energy determination is estimated to be 10% or less. The statistical errors on each of the event energies have also been calculated and listed in Table I. The "measured" energies given in Table I are the visible energies of positrons or electrons. If, as expected, the inverse-β-decay reaction is responsible for the events, then the antineutrino energies depend slightly on scattering angle. These energies are also listed.

Correcting the eight events for the trigger efficiency and 13% detector dead time during the burst, we estimate a total of 35 ± 15 events with neutrino energy above 20 MeV occurred in our 6800-m^3 detector. Standard theoretical supernovae calculations would indicate that our 20-MeV threshold is 5–10 MeV above the peak of the emitted neutrino spectrum.

Finally, although the absolute event times measured during the burst are only accurate to ±50 ms, the relative times of the events are good to ±0.5 ms. Therefore, the times of the events to the nearest millisecond are also given in Table. I.

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[1]R. M. Bionta *et al.*, Phys. Rev. Lett. **58**, 1494 (1987).

[2]Further details can be found in T. Haines, in *Neutrino Masses and Neutrino Astrophysics,* proceedings of the Fourth Telemark Conference, Ashland, Wisconsin, 1987, edited by V. Barger, F. Halzen, M. Marshak, and K. Olive (World Scientific, Singapore, 1987), p. 63.

[3]K. Hirata *et al.*, Phys. Rev. Lett. **58**, 1490 (1987).