Interpretation of events in underground detectors at 7 h 35 min UT on 23 February 1987

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The possibility of interpreting events in underground installations at 7 h 35 min UT on 23 February 1987 as the detection of neutrino fluxes from supernova SN1987A is discussed. That interpretation leads to several difficulties in reconciling the data from the Kamiokande-2 and IMB detectors and also in explaining the observed anisotropy of the interaction products.

Events whose simulation by the background is improbable were found at underground installations[1–4] on 23 February 1987. Events at the Kamiokande-2 (K2) and IMB detectors and at the Baksan scintillation telescope[2–4] were grouped around the time 7:35 UT and were interpreted by the authors as the interaction of $\tilde{\nu}_e$'s emitted in the outburst of supernova SN1987A in the Large Magellanic Cloud. The first two pulses of the 11 in the K2 detector were discussed in Ref. 4 as resulting from $\nu_e e$ scattering. Estimates of the total energy of the flux of neutrinos of all types ($\nu_{e,\mu,\tau}\tilde{\nu}_{e,\mu,\tau}$), E_ν^{tot}, which have been carried out in several papers (Refs. 5 and 6, for example), agree with the value $\sim 3\times 10^{53}$ erg, according to the assertions of the authors.

An analysis of the K2 event shows that the component which is linked with νe scattering in the neutrino interpretation might actually be more significant. On the other hand, an estimate shows that the number of detectable νe scattering events at $E_\nu^{\text{tot}} \sim 3\times 10^{53}$ erg should be substantially smaller than two. Let us examine these questions in more detail.

If the present understanding of the ν emission during gravitational collapse is correct, the observable effect[7,8] will be dominated by the interaction

$$\tilde{\nu}_e + p \rightarrow n + e^+ - 1{,}8\ \text{MeV}\,; \quad E_\nu \lesssim 50\ \text{MeV}\,. \tag{1}$$

The cross section for reaction (1) at $E_\nu \gtrsim 1.8$ MeV is[9]

$$\sigma(\tilde{\nu}_e p) = 2{,}43\frac{E_e}{m}\left[(E_e/m)^2 - 1\right]^{1/2}\times 10^{-44}\ \text{cm}^2\,, \tag{2}$$

where $E_e = T + m$ is the total energy of the positron, T is its kinetic energy, and m is the electron mass expressed in energy equivalent. If we ignore the recoil energy of the neutron, we find $T \approx E_\nu - 1.8$ MeV and the positron energy spectrum

$$n_{e^+}(T)dT \approx \frac{N_p\,dE_\nu}{4\pi R^2}\,n_{\tilde{\nu}_e}(E_\nu)\sigma(E_\nu), \tag{3}$$

where N_p is the number of free protons in the working material, $R \approx 52$ kpc $= 1.56 \times 10^{23}$ cm is the distance to SN1987A, and $n_{\tilde{\nu}_e}(E_\nu)dE_\nu$ is the $\tilde{\nu}_e$ energy spectrum. The spectrum of the positrons is bell-shaped with a maximum at[8] 1–20 MeV, so a large fraction of the positrons is detected at a detection threshold ~5–10 MeV.

The differential cross sections for the production of electrons with a kinetic energy in the interval $(T, T + dT)$ in νe scattering are[10]

$$\begin{aligned} \frac{d\sigma_\nu}{dT} &= 1.68\left[g_L^2 + g_R^2\left(1 - \frac{T}{E_\nu}\right)^2\right]10^{-44}\,\mathrm{cm}^2/\mathrm{MeV}^{-1} \\ \frac{d\sigma_{\tilde{\nu}}}{dT} &= 1.68\left[g_R^2 + g_L^2\left(1 - \frac{T}{E_\nu}\right)^2\right]10^{-44}\,\mathrm{cm}^2/\mathrm{MeV}^{-1}, \end{aligned} \tag{4}$$

where $E_\nu \gg m$. Here $g_R = \sin^2\theta_W \approx 0.23$, $g_L = 0.5 + \sin^2\theta_W$ for ν_e and $\tilde{\nu}_e$, and $g_L = -0.5 + \sin^2\theta_W$ for $\nu_{\mu,\tau}\tilde{\nu}_{\mu,\tau}$. The energy spectrum of the scattering electrons is

$$n(T)dT = \frac{N_e dt}{4\pi R^2} \sum_{\nu_i} \int_{E_{\min}}^{\infty} n_{\nu_i}(E_\nu)\, \frac{d\sigma_{\nu_i}}{dT}\, dE_\nu\,, \tag{5}$$

where N_e is the number of electrons in the working material, $\nu_i = \nu_{e,\mu,\tau}\tilde{\nu}_{e,\mu,\tau}$, and $E_{\min} \approx T$ at $E_\nu \gg m \approx 0.5$ MeV. The electron spectrum falls off sharply with increasing T, and at a detection threshold ~5–10 MeV a large fraction of the scattering electrons will not be detected.

The direction in which the e^- moves after the νe scattering deviates by no more than 5° from the direction of the neutrino's momentum. As an electron moves in water, it is scattered repeatedly, being deflected through an angle $\approx 28°$ on the average.[3] Consequently, despite the scattering in water, the angular distribution of the electron tracks retains an anisotropy.

To carry out some specific estimates, we adopted neutrino spectra from the model of Ref. 11 and assumed that these spectra do not change in the course of an outburst. Convolving spectra (3) and (5) with the response function of the K2 detector,[12] we find the expected magnitude of the effect in the installation. With $E_\nu^{\text{tot}} = 3 \times 10^{53}$ erg, the average number of detectable positrons would be $\overline{K}(e^+) \approx 5.3$ or 61% of the total number of interactions (1) expected in the K2 detector, $\overline{K}^{\text{tot}}(e^+)$. The average number of detectable νe scattering events would be $\overline{K}(e^-) \approx 0.46$ or 16% of $\overline{K}^{\text{tot}}(e^-)$. The scattering $\nu_{\mu,\tau}\tilde{\nu}_{\mu,\tau}$ would provide 7.5% of $\overline{K}^{\text{tot}}(e^-)$. We would have a ratio $\overline{K}(e^+)/\overline{K}(e^-) = 11.7$. If we appealed to other collapse models, which predict large $\tilde{\nu}_e$ fractions in the total flux of neutrinos (see Refs. 13 and 14, for example), we could reconcile $\overline{K}(e^+)$ with the K2 data. However, we would then have $\overline{K}(e^+)/\overline{K}(e^-) > 11.7$. In other words, the model of Ref. 11 leads to the greatest anisotropy in the angular distribution of the $e^\pm$ tracks (this is why that model was chosen).

Figure 1 shows the pulse heights and the track directions for the K2 events (Ref.

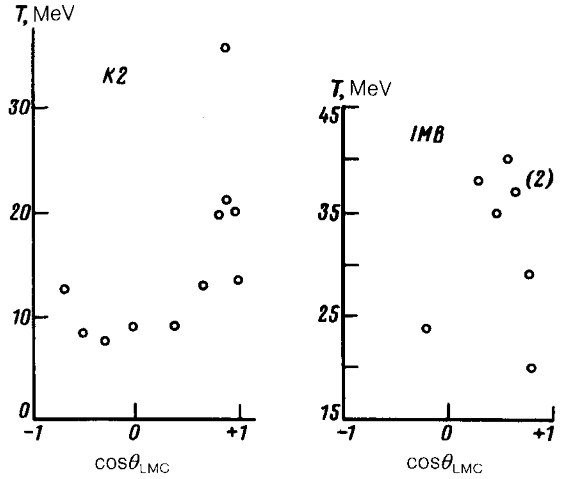

FIG. 1. Energies of the pulses and track angles in the K2 and IMB events.

4) and the IMB events.[3] As was pointed out in Refs. 15 and 16, the angular distributions of the tracks in these events do not agree well at all with the assumption of isotropy. An anisotropy might have been caused in the IMB detector because some of the photomultipliers were not working at 7:35, but an analysis[17] has shown that the changes turned out to be insignificant.

Let us assume that the K2 event consists of anisotropic and isotropic components, which on the average contribute $\overline{K}_{\rm an}$ and $\overline{K}_{\rm iso}$ events, respectively. We also assume that all the tracks of the anisotropic component lie within a cone with a vertex angle $\theta_{\rm LMC} = 60°$ (the axis of the cone is directed away from the Large Magellanic Cloud). The distribution of estimates ($\overline{K}_{\rm an}$; $\overline{K}_{\rm iso}$) follows from the expressions for the probability for obtaining five tracks of the isotropic component in the interval $-1 \leqslant \cos\theta_{\rm LMC} < 0.5$,

$$P_5 = \frac{(0.75\overline{K}_{\rm iso})^5}{5!} e^{-0.75\overline{K}_{\rm iso}}, \tag{6}$$

and the probability for finding six tracks of 11 with $0.5 \leqslant \cos\theta_{\rm LMC} \leqslant 1$,

$$P_{6,11} = C_{11}^6 p^6 (1-p)^5 , \tag{7}$$

where $p = (0.25\overline{K}_{\rm iso} + \overline{K}_{\rm an})/(\overline{K}_{\rm iso} + \overline{K}_{\rm an})$ is the probability for obtaining one track with $\cos\theta_{\rm LMC} \geqslant 0.5$. Figure 2 shows the boundaries of the 90% confidence region. At a 99% confidence level we have $\overline{K}_{\rm an} \geqslant 0.6$. The most probable estimates are $\overline{K}'_{\rm iso} \approx 6.7$; $\overline{K}'_{\rm an} \approx 4.3$.

If we work from a neutrino interpretation of the K2 events, we would naturally link the anisotropic component with νe scattering and the isotropic component with interactions (1), so we would have $\overline{K}_{\rm iso} = \overline{K}(e^+)$; $\overline{K}_{\rm an} = \overline{K}(e^-)$. It follows from an analysis of the data that the 95% confidence interval for $\overline{K}_{\rm an}/\overline{K}_{\rm iso}$ is $0.65 \pm ^{4.53}_{0.49}$. Comparing the boundaries of this interval with the value $\overline{K}(e^+)/\overline{K}(e^-) = 11.7$ found

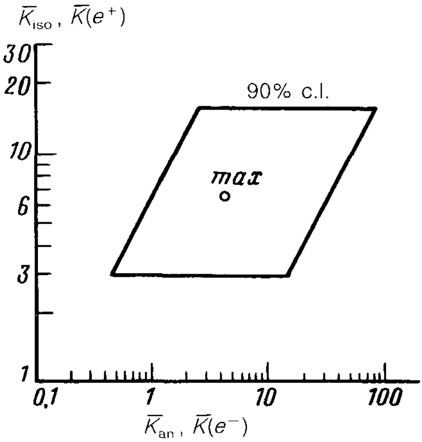

FIG. 2. Ninety-percent confidence region for the estimates of $\overline{K}_{\rm iso}$, $\overline{K}_{\rm an}$; max—most probable value ($\overline{K}'_{\rm an}$, $\overline{K}'_{\rm iso}$).

above, we arrive at the conclusion that the expected ratio does not agree with the experimental data even for the model of Ref. 11, which predicts the largest fraction of νe scatterings in the overall effect.

The energy spectra of the isotropic and anisotropic components of the K2 event do not agree well at all with the existing models of collapse.[18] In order to fit the experimental data, we would have to introduce "soft" ν_e and $\widetilde{\nu}_e$ spectra. The anisotropic component may be due entirely to $\nu_{\mu,\tau}e$ and $\widetilde{\nu}_{\mu,\tau}e$ scattering; if so, we would have $E_\nu^{\rm tot} \sim (5\text{–}6) \times 10^{54}$ erg.

Looking at the K2 and IMB data jointly, we find that the inconsistency which exists also makes a neutrino interpretation difficult. 1) Working from the K2 data, the detection efficiency, and the difference in the masses of working medium, we find an estimate of the number of interactions which should have been detected by the IMB detector: $\overline{K}_{\rm LMC} \approx 2.7$. Eight pulses were detected. The probability for a random fluctuation is $< 10^{-2}$. 2) Over the entire range $T \gtrsim 20$ MeV, the average angles are $\overline{\theta}_{\rm LMC}({\rm K2}) = 29^\circ 5 \pm 8^\circ 4$ and $\overline{\theta}_{\rm LMC}({\rm IMB}) = 59^\circ 8 \pm 20^\circ 5$. The angles of six of the eight tracks in the IMB event deviated from $\overline{\theta}_{\rm LMC}({\rm K2})$ by more than $20^\circ 5$. The probability for a random fluctuation is $< 10^{-3}$.

We thus see that a neutrino interpretation of the events at 7:35 UT runs into a series of difficulties. A random background fluctuation in several devices is extremely improbable, especially in view of the proximity of this event to the time at which SN1987A was observed. In our opinion, we should not limit ourselves to a single hypothesis regarding the reason for the operation of the devices. It may be necessary to study the effect of disturbances in the geomagnetic field on the count rate of the underground installations. Such a study would require a correlation analysis of the experimental data of the various installations over the entire time of their operation.

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