Events detected by underground detectors on February 23, 1987

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This report describes the principles of search for and detection of neutrino radiation from stars undergoing gravitational collapse. The authors describe the design and parameters of all underground neutrino detectors that were operational on February 23, 1987, and furnish a summary of experimental data from all working detectors on that day. The consistency of the experimental data from various detectors and the agreement with theoretical predictions are analyzed. The authors discuss whether the events registered by underground detectors on February 23, 1987, can be explained by neutrino radiation from the 1987A supernova.

1. GENERAL STATEMENT OF THE PROBLEM AND THE PRINCIPLES OF DETECTING NEUTRINO RADIATION FROM COLLAPSING STARS

The supernova flash (SN 1987A) in the Large Magellanic Cloud was detected on February 23, 1987.[1] According to current understanding, supernova ignition is preceded by a gravitational collapse. Zel'dovich and Guseinov[2] were the first to demonstrate that this process should be accompanied by a short, intense burst of neutrino radiation. The theory predicts that the total energy carried off by neutrinos of all types—ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$—corresponds to ~ 0.1 of the core mass and is divided about evenly between the six components of neutrino radiation.

The proposal of detecting stellar collapse by its neutrino flash was first advanced in Ref. 3. The most complete theoretical description of the collapse dynamics of nonmagnetic, nonrotating, spherically symmetric stars is available in Refs. 4–9, which contain the neutrino radiation characteristics of various collapse scenarios. Table I cites the typical calculated results for the simplest, most natural assumptions about the collapse process. The following reactions can be employed in the search for neutrino bursts emitted during stellar collapse:

$$\bar{\nu}_e + p = e^+ + n, \quad \sigma_{\bar{\nu}_e p} \approx 9.3 E^2_{e^+} \cdot 10^{-44}\ \text{cm}^2, \qquad E_{e^+} \gg 0.5\ \text{MeV}, \tag{1}$$

where E_{e^+} is the positron energy;

$$E_{e^+} = E_{\bar{\nu}} - 1.3\ \text{MeV},$$

$$\begin{aligned} &\nu_e + e^- = \nu_e + e^-, \quad \sigma_{\nu_e e^-} = 9.4 E_{\nu_e} 10^{-45}\ \text{cm}^2, \\ &E_{\nu_e} \gg 0.5\ \text{MeV}, \\ &\nu_i + e^- = \nu_i + e^-, \quad \sigma_{\nu_i e^-} = 1.6 E_{\nu_i} 10^{-45}\ \text{cm}^2, \\ &E_{\nu_i} \gg 0.5\ \text{MeV}, \end{aligned} \tag{2a}$$

$$\begin{aligned} &\bar{\nu}_i + e^- = \bar{\nu}_i + e^-, \quad \sigma_{\bar{\nu}_i e^-} = 1.3 E_{\bar{\nu}_i} 10^{-45}\ \text{cm}^2, \\ &E_{\bar{\nu}_i} \gg 0.5\ \text{MeV} \end{aligned} \tag{2b}$$

$$(i = \mu, \tau), \quad 0 < E_{e^-} \lesssim E_{\nu_i, \bar{\nu}_i, \nu_e}.$$

The scintillation or Cherenkov detector is filled with a hydrogen-containing material and weighs $\gtrsim 100$ tons. Scintillations from e^+ or e^- are monitored using photomultiplier tubes (PMTs). A neutrino burst is identified by a series of scintillations in the E_t—50 MeV amplitude range over a period T, where E_t is the threshold energy for detecting the scintillation and T is the duration of the neutrino burst (from several seconds to several tens of seconds, depending on the collapse model). All other conditions being equal, the number of scintillation pulses in the train is proportional to the detector mass and efficiency, and inversely proportional to the square of the distance to the star. Background pulse frequency fluctuations can imitate true events. The imitation frequency is

$$N_K(m, T) = \sum_{i=K}^{\infty} m \frac{(mT)^{i-1}}{(i-1)!} e^{-mT}, \tag{3}$$

where m is the frequency of background pulses; T is the duration of a pulse train; and K is the number of pulses in the train. Since the expected frequency of collapses in the Galaxy is once in 5–50 years, the imitation frequency should ostensibly be reduced below this value. In fact this constraint can be significantly relaxed, as we shall discuss below. Nonetheless, the suppression of the background is the major concern of experiments searching for stellar collapse.

To this end the detectors are buried deep into the earth and anticoincidence shielding is used. Still, even with a minimal background, fluctuations can imitate real events. Various malfunction effects are even more problematic. The frequency of the latter is impossible to predict or estimate and suppressing interference effects to the ~ 1 per year frequency range is probably unfeasible. Consequently, reliable collapse detection can be accomplished by several independent detectors working in parallel. Already two detectors can provide a reliable collapse registration, even if imitation frequency in each reaches ~ 100 per year. In this case an accidental coincidence could occur once in a 100 years. Similar considerations apply to parallel detectors registering other types of radiation—electromagnetic and gravitational—expected from supernova flashes.

2. NEUTRINO RADIATION DETECTORS

Currently, six detectors can register neutrino bursts from a stellar collapse. The parameters of these detectors are cited Table II. At the time of the SN 1987A flash two of these

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TABLE I.

Model	W_1, erg	W_2, erg	W_3, erg	$\bar{E}_{\bar{\nu}_e}$, MeV	$\bar{E}_{\nu_e}$, MeV	$E_{\nu_{\mu,\tau}}$, MeV	T, s
Ref. [6]	$(3—14)\cdot 10^{53}$	$(0.5—2.3)\cdot 10^{53}$	10^{52}	12.6	10.5	—	20
Ref. [8]				10	8	25	5

W_1 is the total energy of the flash transformed into all types of neutrinos; W_2 is the total energy carried off by ν_i, where $\nu_i = \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$; W_2 is the energy carried off by ν_e during the neutronization of the star in a time of 3×10^{-2} s; $\bar{E}_{\bar{\nu}_e}, \bar{E}_{\nu_e}, \bar{E}_{\nu_{\mu,\tau}}$ are spectrally averaged energies of $\bar{\nu}_e, \nu_e, \nu_{\mu,\tau}$ respectively; T is the duration of the neutrino flash.

were inoperative: ASD (scintillation detector of the Institute of Nuclear Physics of the USSR Academy of Sciences in Artemovsk) was in the process of modernization, while HSD (scintillation detector in Homestake) was involved in searching for magnetic monopoles and thus operated with a very high detection threshold. Of the four operating detectors, two were scintillation detectors (USSR and Italy) and the other two were Cherenkov (U.S. and Japan).

The effects predicted from reactions (1) and (2a), (2b) by the standard collapse model for a star in the Large Magellanic Cloud are summarized in Table III. In the case of LSD and BUST the effects are weak, because these detectors were designed for studying collapses in our Galaxy, i.e., their intended range was factor of five smaller than the distance to SN 1987A. From Table III we find that the main contribution is due to reaction (1). On the other hand, given favorable conditions, the reaction products of (2a) and (2b) detected by Cherenkov detectors could yield information on the initial stages of the collapse, when $\bar{\nu}_e$ are absent, and also determine the direction pointing to the neutrino radiation source.

We note that in all detectors $\nu_{\mu,\tau}e^-$-scattering effects are stronger than $\nu_e e^-$-scattering: first, the energies of $\nu_{\mu,\tau}$ are higher and, second, the experimental energy thresholds make it impossible to detect most electrons from $\nu_e e^-$-scattering since their spectrum falls off sharply at higher energies (see the sixth column of Table II). All detectors listed in Table II are multipurpose machines designed to detect penetrating radiation. This criterion determined their design parameters, which we shall discuss shortly.

The Baksan underground scintillation telescope (BUST)[10] contains 3130 liquid scintillator (LS) modules with total LS mass of about 330 tons. The telescope consists of a cube with ~14 m edges; each face contains 400 modules, with two more horizontal planes of 400 modules located inside the cube. The distance between the horizontal planes is about 3.6 m, the absorber thickness between them is ~170 $g\cdot cm^{-2}$. The modules are rectangular in shape, with dimensions of $0.7\times 0.7\times 0.3$ m^3. They are filled with a liquid scintillator based on the "white spirit" solution[11] (molecular composition—C_nH_{2n+2}, $\bar{n} = 10$). Each module is monitored by a single PMT with 15 cm photocathode diameter.

TABLE II.

Detector	Equivalent depth in water, m	Active mass (tons), material	Detection threshold, MeV	Detection efficiency		Background pulse frequency m, s^{-1}***
				e^+ spectrum, reaction (1)	e^- spectrum, reactions (2a),(2b)**	
ASD, USSR	570	105. C_nH_{2n+2}	5	0.97	0.45(0.75)	0.16
BUST, USSR	850	130(200) C_nH_{2n+2}	10	0.6	0.15(0.54)	0.013 (0.033)
LSD, USSR–Italy	5200	90 C_nH_{2n+2}	5—7	0.9	0.4(0.7)	0.01
HSD, U.S.	4200	140 C_nH_{2n}	10	0.6	0.15(0.54)	
KII, Japan–U.S.	2700	2140 H_2O (1540) *)	7—14	0.7	0.17(0.54)	0.022
IMB, U.S.	1570	5000 H_2O (3600) *)	20—50	0.1	0.02(0.18)	$3.5\cdot 10^{-6}$

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*Equivalent mass of C_nH_{2n+2} scintillator with respect to reaction (1) shown in brackets.

**Detection efficiency for the spectrum of electrons produced by reaction (2b): $\nu_{\mu,\tau} + e^- \to \nu_{\mu,\tau} + e^-$.

***Background in the $E_1 - 50$ MeV energy range; for Cherenkov detector the background refers to the detection of internal events.

TABLE III.

Detector	K_{e^+} (1)	K_{e^-} [(2a) + (2b)]	K_{e^-} (2b)
LSD	1.5	0.043	0.024
BUST (200 tons)	2	0.052	0.036
KII	17	0.53	0.36
IMB	6	0.4	0.35

The sensitivity of these modules is high, with an energy evolution of 1 MeV corresponding to a signal amplitude of ~40 photoelectrons at the PMT photocathode.

In order to reduce the background, the collapse search program involved using five external faces of the cubic telescope (the four vertical faces and the upper horizontal one) for anticoincidence shielding. The active volume consisted of three horizontal planes—the two internal ones and the lower horizontal face, containing some ~40% of the total active mass of the detector. The amplitude and time of the pulses are monitored by computer.

The cellular structure of BUST permits additional background suppression if anticoincidence schemes are used to select events in the working volume. For the same reason, the threshold to register energy emission in a module was set at the relatively high value of 10 MeV. Finally, the analysis discards those modules which have the highest monitored counting rate at a given moment. This last condition suppresses the background contribution arising from the spontaneous PMT instabilities. All these measures combined reduce the background to ~0.013 s^{-1}.

In analyzing the 23/2/87 data, the authors relaxed the suppression of the background somewhat in order to increase the working volume of the detector. Due to this measure the working volume increased to 200 tons, while the mean background counting rate rose to 0.033 s^{-1}.

The liquid scintillation detector LSD[12] consists of 72 modules positioned in a three-story parallelepiped with a 6×7 m^2 base and 4.5 m height. In order to reduce the effects from natural radioactivity it is shielded by steel plates with a total mass of some 200 tons. This detector also uses a liquid scintillator based on the "white spirit" solution[11]; the total scintillator quantity reaches 90 tons. Each module has the shape of a $1.0\times 1.5\times 1.0$ m^3 rectangular parallelepiped and is monitored by three PMTs with 15 cm photocathode diameters. Energy evolution of 1 MeV inside a module produces a summed signal amplitude of ~15 photoelectrons from the three PMTs. The energy evolution in the module is analyzed only when the signals from the three PMTs coincide with 200 ns resolution. The pulse from a coincidence circuit in any of the 72 modules triggers the entire detector. A computer then records the amplitude and time of the energy evolution in all 72 modules.

The high sensitivity and low background of this detector make it possible to register both e^+ and n in reaction (1). The neutrons are moderated by the scintillator and captured by hydrogen in a time of 170 μs. This reaction produces a deuteron and a γ-ray. The γ-ray scintillations ($E_\gamma = 2.2$ MeV) are registered in a low-threshold window (0.8 MeV threshold) which is opened for 500 μs by the positron pulse. The efficiency of detecting a neutron in the same module as the positron reaches 40–50%; when the adjacent modules are considered the neutron detection efficiency increases to 75–80%. This method was first proposed and realized by the designers of the Artemovsk scintillation detector (ASD; see Table II).[13]

The Kamiokande II (KII) Cherenkov detector[14,15] consists of two coaxial cylinders. The outer cylinder has a diameter of 19.6 m and a height of 22.5 m, the inner has a diameter of 15.6 m and a height of 16 m. The detector is filled with water that is constantly purified in a closed cycle system. The mean free path for the absorption of Cherenkov radiation is approximately 45 m. Cherenkov radiation is registered by PMTs with 50 cm photocathode diameters. The water layer between the cylinder walls is monitored by the PMTs and acts as both active and passive shielding. The inner cylinder contains 2140 tons of water. About 900 PMTs are distributed uniformly on the interior surface with a step size of ~1 m; the total area of the photocathodes makes up ~20% of the cylinder surface. We know that a relativistic, singly charged particle traveling through water emits ~200 photons/cm into a cone angled ~40° from the propagation direction. This radiation is projected onto the sidewalls in the shape of a ring whose thickness is approximately equal to the mean free path of the radiating particle. A 10 MeV electron produces a signal amplitude of ~30 photoelectrons. The detector is triggered when more than 20 PMTs register a signal during a 100 ns time window. The information on the amplitude and time of the signal in each PMT is then fed into the computer. An analysis of this information, based on the position of the signaling PMTs, makes it possible to determine the energy evolution, vertex, and trajectory angle of the radiating particle. The accuracy of this analysis for near-threshold energies is a strong function of the energy, spatial position and orientation of the trajectory—the accuracy suffers near the walls. The scientists at KII believe they can register 8.5 MeV and 14 MeV electrons with efficiencies of 50% and 90% respectively over the entire detector volume. The triggering rate is 0.6 Hz, of which 0.37 Hz is reliably attributed to cosmic ray muons and the rest is due to natural radioactivity. A computer analysis of the events, based on the time and position of the PMT signals, indicates that the intrinsic experimental background is ~0.022 s^{-1} for electrons in the 8.5–50 MeV range.

The large IMB (Irvine–Michigan–Brookhaven) Cherenkov detector[16] consists of a $22.5\times 17\times 18$ m^3 rectangular parallelepiped filled with purified water. The working volume of 5000 m^3 is monitored by 2048 PMTs with 20 cm photocathode diameters. The PMTs are evenly distributed on the six detector faces with a step size of ~1 m. The detector is triggered by 25 PMTs signaling in a 50 ns window. The information on the time and amplitude of the signal in each PMT is then analyzed by a computer. The analysis determines the energy, vertex, and propagation direction of the particle. A 20 MeV electron produces a signal amplitude of ~20 photoelectrons. The largest errors in this analysis occur for particles near the detector walls. The detection efficiency depends on the energy: for 20, 30, and 50 MeV electrons it is 14%, 56%, and 89% respectively. Cosmic ray muons trigger the detector with ~2.7 Hz frequency—they are identified by the fact that these particles enter the detector through one of the walls. The particles whose vertex lies inside the working volume constitute the experimental background, with a counting rate of ~0.3 per day.

3. OBSERVATION RESULTS

Figure 1 illustrates the sequence of events recorded by the various detectors on February 23, 1987. The observation results are cited in the vicinity of 2:52 UT and 7:36 UT times.

3.1. Optical observations

The first optical observation of the SN 1987A supernova in the Great Magellanic Cloud, located ~52 kpsec from Earth, occurred at 10:40 UT.

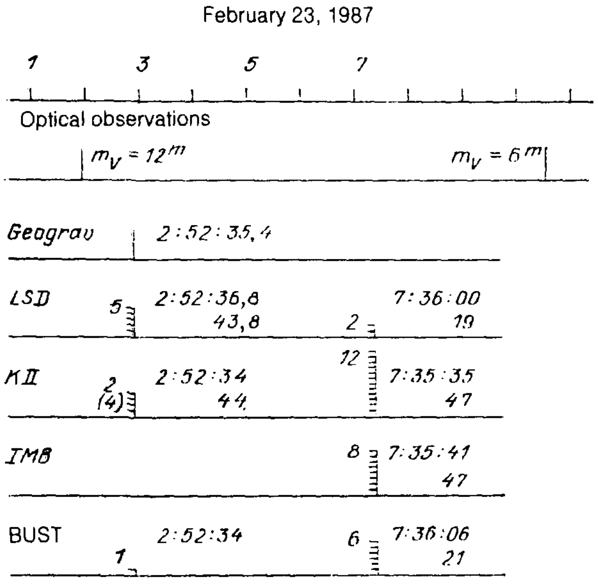

FIG. 1. Temporal sequence of effects registered by the various detectors on February 23, 1987.

3.2. Room-temperature gravitational antenna in Rome

(Geograv)[17]

According to current understanding, nonsymmetrical collapse or supernova explosion must be accompanied by gravitational radiation. When the data from the gravitational antenna in Rome were juxtaposed with the events recorded by the LSD detector during the SN 1987A supernova flash, the analysis indicated an approximately sixfold increase in the energy flux with respect to the noise floor at 2:52:25.4 ± 0.5 s UT. This preceded by 1.4 ± 0.5 s the first of the five pulses recorded by LSD. The authors of Ref. 17 claim that no electromagnetic or magnetic disturbances had occurred at that time. The background imitation frequency for the given sequence of events is once every 2 hours.

3.3. LSD[18a,19] (Table IV).

TABLE IV.

Event No.	Time, UT ± 2 ms*	Energy,** MeV
1	2 : 52 : 36.79	6.2
2	40.65	5.8
3	41.01	7.8
4	42.70	7.0
5	43.80	6.8
1	7 : 36 : 00.54	8
2	7 : 36 : 18.88	9

*Uncertainty in experimental time with respect to UT.

**E is the energy evolution in the module. In the detection of the $\tilde{\nu}_e p \rightarrow e^+ n$ reaction the measured energy corresponds to the positron energy plus the energy of the annihilation γ-ray, $E\gamma = 1$ MeV, $E = E_{e^\pm} + 1$ MeV. The E values in this table differ from those previously reported [Ref. 18a] because of improved calibration [Ref. 18b]. The calibration precision is approximately 20%. The No. 3 event was accompanied by a neutron-like pulse of approximately 1.4 MeV energy and 278 μs delay time. Events No. 2, 4, 5 were detected in the internal modules with low intrinsic background.

3.4. KII[15] (Table V).

TABLE V.

No.	Time, UT ± 1 min*	E, MeV	θ, deg**
1 ***)	2 : 52 : 34	5.3	59
2	37	5.8	47
3	40	11.4	15
4	2 : 52 : 44	4.8	130
1	7 : 35 : 35.0	20.0±2.9	18±18
2	35.107	13.5±3.2	15±27
3	35.303	7.5±2.0	108±32
4	35.324	9.2±2.7	70±30
5	35.507	12.8±2.9	135±23
6	35.686	6.3±1.7	68±77
7	36.541	35.4±8.0	32±16
8	36.728	21.0±4.2	30±18
9	36.915	19.8±3.2	38±22
10	44.219	8.6±2.7	122±30
11	45.433	13.0±2.6	49±26
12	7 : 35 : 47.439	8.9±1.9	91±39

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*Uncertainty in experimental time with respect to UT.

**Angle with respect to the vector pointing at the Large Magellanic Cloud.

***The data on the four pulses near 2:52:34 UT were furnished by Hirata and co-workers [Ref. 15] in their report at the Neutrino Mass and Neutrino Astrophysics conference [Ref. 20] and subsequently reproduced in preprint [Ref. 21].

3.5. BUST[22] (Table VI).

TABLE VI.

No.	Time, UT $^{-54s}_{+2s}$*	E, MeV
1	2 : 52 : 34	10,8
1	7 : 36 : 06.571	17.5±3,5
2	11.818	12±2,4
3	12.253	18±3,6
4	13.528	23.3±4.7
5	19.505	17±3,4
6	7 : 36 : 20.917	20.1±4,0

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*Uncertainty in experimental time with respect to UT. In analyzing the data at 7:36 UT the working mass of the detector was increased from 130 to 200 tons, increasing the background pulse counting rate to 0.033 s^{-1}.

3.6. IBM[16] (Table VII).

TABLE VII.

No.	Time, UT ± 50 ms*	E, MeV**	θ, deg**
1	7 : 35 : 41 : 37	38	74
2	41.79	37	52
3	42.02	40	56
4	42.52	35	63
5	42.94	29	40
6	44.06	37	52
7	46.38	20	39
8	7 : 35 : 46.96	24	102

No pulses with vertices internal to the detector were observed in or near the 2:52:37–2:52:44 time interval.

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*Uncertainty with respect to UT.

**Energy measurement precision ± 25%.

***Angle with respect to the vector pointing at the Large Magellanic Cloud. Angle measurement precision ± 15°.

4. ANALYSIS AND INTERPRETATION OF EXPERIMENTAL RESULTS.

Since the effects recorded by the detectors are quite weak, the energy and angular distribution characteristics of the pulses have little statistical confidence, which hinders the analysis and comparison of these characteristics. For this reason a number of foreign and Soviet authors have ignored the distribution characteristics to a greater or lesser extent.[27,28,30] The ostensible motivation for this is that given the small number of events there exists no reliable method of estimating the probability of occurrence of the measured pulse combinations. We note that the information which contradicts the theory is the one usually ignored, in this case the angular distributions of the pulses. At the same time, the authors do analyze the energy distributions, which appears inconsistent at the very least, since the statistical confidence is the same for both the energy and angular distributions. We believe that all neutrino detector information relevant to the SN 1987A supernova flash should be considered and analyzed in full. In this section we shall attempt such an analysis, despite its difficulty and susceptibility to criticism.

The events registered by neutrino detectors on February 23, 1987, are grouped near two moments in time: 2:52 UT and 7:35 UT. The frequency with which an event can be imitated by a background fluctuation is listed in Table VIII for each detector.

The numbers were obtained from formula (3) or a similar expression (in all cases it was assumed that the fluctuations obey Poisson's law). Such an approach is indisputable, as long as the parameter m in formula (3) is experimentally determined over a period comparable to the expected interval between imitations. This is indeed the case for the LSD and BUST detectors: over their working spans (about 2 and 5 years respectively) the experimental values of $N_K(m,T)$ agree with the Poisson distribution. The scientists at KII and IMB, on the other hand, extrapolated the results of formula (3) to periods that exceed the time of the experiment by many orders of magnitude, thus obtaining rather low expected imitation frequencies for the recorded events. We believe this extrapolation to be unwarranted. Until the authors perform the appropriate analysis, the experimentally justified imitation frequencies are $\leqslant 0.25$ per year and $\leqslant 0.4$ per year for IMB and KII respectively (since over the 4 and 2 year working spans of these detectors no such effects have been observed).

The coincidence of the neutrino detector effects with the visual observation of the supernova flash is an important factor. Due to uncertainty in the theoretical models, we can state that the collapse precedes the visually observed flash by no more than 24 hours. For any of the three detectors—LSD, KII, and IMB—a coincidence in this time window reduces the probability of a random events by a factor of 1/365, i.e. a spurious coincidence of this type occurs no more than once in 10^3 years. For the BUST detector, where the imitation frequency is ~ 1 per day, the coincidence with the supernova flash in a 24 hour time window is a trivial result. Thus, the events recorded by LSD, KII, and IMB are significant and should be given equal weight, whereas the BUST event is nontrivial only in conjunction with data from other neutrino detectors.

TABLE VIII.

Detector	Imitation frequency, year^{-1}		
	2 : 52 UT	7 : 35 UT	
		From formula (3)	Experimental
LSD	< 0.3		
BUST		120	120
KII		10^{-7}	$\leqslant 0.4$
IMB		$3\cdot 10^{-30}$	$\leqslant 0.25$

If the events are caused by neutrino radiation, several necessary but by no means sufficient conditions must be satisfied: 1) the pulse amplitudes should have an upper limit of ~ 50 MeV; 2) the interaction points should lie inside the detector and be uniformly distributed throughout the target mass; 3) the angular distribution of ionizing particles should be isotropic when measuring the inverse β-decay (in some cases, in addition to e^+ one can observe the neutron by its hydrogen capture—see description of the LSD experiment above); 4) when measuring the elastic neutrino scattering by electrons the angular distribution of the ionization particles should be anisotropic, with a strong peak along the incident direction of the neutrino. If the events recorded by several detectors are caused by the same neutrino burst, the following additional conditions come into play: 5) the events should be simultaneous within the limit of ordinary fluctuations which occur during the detection of the individual pulses in a group; 6) the signal should be proportional to the detector mass M_i and the detection efficiency $\varkappa_i$ of the appropriate neutrino interaction, i.e., $k_i \sim \varkappa_i M_i$ (i is the index labeling one of the four detectors); 7) the energy spectra $k_i(E)$ of the pulses are identical when normalized with respect to the detector efficiency $\varkappa_i(E)$; 8) the angular distributions $k_i(\theta)$ of the pulses are identical among detectors that register the same type of interaction.

Let us now examine how the discussed events satisfy conditions 1–8. The data from all four detectors satisfy or at least do not contradict conditions 1–4, within the limits of detector capabilities. Only the obviously anisotropic angular distribution in the IBM, which is simultaneously too broad for the $(\nu e^-) \to (\nu e^-)$ reaction is problematic, as acknowledged by the IBM scientists (see Fig. 2,b). The angular distribution of the KII event is shown in Fig. 2,a. We find that for $E > 12$ MeV, 6 of the 7 pulses have an angle $\theta < 60°$ with respect to the source vector. If the distribution is isotropic, the probability of such a fluctuation is $\sim 10^{-3}$. The angular distribution of the other five pulses with $E < 12$ MeV is isotropic.

Now let us proceed to analyze the response of the set of detectors to the same neutrino flash. We note that, at least in principle, the star's rotation and magnetic field could result in a two-step collapse with two neutrino bursts, separated by several hours.[21,23–25] This justifies treating the events at 2:52 UT and 7:36 UT as arising from two separate neutrino bursts.

First, consider the events near 2:52 UT. A strong effect is measured by LSD only: $k_1 = 5$, $T = 7$ s. Recall that in measuring inverse β-decay LSD detector registers the neutron as well as the positron. However, the small number of interactions making up the event makes it difficult to identify the neutrons because of the background in the neutron channel. A preliminary analysis indicates that the neutron channel contains pulses that can be assigned with equal

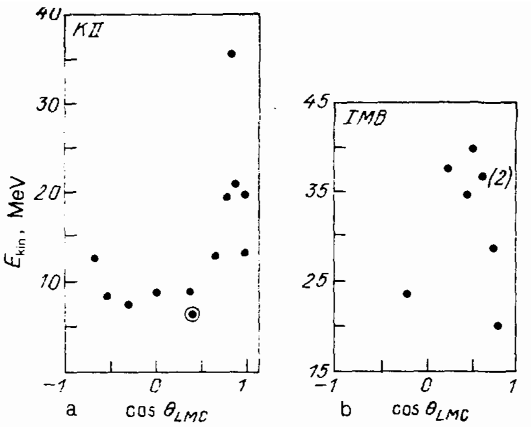

FIG. 2. Energy E as a function of the incident angle $\theta_{\rm LMC}$ for particles detected KII (a) and IMB (b) detectors.

probability either to actual neutrons or to the background. In this regard the LSD event does not contradict the detection of inverse β-decay. In all other detectors we expect

$$k_i = \sum_{j=1}^{5} \frac{M_i}{M_1} \frac{\varkappa_i (E_j - 1)}{\varkappa_1 (E_j)}, \qquad (4)$$

where M and $\varkappa_1$ are the target mass and efficiency of the LSD detector; E_j is the energy (in MeV) of the five events in the LSD; $i = 2,3,4$ refer to BUST, KII, and IMB respectively. Expression (4) is valid if the LSD effect is caused by the inverse β-decay reaction, which produces a positron. The (e^+e^-) annihilation energy of about 1 MeV is easily detected by the large scintillation modules of the LSD, markedly worse by the smaller BUST modules, and practically not at all by KII and IMB. Consequently, a flux of monoenergetic $\bar{\nu}_e$ evolves 1 MeV more energy in the LSD than in BUST, KII, or IMB. Taking this into account, $\varkappa_2 \approx \varkappa_4 \approx 0$ and the expected in BUST and IMB is zero. In KII one would expect $k_3 \approx 5$–7 (we note that the cited efficiency $\varkappa_3$ at 5–6 MeV energy is far from accurate[20]). We see in Fig. 3 that this detector registered 2 to 4 pulses, which is consistent with the LSD data. The uncertainty in the number of pulses is related to the method of matching the KII time scale with the universal time. The amplitudes of these pulses were 5.3, 5.8, 11.4, and 4.8 MeV. The scientists at KII believe these pulses arose from the background; their θ values are listed in Table V. Thus the events at 2:52 UT do not contradict any of the conditions 5–8.

Now consider the events near 7:36 UT. At that time two significant effects were observed: in KII ($k_3 = 11$, $T = 13$ s) and IMB ($k_3 = 8$, $T \approx 6$ s). These effects did not coincide in

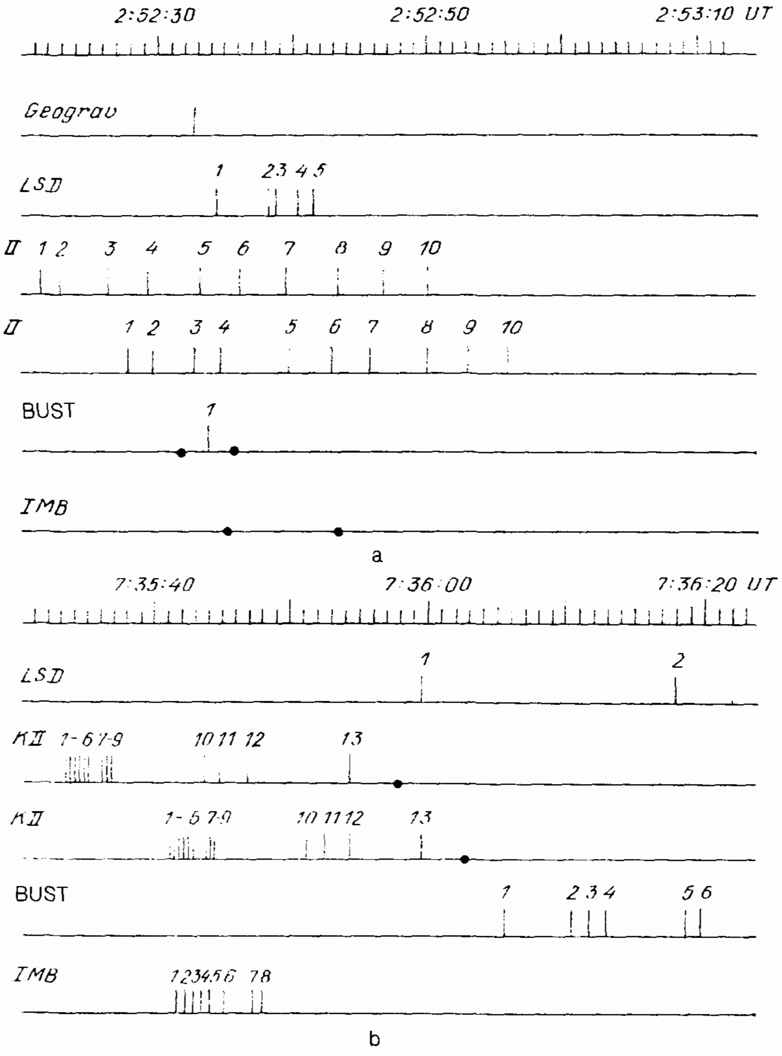

FIG. 3. Temporal diagrams of pulses registered by the various detectors near 2:52 UT (a) and 7:36 UT (b). The KII results are shown twice (see II): first, as recorded; second, shifted to the right by 6.5 s.

time. In order to bring them into coincidence the KII time scale must be shifted to the right by approximately 6.4 s, as illustrated in Fig. 3. The ± 1 min uncertainty in matching the KII experiment time scale to the universal time makes such an adjustment possible. We stress, however, that this "manually" adjusted simultaneity only dispels the arguments against, but provides no solid evidence for the reliability of this neutrino burst detection. All of the above also applies to the simultaneity of the IMB and BUST detectors. The BUST data must be shifted by at least 25 s for temporal coincidence, as long as one considers all 6 pulses recorded near 7:36 UT. We believe that discarding one pulse in the data analysis is unwarranted.[22] Thus we find that the effects in KII, IMB, and BUST do not contradict condition 5, within the scope of the discussed caveats.

On the basis of the time-shifted KII effect we can calculate the expected number of events in all other detectors from a formula analogous to (4). The results are: $\bar{k}_{1,\text{calc}} = 1.22$, $\bar{k}_{2,\text{calc}} = 0.98$, and $\bar{k}_{4,\text{calc}} = 2.70$ respectively for LSD, BUST, and IMB. The experimental data, shown in Fig. 3, are $k_{1,\text{exp}} = 1$, $k_{2,\text{exp}} = 6$, and $k_{4,\text{exp}} = 8$. In the case of the LSD, the probability of observing $k_{1,\text{exp}} \leqslant 1$ given $\bar{k}_{1,\text{calc}} = 1.22$ is $P_1(\leqslant 1, \bar{k}_{1,\text{calc}} = 1.22) \approx 0.3$, i.e. the experimental data do not disagree with the predicted KII effect. For the BUST and IMB detectors, however, we obtain $P_2(\geqslant 6, \bar{k}_{2,\text{calc}} = 0.98) \approx 0.001$ and $P_4(\geqslant 8, \bar{k}_{4,\text{calc}} = 2.7) \approx 0.01$ respectively. Thus, the effects in BUST and IMB are inconsistent with the magnitude of the KII effect and condition 6 does not obtain.

Regardless of which spectrum, the KII or the IMB, is taken as the starting point, the spectrum calculated for the other detector via a formula analogous to expression (4) is in poor agreement with the experiment. The probability that this discrepancy is caused by a fluctuation is $(1\text{–}5)\cdot 10^{-2}$. Accordingly, condition 7 is satisfied poorly by the KII and IMB effects.

In order to compare the angular distributions, we calculated $\bar{\theta}$ and the mean-square data point scatter for $E \gtrsim 19$ MeV. There are four such points in KII and eight in the IMB. We obtained $\bar{\theta} = 25°$, $\sigma = 7°$ and $\bar{\theta} = 60°$, $\sigma = 20°$ respectively. If the IMB distribution is taken as normal, with $\bar{\theta} = 60°$ and $\sigma = 20°$, then the probability that the four KII points deviate to one side by more than one standard deviation is $P \sim (0.17)^4 \sim 10^{-3}$. Hence the angular distributions of the KII and IMB effects disagree and condition 8 is violated.

Regardless of any assumptions about the neutrino radiation source, our simple analysis leads to the following conclusions:

a) the effects near 2:52 UT do not contradict the detection of a neutrino radiation burst;

b) taken separately, the effects near 7:36 UT in either of the BUST, KII, or IMB detectors do not contradict the registration of a neutrino radiation burst, but the consistency of these effects is poor.

Our analysis is intended largely as a simple illustration, especially the section concerning the consistency of energy spectra. More accurate calculations, employing various types of neutrino spectra allowed by current models of stellar collapse, have been carried out by a number of authors,[30–36] who arrived at the same conclusion that the data are contradictory.

We have already indicated in our analysis of the experimental results that the effect in any one of the four detectors could have been due to a neutrino burst. Let us discuss the possible source of the neutrinos. Generally speaking, the effects are similar to those expected from a gravitational stellar collapse. Consequently, one would try to connect these effects with the SN 1987A supernova flash, the more so since their temporal consistency is obvious.

Consider the effects near 2:52 UT. If we assume that these events were caused by antineutrino radiation emitted during stellar collapse, the emission spectra of neutrino radiation should be quite soft, corresponding to a neutrinosphere temperature $kT \sim 2$ MeV. The neutrino and antineutrino spectra can be approximated by a distribution similar to the Fermi–Dirac result[6]

$$\Phi_{\bar{\nu}}\,(\text{c}^{-1}\text{MeV}^{-1}) \sim \frac{\varepsilon^2}{1+e^{\varepsilon}}\,e^{-\alpha\varepsilon^2} \quad \left(\varepsilon = \frac{E_{\bar{\nu}}}{kT}\right), \tag{5}$$

where $E_{\bar{\nu},\nu}$ is the energy of $\bar{\nu},\nu$ in MeV; kT is the effective neutrinosphere temperature in MeV; and the $e^{-\alpha\varepsilon^2}$ factor accounts for the spectral attenuation as neutrino radiation traverses the star.

Within this framework, Table IX lists the energies of antineutrino radiation for two values of kT normalized with respect to the LSD detector. The neutrino source $W_{\bar{\nu}_e}$ is taken to be 52 kpsec distant. The magnitude of the expected effects in the four detectors is also given.

Comparing these estimates with the experimental data (see Fig. 3) we find that the observed effects are consistent with the expected values. If all types of neutrinos are counted, the total neutrino radiation energy of the SN 1987A star turns out to be approximately $6W_{\bar{\nu}_e} \approx (1\text{–}2)\cdot 10^{55}$ erg, i.e. an order of magnitude higher than the gravitational binding energy of a neutron star. In this particular model, given the detector parameters, the contribution of reaction (2) to the observed effects would not exceed several percent in any of the four detectors.

On the other hand, if we abandon our models and estimate the energy of the source 52 kpsec away on the basis of the LSD effect only (5 pulses of inverse β-decay, caused by a burst of neutrinos with an average energy of 7.5 MeV), we obtain $W_{\bar{\nu}_e} = (6.4 \pm 3.2)\cdot 10^{53}$ erg and the terrestrial flux density $J_{\bar{\nu}_e} = (9.5 \pm 4.7)\cdot 10^{10}$ cm^{-2}.

TABLE IX.

kT, MeV	α	$W_{\bar{\nu}_e}$, 10^{54} erg	k_i			
			LSD	BUST	KII	IMB
1.7	0.1	2.7±1.0	5	0.2	5±2.5	0
2.1	0.1	1.8±0.8	5	0.5	12±6	0

TABLE X.

Detector	Expected k_i		Experimental k_i
	Reaction (1)	Reaction (2)	
LSD	1.5	0.04	0—1
BUST	2	0.05	6
KII	17	0.5	12
IMB	6	0.4	8

Now consider the effects near 7:36 UT. Table X contains the actual and expected numbers of pulses in the group for each detector. The expected values are obtained from the standard collapse model[6] ($W_{\bar{\nu}_e} \sim 10^{53}$ erg, $kT = 4.6$ MeV, $\alpha = 0.024$, $R = 52$ kpsec) and the detector parameters. Since the contribution of reaction (2) does not exceed several percent, the entire effect is determined by the inverse β-decay reaction.

At first sight it appears that the experimental values agree with the theoretical predictions wherever significant effects were observed—that is, in the KII and IMB detectors. Yet this agreement could prove illusory. In the preceding section we have demonstrated that half the events registered by KII were sharply anisotropic and hence could in no way be ascribed to inverse β-decay. This applies to all events with energy evolutions of more than 12 MeV. The events registered by IMB were also anisotropic. We shall now discuss how this situation could possibly be explained by ascribing the anisotropic events to neutrino scattering by electrons.[38] Indeed, consider the KII effect and the events concentrated near the vector pointing at the Large Magellanic Cloud (LMC). These events number 5 out of 12 and they have an average energy of approximately 22 MeV. The other 7 events are isotropic and have an average energy of approximately 7 MeV. We can ascribe the former events to electron scattering and the latter to inverse β-decay. Here it becomes necessary to assume that the effective neutrinosphere temperature for $\bar{\nu}_e$ is 2.2 MeV. Since the energy of the anisotropic events is high, they can only be ascribed to $\nu_{\mu,\tau}e^-$ scattering, given that $kT \approx 8$–9 MeV for ν_μ, ν_τ. These assumptions do make it possible to accommodate the energy spectra for the anisotropic KII and IMB events (all IMB events are then ascribed to electron scattering, notwithstanding their excessive angular distributions). However, the resulting neutrino radiation energy now exceeds the standard collapse value by almost an order of magnitude. In this scenario the full neutrino luminosity reaches approximately $6 \cdot 10^{54}$ erg and hence the supernova energetics fares almost as poorly in explaining the 7:36 UT effects in KII and IMB as in explaining the 2:52 UT effect in LSD. Note also that ascribing the pulse registered by the Rome antenna at 2:52 UT on 23/2/87 to the SN 1987A supernova flash places its energy at least hundreds of times above the gravitational radiation emission predicted by the standard collapse model. Clearly, interpreting the effects observed by detectors on 23/2/87 in terms of neutrino or gravitational radiation from a stellar collapse in the LMC runs into severe problems. First, the energy of the neutrino radiation exceeds the binding energy of a neutrino star by at least an order of magnitude. Moreover, we have no adequate explanation for the "two-step" collapse (2:52 UT and 7:36 UT) or the discrepancies in the 7:36 UT data from three detectors. In discussing the detection of neutrino radiation from SN 1987A, many authors follow Ref. 27 in proposing that, given the small number of detected events, the greatest weight should be given to integral characteristics: total number of events; dependence of the total number of detected pulses on time; and the stellar energy carried off by neutrinos. This position is difficult to gainsay, but the majority of the authors explain the entire effect by $\bar{\nu}_e p$ interaction, ignoring the angular distributions. Then the energetics of the KII and IMB events becomes reasonable, $W_{\bar{\nu}_e} \sim 10^{53}$ erg, the temporal characteristics turn out as expected, and the total number of detected events also matches the theoretical estimates. As a result it is claimed that the events recorded by the IMB and KII detectors support the theoretical model. Yet the theory of the late stages in stellar evolution, including the last hours of a star, is far from complete. The behavior of rotating stars with magnetic field remains to be computed. Thus it appears dubious that the first detection of neutrino radiation from a remote collapsing star should "corroborate" very incomplete calculations.

Another series of papers[34–37] analyzes the full data, but in order to reduce the energy of neutrino radiation the authors either propose some flux of high-energy electron neutrinos or neutrino oscillations between ν_μ and ν_e.

We believe that further efforts are required to interpret the experimental results.

5. LIMITS ON THE NEUTRINO REST MASS

If we assume that the effects discussed in this review are due to neutrino radiation from a stellar collapse in the LMC, we can evaluate the neutrino rest mass using a simple principle originally proposed by Zatsepin.[26] If two neutrinos of energy E_1 and E_2 are emitted together and travel the same distance d, at the end of their journey they will be separated by a time interval Δt. Knowing all these quantities the neu-

TABLE XI.

Reference	Limit on m_ν, eV	Experiment
[25]	7.8^{+4}_{-3}	KII pulses 1—6 (Table V)
[27]	6.5	» 1—6
[28]	9.5	» 1—8
[29]	4 ± 1	» 1—6
[25]	20^{+9}_{-7}	KII pulses 7–11 (Table V)
[29]	24	IMB pulses (Table VII); KII pulses 7–11 (Table V)
[17]	7.2	LSD, delay with respect to pulse observed at the Rome antenna.

trino rest mass can be calculated as follows:

$$m_\nu = E_1 \left[\frac{2c\, \Delta t E_2^2}{d\,(E_2^2 - E_1^2)} \right]^{1/2}; \tag{6}$$

given that $m_\nu \ll E_1 < E_2$; c is the speed of light.

Actually, the finite duration of the neutrino burst means the start time of the neutrinos is smeared over several seconds. Consequently, the duration of the observed effects T or, sometimes, the "fine structure" of the group of pulse (see Fig. 3) can be used only to place an upper limit on m_ν. Such estimates have been carried out by a number of authors.[17,25,27–29] The results are summarized in Table XI. These results place an upper limit on the rest mass of the electron neutrino under the assumption that all detected events are due to inverse β-decay. In view of the preceding section, however, we should keep in mind that these estimates may actually hold for some aggregate of electron, muon and τ-neutrinos.

6. CONCLUSIONS

a) Three neutrino detectors located at the opposite ends of the earth, LSD, KII, and IMB, detected short pulse trains on February 23, 1987. Each of these pulses satisfied all the detection criteria for neutrino interaction inside the detector. No such pulse packets had been observed previously during the operational life of these detectors, ranging from 2.5 to 4 years. Several hours later astronomers visually observed a supernova flash in the Large Magellanic Cloud. A random correlation of these effects in either of the three detectors is expected less than once in a thousand years.

b) The interpretation of the 23/2/87 effect in either of the three detectors as the detection of neutrino radiation from a gravitational collapse that produced the supernova in the LMC is fraught with great difficulties within the framework of current collapse theories.

c) We believe that these difficulties cannot be avoided by explaining away from some fraction of the experimental data (data from one of the detectors, nonsimultaneity of events in various detectors, discrepancies in angular and energy distributions in various detectors) by statistical fluctuations or experimental error. Our estimates show that the probability of such statistical fluctuations is no greater than 10^{-2}. Nor are there sufficient grounds for suspecting experimental error at any of the three detectors.

d) Consequently, we believe the experimental results deserve further analysis and elaboration, and that work on collapse models and the resulting calculations should be intensified. We cannot exclude that this problem will be solved only by turning to completely different mechanisms for the observed effects, only indirectly related to the supernova flash. Our main hopes lie with the continuing search for stellar collapses and the construction of new detectors with greater mass, lower energy thresholds, and better duty cycles. These new detectors would be poised to exploit the detection of future collapses within our Galaxy, closer to the Earth.

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