What effect was recorded by the underground detectors and gravitational wave antennas several hours before the observation of Supernova 1987A?

E. N. Alekseev, L. N. Alekseeva, V. N. Zakidyshev, I. M. Kogaĭ, I. V. Krivosheina, and V. Ya. Poddubnyĭ

Institute for Nuclear Research of the USSR Academy of Sciences
(Submitted 21 June 1990)
Zh. Eksp. Teor. Fiz. **99**, 1057–1065 (April 1991)

The data recorded by the underground detectors LSD, IMB, the Baksan telescope, and the gravitational-wave antennas at the Universities of Rome and Maryland were analyzed in search of time-correlations between them. Such correlations were found; the maximum effect occurred within a one-hour period between 1:45 and 2:45 UTC on 23 February 1987. The difficulties of interpretation of this effect are discussed.

Among the many unexpected phenomena recorded during the period of the flareup of Supernova 1987A in the Large Magellanic Cloud there is one more which until now has not received an adequate explanation, namely the correlation between signals detected by underground detectors and gravitational wave antennas.[1-3]

At first the effect was observed in a comparison of the Soviet-Italian LSD detector and the gravitational wave antennas at the Universities of Rome and Maryland, during the period 01:45–03:45 UTC on 23 February 1987.[1] The essence of the phenomenon was that the number of coincidences of events in the various installations within a time window of ± 1 s significantly exceeded the expected number. In the LSD detector use was made of the arrival times of low-energy events, whereas for the gravitational wave antennas the position along the time axis of the total signal of both antennas in excess of some threshold was utilized. The indicated time interval contains a narrow group of 5 events at the LSD detector which was originally interpreted as a neutrino signal from the Supernova 1987A.[2,4]

Subsequently correlations were found between the LSD events and the low-energy ($\leqslant 50$ MeV) events at the Baksan telescope with a probability of background imitation of $\sim 10^{-4}$.[2,3] In addition, the analysis of other programs of the Baksan telescope, related to muons traversing the telescope, has shown that a similar effect is also observed for cosmic-ray muons.[3]

Since the phenomenon manifested itself most strongly during the first hour of this indicated period, the present paper uses for its analysis the information recorded by the various detectors during that hour 01:44–02:45 UTC 23 February 1987. Various authors have different coincidence windows for the analysis of correlations: 0.5 s, 0.75 s, 1.0 s, 1.3, s, and 1.5 s. Here we use a time window of ± 1 s and make use of the dependence of the effect on the magnitude of the event coincidence window.

As was already pointed out, at the beginning correlations were sought between the LSD events and the low-energy events in the Baksan telescope, which were recorded according to the program searching for neutrino signals coming from the collapse of stellar cores. The selection principle for these events is described in detail in Refs. 3,5. The mass of the scintillator in the counters used in this program and having the best shielding against cosmic-ray muons was 200 tonnes. The counting rate of isolated background pulses was $\sim 0.034\ \text{s}^{-1}$.

Figure 1 shows the distribution of the number of coincidences between the LSD events and the events in the Baksan telescope in the time window of ± 1 s, as a function of the backward shift of the absolute time of the telescope, ΔT_{Bak}. As can be seen from Fig. 1, for a shift $\Delta T_{\text{Bak}} \sim -30$ s of the telescope events relative to the LSD events one observes a peak consisting of 11 events.

The expected average number of coincidences between the events of these two detectors with counting rates n_1 and n_2 can be estimated according to the formula

$$N_{\text{exp}} = \frac{n_1 n_2 2\tau}{T}, \tag{1}$$

where τ is the size of the temporal window and T is the duration of observation. Substituting into Eq. (1) the number of coincidences recorded during that hour by the LSD installation ($n_1 = 44$) and the Baksan telescope ($n_2 = 116$), as well as the values $\tau = 1$ s and $T = 3600$ s, we obtain

$$N_{\text{exp}} = 2{,}8.$$

The probability that the observed excess is simulated by background pulses is

$$P \sim 1{,}3 \cdot 10^{-5}.$$

In order to understand the meaning of the time shift of the Baksan clock (-30 s) for which one observes an enhanced number of coincidences between the events of the two detectors, it is necessary to recall that on February 23, 1987 the accuracy with which the clock at the telescope was bound to absolute time was (-54 s, $+2$ s), whereas the clock at LSD had an accuracy of ± 2 ms.

It is interesting to note that if one considers the effect observed for $\Delta_{\text{Bak}} \sim -30$ s as an independent calibration of the Baksan clock, then the start of the neutrino signal recorded by the Baksan telescope at 07:35 UTC coincides with the start of the neutrino signal recorded by the IMB detector.[5]

In Ref. 3 the data of the other programs of the Baksan Telescope were analyzed and it was shown that two other kind of events correlate with events at the LSD detector for the same time shift, $\Delta_{\text{Bak}} \sim -30$ s, namely, muons which have experienced interactions in the installation ($E_\mu \geqslant 300$ GeV, "showers"), and muons coming in under large angles ($\theta > 50°$) which have penetrated a large thickness of matter ($E_\mu \geqslant 2$ TeV).

At the same time these two neutron types also correlate

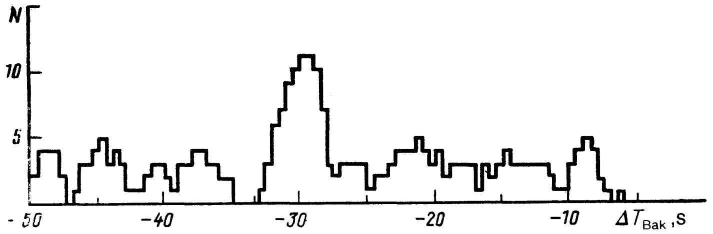

FIG. 1. The distribution of the number of coincidences N between the events at LSD and at the Baksan telescope, found within one hour, 01:45–02:45 UTC on 23 February 1987, as a function of the shift of the absolute time ΔT_{Bak} (s); the time window of the coincidences is ± 1 s.

with the low-energy events of the telescope, naturally for a time-shift of zero between the two.

Figures 2, a and b show the numbers of coincidences in a time window of ± 1.3 s of the "showers" generated in the telescope with the events of LSD (Fig. 2, a) and with the low-energy events of the telescope (Fig. 2b) as a function of the shift in the absolute time Δ_{Bak}. As can be seen from these figures, in both cases one observes clearly expressed peaks at time shifts of -30 s (Fig. 2a) and 0 s (Fig. 2b). The probabilities that such coincidences are imitated by background are respectively $\sim 1.5\times 10^{-4}$ and $\sim 7\times 10^{-4}$.

A similar effect, but at a lower confidence level, is observed for the large-angle muons traversing the telescope.[3] An analysis of the low-energy Baksan events which correlate with LSD has shown that they are mainly related to cosmic-ray muons.[3] In this case one may expect a similar effect in the data from other underground detectors.

A search for time correlations between the data of the IMP detector and the low-energy events at LSD and the Baksan telescope was recently carried out by the IMB collaboration.[6]

Since the total counting rate of events at IMB is quite high (~ 2.7 s^{-1}), the small positive excess of coincidences found by the authors of Ref. 6 did not permit them to draw a conclusion about the existence of a significant effect.

However, one can approach the problem of existence of correlations between the events at IMB, LSD, and the Baksan telescope in the following manner. One first selects the events at LSD which coincide with the events of the Baksan telescope, and then one verifies whether these instants of time fall within the coincidence windows of the IMB detector. The number of such coincident LSD-Baksan events was 11 (01:45–02:45 UTC), but since two of them are separated by a small time interval (0.09 s), the number of IMB events was counted in 10 two-second intervals, one of which is enlarged by 0.1 s ($\tau = \pm 1$ s). Table I lists the observed and expected numbers of IMB events which coincide with the low-energy events of the Baksan telescope.

All the IMB events were split into several classes according to the number of photomultipliers that had fired. The cases with $400 < N_{PhM} < 1750$ having zenith angles $\theta > 70.5°$ (the zenith angles were determined by the IMB collaboration).

As can be seen from Table I, IMB-LSD-Baksan correlations are observed at the level of $\sim 10^{-2}$. Here it should be stressed that the estimates of accidental probabilities listed in the last row of the table, were obtained without taking into account the probability of the appearance of a proper LSD-Baksan correlation. Consequently we are dealing with the fact of the occurrence of triple temporal coincidences.

The main effect is observed for IMB events with the number of fired photomultipliers between $400 < N_{PhM} < 1750$. Moreover, the probability of accidental imitation of such coincidences is $\sim 1\times 10^{-4}$ (without consideration of the probability of LSD-Baksan coincidences, for muons with zenith angles $\theta > 70.5°$.

The same procedure can also be carried out with the LSD events which coincide with signals in the gravitational-wave antennas. It follows from Ref. 1 that eight such LSD events fall within the time span 01:45–02:44 UTC. The re-

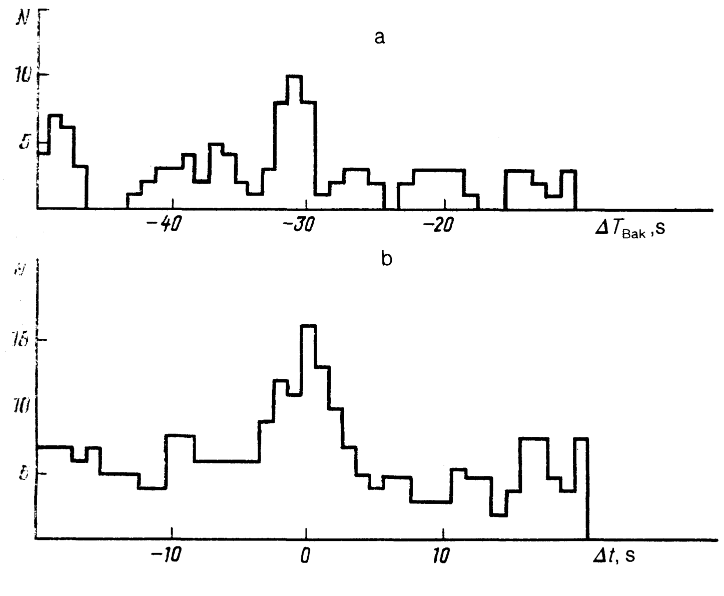

FIG. 2. The distribution of the number of coincidences N found within one hour, 01:45–02:45 UTC on 23 February 1987, for showers generated in the Baksan telescope, and the events at LSD (a), and between the showers generated in the Baksan telescope and the low-energy events at the telescope (b), as a function of the retroshift ΔT_{Bak} (s) and the interval between the pulses Δt (s), respectively; the time window of the coincidences is ± 1.3 s.

TABLE I. The number of IMB events which fell into the time intervals distinguished by the LSD-Baksan coincidences.

Type of event	All events	$N_{PhM} < 400$	$N_{PhM} > 1750$	$400 < N_{PhM} < 1750$	
				all	$\theta > 70.5°$
n	8084	1529	215	6340	317
n_{obs}	58	9	0	49	9
n_{exp}	45,4	8,6	1,2	35,6	1,8
P	$4\cdot 10^{-2}$	0,64	0,20	$1{,}9\cdot 10^{-2}$	$1{,}1\cdot 10^{-4}$

Notation: n is the total number of events during the hour under analysis; n_{obs} is the observed number of events at IMB, falling within the selected time intervals; n_{exp} is the expected number of such events; P is the probability of accidental imitation; N_{PhM} the number of photomultipliers which fired for an event.

sults are exhibited in Table II.

We thus come to the conclusion that during the time span 01:45–02:44 UTC on 23 February 1987 time correlations were observed between the signals of the gravitational-wave antennas in Rome and Maryland, the LSD underground scintillation detector and the Baksan telescope, and the IMB water Cherenkov detector. A detailed analysis making use of low-energy events detected in the water-Cherenkov detector Kamiokande IT, the events at the LSD detector, and the gravitational-wave antenna signals, was carried out in Ref. 7. The excess of coincidences was determined at a probability level of $\sim 10^{-2}$.

In order to verify the accuracy of the estimates of the probability correlations we did the following. Since the data of the muon program of the telescope correlate not only with the events of the LSD detector, but also with the low-energy events of the same telescope, we have obtained the distribution of coincidences among them. Figure 3 shows the distribution of the number of coincidences between low-energy events with the sum of the events of the two muon programs (the muon showers and muons with an angle $\theta > 50°$) obtained over 200 days of operation of the installation in 1989. The arrow points to the number of coincidences ($N = 22$) which were observed between 01:45 and 02:45 UTC on 23 February 1987. The solid line represents a Poisson distribution with a mean equal to 10.28, obtained from Eq. (1). Two important conclusions follow from this picture. First, the correlations observed in 1987 are indeed quite rare, and second, we do not make a big error by using the Poisson formula for estimating the probability of the effect.

It follows from Eq. (1) that the number of coincidences between the detectors is directly proportional to the counting rate of each of them, and the excess of coincidences can be caused by increasing these rates. Figure 4 show the counting rates for 900 of the low-energy events of the LSD detector and of the Baksan telescope, observed during the period 00:00–10:00 UTC on 23 February 1987. As can be seen from this picture, no enhancements of the counting rates have been observed either on the LSD detector or on the Baksan telescope during the indicated hour. This means that the observed phenomenon, i.e., a fourfold increase in the average count of LSD-Baksan coincidences is not related to an increase in the counting rates. No increase in the counting rates were observed in the other programs of the Baksan telescope.

In this case one may assume that the observed time correlations appeared on account of some time synchronization of events in various underground detectors and the signals in the gravitational wave antennas. One can further consider what the time scale of the effect is, or in other words, how the number of coincidences depends on the width of the time window.

Figure 5 shows the excess over the expected ones of observed coincidences between the low-energy events of LSD and the Baksan telescope as a function of the width of the time-window. As can be seen from Fig. 5 the magnitude of the excess increases with the width of the window up to ± 2 s. This leads to the conclusion that coincident events in different detectors do not occur simultaneously, but are scattered over an interval of several seconds. This scatter is significantly larger than the dead time of the LSD detector (~ 1 ms) and the Baksan detector (~ 4 ms).

It is possible that the time synchronization of events in different detectors could appear on the scale of several seconds on account of a temporary increase of the local counting rates on the whole Earth. Without going into the details of the physical process which could generate such enhancements, we note that this scheme runs into a series of difficulties, the principal one being the absence of autocorrelations. This means that in each of the detectors one would observe an excess number of narrow groups of events which appear for short-term increases of the counting rate. This was first

TABLE II. The number of IMB events which fell into the time intervals distinguished by the LSD-gravitational-wave-antenna coincidences.

Type of event	All events	$N_{PhM} < 400$	$N_{PhM} > 1750$	$400 < N_{PhM} < 1750$	
				all	$\theta > 70.5°$
n	8084	1529	215	6340	317
n_{obs}	40	5	0	35	6
n_{exp}	31,9	6	0,85	25,1	1,25
P	$9{,}2\cdot 10^{-2}$	0,45	0,42	$3\cdot 10^{-2}$	$1{,}8\cdot 10^{-3}$

Notation: n is the total number of events during the hour under analysis; n_{obs} is the observed number of events at IMB, falling within the selected time intervals; n_{exp} is the expected number of such events; P is the probability of accidental imitation; N_{PhM} the number of photomultipliers which fired for an event.

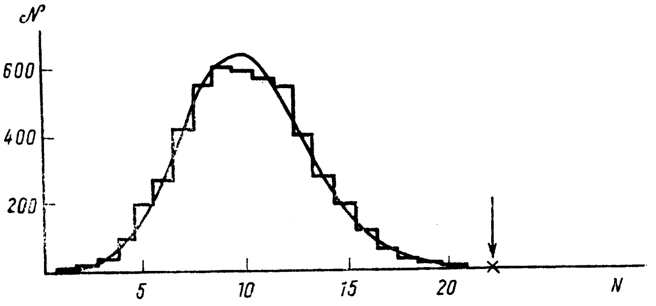

FIG. 3. The distribution of the number of coincidences $\mathcal{N}(N)$ between the low-energy events of the telescope and the sum of events of the two muon programs (muon showers and muons at angles $\theta > 50°$), obtained over 200 days of running of the installation in 1989. The arrow points to the number of such coincidences ($N = 22$) observed in the hour 01:45–02:45 UTC on 23 February 1987; N is the number of coincidences between events.

noted by Chudakov.[2] He derived a relation between the number of coincidences among the data from two detectors (N) and the number of narrow groups of events in each of these detectors (μ and ν):

$$N=2(\mu\nu)^{1/2}.$$

The values of N,μ,ν for the low-energy events of the LSD detector and the Baksan telescope in a time window ± 1 s are listed in Table III.

As can be seen from Table III no excess of narrow groups was observed in either installation, in spite of the significant abundance of coincidences between them. The estimate of the probability of such an observation is $\sim 1\%$ (Ref. 2). One does not observe an excess of autocorrelations in the other programs of the Baksan telescope either.

Thus, the proposed scenario for the appearance of correlations between the events (simultaneous short-time increases in the counting rates) does not agree with the observations. It follows that if there were indeed a synchronization in time of the events in different detectors, it must occur in a more complicated manner.

The phenomenon under discussion arises in the field of events of different origins. As already stated the coincidence events of the Baksan telescope and the IMB detector are caused mainly by cosmic-ray muons. As an example, Fig. 6 shows one of the coincident Baksan events—a muon generating a shower in the telescope. The event has a trajectory

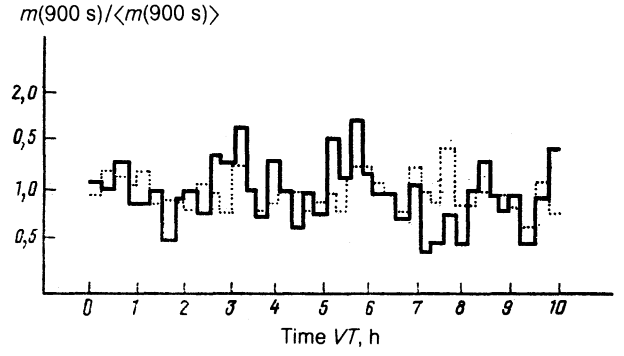

FIG. 4. The counting rates over 900 seconds of low-energy events at the LSD detector (solid line) and at the Baksan telescope (dotted line), observed in the period 00:00–10:00 UTC on 23 February 1987.

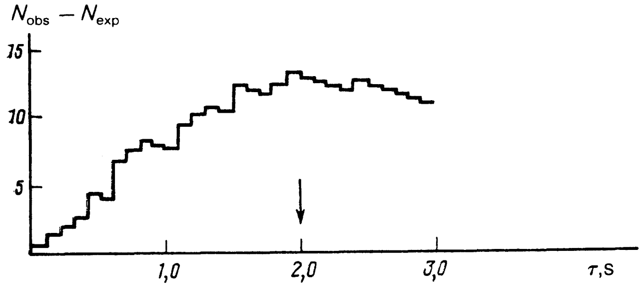

FIG. 5. The excess of observed coincidences N_{obs} over expected coincidences N_{exp}, between low-energy events at LSD and at the Baksan telescope as a function of the width of the time window τ.

and is externally similar to an ordinary muon. If the correlations between the data of the two detectors are caused by some synchronous perturbations of the background, then these perturbations should manifest themselves obviously also in cosmic-ray muons.

The low-energy events at LSD have a radically different nature. In the estimate of the authors of Ref. 8 their natural source is natural radioactivity, in particular decays of ^{238}U. If one assumes that the coinciding events in this detector are of a different nature, there arises a difficulty with this additional flux of particles, since the total number of coincidences in LSD during the hour under consideration is 44, whereas the average over a 10-hour period is 45. Since 24 of the 44 events coincide with the events of one or the other detectors (naturally part of the coincidences are random), then, assuming that they are of a different nature, we must observe an increase in the counting rate during that hour, which was not the case (see Fig. 3).

The energy distribution of all the events of LSD recorded during 10 hours of operation on 23 February 1987 is shown in Fig. 7. The darkened region denotes the energies of those 15 events which coincide twice or more often with events of other detectors. As can be seen from the figure, the energies of the coinciding events lie approximately in the same range as the background events. However we can neither confirm nor deny that they correspond exactly to background events.

The main source of background for gravitational wave antennas is thermal noise.[7] The energy distribution of the signals in the gravitational wave antennas in Rome and Maryland obtained during 18 hours of running agrees well with thermal noise at 28.6 K and 22.1 K for the Rome and Maryland antennas, respectively (Ref. 9). Although during the period 01:45–03:45 UTC no anomalously large amplitudes were observed in these antennas, nevertheless, the energy distributions of the total signals from the antennas

TABLE III. The number of coincidences (N) between the events at the LSD detector and the low-energy events of the Baksan telescope.

Parameter	Expected	Observed	Excess
μ(Baksan)	3,74	3	0
ν(LSD)	0,54	1	0
N(LSD and Baksan)	2,84	11	8

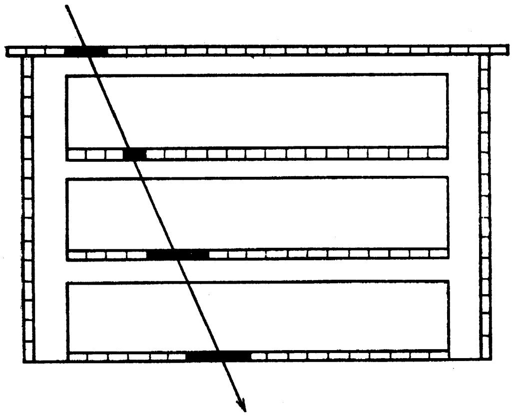

FIG. 6. One of the coincident Baksan events: a muon generating a shower in the telescope. The black blocks denote the detectors which have fired.

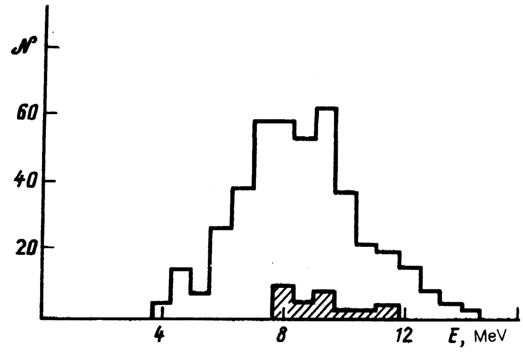

FIG. 7. The energy distribution $\mathcal{N}(E)$ of all LSD events recorded over 10 hours on 23 February 1987. The darkened region shows the energies of those 15 events which coincide twice or more with events in the other detectors.

which coincide with the events of the LSD detector differs from the distribution of all signals during that period. This could possibly point to some additional radiation during that period.

The influence of cosmic rays on gravitational wave antennas was studied repeatedly.[10-13] For this purpose, the scintillator detectors were installed above the antennas,[10] a model of the antenna was irradiated by beams of electrons and protons from an accelerator[11] and then a calculation was done for a working antenna[12] and in Ref. 13 an estimate was obtained for the effect of high-energy cosmic-ray muons. Thus, the authors eliminate cosmic rays as a possible source of signals in gravitational wave antennas, in coincidence with the events in the underground detectors.

A gravitational wave from the collapse of the core of the star SN 1987A as a source of the signal in the antennas is of very low probability, as was shown by estimates based on the classical cross sections of these antennas for such waves.

Thus, the problem of the nature of the coincidences between signals in the gravitational wave antennas is most complicated and maybe holds the key to understanding the whole phenomenon.

One question remains central: is the effect observed in the period 01:45–03:45 UTC on 23 February 1987 related to the supernova SN 1987A? The only argument in favor of this could be the fact that it was observed immediately before the flareup of the supernova, 5 hours before the neutrino signal recorded by the detectors at IMB, Kamiokande II, and the Baksan underground telescope.

The authors express their gratitude to the IMB collaboration, in particular to F. Reines and R. Svoboda, for making available unpublished data, as well as to A. E. Chudakov and G. Pizzella for useful discussions and critical remarks.

[1] M. Aglietta, G. Badino *et al. Proc. Rencontres de Physique de la Vallée d'Aoste, La Thuille (France), 1988*, p. 49.
[2] A. E. Chudakov, Ann. NY Acad. Sci. **571**, 577 (1988).
[3] E. N. Alekseev, L. N. Alekseeva, V. I. Volchenko *et al.*, Pis'ma v ZHETF **49**, 480 (1989). [JETP Lett. **49**, (1989)].
[4] M. Aglietta, G. Badino, G. Bologna *et al.*, Europhys. Lett. **3**, 1315 (1987).
[5] E. N. Alekseev, L. N. Alekseeva, I. V. Krisvosheina *et al.*, Phys. Lett. **B205**, 209 (1988).
[6] R. Becker-Szendy, C. B. Bratton, D. Casper *et al.*, *Proc. XXII Int. Cosmic Ray Conference, Adelaide, Australia, 1990*, Vol. 10, p. 40.
[7] E. Amaldi, *Proc. Workshop on Cosmic Gamma Rays and Cosmic Neutrinos, Erice, 1988*, p. 563.
[8] M. Aglietta, G. Badino, G. Bologna *et al.*, Nuovo Cimento **9**, 185 (1985).
[9] M. Aglietta, G. Badino, G. Bologna *et al.*, Nuovo Cimento **12**, 75 (1989).
[10] N. S. Ezrow, Phys. Rev. Lett. **24**, 945 (1970).
[11] A. M. Grasi, J. Appl. Phys. **51**, 948 (1980).
[12] E. Amaldi and G. Pizzella, Nuovo Cimento **9**, 612 (1986).
[13] F. Ricci, Nucl. Instr. Methods A **260**, 491 (1987).

Translated by M. E. Mayer