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Creation of the FIAN Neutrino Laboratory and underground laboratories

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Contents

Abstract. We describe the history of how the FIAN Neutrino Laboratory was created and how the main methods, later to underlie the construction of the BUST (Baksan Underground Scintillation Telescope), ASD (Artyomovsk Scintillation Detector), LSD (Liquid Scintillation Detector), and LVD (Large Volume Detector) underground facilities, were developed and first implemented. This work, initiated by G T Zatsepin, was crucial for the development of underground physics and gave the Institute for Nuclear Research, RAS, a leading role in experiments to study stellar-collapse neutrinos. We discuss underground physics as an effective method for studying a wide class of rare processes related to cosmic rays, neutrino physics, neutrino astrophysics, and elementary particles. The latest LVD and LSD results on the search for stellar-collapse neutrinos are discussed, and research on cosmic ray muon characteristics and on muon interaction products at various depths underground is reviewed.

Keywords: underground physics, scintillation methods, neutrino, supernovae

1. Introduction

May 28, 2017 was the centennial of the birth of Georgii Timofeevich Zatsepin, a prominent researcher and a specialist in cosmic-ray physics. From the very beginning of his scientific carrier, Zatsepin was interested in the area of physics referred to as cosmic-ray physics. A favorite student of D V Skobeltsyn, he, like his teacher, believed that "cosmic rays are unarguably one of the most interesting phenomena of modern physics, whose studies yielded very important results and which per se are of exceptional interest.'' Zatsepin's scientific school, a community of experimentalists and theorists, was a continuation of Skobeltsyn' school. Zatsepin usually said: "In physics, the decisive word belongs to experiment; experiment is the chief arbiter. The most important task is to correctly understand experimental results.'' In addition to understanding the decisive role of experiment, Zatsepin had a deep knowledge of theory.

In the early 1960s, a new area, cosmic neutrino physics, emerged in cosmic-ray physics. In this area, cosmic neutrinos mean those of natural origin, as opposed to neutrinos generated by reactors and accelerators. Three main components can be distinguished: (1) neutrinos generated in the interaction of cosmic rays with Earth's atmosphere (atmospheric neutrinos); (2) neutrinos radiated by astrophysical objects (the Sun and other stars, supernovae, radio galaxies, etc.), and (3) relict neutrinos that existed at the primordial stage of the Universe's evolution.

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2. Generation of neutrino in the atmosphere

The idea to use cosmic-ray neutrinos for studying high-energy neutrino physics was put forward for the first time by M A Markov at the Annual International Conference on High Energy Physics in Rochester [1], held in 1960. The spectrum of the neutrinos generated by cosmic rays in the atmosphere extends to energies above 10^{12} eV, the value 1.5 to 2 orders of magnitude larger than the maximum energies of the neutrinos generated by accelerators that were in operation until the mid-1960s. Therefore, experiments with atmospheric neutrinos enabled obtaining new results of importance for elementary particle physics and, primarily, allowed studying weak interactions at high energies and clarifying some problems of conceptual importance for the theory. On the other hand, experiments with cosmic-ray neutrinos provided new tools for understanding some astrophysical problems.

The underground experiments with cosmic-ray neutrinos proposed in [2–7] mainly focused on studying reactions of neutrinos with an energy above 1 GeV with nucleons:

$$\nu_\mu + N \to N' + \mu\,, \qquad \nu_\mu + N \to N'' + \mu + n\pi\,, \tag{1}$$

where N are baryons.

Atmospheric neutrinos are a convenient tool for studying weak interactions at high energies, because their energy spectrum and angular distribution can be calculated reasonably accurately. However, the low intensity of neutrino fluxes imposes stringent requirements on experimental conditions.

G T Zatsepin, V A Kuzmin, and independently M A Markov and I M Zheleznykh calculated the spectra of neutrinos in the decays of π mesons ($\pi \to \mu + \nu$) generated in the collisions of primary cosmic rays with atmospheric atom nuclei, the neutrino spectra in decays $\mu \to e + \nu + \bar{\nu}$ with energy losses by muons taken into account, and angular distributions of neutrino fluxes in the atmosphere [5, 6].

To detect the muons generated in reactions (1), it was proposed to create a facility consisting of mosaic layers of scintillation counters located at a sufficiently large distance from each other. They were intended to determine the trajectories of the muons passing through the array and measure the relative delay times in counter pulses. These features enable selecting the muons that come from the lower hemisphere. The space between the scintillators is filled with an absorber whose thickness determines the energy threshold of muon detection.

Due to the high penetrating power of neutrinos, the array can be placed underground, thus enabling the events caused by the neutrinos coming from Earth's lower hemisphere to be distinguished. The experiment must be conducted at a sufficiently large depth to eliminate the 'reverse flux' of cosmic muons that may mimic neutrino events.

To obtain acceptable statistics, the size of the array is to be of the order of several hundred square meters.

3. Neutrinos emitted by astrophysical objects

Progress in experimental techniques for the first time allowed observing the interaction of neutrinos with matter in the early 1960s. This event opened new options for studying the properties of elementary particles and raised hopes that neutrinos would enable obtaining information about the processes that occur in the interiors of stars.

The neutrino is a weakly interacting particle that has high penetrating power. Any body, of an arbitrarily large mass, is transparent to neutrino fluxes. This property of neutrinos is a basis for neutrino astronomy.

The neutrinos generated in the interior of the Sun or another star escape from the star without being absorbed or scattered.

The energy radiated by stars is generated in thermonuclear fusion reactions in which light-element nuclei merge to form the nuclei of heavier elements. The rate of these reactions, which depends on the temperature, density, and chemical composition of the star, falls so rapidly with decreasing density and especially temperature that the reactions can only occur in a small-size central core of the star. This area occupies only about one millionth of the star's volume. It is believed that the temperature of the Sun's central core is $(14–16) \times 10^6$ K. At such temperatures, reactions occur in which helium nuclei (α particles) are synthesized as a result of fusion of hydrogen nuclei (protons). At temperatures over 15×10^6 K, neutrinos are generated with the energies in the range 0.8–14 MeV, while at lower temperatures, neutrinos of lower energies are produced. In all thermonuclear reactions, electron-type neutrinos are generated; they escape from the star and can therefore provide information about the processes occurring in the interior of the Sun and other stars.

A radiochemical method was considered in the early 1960s as a tool for studying the Sun's neutrino activity. This method, proposed in 1946 by Pontecorvo [8] and developed by Davis [9], is based on using the chlorine–argon reaction for detecting neutrinos:

$$\nu_e + Cl^{37} \to Ar^{37} + e^-\,. \tag{2}$$

As the chlorine-containing substance, Davis used carbon tetrachloride (CCl_4), a liquid 92 mass % of which is chlorine. Cl^{37} makes 25% of the total chlorine amount. The energy threshold of reaction (2) is 0.8 MeV.

The essence of the Pontecorvo–Davis method is that physicochemical methods are used to extract the Ar^{37} that was created in CCl_4 during a month and to determine the amount of accumulated argon. This technique allows the cosmic-ray background to be significantly suppressed. Davis used a chlorine–argon detector to measure the argon production rate at sea level and in the mountains and detected the background emerging as a result of interactions between cosmic rays and chlorine. The main background reaction is the one where a proton is captured by the chlorine nucleus to emit a neutron:

$$p + Cl^{37} \to Ar^{37} + n\,. \tag{3}$$

The conclusion made by Davis was that the experiments intended for measuring solar neutrinos have to be conducted at great depths underground.

4. How the FIAN neutrino laboratory and underground laboratories were created

The results of the studies conducted by Zatsepin, Markov, Pontecorvo, and their students prompted the idea to create a laboratory for cosmic neutrinos and neutrino astronomy. In this laboratory, experimental facilities were to be developed for studying the cosmic neutrinos generated by various sources and obtaining information about the life of stars. Zatsepin proposed projects of large-scale underground experiments that for many years were ahead of similar proposals abroad.

The new laboratory was established in 1963 at the Lebedev Physical Institute, the USSR Academy os Sciences (FIAN); Zatsepin was appointed the head of the neutrino laboratory. This laboratory stuff included FIAN researchers A E Chudakov, A A Pomanskii, V A Kuzmin, V L Dadykin, and I M Zheleznykh. L V Volkova, whose graduate thesis "Energy spectra of neutrinos in the atmosphere" was supervised by Zatsepin, was also invited to join the new laboratory. Pomanskii selected young researchers, sixth-year students at the Physics Department of Moscow State University, for the laboratory.

Several students in the sub-faculty of Cosmic Rays and other sub-faculties of the Department of Physics, including

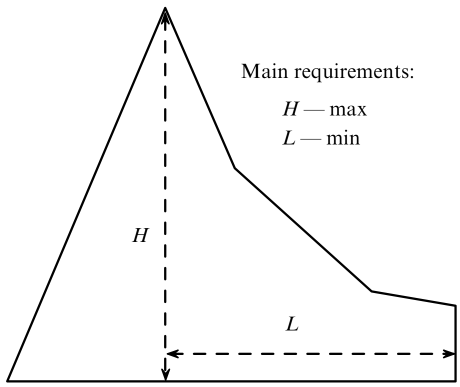

Figure 1. Requirements for a mountain with the characteristic profile.

the author of this paper, applied for employment at the FIAN neutrino laboratory. Zatsepin met with us and invited us to attend the first neutrino laboratory seminar. At the seminar, he spoke about the Sun, thermonuclear reactions, neutrinos, the neutrino spectroscopy of the Sun, and the future underground laboratory (neutrino station). Zatsepin proposed after the meeting that I start working at the laboratory immediately after completing my diploma thesis and passing state exams, on February 1, 1964.

Urgent work had to be done: it was necessary to find the best site for the underground laboratory. A high mountain with maximum steepness had to be found in the North Caucasus, in the valley of the Baksan River. The main requirement was that the length of the tunnel connecting the entrance to the underground laboratory and protected by a soil layer equivalent to 4,000 meters of water be minimal (Fig. 1). After a mountain that met those requirements was found (it was the Andyrchi mountain), Zatsepin and a team of researchers and construction specialists went to the Mt. Elbrus region in late February 1964 to explore the situation on the ground and determine where the entrance to the tunnel was to be located.

The neutrino laboratory consisted at that time of three groups: the solar neutrino group (Pomanskii), the atmospheric muon and neutrino group (Chudakov), and a group that studied energy spectra of high-energy muons using magnetic spectrometers (B V Tolkachev). The last group only existed for a short time.

The solar neutrino group commenced active development of radiochemical methods for detecting neutrinos in early 1964. First, the chlorine–argon and gallium–germanium methods were reviewed. The first method was developed by Davis at the Brookhaven National Laboratory in the USA, and at the FIAN neutrino laboratory under the guidance of Zatsepin and Pomanskii. The method involved a large amount of a chlorine-containing substance (perchlorethylene) exposed to a neutrino flux. In interacting with chlorine, neutrinos create argon [see reaction (2)], which is accumulated for some time and then extracted from the tank. For this, the tank is blown through with helium, the flow of which takes out the argon, also an inert gas, from the detection volume. Afterwards, the argon is adsorbed by activated carbon in a trap. Next, radioactive argon-37 is input into a small proportional counter that registers gas atoms. Even a brief description of the method shows that the radiochemical detectors are not protected against background reactions (for example, the $Cl^{37}(p, n)Ar^{37}$ reaction) that produce the sought atoms in the final state. The probability of neutrino interaction with nuclei is very small and it is therefore not infrequent that background-related issues prove to be a criterion of whether the experiment is feasible at all.

At a seminar held at the neutrino laboratory in early 1964, Kuzmin discussed a proposal to create a network of radiochemical detectors to measure solar neutrinos primarily using the chlorine–argon and gallium–germanium methods [10–13]. The $Ga^{71}(\nu, e^-)Ge^{71}$ detector is a low-threshold facility ($E_{\nu,\,th} = 231$ keV) with a fairly good sensitivity to the neutrinos from the pp interaction and Be^7 (the main components of the solar neutrino flux). The energy released in the K-capture in Ge^{71} is rather large (11 keV), and this circumstance facilitates background discrimination in the counters. The Ge^{71} half-life time, 12.5 days, is quite convenient for the experiment. The discussion focused on the depths at which the detector was to be installed to suppress the cosmic-ray background. All of a sudden, Zatsepin proposed that I sort out the mechanisms through which the nuclear active component of cosmic rays is generated underground.

Prior to 1964, the general belief was that the nuclear active component is produced in electromagnetic cascades generated by muons underground. Muons generate those cascades as a result of bremsstrahlung, whose γ quanta interact with nuclei in the soil: $\gamma A \to A' + (\pi^{\pm}, \pi^0, p, n, \alpha)$. A small number of low-energy nuclear active particles is generated in those reactions. The inelastic interaction of muons was believed to only be the muon–nucleus interaction, in which low-energy hadrons are created. Zatsepin pointed out to me that the deep-inelastic interaction of muons with soil nuclei of the type $\mu A \to \mu + m\pi + \chi$, where $m\pi$ is the sum of π mesons and χ are nuclear fragments, also had to be taken into account. In those reactions, high-energy π mesons are generated that initiate nuclear cascades. Our calculations showed that most hadrons are generated in the nuclear cascades and, moreover, high-energy hadrons are only generated as a result of the development of nuclear cascades. The reason is that despite the small cross section of deep-inelastic muon scattering, the multiplicity of particles in nuclear cascades is high, a factor that proves to be decisive.

For example, the background at a depth of 4,000 meters of water equivalent (m.w.e.) is 2.5 times higher than estimated by taking only the electromagnetic interaction of muons with nuclei in the soil into account. Moreover, background events whose energy exceeds 100 MeV are due to the deep-inelastic muon interaction alone.

A National cosmic-ray conference was held in Apatity in August 1964, where I delivered the report "Calculation of the generation of neutrons by μ mesons at different depths in soil" [14, 15], my first professional presentation. It attracted the attention of Pontecorvo. He was surprised to learn that at depths of 4,500 m.w.e. the background from the nuclear component of cosmic rays in a chlorine–argon detector is over 10% of the effect from detecting the $\nu_e + Cl^{37} \to Ar^{37} + e^-$ reaction; conducting the experiment at smaller depths is not reasonable. The nuclear active component of cosmic rays can generate Ar^{37} in interacting with Cl^{37} as a result of the reaction

$$Cl^{37} + p \to Ar^{37} + n\,.$$

Zatsepin then said: "To understand background-related issues, one has to know cosmic-ray physics well."

Zatsepin, together with Chudakov, traveled in late 1964 to the USA to see the experiments conducted by Davis at Brookhaven. Zatsepin presented to Davis a plot showing how the rate of nuclear-effect generation by muons varies with depth [14, 15]. The impression that those results made on Davis is described in Bahcall's book *Neutrino Astrophysics* [16].

Despite the importance of calculations, experiment is the last arbiter. A decision was made to measure the dependence of nuclear-effect generation by muons on the depth of soil. To conduct the experiment, Zatsepin established a research group of electronic methods to detect neutrinos (EMDNs). The group built a facility that consisted of three rows of liquid scintillation counters based on white spirit [17]. The scintillator was designed at the FIAN Neutrino Laboratory [18]. The upper and lower rows of counters registered charged particles, while the middle row contained a 300-liter counter sensitive to both charged particles and neutrons. The sensitivity to neutrons was due to adding a gadolinium salt, owing to which neutrons could be registered in capture reactions [19]. It was one of the largest scintillation single-unit detectors at that time.

The question arose as to where the experiment should be conducted, because the underground neutrino laboratory at Baksan was still at the design stage. The problem of background resurfaced; however, this time it was related to natural radioactivity. We started looking for a location where low-radioactive mining caverns are available that have a sufficiently large size and horizontal tunnels at different levels. Salt and gypsum mines meet these requirements. A decision was therefore made to conduct studies in the Donbass, near the city of Artyomovsk. The experiment was carried out at two depths underground: at 316 m.w.e. below sea level in a salt mine (the average energy of muons being 86 GeV) and at 25 m.w.e. below sea level (the average energy of muons 16.7 GeV) in a gypsum mine. It was found that the number of neutrons per muon generated by fast muons increases with the average energy of muons as $\bar{E}_{\mu}^{0.7}$, in accordance with the calculated theoretical curve [17, 19, 20].

An analysis of the experimental data clearly showed that nuclear cascades can be well differentiated from electromagnetic ones by the number of neutrons detected in the cascades, thus allowing the cross section of deep inelastic muon scattering to be measured more accurately.

We discussed this issue with Zatsepin several times, and a decision was made to design and create an underground laboratory in a salt mine not far from Artyomovsk at a depth of 570 m.w.e. The mine had to host a 100-ton liquid scintillation detector for studying the penetrative component of cosmic rays underground.

Concurrently, the underground facility of the Baksan Neutrino Laboratory was under active construction in 1970. It included the Baksan underground scintillation telescope for measuring atmospheric neutrinos that come from the other side of Earth and the laboratory of radiochemical methods for detecting solar neutrinos.

The FIAN neutrino laboratory was reorganized in late 1970 to become the Department of High-Energy Leptons and Neutrino Astrophysics (OLVENA) at the new Institute for Nuclear Research (INR), the USSR Academy of Sciences, established at the initiative of Markov. From that time on, Zatsepin was the head of the department. The OLVENA department consisted of four laboratories: the laboratory of high-energy leptons, the neutrino astrophysics laboratory, the laboratory of radiochemical methods for neutrino detection, and the laboratory of electronic methods for neutrino detection.

Searching for neutrino radiation from collapsing stars. Creating underground laboratories. Registering solar neutrinos is a basic problem; however, it is not the sole option to have an insight into star interiors.

Ya B Zel'dovich and O Kh Gusseinov showed in their paper "On neutrino radiation in the process of star collapse" published in 1965 that the evolution of massive stars belonging to the main sequence may end with a gravitational collapse and a powerful short burst (~ 10 ms) of neutrino radiation. Immediately after that, Zatsepin delivered a report at the 9th International Conference of Cosmic-Ray Physics, held in London in September 1965. The title of his report was "On experimental options for observing neutrinos from collapsing stars."

The design and development of underground detectors to search for neutrino radiation from collapsing stars commenced in 1966. Studying that radiation would provide information about the behavior and properties of matter under the extreme conditions of nuclear density, super-high temperatures and pressures, and strong gravitational fields, and about the emergence of neutron stars and black holes, i.e., about the most fundamental processes in the Universe for which experimental results are of utmost importance.

In the standard collapse model (a spherically symmetric nonrotating nonmagnetic star), neutrinos of all types are emitted with equal energy portions [23–26]. The most natural choice in this case is to detect the flux of electron antineutrinos using the reaction with hydrogen, which has the largest cross section. This requires an underground detector, well protected against cosmic-ray background, with 100 tons, or even better 1,000 tons of a hydrogen-containing substance used as a target for inverse beta decay:

$$\begin{aligned} &\bar{\nu}_e + p \to e^+ + n, \quad E_{e^+} = E_{\bar{\nu}_e} - 1.3\ \text{MeV} \\ &\sigma(\bar{\nu}_e,\ p) = 9.3\, E_{e^+}^2 \times 10^{-44}\ [\text{cm}^2]\,. \end{aligned} \tag{4}$$

We note that this reaction is accompanied by the capture of neutrons by hydrogen, in which a 2.2 MeV γ quantum is radiated,

$$n + p \to d + \gamma(2.2\ \text{MeV}), \quad \tau \sim 170-200\ \mu\text{s}\,, \tag{5}$$

where τ is the time of neutron capture in a scintillator. The γ-quantum pulse can be measured using large-volume scintillation counters, thus facilitating identification of $\bar{\nu}_e$. This proposal was put forward for the first time in [27].

The effect from a collapse can be identified in 20 s in the form of a statistically rare accumulation of pulses registered by a detector. Another important signature of the event is that the observation of this effect coincides in time with the optical observation of a supernova explosion. The reliability of the results can be significantly enhanced if several detectors located at different locations on the globe are operated concurrently.

Since the late 1970s, INR has built several large underground scintillation facilities that can detect neutrino radiation from collapsing stars.

The design of large underground detectors developed in several directions. Instead of expensive plastic scintillators that require sophisticated manufacturing technology, it was proposed to use liquid scintillators (LSs), which can be easily

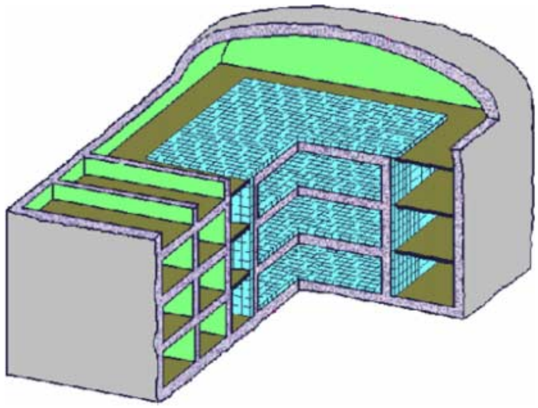

Figure 2. Sketch of the BUST detector in an underground location.

produced in ordinary laboratories. Those LSs were manufactured using cheap and readily available oil products that have a sufficiently high scintillation efficiency, are fast, are transparent to their own radiation, and, as a whole, are rather safe and user-friendly. Here, we first of all mention the Baksan Underground Scintillation Telescope (BUST) (Fig. 2) containing 330 tons of LSs, which was built by Chudakov and collaborators in 1978. The liquid scintillator for that detector was developed at INR by Voevodsky, Dadykin, and Ryazhskaya [18] in 1966. It is at that time that we proposed and implemented the main techniques that were employed later in creating all of INR's large underground detectors. This stage of the activities, which have played an important role in the development of underground physics in Russia, is described in detail in Dadykin's preprint *On the History of Creating BUST* [28]. The first underground detectors in which the LS is used have been operating for more than 40 years, and in none of those detectors has the scintillator deteriorated from its initial condition after so many years elapsed. This shows that the scintillator can be successfully used in long-term projects such as the program for the search for neutrino radiation from star core collapses.

Zatsepin initiated an international cooperation program to organize a neutrino burst observation survey. With his active participation, the EMDN laboratory started developing the 105-ton Artyomovsk scintillation detector (ASD) ('Collapse') in a salt mine near Artyomovsk. This project initiated the deployment of a global network of detectors to search for neutrino radiation from collapsing stars (Fig. 3).

The Collapse facility commenced observations in 1977, correlated with the observations of underground detectors in Italy and the USA. The Collapse detector was used in the 1980s to measure the cross section of hadron production in muon interactions with nuclei. The cross section of the photo production of hadrons on nuclei extracted from those experiments was found to remain constant at energies up to 3×10^{12} GeV. The muon spectrum has been measured with that device up to energies as high as 10^{13} eV [30, 31].

The construction of a system of scintillation detectors was completed with Zatsepin's active participation in 1985. The 90-ton Soviet–Italian telescope LSD (Liquid Scintillation Detector) under Mont Blanc was launched. It was followed in 2002 by the two-kiloton iron-scintillation calorimeter LVD (Large Volume Detector) (Fig. 5) under Gran Sasso [33, 34] (jointly with Italy). The electronics of both detectors were designed in such a way that it was possible to measure both particles (e^+ and n) in the $\bar{\nu}p \to e^+n$ reaction in registering $\bar{\nu}_e$ from collapsing stars. The signal of the energy release > 5 MeV in the scintillator was a trigger that opened gates with a duration of 600 μs and threshold of 0.8 MeV for registering the 2.2 MeV γ quantum from the $np \to d\gamma$ capture.

Those facilities were used to study high-energy inelastic interaction of muons accompanied with hadron production and the dependence of the generation of the nuclear active component of cosmic rays on soil depth (Fig. 6). It was shown that the generation of neutrons underground depends not only on the intensity of muons $I_\mu(H)$ but also on their average energy at that depth as $\bar{E}_\mu(H)^{0.75\pm0.05}$, and that the number of neutrons and π mesons generated in nuclear showers is approximately 10 times larger than in electromagnetic ones [35]. Methods have been developed for studying neutrino radiation that accompanies star collapses. Consequently, it was possible to observe neutrino signals from the burst of supernova SN1987A at two INR scintillation detectors: the Soviet–Italian LSD under Mont Blanc and the BUST under the Andyrchi mountain at Baksan.

The supernova SN1987A burst on February 23, 1987 in the Large Magellanic Cloud at a distance of almost 50 kps from Earth. On that day, four neutrino detectors — two scintillation (LSD and BUST) and two Cherenkov (KII, Kamioka, Japan [36]) and IMB (Irvine–Michigan–Brookhaven, Cleveland, USA [37]) facilities — registered neutrino signals from the gravitational collapse of a star for the first time in human history; however, the registration times were different. The LSD was the first to register the neutrino signal; it occurred in online mode at 2 h 52 min UT (Universal Time).

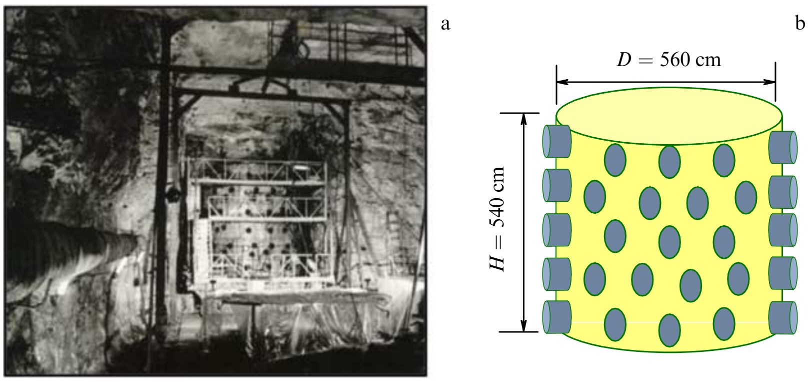

Figure 3. (a) Photo and (b) diagram of the Artyomovsk scintillation detector.

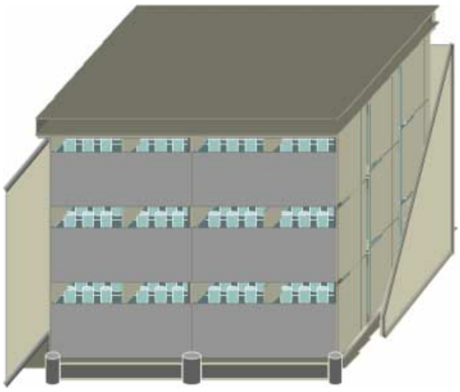

Figure 4. Sketch of the LSD facility under Mont Blanc, the Soviet–Italian 72-module liquid scintillation detector (90 tons of scintillator and 200 tons of iron).

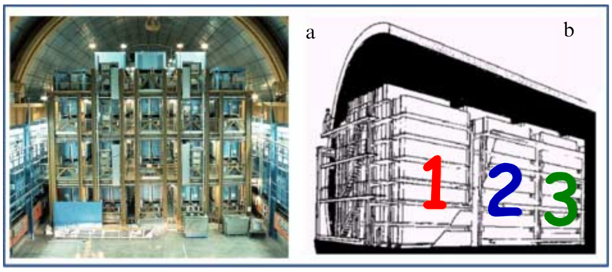

Figure 5. (a) Photo and (b) sketch of the LVD facility under Gran Sasso.

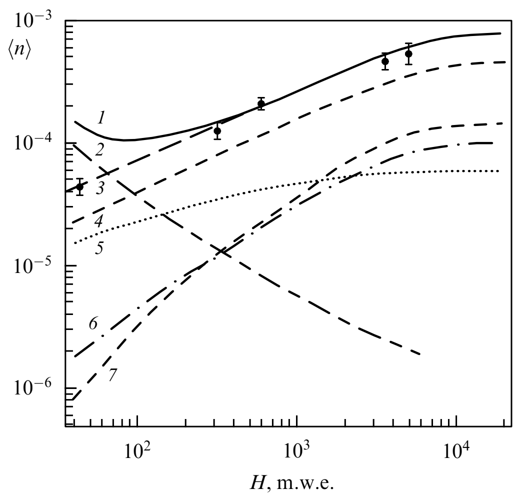

Figure 6. Number of slow neutrons generated in 1 g cm^{-2} of soil per muon as a function of the depth H measured from the atmosphere boundary. *1* is the total number of neutrons generated in all processes; *2* is the number of neutrons generated in μ^- capture; *3* is the number of neutrons generated in all processes except μ^- capture; *4* is the number of neutrons generated by virtual photons with consideration for nuclear showers; *5–7* is the number of neutrons respectively generated by the photons of electromagnetic showers induced by δ-electrons, e^+e^- pairs, and bremsstrahlung. Dots with error bars correspond to the experimental data measured by the ASD, LVD, and LSD scintillation detectors. The curves are normalized to the experimental data for 25 m.w.e.

Five pulses were detected within 7 s [38]. No such events have been registered since the start of LSD operations in January 1985. The probability that this event was due to the background is 10^{-3}. The neutrino signals were registered no less

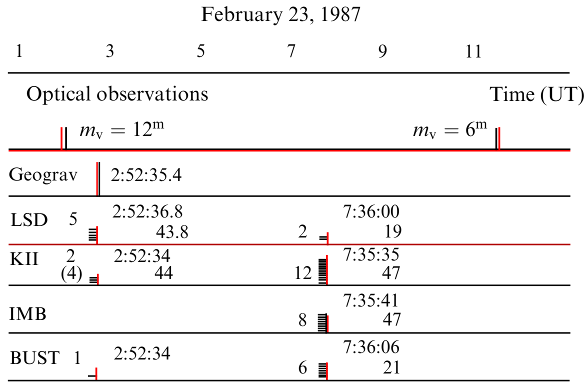

Figure 7. Time sequence of the events registered by various detectors [39] on February 23, 1987. For each neutrino detector the vertical axis show the number of pulses in the batch; next, the time when the first and last pulses arrived is shown (m_v is the apparent stellar magnitude; 6^m and 12^m are the 6th and 12th stellar magnitudes; Geograv is the Rome-based gravitational antenna).

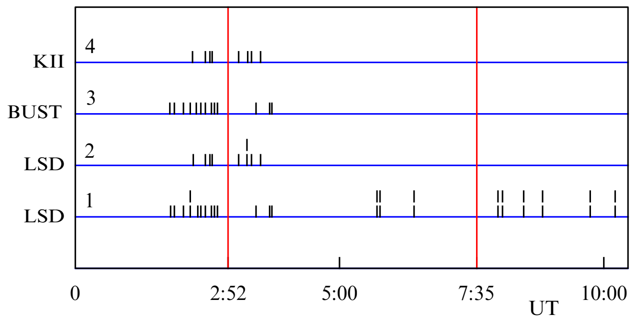

Figure 8. Time sequence of the pulses in BUST (line 3) that coincide with the pulses in LSD (line 1) within a 1-second time interval; similar coincidences for KII (line 4) and LSD (line 2), and double pulses in LSD (line 1, time interval from 5:42 to 10:13 UT, February 23, 1987). The average frequency of background coincidences for both experiments, BUST–LSD and KII–LSD, based on the correlations measured within an interval 23.02.1987 ± 15 days, proved to be the same, about 1 h^{-1} [44]. The measured frequency of the background double pulses for the same period is 0.275 h^{-1}. The figure does not show the background for coincidences outside the interval from 1:45 to 3:45 UT 23 or the background for the double pulses outside the interval 5:42–10:13 UT.

than 5 hours later by the detectors BUST, KII [36], and IMB [37] (Fig. 7). The Collapse detector was out of operation that day because of replacement of electronics.

In addition, a coincidence of the pulses registered by the LSD and BUST, as well as LSD and KII within 1 s, was observed. The time sequence of the events registered by different detectors on February 23, 1987 is shown in Fig. 8 [39]. The long vertical bars on the time scale show positions of the neutrino signals at 2:52 and 7:35 UT. Scales 1 and 2 refer to the LSD, 3 to BUST, and 4 to the KII detector. The number of coincidences during two hours was 8 for the LSD–KII pair close to 2:52 and 13 for the LSD–BUST pair. Two and three of those events, respectively, could be coincidental. The right-hand side scale *1* shows the time when double pulses were coming to the LSD within the time interval from 5:42:48 to 10:13:04 UT. Nine pairs of pulses were detected. The average frequency of background double pulses was 0.275 h^{-1}. Thus, the number of registered double pulses was greater than the number of background pairs by a factor of 7.3. Such an event could coincide with the supernova burst instant only once in 3×10^3 years.

It is noteworthy that the series of five pulses registered in 7 s by the LSD was apparently not caused by the reaction $\bar{\nu}_e + p \to e^+ + n$, $n + p \to d + \gamma$ (2.2 MeV), $\tau \sim 170$ μs. Otherwise, the KII detector would have registered a signal consisting of 50 pulses. In addition, only one of the five pulses measured by the LSD was accompanied by a weak 1.4 MeV pulse delayed by 278 μs after the trigger one. On average, if an antineutrino had been registered, three pulses would have been accompanied with the registration of a 2.2 MeV γ quantum generated in the neutron capture. The probability that only one neutron was registered under such conditions is less than 5%. The absence of a significant signal detected in three detectors at 2:52 in no way compromises the LSD signal. It means that the LSD measured an event that none of the other three detectors was able to detect. This is related to the presence of 200 tons of iron in the LSD owing to which an electron neutrino was detected in the reaction

$$\nu_e + {}^{56}\mathrm{Fe} \to e^- + {}^{56}\mathrm{Co}^* \to {}^{56}\mathrm{Co} + \gamma\,. \qquad (6)$$

Large scintillation counters are efficient in registering the electrons and γ quanta flying from iron to the scintillator. As shown in [40, 41], there is no reason to consider the LSD effect at 2:52 UT as a statistical phenomenon or background.

The standard collapse model fails to provide any explanation for the effect measured at 2:52 UT by the LSD. An interpretation of the effect is provided by the rotating collapsar (collapsed star) model proposed by Imshennik [42] in 1995. He named the model, which was developed to explain the mechanism of shell blow-off at the final stage of the evolution of massive main-sequence stars, the rotating collapsar model (RCM). This model offers a different view of the final stage of star evolution. The central part of the star is strongly distorted as a result of rotation and acquires a pancake-like shape. The temperature in the star core is two orders of magnitude lower than in the spherically symmetric model, and the energy of the electron neutrinos generated in the process of star neutronization is 25–55 MeV rather than 100–200 MeV. Because the cross section of interaction of such neutrinos with matter is several times smaller, and the amount of matter in the broad end close to polar directions is significantly smaller than in the spherically symmetric model, the neutrinos leave the star core and reach the star surface virtually without interaction, preserving their initial energy of about 25–55 MeV.

The rotation results in an instability of the star core at the neutronization stage: the star falls apart. It breaks in the simplest case into two stars that form a binary system of neutron stars rotating with respect to each other. Matter is transferred from the lighter and less dense star to the heavier and denser one. When the light-star mass decreases to 0.095 of the solar mass, the gravitational force can no longer maintain its stability, and the star explodes. This event is observed as a supernova burst. After that, the second, heavier, star collapses in a way similar to that described in the standard collapse model.

Thus, the RCM predicts that a two-stage collapse can occur with no fewer than two neutrino bursts separated by a several-hour-long time interval. Primarily electron neutrinos are emitted with an average energy of 30–40 MeV at the first stage, while at the second stage neutrinos of all types are radiated with average energies of 10–15 MeV, as in the standard collapse model.

We note that recent data of the NuSTAR (Nuclear Spectroscopic Telescope ARray) experiment, where X-ray radiation in the sky is studied [43], evidence that the SN1987A collapse was asymmetric.

A detailed analysis of the situation related to the burst of SN1987A is presented in [44–46].

A continuous search for neutrino radiation from collapsing stars has been conducted at INR for 40 years using the following detectors:

(1) ASD (Collapse), Artyomovsk, 105 tons of liquid scintillator and > 1,000 tons of NaCl, 1977;

(2) BUST, 200 tons of liquid scintillator and 160 tons of iron, 1978;

(3) LSD, Mont Blanc, 90 tons of scintillator and 200 tons of iron, 1984–1998;

(4) LVD, Gran Sasso, 350 tons of scintillator and 330 tons of iron (since 1992) and 1,000 tons of scintillator and 1,000 tons of iron (since 2001).

No neutrino radiation from gravitational collapses of stars in the Galaxy and Magellanic Clouds, including hidden ones (without shell blow-off), has been observed by those detectors during the 30 years of operations. The LVD is registering data 99% of live time. The LVD has been part of SNEWS (SuperNova Early Warning System) since 2004 [47].

A correlation analysis of individual detector pulses is conducted at the LVD jointly with the ASD and BUST to verify the reliability of neutrino signals and confirm experimental data pertaining to the burst of SN1987A [48].

The LVD also conducts experiments related to underground studies of the muon component of cosmic rays. The depth–muon-intensity curve has been measured to a depth of 17 water equivalent kilometers, together with variations in the muon intensity and muon charge ratio. The characteristics of muon groups (multiplicity and decoherence curve) have been determined [49].

The accuracy in reconstructing muon events enabled the LVD to impose a bound on the velocity of CNGS neutrinos.[1] The neutrino velocity was found to coincide with the velocity of light at a 99% confidence level [50].

The LVD is also studying the flux of the neutrons generated by cosmic-ray muons underground as a source of the background in low-background underground experiments. Spatial distributions and seasonal variations of neutrons [51] and the yield of neutrons generated by 280 GeV muons in a scintillator and iron have been measured. The energy spectrum of muon-generated neutrons has been measured in the range 10–500 MeV [52].

Owing to the low energy threshold and continuous operation mode, the LVD can maintain control of radon concentration; this capacity can be used for studying relations between seismic activity and variations in radon concentration underground [53].

The basic concepts of those studies were established by Zatsepin in the early 1960s.

5. Conclusion

Zatsepin was the head of the FIAN Neutrino Laboratory for seven years, and afterward, for almost 40 years, he was head of the INR OLVENA department.

[1] CNGS (CERN Neutrino to Gran Sasso) is the flux of neutrinos from CERN to Gran Sasso.

The studies that Zatsepin conducted for many years in cosmic-ray physics and neutrino astrophysics were very fruitful. They have won well-deserved international recognition and, in some areas, have set trends for the development of world physics.

Zatsepin created a great school of theoretical and experimental cosmic-ray physics and neutrino physics and astrophysics, the importance of which extends far beyond Russia and the former Soviet Union; it also plays a significant role in the countries of Europe, the Americas, and Asia. Many of Zatsepin's students became well-known researchers.

Zatsepin was awarded the Orders of Labor Red Banner (1975 and 1981), October Revolution (1987), and For Services to the Fatherland, 4th class (1997), and the medal For Valorous Labor during the Great Patriotic War, 1941–1945. He was a winner of the USSR State Prize (1951) for the discovery of the nuclear-cascade process, the Lenin Prize (1982) for the creation of the Yakutsk cosmic-ray facility, the Russian Federation State Prize (1998) for creating the Baksan Neutrino Laboratory and conducting studies at the facility, the Pontecorvo international prize (RAS, 2001), the MSU prize (2002), the Markov prize (INR, 2002), and the Skobeltsyn gold medal of the RAS (2005).

Zatsepin was awarded the Lódź University medal (Poland, 1986) and the O'Kelly medal (International Union of Theoretical and Experimental Physics, 1999) and received a Doctor Honoris Causa degree from the Institute of Physics of the University of Turin, Italy (2007). He was awarded the Order of Honor in 2008.

Zatsepin had a vision of the future development of science that universally proved correct and extended far into the future. This especially applies to neutrino astrophysics, of which he is one of the founders. Owing to his creative activity, encyclopedic knowledge of physics, medicine, and history, and remarkable memory, Zatsepin always attracted many people of different ages. He had scientific intuition and commitment to science combined with a natural delicacy and considerate attitude toward people.

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