Physics – Uspekhi **56** (3) 296 – 310 (2013)

CONFERENCES AND SYMPOSIA

PACS numbers: 01.10.Fv, **01.65.+g**, **26.65.+t**, 95.55.Vj, 95.85.Ry, 98.70.Sa

100th anniversary of the discovery of cosmic rays (Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 24 October 2012)

DOI: 10.3367/UFNe.0183.201303g.0315

A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS), entitled "100th anniversary of the discovery of cosmic rays," was held on 24 October 2012 in the conference hall of the Lebedev Physical Institute, RAS.

The agenda of the session announced on the RAS Physical Sciences Division website www.gpad.ac.ru included the following reports:

(1) **Panasyuk M I** (Skobeltsyn Institute of Nuclear Physics of the Lomonosov State University, Moscow) "The contribution of Russian scientists to the centennial history of the development of the physics of cosmic rays";

(2) **Ryazhskaya O G** (Institute for Nuclear Research, Russian Academy of Sciences, Moscow) "On experiments in underground physics";

(3) **Krymskii G F, Berezhko E G** (Shafer Institute of Cosmophysical Research and Aeronomy, Siberian Branch of the Russian Academy of Sciences, Yakutsk) "The origin of cosmic rays";

(4) **Stozhkov Yu I** (Lebedev Physical Institute, Russian Academy of Sciences, Moscow) "Cosmic rays in the heliosphere";

(5) **Troitsky S V** (Institute for Nuclear Research, Russian Academy of Sciences, Moscow) "Cosmic particles of energies $> 10^{19}$ eV: a short review of results."

Papers based on reports 2 and 5 are presented below.

Uspekhi Fizicheskikh Nauk **183** (3) 315 – 330 (2013)
DOI: 10.3367/UFNr.0183.201303g.0315
Translated by G Pontecorvo, S V Troitsky; edited by A M Semikhatov

PACS numbers: **01.65.+g**, **26.65.+t**, 98.70.Sa
DOI: 10.3367/UFNe.0183.201303h.0315

On experiments in Underground Physics

O G Ryazhskaya

1. Introduction

In this article, I would like to present my vision of the main historical steps undertaken in establishing underground physics, to note the most important topics incorporating the work performed during this period, and to recount the most interesting modern experiments. Underground physics is discussed here as an effective method for studying a broad class of rare processes in cosmic ray and elementary particle physics, especially relevant to the role of neutrinos in astrophysics. My work has always been associated with the development of underground physics in Russia. In the course of such activity, I have collaborated for many years with the underground Gran Sasso National Laboratory (Italy), where the 1000-tonne LVD (Large Volume Detector) scintillation detector constructed by us along with our Italian colleagues is situated. I hope readers will understand the somewhat subjective nature of my account due to the above circumstance.

I would like to emphasize that experiments in modern underground physics pertain to an extremely labor-consuming field of intellectual activity. Large groups, often collaborations, of physicists work here, and the most important contributions are due to such groups.

2. Study of the penetrating component of cosmic rays underground

Experiments that initiated underground physics were performed simultaneously with the discovery and investigation of the nature of cosmic rays (CRs). Physicists study CRs at sea level, in the mountains, in the upper layers of the atmosphere with the aid of balloons, underground, and underwater.

Both Domenico Pacini (Italy) and Lev Myssowsky (USSR), who installed their experimental apparata underwater, can be considered pioneers of such studies. The first did so in 1905–1912 [1], and the second in 1926–1929 [2]. During the next 40 years, especially after the discovery of the muon in 1937 [3, 4], a large group of physicists actively studied the muon component underground. The depth dependence of the muon intensity was measured down to 7000 meters of water equivalent (m.w.e.) [5–10].

Since the 1960s, underground experiments have been dominated by neutrino research. This, first of all, concerns studies of neutrinos of atmospheric origin. Zatsepin and Kuz'min, as well as Markov and Zheleznykh [11–13] calculated the fluxes of neutrinos approaching Earth at different angles, both from the upper hemisphere and from the opposite side of Earth.

In 1963–1969, in three experiments: (1) Menon, Wolfendale, et al. [14] (the Kolar Gold Fields mines (India), depth 7500 m.w.e.), (2) Reines, Cropp, et al. [15] (a mine near Johannesburg (South Africa), depth 8640 m.w.e.), and

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Uspekhi Fizicheskikh Nauk **183** (3) 315 – 323 (2013)
DOI: 10.3367/UFNr.0183.201303h.0315
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(3) Keuffel et al. [16] (Utah, USA, depth 1500 m.w.e.), the fluxes of atmospheric neutrinos were first measured for angles $\theta > 50°$ (experiments 1 and 2) and $\theta > 90°$ (experiment 3). The data of these experiments are consistent with a linear growth of the total cross section of neutrino–nucleon interaction with energy [17]. The statistical accuracy of the experiments was not high.

Experiments with neutrinos clearly revealed that success can be achieved only with large detectors of masses 100–1000 t, capable of providing information on particle trajectories. Moreover, it is very important to know the background conditions in underground laboratories. These issues became especially important in connection with proposals to detect solar neutrinos [18, 19], to carry out work for experimental confirmation of the existence of neutrino oscillations, and to search for and detect neutrino radiation from collapsing stars.

The neutrino (ν) is a weakly interacting particle that can be detected either by measurement of the products of its interaction with nuclei or by measuring νe^- scattering. Such events are rare, and it is therefore important to reduce the background capable of simulating the effect. The main source of the background in the case of underground experiments at a depth H (m.w.e) are the muons in CRs, which have a mean energy $\bar{E}_\mu(H)$ equal to several hundred GeV.

Owing to bremsstrahlung, when such muons pass through the ground, they generate electromagnetic cascades whose gamma quanta interact with the nuclei of the ground: $\gamma A \to A' + (\pi^\pm, \pi^0, p, n, \alpha, \ldots)$. In these reactions, a small number of particles are produced that interact with the nuclei and represent a dangerous background in search experiments.

Such a standpoint on the nature of underground backgrounds existed for quite a long time, even though the general impression was that backgrounds were clearly underestimated within the scheme indicated. The opinion concerning this issue changed drastically after calculations were performed by Zatsepin and Ryazhskaya [20] (1965). The authors of [20] examined all possible production channels of particles capable of interacting with nuclei and showed that such particles are mainly produced in nuclear showers generated in deep-inelastic interactions of muons with nuclei in the ground in reactions such as $\mu A \to \mu + m\pi + \chi$, where $m\pi$ is the total amount of pions and χ are nuclear fragments. As a result, the background at a depth of 4000 m.w.e., for example, increases by a factor of 2.5 compared to the estimates that take only the electromagnetic interaction of muons with the ground into account (Fig. 1). Here, background events with an energy exceeding 100 MeV are only due to the deep-inelastic interaction of muons.

The results of these calculations were confirmed in a series of experiments performed by Ryazhskaya and collaborators with the aid of a large liquid-scintillator (LS) detector constructed by them. The authors measured the number of neutrons underground at different depths: 25, 316, 570 m.w.e. (Artiomovsk, 1968–1987) [21–24] and down to 5400 m.w.e. (Mont Blanc, 1985–1998) [25, 26], as well as the energy dependence of the numbers of neutrons and of $\pi \to \mu \to e$ decays in electromagnetic and nuclear showers at a depth of 570 m.w.e. in the salt mines near Artiomovsk (Fig. 2). The underground production of neutrons was shown to depend not only on the muon intensity $J_\mu(H)$ but also on the average muon energy at a given depth H as $\bar{E}_\mu^{0.75\pm0.5}(H)$, and the number of neutrons and π mesons produced in nuclear

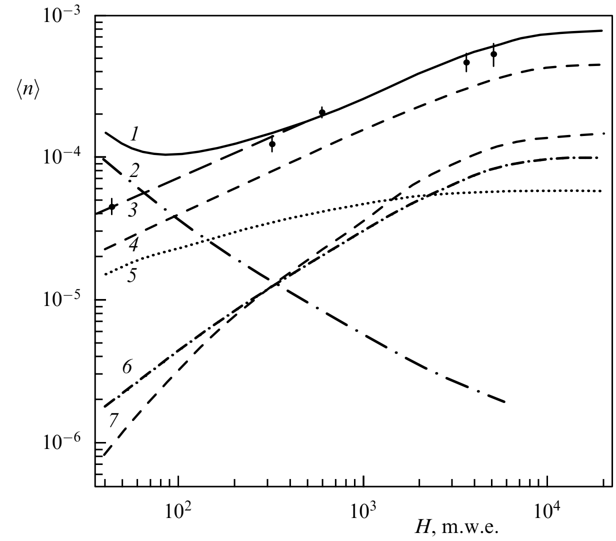

Figure 1. Dependence of the number of slow neutrons produced per g cm^{-2} of ground reduced to a single muon on the depth. *1* — the total number of neutrons produced in all processes; *2* — the number of neutrons generated by μ^- capture; *3* — the number of neutrons produced in all processes but μ^- capture; *4* — the number of neutrons generated by virtual photons with account of nuclear showers; *5–7* — the number of neutrons generated by photons of electromagnetic showers, respectively induced by δ-electrons, e^+e^--pairs, and bremsstrahlung. The black dots represent experimental data. To estimate the backgrounds registered by Cherenkov and scintillation detectors at different depths, the curves are normalized (with the normalization coefficient ≈ 0.7) to the results of the experiment performed at a depth of 25 m.w.e. with the aid of an LS detector.

showers turned out to be approximately 10 times larger than in electromagnetic showers [27].

The established concept of the nature of underground backgrounds, substantiated theoretically and confirmed experimentally in these studies, currently determines the quality and confidence level of all fundamental search experiments, without any exception.

The construction of large underground detectors followed several lines. Instead of expensive plastic scintillators requiring a complicated construction technology, it was proposed to use LSs, whose construction technology is simple and which are readily made in nonspecialized laboratories. These LSs based on cheap and accessible oil products are fast, transparent to their own radiation, and generally quite safe and convenient to operate. As an alternative to LSs, kiloton water Cherenkov detectors were proposed. To make them competitive in sensitivity, it was necessary to increase the relative photocathode area of their photomultiplier tubes (PMTs) by an order of magnitude over the standard for LS detectors. Besides the energy release, Cherenkov detectors permit determining the vertex and the angle of the particle trajectory, which are often valuable. An example of such a Cherenkov detector was Kamiokande II (K II) with a water mass of 2.14 kt [28]. As regards large detectors based on LSs, it is first of all necessary to mention the Baksan underground scintillation telescope (BUST) with an LS mass of 330 t, constructed by Chudakov and collaborators [29] in 1978. The liquid scintillator for this detector was designed by staff members of the Institute for Nuclear Research (INR), Voevodsky, Dadykin, and Ryazhskaya, in 1966 [30]. Precisely in this period we proposed and realized the main techniques with the aid of which all the large INR under-

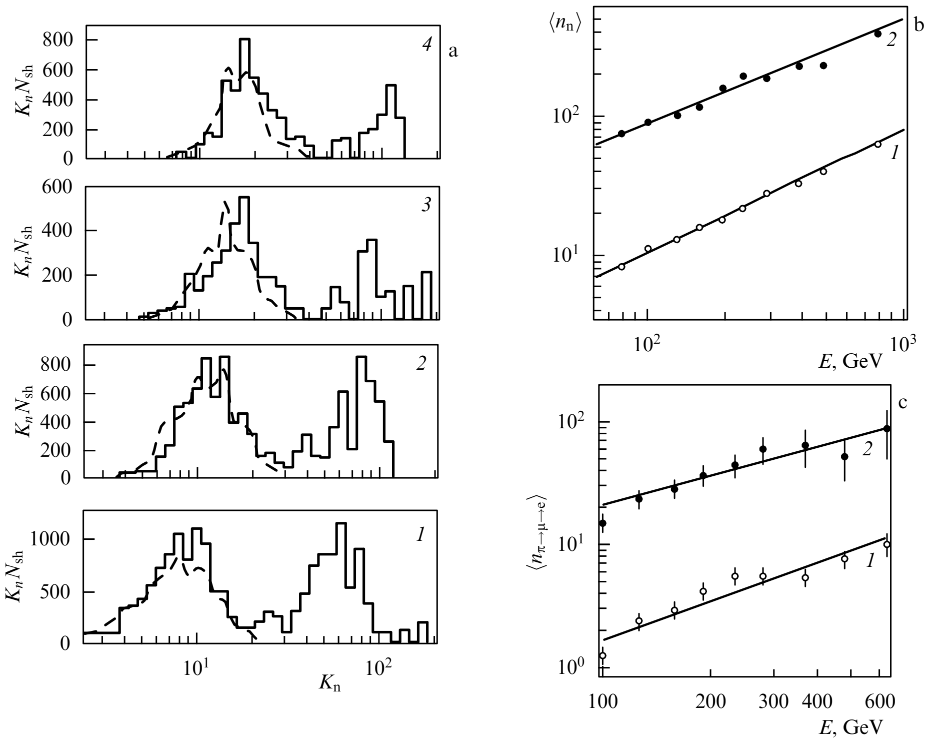

Figure 2. (a) Dependence of the number of showers N_{sh} on the number of neutrons registered in them, obtained with the aid of the ASD detector. K_n is the neutron multiplicity. The histograms show experimental results. The dashed curves show the results of Monte Carlo calculations. *1* — $\Delta E = 90-115$ GeV, *2* — $\Delta E = 145-170$ GeV, *3* — $\Delta E = 212-250$ GeV, *4* — $\Delta E = 250-344$ GeV. (b) Dependence of the average number of slow neutrons $\langle n_n \rangle$ on the energy release E in detectors of nuclear (*2*) and electromagnetic (*1*) showers. (c) Dependence of the average number of $\pi \to \mu \to e$ decays, $\langle n_{\pi\to\mu\to e} \rangle$, on the energy release and electromagnetic (*1*) showers.

ground detectors were constructed. This stage of work, which was important in developing underground physics in Russia, has been accurately presented in detail in the preprint by Dadykin "On the BUST installation history" [31]. Since 1977, we have constructed ASD (Artiomovsk scintillation detector (1977) [32], BUST (1978), LSD (Liquid Scintillation Detector) (1984) [33], and LVD (1992, 2001) [34, 35]. Much has been said about the merits of the LS we developed. One important circumstance is worth noting. The first underground detectors with this LS have already been in use for over 35 years, and in all this time, not even in a single detector has any scintillator lost its starting conditions. This superstability of our LS permits applying it effectively in long-term megaprojects such as the program of searching for and studying neutrinos from collapsing stars.

Besides the aforementioned scintillation and Cherenkov detectors, iron calorimeters with various devices for determining the trajectory coordinates of registered particles have been used in underground neutrino experiments since the 1980s. These are Fréjus [36, 37] with spark chambers and Geiger counters, NUSEX (NUcleon Stability EXperiment) [38] with streamer chambers, and Soudan 2 [39, 40] with proportional drift tubes. One of the most perfect scintillation detectors of its time, KGF (Kolar Gold Fields) [14], equipped with a magnetic spectrograph and neon tubes, is still in operation. Later, the scintillation detector MACRO (Monopole, Astrophysics, and Cosmic Ray Observatory) [41], with streamer chambers, the Cherenkov water detector IMB (Irvine–Michigan–Brookhaven) [42], with a mass of 5 kt, and the largest of all the modern Cherenkov detectors, SuperK [43], with an active water mass of 22.5 kt, were constructed.

With the aid of underground detectors, the intensity of muons has been measured at depths down to $H =$ 18,000 m.w.e. The muon intensity has been shown to saturate at $H > 15000$ m.w.e., because at such depths the main flux of muons is produced in interactions of atmospheric neutrinos with nuclei in the ground (Fig. 3) [44, 45].

In these experiments, the muon bremsstrahlung cross section and the muon inelastic interaction cross section were also measured for energy transfers up to 3 TeV [46]. Muon energy spectra were studied, and characteristics of the spectra of π and K mesons and of the parent muons were obtained at $E \approx 40$ TeV [47].

The BUST, KGF, Fréjus, MACRO, and Soudan 2 detectors were used in searches for astrophysical pointlike sources of neutrinos by observing muons arriving at the detectors from directions where the background of atmospheric muons was minimal: from the opposite side of Earth and close to the horizon [47].

Such sources have not yet been identified. Currently, only the upper bounds have been obtained for the neutrino fluxes from these sources: $\leqslant 10^{-15}$ cm^{-2} s^{-1}.

3. Detection of solar neutrinos and experimental studies of neutrino oscillations

The idea that neutrinos of one type can spontaneously transform into neutrinos of another type and back was put forward by the Soviet physicist Pontecorvo [48] in 1958. In 1968, Davis [18] measured the flux of solar neutrinos, which turned out to be three times smaller than predicted by the standard solar model (SSM) [49, p.104]. This fact was interpreted as the result of neutrino oscillations, and it

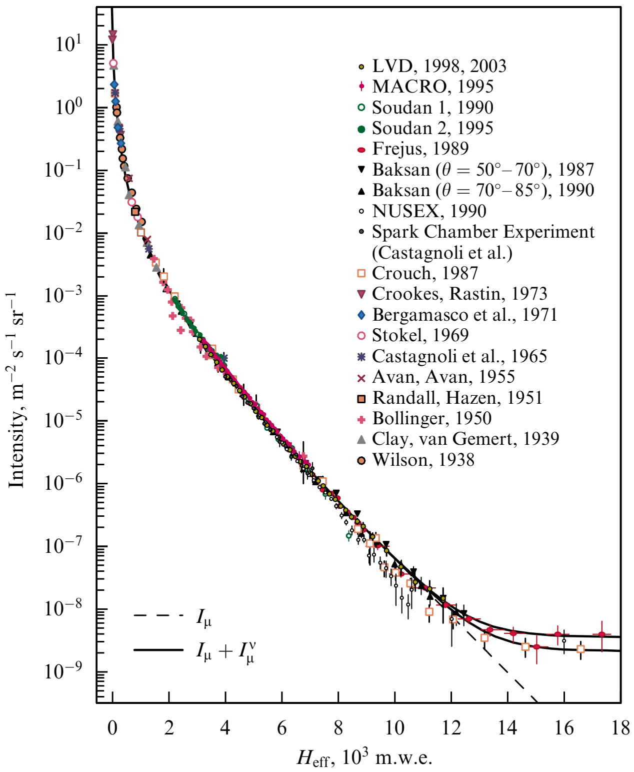

Figure 3. Dependence of the muon intensity on the effective depth of the soil, H_{eff} [44, 45].

strongly renewed interest in Pontecorvo's idea. The hypothesis of neutrino oscillations was developed by S M Bilenky, B M Pontecorvo, S P Mikheev, A Yu Smirnov, L Wolfenstein, C Giunti, and others [50, 51], and it acquired a modern approach.

About ten groups of physicists tried to confirm the existence of oscillations in experiments with atmospheric neutrinos. In these experiments, neutrinos were observed that arrived at underground detectors from the lower hemisphere of the opposite side of Earth and along nearly horizontal directions. The background from CR muons in all these directions was minimal. Such an experiment is essentially simple. Atmospheric neutrinos ν_μ and ν_e interact in the detector or near it. The first produce a muon, i.e., a single particle, in the detector, and the second produces an electromagnetic cascade, i.e., many particles, and in this case no muon is present. This allows determining the number of registered ν_μ and ν_e. The result obtained is compared with calculations. The experimenters represented the results in the form of a double ratio of the number of registered ν_μ and ν_e, $R^{data}_{(\mu/e)}$, and the corresponding number calculated by the Monte Carlo method, $R^{MC}_{(\mu/e)}$, i.e., the quantity $R = R^{data}_{(\mu/e)}/R^{MC}_{(\mu/e)}$. If there are no manifestations of oscillations in the experiment, then $R = 1$. A significant deviation of R from unity can be interpreted as the influence of oscillations.

The following detectors were used in these experiments (listed in the order of increasing depths): IMB ($H = 1570$ m.w.e.), Soudan 2 (1800 m.w.e.), KII (2700 m.w.e.), SuperK (2700 m.w.e.), MACRO (3650 m.w.e.), Fréjus (4710 m.w.e.), NUSEX (5300 m.w.e.). For the first five detectors, the values obtained for R varied from $0.54 \pm 0.02 \pm 0.07$ to $0.71 \pm 0.05 \pm 0.18$, while for the last two, at the largest depths, R was close to unity: $1 \pm 0.15 \pm 0.08$ and 0.99 ± 0.25 [47].

A large spread can be seen to exist in the values of R. This is related to the inaccuracies in calculations of the generation of different sorts of neutrinos in the atmosphere, in the calculated interaction cross sections of ν_e and $\tilde{\nu}_e$ with matter, and in taking the dependence of the calculated ratio on the geomagnetic effect into account. Attention must also be drawn to the fact that events interpreted as caused by ν_e may be simulated by the backgrounds, discussed above, of particles capable of interacting with nuclei and generated near the detector. The main risk is here due to isolated neutrons with energies exceeding 400 MeV, which easily penetrate several meters of shielding and can generate a cascade simulating the registration of ν_e in the detector. The influence of this effect decreases with the depth of the detectors and is manifested less in the results from Fréjus and NUSEX.

Experiments in which a neutrino beam from a modern proton accelerator is directed through a large thickness of ground toward an underground detector seem to be more promising. In such experiments, the detector registers a flux nearly 99% of which consists of muon neutrinos. The direction and energy spectrum of this flux, synchronized with the accelerator beam, are well known. At present, such experiments at various accelerators are under way with the detectors SuperK (Tokai-to-Kamioka, the T2K experiment) [52], OPERA (Oscillation Project with Emulsion-tRacking Apparatus) (CERN Neutrinos to Gran Sasso, the CNGS experiment) [53], ICARUS (Imaging Cosmic And Rare Underground Signals) (CNGS) [54], and MINOS (Main Injector Neutrino Oscillation Search) (NuMI, Neutrinos at Main Injector) at Fermilab [55, 56].

For data analysis, it is very important to know the neutrino beam composition at the exit from the decay channel. The detector nearest to the accelerator, which should control the composition of the beam at its exit, cannot always be placed where it should be, and this may give rise to difficulties. If the nearest detector is too close to the accelerator, it is overloaded with background events, which significantly complicates processing data from it. It is desirable that both detectors, the nearer and the more distant ones, be of the same type, which simplifies the analysis of experimental results.

The uncertainties in calculations here are naturally smaller than in the case of experiments with atmospheric neutrinos, but calculations are necessary in any case. The disappearance of ν_μ from the beam may not only be a result of oscillations, but also be due to scattering in the 1000 kilometer thickness of soil along the path from the accelerator to the detector. Everything that is not taken into account by calculations is attributed to the result of oscillations.

A way of studying oscillations that is more independent of calculations consists in looking for the 'appearance' in the detector of, say, τ-mesons, that could never be produced by the ν_μ beam from the accelerator in the absence of oscillations. Recently, observations of τ-like events in the OPERA [57] and SuperK [58] detectors were announced. The authors of the experiments are analyzing the registered data.

We digress from oscillation experiments to discuss how we applied the CNGS beam for a totally different purpose, namely, for studying underground backgrounds. For a long time, I have wanted to use the LVD detector for measuring the number of neutrons produced not by atmospheric muons but by muons produced by ν_μ deep underground, where the muon intensity becomes constant. For this, it is necessary to work with muons arriving at the detector from directions where there are practically no atmospheric muons, i.e., from the region close to the horizon and from the lower hemisphere. Collecting the statistics for these directions would require a period of several decades. The lucky possibility to use a neutrino beam from an accelerator instead of atmospheric ν_μ permitted us to reduce this time by approximately a factor of 20. At present, the results are being processed and are being prepared for publication.

In another experiment, involving the use of the LVD detector (CNGS), we measured the speed of ν_μ in the beam along a path 732 km long from CERN to Gran Sasso. The result depended on three quantities: the path length, the starting time of the neutrinos, and their arrival time. In principle, an uncertainty is present in the starting time, which is determined by the probabilistic character of ν_μ production in the decay channel. To enhance the precision of determining the starting time, bunches 3 ns long were used in the experiment. Synchronization of the measurements in the detector with these bunches was provided by CERN. The path length was determined by a geodesic service, while we measured the arrival time ourselves.

In the period from 10 to 24 May 2012, the LVD detector registered 48 muon neutrinos with an average energy of 17 GeV. The result of this experiment turned out to be quite predictable. The following relative difference between the neutrino speed and the speed of light was obtained at a 99% confidence level: $-3.3\times10^{-6} < (v_\nu - c)/c < 3.5\times10^{-6}$ [59].

Proceeding to a discussion of the question of the Sun, we note that thermonuclear transformations of hydrogen into helium, accompanied by intense emission of electron neutrinos, serve as the source of solar energy. The first measurements of ν_e from the Sun, initiated by Davis in 1968, have been under way for about 20 years [18; 49, p. 333]. In these experiments, a radiochemical detector of ν_e proposed back in 1946 by Pontecorvo [60] was used. A chlorine-containing liquid of mass 615 t was exposed underground at a depth of 4.1×10^3 m.w.e. in conditions of a reduced CR background. Radioactive ^{37}Ar atoms produced in the reaction ^{37}Cl (ν_e, e$^-$) ^{37}Ar were extracted from the detector by barbotage and pumped into a proportional counter to count the number of ^{37}Ar atoms accumulated during the exposure ($\approx$ 30 days). The authors took all the measures necessary to provide reliability of the experimental results. Two very important facts were readily established: a neutrino emission from the Sun actually exists, but the number of registered ν_e is three times smaller than expected in accordance with the standard solar model (SSM). Measurements performed in subsequent years introduced corrections, but did not essentially change the result. This experiment was sensitive to approximately 6% of all the ν_e from the Sun.

Two other experiments with ^{71}Ga$(\nu_e, e^-)\,^{71}$Ge radiochemical detectors, which operated in a way similar to the experiment performed by Davis, also revealed a nearly twofold deficit of the neutrino flux from the Sun compared to the SSM predictions. These are the experiments SAGE (Baksan neutrino observatory, the Soviet–American Gallium Experiment, V N Gavrin et al., with 50 t of ^{71}Ga and $H = 4700$ m.w.e., started in 1991 and still under way today) [61, 62], and GNO (Gallium Neutrino Observatory) + GALLEX (Gallium solar neutrino experiment) (international collaboration, Gran Sasso — 30 t ^{71}Ga, $H = 3650$ m.w.e., 1991–2008) [63]. Owing to the very low energy threshold in the ^{71}Ga (ν_e, e$^-$) ^{71}Ge reaction, gallium experiments are sensitive to nearly 100% of the ν_e emitted by the Sun, which is very important. The idea of a gallium experiment was put forward in 1964 by Zatsepin and Kuz'min [19].

Solar neutrinos were also measured by the Borexino scintillation detector (international collaboration, Gran Sasso, with 300 t pseudocumene and $H = 3650$ m.w.e., started in 2007 and still ongoing) [64, 65]. Owing to special purification measures for freeing the scintillator from natural radioactivity, this detector turned out to be the most sensitive (with a threshold of 0.2 MeV) of all the devices registering neutrinos by ν_ee scattering. Measurements confirmed the existence of a deficit of solar neutrinos.

In three other experiments, solar neutrinos were measured by $\nu_e e^-$ scattering with the aid of Cherenkov detectors: the aforementioned KII (2.14 kt of water) and SuperK (22.5 kt of water) [66, 67], and the SNO detector (Sudbury Neutrino Observatory), which is discussed in greater detail below. Cherenkov detectors measure the trajectory angles of the registered charged particles. With account of the strong angular anisotropy of $\nu_e e^-$ scattering, the experiments demonstrated that the particles indeed arrive from the Sun, as was expected. The large deficit of ν_e compared with the flux of ν_e expected in accordance with the SSM remained the same in these three measurements.

The common opinion was that the deficit of neutrinos revealed by all the radiochemical, scintillation, and Cherenkov detectors tended to be considered a manifestation of oscillations. However, all the aforementioned experiments were based on the disappearance scheme, and hence there essentially always remained a possibility of explaining the deficit of neutrinos by some correction of the SSM or by an underestimation of certain computational factors. From this standpoint, the result obtained with the SNO detector is very important.

The SNO Cherenkov detector (Sudbury, Ontario, Canada, A B McDonald et al.; 1 kt of heavy water, D_2O, $H = 6000$ m.w.e., 1999–2010) [68–70] measured solar ν_e not only by the $\nu_e e^-$ scattering but also by the reaction $D + \nu_e \rightarrow 2p + e^-$, charged currents (CCs) and any type of neutrino by the reaction $D + \nu_i \rightarrow p + n + \nu_i$, where $i = e^-, \mu^-, \tau^-$, and neutral currents (NCs). The authors took special measures that permitted registering neutrons produced in reactions by neutral currents.

The results of measurements using CCs confirmed the existence of a deficit of ν_e, while measurements by NCs did not reveal it. This may point to the deficit of ν_e being due to oscillations.

But it must be noted that in the SNO experiment with the detection of neutrons produced in reactions by NCs, the authors do not discuss how they account for the background related to fast neutrons produced by CR muons in the soil. In principle, these neutrons could compensate the deficit of solar neutrinos, obtained in measurements using CCs.

It is clear from the foregoing that experiments on registering solar neutrinos are closely related to the issues of investigating neutrino oscillations. Here, attention must be drawn to the fact that most of the experiments that prove the existence of neutrino oscillations more or less convincingly were performed according to the disappearance scheme. This concerns all the experiments with atmospheric neutrinos, the major part of experiments with neutrino beams from accelerators, and the results of observations of solar neutrinos. In other words, we constantly attempt to prove the existence of certain phenomena on the basis of not finding something. Here, an alternative exists: maybe we just search badly? It always seemed to me that everything would be resolved if we see how one type of neutrino transforms directly into another type; in other words, we need experiments according to the 'appearance' scheme. Actually, proofs of existence are more convincing than proofs of the fact of absence. Therefore, it seems to me that success is for those who are capable of convincingly identifying the appearance of a τ-meson in a detector. And the existence of nuclear emulsions in the OPERA experiment may provide certain advantages for fulfilling this task.

4. Searching for and detecting neutrinos from gravitational collapses of stars

Theory predicts that the evolution of massive main-sequence stars may come to an end by a gravitational collapse and a powerful short pulse of neutrino emission [71]. In the standard collapse model (SCM) (of a spherically symmetric, nonrotating, nonmagnetic star), all types of neutrinos are emitted in equal energy parts [72]. In this case, it is most natural to try to register a flux of electron antineutrinos produced in a reaction involving hydrogen, which has the maximum cross section. For this, an underground detector is required that is well shielded from the cosmic ray background and involves 100 t, or even better, 1000 t of a substance containing hydrogen as a target for the reaction $\tilde{\nu}_e p \to e^+ n$. The effect due to a collapse is identified by the appearance, during 20 s, of a statistically rare concentration of pulses registered by the detector. An important point is the coincidence in time of the effect and the optical observation of the burst of a supernova. Significant improvement in the reliability of results can be achieved by parallel operation of several detectors placed at different points on the globe.

The study of neutrino radiation from the collapse of stars will permit obtaining information on the behavior and properties of matter in the extreme conditions of nuclear density, of superhigh temperatures and pressures, of powerful gravitational fields, of the formation of neutron stars and black holes — the most fundamental processes in the Universe, which can make the results of experiments especially valuable.

At the INR, since the end of the 1970s, we have constructed several large underground scintillation detectors capable of measuring the neutrino radiation from a collapse: ASD (1977), BUST (1978), LSD (1984), and LVD (the first 330 t, 1992). The last two detectors were constructed jointly with our Italian colleagues in a tunnel under Mont Blanc and in a tunnel under Gran Sasso.

On 23 February 1987, when the supernova SN1987A burst in the Large Magellanic Cloud galaxy, the BUST and LSD detectors were in operation. The ASD detector was, regretfully, switched off at that moment, but luckily two Cherenkov detectors, KII and IMB, intended for searches for proton decay, were in operation. The burst was very distant, at a distance of 50 kpc. Therefore, the signals in the detectors were small and statistically unreliable, while the schemes of interpretation gave rise to questions and doubts. Nevertheless, the information obtained on 23 February 1987 turned out to be interesting and instructive [73–75] (Figs 4, 5).

First of all, the registration of neutrinos from the SN1987A collapse is an outstanding achievement in experimental neutrino astrophysics of recent years, not only because the result is fundamental but also because the fact itself is highly convincing. Three aspects must be singled out in the data analysis.

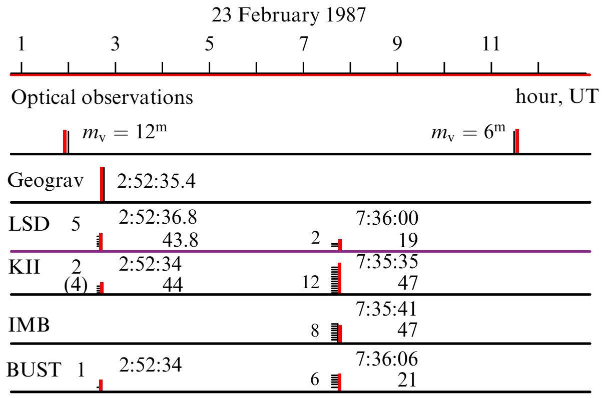

Figure 4. Time sequence of events registered by different detectors on 23 February 1987 [62]. For each neutrino detector, the y axis arbitrarily shows the number of pulses in the bunch; the nearby numbers are the arrival times of the first and last pulse (m_v is the visible stellar magnitude, 6^m and 12^m are the 6th and 12th stellar magnitudes, Geograv is the gravitational antenna in Rome.)

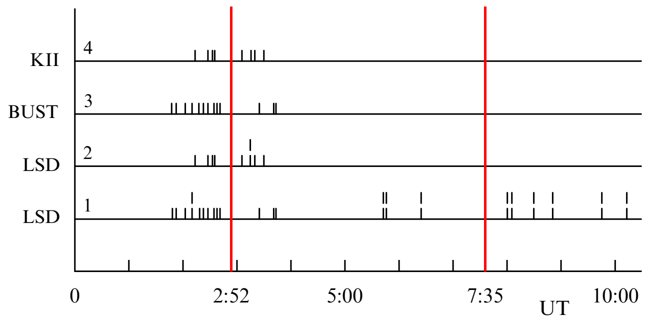

Figure 5. Time diagram of pulses in BUST (line 3) coinciding with the pulses in LSD (line 1) in a time window of 1 s, and similar coincidences for KII (line 4) and LSD (line 2), and also double pulses in LSD (line 1, time interval 5:42–10:13 UT) on 23 February 1987. The average frequency of background coincidences for both experiments by correlations, BUST–LSD and KII–LSD, was measured within the interval 23.02.1987 ± 15 days and turned out to be approximately the same, about 1 h^{-1}. The measured average frequency of background double pulses during the same period is 0.275 h^{-1}. The figure does not show the background for coincidences outside the interval 1:45–3:45 UT and the background for double pulses outside the interval 5:42–10:43 UT.

(1) The relation between registration of neutrinos from SN1987A with the aid of the KII and IMB detectors at 7:35 UT (Universal Time) has led to a stable opinion, formed from the very beginning, that the result confirms the SCM well. If the SCM is realized, a great majority of interactions in the Cherenkov counters must be caused by the reaction $\tilde{\nu}_e p \to e^+ n$, and the energy spectrum of the positrons registered by the detector must be consistent with the spectrum expected in this model and serve as good and conclusive proof. Therefore, to verify that the SCM is realized, it is necessary to show that the main part of pulses is precisely due to the inverse β-decay reaction. This reaction could be identified by the characteristic isotropic angular distribution of positrons in Cherenkov detectors. But the experiment revealed a sharp anisotropy of particles in KII and IMB. The probability of the sum of the pulses from KII and IMB being due to fluctuations and exhibiting an

Table. Main detectors participating in the modern service of searching for neutrinos from star collapses.

Detector	Country*	Mass and type	Number $N_{\tilde{\nu}_e}$ (SCM)**	Number N_{ν_e} (RCM)***
ASD	Russia	0.1 kt LS, 1 kt NaCl	57	44
BUST	Russia	0.2 kt LS, 0.16 kt Fe	67	8
KamLAND	Japan, USA	1 kt LS	500	180
Borexino	Italy	0.3 kt LS	120	60
LVD	Russia, Italy	1 kt LS, 1 kt Fe	500	410
SuperK	Japan, USA	22.5 kt H_2O	9400	650

* Country (countries) that implemented the design and construction of the detector.
** The number of electron neutrinos detected in accordance with the SCM.
*** The number of electron neutrinos detected at the first stage of collapse in accordance with the RCM under the condition of a burst of a supernova such as SN1987A.

anisotropy of the degree observed experimentally does not exceed 2%. The chance that the result of KII and IMB would confirm the SCM for SN1987A must be estimated to be of the same magnitude. As we see, these chances are not high. Therefore, the main SCM parameters cannot be used as the only correct template in the analysis of the experiment with SN1987A.

(2) The effect measured at 2:52 UT by the LSD is absolutely inexplicable in the SCM. This effect was interpreted within a model that takes rotation of the star core into account. This model was constructed by Imshennik [76] in order to obtain the mechanism of shell-shedding at the final stage of evolution of massive main-sequence stars, and he called it the rotating collapsar model (RCM). This model predicts the possibility of a two-stage collapse. At the first stage, mostly electron neutrinos are emitted with the mean energy 30–40 MeV, and at the second stage, all types of neutrinos are emitted, as in the SCM, with mean energies 10–15 MeV.

(3) The data presented in Fig. 5 concerning the mutual correlation of individual pulses in different pairs of neutrino detectors and of double pulses in the LSD have not been explained yet in the framework of modern models.

Commenting on the results presented in Figs 4 and 5, we note that the effects in all detectors at 7:35 UT were doubtless as regards a supernova burst. They coincided in time with each other with a precision of up to a minute, as well as with optical observations of the supernova within several hours. This assertion mainly concerns the KII and IMB detectors, in which the effects were significant, and the probability of simulation negligible. The effects in LSD and BUST at the time were consistent, within the statistical accuracy, with the effects from KII and IMB, with account of the difference in the masses of hydrogen.

The main intrigue of the experiment is related to the LSD. At 2:52 UT, the LSD registered a series of five pulses that arrived within a period of 7 s. This series was evidently not due to the $\tilde{\nu}_e p$ reaction; otherwise, the KII detector would have registered a signal consisting of 50 pulses. The fact that no significant signal was registered at 2:52 UT by the other three detectors does not undermine confidence in the signal from the LSD in any way. Actually, this fact only signifies the following: the LSD registered what none of the other three detectors could register. This is due to the presence in the LSD composition of 200 t of iron and to registration of electron neutrinos by the reaction $\nu_e + {}^{56}Fe \to e^- + {}^{56}Co^* \to e^- + {}^{56}Co + \gamma$, as well as to the large scintillation tanks of the LSD effectively registering the secondary products of interactions in iron that succeed in entering the scintillator. All this is discussed in detail in Refs [74, 77], where it is shown that there is no reason to consider the effect at 2:52 UT in the LSD a game of statistics or of some kind of noise. The effect is of high quality and without a doubt related to the burst of SN1987A, and it is stable with respect to the conventionally adopted schemes of neutrino oscillations.

As regards the results of studies of coincidences in a time window about 1 s long between pulses for different pairs of detectors, LSD–BUST and LSD–KII, and of double pulses in LSD (see Fig. 5), a statistically significant excess of coincidences and of double pulses was observed in these experiments. Attention must be drawn to the fact that the excess in coincidences is concentrated in time around 2:52 UT, while the excess of double pulses is at 7:35 UT. The probability of this to occur accidentally is extremely small. This is evidence of the genetic relation between the effects discussed and the burst of the supernova.

We recall that 2:52 UT and 7:35 UT were two key moments of time in the evolution of SN1987A, which are marked by neutrino signals in the LSD (2:52 UT) and in three other detectors (at 7:35 UT). And, while the neutrino signals in KII, IMB, and BUST somehow confirm with each other, the neutrino signal in the LSD was absolutely solitary, which still gives rise to perplexity and scepticism with respect to this effect. In this connection, it is especially important that the excess in coincidences of pulses for all combinations of detector pairs group precisely around 2:52 UT, the 'LSD time', while the excess of double pulses in the LSD is concentrated around 7:35 UT, the 'KII time'.

The registration of neutrino emission from SN1987A has given rise to questions, many of which have still not been answered. We can hope to obtain such answers when neutrinos are registered from subsequent collapses.

The main detectors participating in the modern service of searching for neutrinos from star collapses (see the Table) are sensitive not only to $\tilde{\nu}_e$ but also to other types of neutrinos, first and foremost to electron neutrinos emitted at the first stage of collapse according to the RCM.

The large megatonne detector IceCube (USA) [78], with $H = 1450 - 2450$ m.w.e., situated at the South Pole, registers Cherenkov radiation in a 1000 meter layer of ice with the aid of photomultipliers frozen into the ice. IceCube is very sensitive and is good for monitoring the situation; however, it gives no information on the details of a neutrino burst. It can be useful in joint operation with the detectors indicated in the Table.[1]

Above, we discussed how important it is to have a method for identification of the inverse β-decay reaction. For this, a detector must be capable of registering not only e^+, but also n. This is possible with the LVD, Borexino, KamLAND and ASD detectors.

Owing to the presence of ^{12}C in the scintillator, neutrinos of all types with energies above 15 MeV can be measured with ASD, BUST, LVD, Borexino, and KamLAND in reactions involving neutral currents.

At present, electron neutrinos can be reliably registered only by ASD and LVD; in the first case, owing to the presence of NaCl salt around it, and in the second, owing to its structure containing 1000 t of Fe.

5. Conclusion

To conclude, we draw the attention of the reader to the following.

(1) The investigation of rare events requires a careful analysis of the background in an underground laboratory. Simulations caused by an uncontrolled background often depreciate the results of an experiment.

(2) In our opinion, success in experimental studies of neutrino oscillations will be achieved when a determined transition occurs from the 'disappearance' scheme to the 'appearance' one in searches.

(3) During the past 20 years, about ten groups have been active in searching for sources of high-energy neutrinos, using various methods of observation. In spite of all the efforts, not a single source of high-energy neutrinos has yet been found.

(4) Experiments devoted to detecting neutrinos from the Sun and from stellar collapses have much in common. First of all, in both types of experiments, the very fact of detection of neutrinos has been established without a doubt. In both cases, the experimental result is inconsistent with the predictions of the models. In neither case can it be ruled out that correcting the models may resolve the contradictions. Experiments along these lines have clear prospects and have priority in experimental neutrino astrophysics.

The author is grateful to I R Shakirianova and N Yu Agafonova for help in preparing the article for publication.

This work has been performed with the support of the Russian Foundation for Basic Research (grants 12-02-00213-a and 12-02-12127_ofi_m), the scientific school SS-871.2012.2, and the program of fundamental research of the RAS Presidium, "The Fundamental Properties of Matter and Astrophysics."

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PACS numbers: 95.55.Vj, 95.85.Ry, 98.70.Sa
DOI: 10.3367/UFNe.0183.201303i.0323

Cosmic particles with energies above 10^{19} eV: a brief summary of results

S V Troitsky

1. Introduction

Ultra-high-energy (above 10^{19} eV) cosmic rays (UHECRs) have continued to attract the interest of researchers in both particle physics and astrophysics for decades. Questions arising in this field have been related to the origin of particles with these high energies, which do not appear in the Universe under any other conditions, and to searches for new physics, which may reveal itself in this energy range and result in deviations of experimental results from theoretical expectations. As we see below, these two groups of questions remain topical and, to a large extent, determine the present development of research in the overlap of particle physics and astrophysics.

Studies of UHECR physics are restricted by two principal complications related to specific properties of the phenomena under investigation. First, the flux of these particles is very low (on average, only one particle with the energy we are considering arrives at one square kilometer per year). Hence, direct registration of primary particles, which interact in the upper layers of the atmosphere, with the help of flying detectors is impossible, and we have to study them indirectly with ground-based installations capable of detecting extended atmospheric showers (EASs) caused by these particles. Moreover, even large ground-based detectors working for many years collect the number of events that is negligible compared, for instance, with the number of astrophysical photons detected by a telescope in any other energy range. Second, the interaction of the particles with the atmosphere occurs at energies far beyond the laboratory reach (for a 10^{19} eV proton interacting with an atmospheric nucleon at rest, the center-of-mass energy is hundreds of TeV); therefore, the models that relate the EAS development to properties of the primary particle inevitably include extrapolation of the interaction properties into yet unexplored domains of energy (and momentum transfer).

The experimental installations in operation at present may be divided based on the techniques they use into ground arrays of surface detectors (SDs) and fluorescent telescope detectors (FDs). SDs detect particles from an EAS at the surface level. Detectors form an array with a spacing of ~ 1 km and are capable of determining the lateral distribution function (LDF) of the particle density in a shower. An FD is a telescope that detects ultraviolet emission caused by fluorescence of atmospheric nitrogen molecules excited by charged particles of the shower. An SD registers a two-dimensional slice of an EAS only, but it works independently

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Uspekhi Fizicheskikh Nauk **183** (3) 323 – 330 (2013)
DOI: 10.3367/UFNr.0183.201303i.0323
Translated by S V Troitsky; edited by A M Semikhatov