Study of the penetrating component of cosmic rays underground using large scintillation detectors

O G Ryazhskaya
Institute for Nuclear Research Russian Academy of Science
Ryazhskaya@lvd.ras.ru

Abstract. The study of penetrating component of cosmic ray underground using large scintillation detectors situated in Russia and Italy is carried out during more than 40 years. The main results obtained at the different depths from 25 m w.e. to 5200 m w.e. are presented in this report.

1. Introduction
The term “Underground Physics” was introduced by prof. C. Castagnoli during the 1st symposium on Underground physics in Saint-Vincent (UP-85) dedicated to the opening ceremony of the russian-italian LSD detector under MontBlanc [1]. In this year we can celebrate 30 years of Underground Physics (UP). UP as physics in general is the experimental science. The mother of the truth in physics is the experiment. Therefore paying tribute to the wonderful works of theoreticians in this field of knowledge we will say here about the experiments carried out by collaborators of Russian Academy of Science and collaborators of RAS with their Italian colleagues in UP during that time: ASD (Arteomovsk Scintillation Detector) [2], BUST (Baksan Underground Scintillation Telescope) [3], LSD (Liquid Scintillation Detector) [4, 5], LVD (Large Volume Detector) [6, 7], SAGE (Ga-Ge experiment for solar neutrino detection in Baksan) [8], Baikal underwater experiment [9].

The main problems of UP are: 1. Study of neutrino radiation (atmospheric neutrinos; solar neutrinos; neutrinos from collapsing stars); 2. Construction of underground detectors; 3. Detection of neutrino radiation from SN1987A; 4. Study of penetrating component of cosmic rays (energy spectrum; study of deep inelastic scattering of muons; generation of nuclear active component underground; depth-intensity curve of muons; depth-intensity curve of neutrons; seasonal modulation of the cosmic ray muon flux and neutron flux from muons; \( \mu^+ / \mu^- \) ratio).

2. Neutrino physics
In the middle of 60th neutrino physics became to dominate in underground experiments. The sizes of detectors were increased and increased. The first underground laboratories were created.

New methods for studying low-energy neutrinos, solar neutrinos, neutrinos from collapsing stars became to be developed.

Neutrinos going in the horizontal direction by using scintillation detectors, and neutrinos, coming from the back side of the Earth proposed in [10] in 1962 became to be studied. In 1963 – 1971 the flux of atmosphere neutrino for the angles higher than 50° was measured for the first time by 3 experiments situated in Kolar Gold Fields mines (India) depth 7500 mw.e. [11]; a mine near Johannesburg, (South Africa) depth 8640 mw.e. [12]; Utah, USA, depth 1500 mw.e., from the back side of the Earth [13].
However the statistic accuracy at these experiments was not high. In 1964 it was decided to create the Baksan Underground Scintillation Telescope (BUST) in the Baksan Neutrino Observatory (BNO) to measure neutrino flux from the back side of the Earth. For that the new liquid scintillator on the bases of the white spirit was elaborated [14]. The transparency of this scintillator is higher than 30 m, the stability is more than 40 years. Just in that time we proposed and realized the main methodic using which the large underground detectors of INR (ASD and BUST) were constructed. Both detectors use the same liquid scintillator. In 1979 the first results of up-going atmospheric neutrino detection were obtained in the BUST at the depth of 750 m w.e. [15].

In the same time radio chemical methods for solar neutrino detection were developed. Cl-Ag experiment proposed by B. Pontecorvo in 1946 [16], was realized by R. Davis in 1967 [17]. Due to this reason the questions of a background play very important role. The main background for this reaction is nuclear active component of the cosmic rays, on the whole, protons, p+Cl37 → Ar37+n. In 1964 we started to study the cosmic ray background. Before that it was supposed that the nuclear active component is produced due to electromagnetic cascades generated by muons underground. This point of view on the problem was changed after the work [18]. The authors of this paper considering all possible processes of nuclear particle generation showed that the main part of these particles is generated in nuclear showers developed after deep inelastic scattering of muons with nuclei in the ground in reaction such as: µA → mp+χ, where mp is the total amount of pions and χ are fragments of nucleus.

As a result the background at a depth, of 4000 m w.e. for example, increases by a factor of 2.5 compare with previous estimations. The dependence of the number of slow neutrons produced per 1 g/cm² of ground reduce to a single muon on the depth and on the average muon energy was obtained. It was shown that neutron generation underground depends not only on muon intensity I, but also on average muon energy at a given depth H as: Iₙ ∼ I(H) Eₜ⁻⁰.₇₅ ± 0.₀₅.

This dependence was measured using scintillation detectors in the salt mines near Arteomovsk at the different depths: 25 m w.e., 315 m w.e., 570 m w.e. (1968 - 1987) [19 – 22] and down to 5400 m w.e Mont Blanc (1984 - 1998) [5, 23].

3. Construction of underground large scintillation detectors
During last 40 years the following underground detectors were constructed by the Institute for Nuclear Research of the USSR: 1. ASD: (INR RAS, Arteomovsk, 570 m w.e.) the single-unit detector with a mass 105 t of liquid scintillator, 1 kt of NaCl, 1977 [2, 20 – 22]. 2. BUST (INR RAS, Baksan), the multi-unit detector with a total mass 330 t of liquid scintillator and 160 t of iron, 1978 [3]. 3. LSD (INR RAS together with Institute of Cosmo Geophysics of CNR, Italy) Mt. Blanc, the multi-unit detector with a mass 90 t of scintillator and 200 t of iron, 1984 [4, 5, 23]. 4. LVD (INR RAS together with LNGS INFN, Gran Sasso, Italy) the multi-unit detector with a mass 0.35 kt of scintillator and 0.33 kt of iron, 1992 [6], last version: 1 kt of scintillator and 1 kt of iron 2001 [7].

One of main goals of these experiments is the search for neutrino burst from collapsing stars. These detectors are used also for different studies in the field of underground physics. The possibility of a simultaneous detection of a neutrino burst by several detectors located in different places on the Earth strongly reduces noise and increases the reliability of results.

4. Search for and the registration of neutrinos from collapsing stars
The theory predicts that the evolution of massive main-sequence stars may come to the end by gravitational collapse and a powerful short pulse of neutrino emission [24]. In the standard collapse model (SCM) (of a spherically symmetric, nonrotating, nonmagnetic star) all types of neutrinos are irradiated in equal energy parts [25]. In this case 1) the advantage for neutrino detection has the reaction νp →e⁺n due to its large cross section and 2) the duration of neutrino burst is very short: from 5 to 20 s. Basically, the experiment is simple. The detector, a scintillation or Cherenkov one, is
filled with a hydrogenous material. A neutrino burst is identified by a series of scintillations in the range of amplitudes 5 - 50 MeV in a time less than 20 s.

4.1. A Supernovae explosion SN1987A
On February, 23, 1987 astronomers observed a supernova in a nearby galaxy - the Large Magellanic Cloud. That day at about 2:52 UT LSD detector [26] and at about 7:35 UT BUST [27], KII (Japan-USA, Kamioka) [28] and IMB (USA, Cleveland) [29] detectors measured neutrino radiation from collapsing star for the first time in the history of science. 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 [30 – 32] (Figs. 1, 2).

The results are not explained in the frame of the standard collapse model, but can be naturally explained by rotating collapsar model (RCM) [35, 36] which predicts two-stage collapse. At the first stage, stage of neutronization mostly electron neutrinos are emitted with the mean energy 30 – 40 MeV and at the second stage, all types of neutrinos are eradiated as in the SCM with average energies 10 – 15 MeV. LSD detected electron neutrino from the stage of neutronization of the star due to the presence of the iron in LSD [31, 36]. The first stage was ~ 5 hours early then second one.

The rotation effects make it possible:
To resolve the problem of the transformation of collapse into an explosion for high-mass and collapsing supernovae (all types of SN, except the type Ia– thermonuclear SN). To resolve the problem of two neutrino signals from SN 1987A, separated by a time interval of 4.7 h.

The experiments running to search for neutrino radiation from collapsing stars up to now traditionally take one's bearings for the detection of the inverse $\beta$-decay reaction and, accordingly, for the use of the hydrogenate targets. The observation of neutrino radiation from SN1987A showed that it is important to have in the composition of the targets beside the hydrogen also other nuclei suitable to neutrino radiation detection. In particular the presence of iron nuclei in the LSD (200 t) provided for the sensational detection of electron neutrino at 2:52 UT on February 23 1987 when other more powerful detectors with their hydrogenate targets could not respond to this type of neutrino.

2:52 UT results and 7:35 UT results correspond to a certain extent to the model of standard collapse (7:35 UT) [25, 36]. Review about explanation of experiment results (2:52 UT; 7:35 UT) in the frame of the model (RMS) is published in [36, 37]. However, a numbers of questions still remains!

Apart from the results concerning the signal in the four neutrino detectors at 2:52 and 7:35 UT on February, 23, 1987 there are also other results obtained at the same time that day. They are published in the papers in which the coincidences between the pulses in the different detectors (LSD, BUST and KII) in a very narrow time window of about 1 s in width [23, 32] as well as coincidences between the signals in these detectors and Maryland and Rome gravitational antennas were studied.

5. The Large Volume Detector at Gran Sasso

LVD is 10 times expanded version of the LSD (Mont Blanc) apparatus which has detected the $\nu$-burst from SN 1987A at 2:52 UT on February, 23, 1987. LSD & LVD are Russian-Italian projects. Scintillator & scintillation counters were elaborated and produced in INR, Russia.

LVD consists of an array of 840 scintillator counters, 1.5 m$^3$ each, viewed from the top by three photomultipliers (PMTs). It is a modular detector. From the viewpoint of PMTs power supply, trigger and data acquisition, the array is divided in sectors (dubbed towers): each sector operates independently of the others. This modularity allows LVD to achieve a very high duty cycle, that is essential in the search of unpredictable sporadic events.

The capability of LVD to detect in real-time (i.e., “on-line”) a supernova event is extensively discussed in [38]. It is necessary to say that LVD can identify all types of neutrinos [31].

The neutrino-burst detection technique is based on the search for a sequence of candidate neutrino events whose probability of being simulated by fluctuations of the counting rate is very low.

During 38 years [ASD – 1977, LSD – 1984-2002, LVD – 1992(1 tower), 1998 (3 towers)] there were no observation of neutrino radiation from collapsing stars in the Galaxy. The collapse rate is less than 1 / 16 years at 90% c.l. From 2010 it was started the joint analysis of experimental data to search for neutrinos from collapsing stars using the LVD and BUST apparata [39]. Also we study experimental search for BUST and LVD coincidences of pulses within 1 s. The average number of coincidences within the 1 second time interval is less than 1 event per day (total 294 evens for 2013 year and 297 events for 2014 year was obtained). The results are corresponding to random coincidences. It should be noted that on February 23, 1987 13 events in time interval from 1:50 UT till 3:50 UT were detected, number of random events was 3.

In addition, the prompt identification of a neutrino signal could provide astronomers with an early alert of a supernova occurrence (SuperNova Early Warning System, SNEWS, [40] of which LVD is a founding member) allowing one to study phenomena like the shock break out, a flash of radiation as the shock wave breaks out from the surface of the star, and to detect, for the first time directly, the signal due to the emission of gravitational waves.

During last 17 years the depth-intensity curve of muons, depth-intensity curve of neutrons generated by muons underground, seasonal modulation of the cosmic ray muon flux and neutron flux from muons, the neutron energy spectrum and their space distribution, $\mu+/\mu-$ ratio were obtained using LVD.

Acknowledgments
The author is grateful to Natalia Agafonova for help in preparing the article for publication.

This work was partially supported by the Russian Foundation for Basic Research, project № 15 - 02 - 01056_a; the Program for the Support of Leading Scientific School, contract SS-3110.2014.2; and the Presidium of the Russian Academy of Sciences’ basic research program Fundamental Properties of Matter and Astrophysics.

References

[1] Underground Physics 1984 Saint-Vincent, 25-28 April 1985, Il Nuovo Cimento 9C (2) 111
[2] Korchagin P et al 1979 Proc. 16th Int. Cosmic Ray Conf., Kyoto 10 299
[3] Alexeyev E et al 1979 Proc. 16th Int. Cosmic Ray Conf., Kyoto 10 276
[4] Dadykin V et al 1979 Proc. 16th Int. Cosmic Ray Conf., Kyoto 10 285
[5] Badino G., et al 1984 Nuovo Cimento C 7 573
[6] Aglietta M et al 1992 Nuovo Cimento A 105 2579
[7] Aglietta M et al (LVD Collab.) 2001 Proc. 27th ICRC, Hamburg 3 1093
[8] Abdurashitov J et al (SAGE Collab.) 1999 Phys. Rev. C 59 2246
[9] Belolaptokov I et al. 1997 Proc. of the 10th Annual Intern. Rochester Conf. on High-Energy Physics (Eds E C G Sudarshan, J H Tinlot, A C Melissinos) (New York: Interscience, 1960) 578
[10] Menon M et al. 1967 Proc. Phys. Soc. 90 649
[11] Reines F 1967 Proc. R. Soc. Lond. A 301 125
[12] Keuffel J 1969 Trudy Mezhdunarodnogo Seminar po Fizike Neitrino i Neitrinoi Astrofizike (Works of Intern. Seminar on Neutrino Physics and Neutrino Astrophysics), Moscow: FIAN SSSR 3
[13] Voevodskii A, Dadykin V and Ryazhskaya 1970 Prib. Tekh. Eksp. 1 85
[14] Alexeyev E et al 1979 Proc. 16th Int. Cosmic Ray Conf., Kyoto 10 282
[15] Pontecorvo B 1946 Chalk River Report PD-205 (Chalk River: Chalk River Laboratories)
[16] Ryazhskaya O, Zatsepin G 1965 Proc. of the 9 ICRC, London, UK
[17] Beznosov V et al 1973 Sov. J. Nucl. Phys. 71 51
[18] Bezrukov L et al 1978 Yad. Fiz. 28 1548
[19] Enikeev R et al 1982 Izv.Akad. Nauk SSSR Ser.Fiz. 46 1847
[20] Malgin A et al 1982 JETP Lett. 36 376
[21] Aglietta M et al Nuovo Cimento C 12 467
[22] Zel’dovich Ya and Guseinov O 1965 Sov. Phys. Dokl 10 524
[23] Imshennik V, Nadezhin D 1988 Usp. Fiz. Nauk 156 561
[24] Aglietta M et al 1987 Europhys. Lett. 3 1315
[25] Alekseev E et al 1987 JETP Lett. 45 589