ELEMENTARY PARTICLES AND FIELDS

Experiment

LVD—Multipurpose Russian–Italian Detector

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Abstract—Selected results from the multipurpose Large Volume Detector (LVD) are presented. Investigations at the LVD setup are being performed according to the program of continuous searches for neutrinos from supernova explosions in the Milky Way Galaxy and muon- and neutron-physics programs. At the present time, the LVD setup is the largest scintillation detector, which possesses a unique potential for studies in the realms of underground physics.

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1. INTRODUCTION

At the Laboratory of Electronic Methods for Detection of Neutrinos (EMDN) (Institute for Nuclear Research, Russian Academy of Sciences), Olga G. Ryazhskaya, corresponding member of Russian Academy of Sciences, and her colleagues developed a scintillation counter in the form of a module 1.5 m$^3$ in volume equipped with three photomultiplier tubes with a photocathode diameter of 15 cm and characterized by a high neutron-detection efficiency of about 70%. A liquid scintillator developed by a group including O.G. Ryazhskaya [1] possesses a high transmission at the emitted-light wavelength of $\lambda = 420$ nm and ensures a high detection efficiency for photons of low energy above approximately 1 MeV. The size of the counter (1.5 $\times$ 1.0 $\times$ 1.0 m$^3$ in size) makes it possible to assemble a setup of any volume whose shape and dimensions are restricted by the dimensions of the experimental hall intended for it. Grouped together into a large detector, the counters provide the possibility of measuring the energies of high-energy particles and of electromagnetic and hadronic cascades on the basis of their total energy deposition—that is, endow it with the calorimeter properties. Thus, a detector of this type enables one to conduct experiments over an extremely wide range of energy depositions—from MeV units to several hundred GeV units.

This counter was developed for the long-term LSD (Liquid Scintillation Detector) underground experiment deployed under Mont Blanc at a depth of 5200 m w.e. [2] and devoted to searches for neutrino-radiation bursts from gravitational core collapses. The main reactions used to detect neutrinos are the following:

(i) inverse beta decay in the scintillator (Cowan-Reines reaction)—$\bar{\nu}_e p \rightarrow ne^+ [E(e^+) = 5–100$ MeV], $np \rightarrow D\gamma [E(\gamma) = 2.2$ MeV].

(ii) $\nu_e$, $\nu_{12}$C, and $\nu_{56}$Fe reactions of charged- and neutral-current neutrino interaction with electrons and nuclei. These reactions predominantly produce $e^\pm$ and gammas of energy expected to be between 2 and 60 MeV.

In 1984, the International Science Committee approved the implementation of the project of the Large Volume Detector (LVD) at the Gran Sasso Underground Laboratory (Italy) at a depth of 3650 m w.e. The LVD project [3] was developed jointly by physicists from the laboratory headed by O. Ryazhskaya and Institute of Cosmo-Geophysics (Torino, Italy). Its scintillation part is an extended version of LSD.

An analysis of the first data from the scintillation counters of the LVD setup at the Gran Sasso laboratory started in 1992. The construction of the third tower was completed in 2000. The total size of the detector, which consists of 840 counters (1010 t of scintillator), is 22.7 $\times$ 13.2 $\times$ 11 m$^3$. The setup also includes iron structures of total mass 1000 t and a tracking system, which operated till 2002.

2. IN EXPECTATION OF SUPERNOVA EXPLOSION

Gravitational star collapses are astrophysical events of great interest. Because their observation is difficult, a simulation of respective physical processes is still dealing with the stage of evolution, but it is
common practice to assume that the role of neutrinos is of crucial importance for supernova formation upon a collapse [4]. The only corroboration of the discovery of a neutrino signal from SN 1987A inaugurated a new era in neutrino astrophysics (see, for example, [5]), despite some unresolved controversies [6].

All experiments aimed at discovering neutrino bursts from core-collapse supernovae should take into consideration an extremely low frequency of such events—one per 30 to 50 years [7]. This requires installing detectors that would remain stable for a rather long time. The LVD setup is expected to be one of the few detectors that would possess this property.

The main task of LVD is to detect neutrino bursts from collapsing stars. In relation to large water detectors, LVD has the advantage of containing carbon in the scintillator and iron, whereby it is possible to separate different neutrino flavors. The LVD setup is able to detect both electron antineutrinos ($\bar{\nu}_e, p \rightarrow ne^+$) and muon and tau neutrinos and antineutrinos (reactions on carbon and iron). For the first process, it is natural to expect 300 to 600 events upon supernova explosion at the Milky Way Galaxy center (8.5 kpc). The other processes will yield a substantially smaller number of events. For example, only six events from electron-neutrino interaction with scintillator carbon will be detected in the absence of oscillations. The main reason for this smallness of the yield is that electron-neutrino energies are overly small. However, oscillations transform muon and tau neutrinos, which are produced with higher energies (approximately two times higher), into electron neutrinos. As a result, the yield will increase to several tens of events. An implementation of a different supernova-explosion mechanism (see, for example, [8]) will give rise to a still greater number of events in the detector and will lead to a higher neutrino energy. Thus, the detection of neutrinos from supernovae may provide useful information about neutrino physics—primarily about neutrino mixing—and, in addition, about the astrophysics of collapses.

It would be of importance to compare data obtained with various detectors that have different sensitivities to energy and flavors. At the present time, there exists a global international network of various detectors for tracing star collapses. This network, known as SuperNova Early Warning System (SNEWS), includes, along with LVD [9], the Super-K, IceCube, Borexino, KamLAND, HALO, and Daya Bay detectors and several gravitational antennas. The objective of SNEWS is to provide the astronomical community with a early warning of a supernova explosion in the Milky Way Galaxy with the aim that experimentalists could observe astronomical consequences of a gravitational star collapse. The SNEWS network increases the reliability of events recorded simultaneously by several detectors at the threshold of their sensitivity.

Searches for neutrino bursts are based on identifying clusters of events such that the probability for mimicking them because of background fluctuations is low. Twenty-eight years of searches did not provide any of such clusters at LVD—that is, there were no observations of gravitational collapses, including hidden ones (without the ejection of an envelope) in the Milky Way Galaxy or in Magellanic Clouds. On the basis of the data accumulated over the 28 years (from 1992 to 2020) operation of the LVD neutrino telescope, the frequency of neutrino bursts from gravitational star collapses in the Milky Way Galaxy was constrained to be less than one event per 12.2 years at a 90% confidence level (C.L.).

3. MUON PHYSICS

The detector has a modular structure. Each module (portatank) contains eight scintillation counters forming five columns and seven levels in one tower. In all, there are three towers. The modular structure makes it possible to perform maintenance work without switching the detector off and to select muons in the geometry of arrangement of the counters.

The long axis of the detector is oriented toward CERN, while its short axis is oriented in the north–east direction. The shape of the mountain permits recording muons that arrive from different directions specified by the angle $\theta$—from $0^\circ$ to $90^\circ$—and at rock depths $H$ from 3 km w.e. (minimum depth) to 20 km w.e. [10].

The application of the muon-event reconstruction code permitted determining the multiplicity distribution of muon groups (Fig. 1a); the distribution of muon pairs with respect to the distance between the muons—the incoherence curve (Fig. 1b); and the muon charge ratio [11]. The maximum multiplicity of muons traversing two LVD towers was 27 muons in one muon beam.

The distribution of distances between muons in a group provides information about transverse momenta. Along with muon multiplicities, one can also obtain information about the energy spectrum of hadrons. Measurements of the spectra of atmospheric muons and their distributions with respect to distances provide the possibility of testing models of the nuclear cascade in the Earth’s atmosphere—that is, parameters of primary cosmic radiation (energy spectrum and chemical composition) and particle interactions at high energies.

In 2009, there arose interest in seasonal variations of underground muons. This was motivated by publications of data from the DAMA experiment [12].
Fig. 1. (a) Multiplicity \( N(k) \) distribution of muon groups measured at LVD. The function used to approximate this distribution has the form \( dN/dk = Ak^{-B} \), where \( A = 0.148 \times 10^7 \) and \( B = 4.32 \). (b) Distribution of muon pairs with respect to distances between muons in pairs. The curve represents an approximation of the form \( f(r) = (Ar/r_0^2) \exp(-r/r_0) \), where \( A = 4.728 \times 10^4 \) and \( r_0 = 2.61 \).

Fig. 2. Scheme of neutron detection at LVD.

aimed at searches for signals from dark-matter interactions. We have performed a long-term analysis of the intensity of LVD muons and estimated the variation amplitude at 1.5\% in describing the data in terms of a harmonic function. The phase, defined as the maximum of the intensity, corresponds to the 185th day from the beginning of the year [13]. We have also studied the spectral composition of the muon-intensity time series by means of the Lomb–Scargle analysis. The result suggests a period of one year and is also indicative of shorter and longer periods. One can notice that this series is not a pure sinusoidal wave. Therefore, we characterized for the first time the observed modulation from the point of view of the amplitude and positions of the maximum and minimum in years [14].

4. NEUTRON PHYSICS

The dimensions and structure of the LVD setup and the composition of the detector material, which consists of the scintillator and iron, permit detecting, with a high efficiency, neutrons produced by muons in the detector (see Fig. 2).

Neutron are recorded primarily by photons of energy \( E_\gamma = 2.2 \) MeV emitted upon radiative thermal-neutron capture by scintillator protons \((n + p \rightarrow D + \gamma)\), the capture time being \( \tau \approx 180 \) \( \mu \)s, as well as by photons of energy \( \langle E_\gamma \rangle = 7 \) MeV from the capture of neutrons by iron nuclei \((n + ^{56}\text{Fe} \rightarrow ^{57}\text{Fe} + \Sigma \gamma)\) in the LVD structure, in which case the capture time is \( \tau \approx 100 \) \( \mu \)s. The number of neutrons was determined on the basis of the time distribution of capture gamma-quanta.
We have determined important features of neutrons such as the neutron yield (that is, the specific number of neutrons generated by one muon per muon-range unit) in the scintillator and iron, the energy spectrum of neutrons and their lateral distribution, and seasonal variations of neutrons.

The yield of neutrons from muons was measured at LVD in the scintillator. The result was $Y_n(C_nH_{2n}) = 3.6 \pm 0.01 \text{(stat.)} \pm 0.3 \text{(syst.)} \times 10^{-4} \text{ n/}\mu\text{g/cm}^2$ [15]. There were difficulties in separating the fractions of neutrons produced by muons in a mixed substance (scintillator and iron). The neutron yields in iron and lead were measured by supplementing the structure of the setup with an additional substance in the space between the counters [16]. The developed procedure makes it possible to measure the neutron yield in various substances. A limitation is imposed by the structural feature of the space between the counters (10 cm). One can compensate for this drawback (a) by enlarging statistics and (b) by adding matter between the columns and selecting, in that case, inclined muons.

Measurements of the neutron yield in various substances agree with the dependence $Y_n(E_\mu, A) = b_n A^\alpha E_\mu^\beta$, where $\alpha = 0.78$, $\beta = 0.95$ [17]. $A$ is the mass number of the substance, $E_\mu$ is the average energy of muons (in GeV units) at the depth of the measurements, and $b_n = 4.4 \times 10^{-7} \text{ (g/cm}^2\text{)}^{-1}$.

Knowledge of the energy spectrum of neutrons produced by cosmic-ray muons under ground is of paramount importance in detecting rare events. Measurement of the energy of neutrons directly in the muon-created shower is next to impossible, but, owing to their long ranges, neutrons escape from the shower core and become isolated particles. The flux and spectrum of such particles are readily measurable. For the first time, these features were studied in the 1980s by means of the ASD detector [18] and Barton’s setup [19]. Such experiments are also of importance for finding out which spectra neutrons produced in the source had and how they propagated through various materials.

Measurement of the neutron spectrum in the energy range between 20 and 150 MeV, and especially at energies above 150 MeV, is a difficult experimental challenge. The neutron energy is determined by the energy deposited by recoil protons, as well as by secondary particles produced upon neutron interaction with a carbon nucleus. For energies of up to about 150 MeV, the measurements are therefore affected by the process of concentration quenching of the light output from protons and alpha particles. At energies in excess of 150 MeV, the detection efficiency for the total neutron energy becomes the main problem.

We have determined the differential energy spectrum of isolated neutrons in the range between 20 and 450 MeV that were produced both directly by muons and in the electromagnetic (em) and hadronic (h) cascades initiated by muons in LVD matter. The spectrum of such neutrons has a two-component shape. These components have a $T_n^{-1}$ and $T_n^{-2}$ form and feature a kink at an energy of $T_n^{\text{cr}} \approx 60(A^{0.25} - 0.67) \text{ MeV} \approx 100 \text{ MeV}$ [20].

The lateral distribution of neutrons was measured at LVD by employing two different procedures in order...
to eliminate the side effect. One method \((T1 + T2)\) employed two LVD towers and the tracking system (which operated till 2002). The muons that traversed a tower were reconstructed on the basis of data from the tracking system. The distance \(R_\perp\) was calculated from the center of the counter that fixed a neutron to the center of the counter that was closest to it among those that were actuated along the muon track (Fig. 3, closed symbols). The appearance of two pulses at the output of a counter within a time window of about 1 ms after the trigger that were a triggering pulse with \(E > 5\) MeV (primarily from the recoil proton in \(np\) scattering) and a pulse generated by a 2.2-MeV photon from \(np\) capture meant neutron detection by this counter. With allowance for the quenching of the scintillator, the apparent recoil-proton energy of 5 MeV corresponds to a neutron energy of about 20 MeV.

The other method \((T1–CI)\) consists in detecting neutrons in one column \((CI)\) that were produced by vertically going muons. This method for determining the distance \(R_\perp\) on the basis of the counter farthest from column \(CI\) is similar to the last-collision method developed for calculating the angular distributions and fluxes of fast neutrons incident to flat shields [21]. Within this method, one assumes that the direction and energy of scattered fast neutrons traversing a layer of matter depend only on the last collision. In our case, the last collision occurred precisely in the counter farthest from column \(CI\) among those that developed a triggering pulse. As the result of this (last) collision, the neutron loses energy and changes direction to such an extent that it is unable to penetrate into the next counter that is farther from \(CI\). The results of these measurements are shown in Fig. 3 (open symbols).

The graph in Fig. 3 demonstrates agreement between the resulting lateral distributions obtained by the above two methods—\((T1 + T2)\) and \((T1–CI)\)—and their agreement with the law \(N(R_\perp) \propto R_\perp^{-2.3}\) [15] at distances from the muon track in the region of \(R_\perp > 2.0\) m.

In the range of distances \(R_\perp\) shorter than 2 m, the lateral distribution is characterized by the presence of a maximum in the vicinity of the muon track and is formed by neutrons evaporated from hadronic and electromagnetic showers [15].

Seasonal variations of the specific number of neutrons produced by muons were measured over 16 years of detector operation from 2001 to 2017 [22]. The amplitude of neutron variations was 7.7%; this made it possible to determine the variations in the energy of atmospheric muons under ground [15].

5. DETECTOR BACKGROUND

Investigation of the low-energy background under ground is yet another interesting problem being solved at LVD. Measurement of this background is of importance for experiments devoted to searches for rare events—for example, those associated with dark matter and neutrinoless beta decay.

The counting rate is being monitored at LVD with the aim of studying variations in the concentration of radon escaping into the atmosphere of underground rooms from rock before earthquakes. Radon arises in rock upon the fission and decays of elements of uranium and thorium series and escapes into the atmosphere of underground rooms through multiple microcracks in rock or from water saturated with radon (radon is readily soluble in water) on the path through rock to the underground hall. Since the number of microcracks increases owing to deformations of the Earth’s crust before earthquakes, radon emission becomes more intense.

The LVD detects photons from the decays of daughter nuclei of radon, whose half-life is 3.8 days. The most probable chain of radioactive decays is

\[
\begin{align*}
{^{222}\text{Rn}} & \rightarrow {^{218}\text{Po}} \rightarrow {^{214}\text{Pb}} \\
& \rightarrow {^{214}\text{Bi}} \rightarrow {^{214}\text{Po}} \rightarrow {^{210}\text{Pb}}.
\end{align*}
\]

Gamma radiation is due predominantly to bismuth nuclei, which transform to polonium via beta decay with a characteristic time of 19.7 min. The energy spectrum of gamma radiation covers the range from 0.6 to 2.5 MeV.

Components of a seasonal variation (its phase was found to correspond to the beginning of September),
as well as weekly and diurnal variations, were found in the behavior of the background [23]. The LVD setup may record enhanced radon emission associated with seismic activity in the region (Fig. 4). Such investigations may be helpful to geophysicists in predicting devastating earthquakes.

6. CONCLUSIONS

At the present time, it is reasonable to summarize the results of 30-year operation of the LVD setup.

In the present article, we have described briefly the most recent results obtained by means of this multipurpose detector. They cover a broad range of underground-physics problems in the realms of astrophysics and cosmic-ray physics. The procedures used to obtain these results have been described briefly, and references to detailed descriptions of respective measurements have been given.

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