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ELEMENTARY PARTICLES AND FIELDS
Experiment

Latest Results Obtained on the LVD Experiment

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Abstract—The LVD detector, located in the Gran Sasso Laboratory at a depth of 3600 m w.e., is designed for research in the field of neutrino physics, astrophysics, cosmic ray physics and the search for rare processes predicted by theory. The LVD experiment was built in 1991 to detect neutrinos from collapses of stellar nuclei in our galaxy. The background of the detector is atmospheric muons, neutrons generated by muons in the detector material and natural radioactivity underground. The report presents the latest experimental results obtained at LVD: a limit on the frequency of supernova outbreaks, muon variations with a period of 1, 4, 10 years, and also describes the problems of studying the low-energy background underground.

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1. INTRODUCTION

The main goal of the LVD (Large Volume Detector) project is to create a detector under low background conditions for detecting a burst of neutrino radiation that occurs during the gravitational stellar core collapse. LVD is a multi-purpose project [1, 2], in addition to the mode of waiting for neutrinos from supernovae, the characteristics of the detector make it possible to study neutrino fluxes of atmospheric and astrophysical origin, as well as processes caused by high-energy muons. Of particular interest are the LVD observations of various cosmic ray modulations, neutrons and gamma rays and various particles associated with gravitational, geophysical, and atmospheric effects.

Recently, research has been carried out to find a connection between global tectonic phenomena and cosmic radiation. Some studies have found correlations between the intensity of earthquakes and variations in the solar magnetic field [3] and with solar activity and with the intensity of the flux of galactic cosmic rays [4, 5].

Gamma quanta, detected in the LVD as a control of the background level, correlate with the concentration of the radioactive gas radon released into the atmosphere of the hall. Variations in the counting rate of gammas and, consequently, the concentration of radon, are measured in LVD with good accuracy: for a 10-second measurement interval, the installation will record a 5% deviation in the radon concentration with $\sim$99.7% confidence [6].

The purpose of this work is to show the range of problems solved on the LVD and present the latest results of the experiment.

2. LVD EXPERIMENT

The LVD [1], built in the INFN Gran Sasso National Laboratory, at the depth of 3600 m w.e., is a 1 kton liquid scintillator detector whose major purpose is monitoring the Galaxy to study neutrino bursts from gravitational stellar collapses [7] by the characteristic signature of the inverse beta-decay:

$$\tilde{\nu}_e + p \to n + e^+, \qquad (1)$$

followed by neutron capture by a proton or iron nuclei. An electron antineutrino interacts with a proton in the liquid scintillator originating a positron that gives a prompt signal with energy threshold 4 MeV. For the detection of gamma quanta from neutrons, the low threshold is 0.5 MeV. The detector is divided in 3 towers (5 columns and 7 levels). Each tower has 35 modules, called portatank, that contain 8 counters. Each counter is filled with 1.2 ton of liquid scintillator: C_nH_2n, where $n = 9.6$. The total amount of liquid scintillator in the detector, about 1 kton, is used as a sensitive target for neutrinos, but the iron support structure (1 kton) can also act as target for neutrinos and antineutrinos.

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The energy calibration of linear ADC channels of each counter is made by using cosmic muons detected by LVD. A muon event is defined as an event which has registered two or more high threshold signals in time coincidence within 250 ns. The muon mean path length in a counter is about 70 cm and the mean energy released in a tank has a value of 185 MeV. By means of an automatic procedure, every month an energy calibration is performed fitting the muon spectrum in ADC channels to get the muon peak mean value. The energy resolution of the experiment can be described by the following formula: $\sigma/E = 0.07 + 0.23/\sqrt{\mathrm{E/MeV}}$ [8].

3. THE SEARCH FOR NEUTRINO BURST

The LVD trigger logic is optimized for the detection of both products of the inverse beta decay (1), and is based on the three-fold coincidence of the PMTs of a single counter.

In addition to inverse beta decay, the observable neutrino reactions in the LVD scintillator are:

$\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N} + e^-$, the prompt signal due to the e^-, followed by the signal due to the β^+ decay of ^{12}N with a mean life $\tau = 15.9$ ms;

$\bar{\nu}_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{B} + e^-$, the prompt signal due to the e^-, followed by the signal from the β^- decay of ^{12}B with a mean life $\tau = 29.4$ ms;

$\nu_i\,(\bar{\nu}_i) + {}^{12}\mathrm{C} \to \nu_i\,(\bar{\nu}_i) + {}^{12}\mathrm{C}^*$, with $i = e,\ \mu,\ \tau$, whose signature is the monochromatic photon from carbon de-excitation of 15.1 MeV;

$\nu_i\,(\bar{\nu}_i) + e^- \to \nu_i\,(\bar{\nu}_i) + e^-$, which yields a single signal due to the recoiling electron.

The higher energy part of the neutrino flux can be detected also with the interaction, resulting in an electron (positron) that may exit the iron structure and release energy in the liquid scintillator. The reactions are $\nu_e + {}^{56}\mathrm{Fe} \to {}^{56}\mathrm{Co} + e^-$ and $\bar{\nu}_e + {}^{56}\mathrm{Fe} \to {}^{56}\mathrm{Mn} + e^+$.

For these reactions the efficiency for electron and gammas to reach the scintillator with energy higher than 4 MeV is greater than 20% for $E_\nu > 30$ MeV and grows up to 70% for $E_\nu > 100$ MeV. With these characteristics and detectable neutrino interactions, LVD can provide astrophysical parameters of the supernova explosion mechanism, up to now not well defined, such as the total energy emitted in neutrinos, the star distance, the neutrino-sphere temperatures and the partition of the energy among the neutrino flavors.

Search for neutrino burst candidate is performed by studying the temporal trigger sequence looking for signal clusterization. The neutrino burst candidate selection, discussed in [9], processes all possible clusters up to 200 s of duration, initiated by each single pulse belonging to the trigger sequence. For each selected cluster with multiplicity and duration Δt, the Imitation Frequency is calculated as a function of the cluster parameters and of the background events' rate.

The basis of the search for neutrino bursts is the identification of event clusters with a low probability of event imitation (F_{im}) due to background fluctuations (Fig. 1, [10]). Details about the procedure for searching and registering clusters are described in the latest work of the LVD [11].

The LVD experiment has been monitoring the Milky Way since June 1992 under increasing larger configurations, reaching in January 2001 the final active mass of 1000 t. No burst candidate has been detected over all the 31 years of observation. Since the LVD sensitivity is higher than expected from GSC models (even if the source is at a distance of 20 kpc and for soft neutrino energy spectra), the resulting 90% c.l. upper limit to the rate of gravitational stellar collapses in the galaxy ($D \leq 20$ kpc) is 0.07 y^{-1}.

4. ATMOSPHERIC MUONS' VARIATIONS

The average 1400 m rock coverage at the LNGS underground laboratory gives a reduction factor of one million in the cosmic ray flux. The residual muon flux is about 1.17 μ/(m^2 hour) and that let to study the cosmic rays.

The muon depth-intensity relationship, the spectrum of high-energy muons in an extensive air shower, the seasonal modulation of the cosmic muon flux, muon-induced neutron yield are the main topics of muon cosmic ray research.

It is well known that the flux of cosmic muons underground is related to the temperature of the Earth atmosphere (the higher the temperature, the higher the muon flux underground) because the change in the air density implies a variation in the decay and interaction rate of the parent mesons. This effect has been measured by various experiments at LNGS, including LVD (see [12] and links there) but only for several decades.

Using a 24-year series of data on the observation of muon fluxes at the LVD, significant variations were found with periods of about 4 and 10 years, associated with temperature variability in the lower stratosphere [13]. We have shown that these fluctuations are characteristic not only of the Gran Sasso region, but are present on a large scale throughout the Northern Hemisphere.

Analysis of the muon flux series also reveals evidence of diurnal and monthly variations, especially during the highly variable winter period. Although such transient modulations are also found in the effective temperature series, we show that variations of

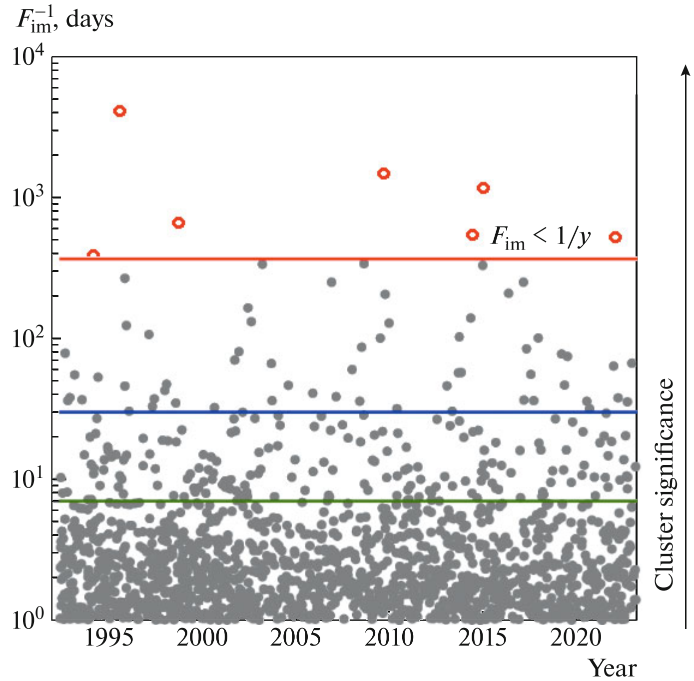

Fig. 1. Registered clusters with $F_{im} < 1$ day^{-1}. Clusters with high significance are marked with empty circles above line $F_{im} = 1$ year^{-1}.

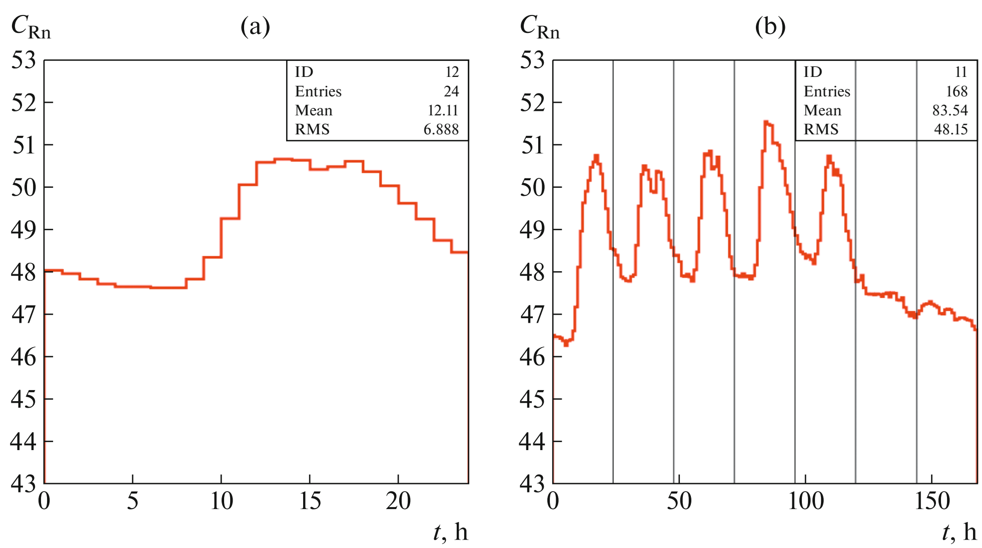

Fig. 2. Daily (a) and weekly (b) gamma counting rate variations obtained with the LVD epoch folding method for 2010 data.

the two series lead to a better match when considering only certain layers of the atmosphere, depending on the particular event. The amplitudes of long-term variations are much larger than those expected based on temperature modulations.

Our study shows that the underground muon flux can be used as a powerful tool for studying stratospheric temperature variability around the tropopause.

5. GAMMAS FROM RADIOGENIC BAKGROUND

The LVD constantly detects gammas from the natural radioactivity of the rock and setup materials. The greatest danger is the radioactive gas radon, which is a product of the decay of uranium–thorium series and is released into the atmosphere of the underground hall where the LVD setup is located. The yield of gammas from the rock can be estimated by

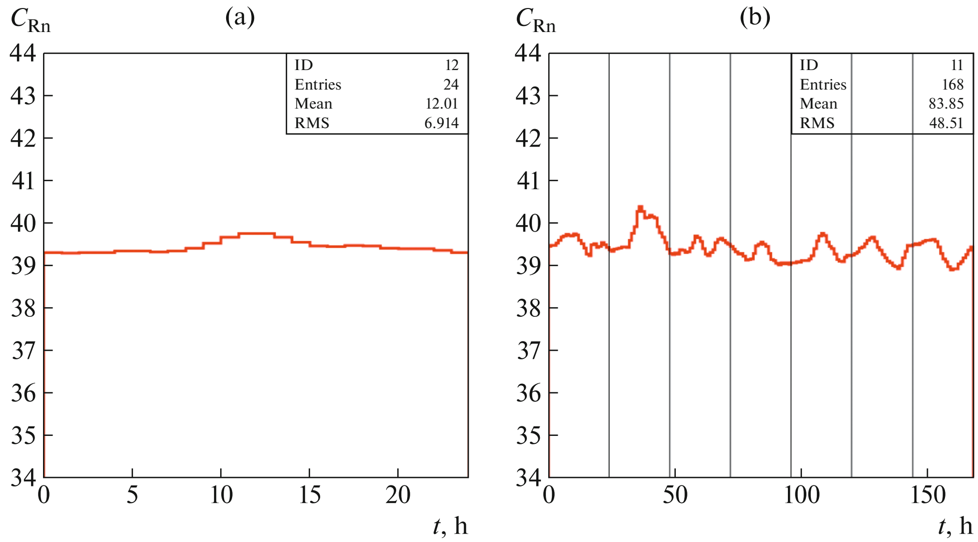

Fig. 3. Daily (*a*) and weekly (*b*) gamma counting rate variations obtained with LVD using the epoch folding method for 2020 data (pandemic year).

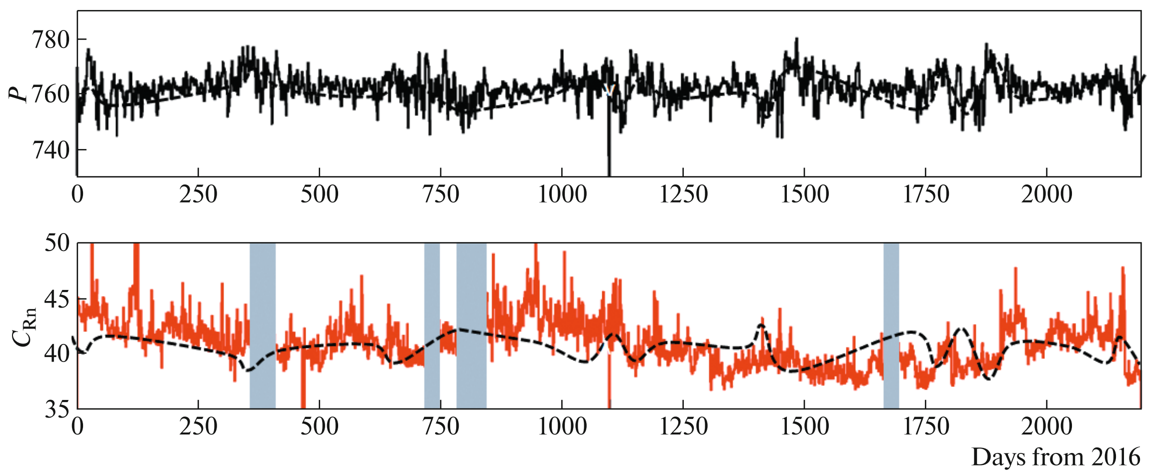

Fig. 4. Time series of atmospheric pressure on the surface (accurate near the LNGS) and the LVD gamma counting rate. The curves are a smoothed function obtained from the time series of pressure and it is also reflected for the time series of gamma rays.

various methods and shielded from it by passive protection. Gammas from radon in the atmosphere of the underground hall, in addition to the equilibrium one, have a variable component associated with various technogenic, atmospheric and geophysical factors. The LVD constantly monitors the gamma quanta counting rate. The technique for detecting gammas is described in detail in [6]. Time series analysis showed that gamma quanta have seasonal—annual, weekly, daily variations.

Weekly and daily variations are technogenic in nature, associated with the work in the underground hall of employees and the movement of vehicles in the adjacent tunnel. Peaks in the time series (radon emissions) are absent on weekends, and on weekdays they clearly have the nature of working hours (Fig. 2): increase from 08 : 00 to 12 : 00, decrease 2 hours, and again increase and decrease after 17 : 00 [14].

An interesting time for analyzing the time series of gamma quanta was the time of the Covid-19 Pandemic. Between February 2020 and the end of 2021, there was virtually no technical activity in the underground halls. During this period, there were only observation duties and security rounds. Therefore, technogenic weekly and daily variations are not observed (Fig. 3).

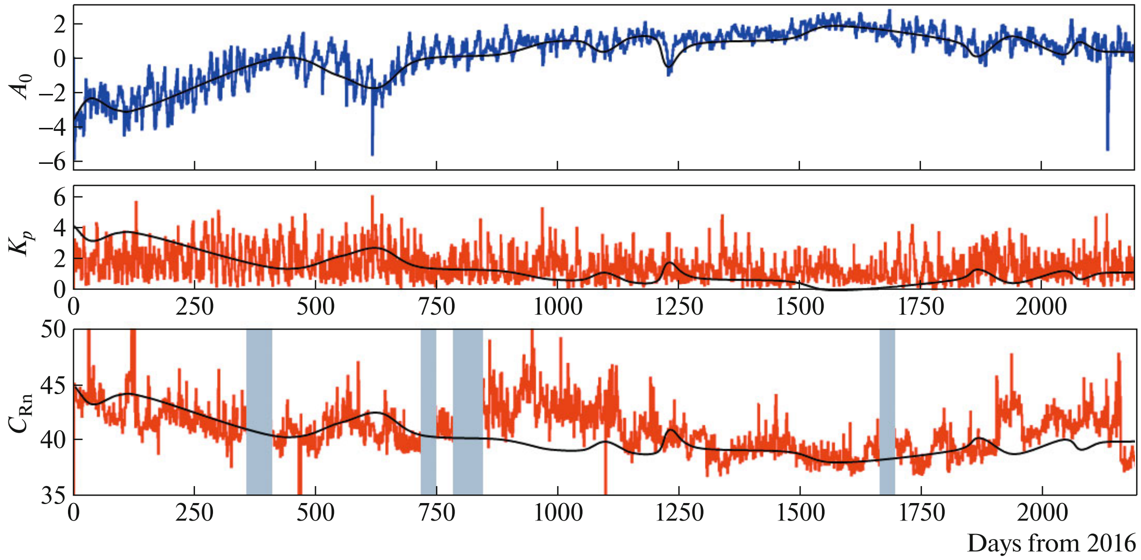

Fig. 5. Time series of characteristics of variations in cosmic ray density (A_0), total global planetary index of geomagnetic activity (K_p), and LVD gamma counting rate (C_{Rn}). Curves are a smoothed function obtained from the time series A_0 and it is also reflected for the time series K_p and C_{Rn}.

6. RELATIONSHIP OF THE GAMMA BACKGROUND OF THE LVD DETECTOR WITH GEOPHYSICAL FACTORS

Gammas detected in the LVD are associated with radon emissions into the atmosphere of the hall [15], so it was interesting to search for their correlations with all kinds of geophysical and atmospheric effects. Moreover, large LVD statistics make it possible to search for different types of correlations.

For the analysis, we used time series:

a) counting rates of gammas detected in LVD, given at 1 counter per second;

b) atmospheric pressure taken from the ER-Interim reanalysis dataset by the European Center for Medium-range Weather Forecast (ECMWF, [16]) at a point near the laboratory, normalized to sea level;

c) the density of galactic cosmic rays obtained from the total number of Forbush decreases processed by the GSM method [17]. Forbush decreases include a wide variety of phenomena in the variations of galactic cosmic rays [18, 19], which are mainly due to ejections of solar matter and/or high-speed solar wind streams from coronal holes.

d) total global planetary index of geomagnetic activity.

We used statistics from January 1, 2016 to December 31, 2021 (6 years). For pairs of time series: pressure (P_0)—LVD gamma quanta (C_{Rn}) and cosmic ray density (A_0)—LVD gamma quanta (C_{Rn}), a correlation analysis was carried out.

Figure 4 shows the time series of atmospheric pressure on the surface (a point near the Laboratory) and the counting rate of gammas on the LVD. The curves are a smoothed function obtained from the time series P_0 and it is also reflected for the time series C_{Rn}. One can see the anti-correlation of the P_0 and C_{Rn} series, on large scales, while the Pearson correlation coefficient gives a value of 0.2.

Time series of characteristic variations in cosmic ray density (A_0), total global planetary geomagnetic activity index (K_p), and LVD gamma counting rate (C_{Rn}) are shown in Fig. 5. The curves are the smoothed function obtained from the time series A_0 and it is also reflected for the time series K_p and C_{Rn}. The anticorrelation between A_0 and K_p was discovered in [5]. The anticorrelation of A_0 and C_{Rn} on large scales was discovered for the first time. Pearson correlation coefficient 0.5.

The 2018 LVD data passes above the smoothed curves for both cosmic ray density and pressure. Despite short-term spikes (of the order of a week-month) in the C_{Rn} time series, the overall behavior of the reflected curves for the C_{Rn} series is similar to the A_0 and P_0 curves.

Most likely, both effects and the change in pressure and the change in the density of cosmic rays (or their superposition) entail a change in the radon yield on a large scale. As was pointed out in [5], a change in the intensity of cosmic rays causes atmospheric rearrangements, as a result of which the balance of pressures at the junction of blocks of faults in the earth's crust is disturbed. If the accumulated elastic deformations are already large enough at the block boundary, then they become greater than the strength limit that the rock can withstand, the blocks are displaced relative to each other, and then, according to Reid's Elastic Rebound Theory [20], tectonic movements and earthquakes occur, which carry out radon.

7. CONCLUSIONS

The paper presents the results of the LVD experiment obtained over the past year:

1. A limit on the frequency of supernova explosions in our galaxy has been obtained: less than 1 event per 13.5 y at a 90% confidence level.

2. Observation of muon fluxes revealed their significant variations with periods of about 4 and 10 years, associated with temperature variability in the lower layers of the stratosphere.

3. Studying the variations in the gammas' background according to LVD data, it was obtained that there were no daily and weekly variations in the count rate of gamma quanta associated with the release of radon into the atmosphere of the hall from the ground during the Covid-19 pandemic. This confirms the technogenic causes of variations found in the data up to 2020 [13].

4. Indications have been obtained that the counting rate of gammas in LVD is related to variations in cosmic ray intensity and atmospheric pressure.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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