The Large-Volume Detector (LVD) of the Gran Sasso Laboratory.


Istituto Nazionale di Fisica Nucleare - Sezione di Bologna

G. BARBAGLI and P. O. PELLEGR

Dipartimento di Fisica dell'Università - Firenze

R. CASACCIA, L. LAASKO, A. RENDI, G. C. SUSINNO and L. VOTANO

INFN - Frascati

F. CARDONE, G. DI SCARICIO and R. SCIRIAGLIO

Dipartimento di Fisica dell'Università - L'Aquila

G. D'ALI

Dipartimento di Fisica dell'Università - Palermo

M. AGGIETTA, C. CASTAGNOLI, A. CASTELLINA, W. FULCHIONE, C. MORELLO, L. PESELLERI, G. TRENNERO, P. VALLEANZA and S. VERNET

Istituto di Geofisica e del C.N.R. - Torino

G. BADINO, L. BERGAMASCO, G. CAI, M. DAUDIO, P. GADOTTO, G. NAVARRA and O. SALVEDRA

Istituto di Fisica Generale dell'Università - Torino

Istituto Nazionale di Fisica Nucleare - Sezione di Torino

R. MEUNIER, F. ROLLIBACH and A. ZICCHI

GEPN - Genève

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Summary. We describe here the LVD experiment (Large-Volume Detector) of the Gran Sasso Laboratory, which is the natural improvement of the LSD experiment (Liquid Scintillation Detector) running in the Mont Blanc Laboratory. The LVD $(31 \times 13) \text{ m}^2$ area, height 12 m) consists of $\sim 1800$ tons of liquid scintillator and of a system of streamer tubes on 5 layers for reconstructing tracks of charged particles. As any experiment in an underground laboratory, which has a low statistics of events and requires long running times, the LVD is a multipurpose experiment but with different priorities of the researches. The main goal is neutrino astronomy, firstly detection of neutrinos from collapsing stars and secondly high-energy neutrinos and solar neutrinos. Since the expected number of interactions of neutrinos from a stellar collapse is very high (of order of 800 for a collapse at the distance of the galactic centre), the LVD is, contrary to the present experiments, a real neutrino observatory, able to make a detailed analysis of the energy and temporal distributions of the burst. In addition to neutrino astrophysics, with the LVD experiment excellent possibilities exist to perform researches in cosmic-ray and high-energy elementary-particle physics.

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1. Introduction.

The Large-Volume Detector (LVD) for the Gran Sasso Laboratory is based on the experimental results obtained with the Liquid Scintillation Detector (LSD), fully running since October 1984 in the Mont Blanc Laboratory. However, LVD is not only an upgrading by a factor of 20 in mass of LSD, but allows also for penetrating new studies in the fields of particle physics and astrophysics. In fact, the experiment is based on the following motivations:
Our experimental results (1,2) in the Mont Blanc Laboratory show that a thick, large-volume detector, sectioned in identical scintillation counters, carefully shielded with Fe slabs and located deep underground, is an extremely sensitive apparatus for detecting neutrinos from collapsing stars. This is because it has a very low background and allows detection of both products of a $\nu_e$ interaction:

\[
\begin{align*}
\bar{\nu}_e + p &\rightarrow n + e^+ \\
\rightarrow n + p &\rightarrow d + \gamma,
\end{align*}
\]

whatever be the structure of the burst at the earth.

Moreover, the detector's core (consisting of the inner counters) is very well shielded against low-energy radioactive background by the passive anticoincidence with the surface counters. As a consequence the total noise in the detector's core is so low that its sensitivity to detecting gravitational collapses easily reaches extragalactic sources. Since any single $\bar{\nu}_e$ interaction can be detected in LVD experiment, the time and energy distributions of the neutrino burst at Earth can be used to derive the neutrino rest mass. The LVD experiment can detect $\nu_e$ through the elastic-scattering reaction

\[
\nu_e - e^- \rightarrow \nu_e + e^-
\]

which adds further information on the study of gravitational stellar collapses from the neutronization peak at the initial stages of the collapse, where only $\nu_e$ are produced. Reaction (3) makes LVD also a detector of solar neutrinos, produced by the $^8$B decay in the Sun. To this aim, a volume detector is particularly well suited since the core has a very low counting rate even at low energies.

The detector is a good telescope for high-energy neutrino astronomy, where several layers of streamer tubes are added in between the scintillation counters to increase its directionality properties. In addition fast measurements of times of flight allow us to study high-energy $\nu_e$ and $\nu_\mu$ in upward directions. The LVD experiment is also a sensitive apparatus to study atmospheric neutrinos and neutrino oscillations.

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The LVD is a good detector of cosmic-ray muons; intensity, high-energy interactions, anisotropies, etc. In addition, being an omnidirectional telescope, LVD is well suited to detecting horizontal muons which are particularly important to study heavy flavours.

The LVD experiment is a good apparatus for detecting magnetic monopoles (which are omnidirectional) through simultaneous measurements of ionization and time of flight.

More difficult is to use the LVD to measure nucleon instability processes ($\Delta B = 1$ and $\Delta B = 2$). This because of the difficulties in localizing the event vertex and in discriminating the atmospheric neutrino background. Obviously the best techniques for this research are those based on a volume apparatus with high spatial resolution, i.e. those detectors which visualize the events. However some important channels favoured by SUSY theories (i.e. $p \rightarrow K^+\bar{\nu}$) and those leading to $\mu$s can be studied fairly well with LVD. The same considerations apply to studying $\mu$-$\tau$ oscillations.

Finally, it is worthwhile pointing out that all the electronics, read-out and data acquisition systems are based on well-tested and conventional modules; this makes the LVD an apparatus suitable for long periods of operation with high reliability and low running cost. This conclusion is born out by our experience in the Mont Blanc Laboratory.

2. Neutrinos from collapsing stars.

Theoretical models of stellar evolution predict that massive stars ($M > 6 M_\odot$ on the main sequence) should end their lives with core implosion, eventually followed by envelope explosion. The gravitational collapse is brought about by many effects among which the most important ones are thermonuclear burning in the shells surrounding the core (which makes the core mass $M_\star$ to exceed the Chandrasekar limit mass, $M_{\text{Ch}} = 1.47 \odot M_\odot$) and neutronization of matter (which reduces both the electron pressure and the lepton fraction $y_e$ in the core).

Recently we have reviewed (2) the main features of neutrino emission which are important for burst detection at the earth in an underground laboratory. The total energy output is of order $0.1 M_\odot c^2$ in neutrinos and antineutrinos with a Fermi spectrum and an average energy $\sim 14$ MeV. During the collapse, 3 stages of neutrino emission can be identified:

a) neutronization: only $\nu_e$ are emitted, with a peak luminosity of $\sim 10^{51} \nu_e s^{-1}$ during a time scale of the order of a few ms;

b) **deleptonization**: after the full trapping and formation of the neutrino-sphere, $\nu_e$ and $\bar{\nu}_e$ emission continues for $\sim 1$ s;

c) **cooling**: the neutrino emission continues from the neutrino-sphere during the Kelvin cooling of the new born neutron star, for times as long as several seconds. The bulk of the neutrino luminosity is emitted during this stage: $\sim 10^{53}$ erg in each neutrino flavour.

The time structure of the collapse is still rather uncertain. As a consequence, a neutrino detector must be able to record pulses for times as long as several seconds in a low-background environment in order that all the neutrino interactions should be recognized. From a collapse originating at the distance of the galactic centre a flux at the earth of about $10^{32} \frac{\nu_e}{cm^2}$ is predicted, and these neutrinos are most readily detected through reactions (1) and (2). In an homogeneous target detector with mass 1.8 ktons, such as LVD, one expects to observe about 900 such interactions during the burst duration at the energy threshold of 7 MeV.

However, recording low-energy pulses over long time scales increases the number of background pulses also. Thus one must ensure that a good signature is chosen for real physical events. This could be realized by detecting both products of reactions (1) and (2), in which the delayed (on the average $\sim 170 \mu s$) coincidence between $e^+$ and $\gamma$ pulses gives a good signature for a single neutrino interaction. Among the existing detectors, those based on measuring Čerenkov light in water have an energy threshold of order 12 MeV, and no $\gamma$-ray from reaction (2) can be detected. On the contrary, a liquid scintillation target in a low-background environment properly works as a neutrino detector in which both products of reactions (1) and (2) could be detected. This possibility has been successfully tested (1) in LSD.

The background counting rate in LSD is on the average 0.3 counts/hour per counter at the energy threshold $E > 7$ MeV. This figure gives a noise level $N \sim 0.1$ counts/s for the whole LVD apparatus. In addition, it should be noted that the background counting rate is much lower for the inner and well-shielded counters in the detector's core ($\sim 1.0$ ktons of scintillator over $\sim 1.8$ ktons) making the value $N$ as an upper limit. Since in the LVD one expects to observe $\sim 900 \bar{\nu}_e$ interactions from a galactic stellar collapse, and assuming a long burst duration of 20 s, the signal-to-noise ratio is extremely high.

At the distance of the Magellanic Clouds ($\sim 60$ kpc) for which the efficiency for detecting a stellar collapse in the LSD is low, the signal in the LVD is still of order 22 $\bar{\nu}_e$ interactions; then the efficiency to detect a gravitational stellar collapse from these external galaxies is practically 1. By assuming more optimistic collapse parameters (shorter time duration and larger $\bar{\nu}_e$ flux, which are not at all impossible, given the present uncertainties in the theory of final evolution of massive stars), a larger sample of galaxies in the local group of collapses with a smaller neutrino emission can be surveyed by the LVD. This is
a very important feature of the proposed detector, since the predicted rate of gravitational collapses in our Galaxy is rather small, i.e. of order 1 every few years from the pulsar formation rate.

Finally, if the collapse occurs within our Galaxy, a large amount of information on the dynamics of the collapse and on the physical conditions inside the pre-supernova core can be obtained by observing not only the 𝜈s through reaction (1), but also the 𝜈s through the elastic-scattering reaction (3), which, however, produces a lower number of interactions in the detector. Since 𝜈s are emitted as early as the neutronization stage of the collapse, the initial phases of the development of a collapsing star can be studied.

Besides reactions (1), (2) and (3), it is important to point out that neutrinos could be detected through other different reactions in LVD, as shown in Table I.

**Table I.**

<table>
<thead>
<tr>
<th>Charged currents</th>
<th>Neutral currents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) 𝜈e+14C → 14N + e−</td>
<td>5) 𝜈e+e− → 𝜈e+e−</td>
</tr>
<tr>
<td>2) 𝜈e+14C → 14B + e+</td>
<td>6) 𝜈e+e− → 𝜈e+e−</td>
</tr>
<tr>
<td>3) 𝜈e+56Fe → 56Co + e−</td>
<td>7) 𝜈e+e− → 𝜈e+e−</td>
</tr>
<tr>
<td>4) 𝜈e+58Fe → 58Mn + e+</td>
<td>8) 𝜈s(e,e′)+12C → 12C* + 𝜈s(e,e′)</td>
</tr>
<tr>
<td>9) 𝜈s(e,e′)+12C → 12C* + 𝜈s(e,e′)</td>
<td></td>
</tr>
</tbody>
</table>

Reactions (8) and (9) of Table I give a very clear pulse in the LVD. They have a cross-section 𝜎 = 6.10−43 Ee cm² up to energy 𝐸 ≈ 10 MeV and the 12C de-excitation occurs with the emission of a 15.1 MeV γ-ray in 96% of the events, while 4% of 12C de-excitation occurs with the emission of 2 γs with energy 10.7 MeV and 4.4 MeV, respectively.

As regards reaction (1) of Table I, the energy threshold is 𝐸th = 16.4 MeV and up to ≈ 80 MeV the target nucleus is not torn away from the parent nucleus. Thus in the range 10 MeV ≪ 𝐸 ≪ 80 MeV the signature of a 𝜈e interaction is very good: a prompt 𝜖+ pulse with energy (𝐸 − 𝐸th) followed after 11 ms a 𝜖+ pulse from the 𝜃+ decay of the 12N, with 𝐸max = 15.4 MeV and an average value 𝐸 = 5 MeV.

The same process occurs for reaction (2) of Table I, where the prompt 𝜖+ pulse is followed after 20 ms by an 𝜖− pulse with 𝐸max = 13.4 MeV and average energy 𝐸 = 4.5 MeV. In any event, both reactions give a very strong signature of a 𝜈e or 𝜈s interaction as a pair of large pulses in a single counter during a very short time.

Figure 1 shows the number of interactions per MeV in the LVD as a function of the neutrino energy for the reactions previously considered.

One can see that the collapse dynamics can be followed in detail by the information given by these additional reactions. The possibility to use these
Fig. 1. – Energy spectrum of neutrino interactions in LVD. The curves refer to
a) ¯νp-He, b) νe-He, c) νC-Ne, d) νC-ν*C.

reactions was also evaluated in the past for the Mont Blanc LSD experiment. However this seems to be possible only for the LVD, given the large mass of the detector and the high sensitivity of the experiment.

3. – Solar-neutrino astrophysics.

It is well known that the Brookhaven detector of solar neutrinos has observed, after more than a dozen years life time, only about 30% of the neutrinos that the standard solar model predicts to be emitted through the ⁸B decay. By using the experimental value of the ⁸B νe flux at Earth (3×10⁻⁹ cm⁻² s⁻¹) we estimated that the number \( N_e \) of detected elastic-scattering reactions (3) with the electrons in the LVD is \( N_e \sim 5 \) per day for an energy threshold \( E_{th} > 5 \) MeV in the detector’s core. This result would be possible in the core of the LVD after reducing the local radioactivity background from the surrounding rock to very low values by the shell counters and Fe shield.
In addition, the possible correlation between neutrino flux, cosmic rays and solar activity can be directly checked by the LVD in real time. In particular, an enhancement of a factor 3 in the solar neutrino flux during energetic solar flares can be observed during the occurrence of the flare itself, while any radiochemical experiment integrates the neutrino flux over long times.

4. - Neutrinos from stellar collapses in the past evolution of the Universe.

Some evidence of stellar nucleosynthesis, e.g. formation of heavy elements and their uniform distribution in space, is generally interpreted as due to a first generation of massive stars that evolved toward a supernova explosion in short time scales; thus the rate of gravitational collapses in the past evolution of the universe should have been higher than the present rate. Anyway, we assume here the present rate of stellar collapses over the age of the universe. Since LVD records any $\bar{\nu}_e$ interaction through reaction (1), the diffuse isotropic neutrino background from stellar collapses can be measured. It is reasonable that we could observe some dozens interactions per year in the LVD due to stellar evolution in the past $10^{10}$ years, with the average $\bar{\nu}_e$ energy slightly reduced by the red-shift.

5. - High-energy neutrino astronomy.

With the LVD experiment several kinds of cosmic objects, characterized as powerful point neutrino sources with $E > 1$ GeV, can be detected. The main detection process is

\[ \bar{\nu}_e + N \rightarrow \mu + X, \]

where neutrinos are observed through the muon flux they produce interacting with the rock surrounding the apparatus.

In this connection, sources in the southern hemisphere or observed in horizontal direction are the most important ones since in this case the background of atmospheric muons is negligible along the direction of the source within the resolution angle of the detector.

In particular, according to our detailed calculations (4), LVD can detect the following cosmic sources of high-energy neutrinos.

5'1. Young supernova remnants. - The neutrino luminosity, after the gravitational collapse of the core of a massive star, continues for times of order of

months, being high-energy neutrinos mainly produced by $p$-$p$ interactions in the envelope surrounding the collapsed object. Neutrino production at the source is competitive with production of high-energy $\gamma$-rays, for which experimental evidence has been obtained by satellites in recent years. The thickness of the envelope around the collapsed object is the most critical parameter for $\nu$ and $\gamma$ emission, being the latter possible only for a restricted range of optical depths; i.e. when the column density is thick enough for $\gamma$ production and, at the same time, thin enough for $\gamma$ escape from the stellar envelope.

On the contrary neutrinos are produced and easily escape both from optically thin and optically thick objects. Thus the possibility to detect hidden sources is a real one and, about 200 neutrino produced muons per year are predicted to be observed in the LVD. Moreover, one knows that the high-energy neutrino burst is delayed by several weeks after detection of the low-energy neutrino burst from the collapsing core.

5.2 Binary X-ray sources. – The same mechanism of neutrino production through $p$-$p$ interactions, discussed in the previous section, occurs in a stellar non-evolved companion of a collapsed object in a binary system; indeed some sources of this kind, among which Cygnus X-3, have recently been observed to be powerful $\gamma$-ray sources, with the flux modulated according to the binary period. Since the observed $\gamma$-emission has a duty cycle of the order of 1%, the models generally assume that $\gamma$'s escape only from the thin atmosphere of the companion or from a jet, during the short periods at the beginning and/or the end of eclipse of the collapsed object. On the contrary, neutrino emission continues during the whole period of the eclipse which, for giant companions extending to the Roche limit, involves emission for about half the binary period. For this reason, the neutrino flux at the earth may be much greater than the flux in high-energy $\gamma$-rays, and it can be detected through the excess of muons. In the case of Cygnus X-3 a few muons per year with $E > 10 \text{ GeV}$ can be detected (*) in LVD along the direction of the source within the resolution angle of the detector if the enhancement factor between neutrino and gamma emission is of order $10^2$.

6. – Atmospheric neutrinos.

No experimental evidence of low-energy atmospheric neutrinos, in the range $10 \text{ MeV} < E < 200 \text{ MeV}$, is available up to now. Neither are theoretical predictions in this energy range well defined, although some preliminary calculations have been recently made. Most of the calculations to estimate the neutrino

background for proton decay experiments in underground laboratories concern energies $\geq 200$ MeV. The LVD is a very sensitive experiment to both $\nu_e$ and $\bar{\nu}_e$ interactions at low energies; for example we can measure the $\bar{\nu}_e$ atmospheric neutrinos above an energy threshold of $\sim 10$ MeV through reaction (1). By measuring inside the fiducial volume of the LVD both the energy of the contained $e^+$ and the associate $\gamma$-pulse from neutron capture, we can obtain a direct experimental measure of the $\bar{\nu}_e$ atmospheric spectrum, with a very clear signature that makes such events easily distinguishable from any other type of neutrino interactions. At a threshold of 10 MeV, the total number of atmospheric neutrino interactions inside the detector has been estimated to be of the order of a few hundreds per year.

It is now established from current proton decay experiments that the rate of confined events is $\sim 150$ kton-year. Then the ratio $\nu_e/\nu_x$ can be measured as well as the charge ratio of secondary particles produced by those interactions inside LVD.

As regards high-energy atmospheric neutrinos, the flux of near-horizontal neutrinos is higher by a factor of $\sim 2$ compared to the upward going neutrinos; the LVD present a very large area ($\sim 1000$ m$^2$) for detecting the flux of muons, at zenith angle $\geq 80^\circ$, produced in the interactions (4) of atmospheric $\nu_x$ in the rock surrounding the apparatus. In this connection, it is worthwhile to observe N-S and E-W asymmetries which could be related to neutrino oscillations.

Both near-horizontal and upward-going muons produced by neutrinos can be measured by the fast-timing method. The total number of events of this type (for zenith angles $\geq 80^\circ$) is $\sim 200$ year. On the other hand, since the LVD is sensitive to stopping muons inside the detector and recognizes the $e^+$ from $\mu^+$ decay, it is possible to measure the ratio $\mu^+/\mu^-$ of low-energy muons at zenith angle $\geq 80^\circ$ produced at the rate of a few tens per year by neutrino interactions in the rock or even inside the detector (Fe shield + liquid scintillator).


7.1. Measurement of the neutrino mass from stellar collapses. — A nonzero neutrino rest mass is of utmost importance both for physics and for astrophysics (5); thus is a very important goal to measure this parameter. After the neutronization $\nu_e$ peak, which can be detected through reaction (3) in the detector’s core, pair annihilation of electrons produces the bulk of neutrino emission from the collapsing star. Since particles with a nonzero rest mass

and different energy reach the earth at different times, the time and energy
distributions of the interactions in the LVD could be used to determine the
neutrino mass.

In addition, given the large distance of a collapsing star, the effect of the
time spread is large enough to measure the masses with a fairly good accuracy.
Furthermore, as discussed previously, the neutrino burst consist of any neu-
trino flavour; in particular muon neutrinos will arrive at the earth much later
than electron neutrinos if the difference between their masses is relevant.
The detection of both neutrino flavours interacting with the $^{12}$C nuclei in
LVD gives an additional excellent temporal signature to estimate their rest
mass.

In conclusion, since any neutrino interaction is recorded in the LVD
whatever be the time structure of the burst at earth, the detector works in
in a model-independent way and no constraint is made on the predicted burst
duration. For massive particles of any kind the low-energy interactions are
delayed in comparison with the high-energy ones in a detectable fashion. The
effects of the delay are: for a given particle the spread in time of the interac-
tions gives a train of pulses separated in time; for different particles this train
of pulses occurs at different times, whose separation depends on the mass dif-
fERENCE. Finally we have suggested (?) that the correlation with a gravita-
tional wave antenna not only is a powerful tool to investigate the dynamics
of a collapsing core, but also allows recording the absolute time of the onset
of the burst to evaluate the neutrino rest mass with a higher precision.

7.2 Neutrino oscillations. — The parameters which characterize the sen-
tsitivity of various experiments of neutrino oscillations are the minimum value
of the squared mass difference $\Delta^2$ to which the experiment is sensitive for max-
imum mixing ($\sin^2 2\theta = 1$) and the minimum value of $\sin^2 2\theta$ corresponding to
the largest value of $\Delta^2$ to which the experiment is sensitive. Today's experiments
allow detection of neutrino oscillations due to $\Delta^2 > 1$ (eV)$^2$. Future experiments
with accelerators will improve this upper limit to $\Delta^2 \sim 10^{-2}$ (eV)$^2$. With detecting
atmospheric neutrinos in underground experiments it is possible to further
improve the range to $(10^{-2} - 10^{-4})$ (eV)$^2$. We note that: a) the atmospheric
neutrino flux at sea-level in the range $(0.1 - 100)$ GeV comes mainly from $\pi^0$
decay, and for $E > 100$ GeV from $K$ decay (because of time dilatation); b) at
high energies $\nu_\mu$ are dominant in respect to $\nu_e$, and for this reason the angular
distribution becomes anisotropic.

Figure 2 shows the ranges of $\pi$ (distance detector-source) and $d_{\text{max}}$ for the
Gran Sasso Laboratory ($k_x = 1500$ m, $\sim 4000$ kg cm$^{-2}$ of standard rock) in the

(?) C. CASTAGNOLI, P. GALLOTTI and O. SAAVEDRA: Astophys. Space Sci., 55, 511
(1978).
different zenithal directions. Experiments to search for atmospheric $\nu_\mu \rightarrow \nu_e$ oscillations can be performed with two methods:

4) By detecting the $\nu_\mu(\nu_e)$ induced events in the detector: a difference in the rates up/down, comparison of the ratios $\nu_\mu(\uparrow)/\nu_\mu(\downarrow)$ and $\nu_e(\uparrow)/\nu_e(\downarrow)$, or a difference in the types (comparison of the ratios $\nu_e(\downarrow)/\nu_\mu(\downarrow)$ and $\nu_e(\uparrow)/\nu_\mu(\uparrow)$) may signal neutrino oscillations;

5) By detecting muons induced by $\nu_\mu$ through reaction (4) in the rock surrounding the detector. A loss of muon flux (disappearance experiment) from atmospheric $\nu_\mu$ in the horizontal or in the upward direction may signal neutrino oscillations.

The sensitivity of the LVD to oscillations gives a 3$\sigma$ effect after several years of running time with method $A$ ($A^2$ between $10^{-4}$ and $10^{-5}$) and in twice that time with method $B$ ($A^2$ between $10^{-5}$-$10^{-6}$).

We have three final remarks:

a) $\nu_\mu$-$\nu_e$ oscillations, for $A^2 > 10^{-3}$ (eV)$^2$, result in a lack of $\nu_e$ neutrino flux relative to $\nu_\mu$ in the downward direction.

b) Matter oscillations. Vacuum oscillations are modified in matter by charged-current scattering in a significant way if the neutrino traverses $x > 10$ km, and have $E$(GeV)~$\geq 5 \cdot 10^2 A^2$ (eV)$^2$. This effect may be significant for upward neutrinos and for $A^2 < 10^{-4}$ (eV)$^2$. In this case the ratio $\nu_e(\uparrow)/\nu_\mu(\uparrow)$ is lower ($\sim 15\%$) than the corresponding ratio for vacuum oscillations.
c) Finally we note that (in addition to up-down measurements) we can measure ν-oscillations in the LVD also by comparing the rates of horizontal muons at $\theta \approx 80^\circ$ without contribution to the noise due to atmospheric neutrinos.

3. Neutrino geophysics.

One of the main important mechanisms of heat production in the Earth's core is the decay of very heavy nuclei, in particular uranium and thorium. To measure the associated neutrino flux thus seems to give a valuable method for deriving the heat production of the Earth, and provide information on its internal structure and on the mass fraction in uranium. Although there are many other decay modes (e.g., $^{237}\text{U}$, $^{239}\text{Rh}$, etc.) which contribute to the total neutrino flux, the LVD core will be sensitive only to $\bar{\nu}_e$ emitted in the $^{238}\text{U}$ decay, whose maximum energy is 3.26 MeV with a predicted flux of $3.5 \times 10^{10}$ $\bar{\nu}_e$/cm$^2$·s$^{-1}$. Since terrestrial neutrinos have never been detected so far, it seems really a good chance to try to detect them with the LVD core through reaction (1), where the expected number of interactions is of order of a few events/day. The detection of $\bar{\nu}_e$ of such an origin will be possible provided a very low background counting rate be reached inside the apparatus.

In any case, from the LVD experiment lower limits for future experiments can be obtained, and the abundance of heavy elements in the interior of our planet can be roughly estimated.


The relevant aspects of muon physics underground can be accomplished by measuring the muon depth-intensity curve over a large range in order to derive the energy spectrum and angular distribution; by measuring the rates of muon bundles of different multiplicities and separation between the muons themselves; by detecting low-energy components (muon or pion) from local muon interactions or by studying the products of muon interactions along the path in the mountain rock; by measuring with high precision the arrival direction of the muons.

9.1 Energy spectrum and angular distribution. - The muon differential spectrum is closely related to the primary cosmic-ray nucleon spectrum (essentially protons) in the energy range ($10^{18}$–$2 \times 10^{19}$) eV as calculated in (9). These results can be easily modified and generalized for the effect of

scaling. Single muons provide information on both particle physics (proton-nucleus interactions in the fragmentation region) and astrophysics (all nucleon spectrum) in the (10–100) TeV region. These data will be complementary to those obtained from direct primary cosmic-ray measurements and from accelerators at the highest energies (CERN pp collider, Fermilab Tevatron). Measurements of the muon angular distribution provide an indirect way to estimate the hadron production cross-section up to about 100 TeV. In (7) the angular distributions are given for different depths as a function of the ratio between prompt and conventional muons. Extended measurements of good precision (typically, at a given slant depth higher than 5000 bg/cm$^2$ many experimental points are required up to at least 70$^\circ$ zenith angle with an associated statistical error less than 5\% could resolve cross-sections of the order of a few millibarns. At the same time one could reconcile discrepancies between the muon energy spectrum in the TeV region measured at vertical (underground) and inclined (magnetic spectrograph) directions.

9') Muon bundles. — Rates of underground muons are sensitive to shape and composition of the primary spectrum and properties of hadronic interactions. The primary energies involved at our depth extend up to $10^{16}$ eV, i.e. where the spectrum begins to steepen. A detailed analysis of the multi-muon events at 6000 m w.e. has been done in (10,11), with the conclusion being limited essentially by the low statistics. A large apparatus, the LVD, eventually implement with a surface array (12) at the top of a mountain to detect the air shower electrons, should allow for the possibility to check different trial compositions.

Moreover, a correlated study of rates and lateral separation of muons allows one to measure the transverse momentum distribution in hadronic interactions of increasing energy. Phenomena out of the standard picture of hadronic interactions (as, for instance, the transition to quark matter in nucleus-nucleus interactions) are expected to give peculiar signatures, i.e.


more widely spread muon bundles, higher transverse momenta, azimuthal asymmetry in primary interactions and enhanced prompt muon production. The identification of these events demands a very large apparatus (at our depth the lateral spread corresponding to a \( p_t \sim 1 \text{ GeV/c} \) is \( \sim 10 \text{ m} \)) and muon detection with good spatial resolution (\( \leq 5 \text{ cm} \)).

93. Muon interactions. — Local muon interactions have been studied for many years by detecting muons or pions of low energy. The mean muon energy in the Gran Sasso Laboratory is \( \sim 280 \text{ GeV} \), i.e. in the accelerator range, so that a substantial improvement requires some way to tag the high-energy muon physics. A more promising possibility is to study muon interactions along the path in the rock by comparing the underground intensities at very high depths (\( \geq 7000 \text{ kg/(cm}^2\) to the sea-level muon energy spectrum over 10 TeV. We point out that high-energy muon interactions provide information on real photon interactions: indeed this study should allow us to determine the photoproduction cross-section at high energy (1 TeV region). The accelerator measurement extend up to \( \sim 200 \text{ GeV} \) and the question is open whether the cross-section rises logarithmically with energy or remains constant. In conclusion this physics requires a large acceptance detector with tracking capability and high spatial and angular resolution, covering at least 75 degrees angle. For this reason, in LVD the liquid scintillator is interfaced with layers of streamer chambers.

94. Neutron production by high-energy muons. — High-energy muons (\( E_\mu > \sim 10^{11} \text{ eV} \)) can produce, by inelastic interactions either in the rock or in the LVD detector, copious numbers of slow neutrons which can be easily detected in a single counter through reaction (2). Then, by comparing the shower size of electromagnetic or nuclear cascades with neutron multiplicity, we can clearly separate the two types of cascades (\( \gamma \rightarrow n \)). In particular, in a nuclear cascade of \( E_\mu > 5 \times 10^{12} \text{ eV} \) we expect to detect a some hundreds of neutrons in a \( \mu \) path length of 5.0 m of liquid scintillator. In addition, we can detect \( \mu^+ \rightarrow e^+ \) decays from \( \pi^+ \) production, which is a characteristic of nuclear cascades. The produced number of neutrons in the LVD counters, together with their lateral and longitudinal distributions, is related to the energy spectrum of muons (\( \geq 5 \times 10^{14} \text{ eV} \)). These measurements are interesting for evaluating the cross-section of inelastic interactions of leptons with nuclei in the region of several TeV, consistent with present accelerator energies, and to obtain useful information on hadroniclike characteristics of high-energy virtual photons.

9.5. Localized discrete cosmic-ray sources. — The interest in studying high-energy photons \((10^{11} - 10^{16})\) eV from discrete sources rests on the experimental evidence obtained from Cygnus X-3, Crab Nebula and Vela X-1. With EAS-surface arrays the identification of localized sources stands on the possibility to separate the events produced by \(\gamma\)’s from the nuclear background by means of fine angular resolution. Moreover, it is very important to select high energies and, eventually, to use specific trigger criteria in the operation of the surface detector. But it is possible to detect this type of discrete sources also through the muon component which can be observed underground in the LVD with or without correlations with the surface EAS array. Indeed the Mont Blanc data have already provided evidence \((14)\) for an excess of underground muons from the direction of Cygnus X-3 and time correlated with the binary period of the source.

Typical angles from multiple Coulomb scattering in rock are less than \(1.5^\circ\); thus a tracking device should provide an angular resolution of this order. The LVD detects \(\sim 1.1 \times 10^{6}\) single muons/year: it is, therefore, possible to detect anisotropies at the level of \((0.3 - 0.4\%)\) for primary protons of energy \(\gtrsim 10^{15}\) eV. With \(\mu\)-bursts it is possible to detect anisotropies 10 times larger, but at an energy \(\gtrsim 10^{14}\) eV.

9.6. Cosmic-ray scintillations at 2 \(\times 10^{9}\) GV — In recent years we have shown that the study of the fluctuations of muons underground is a powerful tool to study solar modulation. By analysing in the frequency and amplitude domain, the data from shallow depth stations we have thus established the persistence of efficient interplanetary modulation of cosmic rays of rigidities up to 300 GV and the existence of nonlinear interactions between particles and interplanetary fields. These particles interact resonantly with the magnetic field (for \(B_0 = 5\) pG, particles of 2 \(\times 10^{9}\) GV have a gyroradius of 1.2 \(\times 10^{4}\) cm). One then introduces a nonlinear parameter which yields a modulation of the magnetic irregularities power spectrum. As a consequence the observable power spectrum of cosmic rays has an enhancement near a resonant frequency (for \(R = 2 \times 10^{9}\) GV, \(f_r = 3 \times 10^{-8}\) Hz) followed at higher frequencies by a definite steepening. Because of the limited length of the time series analysed we see only the postresonant region: however, the model satisfactorily accounts for the observations over a wide range of rigidities. We conclude that interplanetary modulation is still efficient up to rigidities of at least 2 \(\times 10^{9}\) GV.

In the light of these results, it seems no longer adequate to consider the rigidity $10^8$ GV as a threshold for the study of galactic field processes which are free of solar effects. The fact that solar perturbations extend to particles of such high rigidities, with gyroradii of 10 A.U., is a further indication that the dimensions of the solar cavity are larger than originally estimated. In conclusion, we plan to extend with the LVD at Gran Sasso our study to the region of rigidities $\gtrsim 10^8$ GV. We will attempt to test the customary assumption that above this value the particles are not affected by the interplanetary field, but on the contrary one samples the galactic field.

10. Magnetic monopoles.

According to grand unification theories (GUTs), magnetic monopoles should have been produced at the end of the phase transition during which grand unification spontaneously breaks into electroweak and strong interactions. For this reason, magnetic monopoles are the very primordial particles in the universe, and their detection allows one to discriminate between standard big bang theory and inflationary models. In fact, monopole production at the boundary of coherence volumes is strongly suppressed in an inflationary universe while they should be very abundant in the standard model. The possibility to detect magnetic monopoles in a large-volume liquid scintillation detector has been discussed (10) by our group and the first results published (13). It has been shown that the time delay between counters and the time distribution of pulses above the low-energy threshold in one counter during the monopole transit time give a good signature for monopole detection in the velocity range $\beta > 10^{-5}$ and with an ionization $I > 10^{-3} I_4$, where $I_4$ is the ionization of a relativistic particle. Although the ionization mechanisms of a slow moving particle are not well defined so far, in our calculations we assume they are so small that only fluctuations at the level of single photoelectrons may be used to detect monopoles crossing the counters. Indeed, a train of such small

pulses (each with $E \approx 1$ MeV) randomly distributed during the monopole transit time, gives information on $I$ and $\beta$ by one counter, and the time delay among counters gives an additional signature for monopole detection (see fig. 3).

The trigger is given by at least 3 small pulses detected by one counter within a time of 50 $\mu$s; whenever the trigger condition is fulfilled in 1 counter, the 500 $\mu$s general gate for $\gamma$ detection from the $(n, p)$ reaction is opened for all the counters, and we look for 2-fold coincidences between contiguous counters; this corresponds to $\sim 0.3$ trigger conditions per day. In other words, we consider a good signature of monopoles crossing the LVD to be the simultaneous measurements of: a) pulse height in one counter, b) number of low-energy pulses and their time distribution in another counter and c) time delay of such an event among contiguous counters.

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**Fig. 3.**
11. — Nucleon instability.

It is well known that the problems of nucleon stability and neutron oscillations are related to current grand unification theories, which indicate a possible violation of baryon number with $\Delta B = 1$ for proton decay and $\Delta B = 2$ for neutron oscillations. Supersymmetric models of grand unification theories predict that proton decay through the channel $p \rightarrow K^+\nu$ is the dominant mode.

We discussed (15) the possibility to search for proton decay through this channel by performing detailed calculations of the reaction, and comparing the results with the atmospheric neutrino background. It has been shown that the LVD detector will have very good signature for this mode since it can detect the signal from $K^+$, and then from $\nu^+$ decay and finally from $e^+$ decay. At the same time background produced by atmospheric neutrinos is also extremely suppressed since all channels where neutrons are produced (e.g. $\nu + n \rightarrow \nu^- + K^+ + n$) can be detected. For the LVD fiducial mass in the detector’s core we can put the limit for $p \rightarrow K^+\nu$ channel $\tau_p > 10^{23}$ years in one year life time.

In addition, calculations (16) give the average numbers of pions and of evaporation neutrons for radioactive decays induced by the process $N \rightarrow e^+\pi^+$ and by $\pi^-\pi^+$ transitions. This comes as result of internuclear cascade development of pions and $n$ annihilation with one of the nuclei neutron, with total energy $\sim 1$ GeV and $\sim 2$ GeV for the two processes, respectively. The calculation was performed for $^{12}$C and for $^{44}$Fe in our detector. Hence, the LVD seems to be a suitable apparatus to study these processes through the observation of of neutrons via the reaction (2), associated with the $p \rightarrow \pi^0 + e^+$ decay, with a the multiplicity total energy in the range $(0.3 \div 2)$ GeV.

12. — LVD apparatus.

12.1. The liquid scintillation detector. — On the basis of the Mont Blanc LSD experiment, where all the scintillation counters have been successfully tested and excellent results obtained, we describe in the following the LVD experiment for the Gran Sasso Laboratory.

The LVD consists of 1536 stainless steel counters $(1.0 \times 1.5 \times 1.0)$ m$^3$ each) arranged on 8 layers, as shown in fig. 4, filled with a well-tested (16) liquid.

The total mass of the scintillator in this apparatus is about 1840 tons. A Fe module contains 16 counters; and the total number of such modules in the whole apparatus is 96.

Each module is made with Fe slabs and supports the upper layers. The total Fe weight is \(\sim 1600\) tons. The internal scintillations counters, defined by those shielded by at least one external counter, are 840 for a total mass of 1003 tons of liquid scintillator. The ratio of the mass in the detector's core (internal counters) to the total mass is \(M_i/M = 55\%\), while the core total mass is \(\sim 2000\) tons including Fe, which can be considered as the active sensitive volume.

In order to further reduce the local radioactivity background LVD will be shielded with a neutron absorber (paraffin) and Fe slabs (10 cm thick on the floor and on the ceiling). In this case, also the top and bottom layers of the LVD can be considered as part of the detector's core, whose sensitive mass in the form of scintillator increases to \(\sim 1830\) tons, giving a ratio \(M_i/M = 73\%\). The dimensions of the LVD are \((31 \times 13)\) m² area and 12 m height, for a total surface of \(\sim 1800\) m².

A system of 10 layers of resistive streamer tubes, \((12\) m long and \((3 \times 3)\) cm² section) arranged on 3 blocks as shown in fig. 4, will be constructed in between the scintillation counters. A double layer of streamer tubes will be set up on the floor and another double layer on the top of LVD; the other 3 double layers of tubes will be inserted every 2 layers of scintillation counters.

From the top of each counter the liquid scintillator is watched by 3 photomultipliers \((15\) cm photocathode diameter). The total number of photomultipliers is 4608. In order to measure the flight time for all charged particles it is necessary
that such photomultipliers have a short rise time, and good linearity is required in order to have precise energy measurements. The continuous check of all the 4608 photomultipliers is made by a system based on laser pulses transmitted through fiber to each counter.

Table II shows the main characteristics of the LVD and the number of sensitive target nuclei of the experiment.

### Table II. - LVD characteristics.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>((31 \times 13 \times 12)\ m^2)</td>
</tr>
<tr>
<td>Number of scintillation counters</td>
<td>1536 on 8 layers</td>
</tr>
<tr>
<td>Number of photomultipliers</td>
<td>4608 (3 per counter)</td>
</tr>
<tr>
<td>Total volume</td>
<td>4433 m³</td>
</tr>
<tr>
<td>Total weight</td>
<td>3600 tons</td>
</tr>
<tr>
<td>Total surface</td>
<td>1770 m²</td>
</tr>
<tr>
<td>Fc modules</td>
<td>96 on 8 layers</td>
</tr>
<tr>
<td>Streamer tube system</td>
<td>10 layers</td>
</tr>
<tr>
<td>Total scintillator mass</td>
<td>1840 tons</td>
</tr>
<tr>
<td>Active mass in scintillator: free protons</td>
<td>(1.7 \times 10^{22})</td>
</tr>
<tr>
<td></td>
<td>electrons</td>
</tr>
<tr>
<td></td>
<td>(^{12}C) nuclei</td>
</tr>
</tbody>
</table>

12.2. The electronic system. – The electronic system used in the LSD experiment (I) could be the basis for the LVD experiment. The main event to be recorded comes from reactions (1) and (2).

The anodic pulses from the 3 PMs of one counter are amplified and discriminated at 2 different thresholds (high-level and low-level thresholds). The output from the high level of each discriminator is fed to a 3-fold coincidence (resolution time 100 ns): this gives the general trigger to the whole apparatus whenever it exceeds the high threshold, and opens a gate of fixed duration (500 ns). In a similar way, the outputs from the low-level threshold (in a 3-fold coincidence) give a signal whenever they occur within the gate duration. In this way it is possible to measure pulses lower than one MeV during the gate duration; this is because the gate is opened by the general trigger, i.e. by pulses of several MeV that exceed the high-energy threshold. Such a procedure allows us to record efficiently both products of reaction (1) through the detection of a pair of pulses, namely an \(e^+\) pulse above the high-energy threshold and a delayed \(\gamma\) pulse within 500 µs from the first one above the low-energy threshold (while recording of low-energy background pulses is strongly suppressed).

The anodic pulses from the 3 PMs of each counter are also fed to a linear mixer, whose output is sent to 2 ADC and 1 TDC channel, for pulse-height and time measurements. The signal is fed directly from the PMs to ADC1 and, after amplification, to ADC2. In this way each ADC covers a different range of analogic pulse-height measurements, and two ranges of energy loss from charged particles may be recorded inside the counters.
The calibration of the low-energy channel gives \( \sim 300 \text{ keV/ch} \), while that for the high-energy channel is 4 MeV/ch. This gives a range of \((0.7 \div 50) \text{ MeV} \) and \((4 \div 1000) \text{ MeV} \) for the first and second ADC, respectively. The ADCs constructed as a 1 unit wide CAMAC module have the following characteristics: fast conversion time \((\sim 400 \text{ ns})\), 8-bit resolution over a wide dynamic range, a memory buffer, 16 first-in first-out (FIFO). This configuration permits us to accumulate many events before the read-out occurs. The time measurement among subsequent pulses either from the high threshold or from the low one is given by the TDC, which has 32 bits of dynamic range, a FIFO memory buffer, with a resolution time of 100 ns. It continuously counts pulses from a 10 MHz clock, up to when the 32 bits are filled (corresponding to 429.5 ns); then a flag signal resets the full scale, that again begins to count automatically. Whenever a high coincidence \( C_H \) or a low coincidence \( C_L \) occurs, the TDC memorizes the counts at that time and also memorizes the subsequent 16 pulses which occur before the read-out command.

Finally, every trigger signal is fed to a general OR for all the counters; this contains some additional free channels. The output from the OR triggers the whole apparatus, and starts the recording and data collection logic. In addition, the system includes also a 48-bit scaler for recording the absolute time of each event. This is provided by the official signal of Italian standard time as broadcasted by the IEN.

12'3. The calibration method. — The use of \(^{251}\text{Cf} \) as a neutron source has been extensively used \((1)\) in our LSD experiment in the Mont Blanc Laboratory, in order to calibrate all the scintillation counters. The source used is a low activity one, contained in a thin foil placed inside a small stainless steel cylindrical box (28 mm diameter, 12 mm height). A semiconductor silicon surface barrier counter (SBC) of small size is placed near the \(^{251}\text{Cf} \) source, inside the same stainless steel box. The signal from the SBC gives a pulse whenever a spontaneous fission occurs; the pipe with the SBC and the \(^{251}\text{Cf} \) source is placed inside the scintillation counter and is light tight so that no light can diffuse from the outside. The SBC signal is amplified by an external amplifier and a discriminator is used in order to eliminate alpha-particles pulses from the real fission; this is made by discriminating their clear pulse-height distribution. The trigger to the calibration system of the whole apparatus is given by pulses from such a discriminator.

The average number of neutrons emitted from the \(^{251}\text{Cf} \) source is 3.735 n/fission. Results of calibration for one of our counters in the Mt. Blanc experiment show an efficiency of \( \sim 75\% \) for detecting y-pulses from n capture.

12'4 Background considerations. — For neutrino detection with \( E \gtrsim 7 \text{ MeV} \) the background in the LVD does not present a real problem. However, to detect solar neutrinos through reaction \((3)\) and terrestrial neutrinos through
reaction (1) the background must be kept at the minimum level for such low energies ($\geq 3$ MeV). We consider 3 main sources of background:

1) Neutral secondary particles produced by muons either in the rock or inside the LVD. The latest one is easily avoided by coincidences among counters along the path length of the muon. The muon interaction in the rock producing an electromagnetic cascade is also easily rejected because of the continuous energy spectrum of the secondaries which extends over a large range (up to several hundreds MeV), and also by the coincidences of residual electromagnetic cascades between counters.

2) Local radioactivity from nuclear decay (mainly $^{40}$K, $^{238}$U, etc...) in the rock. As we discussed (28), this effect is nearly eliminated by the external counters and by the Fe shield around the detector. From our results experience with the Mt. Blanc LSD detector we know clearly that reduction from an external counter to an internal one is of a factor $\sim 10$ in the energy region $\geq 0.3$ MeV. It seems that the rock radioactivity at Gran Sasso is lower than in Mt. Blanc; thus one expects that the counting rate should be consequently lower.

3) Radioactivity from materials used in constructing the LVD. By considering again our experience with the LSD experiment, we note that the choice of internal reflecting walls of a single scintillation counter is very important. In fact we have shown that by using common TiO$_2$ painting the background counting rate is at least higher by a factor of 2 in comparison with mylar, because the former contains small amounts of $^{40}$K. In any event, accurate background measurements of local radioactivity at the Gran Sasso Laboratory are needed, and tests of radioactivity for all the materials to be used in the experiment are required.

1275. Streamer tube system. -- LVD is also a tracking experiment, since the combined techniques of liquid scintillation counters and resistive streamer tubes are widely used. In the NUSEX and LSD experiments at Mt. Blanc Laboratory limited streamer tubes were also extensively used; 3.5 m long and (1 x 1) cm$^2$ cross-section, with high-resistivity internal coating acting as a cathode allows reading out the 2 co-ordinates from the tubes by using aluminum strips as external pick-up electrodes. By using 100 $\mu$m diameter wires as anodes, and a gas mixture of A-CO$_2$-N-pentane in the proportion of 1-2-1 at atmospheric pressure the discharges are limited to within a few mm inside the tubes which work at an operation voltage of 3.9 kV. The pulses (2 mV/50 $\Omega$)

and 50 ms wide) are collected by a system of X-Y bidimensional strips, parallel and orthogonal to the tubes, discriminated and shaped to 7 μs and loaded to a shift register chain with serial read-out, which allows reconstruction of the X and Y co-ordinates respectively with a resolution of 1.0 cm; the Z co-ordinate is given by the layer itself.

As been discussed previously, five planes of 2 layers of tubes each are set in between the scintillation counters. The total number of wires is \( \sim 30000 \) with 60,000 read-out channels. This allows us to reconstruct tracks of charged particles with a spatial and angular resolution better than \( \pm 1.0 \) cm and \( 0.5^\circ \), respectively.

This configuration of streamer tubes provides a well-established search for physics described in the previous section, namely: direction of muons both from the atmosphere and from neutrino, muon bundles, their topology, multiplicities and anisotropies of muons, angular distribution of muons mainly at large zenith angle to search prompt muon production at very high-energy interactions, point sources as Cyg X-3 \((22)\), etc. On the other hand, the LVD is not able to give accurately a vertex definition inside the apparatus, we can however confine this to a position of \( (50-70) \) cm inside the detector for both neutrino interactions in the apparatus and for proton decay.


**RIASSUNTO**

Si descrive l'esperimento LVD (Large Volume Detector) del laboratorio del Gran Sasso, che rappresenta il naturale sviluppo dell'esperimento LSD (Liquid Scintillation Detector) in funzione nel laboratorio del Monte Bianco. LVD (area \((31 \times 13) \text{ m}^2\), altezza 12 m) consiste di \( \sim 1800 \) tennellati di scintillatore liquido e di un sistema di tubi a streamer su 5 piani per la ricostruzione delle tracce di particelle cariche. Come tutti gli esperimenti in laboratori sotterranei, è celebre un tempo lungo ed a bassa statistica, l'esperimento LVD è a microcensi ma con diverse priorità delle ricerche. L'obiettivo principale è l'astronomia neutrino, in primo luogo la rivelazione di neutrini da colossi gravitazionali stellari, e poi neutrini di alta energia e neutrini solari. Dato l'alto numero previsto di interazioni di neutrini \((\sim 900 \text{ per un collasato alla distanza del centro galattico)}\) da stelle collassanti, l'esperimento LVD costituisce, a differenza degli attuali esperimenti, un vero e proprio osservatorio neutrino, in grado di compiere un'analisi dettagliata delle distribuzioni energetica e temporale dei burst. Oltre all'astronomia neutrino, con l'esperimento LVD si possono compiere ricerche in fisica della radiazione cosmica o di particelle elementari ad alte energie.
Детектор большого объема для лаборатории Гран Сассо.

Резюме. — В данной работе описывается эксперимент LVD (Large Volume Detector), который будет проводиться в лаборатории Гран Сассо. LVD является естественным продолжением эксперимента LSD (Liquid Scintillation Detector) в лаборатории Монблан. LVD (площадь 31×13 м², высота 12 м) содержит 1800 тонн жидкого спинтиллятора и включает в себя систему стримерных детекторов, размещенных на 5 уровнях. Последние используются для реконструкции треков заряженных частиц. Как и любой длительный эксперимент в подземных условиях, когда статистика событий невелика, LVD имеет многоцелевое назначение. Научные программы, однако, будут обладать различным приоритетом. Основное внимание будет уделяться нейтринной астрономии, и в первую очередь — детектированию нейтрино от коллапсирующих звезд. Кроме того, будут проводиться исследования по регистрации нейтрино высоких энергий и солнечных нейтрино. Поскольку ожидаемое количество взаимодействий в случае прихода потока нейтрино от коллапса очень велико, порядка 900, LVD будет настоящей нейтринной обсерваторией, способной, в отличие от ведущихся сейчас экспериментов, детально исследовать энергетическое временное распределение для вспышек нейтрино излучения. В дополнение к нейтринной астрофизике, имеются очень хорошие перспективы и для исследований в области космических лучей и физики элементарных частиц высоких энергий.