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THE LVD EXPERIMENT

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1. THE LVD EXPERIMENT

The large volume detector (LVD) can be defined as an underground observatory devoted to neutrino astronomy and to the measurement of the penetrating components of cosmic rays. The experiment has been optimized for major physics items such as the detection of the neutrino bursts of collapsing stars and the search for astrophysical point sources of ultra-high energy gammas and neutrinos. It can also be defined as a multipurpose experiment where many important issues, especially neutrino oscillations, standard cosmic ray physics, proton decay in the channel ($p \rightarrow K^{+} + \bar{\nu}$), solar neutrinos and monopoles can be studied with varying degrees of sensitivity and on a competitive basis.

The experiment will be located in Hall A of the Gran Sasso Laboratory and will benefit from the very favourable conditions of the site: it is next to the Gran Sasso Rome-Adriatic motorway tunnel, permitting ease of heavy transport; it is only 130 km from Rome; it is at a depth of ~3600 mwe, which is an excellent compromise for the measurement of the penetrating components of cosmic rays; and, particularly important, geologically speaking, the Gran Sasso is low in radioactive elements (for instance, the gamma and neutron fluxes are from 5 to 10 lower than those measured in Mont Blanc).

2. THE LVD DETECTOR

The LVD detector[1] consists of a large volume of liquid scintillator interlayered with streamer chambers and is specifically designed to permit a multipurpose experiment. One of the major experimental objectives is the detection of mu mesons and the measurement of their trajectories and direction-of-flight; the muons can be either cosmic, produced in an atmospheric shower and with an energy of the order of a magnitude of TeV to be able to reach the apparatus, or muons induced by neutrino interactions in the rock surrounding the apparatus. Another important objective is the detection of neutrino interactions inside the detector, either for low energy neutrino interactions and the measurement of their energy, or the pattern identification of neutrino-induced events of higher energy.

Figure 1 is a general view of the LVD which basically consists of 190, 6.6m×2.1m×1.1m or 6.6m×2.7m×1.1m, identical modules inserted into an iron support structure[2]. They are arranged in 8(7) layers in each of five main towers which are divided by corridors transversal to the laboratory axis. Each module comprises

- ~9.6 tons of liquid scintillator divided into 8 modular counters (tanks) housed in Fe module "porta tanks";
- an L-shaped chamber module containing 80 limited streamer tubes on the bottom and on one side of the module, forming the tracking system.

The dimensions of the detector are 40m×12m×13m, and its total weight including the support structure and tracking system is ~3600 tons.

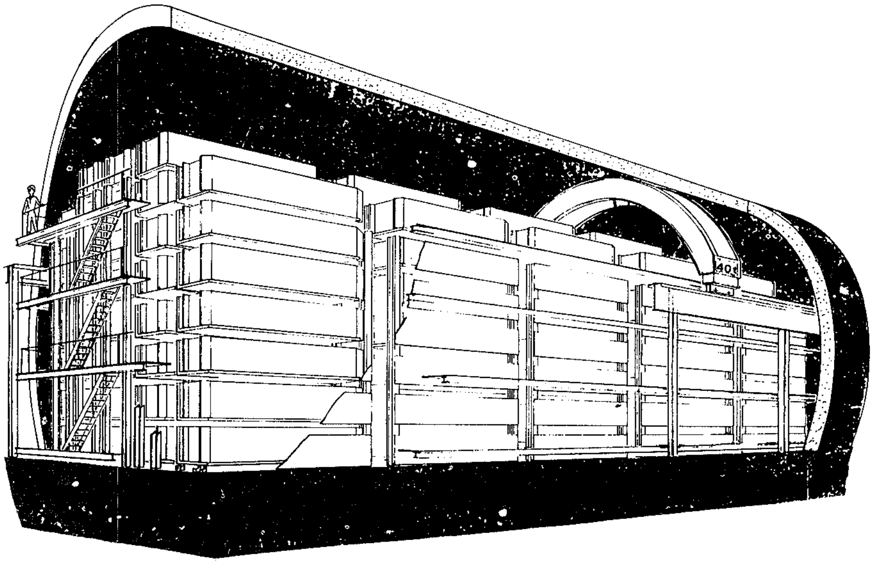

FIGURE 1
General view of the LVD

2.1 Scintillator system

The scintillator system consists of 1520, 1m×1m×1.5m stainless steel boxes filled with well-tested scintillator liquid with the following characteristics: structure C_nH_{2n+2} with n=10; density 0.8 g cm^{-3}; attenuation length 20m (λ=420nm); output light ~5 photoelectrons each PM for 1 MeV of energy loss; energy resolution 20%/$\sqrt{E}$.

Each tank is viewed by three phototubes for energy determination and time-of-flight measurements. The pulses of the three photomultipliers of one counter are amplified and discriminated at two different thresholds: a high level threshold of ~6 MeV and a low level one of 0.8 MeV. The high-level output of each discriminator is fed into a threefold coincidence which is the general trigger from the scintillators for the whole apparatus. The general trigger also opens a 500-μsec-gate where the second-level trigger for the low energy antineutrino detection operates. Steel structures house groups of eight tanks, as shown in Fig.2, and form part of the basic module of the experiment. The "porta tanks" also support the horizontal and vertical segments of the tracking chamber. The total mass of the liquid scintillator is 1800 tons.

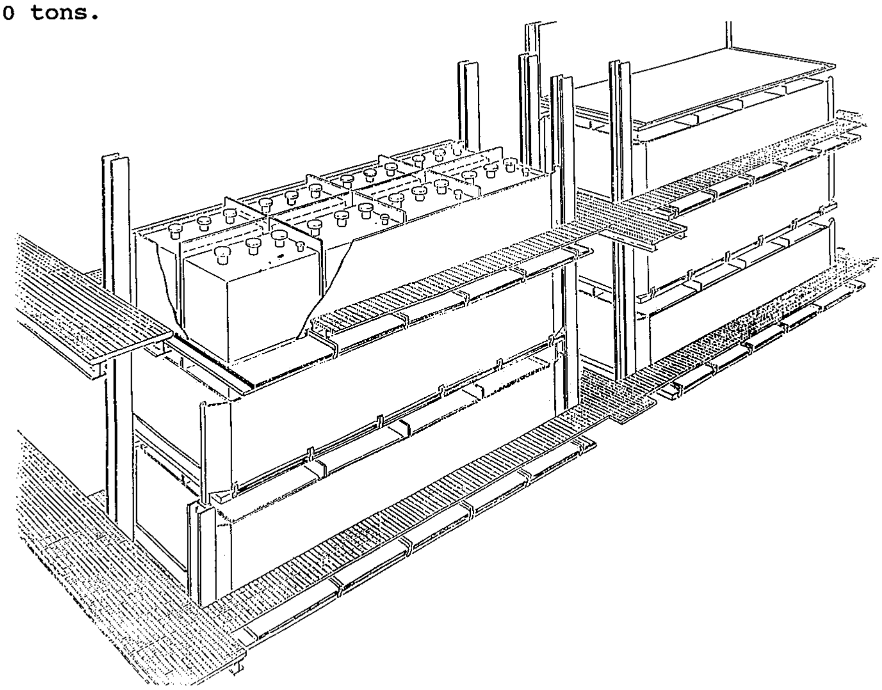

FIGURE 2
Detail of the LVD assembly system

2.2 Tracking system

The tracking system consists of 190 L-shaped chambers containing a double layer of limited streamer tubes. Each chamber is formed of two iron panels - a horizontal one and a vertical one - linked by hinges and fastened to each "porta tank"; thus, each basic module is surrounded by a double layer of streamer tubes (see Fig.3). The streamer tubes total 15000, arranged in 8(7) horizontal planes and 5 vertical planes, each one consisting of 8-wire PVC chambers, 6.3m long and 1cm×1cm in cross section. Each tube layer is equipped with a digital read-out in two coordinates and the signal is picked up by 4-cm-wide pick-up strips. The double layers are staggered by 2 cm. The resulting precision is ~0.5 degrees, while the efficiency of the double layer is ~100%.

Each chamber has 470 read-out channels and the complete tracking system contains ~80,000 channels which are each discriminated and fed into a shift register. A serial read-out chain is then performed by a Camac module. The tubes are filled with a standard (30/70) (Argon, Isobutane) mixture. The geometrical acceptance of the apparatus for an isotropic flux is 7000 m^2sr.

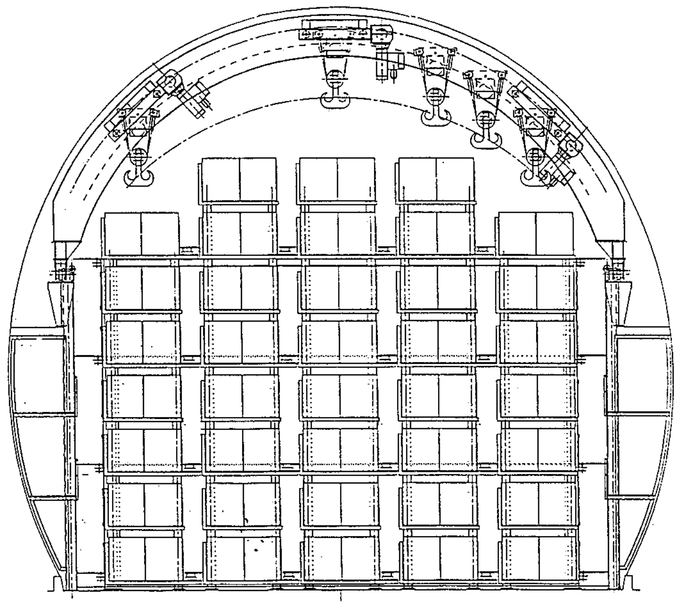

FIGURE 3
Cutaway view of the LVD

3. NEUTRINOS FROM GRAVITATIONAL COLLAPSE

Type II supernovae, one of the most spectacular events in the sky, are generally believed to occur at the end of the evolution of massive stars ($M>8M_{\odot}$). When the nuclear fuel is exhausted, the star cannot support itself against gravity and its core becomes dynamically instable and begins to implode. The final evolution of the core collapse is a neutron star, or, eventually, a black hole. If the outer parts are ejected, the brilliant supernova event can be seen as the external sign of a catastrophe marking the end of the star evolution. However, as regards our underground experiment, the most peculiar characteristic of this class of supernovae is the copious emission of neutrinos. In fact, the most important form of energy transport comes from neutrino interaction.

Type II supernovae are characterized on the basis of the optical spectrum by the presence of hydrogen lines and are seen only in the spiral arms of spiral galaxies, confirming that they are associated with massive stars[3]. Their evolution is so rapid that they cannot appear a long way from the sites of star formation.

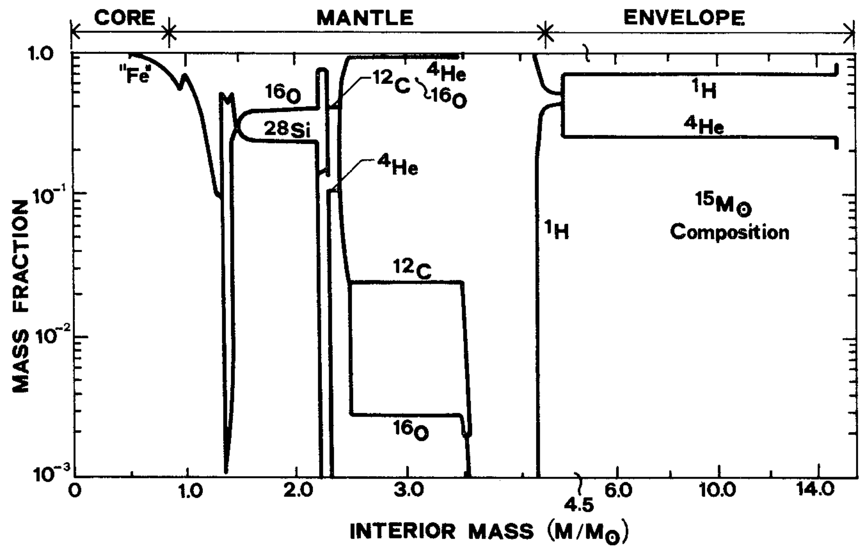

FIGURE 4
Composition of a 15 $M_\odot$ presupernova star when the edge of its iron core begins to collapse at 1000 km/s. (Woosley and Weaver)

We know that the final stage in the evolution of a massive star is an "onion skin" with a central iron core surrounded by burning layers of SI, O, Ne, C, He, H. The advanced burning stages proceed through the ignition of heavier nuclei to the nuclear statistical equilibrium (A~Fe), with the star contracting at each stage as the burning of heavier fuel requires a higher temperature due to the increasing Coulomb barriers. The properties of a 15-$M_\odot$ presupernova star are shown in Fig.4.

After the final esoenergetic nuclear reaction (Si ignition), the iron core becomes a mass in excess of what the electron pressure can support and begins to collapse. Two processes then lead to pressure decrement accelerating the collapse of the core:

1. Photodisintegration of Fe nuclei on alpha-particles. This reaction ($^{56}Fe \rightarrow 13\alpha + 4n$) subtracts energy (124.4 MeV) as the electron pressure does not rise as rapidly as it would in the absence of breakup and so it cannot support the star against gravity.
2. Electron capture on "Fe" nuclei ($e^- + p \rightarrow n + \nu_e$) which removes the electrons required to support the star.

When either of these dynamical instabilities is encountered, the iron core begins to collapse very rapidly.

One of the most debated problems in the past was how the large[4] gravitational energy released in the core infall is transfered to the mantle and envelope of the star leading to their ejection and explaining the energies and luminosity of type II supernovae. As a major part of the heat generated by the gravitational collapse is converted into neutrinos through electron capture, it was long believed that their interaction with the mantle would transmit their outward momentum causing the explosions. With the discovery of weak neutral currents in the mid '70's, this mechanism was inadequate to explain explosion because a great number of neutrinos remain trapped in the core due to these currents.

Since then, theoreticians have been studying a model where the outward ejection of the mantle and envelope is due to the formation of a hydrodynamic shock wave formed after the "bouncing" of the central collapsing core as supranuclear density is reached.

The solution of the equation-of-state shows that, during the collapse, the iron core breaks up into an inner part (0.6, 0.8 $M_\odot$) which collapses homologously ($u \propto r$) with its surface falling at about the sound of speed, and an outer part falling at supersonic speed ($u \propto r^{-1/2}$), roughly half free-fall speed.

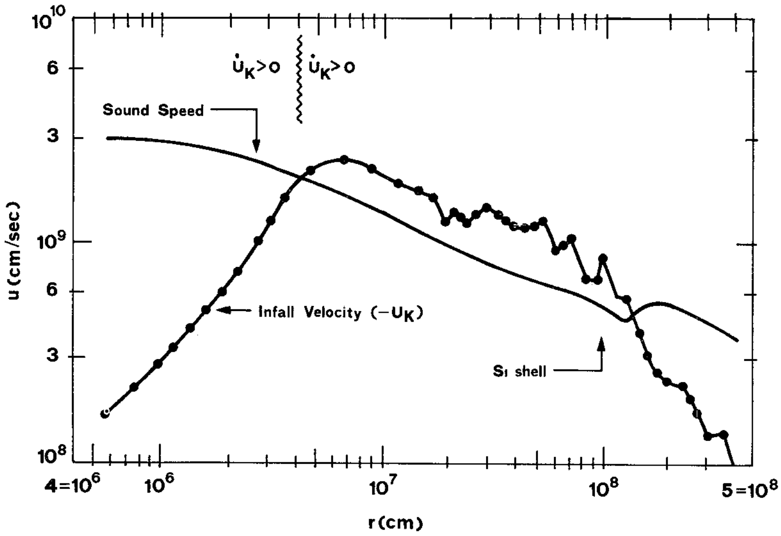

FIGURE 5
Material velocity u and sound speed as a function of r, about 1 ms before bounce. (Arnett)

Figure .5 shows the velocity of the infalling material, u, as a function of its distance r from the center at 1 ms before bounce[5]. Up to r~40 km, the velocity is proportional to r; it then reaches a maximum at ~75 km and is supersonic until r~1000 km. In the sonic point r_{sp}, the infall speed $|u|$ is equal to the sound of speed a, so that $u+a = 0$. This means that a signal generated in a point $r<r_{rs}$ cannot move outwards from the sonic point, and that the material outside r_{sp} is unable to receive signals from inside r_{sp}. The material can, therefore, preserve homologys only inside r_{sp} through the rearrangement of pressure and density, while the exterior matter continues to move in a quasi-free fall.

As soon as the density of the inner region of the core exceeds the nuclear density, the collapse of the homologous core is brought to a sudden halt. Peak of pressure reaches $3\cdot\rho_{nucl}=8\cdot10^{14}$ g cm^{-3} with a temperature of ~10-15 MeV.

A pressure wave accumulates in the sonic point from where a shock wave begins to move out into the outer layer of the star. However, it is important to underline that the shock does not start at the center of the star, but around (0.8, 0.9 $M_\odot$). The energy available to the shock can be evaluated by calculating the gravitational binding energy of the homologous unshocked core. This is why the inner core quickly reaches hydrostatic equilibrium and it is possible to calculate the energy of the hydrostatic configuration, which is approximately $4\text{-}7\cdot10^{51}$ erg.

Neutrino emission and photodisintegration of iron nuclei cause strong energy losses to the wave during its passage through the remainder of the infalling core. If the shock wave reaches the envelope of the star with enough energy, the resulting explosion and ejection of the envelope is the spectacular event of type II supernova. This favorable condition occurs only with mass range $8_{M_\odot}<M\leq16_{M_\odot}$ when it is possible to have a "prompt explosion".

Thus, an important criterium for the success of the core bounce mechanism is that the total mass of the collapsing core must not be too large and, as a consequence, the mass difference between the homologous and total core mass not too great to consume the total energy shock in stripping iron nuclei in free nucleons.

It has been confirmed that, before the bounce, the core is no longer transparent to neutrinos for a density greater than $\sim2\cdot10^{11}$ g cm^{-3}. At this density, the drift velocity V_d of neutrinos relative to the nuclear material which causes the scattering is such that the net velocity of neutrinos relative to the star center is $u+V_d\leq0$ with u being the infall velocity.

Once neutrino trapping has occurred, the total number of leptons remains constant and the neutrinos are in equilibrium with the matter. When the shock wave is formed, the inner core is never touched by the shock, so the nuclear matter is in the form of complex nuclei which makes neutrino diffusion very slow. It has been estimated that it takes ~100 ms for a neutrino to diffuse out of the core, which is very long compared to dynamic time.

On the other hand, the nuclei are completely dissociated into nucleons inside the shock wave; outside, the material is still in its original status of heavy nuclei. The neutrino mean free path is, therefore, smaller outside than inside, and it is the external matter that determines the ability of the neutrino to flow away.

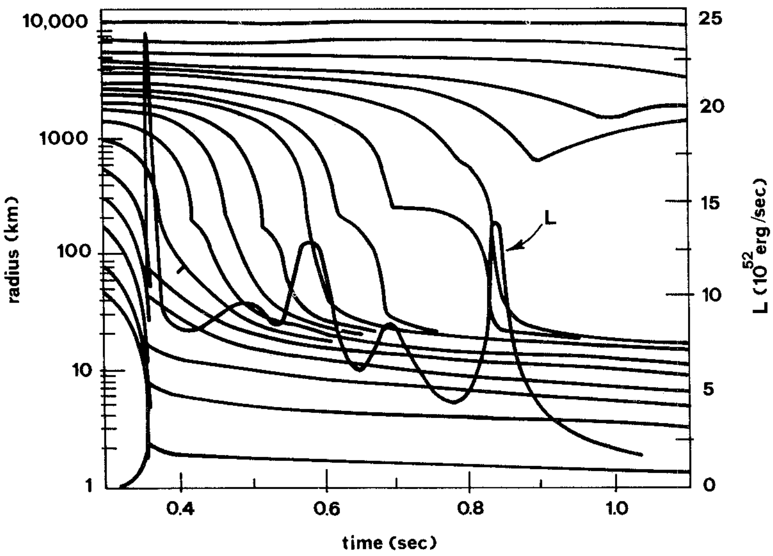

FIGURE 6
Electron neutrino luminosity vs time for a $25M_\odot$ star superposed on the constant mass point trajectories. (Mayle, Wilson and Schramm)

We can define[6] a "neutrinosphere" r_ν by the condition that there is one neutrino mean free path between r_ν and infinity. When the shock radius r_S is less than r_ν, the neutrinos remain confined in the shock because if the neutrinos diffuse out of the shock, their drift velocity due to the high density is less than the velocity of the shock, and the neutrinos are reassorbed by the shock. When $r_S \geq r_\nu$, the neutrinos can move freely away.

However, the prompt explosion described previously cannot be invoked for stars in the range $16M_\odot \leq M \leq 80M_\odot$. During their evolution, the shock wave stalls and becomes accretionary. Following the failure of the shock, a stationary "neutrinosphere" develops at about 40 km, while the stalled or accretion shock remains external to the neutrinosphere at ~100-300 km. Wilson et al. have proposed a model where the envelope explosion can also occur in this case. This is possible because the neutrinosphere heats the region just below the shock wave causing it to resume its outward course. As a result, the envelope explosion occurs, but is delayed by the amount of time characteristic of neutrino diffusion. However, Wilson's "delayed mechanism" has not yet been verified by other theoreticians.

Figure 6 shows the electron neutrino emission superposed on the mass point trajectories of $25M_\odot$ collapsing star.

3.1. Energy and time considerations

It has been calculated that $\sim 3 \cdot 10^{53}$ ergs (binding energy)[7] must be released to form a neutron star. During the supernova explosion, $\sim 10^{49}$ ergs of photons and $\sim 10^{51}$ ergs of kinetic energy are released. The difference in the calculated and observed energies is emitted in the form of neutrinos or gravitational waves. As the gravitational radiation can only be 1%, most of the binding energy is released in the form of neutrinos.

The collapsing core has $\sim 10^{57}$ protons which are converted to neutrons through electron capture

$$p + e^- \rightarrow n + \nu_e$$

As the average energy of ν_e emitted from the core is about 10 MeV, 10^{52} ergs are emitted by neutronization during the initial collapse, which is less than 10% of all the neutrinos radiated. The remaining neutrinos are given in pair processes (deleptonization)

$$e^+ + e^- \rightarrow \nu_i + \bar{\nu}_i$$

with $i = e, \mu, \tau$.

Muon and taon neutrinos are produced via neutral currents, while electron neutrinos are produced through both charged and neutral currents. The electron capture (neutronization) occurs in the initial collapse: initial ν_e burst takes place in times of the order of a few milliseconds during which the lepton rich core settles into hydrostatic equilibrium. The neutrino pairs are thermally radiated on a time scale of the order of the diffusion process (~ seconds). Core implosion, bounce and shock wave take about 1 s during which the first half of neutrino emission is released. The second half is emitted over the next few tens of seconds as the hot newborn neutron star cools down to become a standard cold neutron star (cooling phase). In any case, nearly all the neutrinos are emitted in about 20 s.

The luminosity of the mu and tau neutrinos during the deleptonization phase is less than the electron neutrino luminosity because they are emitted only via neutral current processes. It should also be pointed out that as the first burst ν_e comes from the homologous core region, whose size is largely independent of the original iron core mass, the first signal is model independent, while differences can be seen in the other phases.

In the "delayed" Wilson model for $M>16M_{\odot}$ stars, apart from the first burst, the neutrino luminosity has an oscillatory behavior superimposed on an exponentially decaying signal.

However, if we want to summarize the situation, we can say that average neutrino luminosity, mean neutrino energy and total emitted energy depend only on the initial iron core mass and are independent of the explosion mechanism, while the time structure of the neutrino luminosity is strictly related to these mechanisms.

On the other hand, the general scenario of the collapse is well known, while the mechanism for the ejection of the envelope in a supernova requires further study.

We can conclude that more information on the time scale structure of the neutrino emission is necessary to clarify the hotly-debated explosion mechanism of type II supernovae.

As we have seen, supernova events are involved in several important phenomena such as the production of neutron stars and most of the known X-ray sources of high energy cosmic ray emission. They also play an important role in the synthesis of almost all the elements which are heavier than helium, especially of the intermediate mass elements ($16\leq A\leq 60$). Thus, the ejecta abundance well fits the observed cosmic abundance pattern.

Despite the great importance of the type II supernova event, our understanding of the phenomenon is incomplete for many reasons: Studies have, so far, been based on the observation of only electromagnetic radiation from the explosion or its remnants, but, due to the association of type II supernovae with massive stars, they are formed near the spiral arms of spiral galaxy regions that are often optically obscured. Furthermore, the expected rate of supernovae is also very low, approximated for galaxies and clusters of galaxies at (3-4) events in one hundred years. However, the fact that most of the energy is released through neutrinos indicates them as being the most important probe for studying stellar collapse.

As already stated, the LVD experiment is optimized for the detection of low energy neutrinos and antineutrinos from collapsing stars. Neutrinos, of course, are not obscured by matter, so their detection will resolve many of the difficulties in the current studies of collapsing stars, either by statistics so that the type II supernova event is not obscured by optical effects, or in model identification by measuring the time structure of neutrino luminosity.

4. DETECTION OF LOW ENERGY NEUTRINOS IN THE LVD

The most convenient way to study stellar collapse in the LVD is to detect the antineutrinos from the collapsing object through the inverse β decay reaction on free protons[8]

$$\bar{\nu}_e + p \rightarrow n + e^+$$
$$\downarrow$$
$$n + p \rightarrow D + \gamma \qquad (E\gamma = 2.2 \text{ MeV})$$

If the scintillator modular counters are operated in a low background environment, they are suitable for detecting both the pulses which give the signature for an antineutrino:

- a prompt pulse from the positron with the energy above the high energy threshold;
- a delayed pulse from a neutron during a gate width $\Delta t = 500\ \mu s$ and an energy threshold of about 0.8 MeV.

This method has already been checked in the LSD at Mont Blanc.

The neutron moderation time plus deuterium fusion have been measured experimentally using a ^{252}Cf source in the Mont Blanc scintillator counter:

$$^{252}Cf \to n+\gamma+X$$

$$n+p \to D+\gamma \qquad (E\gamma=2.2\ MeV)$$

The equipment is triggered by detecting the decay of ^{252}Cf. By comparing the number of triggers with the number of fusion events, it is possible to measure the efficiency for the detection of the neutron. The measured efficiency is 70%. Due to the lower background expected at the Gran Sasso and to the presence of an inner well-shielded fiducial volume in the LVD, the energy threshold will be lower.

From a collapse in the galactic center (10 Kpc), we can expect about 1000 interactions in the 1800 tons of liquid scintillator of LVD at a threshold of (5-6 MeV). With the expected noise level of 0.1 counts/sec in the 20 s of collapse time, the signal/noise ratio will be optimal.

More information about the dynamics of collapse can also be obtained observing the ν_e's through the elastic scattering reaction which produces, however, a lower number of interactions in the detector. As the ν_e also occurs in the first neutronization phase, the signal from the ν_e can provide information immediately at the very beginning of the collapse process.

Other reactions can also be detected in the LVD:

1. $\nu_e + {}^{12}C \to \nu_e + {}^{12}C^*$ is detected through the ^{12}C de-excitation with emission of one gamma of 15.1 MeV (96%), and two gammas of 10.7 and 4.4 MeV (4%).
2. $\nu_e + {}^{12}C \to {}^{12}N + e^-$ with E_{th}=16.4 MeV whose signature is a prompt electron of energy ($E-E_{th}$) followed after 11 ms by a positron from the β decay of the N with E_{max}=15.4 MeV and $\bar{E}$=3 MeV.
3. $\bar{\nu}_e + {}^{12}C \to {}^{12}B + e^+$ with the same signature as 2, but with a prompt positron pulse followed by an electron with E_{max}=13.4 MeV and $\bar{E}$=4.5 MeV.

For a supernova collapse occurring in the Magellanic clouds at 60 Kpc, the signals will be weaker but still detectable.

The LVD will no doubt be superior for detailed studies of stellar collapse in our galaxy.

5. THE PROBLEM OF THE ORIGIN OF COSMIC RAYS

Another of the most debated problems in the field of astrophysics concerns the origin of cosmic radiation. It is mostly formed of atomic nuclei which move with nearly the speed of light and is composed of

- protons - 92%
- helium nuclei - 6%
- heavier nuclei - 1%
- electrons - 1%
- gamma rays - 0.1%

The power radiated as cosmic rays in our galaxy is much stronger than that radiated in the form of radio waves and X-rays. The energy distribution of cosmic rays has a tail extending to energies higher than thousands of TeV.

The main characteristic of the composition of cosmic rays is the fact that its chemical composition exactly reproduces that of the whole galaxy, which excludes some of the hypotheses on the origin of cosmic radiation. For example, we cannot say that the rays form part of what remained after the big bang which produced nearly exclusively hydrogen. The most credible models today hold that cosmic rays must be generated either by an object of particular composition, or by many exotic sources. Several different sources have been proposed which would be able to act as extremely powerful particle accelerators and thus explain the energy of the cosmic rays, such as pulsars, binary systems, supernova explosions, quasars, etc. It is also believed that cosmic radiation comes mostly from outside our galaxy. A few discrete sources of cosmic radiation have been discovered in recent years, in particular of ultra-high gamma energy such as Cygnus-X3[9], Vela-X1, LMC-X4 with the gammas having a spectral power of E^{-2} and a characteristic modulation time of the signal emitted.

In order to study these point-form sources of cosmic rays, it is necessary to use neutral particles only, as charged particles have completely lost the memory of their initial direction due to the magnetic field of the galaxy through which they have travelled for at least 20 million years.

The obvious candidates are the gamma-rays and neutrinos; in fact, the neutrons should have too high an energy for their average life to be long enough to survive a long journey.

There are essentially two kinds of earth surface apparatus which can detect this radiation. They both exploit the property of the gamma rays of being able to produce electromagnetic showers in their interaction with the higher atmospheric layers. The apparatus can either be of the Cerenkov-light type and in this case covers an interval in energy between $3 \cdot 10^{11}$ and 10^{13} eV, or an extensive air shower array which measures directly the density of the particles in the shower using scintillation counters and streamer tubes and, in this case, the threshold at sea level is 10^{15} eV.

In order to explain how a cosmic object can produce particles with an energy >TeV as well as the emission periodicity, Verstand and Eichler[10] have proposed a model where it is held that the sources are binary systems formed from a massive star (neutron star, pulsar) orbiting around another standard star. In this model, charged particles (mainly protons) are accelerated in the strong electromagnetic field of the massive star and thus interact in the atmosphere of the neighboring star producing π^0 which then decay into gammas. The atmosphere must be thick enough to create π but not too thick to reabsorb the gamma rays (see Fig.7).

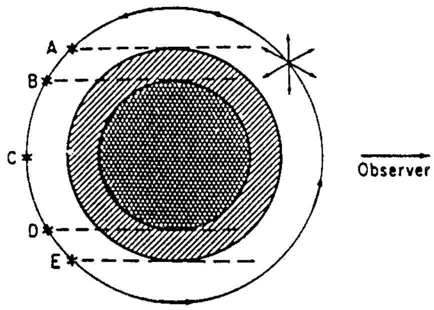

FIGURE 7
Verstand and Eichler model

These models also claim the emission of charged pions and thus of neutrinos from the decay of muons. As the ν_μ are not obscured by the neighboring stars, their intensity should, therefore, be at least a factor 10 greater than that of the gammas. Research regarding discrete sources can be successfully carried out using underground apparatus[11] by examining the muons produced either by gammas in their interaction with the atmosphere, or by neutrinos in their interaction with the rock surrounding the apparatus. The studies regarding muons produced by gammas are limited to sources such as Cygnus-X3 which are low over the horizon so that the signal expected is not covered by the normal flow of cosmic muons. Research on muons produced by neutrinos is restricted to sources below the horizon like VELA-X1 or LMC-X4 and, in this case, the target is the whole earth[12].

As the LVD has both horizontal and vertical tracking surfaces distributed across the entire apparatus, it is an excellent omnidirectional detector for the study and research of discrete sources of cosmic rays with its geometrical factor of 7000 m^2sr.

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