GRAN SASSO PHYSICS

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INTRODUCTION

Underground physics plays a leading role in current-day physics research and the experimentalists and theoreticians are showing a growing interest in the possibilities and availability of underground laboratories. The importance of this branch of physics and the relevant laboratories can be attributed to two main aspects:

1) Neutrino astronomy, i.e., the study of the universe using neutrinos as probes instead of the more traditional e.m. radiation in the form of visible radiation, X-rays, etc., is a new method of exploring the sky and represents a grand opportunity for physicists to further their knowledge of the universe, its origin and evolution, as well as the evolution of the stars.

2) The second aspect is connected to the study of elementary particles: physicists have long sought the unification of the forces of nature that are supposed generated by a unique force. The next objective is to unify electroweak with strong interaction, i.e., quarks with leptons. However, the energy scale for this to happen ($>10^{14}$ GeV) is not accessible to the particle accelerators either in operation or foreseeable in the near future. On the other hand, some of the predictions of the Grand Unification Theory regarding the stability of matter, the neutrino mass and the magnetic monopoles can be addressed in experiments carried out in underground laboratories which could, therefore, greatly contribute to the unification of the fundamental forces.

The Superworld III
Edited by A. Zichichi
Plenum Press, New York, 1990

THE GRAN SASSO LABORATORY

Anticipating the interest in underground physics, at the beginning of the '80's Antonino Zichichi proposed[1] the Gran Sasso project. Its 200,000 m^3 of excavations and nine approved experiments make it the biggest international underground laboratory of the moment. The winning idea was to have a laboratory with the same characteristics and general facilities as the largest and best equipped connected to the particle accelerators; it had to be able to house complex and sophisticated apparatus equal to any of the biggest particle physics experiments. The Gran Sasso Laboratory has other extremely favourable conditions such as its geographic location and its proximity to the Gran Sasso Rome-Adriatic motorway which permits ease of access and heavy transport. In fact, before the Gran Sasso, underground experiments were installed in mines or in small "garages" near motorway tunnels, the only exception being Baksan which was conceived exclusively as a laboratory, but on a much reduced scale. From the physics point of view, the Gran Sasso can boast the following advantages. The laboratory depth (3,600 mwe) is a crucial parameter: in fact, for particles deriving from rare cosmic phenomena, there is an optimum depth at which these particles can be detected by the apparatus without being completely absorbed by the overlying rock when it is too thick, or being hidden by the background of low energy cosmic rays when it is too shallow. Another basic parameter is the natural radioactivity in the surrounding rock, which can constitute undesirable noise and submerge the signals from the rare phenomena under observation: the Gran Sasso is formed mainly of limestone which has a very low content of natural radioactivity[2] (for instance, the gamma and neutron fluxes are from 5-10 lower than those measured in Mont Blanc).

Table I outlines some of the principle characteristics of the Gran Sasso Laboratory.

TABLE I

Total volume	~200000 m^3
Depth	>1400 m of rock CaCO3 ~2.81g cm^{-3}, <Z>~9.4>3600 mwe
Location	47°27'09" Lat N 13°34'28' Long E 963 m a.s.l.
Rock activity	^{40}K<5.1 Bq/Kg ^{114}Bi<4.2 Bq/Kg ^{232}Th<0.25 Bq/Kg ^{238}U<5.2 Bq/Kg
Muons	1 m^{-2}h^{-1}
Thermal neutrons	$(1.09\pm0.08)10^{-6}cm^{-2}s^{-1}$
Fast neutrons	$0.77\times10^{-6}<\Phi<1.25\times10^{-6}cm^{-2}s^{-1}$
Natural conditions	6°C,98% humidity
Operational conditions	20°C,50% humidity
Ventilation	~30000 m^{3}h^{-1} steady ~200000 m^{3}h^{-1} in emergency

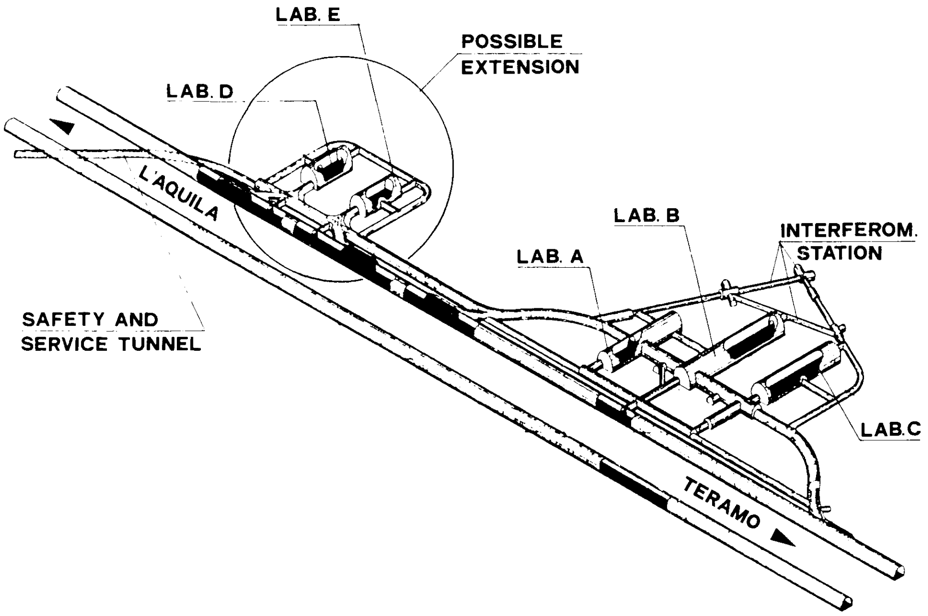

Fig.1. Present Gran Sasso Laboratory and probable extensions.

The scientific community has shown such an enormous interest in the laboratory that not only has the available space been completely allocated, but it has been felt necessary to increase it to make place for further experiments. In June 1988, the International Scientific Committee for the Gran Sasso unanimously approved a document requesting the Italian authorities to promote the excavation of more tunnels. A plan of the laboratory and its probable extensions is shown in Fig.1.

The Main Lines of Underground Physics

If we look at the main physics and astrophysical issues which will be researched at the Gran Sasso, two stand out, with neutrino physics playing a prominent role:

a) Neutrino astronomy comprising

- *the study of stellar collapse* ($E\nu$~10 MeV), the main research object of the LVD experiment;
- *solar neutrino physics*, the primary objective of the GALLEX and ICARUS experiments and of the new one under study, BOREX;
- *the search for astrophysical point sources of very high energy neutrinos and gammas*, primarily under the LVD and MACRO experiments.
- *the search for supersymmetric particles*, good candidates for dark matter, through their annihilation in neutrinos.

b) Problems related to the Grand Unification Theory

- *neutrino masses* studied from two different aspects: the possible oscillations of neutrinos, using as source atmospheric neutrinos or solar neutrinos, and research on the neutrinoless double *β decay*;
- *the search for monopoles*, the main objective of the MACRO experiment and also feasible with the LVD;
- *proton decay in new channels*, one of the aims of ICARUS and LVD.

The study of the penetrating components of cosmic rays, tied to the problem of the composition and origin of primary cosmic rays, the research on gravitational waves from stellar collapse, as well as some geophysical experiments contribute to paint an extremely exciting picture of the Gran Sasso Laboratory.

STELLAR COLLAPSE AND TYPE II SUPERNOVAE

A Type II supernova explosion[3] is one of the most spectacular events in the sky and is the outer brilliant sign of a catastrophe marking the end of the evolution of massive stars: $M>8M_{\odot}$..

These events are associated with neutron star or black hole birth and are copious sources of neutrinos detectable in underground experiments.

The final stage of the evolution of massive stars is an "onion skin" configuration: a central iron core surrounded by burning layers of Si, O, Ne, C, He, and H. When the fuel has been consumed, the star cannot support itself any longer against gravity and the core begins to collapse. As soon as the density of the inner region of the core exceeds the nuclear density, the collapse of the core stops and a shock wave begins to move outwards. If the wave reaches the outer envelope with enough energy, the supernova explosion can take place.

It has been calculated that about 3×10^{53} ergs (gravitational binding energy) must be released to form a neutron star: during the supernova explosion, $\sim10^{49}$ ergs photons and $\sim10^{51}$ ergs kinetic energy are emitted. The difference between the calculated and observed energies is in the form of neutrinos (99%) and gravitational waves (1%). Less than 10% of the neutrinos is radiated in the delta capture (neutronization) of the $\sim10^{57}$ protons: $p+e^{-}\rightarrow n+\nu_e$, and the remainder in pair processes (deleptonization): $e^{-}+e^{+}\rightarrow\nu_i+\bar{\nu}_i$ $i=e,\mu,\tau$.

The delta capture occurs in the initial collapse, the initial ν_e burst takes place in $<10^{-2}$ s. When the density is $\geq2\times10^{11}$ g cm^{-3}, the inner core is no longer transparent to the neutrinos and they are in equilibrium with matter. The pair neutrinos are thermally radiated in 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

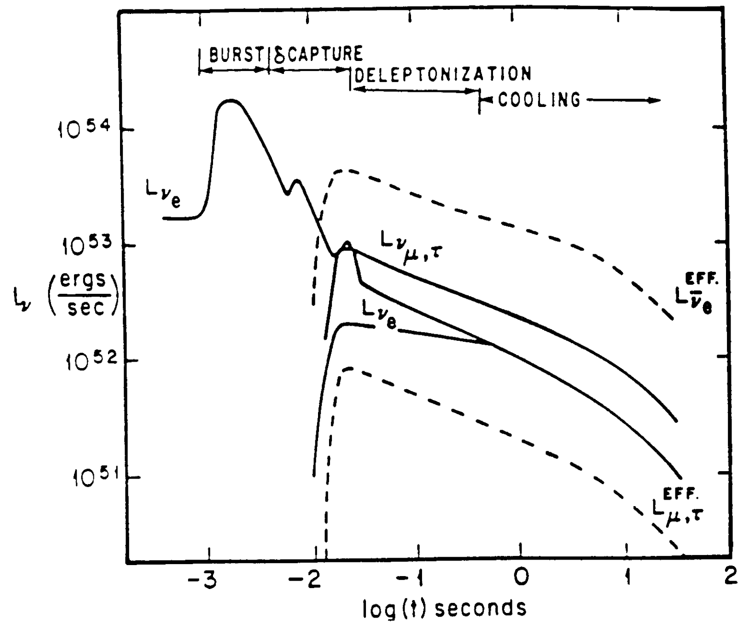

Fig.2. Neutrino emission time scale.

half of the neutrinos is emitted. 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). See Fig.2.

The general scenario of collapse is well understood, but the explosion mechanism and envelope ejection still need clarification. On the basis of the present models, the 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. As the time structure of the neutrino luminosity is strictly related to the explosion mechanism, it is crucial for an experiment to perform detailed studies on the time scale structure of neutrino emission.

THE LVD EXPERIMENT

The detector[4] consists of a large volume of liquid scintillator divided into modules surrounded by streamer chambers. Its design fulfills the following objectives:

The detection of neutrino interactions inside the detector: low energy neutrino interactions and measurements of neutrino energy; pattern identification of neutrino-induced events of higher energy.

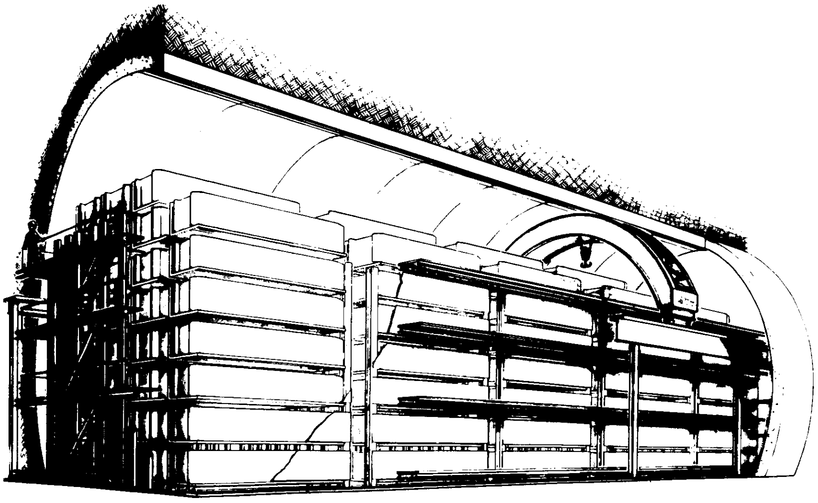

Fig.3. LVD - layout.

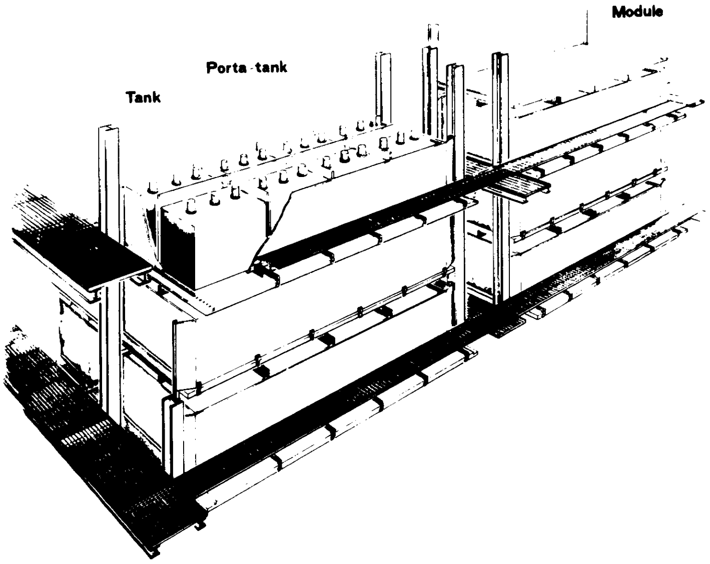

Fig.4. LVD - assembly.

The detection of mu mesons and measurements of their direction of flight: cosmic muons of very high energy ($E \geq 2$ TeV) crossing the apparatus; muons induced by neutrinos in the surrounding rock.

The LVD is basically formed of 190 identical modules, each one containing 9.6 tons of liquid scintillator, 6.7 tons of steel and surrounded on the bottom and one one side by a double layer of streamer tubes which makes up the tracking system (see Figs.3 and 4). The modules can be either 6.6 m × 2.1 m × 1.1 m or 6.6 m × 2.6 m × 1.1 m placed in an array of 40 m × 12 m × 13 m and are inserted in an iron support structure. The total weight including the support structure and tracking system is 3,600 tons.

The scintillator system. The basic element is a 1m × 1m × 1.5m stainless steel tank filled with well-tested Russian scintillator and housed eight-by-eight in the iron "portatank". Each tank is viewed by three 15 cm phototubes. The characteristics of the scintillator system are as follows: structure C_nH_{2n+2} with n=10; density 0.8 g cm^{-3}; attenuation length 20 m (λ=420 nm); decay time of a signal in the scintillator 5 ns; output light ~5 photoelectrons each PM for 1 MeV of energy loss; energy resolution $20\%/\sqrt{E}$.

The tracking system. The basic element of the tracking sytem is an L-shaped chamber containing ~80 6.3 m long standard PVC streamer tubes (LST) for a total of 15,000, with eight 1 cm × 1 cm cells assembled in a double layer. The chambers are arranged in eight (seven) double horizontal planes and five vertical double planes. The LST signals are picked up by 4-cm-wide Al+PVC strips. The characteristics of the tracking system are angular resolution 0.5 degrees, double layer efficiency ~100% and geometrical acceptance 7,700 m^2sr.

Detection of Stellar Collapse in LVD

The most convenient way to study stellar collapse is the detection of antineutrinos through the inverse β decay reaction (σ=10.3 $10^{-42}cm^2$ for E>4 MeV):

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

Another source of information can be the ν-e scattering, essentially at the very first phase of collapse, even if it produces a lower number of interactions in the detector (σ=6.41 $10^{-44}cm^2$ for E>4 MeV).

When operating in a low background environment, the scintillator modular counters of the LVD are suitable for the detection of both the pulses that give the signature for an antineutrino:

- a prompt pulse from the positron with the energy above the high energy threshold (~6 MeV);

- a delayed pulse from the neutron during a gate width $\Delta t=500$ μs and energy threshold of about 0.8 MeV.

Antineutrino detection with this double signature in the same type of scintillator counter has already been checked in LSD at Mont Blanc[5]. The neutron moderation time plus deuterium fusion have been measured experimentally using a ^{252}Cf source and the efficiency for the detection of the neutron was found to be 70%. At Mont Blanc the trigger threshold is 6 MeV, limited by the natural radioactivity in the laboratory. The threshold could be lower in the Gran Sasso Laboratory.

In LVD we can expect about 1000 events ($E \geq 6$ MeV) in 20 s for a collapse in the galactic centre (10 Kpc). On the basis of the background measured by LSD at Mont Blanc, and of the lower background presumed at the Gran Sasso, we can expect a noise rate of 0.1 counts/s, which means that the ratio signal/noise should be optimal. For an extragalactic source (i.e., Magellanic Clouds ~52 Kpc), the signal will obviously be lower but still detectable. Recent observations of neutrino signals from SN1987A have increased the interest in this field.

CRIOGENIC GRAVITATIONAL ANTENNA EXPERIMENT

A supernova explosion should also lead to a burst of gravitational waves as a consequence of the large and fast variation of the supernova quadrupole moment. Two different experimental methods can be used to observe gravitational waves: the laser interferometric system and resonating bars at a very low temperature.

A criogenic gravitational wave antenna[6] (3 m long, 2,300 Kg of Al 50/56) will be installed in the Gran Sasso laboratory to operate at about 50 m°K. The sensitivity to energy variation of the antenna fundamental vibration will be 10^{-6}-10^{-7} °K, sufficient to detect pulses coming from the Virgo Cluster (≥ 20 Mpc). At this level, the antenna is also sensitive to cosmic rays; this can be avoided by veto shielding, but the effective "duty cycle" will be optimal only in an underground laboratory.

SOLAR NEUTRINOS

Solar neutrinos are produced in the hot interior of the sun (15×10^{6} °K) by a series of nuclear fusion reactions which, according to the standard solar model, provide more than 98% of the energy required to explain the observed solar luminosity. Due to the small mean energy E_{ν} of neutrinos and their weak interaction with matter, they are the best probe for studying the interior of the sun. In fact, neutrinos can escape directly from a stellar interior, unlike photons which are emitted from the stellar surface - the photosphere - and give us conventional information about the stars; the mean free path for photons in stellar interiors where the nuclear fusion occurs is less than a centimetre. By letting us look inside a star, the neutrinos allow us to study and test

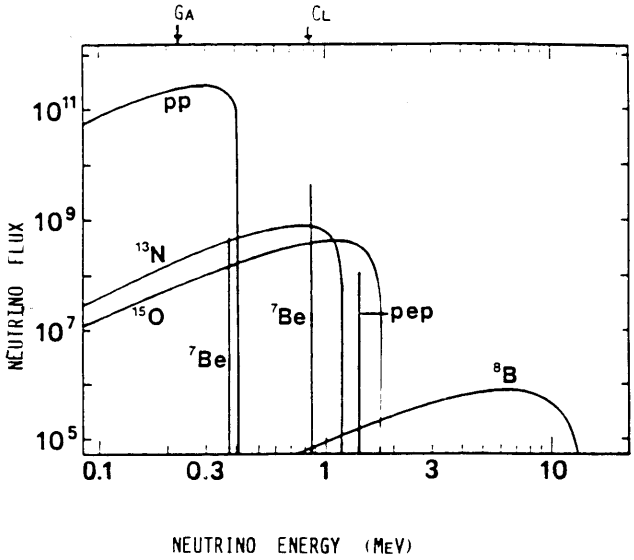

Fig.5. Flux of solar neutrinos reaching the earth vs neutrino energy.

the predictions of the Standard Solar Model. The measurement of the expected solar neutrino fluxes is thus the best test of the theory of stellar evolution.

We know more about the sun than any other star; we know all about its mass, luminosity, radius, temperature, surface composition, age, and its evolutionary phases in the context of the quiescent main sequence. Consequently, we can use the solar model to formulate theories on stellar evolution and their astronomical and cosmological applications.

Figure 5 shows the expected flux[7] at the earth of solar neutrinos vs neutrino energy. Most of the neutrinos come from the $pp \rightarrow de^+\nu_e$ reaction with neutrinos $0<E_\nu<0.47$ MeV, while the most energetic neutrinos come from the ^{8}B decay with $0<E_\nu<14.06$ MeV.

Experimental Situation and Solar Neutrino Puzzle

The first solar neutrino experiment was performed by Davis[8] et al. using ^{37}Cl and the capture reaction $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$. The radioactive ^{37}Ar is extracted from a large volume of C_2Cl_4 and put in a small proportional counter where the Auger electron from the $^{37}Ar \rightarrow {}^{37}Cl$ decay is measured. The threshold of the reaction is 814 KeV. The Davis results are

- (1970-1984): A rate of 2.18 + 0.25 SNU corresponding to a ν_e flux at the earth $\Phi(\nu_e)(^8B) < 2\times10^6 cm^2 s^{-1}$.

- (1986-1987): The results seem to agree better with SSM 4.2±0.7 SNU.

Other preliminary and recent results come from the KAMIOKANDE[9] experiment which measures the $\nu_e e^-$ scattering with a threshold of 9.3 MeV in a fiducial volume of 680 tons of water Cerenkov detector:

- (1987-1988): $\Phi\ \nu_e(^8B)=2.6\ 10^6 cm^{-2} s^{-1} \pm 30\%$

The origin of discrepancies between the experimental results and theoretical predictions can derive from a lack of knowledge of the nuclear reactions inside the sun (Standard Solar Model), or the behaviour of neutrinos (neutrino oscillations such as $\nu_e \rightarrow \nu_\mu$ on their path from the sun to the earth, or matter oscillations in the interior of the sun).

As a general comment we have to say that both Davis and Kamiokande are only sensitive to the most energetic neutrinos originating from the decay of ^8B, which are a strongly solar-model-dependent production and a rare side-branch of the fusion reaction chain. On the other hand, the neutrinos from the $pp \rightarrow D+\nu_e+e^+$ reaction are somewhat model independent and constitute the majority of the neutrinos emitted.

Gran Sasso Laboratory - A Challenge for the Solar Neutrino Puzzle

Many experiments are foreseen at the Gran Sasso regarding such a crucial problem:

- GALLEX - a radiochemical experiment able to measure the pp neutrinos.
- ICARUS - a direct counting experiment of the ^8B neutrinos with additional information on the direction of the incoming neutrinos.

The LVD experiment may well give additional measurements of the flux of ^8B neutrinos provided the noise is kept very low.

A new experiment - BOREX - is also foreseen for measuring both neutral and charge current interaction in ^{11}B. This could allow the simultaneous measurement of the total flux of neutrinos of all flavours and of the ν_e flux and is particularly important to distinguish between problems related to neutrino oscillations or to the Standard Solar Model.

THE GALLEX EXPERIMENT

The GALLEX[10] experiment (Fig.6) will provide measurements of solar neutrino fluxes using a 30-ton Gallium detector to study the reaction: $\nu_e+^{71}Ga \rightarrow ^{71}Ge+e^-$. As the energy threshold is 233.2 keV, the experiment is sensitive to pp neutrinos. The expected capture rates on the basis of SSM are given in Table II.

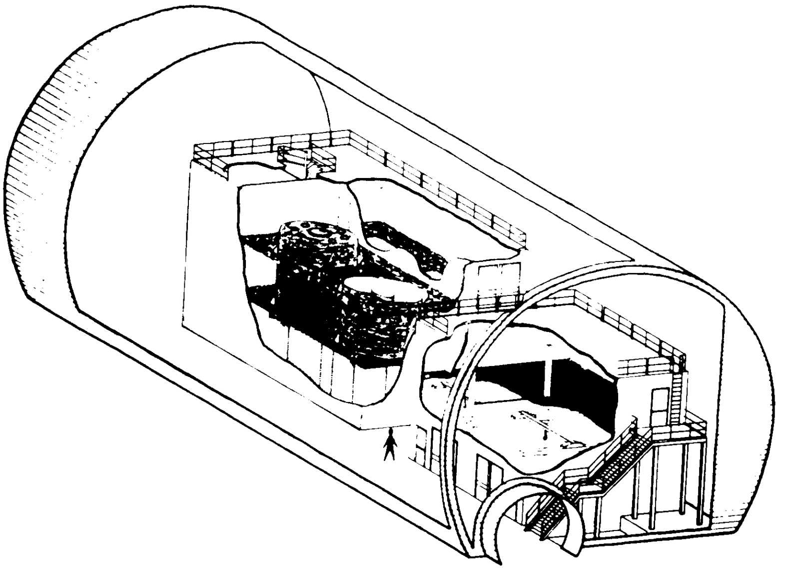

Fig.6. Sketch of the GALLEX experimental setup.

TABLE II

ν_e Source	Capture Rate
pp (0÷0.42 MeV)	71.0 SNU
pep (1.44 MeV)	2.5 SNU
^{7}Be (0.38÷0.86 MeV)	31.3 SNU
^{8}B (0÷14.06 MeV)	1.4 SNU
^{13}N (0÷1.20 MeV)	2.9 SNU
^{15}O	4.0 SNU

Detection Technique

The target material is a solution of $GaCl_3$ and the expected ^{71}Ge production rate is ~1 atom/day. The resulting $GeCl_4$ compound produced is highly volatile and has a half-life of 11.4 days; thus, every two weeks, the $GeCl_4$ will be swept away by a circulating stream of He. The $GeCl_4$ extracted will then be reduced to gaseous GeH_4 and after chromotographic purification put into the proportional counter where the decay $^{71}Ge+e^- \rightarrow ^{71}Ga+\nu_e$ is measured by X-ray and Auger electrons. With the one neutrino capture/day expected in the 30-ton detector, it is clear that the background in the proportional counter (β particles from natural radioactivity, Compton electrons caused by external gamma rays, and electronic noise) must be kept as low as possible by using ultra pure materials and passive and anticoincidence shieldings. The aim of the experiment is to have a counting background of less than one count/week that will ensure a ±10% measurement with a three years' run.

Further problems could arise from concurrent reactions such as $^{71}Ge(p,n)^{71}Ge$ where the protons provoking this reaction are produced as secondaries of (α,p), (n,p) or cosmic ray reactions. This contribution has been estimated as less than a few percent. It will also be possible to calibrate the experimental setup using a 1-MC artificial ν source of ^{51}Cr yielding ν_e of 746 keV, which can populate both the 175 and 500 keV states in ^{71}Ge.

ICARUS I EXPERIMENT

ICARUS I (Imaging Cosmic and Rare Underground Signals) is the first step to a more ambitious programme, ICARUS,[11] which foresees a multikiloton liquid argon detector with an analysing magnetic field and which is mainly devoted to proton decay and solar neutrino physics. While most of the approved experiments are based on well-tested techniques, ICARUS represents a large scale innovation in technology; however, as pointed out by its authors, it must grow step-by-step.

The ICARUS I detector consists of a cryostat filled with 300 tons of ultra pure liquid argon. Due to its drift time technique and nondestructive and continuous read-out, this cryogenic image chamber allows a recording of the complete electron image produced by the ionizing event. The chamber has an excellent spatial resolution (±1 mm) and a colorimetric energy resolution of ~3% for 1 MeV electron. The direct observation of solar ν_e from ^8B can be done by measuring the neutrino-electron elastic scattering $\nu+e^- \rightarrow \nu+e^-$ and the neutrino absorption $\nu_e+{}^{40}Ar \rightarrow {}^{40}K^*+e^-$. Assuming a measured flux of ν $2\times10^6 cm^2 s^{-1}$ in 200 tons of fiducial volume, the expected rates per year with an energy cut-off of 5 MeV are 80 scattering events and 90 absorbtion events.

We have to remember that the signature of solar neutrino elastic scattering events is the forward peaked angular distribution of the recoil electrons, so the possibility of measuring the electron direction in the image chamber will be a powerful tool for discriminating events from background. Figure 7 shows the neutrino-electron scattering as it will be recorded in the chamber.

MAGNETIC MONOPOLES

While the concept of magnetic monopoles had already been presented as a possibility before the theory of electromagnetism was formulated, today their existence is required by the Grand Unification and Supersymmetric Theories as a consequence of the breaking of a Grand or

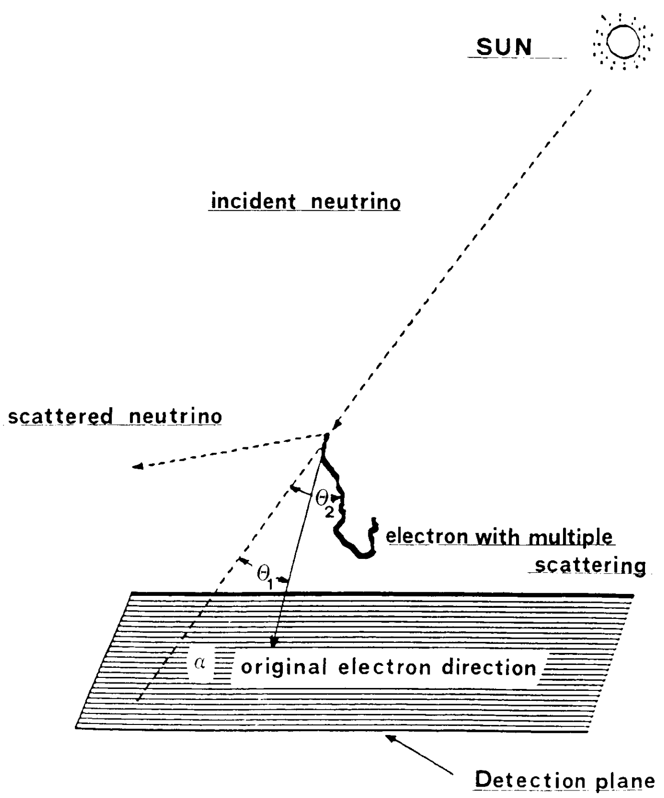

Fig.7. Schematic of the neutrino-electron scattering in ICARUS.

Supersymmetric Group G. Monopole properties can also be predicted by theory: the mass of the monopole is assumed $m_m = m_x/G \sim 10^{16}$ GeV, where m_x (X boson mass) is about 10^{14}-10^{15} GeV and the coupling constant G=0.03.

If unification also includes gravity, the monopole mass should be bigger, with the situation being complicated further if the Supersymmetric Theory is also considered. We can conclude[12] that the Grand Unification and Supersymmetric Theories predict the existence of monopoles of large masses, but that their exact value depends on the theory. Consequently, it is necessary for the experiments regarding monopoles to be sensitive to a large range of masses.

Due to their large mass, monopoles cannot be produced either in the accelerators of today and the near future, or in the cosmic ray collisions of high energy; the only time when such a high energy was available was during the first instants of the Big Bang when the temperature of the universe was comparable to the monopole mass. In the Standard Universe Model, GUT monopoles are thought to be produced at 10^{-35}s after the Big Bang during a phase transition when the unification between strong and electroweak interactions was broken down. It has been shown that due to the fast expansion of the universe, the pairs of stable monopoles produced had no chance to annihilate, so have had the possibility of surviving up to the present. In this case, nevertheless, their number density should be comparable to the baryon number density and monopoles should dominate the present density of the universe. The necessity of explaining the apparent suppression of monopoles by a factor $\geq 10^{15}$ has suggested several hypotheses: in the Inflationary Model of the universe, for instance, an exponential expansion of the universe is thought to have reduced the number of monopoles, provided that the inflation took place between the generation of the monopoles and that of the baryons. This model can also reproduce other important physical properties of the universe, while the monopole density, although delimited by inflation, is, in any case, measurable.

Astrophysical limits on the flux and velocity of monopoles

An upper limit on the monopole density and flux can be derived as a consequence of the existence of the galactic magnetic field, based on the consideration that too large a number of monopoles can extract energy at a rate which is unacceptable compared to the value of the galactic magnetic field. This limit - known as the Parker limit - which can be calculated as a function of mass and β of monopoles, $\Phi \sim 10^{-15}$ cm^{-2} $sr^{-1}s^{-1}$, is not fully accepted, but is a reference point in monopole research.

The velocity of monopoles depends on their origin. After their production, the monopoles may have also lost kinetic energy, may have clustered in galaxies, or been accelerated by the galactic magnetic field. For instance, if the monopoles are of extragalactic origin, their velocity would be comparable to the velocity of our galaxy in respect to the rest of the universe $\beta \sim 2\times10^{-3}$. On the other hand, if the monopoles are concentrated in our galaxy, their velocity would be comparable to the velocity of the sun in respect to the galactic centre $\beta \sim 8\times10^{-3}$, or to the galactic escape velocity $\beta \sim 10^{-3}$; if they are concentrated in the solar system, they would have a velocity of the order of 10^{-4}. The expected β-distribution could therefore present a minimum speed of 3×10^{-5} with a peak around 10^{-3} and some poles with higher energy.

It is clear that the Grand Unification Theory and cosmological considerations need more experimental verification in this field.

Detection Techniques

Several different techniques are thought suitable for detecting monopoles.

Induction technique (direct). The very small persistent currents induced by a monopole passing through a superconducting coil can be measured by a Josephson junction device (SQUID).

Ionization/excitation technique. The fundamental parameter is the monopole velocity. The calculation and measurement of the proton ionizing power at low β confirm that the slow monopoles are detectable[13] by a scintillator down to a velocity β of 6×10^{-4} (or 3×10^{-4} according to some hypotheses). For a gaseous detector the conventional threshold is 10^{-3}; through excitation by the Drell[14] mechanism and consequent ionization by Penning effect, the threshold can be as low as 10^{-4} in He.

Track-etch technique. The passage of charged particles creates submicroscopic damage trails in the lattice of the detector and these can be enlarged by chemical etching. Based on the well-defined response function for the development of the etch pit from Z/β, a threshold as low as 2×10^{-5} can be reached.

MACRO EXPERIMENT

The Monopole Astrophysics and Cosmic Rays Observatory experiment is a large area detector[15] with a planar structure and geometrical acceptance of 10,000 m^2sr. The experiment has mainly been dedicated to monopole research, neutrino astrophysics and cosmic ray physics and consists of three types of detector:

- 2(3) horizontal planes of liquid scintillator counters $(0.75\times0.25\times12)m^3$, each one viewed by two photomultipliers;
- 9(18) horizontal layers of streamer tubes; the eight-wire PVC chambers $(0.25\times0.03\times12)m^3$ are filled with a gas mixture of He:CO_2 npentane;
- a track-etch detector consisting of three layers of CR39 and five layers of Lexan.

Slabs of concrete absorbers are placed between the various layers of the detector.

One MACRO supermodule is $(12\times2\times4.5)m^3$ and the final dimensions are $(72\times12\times9)m^3$ (see Fig.8).

The Detection of Monopoles in MACRO

The use of three different kinds of detector allows a good redundancy. In the scintillators the monopole is univocally identified by the long light pulse emitted at the passage of the pole. A waveform digitizer records the pulse with a time granularity of 1% of total pulse duration. The time-of-flight of a particle between two layers is also recorded. In the streamer tubes the monopole appears as a track in space of uniformly delayed hits. The streamer pulse height is recorded too as tests on relativistic ion beams have shown that large ionization losses can be measured. The response from the track-etch detector will be analysed in the case of a monopole candidate.

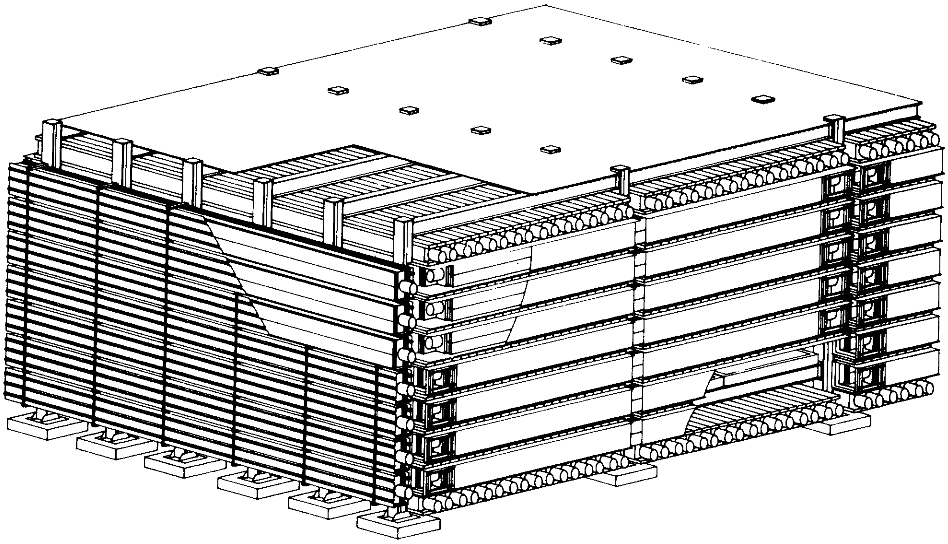

Fig.8. A MACRO supermodule.

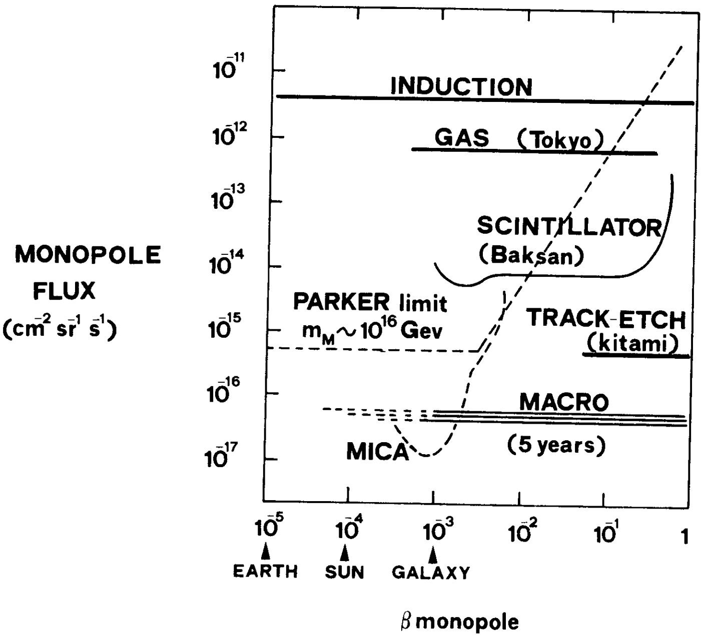

Fig.9. Summary of the monopole research experiment limits.

Figure 9 gives a summary of the results from the main monopole research experiments using the various techniques and shows the expected MACRO sensitivities with respect to the Parker limit.

NEUTRINO MASS

The question of whether the neutrino has a nonzero mass is most important for both particle physics and astrophysics. Masses of the order of (1-10) eV could solve the problem of the dark matter in the universe, while masses of $<10^{-2}$ eV could explain the solar neutrino puzzle.

In the Standard Model, neutrinos are massless and both the individual lepton flavour numbers and the total lepton number are automatically conserved. However, most extensions of the Standard $SU_2 \times U_1$ Electroweak Model predict nonzero neutrino masses.

Direct kinematic limits on the masses of ν_e can be measured from tritium β-decay; for instance, in the Zurich-SIN[16] experiment, $m_{\nu_e}<18$ eV. In addition, the measured flux and arrival times of the neutrinos from Supernova 1987A[17,18] also place a limit on the 20 eV range, while the limits on the m_{ν_μ} for $\pi-\mu$ decay, $m_{\nu_\mu}<0.25$ MeV (SIN),[19] and on the m_{ν_τ} (from $\tau \rightarrow \nu_\tau + 5\pi$) $m_{\nu_\tau}<50$ MeV (Argus) are relatively weak.

A less direct, but more sensitive approach to the problem of detecting the neutrino mass is to look for neutrino oscillations[20]. Two parameters are fundamental: $\Delta m^2 | m_1^2 - m_2^2 | eV^2$, the difference in mass between the two-mass eigenstates, and the lepton mixing angle, $\sin^2\theta$. Oscillations can be looked for in

- appearance experiments - search at a certain distance from the source for the appearance of a different neutrino type;
- disappearance experiments - search for a reduction in the expected flux of a definite neutrino type.

There are presently many limits from accelerator experiments and reactors and some preliminary results from underground experiments (see Fig.10)[21].

The Gran Sasso Approach to the Neutrino Mass

The approach will be twofold:

- a search for neutrino oscillations using atomospheric or solar neutrinos as source;
- a neutrinoless double β decay experiment, $(A,Z) \rightarrow (A,Z+2)+2e^-$, that violates the lepton number by two units and that can take place only if the neutrinos have Majorana masses.

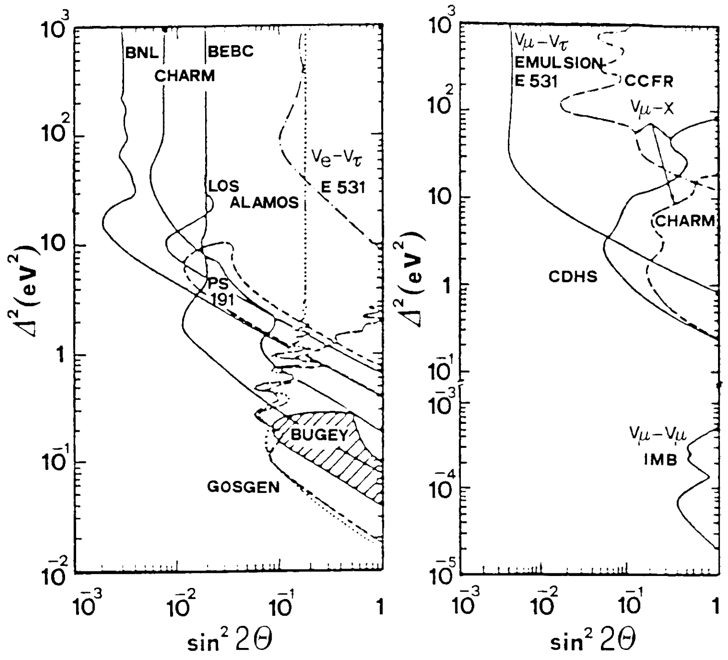

Fig.10. 90% CL limits for neutrino oscillations (from P. Langacker).

Neutrino Oscillations with Atmospheric Neutrinos

The idea of using underground detectors for neutrino flavour oscillations by employing the neutrinos produced in the atmosphere by cosmic rays[22] is very attractive because of the small value of the neutrino mass difference that can be explored. The neutrinos are originated in the (10-20)Km atmospheric shell surrounding the earth: the ones from the nearest zenith are called down-going, while the those which have travelled over a large fraction of the earth's diameter are known as up-going. The distance a neutrino has travelled is a function of its zenith angle $L=[r^2-(r-d)^2\sin^2\theta]^{1/2}-(r-d)\cos\theta$, where r is the earth's radius and d is the height of the atmosphere. If neutrino oscillations occur, it is possible to see differences in the interactions inside the detector of the neutrinos in the up-going solid angle and those in the down-going angle that have travelled only about 10^4 m. Thus, for a full-wavelength oscillation,

$$\Delta m^2(eV^2)\equiv|m_1^2-m_2^2|=2.5 <E_\nu \text{ (MeV)}>/L(m)$$

$$\Delta m^2\simeq 2.5\times 600/1.3\times 10^7 \text{ eV}^2\simeq 10^{-4} \text{ eV}^2$$

a small value of the neutrino mass difference may be explored. In the LVD experiment with its large sensitive volume, it will be possible to search for neutrino flavour oscillations and a 3σ effect could be given after several years of operation.

Due to the low flux of atmospheric neutrinos, another attempt is looking at up-going muons produced by ν_μ in the rock surrounding the detector and their angular distribution. However, in this method the relevant neutrino energy (1-100 GeV) is much higher, which means less sensitivity in Δm^2. Furthermore, there are more uncertainties on the expected muon rate calculation.

DOUBLE B DECAY EXPERIMENT

This experiment[23] is devoted to the search for neutrinoless double β decay, which is forbidden by lepton number conservation. The detector is a multiwire proportional chamber of 61 cells, 80 cm long and with a cross section of 2.5 cm side. Each cell is filled with xenon at high pressure (10 bar) and the decay studied will be $^{136}Xe \rightarrow ^{136}Ba+2e^-$.

A year of effective running without any detection will yield a 10^{23}-year limit on the lifetime corresponding to $m_\nu<1.5$ eV.

In order to increase the performance of the detector, enriched xenon can be used in a low activity environment.

THE ORIGIN OF COSMIC RAYS

One of the most debated problems in the field of astrophysics concerns the origin of cosmic rays. One of their main characteristics is the fact that the chemical composition, at least up to a few GeV/nucleon, exactly reproduces that of the solar system. The power radiated in our galaxy is very high; it emits 10^{40}-10^{41} ergs/s of cosmic rays; 10^{44} ergs/s of visible light; 10^{39} ergs/s of radiowaves; 2×10^{39} ergs/s of X-rays

The most credible models today hold that cosmic rays must be generated either by an object of particular composition or by many different 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 cosmic rays: pulsars, binary systems, supernova explosions, quasars, etc. A few discrete sources of cosmic radiation have been discovered in recent years,[24] in particular gammas of ultra high energy such as Cygnus X3, 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. The obvious candidates are gamma-rays and neutrinos.

Research regarding discrete sources can be successfully carried out in underground detectors by examining either gammas in their interaction with the atmosphere, or neutrinos in their interaction with the rock surrounding the apparatus.

The large area and good spatial resolution of the MACRO and LVD will allow the study of the composition and origin of cosmic rays and the search for discrete sources of gammas and neutrinos of ultra high energy.

CONCLUSIONS

The Gran Sasso Laboratory with its great "observer" experiments provides an unequaled occasion to tackle the vast array of problems connected to both particle physics and astrophysics. This logically explains the enormous interest and participation in the experiments by physicists of different extractions and from all over the world. In the next few years we will no doubt be witness to extremely exciting results and new prospects in frontier physics.

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Chairman: L. Votano

Scientific Secretaries: C. Fordham and P. Colas

DISCUSSION

- *Mincer:*

Is there a surface air-shower array planned at Gran-Sasso, that would operate in conjunction with the underground detectors?

- *Votano:*

At the moment it is a planned experiment. It is in a certain sense small: 28 elements of 10 m^2 liquid scintillator separated by 25 m in the central part and 100 m in the external part.

- *Zichichi:*

The top laboratory is an intrinsic part of the original project of the Gran Sasso. It still has to be done.

- *Mincer:*

Will that information be tied into the other experiments, for instance will MACRO have timing information?

- *Votano:*

Yes, as this is very important for many experiments.

- *Colas:*

As the absolute time measurement is needed to compare experiments and to get precise absolute directions of stellar sources, is there a general clock facility foreseen in the Gran Sasso Laboratory?

- *Votano:*

A facility to have the absolute time with the best accuracy is foreseen at Gran Sasso.

- *Bobbink:*

How much energy does a slowly moving monopole loose in going thru the rock above Gran Sasso laboratory?

- *Votano:*

A monopole has a large energy loss in matter due to excitation and ionization. These losses are proportional to $g^2\beta^2$ and for an ultra-relativistic monopole are of the order of 10 GeV/g.cm^{-2}. For low β there exists a maximum energy transfer which fixes also the threshold for various detectors. As I showed in my lecture, the energy loss in the rock, at least for the standard model, is not a problem, as the monopoles we consider are so massive that they have an enormous energy.

- *Volkas:*

Has the monopole-like event observed by Cabrera a few years ago been explained as a more conventional phenomenon?

- *Zichichi:*

This experiment has been repeated with sensitivity increased by two or three orders of magnitude, and nothing more has been observed. However, this event should still be included in the data sample.

- *Fordham:*

I believe he has written that a physical shock produces the same signal.

- *Marchioni:*

How much can the present limits on proton decay be improved by Gran Sasso?

- *Votano:*

In the LVD, it is possible to make a search for the channel predicted by supersymmetry, $p \rightarrow K^{+} + \overline{\nu}$. LVD can have a good signal since it can, in principle, detect the signal from K^{+} and then from μ^{+} decay. In ten years of running, we should reach a limit greater than 10^{32} years.

- *Calafiura:*

Will the Gran Sasso Laboratory ever have a Kamiokande-like experiment with a water volume two to three orders of magnitude larger than Kamiokande?

- *Zichichi:*

The whole thing was originally planned to be Kamiokande–like technology, but the results from Kamiokande were not considered worth investing an immense amount of money in it. Kamiokande is relevant only if you increase the water volume by three orders of magnitude, which is at present science fiction.

- *Colas:*

What is the fiducial mass of the large volume experiment?

- *Votano:*

It is about 1.2 kilotons.

- *Zichichi:*

The 1.2 kilotons is what we considered the first approach, in order to get experience, but the real size of the experiment is to be 10 kilotons. The originality of the experiment is that we should have the same efficiency in all the decay channels. This is the aim of the experiment.

- *Sarid:*

Will Icarus be able to say anything about neutrinos from supernovae?

- *Votano:*

In the first phase of the detector, Icarus I, it seems to be quite impossible, but it will be possible if the giant chamber is built and filled with methane instead of liquid argon.

- *Zichichi:*

The first Icarus is called "Baby Icarus".

- *Votano:*

Icarus I is 300 tons instead of 4.5 kilotons for the full-size project.

- *Brandt:*

There were about a hundred papers that came out of the 1987 supernova. Have any modifications been made to the detectors as a result of all this information?

- *Votano:*

The results from SN 1987 A are hotly debated because if both Kamio- kande and IMB on one side and Mont-Blanc on the other side are true measurements of the supernova explosion, a special model needs to be invoked. Anyway, no reasons appear from this debate in favor of changes in the detector.

- *Polychronakos:*

I am curious to know what veto shielding is.

- *Votano:*

Cosmic rays can be a source of noise in the gravitational wave detector because of its level of sensitivity. The veto shielding can be used to silence the detector during the time of passage of cosmic rays, but on the surface of the earth the density of cosmic particles is so high that the antenna would be silenced continuously. That is why the detector is underground.

- *Servoli:*

Are there plans to measure the very high energy tail of the cosmic ray spectrum at Gran Sasso?

- *Votano:*

LVD and MACRO have very large tracking detectors, so the physics of multimuon events, anisotropies, etc., can be studied with very great sensitivity.

- *Mannel:*

Is there any estimate of the rate of stellar collapses?

- *Votano:*

The rate should be one about every thirty years in our galaxy. I would like to underline that due to their association to massive stars, Type-II supernovae are seen only in spiral arms of spiral galaxies, regions which are normally optically obscured. However, neutrinos are not obscured, and supernovae can be detected everywhere in our galaxy.

- *Bobbink:*

How many electronics channels are their on the LVD detector?

- *Votano:*

The tracking system is something like 10^5, with 15,000 streamer tubes. The scintillator system has about the same number of channels.

- *Sarid:*

What results do you expect to have one year from now, in summer 1989?

- *Votano:*

LVD and MACRO should have part of their detectors ready and some results. The GALLEX detector, the solar neutrino experiment, should have part of its gallium ready also.