The Gran Sasso National Laboratory of the INFN Scientific program

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Abstract

Experiments in underground laboratories have shown evidence of physics beyond the standard model. The anomalies observed in electron-neutrinos from the sun and muon-neutrinos from cosmic rays interactions in the atmosphere can be explained if neutrino are massive and oscillate. The physics program at the Gran Sasso Laboratory that we are defining will be focussed on the next phase of neutrino physics with a complementary set of experiments.

Experiments on non-baryonic dark matter are reaching a sensitivity that makes them close to be able to detect neutralinos in certain optimistic theoretical expectations. The program at Gran Sasso for the next years will include a strong effort to further increase the sensitivity by orders of magnitude with different complementary techniques.

1. Introduction

Underground laboratories are complementary to those with accelerators in the basic research of the elementary constituents of matter and of their interactions and symmetries. They provide the low radioactive background environment necessary to the search for those extremely rare phenomena, which may give us information of the physics of extremely high energies. Indeed we have now for the first time strong hints for physics beyond the standard model. The evidence is in neutrino physics and has been obtained in underground laboratories, mainly Kamioka in Japan, Gran Sasso in Italy and, more recently, SNO in Canada.

On the basis of this evidence we know now that some of the assumptions of the Standard Model are not correct. Neutrinos have non-zero masses, electron neutrinos, muon neutrinos and tau-neutrinos - the particles produced by weak interactions and detected by our apparatuses - are not the mass eigenstates and their flavour quantum numbers are not conserved. These findings point clearly to new physics.

In the following, after a brief description of the Gran Sasso laboratory and a reminder of neutrino physics, I'll summarise the scientific program of the laboratory. Reviews of the new neutrino physics have been published elsewhere [1].

2. The Gran Sasso Laboratory (LNGS)

The INFN Gran Sasso Laboratories are located besides the freeway tunnel (10.4 km long) connecting L'Aquila and Teramo, at about 6 km from the west entrance, 120 km from Rome.

Fig. 1 shows a view of the facility. The access is through the gallery of the freeway, allowing the transportation of large pieces of apparatus. The underground facilities consist of three experimental halls, called hall A, B and C, and a set of connecting tunnels and service areas, for a total surface of 18 000 m^2. The three halls are approximately 100 m long, 18 m wide, 18 m high. The infrastructures of the laboratory are completed by a number of buildings on the surface, near the western entrance of the tunnel, hosting offices, laboratories, shops, library, canteen, etc.

The flat shape of the massif, with an average rock overburden of 1400 m provides uniform coverage at all angles, giving a cosmic rays muon flux attenuation of a factor 10^6. The neutron fluence from the dolomite rock is particularly low, 1000 times less than on the surface.

The mission of the laboratory is to host experiments in fundamental physics requesting very low levels of radioactive background and researches in other disciplines (notably geophysics and biology) that can profit of the unique environmental characteristics of the site.

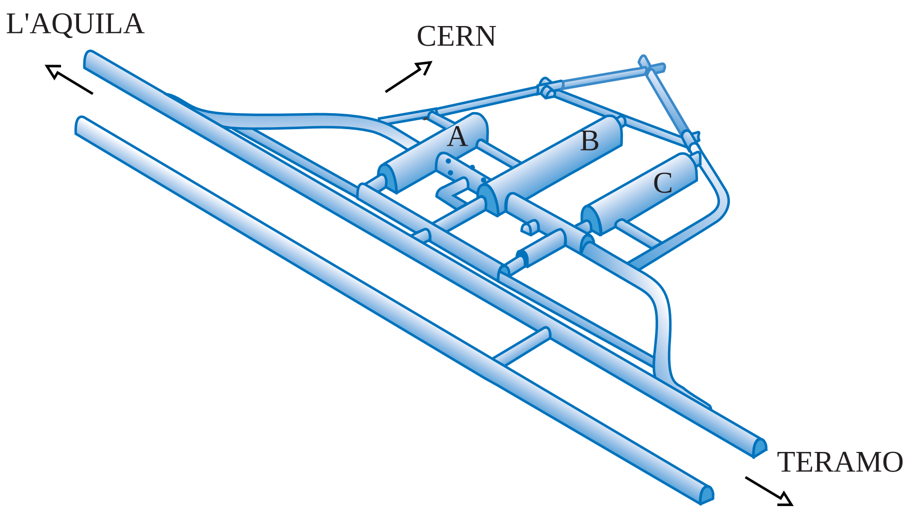

Fig. 1. Artist view of the underground facilities of the Gran Sasso Laboratory

In 1990 the Italian Parliament approved a law committing ANAS to complete the Gran Sasso Laboratory with two new halls and with an independent access tunnel, necessary to guarantee a high safety standard. While in the 80's immediate action had followed the decisions of the Parliament to build the present structure, the different political situation of the 90's slowed down the realisation of the civil engineering works. Finally, the new Government in 2001 has included the project in its public works programme as an "emergency" issue.

Experiments at Gran Sasso, in its little more than ten-year operational life, have already provided major discoveries and given important contributions to science [2]. The first generation experiments, or at least some of them, are reaching or have reached completion. Taking office in 1997, I charged the international Scientific Committee of the Laboratory to examine in depth all the running experiments in order to determine on scientific grounds the data taking time still necessary to each of them to be completed. The experiments had been approved, in fact, without defining their overall occupation time of the laboratory underground space.

The review led to the conclusion that in the year 2001 almost half of the laboratory space would be available to new experiments. The knowledge of availability of space has stimulated the scientific community and a number of very interesting ideas and proposals have been submitted to the Laboratory. It is now clear that first class opportunities are present for the next experimental phase that may, with a bit of fortune, lead to major discoveries of physics beyond the present theory of elementary particles.

Neutrino physics will be the principal, but not the only issue of the research program for the next years. Experiments both with naturally produced neutrinos (from the Sun, from the atmosphere and from Supernova explosion) and artificially produced ones (mainly from CERN, but possibly by other sources too) are being built or planned. Other experiments will try to understand the nature of the electron neutrino and search for the Majorana mass; still others will continue with increased sensitivity the search for non-baryonic dark matter. The measurements of thermonuclear cross-sections at energies relevant for the stars and Sun combustion processes will continue with an improved underground accelerator facility.

3. Neutrino masses and mixing

Experiments in underground laboratories have provided strong evidence for neutrino oscillations. Two and independent are the physical sources of this information: the electron neutrinos from the Sun and the muon neutrinos indirectly produced by cosmic rays in the atmosphere. The corresponding two oscillation phenomena take place with very different periods, inversely proportional to the differences between the relevant mass eigenstates. I'll call δm^2 and Δm^2 the square mass differences for the solar and atmospheric oscillation respectively.

The neutrino states with definite flavour (ν_e, ν_μ and ν_τ), those produced by weak interactions and detected by our instruments, are linear combinations of the mass eigenstates (ν_1, ν_2 and ν_3),

$$\nu_l = \sum_{i=1}^{3} U_{li} \nu_i$$

where $l = e, \mu, \tau$. The mixing matrix being unitary, its elements can be expressed in terms of four independent real parameters. These are usually taken as three "mixing angles" (θ_{12}, θ_{13} and θ_{23}) and a phase factor. The phase factor gives CP violating effects in the lepton sector, extremely important, but unfortunately still very far to be experimentally accessible. As a consequence, I will, for simplicity, forget it and consider only real matrix elements. Two further phases, α and β, irrelevant for oscillations, are present if neutrinos are Majorana particles.

A summary of the present knowledge is the following.

Electron neutrinos are produced by the thermonuclear processes in the core of the Sun. When the ν_e flux is measured on the Earth, substantially lower values than expected are found. A fundamental contribution was given by the GALLEX experiment at Gran Sasso. It measured for the first time the ν_e flux from the pp reaction, that is model independent and known from solar luminosity (2% uncertainty). GALLEX was also the first radiochemical experiment to be absolutely calibrated with an artificial ν_e source. Other important information is provided by the SuperKAMIOKANDE measurement of the high-energy (> 5 MeV) neutrino spectrum both during the day, when neutrinos reach the detector directly, and during the night when they cross the Earth (possible matter effects). The experimental evidence can be explained only if neutrinos behave in a non-standard way, the simplest hypothesis being oscillations (including MSW effect). This phenomenon depends mainly on two parameters, the square mass difference δm^2 and the mixing angle θ_{12}. Solar neutrino data do not select a unique solution, but are compatible with a few, amongst which future experiments will chose. Notice that all but one solutions (SMA, that is disfavoured by data) are close or equal to "maximum mixing" meaning here that $|U_{e1}|^2$ • $|U_{e2}|^2$ • 1/2.

The second anomaly has been convincing observed by Super-Kamiokande and confirmed by MACRO at Gran Sasso in the "atmospheric" neutrinos. The simplest interpretation is we are observing a second oscillation phenomenon mainly between ν_μ and ν_τ. The square mass difference, as measured by Super-Kamiokande, is in the range 1.5 x 10^{-3} $eV^2 < \Delta m^2 <$ 5 x 10^{-3} eV^2. The mixing is compatible to be maximum, meaning now that $|U_{\mu 2}|^2$ • $|U_{\mu 3}|^2$ • 1/2.

Finally the electron antineutrinos disappearance CHOOZ[3] experiment gives the limit $\theta_{13}{}^2$ • $|U_{e3}|^2 < 0.03$. In conclusion, two of the mixing angles, θ_{12} and θ_{23}, appear to be close to •/4 (maximum mixing), while the third, θ_{13} is close to zero. The pattern is very different from that of quarks.

From these pieces of evidence we can assume that the neutrino mass spectrum consists of two nearby levels, m_1 and m_2, and a third more separated one, m_3. The smaller mass difference $\delta m^2 = m_2^2 - m_1^2$ is responsible of the solar anomaly, the larger one $\Delta m^2 = m_3^2 - m_2^2$ • $m_3^2 - m_1^2$ of the atmospheric one. In other words the neutrino mass spectrum is composed of a doublet of states

$$|M_{ee}^M| = \left|\left(|U_{e1}|^2\ m_1 + |U_{e2}|^2\ e^{2i\alpha} m_2 + |U_{e3}|^2\ e^{2i\beta} m_3\ |\right)\right|$$

very close together and of a third, more separate state. The last one is a superposition of ν_μ and ν_τ almost one to one, with possibly a small ν_e component.

As neutrino oscillations depend on the absolute value of the difference between the squares of the masses, we do not know whether the third state is higher ($\Delta m^2>0$, called "normal" spectrum) or lower ($\Delta m^2<0$, called "inverted") than the doublet. Neither we know the absolute scale of the masses. The spectrum may be degenerate, when the three masses are almost equal, or hierarchical, when the masses of the doublet are of the order of the square roots of the two square mass differences.

Notice that mass is a property of the stationary states (the eigenstates) and that talking of ν_e, ν_μ or ν_τ mass (as we have just done) is improper and in some cases misleading. What is meant depends in fact on what and how one measures (or limits).

Consider as an important example the limits on the "electron-neutrino mass" $<m_{\nu_e}>$ that are obtained by measuring the electron energy spectrum in the Tritium beta decay. If neutrinos are massive, the spectrum should show three steps in correspondence with the three masses. But these cannot be resolved and one measures an average effect

$$< m_{\nu e}^2 > = |U_{e1}|^2\ m_1^2 + |U_{e2}|^2\ m_2^2 + |U_{e3}|^2\ m_3^2$$

Presently two experiments give the upper limit $<m_{\nu_e}> <$ 2-3 eV[4].

If neutrinos are massive Majorana particles, a very rare process, the neutrino-less double beta decay ($0\nu2\beta$) can happen in some nuclides. No positive signal has been observed and limits on the corresponding lifetimes have been set. From each of them a limit on the electron-neutrino "effective mass" M^M_{ee} can be extracted, taking into account the relevant nuclear matrix elements. The corresponding uncertainties are typically a factor two. As a consequence, it is mandatory for a complete research program to include different double-beta active isotopes in the search. In the present case the "mass" that is measured, or limited is the quantity

Notice that cancellations can happen due to the phase factors. Presently the best limit, M^{M}_{ee} < 340 meV (90% c.l.) is given by the Heidelberg-Moscow[5] experiment at Gran Sasso, obtained with a 37.2 kg x yr exposure of an enriched ^{76}Ge detector.

The same group has proposed in 1997 the GENIUS[6] experiment aiming for a forward jump in the sensitivity with a large increase in the enriched Ge mass (1000 kg) an a drastic reduction of the background. Naked enriched Ge crystals would be immersed in a liquid N_2 bath, 10 m across used both for cooling the crystals and to screen the external radioactivity. The experience of BOREXINO shows that extremely low radiopurity levels can be reached liquid N_2 and Monte Carlo calculations show that the technique should allow to reduce the background, in the relevant energy, to reach $b = 3 \times 10^{-4}$ events/(kg keV yr). This would allow the experiment to reach the 10 meV neutrino mass range. To prove that such a large reduction in the background is possible in practice Monte Carlo calculations are not enough and a series of tests is necessary. To this aim the GENIUS-TF[7] proposal, based on 40 kg of natural Germanium, has been approved.

The most sensitive experiment on a different isotope is MIBETA, again at Gran Sasso, with 20 TeO_2 crystals operated as bolometers at cryogenic temperatures. The total detector mass is almost 7 kg of natural Te or of 2.3 kg of the double-beta active ^{130}Te isotope. MIBETA has reached an exposure of 3.3 kg yr with a background level b = 0.6 ev/(kg keV yr), giving the limit M^{M}_{ee}<2 eV[8].

The next experiment with the same technique is CUORICINO[9] consisting of 56 TeO_2 crystals, 0.76 kg each, corresponding to a total ^{130}Te mass of 14.3 kg. The first crystals are in the test phase. If the background level will be reduced at b = 0.1 ev/(kg keV yr), as it appears to be feasible from the results of the tests, sensitivity around 400 meV will be reached in M^{M}_{ee}

Further increase in the mass, by an order of magnitude, and drastic reduction of the background are being studied in view of the CUORE project aiming to a 50 meV sensitivity. It will consist in 1000 natural Te crystals equal to those of CUORICINO with a sensitive ^{130}Te mass of 250 kg and aim to a background rate $b = 10^{-2}$ events/(kg keV yr).

In conclusion, double beta decay experiments could reach sensitivities in the range, M^{M}_{ee} = 30 - 50 meV. These are extremely interesting values, being close to the square root of the atmospheric square mass difference, i. e. 40-70 meV. In case of a degenerate or of an inverted spectrum the sensitivity of GENIUS and CUORE might be enough to detect the signal.

4. The next steps

In the previous paragraphs I have briefly described the recent experimental findings that have given origin to the new neutrino physics. Clearly we might just be entered in a new field that can reserve complete new discoveries for the future. The program of the next years should include experiments able to

- observe oscillation signals both for the atmospheric anomaly and the solar one. In neither case we have yet observed a non ambiguous sign of oscillation. In both cases oscillations give the simplest explanation, but more exotic interpretations are not excluded.
- confirm the atmospheric neutrino oscillations with experiments with a neutrino beam produced at a far away accelerator. Composition (mainly ν_μ) and energy spectrum of an

artificially produced beam are under control. Both ν_μ disappearance and ν_τ appearance experiments are planned. The K2K experiment is running since 1999: a muon-neutrino beam is produced at the Tzukuba KEK Center and sent to the Super-Kamiokande detector 250 km away. The low neutrino energies (2-3 GeV) give good sensitivity even with low statistics[10]. The NUMI program at Fermilab is building a muon-neutrino beam to shoot on the MINOS detector being built in the Soudan mine 730 km away in Minnesota. The experiment is now planned to start data taking in 2005 in a disappearance mode[11].

- discover if the flavour into which the atmospheric ν_μ oscillate is indeed ν_τ or else with a ν_τ appearance experiment, as planned by the CNGS project in Europe. This issue is clearly connected with the existence of low-mass sterile neutrinos coupled to known particles.
- improve the knowledge of the mixing parameters.
- measure the sign of Δm^2. Is the spectrum "normal" or "inverted"? We have already recalled the chances for the $0\nu2\beta$ search. In § 9 we will discuss those of Supernova neutrinos. Others exist for a sign sensitive experiment on atmospheric muon neutrinos.
- improve the knowledge of δm^2. Choose solar solution.
- detect, if any, the $\nu_\mu \Leftrightarrow \nu_e$ oscillation at Δm^2. Is $U_{e3} \bullet 0$?
- determine the nature of neutrinos: Majorana or Dirac?
- measure the absolute values of the masses

Experiments at Gran Sasso Laboratory can give important contributions, provided that we will be able to build a coherent program. This will be done on the basis of the many interesting ideas and proposals that have been submitted and that are in different stages of development and of the resources that will become available. In the following I'll briefly describes these proposals.

5. Neutrinos from CERN

An important component of the program will be the CNGS project. An artificial, well-controlled neutrino source will be built at CERN for experiments at LNGS. Both the beam[12] and the experiments will be optimised for ν_τ appearance, where ν_τ's are observed through the process

$$\nu_\tau + N \to \tau^- + N'$$

Running in the "shared" mode, the beam will give 3200 CC ν_μ interactions per year in a kiloton fiducial mass detector at LNGS corresponding to 25 ν_τ interactions for $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2 and maximum mixing (1.7 times more in dedicated mode operation).

The charged daughters of τ's will be detected, in one or more decay channels: $\tau^- \to \mu^-$ ν_μ ν_τ (18%); e^- ν_e ν_τ (18%); $h^- \nu_\tau$ $n\pi^0$ (50%); $2\pi^- \pi^+$ ν_τ $n\pi^0$ (14%). Two main background rejection tools are available: 1. the direct observation of τ decays requiring micrometer scale granularity and sub-micron resolution, which are possible only by the emulsion technique (OPERA); 2. the use of kinematic selection, which requires good particle identification and good resolution in momentum unbalance (ICARUS).

ICARUS[13] is a liquid argon time projection chamber providing bubble chamber quality 3D images of the events, continuous sensitivity, self-triggering capability, high granularity calorimetry and *dE/dx* measurement. The R&D program performed between 1991 and '95 on a

3 t detector solved the major technical problems with the detector continuously running for several years, showing the reliability of the technique. The technique was then developed for the industrial production of a kiloton size detector. Its structure will be modular. A module has a mass of 600 t (T600) and is composed of two 300 t units, transportable on highways. The units will be completely assembled and tested before being separately transported to Gran Sasso. A 300 t unit has been completed and successfully operated in summer 2001. The safety issues connected with the installation of a large cryogenic volume underground are also being studied. The project foresees the construction of a series of T600's to cover a broad physics program, including ν_τ appearance in the CNGS program.

The design of OPERA[14] combines in its basic cell the high precision tracking capability of nuclear emulsion and the large target mass given by lead plates (1mm thickness). The basic building block of the target structure is a "brick", a sandwich of contiguous cells enclosed in a light-tight evacuated envelope. A wall is followed by electronic trackers with moderate resolution with the scope to identify the brick were a neutrino interaction took place and to guide the off-line scanning. Fired bricks will be removed and processed (alignment, development and scanning of the emulsion sheets) on a day by day basis.

6. Atmospheric neutrinos

Atmospheric neutrino experiments are complementary to CNGS. The two principal aims of the MONOLITH proposal[15] are the observation of the oscillation pattern and the accurate measurement of the square mass difference. Notice that both aims are easier if Δm^2 is lower.

The oscillation probability is a periodic function of the L/E variable, the ratio between the muon-neutrino energy E and its flight length L. L is obtained from the neutrino direction, inferred from that of the μ. To have a good correlation, one must use only μ's above a GeV or so, were unfortunately the cosmic rays flux is low. As a consequence several kiloton mass detectors are needed but with coarse resolution. MONOLITH is a 35 kt spectrometer made of 8 cm thick horizontal Fe magnetised plates. The interleaved tracking planes have 1 cm spatial resolution and good (1 ns) timing, for up/down discrimination.

For a given direction, down going ν_μ's do not oscillate, while upward going do. The ratio between the two fluxes is known with small systematic uncertainty. The distribution of this ratio as a function of the zenith angle (i.e. L/E) will show the oscillation pattern (with 100 – 150 kt yr exposures) and precisely determine Δm^2.

7. Solar neutrinos

GALLEX has been concluded, but its improved version, GNO, is running and has published results corresponding to 35 solar runs (each one-month long). The experiment aims to reduce the systematic (now = 4.6%) and statistical uncertainties well below 5%. Increase of the sensitive mass by a factor two to three is foreseen in the proposal. If this will not be feasible, the date of closure of the experiment (a few years from now) will be defined on scientific grounds.

The measurement of the mono-energetic, 0.86 MeV, Be neutrino flux in real time is the principal aim of the BOREXINO[16]. Indeed Be neutrinos flux appears to be particularly sensitive to oscillation parameters. Electrons resulting from a neutrino (any flavour, but ν_μ and

ν_τ with smaller than ν_e cross-sections) scattering in the liquid scintillator detector medium will produce a light flash that will be detected by photomultipliers. 300 t of ultra-pure pseudocumene will be contained in a nylon sphere, the 100 t innermost mass being the sensitive volume. A larger volume of pseudocumene inside a 13.7 m diameter stainless steel sphere hosting the optical modules surrounds the nylon sphere. This sphere is immersed in a 2500 t purified water tank.

The experiment is designed with a threshold of 0.25 MeV. The main problem at such low energies is the control of the background due to the always present radioactive isotopes. An intense R&D program has been carried out in the last ten years to select materials and to purify them at unprecedented limits of radio-purity. In parallel, techniques have been developed to measure ultra-low levels of radioactivity. Record levels of 10^{-16} – 10^{-17} (g of contaminant/g of material) for ^{232}Th and ^{238}U have been achieved.

To complete program on solar neutrino physics we need to measure in real time the neutrino spectrum in order to separate the contributions of the different branches, *pp*, ^{7}Be and ^{8}B with a flavour sensitive experiment. The LENS[17] proposal addresses the problem using ν_e capture by ^{176}Yb nuclides that go into an excited ^{176}Lu state. The Yb is loaded into an organic liquid scintillator to detect the electron resulting from the capture and the delayed γ, used as a tag, from the excited Lu decay. Notice that the ^{176}Lu ground state is higher than that of ^{176}Yb, making this nuclide stable against beta decay. This characteristics and the low (301 keV) threshold for neutrino capture make ^{176}Yb practically unique.

The techniques needed to prepare large quantities of scintillator doped with a large fraction of Yb (at least 8%), with a reasonable light yield, with a good attenuation length (several metres) and chemically have been developed. The R&D are continuing to obtain requested radiopurity levels. Neutrino sources necessary for calibration most be procured.

8. Nuclear astrophysics

The solar model calculations need the values of the cross sections of the nuclear reactions involved in the different branches of the *pp* cycle. These cross sections are so small, due to the extremely low Coulomb barrier penetration probability at the relevant energies (called the Gamow peak), that their measurement became only recently possible in the low background Gran Sasso environment.

The LUNA experiment, based on a 50 kV ion accelerator, has already measured the cross section of the important ^{3}He + ^{3}He$\rightarrow$2p + ^{4}He reaction down to 17 keV[18] (where the cross section is only 20 fb and the rate 2 events/month!) below the Gamow peak. No resonance is present.

LUNA2 is the second-generation experiment. A 400 kV accelerator has been designed and installed. It is now in operation, with beam energy resolution better than 70 eV and long-term stability of 10 eV. A BGO-4•-summing detector completes the new facility. The gas target is located inside a borehole of the detector. A good energy resolution is indeed essential to reduce the background. The reactions ^{14}N (p,γ) ^{15}O, ^{3}He (^{3}He,γ) ^{7}B and ^{7}Be (p,γ) ^{8}B will be studied.

9. Neutrinos from Supernovae

Type II Supernovae in the Galaxy or in the Magellanian Cloud produce enough neutrinos (all flavours) to be observable. Notice that when leaving the Supernova core, electron neutrinos and antineutrinos have a softer spectrum (average energy approximately 10 MeV, I'll call it "soft") than the other flavours (average energy approximately 20 MeV, I'll call it "hard"). Neutrinos then cross the mantle, a medium of very high density in which important matter induced flavour conversions take places. Having left the star, the mass eigenstates propagate, independently one from the other, to our detector, possibly with slightly different velocities. Clearly the flux of a flavour we measure may be extremely different from that produced in the Supernova core. The measurement of the arrival times cannot, neither in principle, measure or limit, as is frequently but wrongly claimed, the mass of the detected neutrino flavour, for example, of the tau neutrino.

On the other hand we can extract information on neutrino mixing. To make an example, consider the case in which $|U_{e3}|^2$ is not too small (> a few 10^{-4}). It can be seen[19] that if $\Delta m^2>0$ the electron neutrino spectrum as detected on Earth is equal to the originally produced muon and tau neutrino spectrum, it is then hard. On the other hand, the electron antineutrino spectrum is halfway between the soft and the hard ones. If $\Delta m^2<0$, the roles of electron neutrinos and antineutrinos are inverted. The measurement of the ratio of neutrino and antineutrino spectra, which is almost model-independent, would allow determining the sign of Δm^2.

At Gran Sasso the LVD dedicated experiment has a 1080 t sensitive mass of organic liquid scintillator. The detector has a modular structure consisting of 912 tanks each seen by three photomoltipliers. The tanks are read out independently, so allowing a very high up time, at least of a part of the apparatus (99.3% in 2000)

LVD is mainly sensitive to electron-antineutrinos through the process $\overline{\nu}_e + p \rightarrow n + e^+$ (a few hundreds events for a collapse in the Galaxy centre), but also to electron neutrinos and antineutrinos via different inverse beta decays on ^{12}C nuclei. The thresholds of these processes are around 15 MeV excluding the largest fraction of the soft spectrum, not of the hard one. As a consequence the expected yield increases by an order of magnitude if electron neutrinos or antineutrinos are made harder by matter effects.

10. The search for cold dark matter

At Gran Sasso different experiments are taking data or are in different stages of their R&D in the search of dark matter, more specifically of non baryonic cold dark matter, or WIMPs. These experiments are extremely difficult and delicate.

If a WIMP elastically scatters the target nucleus can be detected. But its energy is extremely low, a few keV, an energy region were backgrounds are huge. Being the signals very rare, heavy nuclei have to be used as targets. Given the large wavelength of the WIMPs, they "see" the nucleus as an unique object, in other words, scatter coherently, with a probability proportional to A^2. But even for coherent interactions the rates are small. For example supersymmetric models predict rates between 10 and 10^{-6} events per day per kilogram of detecting mass. A low background environment is clearly mandatory. Detectors must have a very low energy threshold, large sensitive mass (tens to hundreds of kilograms or more), good energy resolution, ultra high radiopurity and efficient background discrimination.

The groups active at Gran Sasso have developed three principal world-leading techniques.

The first technique is based on large mass scintillator media both crystals and liquids and has been developed by the DAMA collaboration. As the result of a strong R&D program, DAMA is running since several years a set of NaI (Tl) radio-pure crystals with a total mass of 115 kg. The strategy of the experiment is to search for an annual modulation of the counting rate at low energy, a feature characteristic of the signal, but not of the background (or of the major part of it at least). And the data (four years) indeed show tantalising evidence for a modulation, with all the expected characteristics[20]. Much more work is still needed. While DAMA is still taking data, in its 6th annual cycle, a new phase (dubbed LIBRA set-up) is now starting. With powders of increased radiopurity crystals of NaI are being grown to reach a total mass of 250 g (twice the first phase).

Given the importance of the search for dark matter and its difficulty, the program of the Laboratory must include different approaches employing different techniques and different target nuclei.

The approach of CRESST is based on cryogenic calorimeters. There are two main contributions to the radioactive background: the (dominant) contribution of electrons and photons through ionisation and the (smaller) one of the neutrons. This last comes from the energy deposited by recoiling nuclei and is substantially indistinguishable from the signal. On the other hand, while phonons detection provides full sensitivity to photons, electrons and nuclear recoils, ionisation and scintillation signals are smaller for nuclear recoils and higher for electrons and photons. Profiting of this feature, CRESST2[21] plans to use simultaneous detection of phonons and scintillation light to discriminate.

The third technique is based on Ge detectors. For dark matter search the background at 10-50 keV is relevant, a much more difficult region than that of $0\nu2\beta$ decay (2 MeV). To decrease the background, the Heidelberg group is running the HDMS experiment[22]. It is composed of an inner one (200 g of Ge) acting as the sensitive mass enclosed in an outer Ge crystal acting as an anticoincidence to reject the background from the environment. In the longer run, GENINO with its 100 kg mass and GENIUS[10] with its 1000 kg will be able to explore a large fraction of the parameters space. But a tremendous effort will be needed to reduce the background in inverse proportion to the increase in mass.

12. Conclusions

Neutrino physics has entered in the last years a new age. The discovery of neutrino oscillations has shown that neutrinos have non-zero masses and that the leptonic flavour numbers are not conserved. The search for neutrino-less double beta decays has already reached sensitivity in Majorana mass capable to limit or to contradict some high energy extensions of the standard theory. Dark matter searches are reaching the regions were signals might appear.

These results that point to physics beyond the standard theory have been obtained in underground low background laboratories. Gran Sasso has contributed, as I have discussed.

An extremely interesting future appears to be in front of us were revolutionary discoveries might become possible. In particular the space that will be soon available at Gran Sasso and the quality of its infrastructures have stimulated many interesting ideas and proposals. These are in different stages of research and development, of test and of preparation. Presumably not all of them will become a running experiment, but we have good chances that at least a few will, with a bit of fortune, produce in the next years outstanding results.

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