Neutrino Physics at Gran Sasso Laboratory

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Experiments in underground laboratories have shown strong 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 oscillate and are massive. 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 on the muon-neutrino beam from CERN (CNGS project), on solar neutrinos, on atmospheric neutrinos and on neutrinos from supernova explosion. The relevant thermonuclear cross-sections will be measured. The Majorana vs. Dirac nature of electron neutrinos will be explored with the search for neutrino-less double beta decays in different isotopes.

Experiments on electron-neutrinos from the Sun and on atmospheric electron and muon-neutrinos have shown that, very likely, neutrinos oscillate. This implies that, contrary to the assumptions of the Standard Model: 1. electron, muon, and tau-neutrinos are not stationary states; 2. at least two of the three eigenstates (ν_1, ν_2, and ν_3) have non zero masses; 3. flavour lepton numbers are not conserved. The simplest possibility is to assume that, similarly to quarks, the neutrino states with definite flavour, those produced by weak interactions and detected by our instruments, are linear combinations of the eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (1)$$

The mixing matrix being ortho-normal, its elements can be expressed in terms of three real parameters, usually taken as mixing angles, and a phase factor. Two further phases, irrelevant for oscillations, are present if neutrinos are Majorana particles. From the CHOOZ experiment and from SuperK we know that the atmospheric neutrino oscillation are likely mainly $\nu_\mu \longleftrightarrow \nu_\tau$ with, possibly, a small component of $\nu_\mu \longleftrightarrow \nu_e$, meaning that $| U_{e3} |^2$ is smaller than a few percents. The square mass difference, as measured by Superk is 1.5×10^{-3} eV^2 $< \Delta m^2 <$ 5×10^{-3} eV^2 and the mixing is compatible to be maximum. MACRO at Gran Sasso has confirmed with a tracking detector the anomaly with similar values of Δm^2 and mixing.

Solar neutrino data do not select a unique solution, but are compatible with a few, called SMA, LMA, LOW and Vacuum, each corresponding to a region in the δm^2, vs. mixing angle plane. For all, $\delta m^2 \ll \Delta m^2$ and for all but one (presently not favoured by data) the mixing is close to maximal. Notice that neutrino oscillations depend on <u>the absolute value</u> of the <u>difference</u> between the squares of the masses of pairs of eigenstates, but do not give any information either on the absolute value of the mass scale either on the sign of the square mass differences.

In the program we are developing at the INFN Gran Sasso National Laboratory (LNGS) we are including new experiments on solar neutrino, double beta decay, neutrinos from supernovae, atmospheric muon-neutrinos and on the CNGS [1] (CERN Neutrinos to Gran Sasso) beam. In the following I'll focus on this program, the results of running experiments being reported in these Workshop by other speakers.

Let me recall that LNGS has three large underground halls, about 100 m long, 20 m × 20 m across, easily accessible to large pieces of apparatus through the adjacent freeway tunnel. They have been oriented toward CERN to be able to host experiments on a neutrino beam. Services and shops are hosted in external buildings and halls. A review of the current program have led to the decision to decommission part of the running experiments, making almost half of the laboratory space free for new ones by mid 2001. The construction of two further halls has been approved by the Italian Parliament.

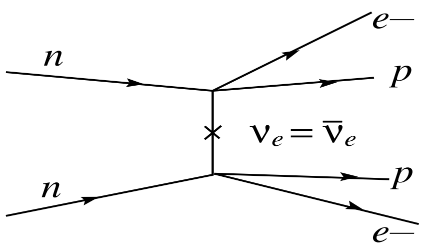

Figure 1.

Neutrino-less double beta decay happens only if neutrinos are Majorana particles and if they are massive. The relevant graph is shown in Fig. 1. Experiments on these decays allow to measure the absolute scale of neutrino mass. Experimentally one measures (or gives a lower limit) on the relevant lifetime and then, knowing the involved nuclear matrix elements, calculates the value (or the limit) of the electron-neutrino "mass". Notice that the uncertainty on the matrix elements gives typically a factor of two to three uncertainty on the "mass". Electron-neutrino is not an eigenstate and it is improper to talk of its mass. What is measured (or limited) is the quantity

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

Notice that, depending on the Majorana phases α and β cancellations may happen. Presently the best limit, 350 meV (90% c.l.), based on the half life limit of 2.1 $\times 10^{25}$ years, is given by the Heidelberg-Moskow [2] experiment at Gran Sasso, obtained with a 35 kg yr exposure of an enriched ^{76}Ge detector. The same group has proposed the GENIUS [3] experiment aiming to reach the 10 meV neutrino mass range with 1000 kg enriched Ge detectors in a liquid N bath acting as a screen from external radioactivity.

The second most sensitive experiment with a different isotope is MIBETA with 20 TeO_2 bolometers in operation 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 (34% natural abundance). The present limit is $< m_{\nu_e} >< 2$ eV [4]. The next experiment with the same technique is CUORICINO [5] approved for 100 TeO_2 bolometers with a total ^{130}Te mass of 25.5 kg. The first 20 crystals are already in operation. The expected sensitivity in the present, reduced with respect to MIBETA, background conditions in $< m_{\nu_e} >$ is between 200 and 400 meV. Further increase in the mass, by an order of magnitude, and improvement in the background are being studied in view of the CUORE project aiming to a 50 meV sensitivity. Given the theoretical uncertainty on the nuclear matrix elements it is mandatory to search for this extremely rare and important phenomenon in different nuclear species.

Detection of Supernova neutrinos can give information both on the still poorly known explosion mechanism and on neutrino masses and mixing. Neutrinos can practically be detected only for SN events in our Galaxy or in the Magellanian Clouds. The explosion produces neutrinos and antineutrinos of all the three flavours in a burst lasting 20-50 s. Non zero masses can lead to longer burst duration. The limit $< m_\nu >< 10$-20 eV obtained from SN 1987A is limited mainly by the uncertainty in neutrinos "light" curve and energy spectra and is difficult to improve.

On the other hand the meaning of $< m_\nu >$ must be clarified. The neutrinos produced in the SN can change their flavour while crossing the core or the ejecta (MSW effect). The process changes both the fractions of each eigenstate and their energy spectra in the burst. The three eigenstates then propagate, with slightly different velocities, to our detector. By measuring arrival times we can only put a limit on a weighted average of m_1, m_2 and m_3 with substantially unknown weights and not, as is frequently but wrongly claimed, a limit on, for example, the tau-neutrino mass.

Flavour sensitive and energy sensitive detection of the neutrinos can on the other hand, give useful information on the mixing parameters, notably U_{e3}, as discussed by F. Vissani [6] at this Workshop. At Gran Sasso the LVD dedicated experiment with its 1080 t sensitive mass of organic liquid scintillator is mainly sensitive to electron-antineutrinos with some sensitivity to the other flavours.

Going now to neutrino oscillations, 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 optimised for ν_τ appearance. The neutrino beam [1], has been designed by a CERN-INFN group. The pions and kaons produced by the 400 GeV SPS proton beam will be focussed by a two horns system followed by a 1 km long decay tunnel, a hadron stop and muon detectors for beam characteristics determination. A close detector station is not needed for appearance experiments. 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).

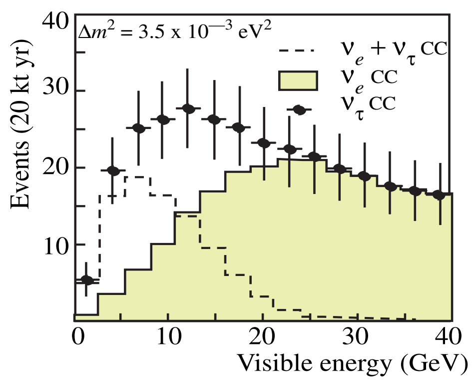

Figure 2.

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

ICARUS [7] 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 all the major technical problems with the detector continuously running for several years, showing the reliability of the technique. The present phase aims to show the feasibility of a large scale detector. A 600 t double-unit is under construction and one 300 t unit is expected to be operational next year. This will be the main milestone to proceed in the program. The safety issues connected with the installation of a large cryogenic volume underground are also being studied. The project foresees the construction of a large modular detector to cover a broad physics program, of which I'll discuss only the CNGS part.

The electron channel will be the main one (but not the only) for the ICARUS search for τ appearance, that will be made mainly by searching for an excess at low electron energies. The background due the ν_e component of the beam (<1%) will be small and the superior e/π^0 separation capability will be exploited to cut out ν_μ neutral current events. Fig. 2 shows the visible energy distribution as expected in a 20 kt yr exposure for $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2 and maximum mixing. After kinematical cuts, 35 τ events will be detected with a residual background of 5 events. If the systematic uncertainty in background calculation, presently being studied, will, as expected, not be large, a 20 kt yr exposure will have more than 4σ discovery potential for $\Delta m^2 > 2 \times 10^{-3}$ eV^2.

The superior detection and energy measurement capability for electrons of ICARUS can be used to search for the minority $\nu_\mu \leftrightarrow \nu_e$, oscillation component. Notice that the commonly used two state formalism is misleading here due to the fact that the "mixing parameter", $\sin^2 2\theta$ has different meanings in the disappearance (CHOOZ) and in the appearance (ICARUS, MINOS) cases. In a disappearance experiment the maximum electron-neutrino disappearance probability is

$$P(\nu_e \text{ disapp.}) = \sin^2(2\theta_{13}) \approx 4\ \theta_{13}^2 = 4 \mid U_{e3} \mid^2$$

Were we have taken into account the smallness of θ_{13}. In an appearance experiment the maximum electron-neutrino appearance probability is

$$P(\nu_e \text{ app.}) = \sin^2(2\theta_{13})\ \ \sin^2(\theta_{23}) \approx$$

$$4\ \theta_{13}^2\ 1/2 = 2 \mid U_{e3} \mid^2$$

were we used the approximately known value of $\sin^2\theta_{23}$.

As a consequence, the disappearance experiment is, in the same conditions, twice as sensible as the appearance one to $\mid U_{e3} \mid^2$. The physical reason is that in the former we do not look to the final state that is a, about fifty-fifty, linear combination of muon-neutrino and tau-neutrino, in the latter that we know that the initial state is purely muon-neutrinos. Taking into account these considerations, one evaluates from the ICANOE proposal [7] that the experiment can improve the present limit on $\mid U_{e3} \mid^2$ by almost a factor two, depending on the systematics, with a 20 kt yr exposure. This limit can be improved, by another factor two, taking into account the electron energy spectrum [8].

For a more substantial improvement one would need a $\nu_\mu \leftrightarrow \nu_e$ appearance experiment at the first oscillation maximum, for example with an high intensity, low energy (2-3 GeV) ν_μ source and a multikiloton detector. This possibility deserves further study.

OPERA [9] design is based on the ECC concept, which combines in one *cell* the high precision

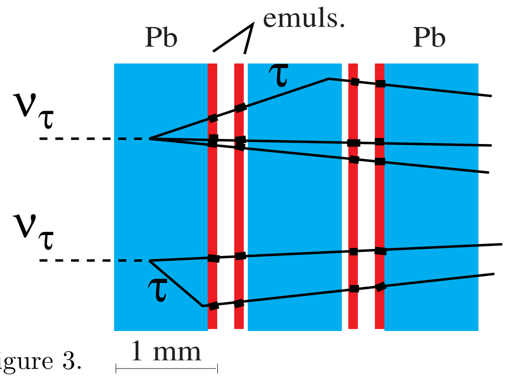

Figure 3.

tracking capability of nuclear emulsion and the large target mass given by lead plates. Fig. 3 shows the cell structure (1 mm thick Pb plate followed by a film made by two emulsion layers 50 μm thick on either side of a 200 μm plastic base). Two topologies of τ events are shown: "long", where the τ production and decay are separated by at least one film (detected via the decay angle), and "short", where they are not (detected via impact parameter).

Several cells are sandwiched in a structure called a *brick*, the basic element used to build vertical planar structures called *wall*. A wall followed by a set of tracker planes makes up a module. A *supermodule* is made of a sequence of modules and downstream *muon spectrometer*. Overall three supermodules are foreseen, providing a sensitive mass of around 2,000 t.

The target trackers, made of scintillator strips, are used to identify the fired brick, for general tracking and for shower energy. A muon spectrometer is made of a dipole magnet (1.5 T) preceded and followed by precision trackers (drift tubes) and low resolution tracking planes (RPC) embedded in the magnet. It provides measurement of muon momentum and charge (to reduce charm background) and beam characteristics. Fired bricks will be removed and processed on day by day basis.

The ECC technique, that has recently lead DONUT to discover the ν_τ, will be further developed. The 176,000 m^2 of emulsion sheets will be industrially produced with an automatic

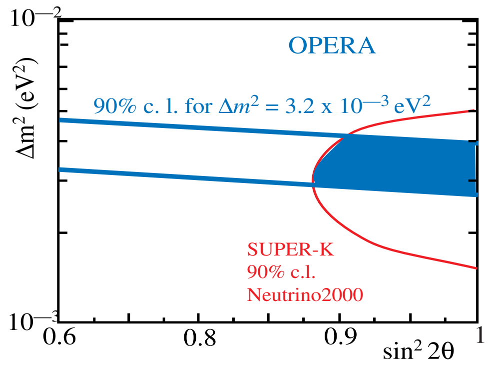

Figure 4.

chain and a new generation of automatic scanning/measuring devices will be produced by the collaboration. All the one-prong decay channels will, almost evenly, contribute to the final OPERA statistics. In a five year run, 18 identified τ decays with 0.6 background events are expected for $\Delta m^2 = 3.2 \times 10^{-3}$ eV^2 (the best fit of SuperK), 44 for 5 $\times 10^{-3}$ eV^2 and 4 for 1.5 $\times 10^{-3}$ eV^2. Fig. 4 shows the expected accuracy in the parameter space.

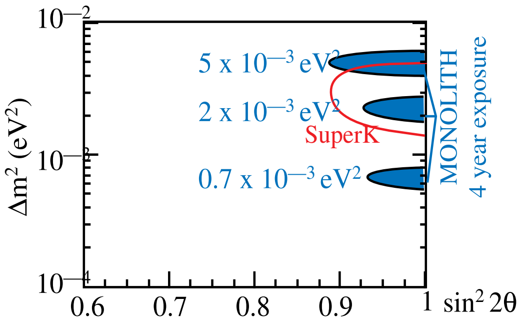

Figure 5.

Atmospheric neutrino experiments are complementary to CNGS, as they become easier for lower values of Δm^2, especially below 1-2 $\times 10^{-3}$ eV^2. To improve on SuperK one must measure as accurately as possible muon-neutrino energy E and flight length L, to have L/E. L is obtained from the neutrino direction, but in practice the μ direction is measured. To have a good correlation, one must use only μ's above a GeV or so, were the cosmic ray flux is low. As a consequence several kt mass detectors are needed. MONOLITH [10] proposal is a 35 kt spectrometer made of 8 cm thick horizontal Fe magnetised (1.3 T) 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 do not oscillate, while upward going do. The ratio between the two fluxes is almost MonteCarlo independent. Its measurement as a function of the angle with the superior MONOLITH L/E resolution, will allow the detection of the first oscillation period. It will also result in a substantial improvement in the knowledge of Δm^2, as shown in Fig. 5.

Solar neutrino physics will be another important component of the program: GNO is taking data, BOREXINO is completing its construction and will be ready to take data early in 2002, LENS is in its R&D phase.

GNO uses the GALLEX structures with 30 t of natural Ge and with several improvements in the counters and in the electronics (a substantial increase in Ga mass has been proposed). It will continuously take data on a long (order of 10 years) period, gradually reducing the overall uncertainty in the flux measurement below 5%. Recalling that the solar luminosity defines an absolute minimum for the yield, equal to 80 SNU, known within 2%, with the project accuracy GALLEX alone might exclude standard neutrinos. For some solutions seasonal veariations might be observable. The result of the first run have been published [11] with a measured yield of 65.8+10.2/-9.6 (stat) +3.4/-3.6 (syst), the systematic uncertainty being already reduced to 5.3%.

The principal aim of the BOREXINO [12] experiment is the measurement of the flux of solar mono-energetic neutrinos due to the 0.86 MeV Be line. Electrons resulting from a neutrino (all flavours) scattering in the liquid scintillator detector medium will produce a light flash that will be detected by photomultipliers. 300 t of ultrapure Pseudocumene will be contained in a nylon sphere, the 100 t innermost mass being the sensitive volume. The nylon sphere is surrounded by a larger volume of pseudocumene inside a 13.7 m diameter stainless steel sphere hosting the optical modules. This sphere is immersed in a 2500 t purified water tank. The neutrino yield from Be is extremely sensitive to the oscillation parameters; it ranges from the 40 ev/day expected by the standard solar model, to zero for some solutions; strong seasonal variations are expected for vacuum oscillations.

But for a complete program on solar neutrino physics we need even more. An ideal experiment should measure in real time the neutrino spectrum in order to separate the contributions of the different branches, pp, ^{7}Be, pep, ^{8}B and CNO. The experiment should provide flavour sensitivity too, at least in combination with others. The only proposal advanced so far approaching these aims is LENS [13]. The proposed reaction is the ν_e capture by ^{176}Yb nuclides that go into an excited ^{176}Lu state. The electron resulting from the capture and the delayed γ, used as a tag, from the excited Lu decay are detected via the scintillation light of a liquid scintillator in which the Yb is doped. The unique characteristics of the ^{176}Yb target are its stability (the ground state of ^{176}Lu is higher in energy compared to that of ^{176}Yb, so that the β decay of the last is forbidden) and the low (301 keV) threshold for neutrino capture. A 20 t natural Yb detector will provide a yield of 200 ev/year in the pp branch, 280 in the Be branch and 16 in pep if the solar standard model would be correct. The expected yield have strong dependence on the mixing parameters allowing to determine them accurately. Notice that, with reference to Be, LENS is sensitive to electron neutrino only, BOREXINO to all the flavours, providing, when taken together good flavour sensitivity.

The presence of the γ tag allows radiopurity levels not so extremely stringent as in BOREXINO, but still a number of problems related to the chemistry and the radiopurity of the scintillator-Yb compound are to be solved, as those related to the mandatory calibration neutrino sources, by the ongoing R&D program.

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, with a 50 kV high intensity ion accelerator has already measured the cross section of the important ^{3}He + ^{3}He $\rightarrow$2p + ^{4}He reaction down to 17 keV, below the Gamow peak. The LUNA2 experiment has been approved and its 400 kV accelerator is now in operation. Starting in 2001 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.

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