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The Homi Bhabha Lecture
Neutrino Physics and Astrophysics

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Abstract

Neutrinos are very elusive particles. Having only weak (and gravitational) interactions they are extremely difficult to detect, but their study has been always extremely rewarding, both for physics and (more recently) astrophysics. In the last several years the progress in neutrino physics has been impressive leading to the discovery, for the first time, of physics of elementary particle phenomena beyond the Standard Theory. We have now a fair knowledge of the main features of neutrino mass-spectrum and mixing, which I'll review in § 2. In § 3 I'll describe the next-generation of experiments, which are under construction or concrete planning. While we know that neutrino masses are extremely small, when compared to the other elementary particles, we do not know their absolute values. This is a very difficult experimental problem, which must be attacked with complementary programmes: precision cosmology, beta-decay and double-beta decay experiments, as I'll discuss in § 4 and § 5.
Photons give information on the surface of the astrophysical bodies, such as stars, neutrinos on the contrary come directly from their inner parts, bringing us precious complementary information. Neutrino astronomy has already started with solar neutrinos and detectors sensitive to a Supernova explosion in our Galaxy are ready to detect the neutrino burst (§ 6). Higher energy neutrino telescopes are at the prototype and even construction stages. Unexpected violent phenomena may be observed in the next several years. I'll discuss these topics in § 7 and 8. Antineutrinos can give information on the inner part of our own planet; neutrino geology has indeed started this summer with the first observation of "geo-neutrinos" by the KamLAND experiment, of which I'll tell § 9.

1. Introduction

Of the known elementary particles (presumably a fraction - perhaps small - of the total) neutrinos are the must elusive because they have only (a part gravity) weak interactions. Neutrino physics, on the other hand, is extremely rich; its study has always given in the past surprises, showing in particular the first evidence of phenomena beyond the standard model. Neutrino mass scale is extremely small when compared to those of the other elementary particles, a fact that gives us hints on the physics at very high energies, close to the grand unification scale.
Notwithstanding the enormous progress in neutrino physics in the last decade there is still a lot to be discovered. We do not even know whether neutrinos and antineutrinos - differently from the other elementary particles and from the assumptions of the standard model - are the same or different particles, formally whether they are described by the Majorana or by the Dirac equation.
There are three kinds of neutrinos, ν_e, ν_μ and ν_τ, with the flavour lepton numbers of the electron, muon and tauon respectively. These are the states in which neutrinos are produced by weak interactions and detected by our apparatuses. These flavour neutrino states are usually classified to belong to the first, second and third family, but, contrarily to the other members, neutrinos have the unique property to change their flavour - hence family - in time.
The mass eigenstates, or simply eigenstates, ν_1, ν_2, and ν_3, with masses, say, m_1, m_2 and m_3 respectively, are the stationary states (in vacuum), linear combinations of the flavour-neutrinos. While the eigenstates cannot

be generated by a reaction at the microscopic level, they are produced, in certain circumstances, by the macroscopic heavenly bodies, the Sun and the Supernovae. Micro- and macro- neutrino physics are complementary. We will see that in other examples.

One is the suppression effect of neutrinos on the large-scale cosmological structures. As a consequence, cosmological observations give very sensitive, albeit indirect, limits (and possibly values in the next future) for neutrino masses.

A further example is the possible CP violation in the lepton sector, an almost unavoidable consequence of neutrino mixing, which might explain through the so-called "leptogenesis" the matter-antimatter asymmetry in the Universe.

For astrophysics, neutrinos are unique in their capability to pass unabsorbed through large depths of matter, messengers of phenomena in the innermost parts of the cosmic bodies. Photons, on the contrary, come from the surfaces. In the words of J. Beacom: "It's the difference between the photograph of a person and an X-ray". But, the very same property makes neutrinos very difficult to detect. Neutrino telescopes must have enormous masses, up to the gigaton scale and further. These experimental challenges are actively pursued world-wide.

2. Neutrino Mass Spectrum and Mixing

Neutrinos have been observed to change flavour in two different ways.

The first phenomenon is called "neutrino oscillations", which, in its purest form, takes place in a vacuum, but happens also in matter. It is a purely kinematical phenomenon (similar to the beats in a dichromatic – more in general, polichromatic - wave), formally described by the kinetic part of the Hamiltonian. It has been discovered as the disappearance of the muon neutrinos indirectly produced by cosmic rays in the atmosphere. Typical neutrino energies (E) are here from sub-GeV to multi-GeV, while the flight lengths (L) are up to a few thousands kilometres (neutrinos cross the Earth without attenuation). The phenomenon has been confirmed by the K2K experiment with an accelerator ν_μ source ($E\approx 1$ GeV) at $L \approx 250$ km flight length.

The probability to observe the flavour state ν_β in a beam initially purely ν_α (monoenergetic, with energy E) contains oscillating terms of the type $P_{\alpha\beta} = A_{\alpha\beta}(\theta_{12},\theta_{23},\theta_{13})\sin^2(1.27(m_i^2-m_j^2)L/E)$, where the m's are the mass eigenvalues in eV, L in km and E in GeV.

One sees that the oscillation frequencies are proportional to the absolute differences between the squares of the masses of the eigenstates. Notice, in particular, that the phenomenon is independent on the sign of $m_i^2-m_j^2$. We call Δm^2 the square mass difference corresponding to the "atmospheric" oscillation. The second flavour transformation, observed in the solar neutrinos, corresponds to a smaller squared mass difference, which we call δm^2.

Each oscillation amplitude $A_{\alpha\beta}$ is a function of the (three in total) mixing angles, $\theta_{ij}\in[0,\pi/2]$. "Amplitude" means here the maximum of the oscillation phenomenon, not to be confused with a quantum-mechanical amplitude. These amplitudes are different for different flavour pairs α and β. In case of disappearance experiments the sum of the contributing amplitudes must be considered. Notice that this simple fact is not always taken properly into account.

Just to make two examples, which will be useful in the following, consider the dominant amplitudes for the $\nu_\mu \to \nu_e$ oscillation and for the ν_μ disappearance $\nu_\mu \to \nu_x$

$$A(\nu_\mu \to \nu_e) = \sin^2(\theta_{23})\sin^2(2\theta_{13}) \quad \text{and} \quad A(\nu_e \to \nu_x) = \sin^2(2\theta_{13})$$

These expressions are symmetrical under the reflection through 45°, a fact true for all the amplitudes, which are then independent on $\mathrm{sgn}(\pi/2-\theta_{ij})$.

To be precise, these two properties of the oscillation probability, independence on $\mathrm{sgn}(m_i^2-m_j^2)$ and on $\mathrm{sgn}(\pi/2-\theta_{ij})$, are rigorously valid only in case of (vacuum) oscillations between two states. In the real case of three flavours, oscillations between all the pairs happen, with interference terms sensitive to those signs.

In practice the ratio between the smaller and larger periods is so tiny, as we will see, that the interference is too small to be observed with sensitivity of the present experiments.
A consequence of the fact that the flavour states are not the stationary states, the concepts of "electron neutrino mass" and similar for the other flavours are not correct.

Flavour states are linear combinations of the eigenstates, $\nu_l = \sum_{i=1}^{3} U_{l,i}\nu_i$, where $l = e$, μ, τ and U is the mixing matrix. U is unitary if, as we will assume, the eigenstates are orthogonal. We can then write U as the product of three rotation matrices including a phase factor, as in the case of quarks, and a fourth diagonal matrix with two more phases (Majorana phases). The last phases can be absorbed in the wave functions only if neutrinos and antineutrinos are different particles (Dirac neutrinos). In general we have

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\frac{\phi_2}{2}} & 0 \\ 0 & 0 & e^{-i\left(\frac{\phi_3}{2}+\delta\right)} \end{pmatrix}$$

where c_{ij}=cosθ_{ij}, and s_{ij}=sinθ_{ij}
In total there are nine quantities to measure, three masses, three mixing angles and the three phases. The last, if $\neq 0$ and $\neq \pi$, (notice that the two are physically distinguishable cases) give CP violation effects in the lepton sector. The "Dirac" phase δ may give observable effects in oscillation experiments, through interference terms, provided that $\theta_{13} \neq 0$ and $\alpha \equiv \delta m^2/\Delta m^2 \neq 0$ (we know that α=0.03, see later). Unfortunately these effects are expected to be very small and very high intensity neutrino beams –presently not available- are needed to search for them.
Majorana phases are irrelevant in oscillation and in the matter conversion phenomenon that we will now discuss; they appear only in double-beta decay (and similar phenomena, too small to be detected).
The second observed flavour neutrino conversion takes place in matter, the Mikehev-Smirnov-Wolfenstein [1] effect. It is a dynamical phenomenon, due to the $\nu_e e$ interaction potential in the matter. The contributions of electrons and protons to neutral current (NC) interactions cancel each other in neutral matter and only the contribution of neutrons, proportional to their density N_n is left. As for the charged currents (CC), the only net contribution is that of electron neutrinos interaction with electrons proportional to their density N_e.
We will limit for simplicity the discussion to the case of two neutrinos, of flavours ν_e and ν_x, with eigenvalues in vacuum ν_1 and ν_2 and masses m_1 and m_2 and mixing angle θ. This is, at a very good approximation, what happens in the Sun, with $\theta=\theta_{12}$. In the flavour base, in vacuum, the evolution is given by the Hamiltonian

$$H_{vac} = p + \frac{m_1^2 + m_2^2}{4E} + \frac{\delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

where p and E are the neutrino momentum and energy, $\delta m^2 = m_2^2 - m_1^2$. In matter, the Hamiltonian of the system becomes

$$H_m = p + \frac{m_1^2 + m_2^2}{4E} - \frac{G_F N_n}{\sqrt{2}} + \begin{pmatrix} -\frac{\delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\delta m^2}{4E}\sin 2\theta \\ \frac{\delta m^2}{4E}\sin 2\theta & \frac{\delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

The potential depends, in particular, on the Fermi constant G_F; it has opposite sign for antineutrinos (formally one can change N_e into $-N_e$ in the above expression). Notice that G_F appears at the first power, not at the second as in the cross section, which explains the importance of the effect.

Two are the important parameters: the mixing angle θ and the ratio between the matter and kinetic terms in the Hamiltonian $\beta \equiv \frac{\text{matter term}}{\text{kinetic term}} = \frac{\sqrt{2}G_F N_e}{\delta m^2 / 4E_e}$. Comparing the two Hamiltonians we can define an effective matter mixing angle θ_m such as $\tan 2\theta_m = \frac{\sin 2\theta}{\cos 2\theta - \beta / 2}$. If the electron neutrinos cross a variable density medium they may reach a density layer at which β=2cos2θ, which correspond to $\theta_m=\pi/4$. It is the resonance condition at which the effective mixing is maximal, even in θ is small, but not zero.
As can be seen the matter effect, contrarily to the oscillation in a vacuum, depends both on sgn (δm^2) and sgn(π/4–θ).
Clearly the eigenstates and their eigenvalues in matter are different than in the vacuum. The situation is shown schematically in Fig. 1.

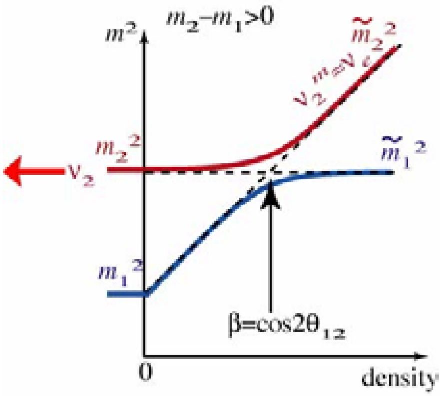

Figure 1. The two eigenvalues of the mass squared as function of the electron density. The position of the level crossing is shown.

With reference to the Sun, consider the two extreme cases: β>>1, which happens in the central regions, where neutrinos are produced and β=0 in the vacuum. Simple calculations show that, for $m_2>m_1$ and for energies larger than about 1 MeV

$$\text{for } \beta >> 1 \qquad \begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} ; \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix} \qquad \Rightarrow \begin{matrix} |\nu_1^m\rangle ; -|\nu_x\rangle \\ |\nu_2^m\rangle ; |\nu_e\rangle \end{matrix}$$

In words, for large enough energies the higher mass eigenstate in the core is ≈ ν_e, while in the vacuum (the same state) is just ν_2. As anticipated, the Sun produces neutrinos in a mass eigenstate, superposition of flavour states, which, in turn will be, as such, detected. Fig. 1 shows the level crossing position.
To be precise, the transition happens only if the crossing is sufficiently "adiabatic"; this condition is met if the mixing angle is not too small. The condition is certainly satisfied in the solar case (the relevant mixing angle is θ_{12}, which is large). We anticipate that this is not necessarily true in the Supernova case, as we will see at § 6.
In conclusion, microphysics, the weak interactions, produce neutrinos as flavour eigenstates (for example, as ν_e in the core of the Sun), macrophysics, the large and dense bodies, such as the stars, under certain conditions, are sources of neutrino eigenstates. An example is the Sun, which, at its surface, produces ν_2's.
The flavour conversion at the "solar" mass difference δm^2 has also been observed as an oscillation (in vacuum) in the KamLAND experiment on $\bar{\nu}_e$ from reactors (see later).

Different groups [2] have performed global fits including all the available data, providing values for the three mixing angles (only an upper limit for θ_{13}) and two squared mass differences. The latest work, including all the published experimental data, is by G. L. Fogli et al. [2a]. The results, with $\pm 2\sigma$ ranges and with the limit at 95% confidence level can be summarised as follows

$$\delta m^2 \equiv m_2^2 - m_1^2 = 79.2 \times (1 \pm 0.09) \;\; \text{meV}^2$$
$$\sin^2\theta_{12} = 0.314 \times (1^{+0.18}_{-0.15})$$
$$\Delta m^2 \equiv m_3^2 - \frac{m_1^2 + m_2^2}{2} = \pm 2400 \times (1^{+0.21}_{-0.26})$$
$$\sin^2\theta_{23} = 0.44 \times (1^{+0.41}_{-0.22})$$
$$\theta_{13}^2 < 3.2 \times 10^{-2}$$

We can now define more precisely the eigenvalues. We count them in order of decreasing content of ν_e: $\nu_1 \approx 70\%$ ν_e, $\nu_2 \approx 30\%$ ν_e, $\nu_3 <$few% ν_e. Fig. 2 shows the spectrum. We do not know whether the singlet is above (so called normal hierarchy) or below (inverse hierarchy) the doublet. Notice that the above definition of Δm^2, proposed by Fogli and collaborators is independent on mass hierarchy. Neither we know the absolute scale; we have only, from "atmospheric" oscillations, the lower limits $m_3 > \sqrt{\Delta m^2} \approx 50$ meV in the first case, $m_1, m_2 > \sqrt{\Delta m^2} \approx 50$ meV in the second.

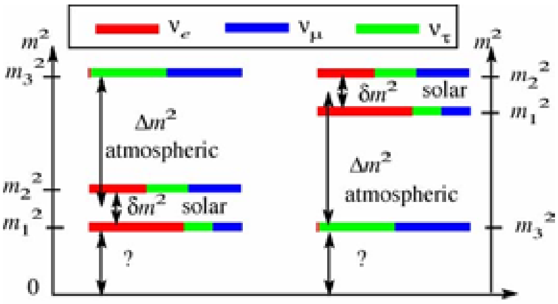

Figure 2. Neutrino mass spectra: "normal" hierarchy on the left, "inverted" hierarchy on the right. For each eigenstate the different fields show approximately the fractions of different flavours

Notice that the ratio of the two square mass differences $\alpha \equiv \delta m^2/\Delta m^2 = 0.03$ is, as anticipated, small; being $|\theta_{13}|$ small too, the two phenomena are almost decoupled.

The flavour conversion in the Sun depends substantially on two parameters, the smaller squared-mass difference δm^2 ($\delta m^2 \in -\infty$, $+\infty$). and θ_{12} ($\theta_{12} \in 0$, $\pi/2$). Due to the smallness of α the phenomenon does not depend much on θ_{13}, but still, the data give some information on this parameter too. The result of an experiment measuring the electron neutrino flux (convoluted with the cross-section) above its energy threshold is compatible with a certain region in the parameters plane (δm^2 vs. $\sin^2\theta_{12}$ or δm^2 vs. $\tan^2\theta_{12}$). Different experiments having different thresholds corresponding to somewhat different regions, global fits give a number of possible solutions, the intersections of those regions, each a smaller area in the plane. Till a few years ago the global solutions were the so-called Vacuum, quasi-vacuum, LOW, SMA and LMA. Additional information comes from the energy spectra, measured above 5-6 MeV by SuperKAMIKANDE and by SNO; also, for some values of the parameters, differences between day and night rates are expected, because during the night MSW effect in the Earth "regenerates" electron neutrinos; these effects have not been observed, further limiting the solution. Finally, the measurement by SNO of the neutral current contribution has chosen just one of the solutions, namely the Large Mixing Angle (LMA). Notice, in particular, that the data choose $\delta m^2 > 0$.

If the mixing angle is just $\theta_{12} = 45°$, the MSW transition is not be effective. That value being now excluded by the solar data at 5.8 σ, the existence of the MSW effect is proven.

Additional data are from the KamLAND experiment, a liquid scintillator detector located in the Kamioka mine in Japan. It measures the $\bar{\nu}_e$ flux and, even more important, the energy spectrum from the power reactors, with a dominant baseline of 180 km. The Collaboration has delivered the latest results for an exposure of 766 t yr (previous was 162 t yr) in 2004 [3]. It is easy to see that a disappearance experiment such as KamLAND is, for mixing angles around 45°, not very sensitive to the mixing, but very sensitive to the oscillation frequency. The results, consistent with the LMA solution, strongly improve the resolution on $|\delta m^2|$ and further improvement is expected in the next years.

The fact that solar neutrinos and reactor antineutrinos give the same solution is non-trivial, it provides evidence, even if not too accurate, of CPT invariance in the neutrino sector.

The best measurement of θ_{12} comes from SNO. It will be further improved in the third phase of the experiment that is ongoing now with neutron counters. The relevant measured quantity is the ratio of the charge current to neutral current fluxes, which is a direct measurement of $\sin^2\theta_{12}$ because $\Phi_{CC}/\Phi_{NC}=\cos^4\theta_{13}\sin^2\theta_{12}\approx\sin^2\theta_{12}$ with a very good approximation. The present value, obtained in the second phase of SNO with salt (published after the fit of [2a]), is $\Phi_{CC}/\Phi_{NC}=0.340\pm0.023(\mathrm{stat})^{+0.029}_{-0.031}(\mathrm{syst})$ [13].

The fit of J. Bahcall et al. [2b] includes amongst the free parameters also the neutrino fluxes due the main sources in the *pp* and *CNO* chains, normalised to the solar standard model (SSM) [4], $f_i=\Phi_i/\Phi_{SSM}$. The only constraint is the solar luminosity. Results are f_{pp}=1.01±0.02, $f_{7Be}=1.03\pm^{024}_{1.03}$, f_{8B}=0.87±0.04, $f_{CNO}=0.0\pm^{2.7}_{0.0}$. We see that the *pp* and ^{8}B fluxes are well determined, independently on the solar model; while ^{7}Be and the (small) CNO are poorly known. BOREXINO [5] at LNGS will soon accurately measure the ^{7}Be flux.

In conclusion we have now a single solution in the parameters space for the solar neutrinos oscillations. Nonetheless this solution is not robust against new physics, such as non-standard neutrino interactions. The reason for this is that the just mentioned value for the *pp* flux, which is 95% of the total, has never been directly measured, rather it comes from a fit assuming that the neutrino flux is that calculated from the photon one. This sounds as a very safe hypothesis, but, given the surprises that neutrinos have always given, this point should be experimentally checked. In other words, we must test the hypothesis of equality of neutrino and light solar luminosities. That needs a flavour-sensitive experiment measuring the electron-neutrino spectrum below ≈ 1 MeV with a few percent accuracy.

As already stated the matter conversion process (MSW) dominates only at energies higher than about 1 MeV; below this energy flavour conversion is due to oscillations. Fig. 3 shows the survival probability of electron neutrinos, which are generated in the centre of the Sun, as a function of their energy. Its limit values, at low and high energy are also shown. Again this theoretical expectation is sound, but it must tested experimentally.

Such experiments are extremely difficult challenges, but several projects exist, some in advanced R&D phase. LENS, in particular, is based on $\nu_e+{}^{115}\mathrm{In}\to e^-+{}^{115}\mathrm{Sn}^*$ with In doped liquid scintillator. The *e* form the inverse beta decay is detected, together with the delayed signal of the γ's from the ^{115}Sn* de-excitation. R&D has shown that the huge ^{115}In β decay background can be controlled. Another project is MOON, based on $\nu_e+{}^{100}\mathrm{Mo}\to e^-+{}^{100}\mathrm{Tc}$, using Mo foils between plastic scintillator sheets.

Low energy solar neutrino spectroscopy is important not only for neutrino physics but for the (astro)physics of the Sun too. This leads the field back to the main scope of the original science by Davis and Bhacall, namely to use neutrinos as messengers from the centre of the Sun.

Consider now the lower frequency oscillation, the "atmospheric" phenomenon. The two main parameters are the larger squared-mass difference $|\Delta m^2|$ and θ_{23}. Also now there is a small dependence on θ_{13}. If this angle would be large enough appearance of electron neutrinos should be observed. Forgetting this last, the results of the fits are reported in the $|\Delta m^2|$ vs. $\sin^2\theta_{23}$ or $|\Delta m^2|$ vs. $\tan^2\theta_{23}$ plane.

The observation here is the disappearance of ν_μ's on distances comparable with the Earth radius. The data set is dominated by the SuperKamiokande experiment. Atmospheric neutrinos have been a powerful tool for searching the oscillation phenomenon due to the wide range of lengths, between ≈ 10 km and ≈ 13000 km – 3 orders of magnitudes – and energies, between 0.1 and 10000 GeV – 5 orders of magnitudes. The final results from phase 1 of the experiment are reported in ref. [6]. Two other experiments, MACRO at LNGS and Soudan2 at Soudan have also measured anomalies in the atmospheric neutrino flux, confirming the SuperKAMIKANDE conclusions.

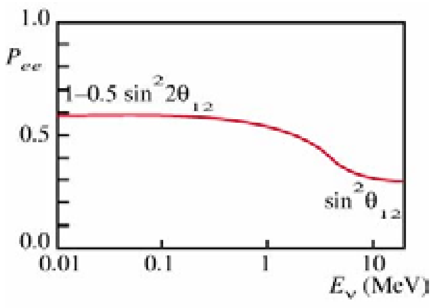

Figure 3. Electron neutrino survival probability in the Sun as a function of their energy

The modelling of the source has been improved in the last years, including three-dimensional modelling of the fluxes and improved cross-section values. Consider for example the results of Gonzalez-Garcia and Maltoni [2c]. Comparing the old and the new fits for the three SuperK samples of Sub-GeV, multi-GeV and up-going μ, the best values of $|\Delta m^2|$ decrease by 200 meV^2, 800 meV^2 and 500 meV^2 respectively. The example shows that the results are dominated by systematic uncertainties. As the authors observe, the main ones are the flux energy-independent normalisation and the uncertainty in its energy dependence, heuristically parameterised as $E^{-\gamma}$.

The effects of the uncertainties in the incoming cosmic rays flux can be reduced considering that, in first approximation, down-going and up-going fluxes are equal at a given zenith angle. The idea, originally put forward in the MONLITH proposal at Gran Sasso [7], is to use a magnetised Fe calorimeter with tracking and timing elements to measure the muon direction and whether it is up- or down- moving. The muon direction is very close to that of the ν_μ that produced that muon (and was, in turn, produced in the atmosphere) and gives the neutrino flight length *L*. The measurement of the muon momentum gives, approximately the neutrino energy *E*. In this way the oscillation variable *L*/*E* is determined for each event. The situation is shown in Fig. 4. The source of the down-coming neutrinos is near to the detector, hence their flux is the original, non-oscillated, one. The source of the up-coming neutrinos is far, depending on the angle, up to an Earth diameter. The ratio of the *L*/*E* distributions for the up-going muons and of the down-going ones provides the oscillation pattern, almost independently of the above-mentioned uncertainties.

It is here worthwhile recalling that this year is the 40th anniversary of the discovery of atmospheric neutrinos. This discovery came from two experiments, both deep underground in two mines: in India at Kolar Gold Field [8] and in South Africa at the East Rand Mine [9]. This old tradition is coming back with the proposal to build an underground observatory in India, the Indian Neutrino Observatory (INO). The first experiment to be built in INO may well be a massive MONOLITH-type detector. All of this will be described by D. Indumathi [10] in the next talk.

The U_{e3} matrix element is particularly interesting; for Dirac neutrinos it is real and $U_{e3}=\sin\theta_{13}\approx\theta_{13}$, being θ_{13} small. Both muon neutrinos disappearance experiments, as those on atmospheric neutrinos and solar neutrino experiments have, even if small, sensitivity to θ_{13}, but the most sensitive experiment is CHOOZ [11], a disappearance experiment on $\bar{\nu}_e$ from (two) reactors (≈1 km baseline), which provides two limits, one close to 0˚, one, symmetrically, close to 90˚; solar data chose the first solution. With this choice, the limit at 95% confidence level using CHOOZ and atmospheric+K2K [12] data is $\theta_{13}^2<4\times10^{-3}$, using solar+KamLAND data is $\theta_{13}^2<5\times10^{-3}$ (notice that it is not very different). All together give $\theta_{13}^2<3.2\times10^{-3}$.

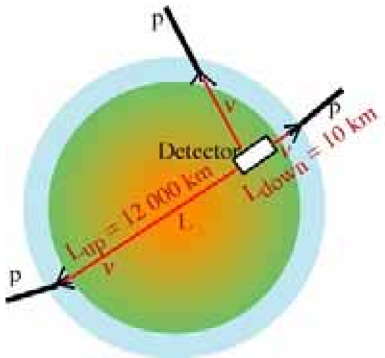

Figure 4. Principle of the MONOLITH proposal

3. Appearance and Disappearance Experiments. The Next Phase

The first generation of solar neutrino experiments and those on atmospheric neutrinos are disappearance experiments, in which one observes that the initial flavour gradually disappears as a function of the distance to energy ratio. Clearly, to completely establish the nature of the phenomenon one needs to observe the appearance of one or two new flavours.

This has been achieved, for the "solar" oscillation by the Sudbury Neutrino Observatory (SNO) [13].

The ν_μ's and ν_τ's produced by matter effects in the Sun (< 15 MeV) have too low energies to produce μ's or τ's via "charged current" (CC) interactions with matter; they can be detected only via NC interactions. Being these cross-sections flavour independent, the rate of observed NC events gives the total neutrino flux, summed on the three flavours.

The SNO experiment detects NC interactions in liquid D_2O, via the process $\nu_x + d \to p + n + \nu_x$ followed by neutron capture. The experiment has completed in October 2004 its "salt phase", in which NaCl was added to the D_2O liquid to increase the NC detection efficiency (via neutron capture). The third and final phase, with salt removed and neutron counters inserted for further increase in NC rate, started in Summer 2004 and will be completed at the end of 2006.

Two other processes are detected. One is the CC process, due to electron neutrinos only $\nu_e + d \to p + p + e^-$, the other is the elastic scattering (ES) $\nu_x + d \to \nu_x + d$.

Both CC and, with a lesser weight, NC contribute to ES or, in other terms, both ν_e's and, with a smaller cross section (≈1/6), ν_μ's and ν_τ's.

The measured fluxes in $10^{10}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$ are

$$\phi_{CC} = 1.68 \pm 0.06(\mathrm{stat})\ {}^{+0.08}_{-0.09}(\mathrm{syst})$$
$$\phi_{NC} = 4.94 \pm 0.21(\mathrm{stat})\ {}^{+0.38}_{-0.34}(\mathrm{syst})$$
$$\phi_{ES} = 2.35 \pm 0.22(\mathrm{stat})\ {}^{+0.15}_{-0.15}(\mathrm{syst})$$

Comparison with the solar standard model [14] shows that, while the CC flux is strongly reduced, the NC one has exactly the expected value, showing that indeed electron neutrinos have not been lost, but have been "converted" into muon and tau neutrinos. The experiment cannot tell which is the fraction of ν_μ's and ν_τ's, but from the "atmospheric" mixing we can infer that ν_e oscillate into about $(\nu_\mu+\nu_\tau)/\sqrt{2}$ (exactly , if $\theta_{23}=45°$).

The long base-line accelerator experiments will strongly contribute to reduce the present uncertainty on $|\Delta m^2|$. K2K [12], on a 250 km long baseline, (completed in November 2004) gave the first important contributions, even if with low luminosity. Improvement is expected from the soon-to-come NUMI+MINOS [15] at Fermi Lab and CNGS+OPERA [16] at CERN+LNGS, in the US and in Europe respectively, but with almost exactly the same base-line, about 730 km. The two programmes are complementary.

MINOS is a disappearance experiment. It is located in the Soudan underground laboratory (joined with a small "near detector" at Fermilab) and illuminated by a neutrino beam produced at the main injector as (mainly) ν_μ and is presently taking data. The beam energy spectrum peaks at a few GeV, optimised for disappearance to the best resolution on $|\Delta m^2|$. It aims at a 10% measurement (i.e. about the present overall uncertainty but in a single experiment). MINOS has also a moderate sensitivity to electron neutrino appearance.

The CNGS programme with the ν_μ source at CERN and the OPERA detector at LNGS [16] is optimised for ν_τ appearance. Neutrino energy spectrum peaks at 15-20 GeV, well above τ production by the "appeared" ν_τ 's. OPERA, a 1800 t high granularity detector, will detect the τ leptons (which decay within a few millimetres) with high spatial resolution emulsion techniques. A few events per year are expected, depending on the precise value of $|\Delta m^2|$. OPERA has also a moderate sensitivity to electron neutrino appearance. The program starts in summer 2006.

The measurement of the small mixing angle and of the corresponding mixing matrix element $U_{e3}=\sin\theta_{13}\approx\theta_{13}$ is extremely important not only *per se* but also because if determines (together with known factors) the size of *CP* violation in the lepton sector. I'll briefly summarise the prospects of the experiments approved or planned for the next ten years or so. For a more complete discussion see reference [17].

There are two classical complementary ways to measure this parameter: disappearance of electron antineutrinos as in the case of CHOOZ, by means of nuclear power reactor(s) as the source; 2. appearance of electron neutrinos in a muon neutrino beam; this is a minority oscillation in a process dominated by that into tau neutrinos. The oscillation probabilities are sums of several terms that can be written as a series in α (=0.03). At 0^{th} order in α the (already mentioned) amplitudes in the two cases are

$$A\left(\nu_e \to \nu_x\right) = \sin^2\left(2\theta_{13}\right) \approx 4\theta_{13}^2 \quad \text{and} \quad A\left(\nu_\mu \to \nu_e\right) = \sin^2\left(\theta_{23}\right)\sin^2\left(2\theta_{13}\right) \approx 2\theta_{13}^2$$

where, in the approximate expressions, we took into account that θ_{13} is small and that $\theta_{23}\approx\pi/4$.

The fact that the first is twice the second has a clear physical reason: in case of disappearance ν_e go to undetected ν_μ and ν_τ, half and half (because $\theta_{23}\approx\pi/4$). In case of appearance, we start with ν_μ only and hence loose a factor 2.

Notice that in the literature oscillation amplitudes are still denoted as $\sin^2(2\theta_{23})$ or even $\sin^2(2\theta_{e\mu})$ which are misleading (first case) or wrong (second case).

A third very interesting possibility has been proposed by J. Bernabeu et al. [18], namely a monochromatic pure electron neutrino beam produced by electron capture in metastable nuclides in an accumulator. The feasibility of the idea is being further studied and might require a not-too-expensive accelerator structure. A detector mass of hundreds kilotons will be needed, but it does not need to be deep underground.

The ongoing Numi+MINOS and CNGS programs will improve, in case of negative result, the limit on θ_{13}^2 by a factor ≈ 2.

Muon neutrinos produced at an accelerator come mainly from π, a two-body decay. As a consequence they are monochromatic in the π centre of mass frame. In the laboratory, the beam is almost monochromatic off-axis at small angles, typically several millirad. An advantage of the off-axis configuration is the (quasi-) absence of a high-energy tail in the beam spectrum, a feature that reduces the π° background in electron neutrino appearance experiments

An off-axis neutrino programme, T2K (Tokai to Kamioka) [19], has been approved in Japan in December 2003. The beam will be produced at the 50 GeV proton synchrotron being built at J-PARC. The far detector, which must be massive, will be in a first stage the existing SuperKamiokande at 295 km distance. A high intensity neutrino beam will be built with a design proton beam intensity on target of 0.75 MW (two orders of magnitude above K2K). The possibility of a higher intensity since the first phase is being studied. Expected to run in 2009, in 5 years will improve the present limit on θ_{13}^2 by about one order of magnitude. In a second phase beam intensity should be further increased (to 4 MW) and a new general purpose 1 Mt water Cherenkov detector, HyperKamiokande, may be built.

A second programme is being developed at Fermilab, based on the existing neutrino beam, with possible improvements and a far (≈ 800 km) detector. The sensitivity in θ_{13} is similar to T2K, but, due to the longer underground flight, the experiment may be more sensitive to the sign of Δm^2.
In the disappearance experiments at a reactor the antineutrino energies are in the range E_ν=0-9 MeV and the oscillation maximum is at $L \approx 2$ km. Improvement over CHOOZ requires not only an increased statistics but also a drastic reduction of the systematic uncertainties. This, in turn, implies a much better knowledge of the initial flux: two detectors, one far and one near are needed. These must be as similar as possible, including their surroundings (which produce backgrounds).
Several proposals have been produced world-wide and a "white paper" [20] published.
The most advanced proposal is D-CHOOZ. An advantage of the project is that the far detector will be located in the existing underground (≈ 100 m) hall in which was CHOOZ, (at L≈1.05 km, not quite the right one). The near detector is on surface (a dangerous asymmetry in my view). With two reactors and total power ≈8.5 GW, the experiment should improve the limit on θ_{13}^2 by a factor ≈ 5, dominated by the systematics.
We must not forget that we may be lucky and that θ_{13}^2 may be close to the present limit. In this case the next generation of experiments will detect it and may already provide some information on *CP* violating phase. For this, both disappearance and appearance experiments will be needed to solve a degeneracy that is present between θ_{13}^2 and of the *CP*-violating phase δ.

4. Neutrino Mass-Scale from Cosmology and from Laboratory Experiments

One physical quantity, or more for redundancy, independent on oscillations must be measured to know the neutrino mass spectrum. Cosmology gives information on the sum of the three neutrino masses, experiments on tritium decay and on double-beta decay are sensitive to weighted sums of the three masses.
Cosmology has made tremendous progress in the last several years both in the modelling and in the quantity and, more important, the quality of the observational data. The basic parameters of the model have been consistently determined with good accuracy. But still, the present "standard model" is purely phenomenological and, in particular, the set of basic parameters is not uniquely defined.
With this caveat, cosmology provides a potentially very sensitive, albeit indirect, means of measuring or limiting the absolute neutrino mass. The relevant property of neutrinos is that, given the smallness of their mass, they are not confined in the large-scale structures of the Universe. Moving from lower to higher density regions, they tend to erase the structures at scales smaller than a certain value D_F. This value is, in first approximation, inversely proportional to the neutrino (average) mass, m_ν

$$D_F\ (\mathrm{Mpc}) \approx 1/m_\nu\ (\mathrm{eV})$$

For example if $m_\nu = 0.1$ eV, the free streaming scale is $D_F \approx 10$ Mpc.
We define Ω_m and Ω_ν as the matter and neutrino densities relative to the critical one respectively. Cosmology provides a limit on (or a value of) the fraction of matter density due to neutrinos $f_\nu=\Omega_\nu/\Omega_m$. Knowing Ω_m (it is known within ≈15%, a rather large uncertainty compared to those of other cosmic parameters) we have Ω_ν, which, in turn, gives the sum of the neutrino masses through the relation $\sum m_i$ (eV) $= 94h^2\Omega_\nu$, where $h^2 \approx 0.5$ is the reduced Hubble constant squared.
The relevant quantity to determine is the large-scale structures power spectrum $P(k)$, which is the Fourier transform of the correlation function between two "point" masses, the galaxies at such huge scales (the probability to find two such objects at a distance d, over that for a random distribution). k, improperly called "wave number", is the variable conjugate of d. The function is schematically shown in Fig. 5. $P(k)$ can be determined with different kinds of observations. Presently, three are the most important sources of data:

1. the CMB anisotropies [21] that correspond to early epochs and extremely large scales (Gpc to ≈30 Mpc); at these scales the spectrum is almost insensitive to neutrino mass. Nonetheless, the experiments that measured with high systematic accuracy and high angular resolution the CMB

anisotropies, the balloon-born BOOMERANG, MAXIMA and ARCHEOPS, the ground-based DASI and later and more precisely the satellite experiment WMAP, have been extremely important to determine the set of cosmological parameters;

2. The large-scale structures (LSS) galaxies spectrum (at later epochs) at intermediate scales (100 Mpc to several Mpc; the 2dFGRS [22] and SDSS [23] surveys), are rather sensitive to sub-electronvolt neutrino masses;
3. The Lyman alfa forest [24] data at still lower scales (< 10 Mpc) and, for this reason, very sensitive, in principle, to neutrino mass.

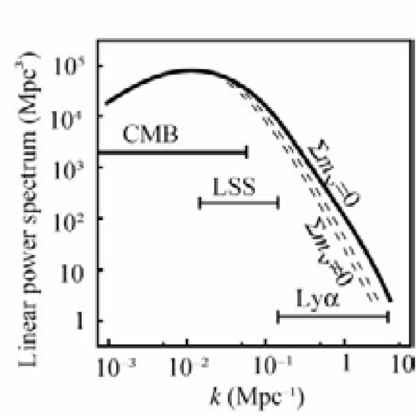

Figure 5. Sketch of the mass power spectrum. Dotted lines show schematically the effect of increasing neutrino masses

Present data do not give evidence for non-zero neutrino masses, providing upper limits that are very low, indeed the best we have. One must be careful, because the limit depends on several assumptions. The Galaxy surveys measure three coordinates for each galaxy: two angles and the red-shift. The determination of the distance from the red-shift is affected by uncertainties due, for example, to the peculiar velocities. Moreover, the measured structures are those of visible matter, which is only a small fraction of the total. To infer the total mass spectrum from the measured visible mass spectrum, their ratio (called "galaxy bias") is determined at a certain scale; then the dependence of the bias on k must be assumed, a rather model dependent assumption.

Moreover, the choice of the set of basic parameters is somewhat arbitrary. Degeneracies are present between some parameters, making the results dependent on the assumed priors.

A further issue is the decision on the inclusion or not of the Ly-α data. The absorption of the Ly-α lines due to large-scale structures between us and a farther source (a quasar) is used to evaluate those structures, which are typically at the scales were the effect of neutrino mass is largest. Unfortunately, the extraction of the correlation function from the data is not completely straightforward and possibly affected by large systematic uncertainties.

Typical analyses including CMB and LSS, but not Lyman alfa, give $\sum m_i$ (eV) <2100 meV [25]. From oscillations we know that at the limit the three masses are almost equal. Hence m_i<700 meV. More recent analysis, including new results from SDSS and Ly-α forest give m_i<130 meV [26] and m_i<157 meV [27]. The situation is sketched in Fig. 6.

In consideration of the constant and rapid progress of cosmology both in modelling and in the richness and systematic and statistic accuracy of the data, we can expect further improvements soon. In particular, progress in weak gravitational lensing, may lead to mapping of total, not only luminous, matter. Cosmology might well be close to detecting neutrino mass.

The classic measurement of the electron neutrino "mass" is based on the search of a distortion very near to the end-point of the electron spectrum from the tritium beta decay $^3H \to ^3He + e^- + \bar{\nu}_e$.

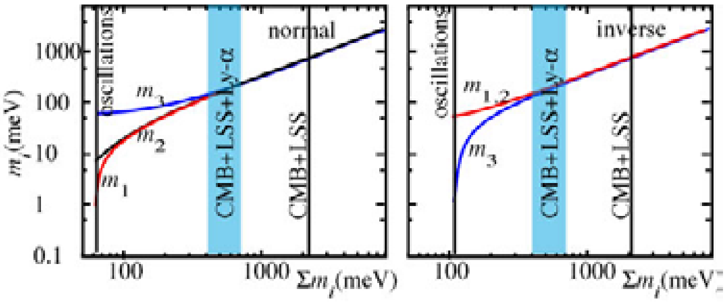

Figure 6. Neutrino masses vs. sum, for normal (left panel) and inverted hierarchy (right panel)

As already recalled neutrino states of definite flavour are not mass-eignestates and terms as electron-neutrino mass are improper. What is measured, or limited, by the experiment is the quantity

$$m_{\nu_e}^2 = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2 \approx c_{12}^2 m_1^2 + s_{12}^2 m_2^2 .$$

where the last approximation is valid for $s_{13} \approx 0$. Present limit is $m_{\nu e} < 2.2$ eV from the Mainz [28] and the Troitz [29] experiments.

In the future the two groups, joining forces, will build a new big spectrometer, KATRIN [30], aiming to reach $m_{\nu e} \approx 200$ meV. Even if this value is at the sensitivity cosmology has already now, it will come directly from a laboratory experiment and, as such, will be extremely important. Notice also that it will be sensitive to the signal level claimed by Klapdor et al. in 0ν2β [31] (see later).

5. The Neutrino-Antineutrino Relation

We know that quarks and charged leptons are Dirac particles, different from their antiparticles. We do not know if the same is true for neutrinos or not. The charge conjugate of the neutrino might be the neutrino itself (Majorana neutrino). In this case a very rare phenomenon, the neutrino-less double-beta decay, 0ν2β, may happen, violating the lepton number by two units. The process is so rare that experiments not only require deep underground laboratories but extreme care in reducing the backgrounds due to radiocontaminats. Background is everywhere, in particular in the detector materials and in its surroundings. The struggle for lower mass sensitivity is the struggle against the background.

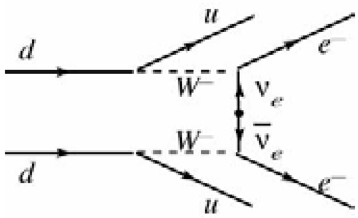

Figure 7. Feynman graph for 0ν2β

The double beta active nuclides are stable against normal beta decay (even-even nuclei) but have the two-neutrino double beta decay (2ν2β) channel open: $Z \to (Z+2) + 2e^- + 2\bar{\nu}_e$. This last is a very rare, but standard, second order weak process and happens if the ground level of the Z isotope is lower than that of Z+1 but higher than that of Z+2.

For massive Majorana neutrinos the process $Z \to (Z+2)+2e^-$, the $0\nu2\beta$ decay, can take place with violation of the lepton number. The observation of this process would prove the Majorana nature of neutrinos. The relevant diagram is shown in Fig. 7.

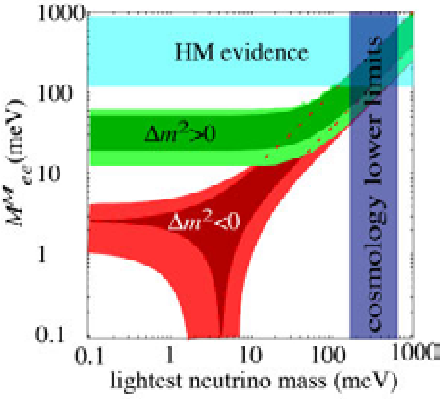

Figure 8. Majorana effective mass vs. the lightest neutrino mass for normal and inverted hierarchies.

The transition amplitude, the inverse of the lifetime, is proportional to the square of the matrix element represented by the graph shown in Fig. 7. The relevant factor is the so-called "Majorana mass" M_{ee} to which the transition amplitude is proportional

$$|M_{ee}| = \left|\sum_i U_{ei}^2\right| = \left||U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\phi_2} + |U_{e3}|^2 m_3 e^{i\phi_3}\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

This expression is similar to that of the "electron neutrino mass" but the addenda are not real (and even if they are they are not positive definite) and may cancel each other in the sum.
Fig. 8 shows the expected value of $|M_{ee}|$ as a function of the lightest neutrino mass, for normal and inverse hierarchies. It is calculated [32] taking into account the oscillation data. The darker bands correspond to the (complete) uncertainty on the Majorana phases, lighter colour bands include uncertainty on the other mixing parameters. The cosmological limit is shown as a dark vertical band; the horizontal band labelled HM evidence is the one reported by Klapdor et al. [31] to be discussed later.
Notice that for M_{ee} = 50 meV, for example, lifetimes are of the order of 10^{26}-10^{27} years, indeed very long. If the spectrum is "degenerate", neutrinos having all almost the same (average) mass m, a lower limit exists, namely (taking U_{e3}=0) $|M_{ee}| \geq m\left||U_{e1}|^2 - |U_{e2}|^2\right| = m\cos 2\theta_{12} \approx 0.4m$. If the spectrum is inverse, the lower limit is $|M_{ee}| \geq \Delta m\left||U_{e1}|^2 - |U_{e2}|^2\right| = \Delta m \cos\theta_{12} \geq 0.4\sqrt{\Delta m^2} \approx 20$ meV. On the contrary, no lower limit exists for the "normal" spectrum. The experimental programme for the future must include the control of the positive HM evidence shown in Fig. 8. If this is not found the sensitivity must be pushed to values as low as possible; sensitivity of a few tens of meV appears to be reachable within several years of efforts.
In nature the quarks represented in Fig. 7 decay within a nucleus implying that the nuclear structures and nuclear matrix elements must be taken into account. The decay probability is given by

$$\Gamma = \frac{1}{\tau} = G(Z,Q)|M_{nucl}|^2 |M_{ee}|^2$$

where $G(Z,Q)$ is a phase space factor, a function of the nuclear charge Z and of the reaction Q-value (increasing roughly as Q^5) easy to compute and M_{nucl} is the above mentioned nuclear matrix element. The last are very difficult to calculate and are presently uncertain within factors 3-10. Theoretical tools exist today to substantially reduce these uncertainties and more theoretical effort, joined to experiments aimed to measure critical quantities, is needed.

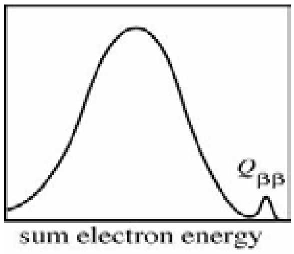

Figure 9. Sum energy spectrum, schematically, for 2ν2β and 0ν2β decays

There are two basic kinds of experiments [33]. The first is calorimetric; the source and the detector coincide and one measures the total energy released in the decay by the two electrons. Ideally, a spectrum as shown in Fig. 9 is expected: continuous for the 2ν2β decay, where some energy is taken by neutrinos, a single line (height exaggerated in the figure) at the transition energy ($Q_{\beta\beta}$) for 0ν2β, where all the energy goes to the electrons (these quantities are very well known and typically $Q_{\beta\beta}$ = 1-2 MeV). In practice the spectrum is superimposed on the background. To fully exploit the advantage given by the mono-chromaticity of the signal, detectors must attain very good energy resolution (a few keV), which must be coupled to extremely low background conditions. In the second type of experiments the source is a sheet of the active metal, thin enough to allow the electrons to exit and be detected in the surrounding tracking chambers. The charges of the electrons are measured in a magnetic field and their energies in calorimeters. The pros are the very clear signature and the possibility to use several different isotopes, the cons are the relative smallness of the source mass and, the main problem, the modest energy resolution and the consequent difficulty to discriminate the ultimate background, the tail of 2ν2β.

For a general discussion of the experimental sensitivity it is useful to define a figure of merit on the lifetime F_τ, which, in presence of background, depends on the exposure (sensitive mass M times live time T), the background rate b (per unit mass, unit time and unit energy window) and the energy resolution ΔE: $F_\tau = \sqrt{(MT)/(b\Delta E)}$. The sensitivity F_{Mee} for $1/M_{ee}$ is, obviously, proportional to the square root of this, namely $F_{Mee} = \sqrt[4]{(MT)/(b\Delta E)}$. The dependence on the 1/4 power is of course dramatic: to gain an order of magnitude in M_{ee} one needs, for example, to increase detector mass by two orders of magnitude and reduce background by two orders of magnitude too.

The "solution" is to work at zero background, in the exposure time and in an energy window of a few ΔE around the energy of the transition ($Q_{\beta\beta}$), which is known, for each isotope, with sub-keV accuracy; the sensitivity is then $F_{Mee} = \sqrt[2]{MT}$, varying as the second root of the exposure. In conclusion, energy resolution in the range of several keV and an extreme control of the background are mandatory.

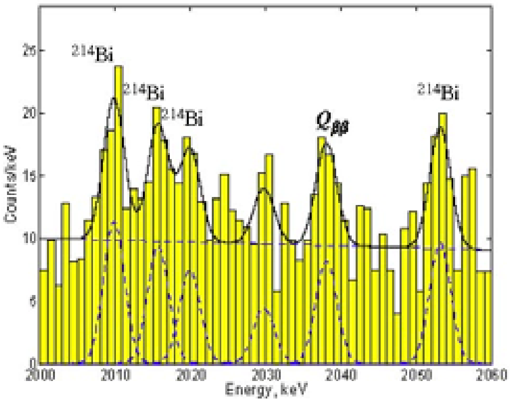

Figure 10. Sum energy spectrum from ref [31]. The labels identified the peaks as interpreted in ref [31]

The most sensitive experiment is Heidelberg-Moscow, now concluded, which ran at LNGS for 13 years, integrating an exposure of 71.7 kg yr. In 2002 [31], part of the collaboration reported positive evidence of the signal with a claimed 4σ significance at the expected position Q_{β}= 2038.99±0.75 keV. The background index is b=0.2/(kg keV yr) before pulse shape analysis, 0.06 after, the energy resolution is 3.27 keV F.W.H.M. Fig. 10 shows the spectrum. The signal is 28.8±6.9 events over a background of approximately 60 events, corresponding to a half-life $T_{1/2}$=(0.3–2)×10^{25} yr. This corresponds to $|M_{ee}|$=(100-900) meV, where the uncertainty is that of the matrix element. Notice that the very good knowledge of $Q_{\beta\beta}$ and the superior energy resolution imply that the relevant backgrounds are only those in a narrow (say 60 keV) window around $Q_{\beta\beta}$.
The background model obtained via Monte Carlo simulations contains a flat component and four lines of ^{214}Bi. It fits the data reasonably well, but the positions of the Bi lines are off by a couple of standard deviations each.

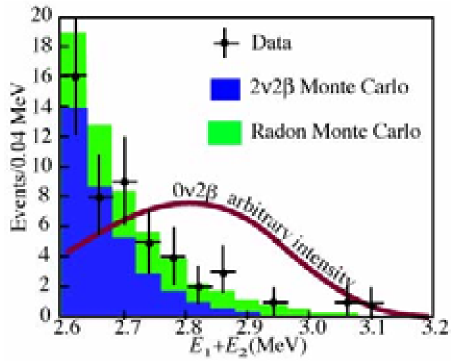

Figure 11. ^{100}Mo spectrum from NEMO3 in the region of 0ν2β

The experiment with closest sensitivity, IGEX [34], again with enriched Ge, gives only the upper limit, $|M_{ee}|$= ≤(330-1300) meV. All the other experiments are even less sensitive.
The claim corresponds to a degenerate neutrino spectrum. The three, almost equal, neutrino masses are close to the cosmological limit (or even larger than the lowest of these).
Two are the presently running experiments: NEMO3 at the Frejus Laboratory (LSM) and CUORICINO at Gran Sasso (LNGS); two other, both at LNGS, have been approved, CUORE and GERDA, while the US proposal MAJORANA is in R&D phase.
NEMO3 [35] is a large apparatus in the Frejus Underground Laboratory, taking data since February 2004. The isotopes (^{100}Mo 6.9 kg,^{82}Se 0.9 kg and several grams of ^{116}Cd, ^{96}Zr, ^{150}Nd and ^{48}Ca) under study are shaped in thin layers located inside drift chambers operated in Geiger mode as tracking devices in a 2.5 mT magnetic field; energies are measured by plastic scintillators with a typical energy resolution of 14-17 % at 1 MeV. Beautiful results for 2ν2β decays on sum energy spectra and on angular correlations between the two electrons have been obtained.
Fig.11 shows the sum energy spectrum of ^{100}Mo in the region of 0ν2β . Histograms are the expected contributions of ^{222}Rn background and of the tail of the 2ν2β decays (the other backgrounds are much smaller and not shown for simplicity). The gaussian curve gives the shape of the 0ν2β signal. The present limit is M_{ee}< 700-1200 meV (depending on nuclear matrix elements).
More recently a tight enclosure has been installed to flux Rn pure air, reducing the Rn background by an order of magnitude. The graph shows that, given the poor energy resolution, the dominant background will then be the irreducible tail of the 2ν2β spectrum. Clearly, to reach the M_{ee} level of the tens of meV one needs FWHM energy resolution of the order of 10 keV or better.

CUORICINO [36], the first step toward the large experiment CUORE [36], is running at the Gran Sasso National Laboratory of INFN since February 2003. The building blocks are natural TeO_2 crystals assembled to build the 0.8 m tall "tower" shown in Fig. 12a. The crystals are both source and detector. Notice that the high natural abundance of the double-beta active ^{134}Te, 34%, makes enrichment unnecessary. The detectors are kept at a few mK temperature inside a dilution refrigerator and used as calorimeters, reading out the small temperature increase due to the electrons energy deposit.

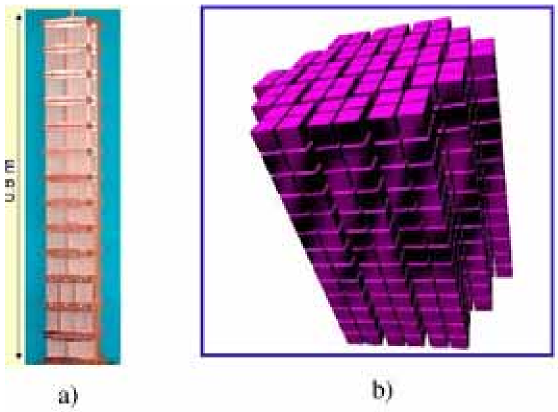

Figure 12. a) The tower of CUORICINO detectors; b) the tower structure of CUORE

The present exposure of 5.3 kg y with energy resolution (FWHM) ΔE=7.5 keV and with a background index b=0.18±0.02/(kg keV yr) has given an upper limit M_{ee}<100-600 meV. The experiment will still gain a factor two in sensitivity in the next 2-3 years, before the installation of CUORE, and has a good chance to have positive evidence, in case HM is right. On the other hand, given the uncertainty of the matrix elements, it cannot disprove HM in case of negative result.

As anticipated, the next step will be CUORE, already approved by INFN and by LNGS. It will consist of 988 detectors arranged in CUORICINO-like towers, as shown in Fig. 12b, with a total mass of 741 kg, corresponding to an active ^{130}Te mass of 203 kg. The experience with CUORICINO has shown that surface contamination is the principal source of background; passive and active techniques are being developed to substantially reduce these backgrounds. Notice that in any case, the inner towers will be actively screened by the outer ones. The aim is to reduce the background index to $b=10^{-3}$/(kg keV yr). If this is achieved and with ΔE=5 keV, the experiment can reach M_{ee}<11-62 meV in 10 years. If, more conservatively, $b=10^{-2}$/(kg keV yr). and ΔE=10 keV, the limit in 10 years will be M_{ee}<24-133 meV.

The GERDA [37] experiment being developed at LNGS aims to reach the "zero-background" conditions, in the above specified sense. The experience of Heidelberg-Moscow experiment has shown that Ge is one of the radio-cleanest materials and that residual backgrounds are largely located outside the detectors. It looks possible to aim at a background index $b=10^{-3}$/(kg keV yr) that would lead to a zero background exposure of a few 100 kg yr.

Heuser [38] in 1995 and Klapdor- Kleingrothaus et al. [39] in 1997 (GENIUS proposal at LNGS) have proposed to operate naked Ge crystals in liquid N2, taking advantage of the techniques developed by BOREXINO to produce extreme radiopurity (10^{-16} g/g) liquid nitrogen. The GENIUS-TF [40] prototype at LNGS has shown that the concept is viable. See also the GEM proposal [41] in 2001 along similar concepts.

GERDA has further developed the idea designing a graded structure with a number of screening materials. The experiment foresees three phases. In the first the existing enriched Ge crystals of HM and IGEX, 17 kg, will be used at design background indices of $b=10^{-3}$/(kg keV yr) externally, and $b=10^{-2}$/(kg keV yr) internally. If the claimed signal is true this phase will confirm it in one year, observing 6.0±1.4 events with a background of 0.5 events.

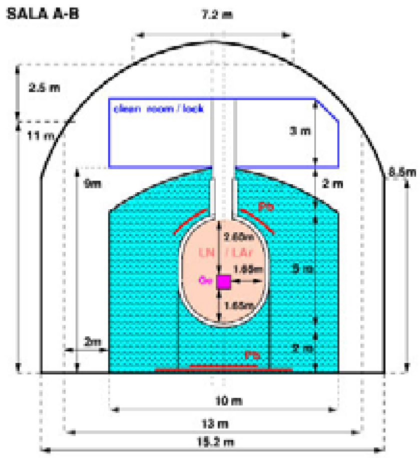

Figure 13. Schematic cross-section of the GERDA structures

The next phase aims to the sensitivity M_{ee}=(100–300) meV. This will need both external and internal background indices at the level of b=10^{-3}/(kg keV yr). New techniques for detectors production are being developed to reduce the cosmogenic sources (mainly ^{60}Co ad ^{68}Ge) in the detectors, minimising the production times on the surface. It already appears that for the next generation of detectors the critical phases of production shall be done underground, even if at shallow depth.

The main backgrounds are gammas depositing energy via Compton scatterings. Usually more than one scattering happens with energy deposits separated by typically a few centimetres. On the contrary, the two low energy electrons from the signal deposit all their energy in a single site. Single site and multiple site events can be distinguished with two complementary techniques: segmenting the crystal in several electrically separated cells and from the shape of the rising edge of the pulse. GERDA will employ pulse shape analysis from phase one and segmentation from phase two.

Fig. 13 shows schematically the GERDA structure inside a section of the LNGS hall. The Ge diodes will be kept naked in an extra-clean liquid N_2 bath contained in a high purity cupper cryostat, to be assembled outside the LNGS. The cryostat is in turn contained in an ultra-pure water bath in a stainless steel tank. LN_2 and H_2O together (and Pb screens where needed) will provide the necessary reduction by 8 orders of magnitude of the gamma ambient fluence. Clean room, electronics and counting room are shown above the tank.

MJORANA [42] is an US proposal for a 500 kg enriched ^{76}Ge detectors array to be located in a deep underground laboratory. Background suppression relies strongly on segmentation and pulse shape analysis, and, obviously, low background materials. The present design foresees 210 crystals with 12 (being optimised) segments each aiming to a sensitivity of M_{ee} = 20-70 meV.

To reach these levels of sensitivity will surely be a very engaging task. Taking into account the complementary approaches of GERDA and MAJORANA, the two collaboration are constantly co-ordinating their work. It is well possible that the two will merge at the several 100 kg mass scale.

Other experiments, such as EXO, MOON and SuperNEMO are presently in R&D phase. These proposals aim, in general, to a drastic background suppression measuring more than simply the total energy deposit at the price of worst energy resolution. These interesting developments must show how to cope with the irreducible $2\nu2\beta$ background.

6. Core Collapse Supernovae

The evolution of the iron-core isolated stars (Type II Supernovae) finishes with the collapse of the core. The released gravitational energy, $E_b \approx 3\times10^{46}$ J is emitted mostly in the form of neutrinos and antineutrinos of all the types. The burst duration is 20-50 s. The neutrino luminosity, until it lasts, is larger than the typical photon luminosity of a Galaxy. In 1987 a dozen of neutrinos from the collapse of a Supernova in the Large Magellanic Cloud was observed for the first time. The detection of Supernova neutrinos and the measurement of the shape and time evolution of their spectra provides important information on neutrino physics and on the implosion dynamics.

The burst can be observed, with sub-megaton mass detectors, only if the explosion is in the Galaxy or in the Magellanic Clouds. From observational data and SN morphology Cappellaro and Turatto [43] estimate 3-4 core collapse SNs per century. An independent estimate can be obtained from the fact that abut 7 SNs have been observed in our Galaxy in the last 1000 years and that all of them have been in about 20% of the Galaxy volume, on our side of the galactic centre. This suggests that many SNs are dark and that we can expect 2-4 explosions per century, consistently with the previous estimate.

Several detectors exist with sensitive masses in the kiloton range: LVD at LNGS, SuperKAMIOKANDE and SNO; Amanda at the South Pole and KamLAND and, in the next future BOREXINO, can contribute. They are sensitive mainly to electron anti-neutrinos, but have also moderate sensitivity to other flavours. For a collapse at 10 kpc (the distance in order of magnitude of the galactic centre) statistics will range from several hundreds to many thousands.

The neutrino burst leaves the star well before its photon luminosity has raised enough to be observed without warning, a warning that the neutrino pulse can provide, making possible the observation of the rising of the light curve. To this purpose (and others similar) LVD, SuperKAMIOKANDE and SNO have created a network, SNEW, the SuperNova Early Watch.

I'll not review the characteristics of the detectors here, rather I'll focus on neutrino physics that can be learned from SN neutrinos.

Two are the mechanisms that produce neutrinos in a Supernova: neutronisation and thermal emission. In the neutronisation process, electrons are captured by protons and nuclei; a ν_e flux results, dominant on the others in the first few milliseconds. Thermal emission follows, due to $e^+ e^-$ annihilation into neutrino-antineutrino pairs of all the flavours. Clearly for each flavour the neutrino and antineutrino fluxes are equal at production. Notice also that muon and tau neutrino fluxes are identical because both are due only to neutral currents. For the same reason ν_μ and ν_τ are in equilibrium into a smaller sphere than ν_e's, which have also charged current interactions. In this smaller neutrino-sphere the temperature is higher and, as a consequence, the spectrum of ν_μ and ν_τ (and of their antineutrinos) is harder (average energy approximately 20 MeV) than that of ν_e's (average energy approximately 12 MeV). There are large uncertainties in these estimates.

Neutrinos and antineutrinos produced by elementary particle processes in the inner part of the Supernova must cross the high density SN medium before leaving the star. The flavour conversion process is similar to that in the Sun and similar are neutrino energies, but there are important differences:

1. As already mentioned, neutrinos and antineutrinos of all flavours are produced, with different energy spectra. Let us focus on electron neutrinos and antineutrinos.
2. The density is much larger; as a consequence two level crossings, one higher (*HC*) at Δm^2 and one lower (*LC*) at δm^2 are present. Indeed in the core $2G_F N_e E >> \Delta m^2 >> \delta m^2$.
3. The adiabatic condition is guaranteed at the lower crossing for the same reason as in the Sun, because the relevant mixing angle is θ_{12}, which is large enough. On the contrary, at the higher crossing, the relevant mixing angle is θ_{13}, which is unknown. The *HC* is adiabatic if $\theta_{13}^2 \approx |U_{e3}|^2 >$ few times 10^{-4}. If not, ($\theta_{13}^2 <$ few times 10^{-4}) electron neutrinos do not "see" the crossing and continue to the *LR*, where the transition happens.

Skipping the details, the conclusions are the following. The neutrinos born as ν_e in the SN core leave its surface as eigenstates, as ν_3's if the hierarchy is normal (Δm^2>0) and θ_{13}^2 > few times 10^{-4} (*HC* adiabatic), as ν_2's in the other three cases (normal hierarchy with *HC* non adiabatic and inverse hierarchy anyway). Taking into account that the matter term for antineutrinos is opposite to that of neutrinos, antineutrinos born as $\bar{\nu}_e$ exit as $\bar{\nu}_3$ for inverse hierarchy with adiabatic *HC*, as $\bar{\nu}_1$ in the other cases.

These possibilities can be experimentally distinguished, at least in principle, detecting ν_e's and $\bar{\nu}_e$'s, because two conditions are satisfied: ν_1, ν_2 and ν_3 have different flavour compositions and neutrinos of different flavours have originally different energy spectra. In conclusion SN neutrinos inform us on the mass hierarchy of the neutrino spectrum (the sign of Δm^2) and the size of the mixing parameter $|U_{e3}|^2$. A caveat is that presently the Supernova models are still rather uncertain.

As we mentioned a Supernova explosion in our Galaxy is a rare phenomenon. On the human life scale, not on that of the Galaxy: neutrinos from the past explosions are still around us, the diffuse supernova neutrino background (DSNB) (not to be confused with the cosmological neutrino background). Theoretical calculations exist and give predictions on the expected neutrino fluxes with typical uncertainties of an order of magnitude. The best experimental limits are those of SuperKAMIOKANDE [44], which are already very close to the predictions. Two years ago a very interesting proposal, called GADZOOKS!, (exclamation mark included) to increase substantially the SuperKAMIOKANDE sensitivity at moderate cost has been advanced by J. Beacom and M. Vagins [45].

Electron antineutrinos are detected by SK through the inverse beta decay reaction $\bar{\nu}_e + p \rightarrow e^- + n$; the main idea is to suppress the background, which dominates the present sensitivity, by tagging the neutron with high efficiency. This can be done by adding to the water 0.2 % of Gd, whose *n* capture cross section is as large as 49 kbarn obtaining 90% tagging efficiency. In a few years exposure DSNB antineutrinos should stand well out of background between 10 and 20 MeV. The Gd doping would increase also the sensitivity to reactor antineutrinos and to those of a Supernova explosion. Preliminary tests to see if the Gd addition would make any damage to SK are going on the 1 kt water Cherenkov detector used, as a near detector, by the completed K2K experiment. It is a small-scale version of SuperKAMIOKANDE.

7. TeV-PeV neutrinos

Neutrinos with energies of the order of the TeV or larger are messengers of the most energetic phenomena in the Universe. Their detection will open a new window on the cosmos, but is extremely challenging. Unlike charged particles that are deflected by the galactic and intergalactic magnetic fields, neutrino direction points back to the source. At high enough energies neutrinos are the only particle with such characteristic. For photons the Universe becomes opaque at around 100 TeV and less due to the opening of the pair production process in collisions on infrared background and on cosmic microwave background. Also, as already said, neutrinos, unlike photons, probe the interior of the massive sources, known or to be discovered.

Two experiments, Lake Baikal and AMANDA, have already proven the feasibility of neutrino observatories in the liquid water and in the polar ice respectively. At their scales of several Mt sensitive mass they have observed atmospheric neutrinos only, but they prove that the larger scales necessary for neutrino astronomy are in reach. To be sure, we do not really know how large a neutrino observatory must be because these are, quoting L. Resvanis, "fishing expeditions for cosmic neutrinos and nobody really knows how big a net you need to catch them".

The high-energy neutrino observatories detect the muons produced in their mass or in the neighbourings by the searched muon neutrinos. They use a matrix of optical modules to observe the Cherenkov radiation of the muons. Clearly on the surface, the atmospheric muons give an enormous background, many orders of magnitude larger that the expected signal. As a consequence, the observatory must be thousands of meters deep in the water. Still this screen is not enough in the lower energy range; detectors use the Earth as a screen, looking to up-going (up to almost horizontal) muons, produced by neutrinos that have crossed the

Earth. The water depth is necessary to avoid the background of down-going muons faking up-going ones. The deeper is here the better. At energies above 100 TeV the Earth becomes opaque to neutrinos, but, provided the detector is deep enough, the atmospheric neutrino background on down-going muons becomes negligible.
The first gigaton scale detector will be ICECUBE [46] using the AMANDA techniques at the South Pole. Its construction already started to be completed in 2010.
A second detector appears to be necessary and sufficient. It should be located in the northern hemisphere, to observe, complementarily to ICECUBE, the southern sky. It should be located in the liquid water, which is complementary to the ice; in water the light scattering length is much longer resulting in better pointing accuracy. The sea, in particular the Mediterranean, offers another advantage, namely available depths up to 4000 km and even more.
The possibility to deploy, maintain and operate with high duty cycle a Gt scale detector in the sea has not yet been finally established. Three projects of smaller scales, NESTOR in Greece, ANTARES in France and NEMO in Italy are presently at various stages of development (NESTOR has already seen atmospheric muon tracks). KM3NeT, a common design study for a Cubic Kilometre in Mediterranean Sea has been approved and funded by the European Union in the 5th Framework Programme.

8. EeV-ZeV neutrinos

Still, even higher energy neutrinos may exist. Anything can happen in the Universe, even something exceeding the fertile fantasy of the theorists. Neutrinos in the 10^{17}-10^{19} eV (0.1 – 10 EeV) energy range (Berezinsky-Zatzepin [BZ] neutrinos [47]) are produced by accelerated high-energy protons colliding with the cosmic microwave background. This is a sound theoretical prediction. On the contrary, the acceleration of protons at still higher energies, larger than a ZeV or so, is a real challenge for astrophysics; no known acceleration mechanism works at these energies.
Non the less neutrinos in the ZeV energy region may well exist; a site for physics beyond our present knowledge, as the decay of topological cosmic defects, the super-heavy dark matter particles, the annihilation of monopoles in strings, the radiation of monopoles in networks, and several similar theoretical speculations.
The Pierre Auger Observatory [48], being constructed and soon completed in Argentina, will produce the first relevant data. Its principal scientific objective is the detection of extreme high energy cosmic rays through the observation of the extensive shower produced in the atmosphere. There are two complementary detectors: a counter array about 3000 km^2 in size and four sets of six telescopes each to observe (during the dark nights) the fluorescence induced by the charged shower particles in the atmosphere. Showers produced by extremely high energy neutrinos can be distinguished from the more frequent hadrons or gamma induced showers from the shorter time evolution of the signal. The effective target mass is that of the atmosphere and, for neutrinos, also that of the earth under the array.
Another project is the Telescope Array planning for a 760 km^2 area effective area hybrid observatory.
Still larger active volumes, up to one million km^3, may be reachable using the Askaryan (1962) effect: a coherent radio-emission by excess electrons in the shower.
A possible detector volume is the 1-3 km deep transparent (to radio-waves) Antarctic ice sheet; a balloon at about 37 km height will see an area of the order of 10^6 km^2. A number of balloon and satellite flights over the Antarctica already have been done (RICE, GLUE, FORTE, ANITA-lite) providing the first useful tests of the technique. ANITA [49] foresees in 2006 a 60 days long balloon flight with an effective target volume of 10^6 km^3 even if in a small (order of 10^{-2}) solid angle; it should observe 9-30 BZ neutrinos.
Other possible detector volumes are the salt-domes. These are geological structures, a few km in diameter and in height (a few 100 km^3 volume), made of pure salt and close to the surface. Being salt transparent to radio waves, the deploying of several vertical strings of antennas (at kilometre scale distance) will transform the dome in a detector. Salt is 2.4 as dense as water and much longer, than balloon borne, exposure times are

possible within a much larger solid angle. The SalSA [50] project, in its R&D phase, foresees a sensitivity of 70 – 230 BZ neutrinos in three years.

9. Geoneutrinos

In July 2005 KamLAND [51] published the first observation of electron antineutrinos produced by radioactive decays inside the Earth. The neutrino geology has started. Indeed neutrinos can give useful information on the energetic of our planet, on phenomena taking place deep underground.
The Erath produces heat, which flux at the surface is known to be between 30 and 40 TW (for comparison the total power of the operational power-stations is 3.5 TW). The mechanisms of heat generation are only partially known. The main contributions are from gravitational energy release due to the solid core separation from the liquid one, from tidal friction and from nuclear fission reactions, which produce electron antineutrinos.

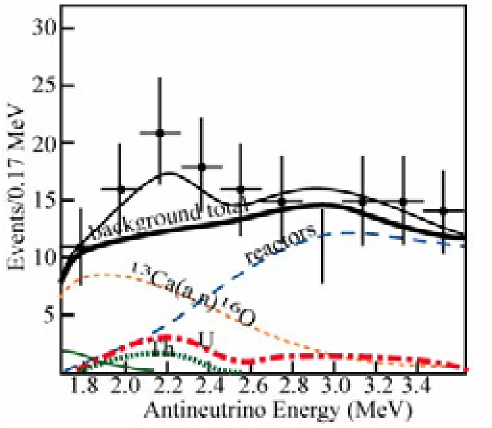

Figure 14. Electron antineutrino spectrum from KamLAND. Shown are the two principal backgrounds, the expected U and Th neutrino spectra and the total spectrum with these expectations

The antineutrino flux at the surface is expected to be of the order of 10^{10} s^{-1} m^{-2}, similar to the ^{8}B neutrino flux from the Sun. Electron antineutrinos are generated in the β^- decays of ^{40}K and in the U, [$^{238}U \rightarrow ^{206}Pb + 8\,^{4}He + 6e^- + 6\bar{\nu}_e + 51.7$ MeV] and Th [$^{232}Th \rightarrow ^{208}Pb + 6\,^{4}He + 4e^- + 4\bar{\nu}_e + 42.7$ MeV] series. Potassium $\bar{\nu}_e$'s have too low energies (maximum about 1.3 MeV) to be detectable; Th series $\bar{\nu}_e$'s energy spectrum ends at about 2.2 MeV, U series at 3.3 MeV, both well above the 1.8 MeV of the KamLAND threshold.
KamLAND detects the antineutrinos via the process $\bar{\nu}_e + p \rightarrow e^+ + n$ observing the prompt positron signal followed by the tag of the neutron capture after thermalisation. The data are the same as for the reactors antineutrinos, but with tighter selection criteria to cope with the larger backgrounds. The largest two are reactor neutrinos (80±7 events from the fit) the $^{13}Ca(\alpha,n)^{16}O$ (42±11 events), due to ^{13}**Ca**, which has a natural abundance of about 1%,
Fig. 14 shows the measured spectrum, together with the backgrounds and the expected (not the fitted) contributions of geological antineutrinos. Performing the fit, which takes into account not only the rate but the shape of the spectrum too, one finds 28^{+16}_{-15} events attributed to geological antineutrinos. It is the first glimpse in the interior of the Earth through neutrinos. The result, still not very precise, is consistent with both the “fully radiogenic” and the “Bulk Silicate Earth” models.

G. Fiorentini and collaborators [52] have noticed that new measurements of the α,*n* cross section have been recently published; using these values they calculate 40±5.8 events for ^{13}Ca(α,*n*)^{16}O, with half the previous uncertainty; the signal becomes 31^{+14}_{-13} , a 2.5 σ effect.

In the next future, the statistics of KamLAND will improve, while BOREXINO should give more background free results, being it very far from nuclear reactors.

10. Conclusions and Outlook

Neutrino physics made enormous progress in the last several years, showing for the first time physics beyond the Standard Theory. This is mainly due to experiments using natural neutrino sources in underground laboratories, complemented by experiments using artificial (hence controllable) sources and long base-lines.

We already know at a reasonable level the structure (a singlet and a doublet) of the mass spectrum and two mixing angles.

The smallness of neutrino masses is an indirect way to look at very high-energy scales, close to the unification, which no accelerator can reach.

Cosmology, beta decay and double beta decay experiments are complementary to fix the absolute value of the mass scale, which is still unknown.

For the future, the opportunities for basic research in astroparticle physics look exciting and challenging.

A standard cosmological model has emerged, with well established features, but it still purely phenomenological. We still do not have a theory of one of the basic forces of Nature, gravity, but only a macroscopic approximation for it.

A new generation of long base-line experiments on accelerator neutrino sources is just started and a higher intensity neutrino beam is already under construction in Japan. New ideas for even higher intensities are being studied worldwide and some of them might lead to a project of affordable costs.

The Standard Theory of subnuclear physics has resisted to the extremely accurate tests performed at the accelerators laboratories. But the Standard Theory

- Explains only a very small fraction of the components of the Universe
- CP violation looks too small for baryogenesis
- No dark matter particles exist
- Dark energy is not at the observed level
- Does not have non-zero neutrino masses and mixing

Neutrino physics with and without accelerators will give certainly important contributions to the understanding of some of these challenges.

For astrophysics, existing neutrino detectors are ready to contribute to low, high and very high neutrino astrophysics and, recently, geophysics. Detectors of new generation are under construction or development.

Much interesting work is in front of us for cosmology, astroparticle and particle physics

- To understand the nature (Majorana or Dirac) of neutrinos
- To determine the hierarchy of the spectrum (normal or inverse)
- Measure the absolute neutrino mass
- Study CP violation in the lepton sector
- And much more

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