INTRODUCTION TO NEUTRINO PHYSICS

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A short introduction to neutrino physics is given, stressing the important theoretical and experimental progresses achieved in the last years as well as the open questions for the future experiments.

1 Introduction

The aim of this short introduction to neutrino physics is to present the recent developments and to summarize the key issues in this field. This is by no means a complete review. Excellent reviews can be found in Ref. [1] [2] [3] [4] [5]. First we will introduce three arguments that illustrate the importance of neutrino in contemporary physics.

Neutrino physics is of special relevance in the context of our current effort to probe the physics beyond the Standard Model. What happens if we give up the criteria of renormalizability for new interaction terms? A very general, model independent study[6] has classified all possible Lagrangian terms invariant under the symmetry group of the Standard Model (SM). This has been done introducing a high energy scale Λ related to new physics:

$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 \\ \mathcal{L}_5 &= (LH)(LH), \end{aligned} \tag{1}$$

where L is a leptonic field and H is the Higgs field. It is remarkable that while there are several terms of order $(1/\Lambda)^2$, related to processes like proton decay, g-2, anomalous triple gauge coupling etc, there is only one term of order $(1/\Lambda)$. This lowest order lagrangian term reads $(1/\Lambda)(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$ which as we will see later is a Majorana mass term for neutrino.

This line of reasonings tells us that no symmetry of the Standard Model protects the neutrino from acquiring a Majorana mass.

A second argument is related to relic neutrinos, that is neutrinos that were in equilibrium in the primordial plasma before decoupling from it [7]. We have gathered many information about our universe from the study of the relic photons, the Cosmic Microwave Background. According to the current cosmological model, neutrinos are the most copious matter particles, with a number density of the order of $300/\mathrm{cm}^3$ (or 10^9 time more abundant than protons). Their total mass would then be comparable to the mass of all the stars. These neutrinos influenced the formation of structures in the early universe. Clearly we must understand neutrino physics in order to understand our universe.

The third argument is related to the observed asymmetry between baryons (N_B) and antibaryons ($N_{\bar{B}}$) in the universe. How can we explain it since the initial state was presumably symmetric ($N_B = N_{\bar{B}}$)? In 1967, Sakharov[8] showed that this asymmetry can be explained provided there are processes out of thermal equilibrium, violating C and CP, and that there is also a violation of the baryon number. According to the theory of leptogenesis [9], baryons were born out of heavy neutrinos decays. These created a Lepton-Antilepton asymmetry that was later converted into a Baryon-Antibaryon asymmetry by processes violating the B+L quantum number. In this case, CP violation takes place in the decays of these heavy neutrinos. This scenario is one of the main motivation to explore CP violation in the neutrino sector.

2 Dirac or Majorana?

This short presentation follows Ref.[1]. Let us consider a massive neutrino field ν, and in particular a left-handed state ν_- that has been observed. Applying a CPT transformation, we obtain a new state $\bar{\nu}_+$. We can also envisage a Lorentz transformation that reverses the sign of the momentum and therefore the helicity. In this case we obtain a state ν_+. Is ν_+ different from $\bar{\nu}_+$ or is it the same state?

In the first case we deal with a Dirac neutrino, described by four degrees of freedom: ν_-, ν_+, $\bar{\nu}_-$, and $\bar{\nu}_+$. According to our understanding of the weak interactions, ν_+ and $\bar{\nu}_-$, would not interact through the weak interactions (sterile neutrinos). However, if ν_+ is equal to $\bar{\nu}_+$, we deal with a new object, described by only two degrees of freedom: ν_- and ν_+. This is a Majorana neutrino.

In Quantum Field Theory, we need to define a particle-antiparticle conjugation operator C. C flips the chirality of a spinor: $(\psi_L)^C = (\psi^C)_R$ and $(\psi_R)^C = (\psi^C)_L$. To describe a massive fermion we need both right and left handed states. A Majorana neutrino is described by a field where the right-handed projection is related to the left-handed by a C conjugation: $\psi_R = (\psi_L)^C$ or $\psi = \psi_L + \eta(\psi_L)^C$ where η is a phase factor. From this follows that $\psi^C = \eta^* \psi$. A Majorana fermion coincides with its own antiparticle and describes therefore a really neutral particle. The Majorana mass terms are

$$M_L(\overline{\psi^C})_R \psi_L + M_R(\overline{\psi^C})_L \psi_R. \tag{2}$$

These terms can be rewritten as $M_L \psi_L \Omega \psi_L + M_R \psi_R \Omega \psi_R$ (where Ω is a 4×4 matrix): they clearly violate by two units the U(1) global symmetry $\phi \to e^{i\alpha}\phi$ associated to the lepton number. We cannot assign a conserved charge to a Majorana field. The presence of Majorana neutrino allows processes violating the lepton number. An example is given by the neutrinoless double beta decay to be described later.

Starting from a Dirac field with mass terms $M_D \overline{\psi_L} \psi_R + M_D \overline{\psi_R} \psi_L$, and introducing the Majorana mass terms of Eq. 2 we end up with two Majorana fields after having diagonalized the mass matrix

$$M = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}. \tag{3}$$

Here we assume that $M_L = 0$ to comply with phenomenological constraints. If we assume that M_R is large ($M_R >> M_L, M_D$), the mass of the lighter neutrino can be written

$$M_\nu \simeq \frac{M_D^2}{M_R} \tag{4}$$

This is the see-saw mechanism. We expect M_D to be of the order of the electroweak scale. To get a neutrino mass of 5 10^{-2} eV (this is the minimum mass of the heaviest neutrino as we will see later), we need a mass M_R of the order of 10^{15} GeV. This scale is close to the mass of grand unification suggested by the Minimal Supersymmetric Standard Model (MSSM) (Fig.1). The explanation for the extremely light mass of the neutrino could then be the presence of a superheavy partner at this very large scale. This model is a concrete realization of the generic lagrangian of Eq. 1. In this case the large scale Λ is related to the mass M_R.

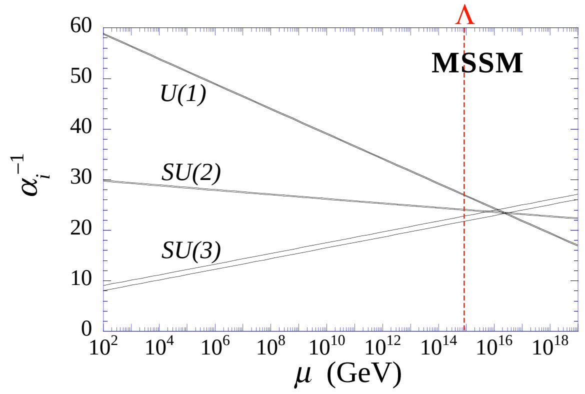

Figure 1: Suggested unification of the gauge couplings α_i in the MSSM at 2×10^{16} GeV, compared to the suggested scale of new physics from the neutrino masses (dashed arrow).

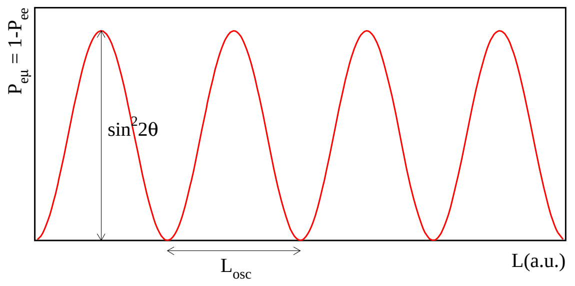

Figure 2: Two neutrino oscillation probability Prob($e \to \mu$) as a function of the experimental baseline L. The oscillation length is $L_{osc} = \frac{4\pi p}{\Delta M^2}$. The amplitude of the oscillation is given by $\sin^2 2\theta$.

3 Neutrino Oscillations

Let us consider a ν_μ produced together with a muon in a pion decay. We would now like to investigate the possibility that at a distance L this neutrino interacts in our detector. Is it possible that it produces by charged current reaction an electron in the final state ?

We know that in the Standard Model, the flavor eigenstates of fermions with the same SM quantum numbers (for instance up or down quarks, neutrinos) may differ from the mass eigenstates. This can be rephrased by saying that in this three dimensional space (for the three families), the weak interaction introduce a basis (the flavor basis) that does not necessarily coincide with the basis defined by the interaction with the Higgs field (the mass basis).

We will assume that this is the case and that we can write

$$|\nu_\alpha\rangle = \sum_i^N U_{\alpha i} |\nu_i\rangle \tag{5}$$

where $|\nu_\alpha\rangle$ is a flavor state (designed here by Greek indices), $|\nu_i\rangle$ is a mass state (Latin indices) and U is a unitary matrix connecting the two basis. This is the state produced at $t = 0$. At time t it has evolved according to

$$|\nu(L,t)\rangle = \sum_i^N U_{\alpha i} e^{-ip_i x} |\nu_i\rangle \tag{6}$$

We now assume that the neutrino is relativistic, $p \gg m$ and $t \simeq L$, and develop using $p_i x = E_i t - pL = p(t-L) + \frac{M_i^2 L}{2p}$ where $E_i = \sqrt{p^2 + M_i^2} \simeq p + \frac{M_i^2}{2p}$. Discarding the irrelevant phase factor $p(t-L)$ common to all terms, we obtain

$$|\nu(L)\rangle = \sum_i^N U_{\alpha i} e^{-i\frac{M_i^2 L}{2p}} |\nu_i\rangle. \tag{7}$$

Using the inverse transformation $|\nu_i\rangle = \sum_i^N U_{\beta i}^* |\nu_\alpha\rangle$ we can recast this as

$$|\nu(L)\rangle = \sum_\beta [\sum_i^N U_{\alpha i} e^{-i\frac{M_i^2 L}{2p}} U_{\beta i}^*] |\nu_\beta\rangle. \tag{8}$$

In this equation it is clear that in principle all neutrino flavors are present in the final state. The phase shift between the lighter states (in advance with respect to a common phase) versus the heavier results in a "distortion" of the original linear superposition and therefore in the appearance of flavor state not present at $t = 0$. All neutrino oscillation experiments are therefore quantum interferometry experiments on a macroscopic scale.

The probability of the transition $\alpha \to \beta$ can be computed from $\text{Prob}(\alpha \to \beta) = |\langle \nu_b | \nu(L) \rangle|^2$ to yield

$$\text{Prob}(\alpha \to \beta) = \delta_{\alpha\beta} - 4 \sum_{i<j} \Re(J_{ij}^{\alpha\beta}) \sin^2 \phi_{ij} - 2 \sum_{i<j} \Im(J_{ij}^{\alpha\beta}) \sin \phi_{ij} \tag{9}$$

where $J_{ij}^{\alpha\beta} = U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}$, $\phi_{ij} = \phi_i - \phi_j = \frac{\Delta M_{ij}^2 L}{2p}$ and $\Delta M_{ij}^2 = M_i^2 - M_j^2$.

From Eq. 9 it can be shown that

- if all the masses are equal this probability reduces to the identity;
- to get appearance/disappearance effects, non trivial mixing is needed;
- the total flux is conserved ($\sum_\beta \text{Prob}(\alpha \to \beta) = 1$).

In the case of two neutrinos, the unitary transformation reduces to a simple rotation matrix

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{10}$$

with mixing angle θ. The probabilities (Fig. 2) are

$$\text{Prob}(\alpha \to \beta) = \sin^2 2\theta \sin^2(\frac{\Delta M_{12}^2 L}{4p}) \tag{11}$$

and

$$\text{Prob}(\alpha \to \alpha) = 1 - \sin^2 2\theta \sin^2(\frac{\Delta M_{12}^2 L}{4p}). \tag{12}$$

The oscillation length is

$$L_{osc} = \frac{4\pi p}{\Delta M^2} \tag{13}$$

and typical values for this length are given in Table 1.

In the case of three neutrino families the mixing matrix, called Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, can be written

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{14}$$

Table 1: Typical oscillation length for neutrinos from various sources.

Source	Energy	Distance	ΔM^2 (eV^2)
Reactor	4 MeV	100m	0.1
Accelerator	1 GeV	1 km	2.5
Atm. down	400 MeV	10 km	0.1
Atm. up		10 000 km	10^{-4}
Sun	1 MeV	500s	10^{-11}
	1 GeV	1000 km	2.5 10^{-3}
	1 MeV	25 km	8 10^{-5}

In the general case this matrix has (N-1)(N-2)/2 phases. If the neutrinos are of Majorana type, there are (N-1) additional phases: for N=3, the PMNS matrix U of Eq. 14 gets multiplied by diag(1,$e^{i\alpha_1}$,$e^{i\alpha_2}$).

3.1 Neutrino Oscillations in Matter

Matter effects - relevant for solar, atmospheric and long baseline neutrinos - modify this picture of neutrino oscillations. What happens can be understood by analogy with the propagation of light in a medium. The interaction with the atoms introduces a refraction index. In the case of neutrinos, there are two kind of interactions: through neutral currents affecting equally all neutrinos, and through charged current on the electrons contained in the medium. The latter terms affects only the electron neutrinos.

It can be shown that the interaction potential, in the flavor basis, is

$$H = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta_V & \sin 2\theta_V \\ \sin 2\theta_V & \cos 2\theta_V \end{pmatrix} + \sqrt{2} G_F N_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \tag{15}$$

where θ_V is the mixing angle in vacuum and N_e is the electron density in the medium. This potential can be rewritten

$$H = \begin{pmatrix} a & x \\ x & b \end{pmatrix} \tag{16}$$

What happens in matter is then that the oscillations proceed with a new mixing angle θ_M

$$\tan 2\theta_M = \frac{2x}{a-b} \tag{17}$$

and with eigenvalues

$$E_\pm = \frac{a+b}{2} \pm \frac{1}{2}\sqrt{(a-b)^2 + 4x^2}. \tag{18}$$

Two remarks are in order here. First, for $a = b$, Eq. 17 shows that the mixing angle is maximal ($\pi/4$). This happens even if the mixing angle in vacuum is tiny. The resonance condition for this effect, called the Mikheyev-Smirnov-Wolfenstein (MSW) effect [10], depends on the energy of neutrino. Second, let us consider the eigenvalues $E_\pm$ as a function of the electron density (contained in the a term). Far away from the resonance, $(a-b)^2 \gg 4x^2$ the eigenvalues correspond to the unmixed case, a and b. However, for non-zero mixing, the quantity under the square root never goes to 0, the energy levels never cross (Fig. 3 from Ref.[2])!

The MSW resonance condition reads

$$\sqrt{2} G_F N_e = \frac{\Delta m^2}{2E} \cos 2\theta. \tag{19}$$

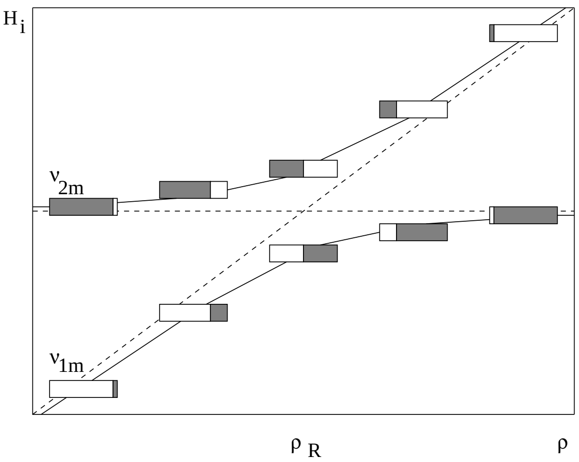

Figure 3: Adiabatic neutrino flavour conversion. The solid curves show the energy levels of neutrino matter eigenstates versus the density ρ, the dashed curves illustrate level crossing in the absence of mixing. The black and white filling corresponds to the weights of neutrino flavour eigenstates in a given matter eigenstate.

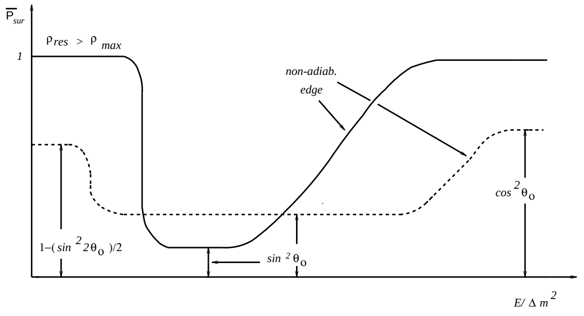

Figure 4: Survival probability of ν_e escaping the sun. The lowest part of the curve corresponds to the MSW effect. Lowest energy neutrino do not cross the resonance while for highest energy neutrinos the adiabatic condition is not satisfied.

In the center of the sun $\sqrt{2}G_FN_e = 0.75\ 10^{-5}\text{eV}^2/\text{MeV}$ and $\frac{\Delta m^2}{2E} = 0.25\ 10^{-5}\text{eV}^2/\text{MeV}$ for E=8 MeV. An electron neutrino of this energy emitted at the center of the sun (Fig.3) finds itself to correspond to the heavier eigenstate of the potential $|\nu_e\rangle \simeq |\nu_{2m}\rangle$. Indeed the second term in Eq. 15 dominates and the flavor eigenstates are also mass eigenstates in this regime. If the adiabaticity condition is met (that is if the variation of the matter density has a typical scale longer than the neutrino oscillation length) it remains an eigenstate of the potential ($|\nu_{2m}\rangle$) through its propagation towards the region of lower density. Then exiting the sun it is still the heavier eigenstate $|\nu_2\rangle$ corresponding to the propagation in vacuum. This state has a component $\sin\theta$ of the electron neutrino and this results in a strong reduction of the flux of solar electron neutrino. The electron neutrino survival probability is in fact a function of the neutrino energy, depicted in Fig. 4 from Ref.[2].

4 Solar Neutrinos

The sun is a very bright source of neutrinos. The basic reaction, i.e. nuclear fusion, that produces them is well understood: $4p + 2e \rightarrow {}^4He + 2\nu_e$ with a Q value of 26.7 MeV. The total neutrino luminosity can be computed from the sun power. In reality things are rather complicated, a whole chain of reactions takes place (Fig. 5) and produces the neutrino spectrum shown in Fig. 6. Depending on the threshold of the detector, it will be sensitive to a fraction of these reactions. For several decades, many experiments have probed the flux of solar neutrinos, showing a consistent picture reported in Fig. 7.

Homestake is a radiochemical experiment running from the 60's to 1994. In a large mass of Chlorine the reaction $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e-$ proceeds with a threshold of 0.814 MeV. The Argon atoms are then extracted and counted by observing their β decay back to ${}^{37}Cl$. Historically the Homestake experiment was the first to observe a deficit[11] (the observed signal was only 30 % of the expectation) in the solar neutrino flux and this observation motivated many further experiments (for instance Gallex and SAGE with Gallium target nuclei) and theoretical efforts.

SuperKamiokande is a large underground detector, comprising 50 kTon pure water and 11146 large PMT. It is sensitive to solar neutrino down to about 6 MeV. Besides confirming the solar neutrino deficit, its data[12] allowed to constrain other important effects like spectral distortions

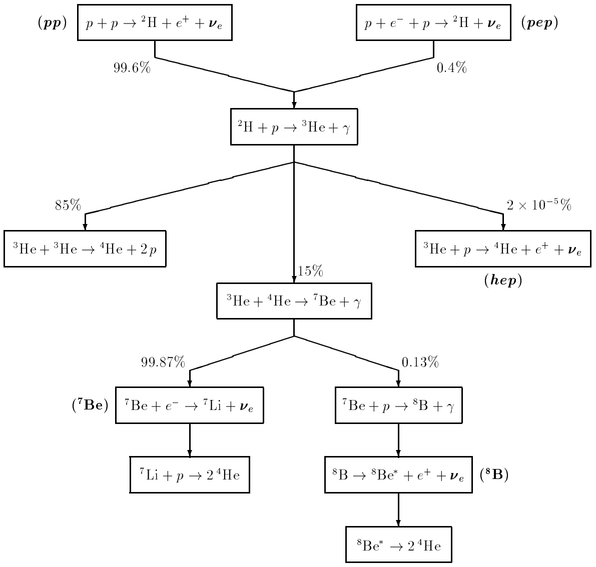

Figure 5: The nuclear reactions producing most of the sun energy and the different types of solar neutrinos.

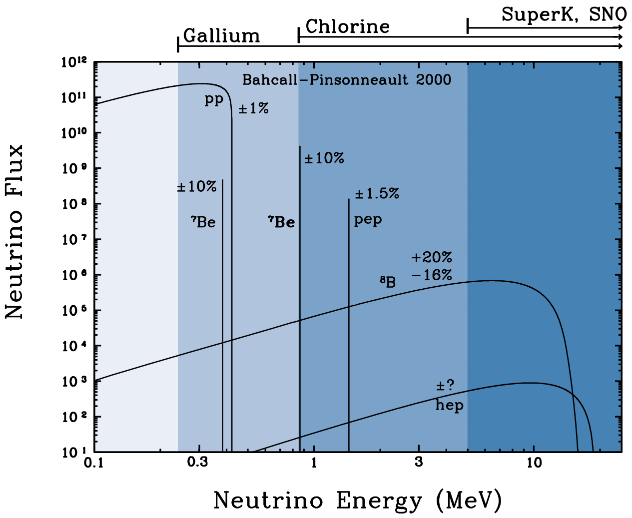

Figure 6: Spectrum of solar neutrinos produced by different processes according to the standard solar model. from http://www.sns.ias.edu//~jnb.

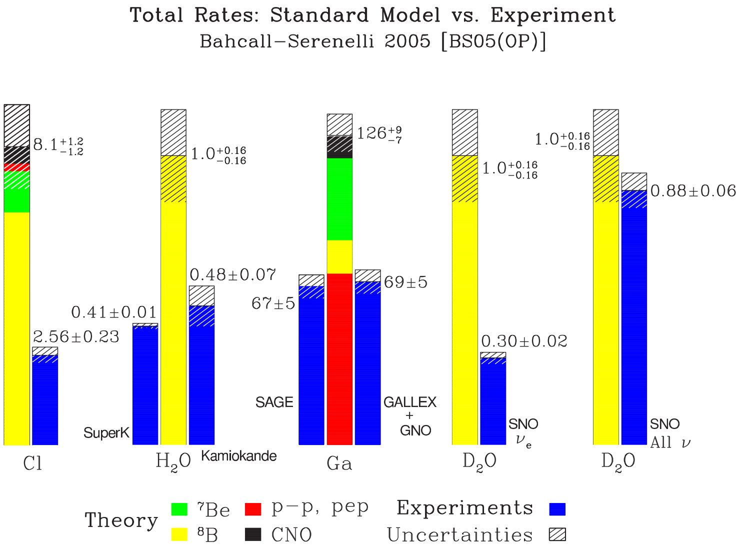

Figure 7: Comparison between the Standard Solar Model expectations (highest bars) and data (blue bars) for the observation of the solar neutrino flux in the Chlorine (Cl), Gallium (Ga), Super-Kamiokande (H_2O) and SNO (D_2O) together with their error bars (shaded areas) and neutrino flux components (in different colors). from http://www.sns.ias.edu//~jnb (Solar Neutrinos, Viewgraphs).

and day-night variations due to a possible neutrino regeneration in the earth.

SNO is a very important experiment in solar neutrino. It consists of 1000 tonnes of heavy water (D_2O) in the Sudbury mine. It is sensitive to the following reactions:

- Electron Scattering (ES): $\nu_x + e^- \rightarrow \nu_x + e^-$ mainly sensitive to ν_e.
- Charged Current (CC): $\nu_e + d \rightarrow p + p + e^-$ that provide a good measurement of the ν_e flux and spectrum.
- Neutral Current (NC): $\nu_x + d \rightarrow p + n + \nu_x$ that provides an equal cross section for all ν types and therefore measure the total ^8B ν flux from the sun.

The SNO measurement[13] (Fig.8) of the neutrino fluxes Φ_{CC} and Φ_{NC}

$$\frac{\Phi_{CC}}{\Phi_{NC}} = \frac{\Phi_{\nu_e}}{\Phi_{\nu_e} + \Phi_{\nu_\mu} + \Phi_{\nu_\tau}} = 0.34 \pm 0.023(stat)^{+0.029}_{-0.031} \tag{20}$$

provides a clear proof of neutrino flavor transformation.

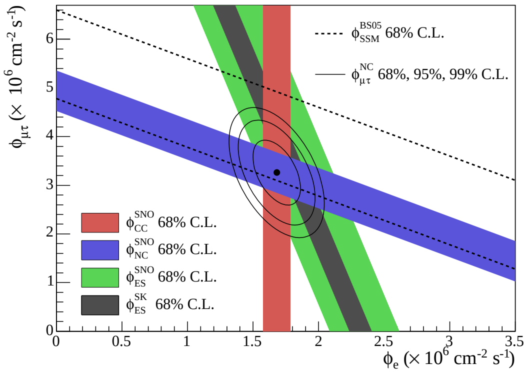

Figure 8: SNO and SK Data. Flux of $\mu + \tau$ neutrinos versus flux of electron neutrinos. CC, NC and ES flux measurements are indicated by the filled bands. The total solar neutrino flux predicted by the Standard Solar Model is shown as dashed lines.

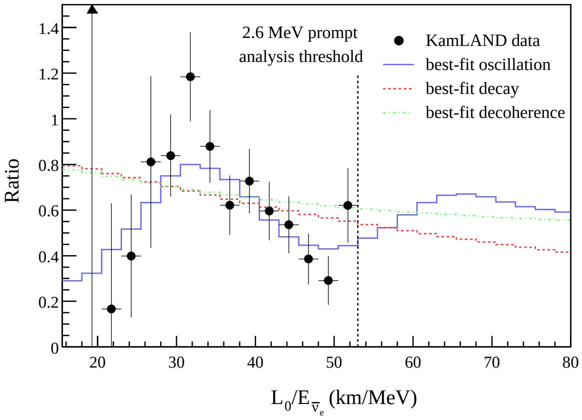

Figure 9: KamLAND data. Ratio of the observed electron antineutrino spectrum to the expectation for no-oscillation versus L_0/E. The curves show the expectation for the best-fit oscillation, best-fit decay and best-fit decoherence.

Finally, KamLAND, an experiment in Japan measuring antineutrinos produced by nuclear reactors, provided a very clean confirmation[14] of "solar" neutrino oscillation (Fig. 9).

5 Atmospheric Neutrinos

High energy cosmic rays (mainly protons) interact in the atmosphere and produce hadronic showers, with abundant pion production. The pions decay producing a ratio of ν_μ to ν_e close to 2. Since the 80's, underground experiments (IMB, Soudan, Kamiokande) measuring these neutrinos gave indications of an anomaly, measuring a ratio $N(\nu_\mu)/N(\nu_e)$ much lower than expected.

The real step forward in this domain came with the data of SuperKamiokande[15], with a large fiducial mass, excellent electron/muon separation and good neutrino direction reconstruction. This allowed to study the muon neutrino deficit versus the zenithal angle (Fig. 10 and 11). For multi-GeV events, there is no deficit for downward ν_μ ($cos\Theta$) $= 1$) while there is a strong deficit for upward $\nu_\mu(cos\Theta) = -1$). This is explained by the large difference of the path length: 10 km for downward versus 12 000 km for upward ν. For upward ν, the data correspond to an average

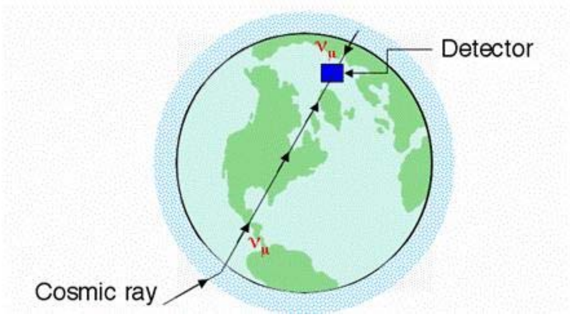

Figure 10: Path length of atmospheric neutrino reaching the detector directly (downward) or after having traversed the earth (upward).

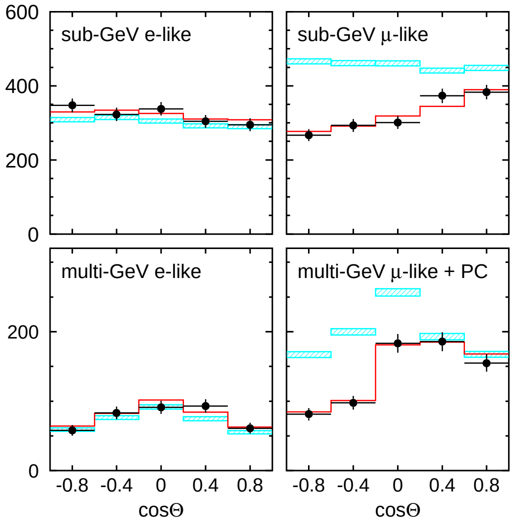

Figure 11: SuperKamiokande atmospheric ν data. The zenith angle distribution for sub-GeV and multi-GeV e-like and μ-like events. The hatched area shows the prediction for the no oscillation hypothesis. The deficit of ν_μ induced events is clear for upward $(\cos\Theta \simeq -1)$ events.

of the very fast oscillations and are therefore sensitive to a disappearance probability derived from Eq. 12

$$\mathrm{Prob}(\nu_\mu \to \nu_\mu) = 1 - \frac{1}{2}\sin^2 2\theta. \tag{21}$$

The data indicate that this mixing angle is close to maximal ($\theta \simeq \pi/4$). The mass difference ΔM extracted from these atmospheric neutrino oscillation is much larger than the mass difference implied by solar neutrino data. Two accelerators experiments, K2K and MINOS, have probed ν_μ oscillation at this ΔM and have provided conclusive evidence of ν_μ disappearance.

6 PMNS today and Open Questions in Neutrino Physics

The evidence for neutrino oscillation has far reaching consequences and imply that

- Neutrinos have non zero mixing angles;
- Neutrinos have tiny but non-zero masses;
- Lepton flavor is not conserved;
- The Standard Model is incomplete.

The last statement deserves some comments. Indeed it is possible to add by hand in the Standard Model (SM) neutrino-Higgs interactions with the correct Yukawa couplings to produce the observed neutrino masses. However, why are these Yukawa couplings 6 or more orders of magnitudes smaller than those of the charged leptons? Morevover, as explained in the Introduction, no SM symmetry protects the neutrinos from acquiring a Majorana mass. These two observations hint that physics beyond the SM is responsible for the neutrino masses and mixing.

Our current knowledge about the neutrino mass and mixing is summarized in the following results from a global fit[16] to solar, atmospheric, reactor and accelerator experiments:

$$
\begin{aligned}
\Delta m^2_{21} &= 7.92\ (1 \pm 0.09)\ 10^{-5} eV^2 \\
\sin^2\theta_{12} &= 0.314\ (1^{+0.18}_{-0.15}) \\
\Delta m^2_{atm} = \frac{1}{2}(\Delta m^2_{31} + \Delta m^2_{32}) &= 2.4\ (1^{+0.21}_{-0.26})\ 10^{-3} eV^2 \\
\sin^2\theta_{23} &= 0.44\ (1^{+0.41}_{-0.22}) \\
\sin^2\theta_{13} &= 0.9\ (1^{+2.3}_{-0.9}) 10^{-2} \qquad (22)
\end{aligned}
$$

It is interesting to notice that two neutrino mixing angles are large. This is in contrast to the situation in the quark sector, where the mixing matrix is close to the identity. This suggests a non trivial structure in the physics responsible for the mass and the mixing. Many theoretical efforts are focussed towards understanding these mixing matrices with various approaches. The oscillation data are sensitive only to mass differences, therefore the absolute value of the neutrino masses is still unknown. Moreover, the sign of Δm^2_{atm} is not known. This leaves open the important question whether ν_3 is the heaviest (normal hierarchy) or the lightest (inverted hierarchy) of the three mass states (Fig. 12 from Ref.[2]).

The data from the LSND experiment[17] hinted to a neutrino oscillation at $\Delta m^2 \simeq 1$ eV^2. This would have been an indication of a fourth neutrino mass state. However recent data from the MiniBooNE collaboration[18] rule out two-neutrino oscillations as the explanation for LSND data.

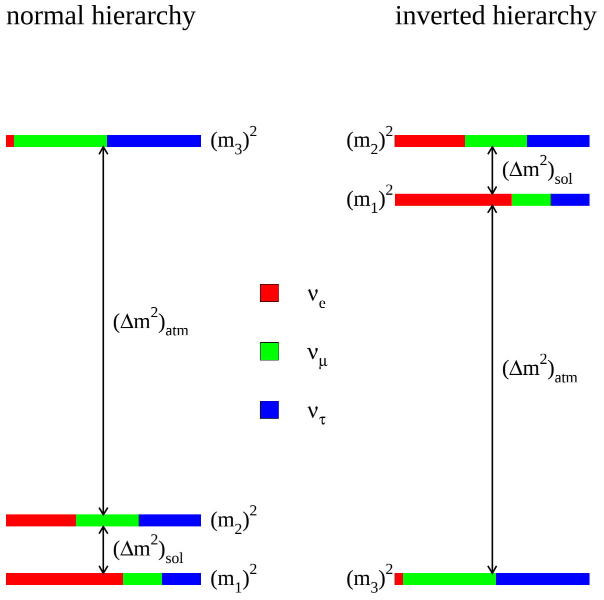

Figure 12: Normal and inverted neutrino mass orderings. The different colors show from left to right the relative weights of the different flavour eigenstates (ν_e, ν_μ and ν_τ) in a given mass eigenstate.

Despite the spectacular progress of experimental investigations in these field, several fundamental questions remains open:

- What are the values of the neutrino masses ?
- Are the neutrinos of Dirac or Majorana type ?

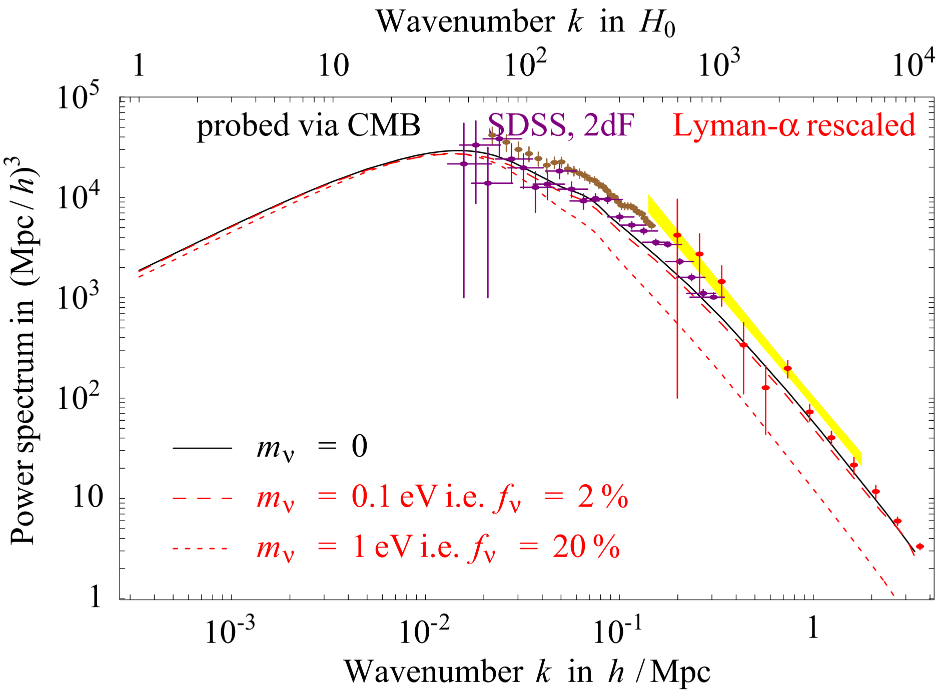

Figure 13: The matter power spectrum $P(k)$ predicted by the best-fit ΛCDM cosmological model (continuous curve) and how neutrino masses affect it (dashed curves).

- What is the neutrino mass hierarchy, normal or inverted ?
- What is the value of the last mixing angle θ_{13} ?
- Is there CP violation in the leptonic sector ?

In the following sections we will see how a rich experimental program is progressing towards an answer to these difficult but extremely important questions.

7 The Mass and the Nature of the Neutrino

The measurement of the neutrino mass is a long and still unfinished effort, starting in the 30's when Fermi showed how a massive neutrino would distort the beta decay spectrum of the electron near the end point. KATRIN is an ambitious experiment aiming at refining the current limit ($m_\nu < 2.2$ eV) from the Mainz experiment [19]. Studying tritium beta decays, it aims at a sensitivity of 0.2 eV and will start taking data in 2010. Other projects like MARE will also explore this field with different techniques.

Given the very small energy scale involved, laboratory measurement of the neutrino mass are very difficult. Today the best limit comes from cosmology. Relic neutrinos were free-streaming (i.e. not gravitationally bound) and therefore suppressed low scale structures in the universe. The neutrino masses determine the fraction of energy that they carry and therefore the amount of "smoothing". Using the matter power spectrum $P(k)$ (Fig. 13 from Ref.[4]) measured using the data from Cosmic Microwave Background (CMB) and from galaxy surveys (SDSS, 2dF), a limit $m_1 + m_2 + m_3 < 1.2$ eV [20] can be set. More stringent limits can be set using the Lyman-α data.

A related experimental effort is focussing on the search for neutrinoless double beta decay. Two-neutrino double beta decay ($2\nu\beta\beta$) (Fig. 14 left, from Ref.[4]) is a nuclear process through which a Z-charged nucleus decays to a $Z+2$-charged nucleus:

$$Z \to (Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e. \tag{23}$$

Such processes have been observed for several nuclei, including ^{76}Ge, ^{100}Mo, ^{130}Te, etc. Typical half-lives are well above 10^{18} years. Similarly, $0\nu\beta\beta$ is characterized by

$$Z \to (Z+2) + e^- + e^-, \tag{24}$$

and violates lepton number by two units. It can be interpreted as a $2\nu\beta\beta$ process where the two antineutrinos "annihilate" into vacuum. The diagram that describes neutrino-mass-induced $0\nu\beta\beta$ is depicted in the Fig. 14 (right plot). This process takes place only if the neutrino is a Majorana particle. The observable is the effective electron neutrino mass

$$|\langle m_\nu \rangle| = m_{ee} = |\sum_k U_{ek}^2 m_k| \tag{25}$$

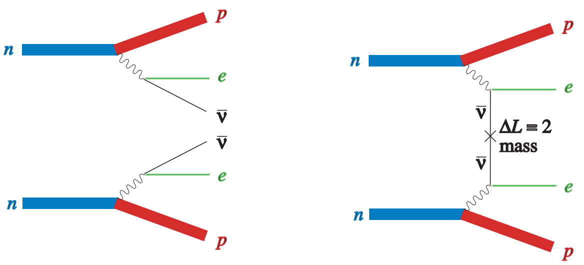

Figure 14: Left: Two-neutrino double beta decay. Right: neutrinoless double beta decay, taking place only if the neutrino is a Majorana particle.

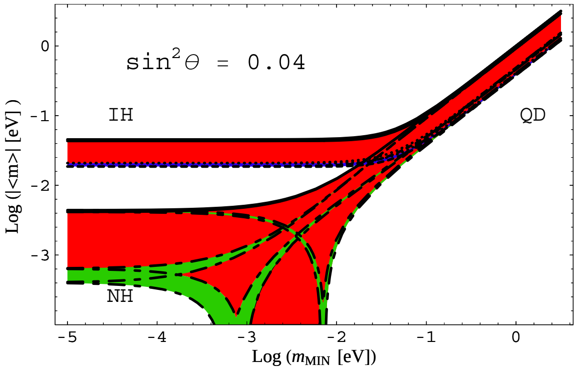

Figure 15: $|\langle m_\nu \rangle|$ probed by neutrinoless double beta experiments as a function of the lightest neutrino mass. To the left the two branches correspond to inverted hierarchy (IH) and normal hierarchy (NH). To the right lies the region corresponing to the Quasi Degenerate (QD) case.

The best sensitivity has been obtained by the Heidelberg-Moscow ^{76}Ge experiment, with a controversial claim of observation[21]. Other experiments like NEMO3 or Cuoricino have upper limits on $|\langle m_\nu \rangle|$ slightly below the eV level.

A large number of projects (CUORE, GERDA, EXO, Super-NEMO, etc.) have been launched to tackle the problem of reducing the background that it is the limiting factor. A variety of solutions - cryogenic detectors, ultra-pure materials, high resolution, TPC - have been applied. The aim is to push the sensitivity down to 0.01 - 0.05 eV. As shown on Fig. 15 (see for instance [22]), this sensitivity would be able to probe the inverted hierarchy scenario.

8 The Last Oscillation Channel

Similar to what happen in the quark sector, CP violation effects due to the phase δ of the PMNS matrix are proportional to the Jarlskog invariant $J \propto \sin\theta_{23} \sin\theta_{13} \sin\theta_{12}$. Therefore, it is necessary to establish that the mixing angle θ_{13} is different from zero before proceeding to the more difficult measurement of CP violation in the leptonic sector.

θ_{13} can be probed by looking at the disappearance of electron antineutrino produced by a nuclear reactor. Several experiments like Double-Chooz and Daya Bay are following this approach. The experimental effect is less than 10 %. The greatest sensitivity is reached by using two or more identical detectors at different distances from the reactor core. Several systematics like the reactor flux, the detection efficiency etc., cancel taking the ratio of the signals in the two detectors.

The T2K experiment follows a different approach. It is a long baseline neutrino experiment with a powerful proton beam (0.75 MW) producing a ν_μ neutrino beam. θ_{13} can be probed searching for ν_e appearance in SuperKamiokande, the far detector, at 295 km from the beam source. The combination of distance L and energy corresponds to the first maximum of the "atmospheric" oscillation. A magnetised detector (Fig. 16) at 280 m from the proton target will precisely characterize the neutrino beam and its interactions. A subdominant $\nu_\mu \to \nu_e$ oscillation will also take place characterized by the much longer "solar" oscillation length. T2K will start taking data in 2009 and will offer the best sensitivity[23] to θ_{13} at the beginning of the next decade (Fig. 17).

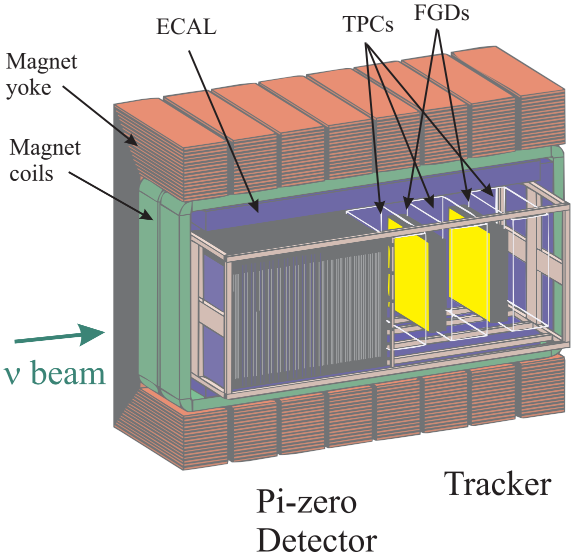

Figure 16: The near detector of the T2K experiment at 280m from the proton target.

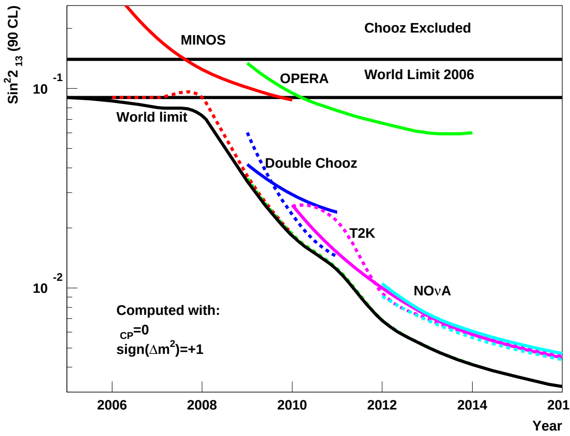

Figure 17: Sensitivity to $\sin^2 2\theta_{13}$ as a function of time for various experiments.

9 Towards CP Violation in the Lepton Sector

The next generation of neutrino accelerators and experiments is under study in order to test CP violation in the neutrino sector. Looking at Eq. 9, we see that the term proportional to $\Im(J_{ij}^{\alpha\beta})$ changes sign under CP. Neutrino facilities producing beams of neutrino and antineutrino can then probe a CP asymmetry defined as

$$A_{\alpha\beta}^{CP} = \frac{\mathrm{Prob}(\nu_\alpha \to \nu_\beta) - \mathrm{Prob}(\overline{\nu}_\alpha \to \overline{\nu}_\beta)}{\mathrm{Prob}(\nu_\alpha \to \nu_\beta) + \mathrm{Prob}(\overline{\nu}_\alpha \to \overline{\nu}_\beta)} \propto \sin\delta. \tag{26}$$

The neutrino and antineutrino beam propagation in the matter (the earth) introduce large effects mimicking a CP violation signal and need to be taken properly into account.

Several projects are under consideration:

- Superbeam, a very intense (4MW) proton beam with a baseline of $\sim$ 100 km and with a Megaton class detector as the far detector.
- Betabeams, where beta decaying ions are accelerated to produce a very pure ν_e and $\overline{\nu_e}$ beam.

- Neutrino Factory, where muons are accelerated and then decay in long straight sections to produce at the same time a ν_μ and $\overline{\nu_e}$ beams.

The study of the feasibility of these projects and their physics reach is the object of detailed studies in USA, Japan and Europe.

10 Conclusion and prospects

The last decade has witnessed spectacular progress in neutrino physics with the discovery of neutrino masses and mixings through oscillations, their confirmation with reactor and beam experiments and a large improvement in precision of the measurements. We are today in the exciting phase of preparation of a new round of experiments. Their goal is to provide answers to fundamental questions, like the nature of this particle and the existence of CP violation in the leptonic sector.

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