Experimental aspects of neutrino oscillation physics

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Abstract

The experimental review of this paper is mainly focussed on a particular aspect of the neutrino physics which is the observation and understanding of the neutrino oscillation process. This quantum mechanical mechanism involves several parameters linked to the neutrino properties which are described through a lepton mixing matrix. The detailed knowledge of those parameters may provide a key tool to answer several fundamental questions including the existence or not of flavour violation in the leptonic sector. The discovery of neutrino flavour oscillation 10 years ago was followed by an intense experimental activity with several key experiments which provided many clues to start to unravel the neutrino oscillation puzzle. The program is still active and impressive experimental challenges are underway to pursue this goal. The aim of the talk is to recall the main neutrino historical path and to give an overview of the many experimental aspects of the neutrino oscillation studies performed since10 years and the main results obtained.

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1 Introduction: some history and neutrino basis

The proof of existence of the particle called neutrino has not been a trivial exercice. Before detailing the experimental measurements it is worth to quote some anecdotes about their birth and existence to understand better the scientific approach and appreciate the evolution of ideas through time. W. Pauli [1] introduced for the first time in 1930 the concept of a new spin half light neutral particle as a remedy to explain the observed violation of the principle of energy-momentum conservation in radioactive β decays. The electron energy spectrum was found to be continuous and not discrete and the new hypothetic neutral particle which could be emitted at the same time as the electron was a good solution to solve this anomaly. However this new idea was even not thought as a serious one by its author. Pauli, in a discussion with one of his friends the german astronomer W. Baade, apparently confessed [2]: 'Today I have done something which no theoretical physicist should ever do in his life: I have predicted something which shall never be detected experimentally'.
In 1933, exploiting the concept of this additional neutral particle, E. Fermi built a coherent theory of beta decays [3] which later became the basis of the weak interaction theory. However this theory was not accepted by everybody as one can see from one referee's comment when he submitted the article to Nature: 'Abstract speculations too far from physical reality to be of any interest to the readers'. To complete this quite strange picture, Bethe and Peierls computed in 1934 [4] the interaction cross section of the neutrinos based on the available theory. Unfortunately, using too simplistic hypothesis they found that few MeV neutrinos resulted to have an interaction length of about one light year of lead and formulate the conclusion: '...this meant that one obviously would never be able to see a neutrino'.
However despite those claims some physicists succeeded in building specific experiments to track and catch those quite 'elusive' particles called neutrinos.

1.1 Neutrino detection and discovery

The discovery path started 30 years after the introduction of the neutrino concept when F. Reines and R. Cowan observed in 1956 for the first time [5] an interaction coming from anti-neutrino produced in the core of the Savannah River nuclear plant. Three large tanks filled with liquid scintillator were used to detect the anti-neutrino using the inverse beta decay reaction ($\bar{\nu}_e p \rightarrow e^+ n$). They saw a number of events corresponding to the process in which a delayed coincidence signature between two flashes of light, one from an electron-positron annihilation and the other one from a neutron capture, separated by a few microseconds is measured. It was the ν_e discovery.
Six years later the second neutrino (ν_μ) was discovered by Lederman et al. [6] at the Brookhaven National Laboratory using for the first time an intense beam of neutrino produced in a pion beam. They found that the neutrino produced in the pion decays interact in the detector differently than would have done a electron neutrino. They saw in their spark chambers several tens of interactions where a muon was produced instead of an electron. The idea of using a neutrino beam was proposed by M. Schwartz in 1960 [7] to provide a tool to investigate the weak interactions. The basis is to use a high intensity proton beam to hit a target and produce an intense source of pions which produce neutrinos when decaying. This principle is the one used in what is called conventional neutrino beams.
Finally the third neutrino type (ν_τ) was only discovered in 2000 by the Donut Collaboration at Fermilab [8]. The collaboration uses an intense beam dump in which charmed mesons decaying into taus and ν_τ are produced. Its existence was expected since the beginnning of the eighties and it was suggested after the discovery of the charged tau lepton in 1974 for which a new flavour neutrino has been theoretically associated. The proof of the existence of the ν_τ is based on the detection of the tau particle produced in charged current interaction in the detector. To detect this short lived particle it has been necessary to use a tracking detector with micrometer position resolution. The technology used for this goal was based on nuclear emulsion cloud chamber principle. This technology is also the one used in the current OPERA experiment [9].

1.2 Neutrino as laboratory tools

In the early time, the neutrino has been extensively used as a probe to study the weak interaction. The first important result came with the discovery of the neutral current in 1973 [10] at CERN with the Garagamelle heavy liquid bubble chamber well suited for the study of neutrino interactions. Figure 1 shows one of those events. Neutrino beams were also intensively used to probe the nucleon structure and to derive the structure functions of the neutrons and protons.

Starting from this period it was possible to measure ν interaction cross sections on various target elements and over a large energy range extending from a few hundred MeV to a few hundred GeV. Figure 2 shows a compilation of the measured cross sections for neutrino and anti-neutrinos [11]. The corresponding values are for neutrinos

Figure 1: Picture of an event seen in the Gargamelle bubble chamber. It corresponds to an elastic ν_μ-e scattering. The observation of such events were essential to confirm the existence of neutral current processes.

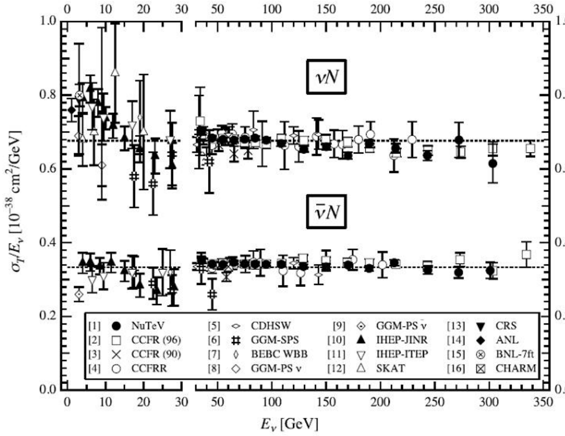

Figure 2: Compilation of neutrino and anti-neutrino interaction cross section from a few hundred MeV to a few hundred GeV [11].

$\sigma_{\nu N}/E_\nu \approx 0.67\text{x}10^{-38} cm^2/GeV$ and for anti-neutrinos $\sigma_{\bar{\nu} N}/E_{\bar{\nu}} \approx 0.34\text{x}10^{-38} cm^2/GeV$. It is interesting to note that those values are 1 million times larger than the cross section computed in 1934 by Bethe and Peierls.
The major activities around the neutrinos in the 80's and 90's were essentially the measurement of the weak interaction parameters (up to a few % precision) and the study of the quark structure of the nucleon. To succeed in measuring those interactions in a large energy range it was essential to build high energy intense pure neutrino beams together with massive detectors. The detector technology has evolved in mainly three categories coming with the electronic development and the computer assisted technology development. The first category of detectors included heavy liquid bubble chambers like the Gargamelle chamber shown in Figure 3 able to offer a large target mass, a long interaction length and a precise tracking reconstruction. The second generation of detectors used from the late 80's were essentially calorimetric detectors similar to the CHARM detector shown in Figure 4 with a few 100 tons of target with gaseous or plastic sintillator planes sometimes in alternance with layers of absorber material.

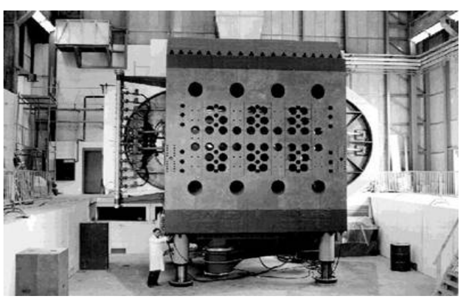

Figure 3: Gargamelle bubble chamber at CERN.

Figure 4: CHARM experiment at CERN.

In more recent times another type of detectors looking at neutrinos appeared. They are of spherical or cylindrical shapes and correspond to large containers of liquid surrounded by large numbers of photodetectors. The principle is to track the light coming from Cherenkov emission of fast particles in the liquid medium or light coming from annihilation or scintillation processes. Three types of such detectors are shown in Figure 5. The left picture shows the internal tank of the Super-Kamiokande detector in Japan filled with 22 ktons of water. The picture in the middle shows the SNO detector in Canada which contained about 1 kton of heavy water. The picture on the right shows the inner vessel of the Borexino detector in Italy which contains 300 tons of pseudocumen liquid scintillator. All those detectors offer large volumes for interaction and necessitate a large number of photodetectors going from 1000 to 10000.

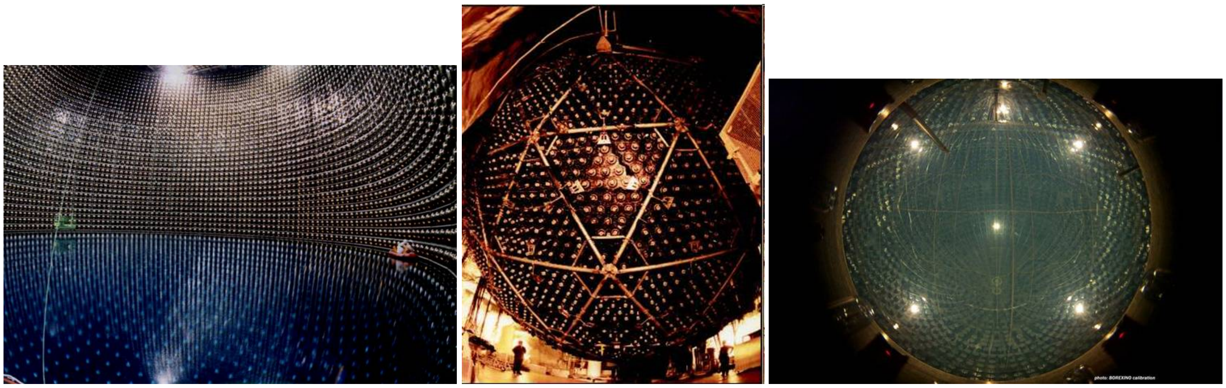

Figure 5: a) Super-Kamiokande water Cherenkov detector; b) SNO heavy water detector; c) BOREXINO liquid scintillator detector.

1.3 The neutrinos and the Standard Model

In the minimal Standard Model (SM) of particle physics the neutrinos are defined as neutral spin 1/2 fermions subject to Weak interactions only. LEP exeperiments have determined from the width of the Z resonance lineshape that the number of active light neutrino flavours is N_ν= 2.9840±0.0082 [12]. There is clearly no room for an additional light ν species. In the Standard Model the ν are always Left Handed (LH) and their mass equals 0. Since 1998 there is evidence for flavour changing process in the neutrino sector. This oscillation mechanism implies that ν are massive which can be translated in the first hints for physics beyond the Standard Model. Obviously the SM should be extended to be reconciled with massive ν and the Higgs mechanism.

In order to find a solution, two main approaches exist. One is to add a new particle called Dirac ν. It is minimal extension with a new Dirac mass term. However it is not very satisfactory since the Right Handed (RH) ν interacts with the Higgs too weakly (10^{12} times weaker than that of the top) to acquire mass. The second idea is to introduce a different type of particle which could be the Majorana ν. In this case heavy RH neutrinos are created for a brief moment (via the See-Saw mechanism) from LH ν interaction with Higgs. The consequence is that there is no fundamental distinction between matter and anti-matter. The question is not yet solved and more studies are needed to find the key for this issue.

It is clear that many fundamental questions concerning the neutrino sector remain open. Here is a brief list of them with the possible experimental steps needed to answer them.

- What is the absolute neutrino mass scale? This question is fundamental for cosmology and unification scheme of interactions. Possible experimental methods to answer is to measure ν time of flight (ex: Supernova 1987A gave the limit m$<$ 20 eV) or to measure precisely the end point of electron beta decay spectrum. The actual limit obtained is m$<$ 2.5 eV. Another method consists of inferring it from fluctuations of Cosmological Microwave Background (ex: WMAP gives m$<$0.23 eV).
- Are neutrinos their own antiparticle (Majorana neutrinos) or not (Dirac neutrinos)? The answer can be obtained through the search for neutrinoless double beta decay which can also provide an additional clue to the absolute mass scale.
- What are the relations between neutrino flavor eigenstates and mass eigenstates? Is there CP violation in the neutrino sector (leptogenesis)? The study to answer those questions are described in the next section. The idea is to exploit all possible neutrino sources which are the Sun, nuclear reactors, atmospheric showers, beam accelerators of various energies.

2 Mixing matrix and 3 massive ν oscillation

2.1 Formalism

There are three known neutrino flavor eigenstates $\nu_\alpha = (\nu_e,\ \nu_\mu,\ \nu_\tau)$. Since 1998 there is clear evidence of the existence of transitions between the flavor eigenstates suggesting that neutrinos have non-zero masses. This oscillation mechanism can be formulated in a way that the mass eigenstates $\nu_i = (\nu_1,\ \nu_2,\ \nu_3)$ with masses $m_i = (m_1,\ m_2,\ m_3)$ are related to the flavor eigenstates by a 3×3 unitary mixing matrix U^ν called Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix,

$$|\nu_\alpha\rangle = \sum_i (U^\nu_{\alpha i})^* |\nu_i\rangle \tag{1}$$

From this formulation, four numbers are needed to specify all of the matrix elements, namely three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and one complex phase (δ). The parametrisation of the mixing matrix is usually represented following the form proposed by Chau and Keung [13] defined by:

$$U^{\nu} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \tag{2}$$

where $c_{jk} \equiv \cos\theta_{jk}$ and $s_{jk} \equiv \sin\theta_{jk}$. Neutrino oscillations are driven by the splittings between the neutrino mass eigenstates. It is useful to define the differences between the squares of the masses of the mass eigenstates $\Delta m^2_{ij} \equiv m^2_i - m^2_j$. With this parametrization the probability that a neutrino of energy E and initial flavor α will "oscillate" into a neutrino of flavor β is given by $P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) = |\langle\nu_\beta|\exp(-i\mathcal{H}t)|\nu_\alpha\rangle|^2$, which in vacuum gives

$$P_{\alpha\beta} = \left|\sum_{j=1}^{3} U^*_{\alpha j}U_{\beta j}\,\exp(-iE_j t)\right|^2 = \sum_{j=1}^{3}\sum_{k=1}^{3} U_{\alpha j}U^*_{\alpha k}U^*_{\beta j}U_{\beta k}\,\exp\left(-i\frac{\Delta m^2_{kj}}{2E}t\right) \tag{3}$$

If neutrinos of energy E travel a distance L then a measure of the propagation time t is given by L/E. Non-zero Δm^2_{ij} will result in neutrino flavor oscillations that have maxima at given values of L/E, and oscillation amplitudes that are determined by the matrix elements $U^{\nu}_{\alpha i}$, and hence by $\theta_{12}, \theta_{23}, \theta_{13}$, and the CP violation phase δ. The oscillation frequency is governed by the ratio L/E and any experiment dedicated to oscillation studies will be designed to control this ratio as much as possible to infer the neutrino oscillation parameters.

2.2 Matter effects- the MSW effect

It is important to understand that the propagation in vacuum is the simplest case. However neutrino sources, like the sun, can be far from the detection point and the neutrinos have to travel also matter densities before reaching the detectors.The induced effect is understood as the Mikheyev, Smirnov, Wolfenstein (MSW) effect [14] which was first confirmed by the solar neutrino observation. The effect is to add an additional term in the hamiltonian for describing the neutrino propagation in matter. The extra term arises because ν_e have an extra interaction via W boson exchange with electrons in the Sun or Earth. This is not the case for the two other neutrino flavours. The MSW effect can produce an energy spectrum distortion and flavor regeneration in Earth giving a day-night effect. If observed, an important consequence is that the matter interactions depend on the mass hierarchy defined by the sign of Δm^2_{31}.

If one includes the matter effects in the 3ν transition probability described above, Eq. 3 becomes much more complicated. As an example here is the probability of transition betweem ν_μ and ν_e including dominant, sub-dominant oscillations, matter and CP violation terms:

$$\begin{aligned} p(\nu_\mu \to \nu_e) = {} & 4c^2_{13}s^2_{13}s^2_{23}\sin^2\frac{\Delta m^2_{13}L}{4E} \times \left[1 \pm \frac{2a}{\Delta m^2_{13}}(1-2s^2_{13})\right] && \theta_{13}\text{ driven} \\ & + 8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m^2_{23}L}{4E}\sin\frac{\Delta m^2_{13}L}{4E}\sin\frac{\Delta m^2_{12}L}{4E} && \text{CPeven} \\ & \mp 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m^2_{23}L}{4E}\sin\frac{\Delta m^2_{13}L}{4E}\sin\frac{\Delta m^2_{12}L}{4E} && \text{CPodd} \\ & + 4s^2_{12}c^2_{13}\{c^2_{13}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\}\sin\frac{\Delta m^2_{12}L}{4E} && \text{solar driven} \\ & \mp 8c^2_{12}s^2_{13}s^2_{23}\cos\frac{\Delta m^2_{23}L}{4E}\sin\frac{\Delta m^2_{13}L}{4E}\frac{aL}{4E}(1-2s^2_{13}) && \text{matter effect (CP odd)} \end{aligned}$$

where the matter densities is embedded in $a = \pm 2\sqrt{2}G_f N_e E_\nu$.

2.3 Experimental status

Several experiments exploiting all the possible sources of neutrino gave important and coherent results to determine the various oscillation parameters. The determination of Δm^2_{31} and θ_{23} came initially from the observation of a clear disappearance of the ν_μ produced in the atmospheric particle showers. This observation was made by the Kamiokande, Soudan II and MACRO experiments in the 90's. However the first compelling evidence for neutrino oscillation in the atmospheric shower came in 1998 with the measurement by Super-Kamiokande [15] of a dependance of this deficit as a function of the zenith angle which is directly related to the distance the neutrinos are traveling through the Earth. While the ν_e were not showing such distortions the preferred hypothesis fitting well all the data is the $\nu_\mu \rightarrow \nu_\tau$ oscillation origin. Applying this hypothesis the best fit result gives $\Delta m^2_{31} = 2.1$x$10^{-3} eV^2$ and a maximal mixing with $\theta_{23} = 1$. This result was confirmed by the K2K experiment [16] which used a home made neutrino source with the first long baseline neutrino beam in Japan. The beam was sent from KEK laboratory to Super-Kamiokande detector 250 km away. The mean neutrino energy was 1.3 GeV and they observed a slight deficit of neutrino interaction compared to what was expected from the extrapolation of the interactions seen in a near detector without oscillation. The resulting values of Δm^2_{31} and θ_{23} were fully compatible with the parameter space measured with the atmospheric neutrinos.

The determination of Δm^2_{21} and θ_{12} is coming essentially from the solar and reactor neutrinos. Since more than 30 years experiments (^{37}Cl, Gallex/GNO, SAGE, SuperK etc...) got a puzzling fact with the observation of a deficit of more than 30-50% of the solar neutrino arriving on the earth compared to the prediction given by the standard model of the sun. The real breakthrough arrived with the SNO detector which observed not only the same deficit but unlike the others was sensitive to all neutrino flavours and not only to ν_e interactions. Thanks to the use of heavy water, it was possible to measure the neutral current process via the breaking of the tritium nucleus liberating a neutron which gives a neutron capture signal in the detector. From their measurements shown in Fig. 6 they found that the 'all flavour' rate is compatible with the model of the sun and that the flux of ν_e is compatible with an oscillation hypothesis favouring also a large mixing angle [17]. The solar neutrino solution

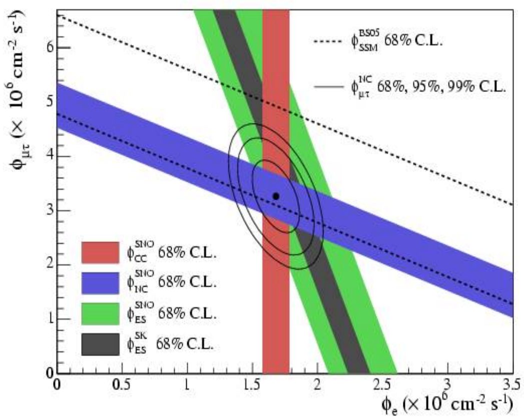

Figure 6: Flux of ^{8}B solar neutrinos that are μ or τ flavor vs flux of electron neutrinos deduced from the three neutrino reactions in SNO [18].

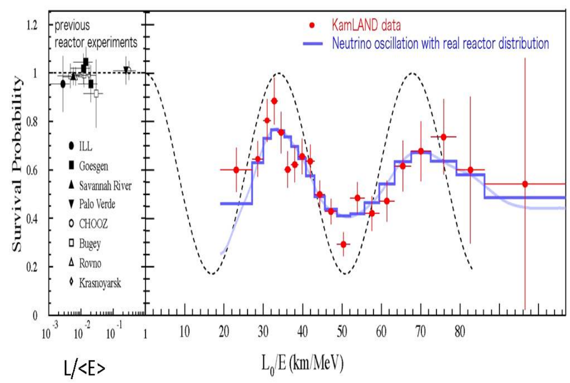

Figure 7: Ratio of the background subtracted anti-neutrino spectrum to the expectation for no-oscillation as a function of L/E. L is the effective baseline taken as a flux-weighted average (L=180 km) [19].

was tested and confirmed by the Kamland experiment [19] which performed the first observation of neutrino oscillations from reactor sources by measuring the energy spectrum of neutrinos produced in about 55 nuclear reactors in Japan. The mean distance for the neutrino to reach the Kamioka mine were the detector is located is about 180 km. The result of the KamLAND measurement, shown in Figure 7, exhibits the expected oscillatory behaviour and constitutes compelling evidence for neutrino oscillations. By combining all solar and Kamland results the oscillation hypothesis fit gives the following values for the second mass difference and the second angle: $\Delta m^2_{21} = (7.59 \pm 0.21)x10^{-5} eV^2$ and a large mixing with $tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$.

The third mixing angle θ_{13} is still not measured. There exist only an experimental constraint from the CHOOZ reactor experiment [20] giving $sin^2(2\theta_{13}) < 0.20$ at 90% CL. Table 1 summarises the present knowledge of the oscillation parameters exploiting all the possible data available. The numbers shown are obtained from a global 3-ν analysis performed in summer 2008 [21].

3 Running accelerator oscillation projects

The goals of the presently running and future experiments are to go deeper in the understanding of the MNSP mixing matrix and oscillation mechanism. The main items are: more precise measurements of Δm^2_{31} and θ_{23}, the quest of θ_{13}, studies of the mass hierarchy with the sign of Δm^2_{31} through matter effects and study possible CP violation in leptonic sector by comparing the transition probabilities of neutrino with the ones of anti-neutrinos.

Table 1: Global 3ν oscillation analysis (2008) extracted from [21]: best-fit values and allowed n_σ ranges for the mass-mixing parameters.

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.67	0.312	0.016	0.466	2.39
1σ range	7.48 – 7.83	0.294 – 0.331	0.006 – 0.026	0.408 – 0.539	2.31 – 2.50
2σ range	7.31 – 8.01	0.278 – 0.352	< 0.036	0.366 – 0.602	2.19 – 2.66
3σ range	7.14 – 8.19	0.263 – 0.375	< 0.046	0.331 – 0.644	2.06 – 2.81

All this list represents a lenghty experimental and theoretical program with several challenging steps. The current phase corresponds to the first long baseline generation using conventional muon neutrino beam. Two projects are running. The Minos/NUMI project in the USA and the OPERA/CNGS european project. They have both a baseline of about 730 km. Minos is performing detailed studies [22] of ν_μ disappearance to improve the parameter precisions while OPERA is designed to provide a direct proof of the existence of $\nu_\mu \to \nu_\tau$ transition looking at direct ν_τ appearance [9, 23]. Both projects aim to measure also θ_{13} looking at the appeance channel $\nu_\mu \to \nu_e$. First results on this subject from Minos have been presented during 2009 winter conferences [24]. Figure 8 shows the ratio of the MINOS Far Detector data energy spectrum to the energy spectrum expected in the absence of neutrino disappearance where a clear distortion and deficit is visible at low energies compatible with the oscillation hypothesis. Figure 9 shows the reconstruction in emulsions of a neutrino interaction vertex recorded in OPERA during the 2008 run. The vertex tracks show a kink on one of them similar to what is expected from a short lived particle like a charm meson or a tau particle decaying in the target emulsions.

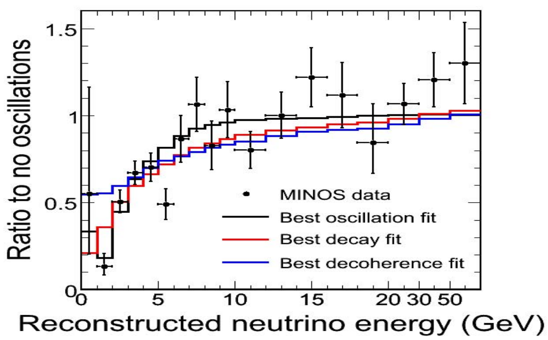

Figure 8: Ratio of the MINOS Far Detector data energy spectrum to the energy spectrum expected in the absence of neutrino disappearance (black points) [22].

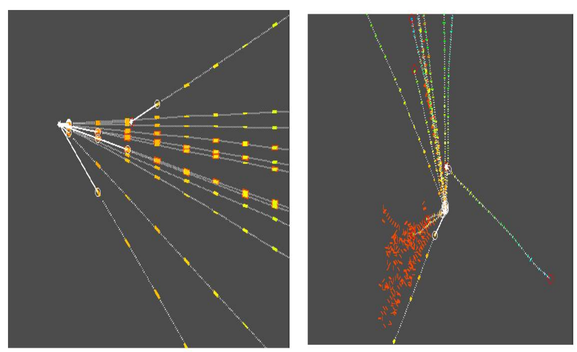

Figure 9: Reconstruction of a neutrino interaction vertex in a emulsion target element of OPERA. One track shows a clear kink similar to the ones expected from tau or charm particle decays.

4 Future experiments

The second experimental phase corresponds to the quest of θ_{13} which remains the missing mixing angle. For this search two approaches are confronted. As it was shown previously the transition $\nu_\mu \to \nu_e$ combines effects from θ_{13} and the CP violation phase δ. The two parameters are correlated in the ν_e appearance channel. In addtion, matter effects could modify the transition probabilities depending on the mass hierarchy. Each experiment should carefully take into account all those effects. A positive result with accelerator experiment will give a bi-parameter contour solution while a disappearance experiment like in reactor experiment will give access to the θ_{13} value.

4.1 Long Baseline Experiments

There are two projects going on. The T2K experiment [25] which is well advanced using a ν_μ beam from Tokai to Super-Kamiokande with a baseline of 295 km. The mean neutrino energy is 0.7 GeV with an ν_e contamination of about 0.4%. The second project called NOνA [26] is under study and is using a baseline of 810 km with mean ν_μ energy of about 2.2 GeV. The very long distance will give possibility to study matter effects on the neutrino

oscillation rate. The neutrino beams are conventional beams but with an increased power going from 0.4-0.8 MW exploiting also the 'off-axis' technique which allows a much narrower neutrino energy spectrum with reduced background contamination as well as a better control of the L/E ratio to maximise the ν_e appearance. Details about the T2K project and the advancement can be found in Ref. [25]. The beam has been already commissioned in May 2009 and a gradual beam power increase is expected from 0.2 MW to 1.0 MW in 4 years. There are two near detectors at 280m from the neutrino source, one at 0 degree angle and one at 2.0 ^{o}. The Super-Kamiokande detector will be used as the far detector and is ready for data taking. A full running period should start at the end of this year.
The NOνA experiment will search for $\nu_\mu \to \nu_e$ oscillations in the existing NuMI neutrino beam using a 15 kiloton liquid scintillator detector. Funding has been recently approved and construction is about to start on the far detector site.

4.2 Reactor experiments

The alternative method is to measure the survival rate of $\bar{\nu}_e$ close to nuclear reactor like it was done with the CHOOZ experiment. Up to second order in $\sin 2\theta_{13}$ and $\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$ the survival probability can be expressed as:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2 2\theta_{13} \, \sin^2(\Delta m^2_{31} L/4E) + \alpha^2 \, (\Delta m^2_{31} L/4E)^2 \, \cos^4 \theta_{13} \, \sin^2 2\theta_{12} \, , \quad (4)$$

The last term of this expression can be easily neglected if the ratio L/E is chosen close to the atmospheric maximum. Reactor experiments thus provide a clean measurement of the mixing angle θ_{13}, free from contamination coming from matter effects and other parameter correlations or degeneracies. They are essentially dominated by statistical and systematic errors. In order to reduce the systematic uncertainties the principle of the new generation of reactor experiment is to use two detectors. One near at about 100 to 200 m from the reactor core and one far at about 1 to 2km. This garantees that the L/E ratio is close to the atmospheric maximum value. The comparison of the measured $\bar{\nu}_e$ between the two sites will cancel part of the systematical uncertainties from the reactor flux and cross sections. The target mass of the two detectors vary from 8 tons to about 100 tons. The real challenge is to be able to reduce the relative normalisation uncertainty below 1%. There are several projects under way. The Double-Chooz experiment is the most advanced one [27]. The far (1km) detector site is constructed and the 11.2 tons detector should start taking data beginning of 2010. The near site (400m) is under construction and will be completed to host a second identical detector in 2011. The full setup should take data in 2011. Figure 10 shows the θ_{13} sensitivity limit as a function of the year which can be obtained by Double-Chooz running in two phases.

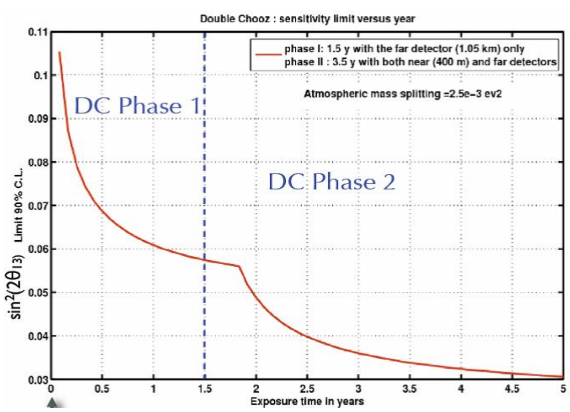

Figure 10: Double CHOOZ prospects for θ_{13} sensitivity limit.

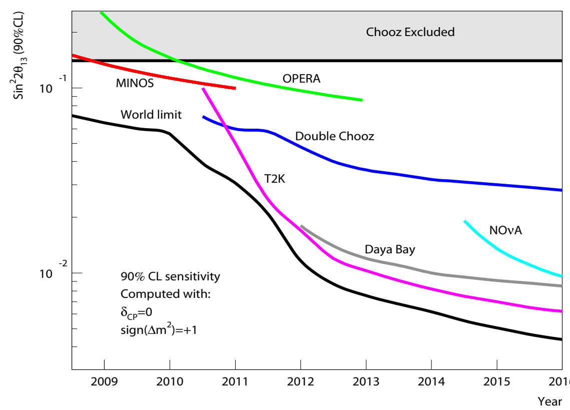

Figure 11: World perspectives for θ_{13} sensitivity limit [29].

The second main project is called Daya Bay [28] and it can be considered as a second generation experiment which is more amibitious since it aims to reduce the systematic uncertainty by a factor 2 and be able to give a limit on $sin^2 2\theta_{13} < 0.01$ at 90% CL. The principle will be to use 6 to 10 mobile detectors which can be interchanged to compare their efficiencies. The project may start after 2011.

Figure 11 shows the world limit which can be achieved as a function of time by combining all the experiments which aim to contribute to θ_{13} measurements. The Double-Chooz, T2K and Daya Bay projects will allow to reduce the limit on $sin^2 2\theta_{13}$ by more than one order of magnitude in a decade if the angle stays too small to be detected.

5 Conclusions and perspectives

The reactor and accelerator experiments are complementary; At the 2016 horizon there should be confirmation of the transition $\nu_\mu \rightarrow \nu_\tau$, more precise measurements of θ_{23} and Δm^2_{31} and more constraints on θ_{13} if not a discovery. And why not maybe the first indication for mass hierarchy choice.
It is the first step to pinpoint the true nature of the leptonic flavour transformation. It will not allow to see CP violation but it will help in defining what should be the path to follow beyond 2015.
This next step will be the quest for δ_{CP} and precision measurements of the neutrino parameters. The technology and experiments foreseen are various. They include more powerful superbeams of second generation together with BetaBeam coupled to large volume detectors like Megatonne Water cherenkov, liquid argon, liquid scintillator detectors and a facility called Neutrino Factory.

Neutrino physics is a very active field. Since 10 years several new results changed our view of the field and comforted us to revise our current knowledge within the Standard Model. A lot of experimental and theoretical challenges are in front of us and worth being pursued.

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