PROCEEDINGS OF SCIENCE

Prospects on Neutrino Physics

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Compelling evidences for oscillactions of solar and atmospheric neutrinos have been acumulated over the last years[1]. The neutrino oscillations have been also confirmed with artificially produced neutrinos. The neutrino oscillations imply the existence of 3-neutrino mixing in vacuum. This vast experimental program has proven the oscillation between sets of two neutrino flavours. The existence of a third mixing angle, the Dirac or Majorana nature of neutrinos, the absolute mass scale and the possibility of CP violation in the lepton sector are still open questions. We present the experimental program for the following years.

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1. Introduction

The hypothesis of neutrino oscillations was formulated in [2]. The evidences of solar neutrino oscillations were first observed in the Homestake experiment and confirmed by the results of Kamiokande[3], SAGE[4] and GALLEX/GNO[5] experiments. Compelling results were presented in the last years by the data of Super-Kamiokande (SK)[6], SNO[7], Kamland[8] and K2K [14] experiments. These results can be economically accommodated in the Standard Model (SM) with neutrino masses and a three-neutrino mixing matrix, the so called Pontecorvo-Maki-Nakagawa-Sakata(PMNS) matrix. In this case, the lepton sector of the SM closely resembles that of the quarks. There are a number of new physical parameters that can be measured: the three neutrino masses, m_i (i = 1, 2, 3),three mixing angles, θ_{ij} , ($i \neq j = 1, 2, 3$), and a CP violating phase,δ.

Of all these new parameters, present experiments have determined just two neutrino mass-square differences and two mixing angles: ($|\Delta m^2_{23}| \simeq 2.5\times10^{-3}$ eV^2, $\theta_{23} \simeq 45^0$) which mostly drive the atmospheric neutrino oscillations and ($|\Delta m^2_{12}| \simeq 7.0\times10^{-5}$ eV^2, $\theta_{12} \simeq 35^0$) driving the solar one. The third angle,θ_{13}, as well as the CP-violating phases δ, remain undetermined. Another essential piece of information needed to clarify the low-energy structure of the lepton flavor sector of the SM is the neutrino mass hierarchy. This is related to the sign of the largest mass-square difference (Δm^2_{23}), which determines if the spectrum is hierarchical (if the two most degenerate neutrinos are lighter than the third one) or degenerate (if they are heavier). The measurement of these parameters requires, for the first time, high precision neutrino oscillation experiments. A number of possible experimental setups have been proposed including neutrino factories, superbeams, reactor neutrino experiments and β beams.

Another fundamental question is whether neutrinos are Dirac or Majorana particles. Neutrinos are the only one among fundamental fermionic constituents of matter that might be their own antiparticles. Neutrinos are not electrically charged, contrary to quarks and charged leptons, and they, as far as we know, do not carry any other conserved, charged-like quantity. A neutrino that is identical to its antiparticle is referred to as a Majorana particle, while the one that is not is referred to as a Dirac particle. Majorana neutrinos implies the conservation of the leptonic number(L). The confirmation that L is not conserved would come from the observation of the neutrino-less double decay ($0\nu2\beta$), a process in which a nucleus decays to another with the emission of two electrons and no neutrinos. The interest on this topic has risen in the last years after claims of first evidence of $0\nu2\beta$ in ^{76}Ge isotopes and by the discovery of neutrinos to be massive particles. We will review the list of future measurements and experiments on $0\nu2\beta$ with special emphasis on the implications on mass hierarchies and mass limits.

Apart from indirect methods presented above, there is only one model-independent strategy to address the neutrino mass directly: investigating the kinematics of electrons from β decays. We will present an overview of the experimental strategies to reach sub-eV sensitivity in the near future by analyzing the electron energy of the ^{3}H β decay endpoint.

Finally, future experiments to study neutrino interactions are presented. The neutrino interaction experiments are profiting from the new generation of high intensity neutrino beams. The understanding of neutrino interactions is fundamental to reduce systematic errors of neutrino oscillations.

2. Oscillation physics

After the first round of neutrino oscillation experiments a set of parameters have been determined with a degree of precision. These parameters include the mixing angles θ_{12},θ_{23}, the mass square difference Δm^2_{12} and $|\Delta m^2_{23}|$. Further important issues will be the determination of the neutrino mass hierarchy (the sign of Δm^2_{23}), the third mixing angle θ_{13} and to check if the mixing angle θ_{23} is maximal which could be the indication of a hidden symmetry. There are three classes of experiments under discussion for the next generation of long-baseline oscillation experiments: conventional beam experiments with increased intensity and reactor experiments will be available in a first phase with expected results around 2015 and β-beams and neutrino factory that are being planned in a second phase to start at the end of the next decade.

The literature on this issue is large and some times not matching in the conclusions as it is expected in a developing field like neutrino oscillations. We are not trying to make an exhaustive review of all possible solutions to the problem but to show the thinking lines and limitations accepted by the community.

2.1 θ_{13} and CP violation

The measurement of the θ_{13} mixing angle is done via the sub-leading transitions $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$. In order to obtain a qualitative understanding of the oscillation parameter measurements, it is sufficient to use simplified expressions for the transition probabilities. The expression for the $\nu_\mu \rightarrow \nu_e$ appearance probability up to second order in $\frac{\Delta m^2_{12}}{\Delta m^2_{23}}$ and $\sin^2\theta_{12}$ is given by [9, 10, 11, 36]

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) &\simeq \sin^2\theta_{13}\sin^2\theta_{23}\sin^2\Delta && (2.1)\\ &\mp \alpha\sin 2\theta_{13}\sin\delta\sin 2\theta_{12}\sin 2\theta_{23}\Delta\sin^2\Delta && (2.2)\\ &+ \alpha\sin 2\theta_{13}\cos\delta\sin 2\theta_{12}\sin 2\theta_{23}\Delta\cos\Delta\sin\Delta && (2.3)\\ &+ \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\Delta^2 && (2.4) \end{aligned}$$

with $\Delta = \frac{\Delta m^2_{31}L}{4E_\nu}$ and $\alpha = \frac{\Delta m^2_{12}}{\Delta m^2_{23}}$. Reactor neutrinos can be described by the disappearance probability to second order in $\sin^2\theta_{13}$ and α

$$1 - P(\nu_e \rightarrow \nu_e) \simeq \sin^2 2\theta_{13}\sin^2\Delta + \alpha^2\Delta^2\cos^4\theta_{13}\sin^2 2\theta_{12} \tag{2.5}$$

As it can be seen the first equation is sensitive to the CP violation phase δ while the disappearance formula does not. The probability for ν_μ to ν_e transition is affected by several uncertainties: the sign of Δm^2_{31}, the correlation between the θ_{13} dependency and δ and the (θ_{23},$\pi/2-\theta_{23}$) (note that this degeneracy vanishes when we adopt the best fit value for $\theta_{23} = \pi/4$.) degeneracy from the $\sin^2\theta_{23}$ and $\cos^2\theta_{23}$ terms. This leads to an overall “eight-fold” degeneracy[12].

It can also be seen that in equation 2.5 the dependency with the solar θ_{12} and atmospheric θ_{23} appears only to the second order of the expansion. From this equation it is obvious that the reactor experiments cannot access θ_{23}, δ or the mass hierarchy, but it allows for a clean (degenerate free) measurement of the $\sin^2 2\theta_{13}$.

The measurement of the CP violation phase has to be done with an appearance experiment like of the type $\nu_\mu \rightarrow \nu_e$. Disappearance experiments, like the one described by Eq.2.5, is not sensitive to this parameter. The CP violation is measured via the asymmetry:

$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \propto \alpha \sin 2\theta_{13} \sin\delta \tag{2.6}$$

It can be seen that the asymmetry is only possible for a value of θ_{13} different from zero. The asymmetry is also proportional to the value α, leading to values of the asymmetry of the order of less than a percent which makes it a difficult measurement.

An important effect that must be taken into account is the matter induced oscillations which neutrinos undergo along their flight path from the source to the detector. The ν_e suffers a different forward coherent scattering off the electrons in the media involving both the exchange of a Z and W bosons. The ν_μ and ν_τ scatters only via the neutral current. This mismatch induces changes in the parameters of the neutrino oscillations in vacuum. In contrast with the vacuum result, the probability in matter depends on the sign of Δm^2_{13} and it is different for neutrinos and anti-neutrinos. Matter effects can be used as a way to resolve the degeneracies, to be able to define the neutrino mass hierarchy and to improve the sensitivity to some measurements.

2.2 Super Beams

The new generation of conventional beams come with a set of common properties. On one side, the off-axis configuration has been adopted the paradigm for better θ_{13} sensitivity in this environments. On the other side, massive far detectors and very high intensity beams are being proposed or built for large statistic experiments.

2.2.1 MINOS and OPERA

The second generation of long base line experiments after K2K [14], MINOS [15] and CNGS [16], are starting during years 2005 and 2006, and they will be completed by the end of the decade.

MINOS detector[15] will make sensitive measurements of muon neutrino disappearance, and thereby make a measurement of Δm^2_{23} accurate to about 10%. The MINOS experiment is a long base line neutrino experiment (700 km) from Fermilab to Soudan mine. The far detector is a 5.4 kT magnetized iron sampling tracking calorimeter that will look for the ν_μ disappearance in a conventional wide band neutrino beam.

The CNGS [16] experiments are using a higher-energy neutrino beam, and are aimed at making a conclusive demonstration of the mechanism for atmospheric neutrino disappearance by actually observing the appearance of ν_τ from $\nu_\mu \rightarrow \nu_\tau$ oscillations. The OPERA experiment is a emulsion detector being build at the Gran Sasso Laboratory in Italy. The emulsion technique helps in identifying the τ appearance signature in a conventional ν_μ beam to confirm the hypothesis of an almost pure $\nu_\mu \rightarrow \nu_\tau$ oscillation.

2.2.2 Off-axis beams

The off-axis beams were developed for the proposed experiment E-889 at Brookhaven[13]. It is possible to obtained an almost monochromatic neutrino beam by viewing the beam at a location off the beam axis, while using a conventional neutrino beam. The off-axis beam relies on the fact that the neutrinos produced with a fixed angle with respect to the parent pion in the beam have almost the same energy. The reduction of the neutrino flux at the peak energy is compensated by the fact that all pions contribute with the same neutrino energy. This can be seen in Fig.1 where the neutrino energy is plotted as a function of the parent pion momentum for different neutrino energies. The main advantage of the off-axis method comes from the fact that the spectrum is almost monochromatic so the background to appearance events from high energy neutrinos is reduced. This is a valid statement for the two projects that are being discussed at the moment: T2K in Japan that implies the third generation of experiments based on SuperKamiokande and NOνA in USA that utilizes the beam developed for the MINOS experiment.

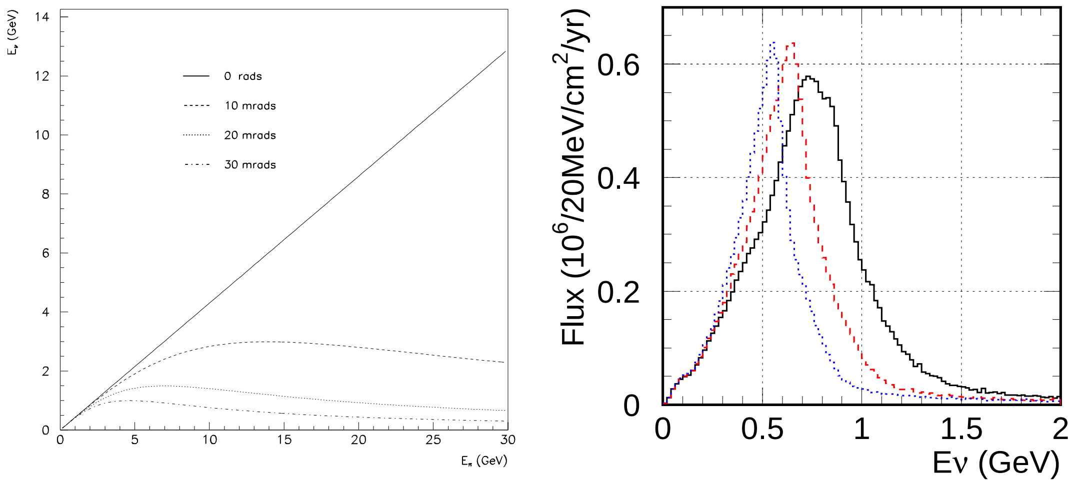

Figure 1: Left:The energy of the neutrino produced at different angles relative to the pion beam direction as a function of pion energy.Right: Energy spectra from T2K off-axis beams: black-solid line (2 degree), red-dashed line (2.5 degree), and blue-dotted line (3 degree). As the off-axis angle increases, the energy peak narrows and moves lower in energy.

2.2.3 T2K and NOνA

The Tokai to Kamiokande (T2K)[17] experiment is aimed at two main goals — the more accurate determination of the "atmospheric" parameters θ_{23} and Δm^2_{23}, and a measurement of θ_{13} with more than an order of magnitude sensitivity than any previous experiment. The project is based on adding a neutrino beam line to at the 50 GeV synchrotron currently under construction at the new JPARC facility in Tokai, Japan [18] to produce an intense neutrino beam. The high power of the JPARC proton beam, 0.75 MW in Phase I, rising to 4 MW in Phase II, expected about 2015, will produce the most intense neutrino beam ever built. This beam then propagates underground for 295 km to the Super Kamiokande detector [19] in western Japan, which is well suited for distinguishing ν_e and ν_μ in the neutrino beam by looking at Cherenkov radiation from μ's and e's produced by charged-current interactions in its 50 kton water target. The baseline distance is small with respect to appearance of matter effects. This is a fact that distinguish T2K from the longer base line NOνA experiment.

The expected sensitivities in Phase-I for the ν_μ disappearance measurements are $\delta(\sin^2(2\theta_{23})) \sim 0.01$, and $\Delta m^2_{23} \sim 4\,10^{-5}$. The sensitivities to the $\sin^2 2\theta_{13}$ has been quoted to be of the order of 0.006. These numbers assume 5 years of operation at the nominal 0.75 MW neutrino beam power.

The NOνA proposal consists on utilize Fermilab's investment in the NuMI beamline by building a second-generation detector, which will have the primary physics goal of measuring $\nu_\mu \to \nu_e$ with approximately a factor of 10 more sensitivity than MINOS. To accomplish this, NOνA has developed major improvements on the MINOS detector design to optimize it for the detection of electron neutrinos by increasing the mass of the far detector from 5.4 kT to 30 kT, increase the capabilities of the far detector to identify electrons with a "totally active" fine segmented tracking calorimeter and using the off-axis method like in T2K. The far detector is located at 810 km from the Fermilab site, this distance makes the contributions from matter effects on the oscillations non-negligible. The matter effects have opposite signs for neutrinos and anti-neutrinos, and for the normal and the inverted hierarchy. The matter effects can be used to distinguish from the different hierarchy (i.e. sign of the Δm^2_{23}). This effect is not existing for the T2K baseline. The synergy's between NOνA and T2K could help in resolving the degeneracies for the mass hierarchy and CP violation phase[21]. The expected sensitivity of NOνA is 0.01 for $\sin^2(2\theta_{13})$ in 5 years assuming 3.4 10^{20} protons/year (0.65 MW).

There are also proposals on how to constrain the degeneracies in Long Base Line experiments using atmospheric neutrino oscillations[22]. The atmospheric neutrinos have a large range of energies and distances that provides sensitivity to the octant and neutrino mass hierarchies. This can be achieved with a new generation of atmospheric neutrino detectors like INO proposal[23] to be located at India. The INO detector is a magnetized sampling calorimeter similar to the MONOLITH proposal[24]. The large mass ($60KT$) and the separation of neutrinos from anti-neutrinos capabilities allow to study the earth matter effects and get sensitivity to the θ_{13} angle and CP violation phase δ via matter effects.

2.3 The reactor experiments Double-Chooz and Reactor II

The reactor neutrino experiment, Chooz, is the source of the most stringent limit on θ_{13}[26]. Chooz looks at the $\bar{\nu}_e$ disappearance as a sign of neutrino oscillation. A new generation of reactor neutrino experiments is trying to improve on the sensitivity by adding a second detector close to the reactor for flux normalization and providing larger facilities to increase the statistics. The reactor neutrino experiments are complementary to those of conventional neutrino beams from the systematics and by the fact that the $\bar{\nu}_e$ disappearance is not sensitive to CP violation phase δ. The reactor neutrino experiments would help to disentangle form the different degeneracies in $\nu_\mu \to \nu_e$ appearance experiments, there is no matter effect and it is also insensitive to uncertainties in solar oscillation parameters.

A set of different proposals are being discussed, including reactors in Brazil, China, France, Japan, Russia, Taiwan and the USA. Among the discussed options are the KASKA project in Japan[27], several power plants in USA[28, 29] (Diablo Canyon or Braidwood) and the double-Chooz[30] in France.

The double-Chooz experiment, planned for installation in 2007, will utilize the cavern of the previous Chooz experiment locate 1.05 km, which is slightly too short for the current best fit value $\Delta^2_{31} \simeq 2\,10^{-3} eV^2$. The far detector will increase in volume by a factor of 2.5 to a total of 12.7 m^3. The near detector will be identical inside the PMT structure, which will allow to keep the systematic of relative normalization below 0.6%. Double-Chooz collaboration claims an expected sensitivity for $\sin^2(2\theta_{13}) > 0.03$ at 90% C.L. in three years of data taking.

Other proposals, like Braidwood in USA, requires a larger investment and starting date will be beyond 2010. The new experiments will be located with the optimal distance between near and far, providing also same background conditions and systematics. Braidwood is also proposing to swap near and far detector to allow keeping the relative normalization error to the minimum. The proposed detector for the near and far sites have a fiducial mass of 6.5 Gd made of Gd-loaded scintillator. The Gd helps in reducing the background identifying the neutron expelled in the inverse β-decay reaction from the photon emission of the neutron in Gd. The expected sensitivity quoted by the collaboration is $\sin^2(2\theta_{13}) > 0.01$ at 90% C.L. in three years of operation. The operation of this experiment is planned for 2010, in synchrony with T2K experiment.

2.4 Sensitivity to $\sin^2(2\theta_{13})$ for the first generation of experiments

Figure 2 reviews the sensitivities to $\sin^2(2\theta_{13})$ at 90% C.L. as a function of the true value of Δm^2_{31} that has been compiled by P.Huber et al.[25]. This picture is the expected status of the $\sin^2(2\theta_{13})$ measurement by 2015 if no positive result is available. The authors of[25] also points that combining reactor and super beam experiments we can rule up to 40% of all possible CP violation phase for a given hierarchy. The wrong hierarchy can be ruled out at a modest CL with $\Delta\chi^2 \simeq 3$ due to matter effects in NOνA.

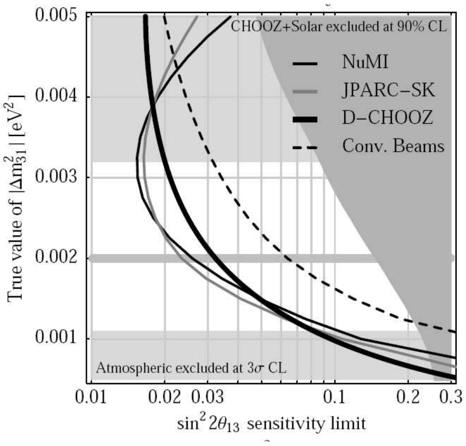

Figure 2: Sensitivity to $\sin^2(2\theta_{13})$ at 90% C.L. as a function of the true value of Δm^2_{31}[25].

2.5 Beta Beams

The β-beam concept was first introduced in[31]. It involves producing a beam of β-unstable heavy ions, accelerating them to some reference energy, and allowing them to decay in the straight section of a storage ring, resulting in a very intense neutrino beam. Two ions have been identified as ideal candidates: ^{6} He, to produce a pure $\bar{\nu}_e$ beam, and ^{18}Ne, to produce a ν_e beam. The golden sub-leading transitions $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ can be measured through the appearance of muons in a distant detector. The β-beams show two very appealing properties: it is a pure beam and the energy spectrum can be computed exactly. The present design, whose feasibility with existing technology has been recently demonstrated [32], envisions a "low-γ" scenario, in which ions are produced by a new facility (EURISOL), accelerated by the present SPS to $\gamma \leq 150$, and stored in a storage ring (also a new facility) with straight sections pointing to the experimental area. An underground location where a very massive neutrino detector could be located has been identified in the Fréjus tunnel, roughly 130 km from CERN. This baseline is ideal for exploring the first peak of the atmospheric oscillation, the optimal environment to search for CP-violating effects.

The capability of this design has been recently reviewed in[33] for different values of the $\gamma(^6\mathrm{He})$. The baseline design includes a far detector of 440 kton fiducial and a total of 10^{19} decays/year (30% ^{18}Ne, 70% ^{6}He) in 10 year operation. The sensitivity reach of such setup for $\sin^2(\theta_{13}) > 2.10^{-4}$ at 90% C.L. for $-120^o < \delta < 120^o$. This sensitivity falls between the reach of SuperBeams phase one and the neutrino factory.

There are recent proposals to resolve the degeneracies by the energy dependency of the neutrino oscillation using a monochromatic neutrino beam based on acceleration of ions that decay by electron capture. Preliminary studies show that with the careful selection of energy points allow for precision measurements, allowing for the discovery of CP violation for values of θ_{13} down to 1 degree. The electron capture is a two body decay process in which an atomic electron is captured by a proton in the nucleus, replacing a proton by a neutron and emitting a neutrino in the final state. The neutrino is fixed since this is a two body decay. The ions can be accelerated to different boosts such that a pure neutrino beam of fixed energy can be obtained. This possibility has been opened after the discovery of ions that decay fast enough via electron capture. There have been few identified candidates: ^{148}Dy, ^{150}Dy, $^{152}\mathrm{Tm}^{--}$ and $^{150}\mathrm{Ho}^{--}$, which lifetimes varies from 72 s to 7 m. One of the investigated scenarios proposed the used to two γ factors ($\gamma =$ 195 and 90) for 5+5 years of operation, 10^{18}ions/year and 440 Kton water Cherenkov as a far detector located at 130 km from source. This scenario provides sensitivity to θ_{13} down to 2 degrees independently of the CP violation phase. A disadvantage of this proposal is the impossibility of producing anti-neutrinos. The anti-neutrino beam can be, however, obtained with standard β-beam. Further studies are needed but it seems to be a promising technique complementary to that of the low γ β-beam.

2.6 Neutrino factory

It has been proposed few years ago the construction of a neutrino factory consisting in a machine capable of accelerating 10^{20} muons to several GeV, injecting the muons into an storage ring with long straight sections. The neutrinos produced in the decay of the muons in these sections will produce a very intense neutrino beam of high energies. The neutrinos produced in $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ and $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ decays open an exciting possibilities to study neutrino oscillations and interactions. Neutrinos are produced in 4 different flavors, with a well known energy spectrum that also distinguishes electron from muon neutrinos. Considering the presence of negative muons (same applies for μ^+) in the storage ring, five types of oscillations are available including disappearance $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_e \rightarrow \bar{\nu}_e$ and appearance $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\tau$, $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\tau$.

The presence of different neutrino flavors place an important role in the detector design. For example, to distinguish between a primary ν_μ from a $\bar{\nu}_\mu$ from $\bar{\nu}_e$ (or even leptons from τ produced in the oscillation oscillation $\bar{\nu}_e \rightarrow \bar{\nu}_\tau$) an excellent lepton charge separation is mandatory. The typical detector designs under consideration assumes a magnetic field a la MINOS[15] and detector masses of the order of 50 ktons. Due to the intrinsic difficulties of identifying the electron charge or positively identify τ's. The baseline design considers only the capability of identifying the muon charge and separating muons and electrons. The events are then classified in four types: right-sign muons (disappearance), wrong-sign muons(appearance), electrons(disappearance) and no leptons (neutral currents).

The neutrino oscillation measurement at the neutrino factory will face also the existence of correlations and degeneracies [36, 37, 38] which prevents the simultaneous measurement of all parameters. Several proposals have been studied to overcome this problem: set different oscillation lengths (or different matter effects), improve energy resolution or make use of the so called "silver channels" with transitions $\nu_e \rightarrow \nu_\tau$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\tau$. The silver channels are very powerful tool in reducing the correlations but they are experimentally more challenging.

The parent muon energy and baseline for "golden" measurement were optimized [36] to be 20 to 50 GeV and few thousand kilometers. The sensitivity to $\sin^2(2\theta_{13})$ using a 40 kton iron calorimeter and the silver channels with a detector similar to the Opera experiment is below 10^{-4} and there is a 99% C.L. discovery potential if $\delta > 10^o$.

The comparison of the performance of the beta-beam and the neutrino factory with respect to the sensitivity to $\sin^2(2\theta_{13})$ is shown in Fig.3[39] for different long base line experiments. The nominal neutrino factory is still the most powerful tool to resolve neutrino oscillations, however the understanding of the optimal beta beam configuration is not complete together with the issue of the total cost and technology availability.

3. Neutrino-less double beta decay

The confirmation that lepton number is violated would come from the observation of neutrino-less double beta decay. The process called neutrino-less double decay consist in the decay of one nucleus to another with the emission of two electrons and nothing else, $(A,Z) \rightarrow (A,Z-2)+2e^-$. It is easy to show that, regardless of what diagrams are involved in $0\nu2\beta$, the observation of this decay would still imply the existence of Majorana neutrino mass term.

The decay rates for this process are given by

$$T_{0\nu2\beta} = G(Q^2_{\beta\beta},Z)|M^{0\nu}|^2\langle m_\nu\rangle^2$$

where $G(Q^2_{\beta\beta},Z)$ is the phase space integral, $|M^{0\nu}|^2$ is the nuclear matrix element and $\langle m_\nu\rangle^2$ is the mass term defined as

$$\langle m_\nu\rangle^2 = |\sum u^2_{ei} m^2_i|$$

where m_i is the mass of the different mass neutrino eigenstates and u^2_{ei} the matrix elements of the PMNS neutrino mixing matrix. The value of the mass term as a function of the lightest neutrino mass is presented in Fig.4 for normal and inverted hierarchy. Clearly $0\nu2\beta$ decay can

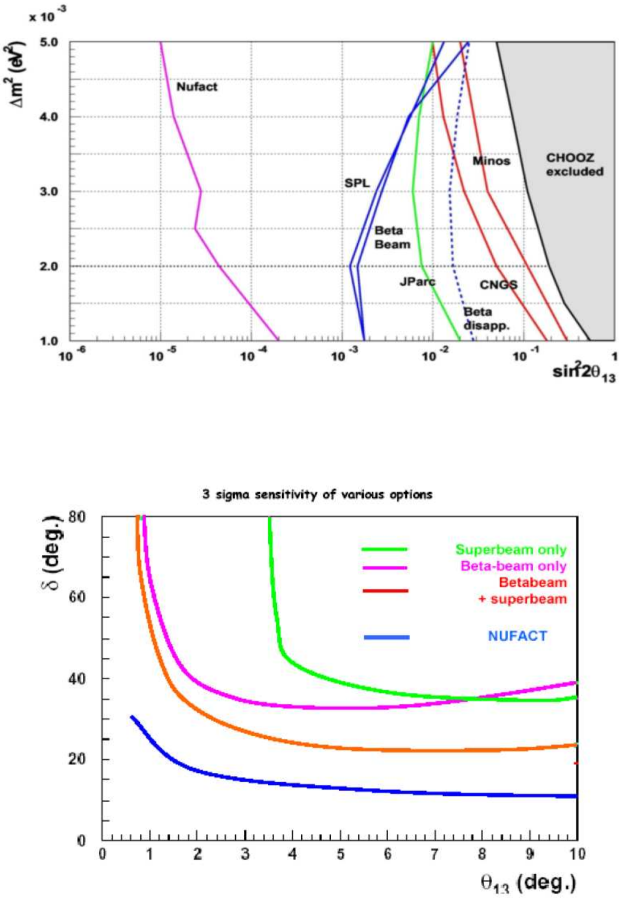

Figure 3: $\sin^2(2\theta_{13})$ sensitivity limits as a function of the Δm^2_{13} (Upper) and 3 σ δ sensitivity as a function of the $\sin^2(2\theta_{13})$(Lower) for different long base line experiments[39]

differentiate between the two hierarchies possibilities and the degenerate scenario. The degenerate scenario would support the recent claim on the observation of $0\nu2\beta$ decays [40].

The decay rate is affected by two kind of uncertainties. The nuclear matrix elements ($|M^{(0\nu)}|^2$) are not accessible experimentally and very difficult to compute theoretically. The mass term is subjected to cancellations depending on the values of the neutrino mixing angles and Majorana phases.

The new generation of $0\nu2\beta$ decays are aiming at precisions better than 0.02 eV which will covers the allowed regions for the inverted hierarchy scheme. All the new proposed experiments are characterize by having very large detector masses and low background levels. The background level changes the sensitivity as a function of the detector fiducial mass. For no background the sensitivity is:

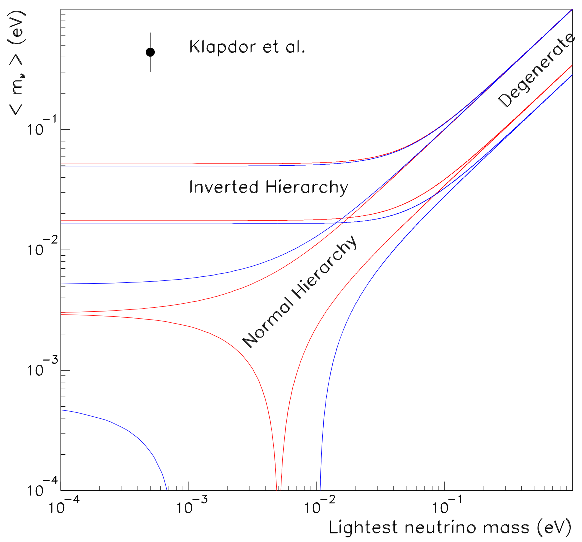

Figure 4: Dependency of the mass term $< m_\nu >$ with the lightest neutrino mass for the normal and inverted scenarios and for two values of the θ_{13} angle: 0 in red and 0.21 in blue. The result form Klapdor et al. [40] is also presented together with the prospects for sensitivity for the first phase of experiments (2010) and second phase (2015).

$$T^{0\nu}_{1/2}(years) > 174/A \times 10^{24}\, \varepsilon\, a\, m\, t$$

with A the isotope mass, ε being the detector efficiency, a the isotope fraction, m the detector mass and t the exposure time. For a large background the figure of merit changes making the measurement less sensitive:

$$T^{0\nu}_{1/2}(years) > 312/A \times 10^{24} \varepsilon\, a \sqrt{\frac{m\, t}{B R}}$$

B the background per mass and exposure time and R the detector energy resolution.

In Table 1 we list the 8 most common isotopes that have large decay energies and are suitable for $0\nu2\beta$ experiments. They are also the most common isotopes used in experimental proposals.

3.1 Germanium experiments

There are at the moment four proposed ^{76}Ge experiments. GEM, Majorana and GERDA. All of them use the Germanium as a high resolution calorimeter. This has been one of the most successful techniques in the past, ended with the claim of neutrino-less double beta decay [40]. This claim is made by only small part of the Heidelberg-Moscow collaboration. In fact, members of the collaboration presented a conflicting interpretation of the experimental results[41]. The new generation of experiments aim to increase the isotope mass and to improve the experimental setup reducing the impurities in the ^{76}Ge, exploiting the locality of the 2β event with proper detector segmentation and adding an active veto (liquid Nitrogen or Argon).

Parent Isotope	$\|Q_{\beta\beta}\|$ keV
^{48}Ca	4271
^{76}Ge	2039
^{82}Sa	2995
^{100}Mo	3034
^{116}Cd	2802
^{130}Ta	2533
^{136}Xe	2479
^{150}Nd	3367

Table 1: The most popular parent isotopes and the total $0\nu2\beta$ decay energy $|Q_{\beta\beta}|$ in keV

GERDA experiment[42], approved to be installed at the Gran Sasso laboratory, will run in two phases. The first phase with a total of 17 Kg of enriched germanium, followed by a second phase with 37 kg. The first phase expect a total of 6 events on a background of 0.5 events assuming the results in [40].

The technology of GERDA is similar to the one proposed for the Majorana[43] experiment. The total isotope mass in the later case is however of the order of 500 kg in the first phase. Majorana is aiming at a limit of 40 meV in 10 years.

3.2 Cryogenic experiments

CUORE[44] is a proposed array of 998 TeO_2 bolometers enriched in ^{130}Te, each one of 750 g. The ^{130}Te has a large Q^2 and a high natural abundance (38%) allowing also for a calorimetric technique. The technique is different form the Ge detectors since it is based on the temperature rise of the TeO_2 during $0\nu2\beta$ decay. A reduced mass prototype has been successfully operated at LNGS with a total of 40.7 kg of TeO_2, this setup is actually the most sensitive experiment ($< m_\nu > >$ 0.3-1.67 eV)[45]. The full detector will be build up and start during the next five years. The sensitivity depends strongly on the background level achieved during the construction and the uncertainties in the nuclear matrix element. The predicted limits varies from 11 meV to 120 meV in five years of operation.

3.3 Large Xe experiments

The EXO experiment[46] proposes to search for $0\nu2\beta$-decay of ^{136}Xe to ^{136}Ba in a multi-ton time projection chamber(TPC). There is an active research and development program to develop a tagging procedure of the daughter $^{136}Ba^{++}$ ion after it is partially neutralize. The scheme involves identifying the more stable $^{136}Ba^{+}$ ion by isolating it and using laser induced fluorescence spectroscopy. The Ba^+ has a very strong allowed transition at 493 nm from the ground state ($6^2S_{1/2}$) to the excited state ($6^2P_{1/2}$). From this state there is a decay branching ratio of 30% to the metastable ($5^4P_{1/2}$) state. The identification is achieved by exciting this state back to ($6^2P_{1/2}$) and observing the decay to the ground state with the emission of 493 nm blue light. In secular equilibrium, the ion will radiate $\approx 6\times10^7$ photons per second. Additional advantage is that in a high pressure TPC, no additional trapping is needed to keep the Ba^+ ion localized.

Proposals are varying from 1 to 10 ton, achieving sensitivities from 50 meV to 11 meV. The EXO collaboration has been funded to construct a 200 kg isotopically enriched prototype detector without the Ba^+ tagging feature and to install it in the DOE Underground Laboratory in the Waste Isolation Pilot Plant(WIPP). The results of this prototype could be competitive with the most sensitive $0\nu2\beta$ experiments performed so far.

3.4 Tracking detectors

NEMO[47] is a tracking detector made of thin source layers alternating with three-dimensional readout drift chambers. The drift chambers are surrounded by plastic scintillators as calorimeters. The source layers can be made of different isotopes simultaneously. During past operations of a NEMO detector (NEMO-3) in the Fréjus Underground Laboratory used planes of ^{116}Cd, ^{130}Te, ^{150}Nd, ^{96}Zr, ^{46}Ca, ^{nat}Te, ^{82}Se and ^{100}Mo. The ability of detecting the full kinematics of the events allows to control the different sources of backgrounds. The usual sources of background like ^{214}Bi and ^{208}Tl can be recognized by their decay chains and life times of their daughter nuclide's. This makes the detector an almost background free. The remaining challenge is the energy resolution, 250 KeV at 3 MeV, that requires a large statistic sample to make a convincing discovery claim. There is a proposal for a SuperNEMO detector with increased isotope mass, 100 kg, that increases by a factor of ten the capacity of the actual NEMO-3. The sensitivity at a reach for SuperNEMO is of the order of 0.04 to 0.11 eV.

3.5 Prospects

It is very difficult to review the large number of existing proposals. We have tried to present some of the available technologies to detect the elusive $0\nu2\beta$ decays, both from active and passive sources. The expected sensitivity of the different proposals can be found in Tab.3.5. We should notice that there are two phases in the future experiments. A first one, ending by 2010, will imply the test and development of the technology for large detectors while covering the are predicted by Klapdor et al.[40]. A second phase, starting in 2010 and finishing by 2015, we would be able to cover the full region of inverted mass hierarchy and the degenerate neutrino mass region with several isotopes and experimental techniques. Anything beyond this point looks very challenging, from the detector size and technology to be implemented, and from the fact that no clear bound can be found in the dependency of $< m_\nu >$ with the lightest neutrino mass. Future measurements of the mass hierarchy and direct neutrino mass could help in constraining the phase space to look for $0\nu2\beta$ decays. We have to notice that for unfortunates combinations of θ_{13}, normal mass hierarchy and lightest neutrino mass we will not be able to exclude the Majorana hypothesis.

4. Kinematical mass determination

The measurement of the neutrino mass described in this letter make use of indirect method: interference in neutrino oscillation that is only sensitive to mass differences and $0\nu2\beta$ decay that provides the average $< m_\nu >$ mass. Neutrino oscillation is not capable of determining the absolute mass scale and $0\nu2\beta$ is able to do son only in the degenerate case, see 4. It is mandatory the usage of a model independent method to determine this mass. This method, developed by the experiments

Experiment	Isotope	Sensitivity $< m_\nu >$ eV/c^2	Technique	Expected year for first result
GERDA	^{76}Ge	0.09-0.29	Calorimeter	2010
Cuore	^{130}Te	0.02-0.13	Bolometer	2015
MOON	^{100}Mo	0.02	Scint. tracker	2015?
Majorana	^{76}Ge	0.02-0.07	Calorimeter	2015?
EXO	^{136}Xe	0.05-0.14	Ba^+ Tagging	2015?
SuperNEMO	^{100}Mo, ^{82}Se	0.04-0.11	Tracker	2016

Mainz and Troist [48, 49], is the measurement of the end point region of the tritium β-spectrum. Recent experiment have resulted in upper limits for m$_{\nu_e}$ of about 2 eV/c^2.

The next generation of tritium beta decays, KATRIN, is aiming at the increase of the sensitivity to one order of magnitude. Values of m$_{\nu_e}$ of the order of 0.4 eV/c^2 can be detected with 5 sigma significance, resulting in an upper limit of 0.2 eV/c^2 in absence of a positive signal. KATRIN consist on two consecutive spectrometers with an magnetic adiabatic collimation (MAC-E Filter), see[50] for more details.

The idea of a new technology based on the ^{187}Re cryo-bolometers is being investigated. This technology similar to the one of CUORE, detects all products of the ^{187}Re β decay in a thermal calorimeter. Two prototypes MANU[51] and MiBETA[52] have been constructed. MANU consists of 1.5 mg metallic Re crystal and has provided an upper limit of 26 eV/c^2. MiBETA has 0.35 mg of AgReO$_4$ providing an upper limit on the electron neutrino mass of 15eV/c^2 at 90%C.L. Starting from these two experiments an international collaboration is being formed around the MARE project [53]. The MARE project is a two phase effort. The first phase to be completed before the end of KATRIN is aiming at an improvement of a factor of two in sensitivity, 2 eV/c^2. The second phase will aim, after an intensive R&D program, at 0.2 eV/c^2 that is competitive to KATRIN results.

The sensitivity for the direct neutrino mass determination will cover the degenerate region during the next decade. This sensitivity complements the search for $0\nu2\beta$ decay that is expected to cover the inverted hierarchy during a similar period. Some indirect measurements from astrophysics and cosmology measurements has very aggressive predictions, a value of the mass of the mass of all neutrino species of $0.56^{+0.30}_{-26}$ eV/c^2 [54](i.e. 0.2 eV/c^2 per neutrino) that will be partially accessible to KATRIN or MARES.

5. Neutrino cross-section experiments

The intense neutrino beams developed for the long base line experiments will be used also to improve the knowledge of the neutrino-nucleus interactions. These measurements are very important to minimize the systematic errors in the oscillation experiments. The MINERνA[55] experiment is a high granularity, fully active scintillator tracker. The design includes the location of different nuclear targets (C,Fe,Pb) at the first detector section that will allow the first measurement of the A dependency of the neutrino cross-section. MINERνA operation will start at the beginning of 2009 at the NUMI neutrino line in Fermilab and it will cover the energy range from nearly threshold to 20 GeV.

6. Conclusions

The neutrino physics is still a very exciting field with many open questions. The nature of neutrinos Dirac or Majorana, the determination of the PMNS matrix, the absolute neutrino mass and the discovery of CP violation in the lepton sector are being explored with a new generation of experiments. On the top of this list there is the possibility of a positive result from MiniBoone experiment that will indicate the existence of a forth generation of sterile neutrinos.

Oscillation experiments are concentrating on the better determination of the atmospheric parameters with the MINOS and OPERA experiments until 2010. The sensitivity to θ_{13} mixing angle is limited in these experiments. The next generation of experiments starting at the end of this decade (Double-Chooz, T2K, NOνA and USA reactor experiment) will try to improve the sensitivity to θ_{13} an order of magnitude with respect of actual limits. A third generation of experiments will gain another order of magnitude in sensitivity and will start exploring the CP violation in the lepton sector. These experiments represent a technological challenge and could start not before 2020. In the mean while, the second phase of experiments like T2K or NOνA could have some sensitivity to these parameters. In addition experiments to understand neutrino interactions are being approved. These measurements are critical to reduce systematic errors and help in the precise determination of the oscillation parameters.

Neutrino-less double beta decay experiments are becoming more massive and precise. These experiments will be built in two phases: the first one finishing by 2010 will cover the region of the Klapdor *et al.* claim corresponding to highly degenerate neutrinos. In a second phase, to be completed by 2015, the sensitivity of experiments will cover the inverted hierarchy region using different technologies and isotopes. Anything beyond this values implies detectors that are not at reach with the actual technology. It is also important to notice that for some unfortunate combination of mixing angles, neutrino masses and hierarchies it will be impossible to reject the hypothesis of Majorana neutrinos.

Additional experiments looking for neutrino mass with kinematical methods are being proposed. These experiments are setting limits in a completely independent way and they could be helpful to interpret indirect results from cosmology and $0\nu2\beta$ decays. Unfortunately, these experiments are extremely difficult and sensitivities proposed for the next generation apparatus are only covering the region of degenerated neutrino masses.

We are entering the phase of precision neutrino physics, but we should also pay attention to indirect ways of measuring neutrino properties from cosmology and astroparticle physics [56].

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