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C. R. Physique 6 (2005) 758–767

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Neutrino Physics/Physique des neutrinos

Accelerator neutrinos

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Abstract

In the last years neutrino physics was shaken by many important experimental results bringing solid proofs in favor of neutrino oscillations. The goal of the present and future generation of experiments at accelerators is to complete the comprehension of neutrino mixing and of the pattern of neutrino masses, perform precise measurements of all these parameters and investigate CP violation in the neutrino sector. Most of these goals will be achieved with the study of $\nu_\mu \to \nu_e$ oscillations, which are mainly ruled by the still unknown mixing angle θ_{13}. A multi-step experimental strategy has to be attempted, depending on the magnitude of θ_{13}. ***To cite this article: D. Autiero, Y. Déclais, C. R. Physique 6 (2005).***

Résumé

Présent et futur de la physique des neutrinos auprès des accélérateurs. Ces dernières années ont apporté la preuve de l'oscillation des neutrinos. Le but des expériences (actuelles ou en projet) auprès des accélérateurs est de compléter notre compréhension du mélange des neutrinos et de leur configuration de masses, de mesurer avec précision l'ensemble des paramètres et de rechercher la violation de CP dans le secteur des neutrinos. La plupart de ces objectifs seront atteints en étudiant l'oscillation $\nu_\mu \to \nu_e$ fortement contrainte par l'angle de mélange encore inconnu, θ_{13}. Une stratégie expérimentale en plusieurs étapes est à l'étude, en fonction de la valeur de θ_{13}. ***Pour citer cet article : D. Autiero, Y. Déclais, C. R. Physique 6 (2005).***

Keywords: Accelerator neutrinos; Neutrino oscillations; Superbeams; Beta beams; Neutrino factories

Mots-clés : Neutrinos auprès des accélérateurs ; Oscillation des neutrinos ; Superfaisceaux ; Faisceaux beta ; Usines à neutrinos

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1. Introduction

During the last seven years the field of neutrino physics had a quite spectacular development with the confirmation of the interpretation of the atmospheric neutrinos anomaly in terms of neutrino oscillations [1] and the final proof that neutrino oscillations are at the origin of the solar neutrino problem [2].

The experimental data are quite well described by a scenario involving three massive neutrinos with two almost independent oscillations. Atmospheric neutrinos data are described by a $\nu_\mu \leftrightarrow \nu_\tau$ oscillation corresponding to a mass difference $\Delta m^2_{23} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$ and almost maximal mixing angle. Solar neutrinos are well described in terms of $\nu_\mu \leftrightarrow \nu_e$ oscillations: an

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1631-0705/$ – see front matter © 2005 Published by Elsevier SAS on behalf of Académie des sciences.
doi:10.1016/j.crhy.2005.07.009

overall fit of the solar neutrino data plus the KamLAND experiment gives $\Delta m^2_{12} = 8.2 \times 10^{-5}\ \mathrm{eV}^2$ and a mixing angle θ_{12} which is not maximal [3].

The existence of a fourth neutrino, probably sterile, has been suggested by the LSND results. It is highly controversial and will be verified soon by the Mini-Boone experiment [4].

In the framework of three neutrinos, the mixing matrix, linking the flavor eigenstates to the mass eigenstates, can be parametrized in terms of 3 angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and one Dirac-like CP phase δ (Pontecorvo–Maki–Nagakawa–Sakata mixing matrix) [5]. The angle θ_{13} is actually unknown, there is just an upper limit of $\sin^2(2\theta_{13}) \leqslant 0.14$ put by the Chooz experiment [6], corresponding to $\Delta m^2_{23} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$.

In the next decades experiments at accelerators are expected to play a key role in the determination of the neutrino mixing matrix and pattern of masses. They will have to perform precision measurements of the parameters and answer to a series of questions:

- Are there only three or more neutrino mass eigenstates?
- How large is the angle θ_{13}?
- Which is the sign of Δm^2_{23}: is the neutrino mass hierarchy normal or inverted? (see [5,7] for details)
- Do neutrinos violate CP symmetry: which is the magnitude of the phase δ?

The study of $\nu_\mu \to \nu_e$ oscillations will be the main handle to answer these questions. Given the values of Δm^2_{23} and Δm^2_{12}, these two main oscillations are not completely decoupled. In order to understand the various contributions, the $\nu_\mu \to \nu_e$ oscillation probability can be developed in terms of the ratio of the two mass differences $\alpha = \Delta m^2{}_{21}/\Delta m^2{}_{31} \simeq 10^{-2}$. An expression up to the second order in α yields [8–11]:

$$\begin{aligned}P_{\nu_\mu\to\nu_e} &\simeq \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2[(1-\hat{A})\varDelta]}{(1-\hat{A})^2} \pm \alpha\sin\delta\sin 2\theta_{13}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin(\varDelta)\frac{\sin(\hat{A}\varDelta)}{\hat{A}}\frac{\sin[(1-\hat{A})\varDelta]}{(1-\hat{A})}\\ &\quad + \alpha\cos\delta\sin 2\theta_{13}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos(\varDelta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\varDelta]}{(1-\hat{A})} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\hat{A}\varDelta)}{\hat{A}^2}\\ &\equiv O_1 + O_2(\delta) + O_3(\delta) + O_4\end{aligned} \tag{1}$$

where: $\varDelta = \Delta m^2_{31}L/4E$ and the sign of the term $O_2(\delta)$ is positive (negative) for neutrinos (anti-neutrinos).

The oscillation probability is thus ruled by four terms which have different behaviors in terms of matter effects, CP violating effects and the sign of Δm^2_{31}. The first term $O_1(\delta)$ is dominant and it is independent on CP and matter effects: the $\nu_\mu \leftrightarrow \nu_e$ oscillation rate depends primarily on the value of $\sin^2 2\theta_{13}$.

Matter effects (see [5] for details) enter through the dimensionless term $\hat{A}$, which represents the ratio between the neutrino energy and the energy (E^{res}) for which the MSW resonance occurs.

$$\hat{A} \equiv 2\sqrt{2}G_F n_e E/\Delta m^2_{31} \tag{2}$$

where G_F is the Fermi coupling constant and n_e the electron density in matter. The sign of $\hat{A}$ depends on the sign of Δm^2_{31}, which is positive (negative) for normal (inverted) mass hierarchy. Matter effects increase linearly with neutrino energy (or with the baseline). In case of neutrinos and normal hierarchy they enhance the oscillation probability. The opposite happens for anti-neutrinos.

The search for CP violation is performed by measuring the asymmetry among the $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillation probabilities. Matter effects can produce the same asymmetry. They can be exploited for baselines larger than 1000 km in order to measure $\mathrm{sign}(\Delta m^2_{23})$ but they interfere with the measurement of CP violation up to baselines of about 2000 km, after which they become dominant (Fig. 1). For the CP search matter effects have to be subtracted, once determined the $\mathrm{sign}(\Delta m^2_{23})$. This can be done with a 2% accuracy. The subtraction has to be performed in bins of the reconstructed neutrino energy, given the different energy behavior matter effect and CP violation.

Given the complex dependence of the oscillation probability on the various parameters, a measurement of the appearance probability $P_{\alpha\beta}(\bar{\theta}_{13}, \bar{\delta})$ for neutrinos at a given energy and distance will not provide a unique solution, the true values $(\bar{\theta}_{13}, \bar{\delta})$, but a locus of points (θ_{13}, δ) [16,10].

The first kind of degeneracy arises when mapping the $\nu_\mu \leftrightarrow \nu_e$ appearance probability on the plane (θ_{13}, δ). The four terms of the equation can be synthetically written as follows for small values of θ_{13}:

$$P(\nu_\mu \leftrightarrow \nu_e) \simeq \theta^2_{13} \times C_1 + \theta_{13} \times (\pm\sin\delta C_2 + \cos\delta C_3) + C_4 \tag{3}$$

The bound $P(\nu_\mu \leftrightarrow \nu_e) =$ constant leads for neutrinos and anti-neutrinos to two independent loci of correlated solutions. The two curves for neutrinos and anti-neutrinos will cross in the point corresponding to the true solution and, depending on L

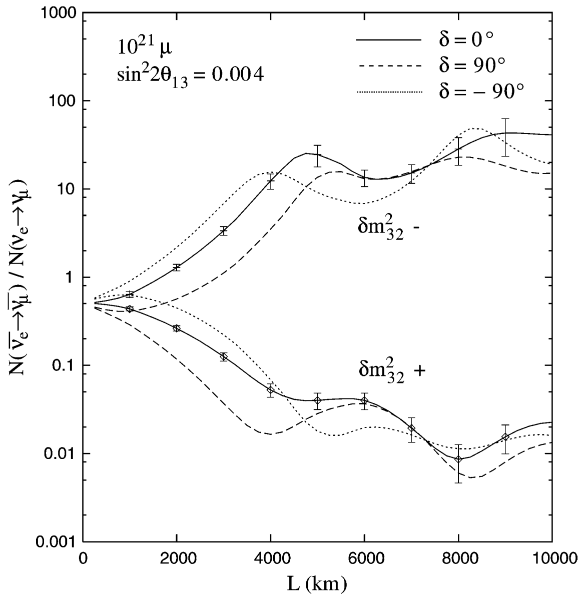

Fig. 1. Ratio of the oscillation probabilities of neutrinos and anti-neutrinos as a function of the baseline. The different lines correspond to values of the CP-violating phase δ of 0°, 90° and −90°. After about 1000 km, matter effects dominate over CP violation. Around 7500 km CP violation effects go to zero [15].

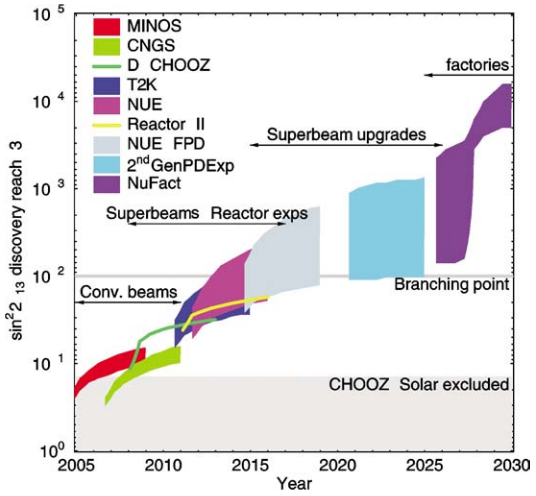

Fig. 2. Expected evolution of the $\sin^2 2\theta_{13}$ discovery reach for the global neutrino program [18]. The "branching point" refers to the decision point for the experimental program between an upgraded beam and/or detector and a neutrino factory program. NUE represents NOVA, Reactor II is a second generation reactor experiment (after Double Chooz) while FPD stands for the Fermilab Proton Driver. The upgrade 2ndGenPDExp (Second Generation Proton Driver Experiment) is assumed to start ten years after T2K starts and the curve uses numbers from the T2HK (T2HyperK) proposal. The neutrino factory is assumed to start about ten years after the branching point and to switch polarity after 2.5 years. The bands reflect the dependence of the sensitivity on the CP violating phase δ.

and E, in another point called 'intrinsic clone'. This degeneration can be solved by repeating the measurements at a different energy/baseline.

Another degeneracy comes from the ignorance of the sign of Δm^2_{31}. The change of the sign of Δm^2_{31} implies in the equation of $P(\nu_\mu \leftrightarrow \nu_e)$: $\alpha \to -\alpha$, $\Delta \to -\Delta$, $\hat{A} \to -\hat{A}$. The terms $O_2(\delta)$ and $O_3(\delta)$ are not invariant under this transformation which can be compensated by a change in δ.

The third degeneracy comes from the fact that the angle θ_{23} is known to be close to 45 degrees but not known to be greater or smaller than that. The terms $O_2(\delta)$ and $O_3(\delta)$ are not invariant under the transformation $\theta_{23} \to \pi/2 - \theta_{23}$. This transformation can be reabsorbed by a small shift in the (θ_{13}, δ) parameters, yielding so another solution called 'octant clone'.

These possibilities are equivalent to an eight-fold degeneracy, which will be present in case $P(\nu_\mu \leftrightarrow \nu_e)$ and $P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e)$ are measured at the same energy and baseline. On the contrary, the parameters can be disentangled by performing measurements at different L or E and/or by studying other oscillation channels like $P(\nu_e \leftrightarrow \nu_\tau)$. Measurements at different energies can also be obtained by using a wide band beam and by defining bins in neutrino energy within the same experiment, depending on its capability and resolution in reconstructing the neutrino energy. This will not be the case for an appearance experiment just measuring the $P(\nu_\mu \leftrightarrow \nu_e)$ oscillation rate without reconstructing any information on the neutrino energy ('counting experiment'). The correlations among the parameters may be taken as limiting aspects of the single measurements but they can also be exploited in order to get a synergy of different experiments.

All these considerations affect at various stages the future experimental strategy on the determination of the mixing matrix. Next experiments will first aim at measuring a finite value of θ_{13}, then at getting a first evidence for CP violation. The final goal is the precise individual measurement of the elements of the mixing matrix free of degeneracies. We can outline the future activity in 3 phases:

- The ongoing long-baseline experiments (2001–2010): MINOS [12] and CNGS [13,14] will attempt for a first search for $\nu_\mu \leftrightarrow \nu_e$ oscillations, which can improve the Chooz limit by a factor 2 and detect the oscillations for $\sin^2(2\theta_{13}) \gtrsim 0.06$.
- The next step (2009–2015): super-beams (T2K [20], NOVA [21]) and new experiments at reactors (Double Chooz, Diablo Canyon, Kashiwasaki) [17] aim to improve the Chooz limit by a factor 20. These experiments will improve the knowledge

of the atmospheric neutrino parameters. They will have a very limited sensitivity of the CP phase, also combining their results.

- The future (2015–2025): The goals will be to get evidence for CP violation, the precision measurements of the mixing parameters and the determination of the mass hierarchy. A first generation of experiments could be performed by using upgraded super-beams coupled with very massive targets like water Cerenkov detectors of 1 Mton (Hyper-Kamiokande, Fréjus), reaching a sensitivity on $\sin^2(2\theta_{13})$ about 100 times better than the Chooz limit. These experiments have chances to discover CP violation only for large values of θ_{13} and in any case will not solve the mass hierarchy. Beams obtained from decay rings like neutrino factories and/or beta-beams have the potentiality to answer all the questions and reach the ultimate precision in the measurement of the parameters. It is interesting to introduce a branching point [18] in the experimental strategy: for $\sin^2(2\theta_{13}) \leqslant 0.01$ it will be more convenient to go directly to the beams produced with decay rings instead of going through an intermediate step of improved super-beams coupled to more massive detectors (see Fig. 2).

2. Current long-baseline experiments

The current generation of long-baseline experiments (K2K, MINOS, CNGS) is aiming at a final confirmation of neutrino oscillations for atmospheric neutrinos and at the measurement of the oscillation parameters θ_{23} and Δm^2_{23}.

The K2K experiment has been looking at the ν_μ disappearance over a baseline of 250 km with a two detector setup, where the far detector is Super-Kamiokande. The experiment was concluded in 2004 reaching a statistical significance of 4σ with the combination of the measured event rate and the spectral distortion [19]. MINOS started at the beginning of 2005, still looking at the ν_μ disappearance with neutrinos of a few GeV over 730 km baseline between Fermilab and the Soudan mine (USA). It should be able to measure Δm^2_{23} with a 10% accuracy. The CNGS program (OPERA and ICARUS) is going to start in 2006 and will look for ν_τ appearance using the beam between CERN and Gran Sasso (Italy).

Both the CNGS experiments and MINOS are sensitive to θ_{13} by performing a $\nu_\mu \leftrightarrow \nu_e$ oscillation search and are going to improve significantly the Chooz limit (by a factor 2 or 3 within 2009). For example the MINOS sensitivity in 2 years is $\sin^2(2\theta_{13}) \leqslant 0.06$. This result can be obtained by OPERA in 5 years with the nominal beam. The CNGS beam upgrade ($\times 1.5$) currently under study would give for the same number of years: $\sin^2(2\theta_{13}) \leqslant 0.05$. These sensitivities have complementary aspects [11]. The CNGS experiments, due to the high energy needed for ν_τ appearance, will be performed at a off-peak baseline with a partial cancellation of matter effects and with the oscillation probability affected mostly by terms CP even, while odd under the inversion of the sign of Δm^2_{31}. In MINOS matter effects are of the order of 20% and the ignorance of the sign of Δm^2_{23} introduces a degeneracy in the θ_{13} sensitivity, if the experiment is considered as stand-alone. This feature can be exploited by combining MINOS with other experiments with a complementary behavior. The sensitivity of this generation of experiment can go down to about $\sin^2(2\theta_{13}) = 0.03$. For a precise measurement of θ_{13} one will have to wait for the next step in the experimental strategy.

3. The next step

The next generation of long-baseline experiments is designed with the purpose of measuring precisely the atmospheric neutrino oscillations parameters and fixing the scale of $\sin^2(2\theta_{13})$, by performing a $\nu_\mu \leftrightarrow \nu_e$ oscillation search with a significative increase in sensitivity with respect to Chooz (about a factor 20). This is feasible by using low energy, high intensity narrow-band beams with a low ν_e contamination, coupled to large detector masses. In order to maximize the sensitivity, the beam setup has to be tuned so that the L/E ratio corresponds to the first maximum in the oscillation probability, given Δm^2_{23}.

The main characteristics of these beams with respect to the ones planned for current experiments are outlined in Table 1.

Table 1
Main parameters of the current and next future long baseline experiments

	MINOS [12]	OPERA [13]	ICARUS [14]	T2K [20]	NOVA [21]
Baseline (km)	735	732	732	295	810
Mean energy (GeV)	3	17	17	0.76	2.22
Exposure (kton × years)	5.4 × 2	1.7 × 5	2.4 × 5	22.5 × 5	17 × 5
L/E (km/GeV)	388	321	245	43	43
Starting year	2005	2006	2006	2009	2010

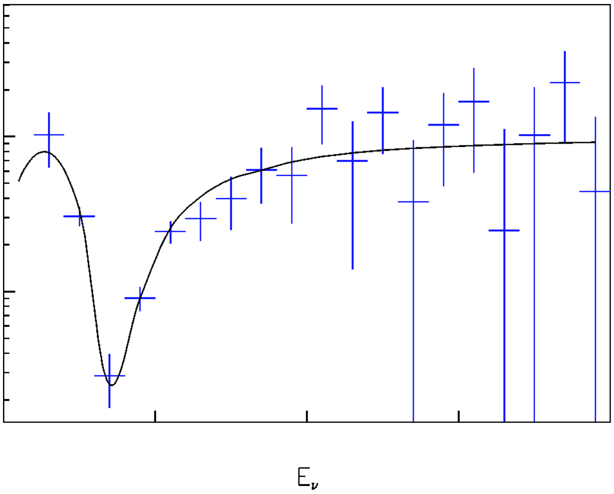

Fig. 3. The ratio of the measured spectrum of ν_μ CC in T2K with neutrino oscillation to the expected one without neutrino oscillation after subtracting the contribution of non quasi-elastic events. The fit result of the oscillation is superimposed [20].

Both the T2K and NOVA projects [20,21] are based on off-axis beams. The off-axis concept is based on the fact that, at small angles, the flux and energy of a neutrino produced from the two body decay of a pion in flight are given in the lab frame by:

$$\mathcal{F} = \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \frac{A}{4\pi z^2}, \qquad E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2} \tag{4}$$

where θ is the angle between the pion direction and the neutrino direction, E_π is the energy of the parent pion, and m_π is the mass of the pion and $\gamma = E_\pi/m_\pi$. A and z are the detector cross-sectional area and distance from decay point.

The neutrino flux peaks in the forward direction for all values of E_π. As the angle to the beam direction increases, however, the relationship (which is linear at zero degrees) between the pion energy and neutrino energy flattens, with all pions yielding neutrinos of roughly the same energy. By viewing a conventional beam from a location off the beam axis it is therefore possible to build a nearly mono-energetic neutrino beam. This technique increases the neutrino yield in the GeV region, while at the same time reducing the high-energy component and therefore the ν_e contamination and its uncertainty.

The T2K project is planning, during its first phase, to shoot on the Super-Kamiokande detector a super-beam obtained from the 50 GeV proton synchrotron (0.75 MW power) of the JPARC accelerator facility. The detector will be 2 degrees off-axis with a baseline of 295 km and the mean neutrino energy will be 0.76 GeV. Matter effects at this energy are negligible (around 10%) and the ν_e contamination will be at the level of 1%. This setup will allow over 5 years of data-taking to improve the Chooz limit by a factor 20, extending the search down to $\sin^2 2\theta_{13} \simeq 0.006$. It will also provide precision measurements of the atmospheric neutrino parameters (Δm^2_{23} with an uncertainty of 10^{-4} eV^2 and $\sin^2 2\theta_{23}$ with an uncertainty of 0.01) and to look for sterile components in ν_μ disappearance. See Fig. 3 for the illustration of a possible achievement of T2K. The project is already approved and data-taking should start in 2009.

The NOVA project [21] will use as neutrino target a 50 kton low-Z calorimeter located on the NUMI beam line at a baseline of 810 km, 0.7 degrees off-axis. The average neutrino energy will be 2.2 GeV. At the peak of the muon rate the ν_e background will be at the level of 0.5%. Matter effects will be of the order of 23% enhancement (or suppression) of the oscillation probability. The experiment is not approved yet and it could eventually start data-taking by 2010. NOVA aims at a sensitivity to $\sin^2(2\theta_{13})$ a factor 10 better than MINOS $\sin^2\theta_{13} \leqslant 0.01$ and to measure $\sin^2\theta_{23}$ with 2% accuracy. The presence of matter effects can be used to attempt a determination of the sign of Δm^2_{23}. However, this possibility would be effective only with a substantial increase of the beam intensity, by building a new machine (the proton driver) with 2 MW power [18].

The parameters $\sin^2 2\theta_{13}$, δ and the sign of Δm^2_{23} all affect in a significant way the $\nu_\mu \leftrightarrow \nu_e$ oscillation rate at the atmospheric neutrinos oscillation length. A large value of δ could even decrease the oscillation probability yielding a negative result for the search for $\nu_\mu \leftrightarrow \nu_e$ oscillations. This aspect can be turned to be synergic when experiments with complementary behavior with respect to CP and matter effects are combined together. This would be the case for the T2K program run in neutrino mode (5 years) and the NOVA program run in anti-neutrino mode (5 years).

The Double-Chooz project [22] is an example of second generation reactor experiments, as well as other projects like Diablo-Canyon and Kashiwasaki [23]. It is aiming to improve the sensitivity of the former Chooz experiment by using a two detector setup. The advantage of a new reactor measurement is that it would be completely independent of the CP phase and matter effects, thus bringing a complementary information in order to solve the correlations and degeneracies in the measurements performed in long-baseline experiments. With an exposure time of 3 years Double-Chooz is foreseen to reach a sensitivity of $\sin^2 2\theta_{13} \leqslant 0.03$ at 90% C.L. for $\Delta m^2_{23} = 2.0 \times 10^{-3}\ \mathrm{eV}^2$ [17].

4. The future

The future will depend on the magnitude of the $\sin^2(2\theta_{13})$ as measured by the current experiments and/or those to be performed with the second step. If $\sin^2(2\theta_{13})$ is large enough, a continuation of the experimental program with the existing technologies is envisageable. Otherwise, if $\sin^2(2\theta_{13})$ is smaller than 0.01, new tools will have to be developed to measure this parameter and also look for CP violation.

4.1. The intermediate tools

In case of observation of $\nu_\mu \leftrightarrow \nu_e$ oscillations the T2K project foresees a second phase aiming to search for a first evidence for CP violation. This will imply the upgrade of the JPARC 50 GeV PS to a power of 4 MW and the construction of a new large mass water Cerenkov detector (Hyper-Kamiokande). The beam upgrade ×5 and the detector mass increase ×25 with respect to Super-Kamiokande, will provide an increase in statistics of a factor 100 with respect to the first phase. Given the low neutrino energy, matter effects have a negligible interference with CP violating effects.

In Europe [24] a similar project to the phase II of T2K is actually under study. It is based on the future Superconductive Proton Linac (SPL) to be built at CERN. This machine would be able to produce a proton beam at an energy of 2.2 GeV, with a power of 4 MW and 10^{23} protons on target per year. The SPL is intended to be the proton driver for a possible future neutrino factory at CERN. The neutrino beam will have an average energy of 270 MeV, yielding the first oscillation maximum at a distance of about 130 km, corresponding to the distance between CERN and the Fréjus underground laboratory. Here, in an future major extension of the present laboratory, a large water Cerenkov detector with a fiducial mass of 440 kton could be installed. This detector, like Hyper-Kamiokande, would also be exploitable for an additional physics program based on the search for proton decay and the study of atmospheric and supernovae neutrinos. Given the low beam energy, the experiment would be a ‘counting experiment’ with identification of the final state charged lepton (muon or electron) but poor neutrino energy reconstruction.

The SPL-Fréjus program would be able to explore $\sin^2(2\theta_{13})$ down to 0.0012, i.e., a factor 100 better than the Chooz limit. The intrinsic ν_e contamination of the beam is around 0.4%, coming only from decays of muons. It can be monitored with a 2% systematic error by using a close detector, needed as well to measure the interaction cross-sections, actually quite uncertain.

The search for CP violation implies running the SPL in neutrino and anti-neutrino mode. Due to the anti-neutrino interaction cross-section, which is about a factor five smaller at these energies than the one for neutrinos and due to the smaller production rate of π^- at the beam target, in order to achieve equivalent statistics, 2 years of neutrino running would have to be accompanied by 8 years of anti-neutrino running.

This facility can be more advantageously exploited by the beta-beam [26,27], which is a pure, intense and well collimated ν_e ($\bar{\nu}_e$) beam. This can be obtained by producing, collecting, accelerating to energies with γ factor around 100 and storing in a final decay ring radioactive ions. The best ion candidates, which are required to be easy to produce and with a lifetime around 1 second, are ^{18}Ne for ν_e and ^{6}He for $\bar{\nu}_e$. The beam setup could be based in part on old equipments, like the CERN PS and SPS, and on installing a ion production targets fed by the SPL with about 5% of its peak intensity. The final stage acceleration performed with the SPS limits the gamma of the ions to about 150. The ν_e and $\bar{\nu}_e$ beams could be produced at the same time. The search for $\nu_e \to \nu_\mu$ oscillations would be based on the ν_μ appearance. At these energies the ν_μ charged current interactions are mainly quasi-elastic, appearing in the detector as a single ring muon-like events. The background is due to inefficiencies in particle identification, such as mis-identification of pions produced in neutral current single-pion resonant interactions and electrons (positrons) mis-identified as muons.

The sensitivity of this experiment can be expressed in the (θ_{13}, δ) plane, having fixed all the other parameters ($\delta m^2_{23} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$), as shown in Fig. 4. In the same plot the sensitivity of the SPL-SB computed for a 5 yrs ν_μ run is displayed.

The synergy among the super-beam and the beta-beam, would offer the opportunity of performing searches for CP, T and CPT violation. The search for CP violation can be performed by running the beta-beam with ^{18}Ne and ^{6}He, and by extracting from the number of muon-like events the $P(\nu_e \to \nu_\mu)$ and the $P(\bar{\nu}_e \to \bar{\nu}_\mu)$ probabilities. The fit can simultaneously determine θ_{13} and δ, see Fig. 5 (right). The 3σ sensitivity to δ, having fixed $\delta m^2_{12} = 7.1 \times 10^{-5}\ \mathrm{eV}^2$, is shown in Fig. 5 (left). This experimental setup has no strong handles to reduce degeneracies. For a detailed study on the degeneracies for the SPL super-beam and the beta-beam see: [28]. The goal of experiments of this type is not considered to be the precise measurements of all the parameters but a first attempt to access CP violation, in case of large enough values of θ_{13}, see Fig. 6. This corresponds also the two-steps logic of the T2K project, with its second phase pending from a from a positive result on θ_{13} in the first phase.

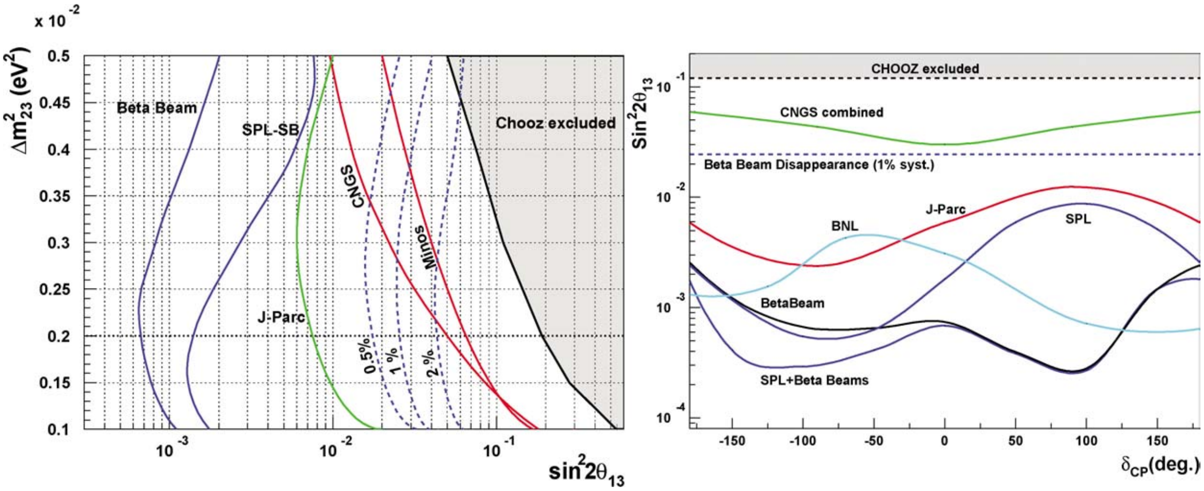

Fig. 4. Left: 90% CL sensitivity of the disappearance channel to θ_{13} in a 5 years Beta-beam run drawn as dotted lines. The labels 0.5%, 1% and 2% indicate the systematic errors assumed in the calculations. The appearance sensitivities of Beta and SPL beams, computed for $\delta = 0$, $\mathrm{sign}(\Delta m^2) = +1$, are shown as well on the same plot [27]. The combined CNGS limit is taken from [11], J-Parc from [20], Minos from [12]. Right: 90% CL sensitivity expressed as function of δ for $\delta m^2_{23} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$. CNGS and J-Parc curves are taken from [11], BNL from [25]. All the appearance sensitivities are computed for $\mathrm{sign}(\Delta m^2) = +1$ [27].

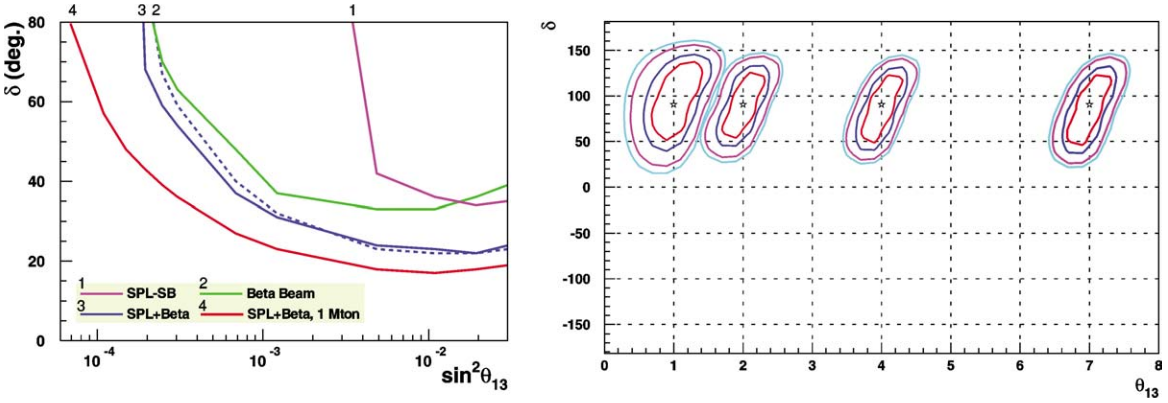

Fig. 5. Left: δ discovery potential (3σ) as function of θ_{13} for the SPL superbeam, the Beta-Beam and their combination. Dotted lines are sensitivities computed for $\mathrm{sign}(\Delta m^2) = -1$. Right: Fits to θ_{13} and δ after a 10 years Beta-Beam run. Plots are shown for $\delta = 1°, 2°, 4°, 7°$. For the other neutrino oscillation parameters see the text. Lines show 1σ, 90%, 99% and 3σ confidence levels.

4.2. The final tools

The assessment of CP violation with precise measurements of the elements of the mixing matrix and the resolution of the mass hierarchy will characterize the experiments of the last phase. Beta-beams could be a convenient tool for these measurements, by increasing the beam energy and the corresponding baseline. Beta-beams at high energy could be competitive to neutrino factories on the search for CP violation [29]. By refurbishing the SPS with super-conductive magnets, ions could be accelerated up to $\gamma \leqslant 600$. Of course there would be important technical aspects to deal with: the power of about 1 MW for the acceleration of the ions and the use of superconductive magnets also in the decay ring in order keep its size reasonable. Considering a water Cerenkov detector of the same size as the one of the Fréjus project but located in Gran Sasso, this option would have the following advantages:

(a) The higher energy would allow one to exit from the region where cross-sections are strongly affected by nuclear effects and poorly known. By taking into account the flux focalization and the increase in cross section, the rate of ν_μ CC events would increase by a factor 10;

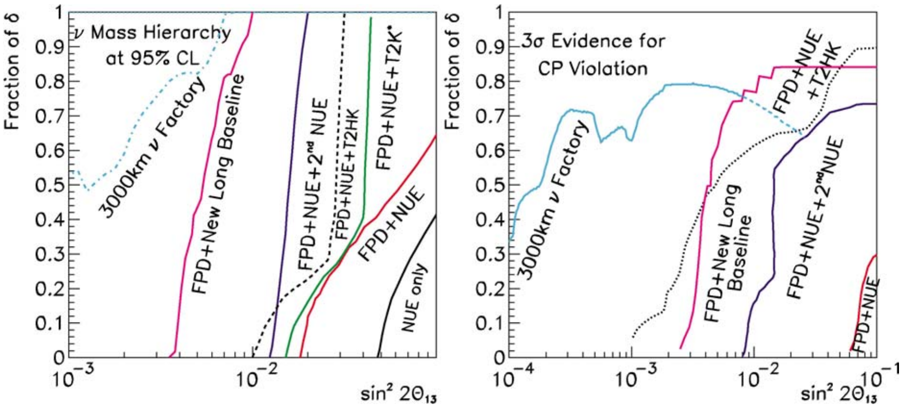

Fig. 6. Discovery potentials for the mass hierarchy and CP violation as a function of θ_{13} and δ, combining various experimental options and comparing to neutrino factories. NUE stands for NOVA, second NUE for another NOVA exposure but with a different off axis angle, FPD for Fermilab Proton Driver. New Long Baseline refers to a HyperK like detector, the upgraded T2K beam/detector is T2KHK [18].

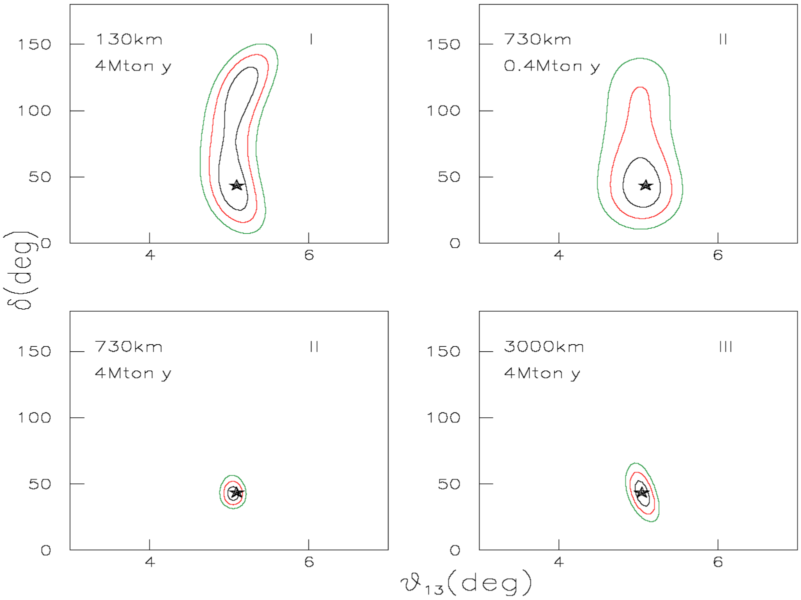

Fig. 7. 1, 2, 3σ contours on the plane (θ_{13}, δ) in the Setups I, II for the 40 kton and 400 kton detectors and for Setup III. The input values of the parameters are indicated by a star.

(b) In this energy range the reconstruction of the energy spectrum becomes possible (the experiment is no more just a counting experiment) and this can be used in order to resolve correlations and degeneracies;

(c) Matter effects become sizable and can be used to measure the sign of Δm^2_{23}.

The energy dependence is particularly helpful in resolving degeneracies for experiments performed with an 'on-peak' baseline. This is shown quantitatively in Fig. 7, where the results of a simultaneous fit of δ θ_{13} are presented for 10 years exposure of: a 400 kton water Cerenkov detector at a baseline of 130 km and $\gamma = 60$ for ^{6}He and $\gamma = 100$ for ^{18}Ne (Setup I); a 40 kton and a 400 kton detectors at a baseline of 732 km and $\gamma = 350$ for ^{6}He and $\gamma = 580$ for ^{18}Ne (Setup II); and a 400 kton detector located at 3000 km with $\gamma = 1500$ for ^{6}He and $\gamma = 2500$ for ^{18}Ne (acceleration of the ions performed with LHC) (Setup III). Considering the same detector, there is a large improvement in the accuracy of the fit between Setup I and Setup II. The intrinsic degeneracies present for the low-energy option, tend to get resolved in Setup II, even with a detector 10 times smaller. Given the sizable matter effects in Setup II, the sign(Δm^2_{23}) becomes measurable simultaneously with θ_{13} and δ for $\theta_{13} \geqslant 3°$.

Table 2
Comparison of the fluxes and CC event rates of various neutrino facilities

Beam	E_ν (GeV)	Flux ($\nu/\mathrm{m}^2/\mathrm{yr}$)	L (km)	CC ($\nu/\mathrm{kton}/\mathrm{yr}$)
CNGS	17.7	3.5×10^{11}	730	2448
T2K1(2)	0.7	1.9×10^{11} (1.2×10^{12})	295	95 (570)
SPL	0.27	4.78×10^{11}	130	31.1
Beta B	0.36	1.88×10^{11}	130	24.5
NUFACT	30	2.4×10^{12}	3000	17700

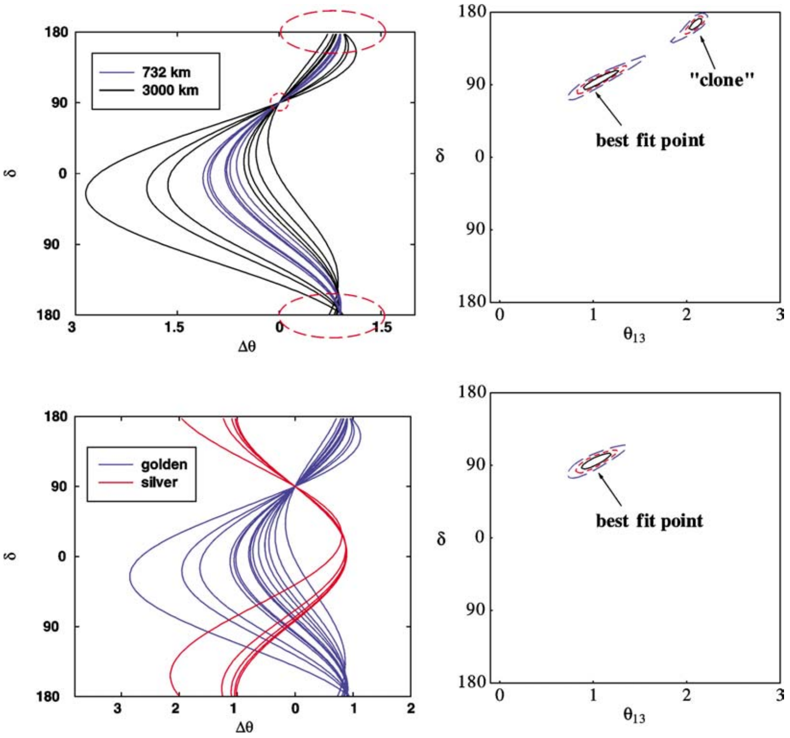

Fig. 8. Curves of equal oscillation probability in the δ, $\Delta\theta$ plane (where $\Delta\theta$ is the difference between θ_{13} and its nominal value of 1°), for the golden channel at two different baselines and for the golden + silver channel at the same two baselines [33]. The curves, generated for different energy bins, all meet at the nominal value of the parameters.

Neutrino factories [15,30–32] will constitute the ultimate tool for the study of neutrino oscillations. As beta-beams, they overcome the major difficulty of conventional neutrino beams based on pion and kaon decays: the purity of the beam and the modelization of the fluxes. Neutrinos will be generated in this case from the decays of muons circulating in a storage ring (ν_e and $\bar{\nu}_\mu$ from the decays of $\bar{\mu}$ or $\bar{\nu}_e$ and ν_μ from the decays of μ) and can be known at 10^{-3} level. The beam, other than by its purity is also characterized by a very high flux, as shown in Table 2.

The most straightforward way of exploiting this beam is to search for $\nu_\mu \leftrightarrow \nu_e$ oscillations by looking at the appearance of wrong sign muons in a large magnetized iron detector (the so called golden channel). The beam is intrinsically pure and backgrounds can be kept at the 10^{-4} level by rejecting neutrino interaction events with low energy muons. The use of a beam obtained from about 2×10^{21} decays of 50 GeV muons with a 40 kton detector located at 3000 km allows one to achieve unprecedented sensitivities on θ_{13}, δ_{CP}, sign(Δm^2_{23}) and to measure the atmospheric neutrino oscillation parameters θ_{23} and Δm^2_{23} respectively at the 10% and 1% level. The sensitivity on θ_{13} can be pushed down to $\sin^2(2\theta_{13}) \leqslant 10^{-5}$ (0.1°), this is actually the only possible way to be sensitive to so low values of θ_{13}.

The correlation among θ_{13} and δ_{CP} in the simultaneous fit of the oscillation probabilities for neutrinos and anti-neutrinos is particularly strong at short baselines. The optimal choice for the CP search is for a baseline around 3000 km. The accuracy in disentangling the parameters can be increased by combining measurements at different baselines [30].

The best way to reduce degeneracies is to combine the observation of the golden channel with the “Silver channel” ($\nu_e \leftrightarrow \nu_\tau$ oscillations). $\nu_e \leftrightarrow \nu_\tau$ oscillations have a opposite CP behavior than $\nu_e \to \nu_\mu$ oscillations. This can be easily understood by considering that for ν_e the sum of the survival probability and the two oscillation probabilities (in ν_μ and ν_τ) must be one. The combination of the measurement of wrong sign muons at 3000 km with $\nu_e \leftrightarrow \nu_\tau$ oscillations at 730 km (a 4 kton OPERA-like detector) solves the ambiguities and eliminates the clone regions (see Fig. 8).

5. Conclusions

After the phase of discovery of neutrino oscillations, mainly based on the use of natural sources, experiments at accelerators will be needed to measure the mixing parameters and investigate the pattern of masses and CP violation in the neutrino sector. In order to reach this goal and enter in an era of precision measurements a new set of tools is being developed, like super-beams beta-beams and neutrino factories. Most of the future measurements will rely on the study of $\nu_\mu \to \nu_e$ oscillations, which are mainly ruled by the still unknown mixing angle θ_{13}. The experimental strategy will consist in several steps, driven by the magnitude of θ_{13}. A strong synergy among different experiments will be needed in order to disentangle the correlations between the mixing parameters present in the single measurements.

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