Next Challenge in Neutrino Physics: the $\theta_{13}$ Angle

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Abstract

A new generation of oscillation experiments optimized to measure $\theta_{13}$ is ready to start. Performances, complementarity and competition of these accelerator and reactor experiments will be shortly illustrated. The capability of measuring $\theta_{13}$ with other neutrino sources, like solar, atmospheric, supernovae neutrinos or neutrinos from a tritium source will be also discussed.

1 Introduction

Three parameters of neutrino oscillations are still unknown: the mixing angle $\theta_{13}$, the mass hierarchy $\text{sign}(\Delta m_{23}^2)$ and the CP phase $\delta_{CP}$; they are all fundamental parameters of the standard model.

The mixing angle $\theta_{13}$ is the key parameter of three-neutrino oscillations and regulates at the first order all the oscillation processes that could contribute to the measurement of $\text{sign}(\Delta m_{23}^2)$ and $\delta_{CP}$.

The best direct experimental limit on $\theta_{13}$ comes from the Chooz reactor experiment [1]. A world limit can be derived [2] by a full $3\nu$ analysis of all the neutrino oscillation experiments, see Tab. 1. The fact that the world limit provides a looser value than the Chooz limit indicates that the best fit for $\theta_{13}$ is different from zero, although at small statistical significance, as discussed in [3].

Table 1: The 90%($3\sigma$) bounds (1 dof) on $\sin^2 \theta_{13}$ from an analysis of different sets of data [2]

$\sin^2 \theta_{13} \leq \begin{cases} 
0.060 (0.089) & \text{(solar + KamLAND)} \\
0.027 (0.058) & \text{(Chooz + atm + K2K + MINOS)} \\
0.035 (0.056) & \text{(global data)} 
\end{cases}$

A preliminary analysis of the MINOS experiment [4] shows a 1.5$\sigma$ excess of $\nu_e$-like events in the far detector, that could be interpreted as a manifestation of a non-zero value of $\theta_{13}$.

In the following will be reviewed the experimental potential of measuring $\theta_{13}$ by using tritium sources, atmospheric neutrinos, supernova neutrinos and solar neutrinos. Then will be described the sensitivities of the next generation of accelerator and reactor neutrino experiments ready to start: T2K, NO$\nu$A, Double Chooz and Daya Bay. The complementarity of these measurements and the competition of the experimental sensitivities along the time will also be discussed.
2 Tritium Experiments

Tritium has been considered as a possible source of neutrinos for table-top-like $\nu_e$ disappearance experiments thanks to its small end-point energy: 18.6 KeV, corresponding to a maximum baseline of 9.2 m for $\Delta m^2_{23} = 2.5 \cdot 10^{-3} \text{eV}^2$. Giomataris et al. [5] proposed to use an extremely intense source of tritium (200 MCi) surrounded by a spherical high-pressure gas TPC, 10 m radius, filled with argon at 10 atm and read-out by large surface Micromegas [6], the NOSTOS experiment, Fig. 1 left.

![Diagram of NOSTOS experiment](image)

Figure 1: Left panel: sketch of the NOSTOS experiment. Right panel The differential rate $dN/dT dL$ (per keV-meter) for Ar at 10 Atm with 20 Kg of tritium as a function of the source-detector distance (in m), averaged over the neutrino energy, for electron energies from top to bottom and left to right 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 keV. The results shown correspond to $\sin^2 2\theta_{13} = 0.170$. This rate must be multiplied by $1e^{t/\tau}$ to get the number of events after running time $t$. From [5].

In such configuration $\nu_e$ disappearance would be measured as a function of the baseline, with some sensitivity to $\theta_{13}$. Both elastic scattering and neutral current events would be detected in the TPC. These processes have different cross-section values as function of the neutrino energy, so the path length disappearance shapes are different at different energies. As an example the path length curves as computed for $\theta_{13}$ around the Chooz limit ($\sin^2 2\theta_{13} = 0.170$) for the full life of the source ($T_{1/2} \simeq 12.33 \text{yr}$) are displayed [5]. The potential of this setup cannot reach sensitivities much below the Chooz limit.

A renewed interest in Tritium experiments came following the publication by Raghavan [7] about the possibility that mono energetic antineutrinos emitted in the bound state
beta-decay of $^3$H can be resonantly captured in $^3$He. The reaction scheme is illustrated in Fig. 2. The resonant character of the reactions is partially destroyed by the nuclear recoil energies $E_R$, $E'_R$, nevertheless about 6 orders of magnitude could be gained with respect to conventional neutrino cross sections. The enhancement of the cross section could be up to eleven orders of magnitude by embedding both $^3$H and $^3$He into solids by which the broadening of the beam due to nuclear recoil is severely suppressed by a mechanism similar to the Mössbauer effect.

Under these assumptions an experiment exploiting 1 MCi $^3$H metallic source and 100g $^3$He metallic detector could register $\sim 10^6$ events/day at 10 m allowing for precision measurements of $\theta_{13}$, order of $\sin^2 2\theta_{13} \simeq 0.004$ (2$\sigma$) [8], or for new ways of measuring the mass hierarchy [9].

Some questions anyway have been raised about the real possibility of gaining these 11 orders of magnitude in cross section [10]. The main question is how far can be set the same binding energies $B_z$, $B'_z$. $^3$H and $^3$He atoms have different sizes, modifying the lattice structure and so the binding energy. This and other solid state effects can weaken the resonant peak, loosing up to 6 orders of magnitude in the cross section.

Furthermore the way itself in which the $^3$He lattice is produced: by loading at first the lattice with $^3$H and waiting a long enough time to have it decayed, makes problematic a precise measurement of the $^3$H generated by neutrino interactions.

While Mössbauer neutrinos could be a very interesting setup to measure neutrino oscillations, it appears that some R&D is needed to set the feasibility and the sensitivity of this experimental approach.

### 3 Atmospheric Neutrinos

The Super Kamiokande analysis of atmospheric neutrinos is sensitive to $\theta_{13}$ through MSW transitions in the Earth, that can generate large oscillation amplitudes, Fig. 3.

The collaboration published limits about $\theta_{13}$ based on a three-neutrino analysis of atmospheric neutrino oscillations in the SK-I data taking [11], Fig. 4 left.
Figure 3: Oscillation probability $P(\nu_\mu \to \nu_e)$ as function of the neutrino energy and the zenith angle ($\cos \Omega_\nu = -1$, 0 correspond to vertically upward and horizontal directions, respectively). The three high probability ($\geq 40\%$) regions are shown which correspond to the MSW resonance at 3 GeV in the core layer, the MSW resonance at 7 GeV in the mantle layer, and the enhancement due to the core-mantle transition interference at the energy between the two MSW regions. From [11].

Figure 4: $\chi^2 - \chi^2_{\text{min}}$ values of the fit to atmospheric neutrinos in the Super Kamiokande experiment (left panel) [11], as a function of $\sin^2 2\theta_{13}$, assuming normal hierarchy. Right panel: the same quantity extrapolated to longer exposures, from [12], the two horizontal dashed lines are $3\sigma$ sensitivities of Super Kamiokande for 20 and 80 years of data taking.
While these limits are not competitive with the Chooz limit, the statistics so far collected is about two times bigger than what published. Having a look to the predicted sensitivities of Super Kamiokande as function of the exposure, see Fig. 4 right, one can reasonably expect that a $3\nu$ analysis of the whole data set collected so far could allow Super Kamiokande to reach a sensitivity equal to, or even better, than the Chooz limit. This could be, in the short term, the best opportunity to see progress in the $\theta_{13}$ hunt.

4 Supernova Neutrinos

Neutrinos generated by a supernova explosion can provide information about the $\theta_{13}$ value, as discussed in [13].

The main mechanism through which neutrino rates at Earth are modulated by $\theta_{13}$ is the MSW crossing probability at the high resonance region inside the supernova, that, after some approximations, can be written as:

$$P_H \simeq \exp \left\{ -\frac{\pi}{12} \left[ \frac{10^{10} \text{MeV}}{E} \left( \frac{\sin^2 2\theta_{13}}{\cos^2 2\theta_{13}} \right) \left( \frac{\Delta m^2_{32}}{1 \text{eV}^2} \right)^{1/2} \right]^{2/3} \right\},$$

where the $C$ parameter takes into account the amount of electron capture during the star collapse, it is estimated to be within the [1, 15] interval.

Several other supernova parameters influence the $\nu$ fluxes like the $\nu$ flavour temperatures $T_\alpha$ and the pinching parameters (deviations from thermal energy distributions) $\eta_\alpha$.

To extract information about $\theta_{13}$, the experiments should provide spectral information about the different neutrino flavours with a sufficient statistics. One could reasonably ask if the present generation of supernova neutrino detectors has enough sensitivity to extract information about $\theta_{13}$ in case of a supernova explosion.

In Fig. 5 are displayed the estimated number of events detected by a supernova explosion at 10 kpc by inverse beta-decay in Super Kamiokande, neutrino-electron scattering in Super Kamiokande and neutrino-carbon interactions in KamLAND, as computed in [15]. Due to the different contributions of neutrino flavors to the detected processes and the different cross-sections, the detected rates have different dependencies from $\theta_{13}$, ranging from a 1% variation from small ($\theta_{13} < 1^\circ$ corresponding to $\sin^2 2\theta_{13} < 10^{-3}$) to large values of $\theta_{13}$ in case of the neutrino-electron scattering in Super Kamiokande to a 25% variation in case of inverse beta-decay in Super Kamiokande.

It is certainly very difficult to make a detailed prediction of the capability of measuring $\theta_{13}$ from supernova data, given the large number of supernova parameters to be fitted and the lack of detailed information about the efficiencies and the capability of correctly identify the interaction channels of the different detectors.

It seems anyway plausible that in case of a supernova explosion at 10 kpc the combination of the detected signals in the several running detectors, including also the spectral information, can allow to decide if $\theta_{13}$ is bigger or smaller than about $1^\circ \left( \sin^2 2\theta_{13} = 10^{-3} \right)$,

\footnote{among which the non inclusion of collective neutrino effects [14]}
Figure 5: Estimated supernova event number observed in three different experimental channels in as a function of $\theta_{13}$ computed for an incident angle $\theta = 30^\circ$ and a supernova explosion at 10 kpc. The solid curves correspond to the normal hierarchy, and the dashed curves correspond to the inverted hierarchy. Also shown the variation of the rates by changing the $C$ parameter, see the text, from 1 to 10. Elaborated from [15].

5 Solar Neutrinos

The non-zero value of $\theta_{13}$ coming from the world fits [3] is driven by the tension of the KamLAND and SNO measurements of the solar parameters. One could wonder if an improvement of the SNO and KamLAND results could allow for more significant evidence of non-zero values of $\theta_{13}$. SNO has already published the whole data set [16], it is expected to perform a full 3$\nu$ analysis of the data together with a lower detection threshold [17], while significant improvements in statistics in KamLAND will be very slow (the published data set covers the period March 2002 to May 2007 [18]).

A breakthrough in this field could come in case of doping with gadolinium of the Super Kamiokande detector [19], that could transform SK in a $\sim 30$ kton neutrino reactor detector. In this configuration it has been shown [20] the potential for a spectacular improvement of the precision of the measurement of the solar parameters (mostly $\Delta m^2_{12}$).

6 Accelerator Neutrinos

When matter effects are not negligible, the transition probability $\nu_e \to \nu_\mu$ ($\bar{\nu}_e \to \bar{\nu}_\mu$) can be written as [21]:

$$P^\pm(\nu_e \to \nu_\mu) = X^\pm \sin^2(2\theta_{13}) + Y^\pm \cos(\theta_{13}) \sin(2\theta_{13}) \cos \left(\pm \delta - \frac{\Delta m^2_{23}L}{4E_\nu}\right) + Z ,$$

(2)
where ± refers to neutrinos and antineutrinos, respectively and $a[eV^2] = \pm 2 \sqrt{2} G_F \rho n_e E_\nu = 7.6 \cdot 10^{-5}[g/cm^2]E_\nu[GeV]$ is the electron density in the material crossed by neutrinos. The coefficients of the two equations are:

$X_{\pm} = \sin^2(\theta_{23}) \left( \frac{\Delta m_{23}^2}{|a| - \Delta m_{23}^2} \right) \sin^2 \left( \frac{|a| - \Delta m_{23}^2}{4E_\nu} L \right)$,

$Y_{\pm} = \sin(2\theta_{12}) \sin(2\theta_{23}) \left( \frac{\Delta m_{12}^2}{a} \right) \left( \frac{\Delta m_{23}^2}{|a| - \Delta m_{23}^2} \right) \sin \left( \frac{aL}{4E_\nu} \right) \sin \left( \frac{|a| - \Delta m_{23}^2}{4E_\nu} L \right)$,

$Z = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \left( \frac{\Delta m_{12}^2}{a} \right)^2 \sin^2 \left( \frac{aL}{4E_\nu} \right)$.

The $\nu_\mu \rightarrow \nu_e$ transitions are dominated by the solar term, anyway, at the distance defined by the $\Delta m_{23}^2$ parameter, they are driven by the $\theta_{13}$ term which is proportional to $\sin^2 2\theta_{13}$. Moreover $P(\nu_\mu \rightarrow \nu_e)$ could be strongly influenced by the unknown value of $\delta_{CP}$ and sign($\Delta m_{23}^2$).

Given the complexity of the $\nu_\mu \rightarrow \nu_e$ transition formula it will be very difficult for pioneering experiments to extract all the unknown parameters unambiguously. Correlations are present between $\theta_{13}$ and $\delta_{CP}$ [21]. Moreover, in absence of information about the sign of $\Delta m_{23}^2$ [22, 23] and the approximate $[\theta_{23}, \pi/2 - \theta_{23}]$ symmetry for the atmospheric angle [21], additional clone solutions rise up. In general, the measurement of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ will result in eight allowed regions of the parameter space, the so-called eightfold-degeneracy [23].

Experimental $\theta_{13}$ searches at the accelerators look for evidence of $\nu_e$ appearance in an intense $\nu_\mu$ beam in excess of what is expected from the solar terms.

The $\nu_\mu \rightarrow \nu_e$ experimental sensitivity with conventional $\nu_\mu$ beams is limited by an intrinsic $\nu_e$ beam contamination of about 1%. Furthermore, neutral pions in both neutral current and charged current interactions can fake an electron providing also a possible background for the $\nu_e$’s.

Therefore the measurement of the $\theta_{13}$ mixing angle will require neutrino beams with high performances in terms of intensity, purity and associated systematic errors. Detectors should combine a very large mass with high granularity and resolution necessary to keep detector backgrounds at as low as possible rates. Ancillary experiments to measure the meson production (for the neutrino beam knowledge), the neutrino cross-sections, the particle identification capability will become necessary. The Harp hadroproduction experiment at CERN PS [25, 26] for instance, measured the hadroproduction for the proton energy and target material of the K2K and MiniBooNE experiments, giving a fundamental contribution to the reduction of the systematic errors. The NA61 experiment at CERN [27] is going to measure the hadroproduction for the T2K setup.

In the following we will focus on T2K and NO$\nu$A, the approved $\theta_{13}$ optimized accelerator experiments.

There are several proposals for next generation experimental setups, based on conventional neutrino beams, capable to significantly improve the sensitivity of T2K and NO$\nu$A in the future [28, 29, 30]. Ultimate performances in neutrino oscillation searches at the accelerators can be reached by neutrino beams based upon innovative concepts, like neutrino factories [31] and beta beams [32].
Figure 6: Left panel: the layout of the T2K beam line, showing the location of primary proton beam line, target station, decay volume, beam dump, muon monitors and near neutrino detectors. Right panel: sketch of the T2K ND280 near detector.

6.1 T2K

The T2K (Tokai-to-Kamioka) experiment [33] will use a high intensity off-axis neutrino beam generated by a 30 GeV proton beam at J-PARC (Japan Proton Accelerator Research Complex) fired to the Super Kamiokande detector, located 295 km from the proton beam target. The schematic view of the T2K neutrino beam line is shown in Fig. 6 left.

A sophisticated near detector complex (ND280) will be built at a distance of 280 m from the target. This complex has two detectors: one on-axis (neutrino beam monitor) and the other off-axis. This off-axis detector (Fig. 6 right) is a spectrometer built inside the magnet of the former experiments UA1 and Nomad, operating with a magnetic field of 0.2 T. It includes a Pi-Zero detector (POD), a tracking detector made by three time projection chambers (TPC’s) and two fine grained scintillator detectors (FGD’s), a 4π electromagnetic calorimeter (Ecal), and a side muon range detector (SMRD). Neutrino rates in the close detector will be about 160000 $\nu_\mu$ (3200 $\nu_e$) interactions/ton/yr at the nominal beam intensity of 0.75 MW·10$^7$ s.

ND280 is expected to calibrate the absolute energy scale of the neutrino spectrum with 2% precision, measure the non-QE/QE ratio at the 5-10% and monitor the neutrino flux with better than 5% accuracy. The momentum resolution of muons from the charged current quasi-elastic interactions (CCQE) should be better than 10%. The $\nu_e$ fraction should be measured with an uncertainty better than 10%. A measurement of the neutrino beam direction, with a precision better than 1 mrad, is required from the on-axis detector.

The sensitivity of T2K in measuring the atmospheric parameters through the $\nu_\mu$ disappearance is shown in Fig. 7 (T2K is expected to collect about 16000 $\nu_\mu$ interactions in 5 years at the nominal beam intensity, neglecting the oscillations).

Fig. 7 center and right show the sensitivity in measuring $\theta_{13}$. The experiment will reach
Figure 7: Left panel: 99% CL contours for two test points selected within the 99% allowed values by the world fits [2]. They are computed for 5 years data taking at 0.75 MW/year, and 5% systematic errors. The T2K values are taken by [34]. Also shown are the allowed regions by fits to SuperKamiokande+K2K and to Minos only. Central panel: 90% CL sensitivity to $\sin^2 2\theta_{13}$, computed for 5 years data taking at 0.75 MW/year, compared with the Chooz limit in the $\sin^2 2\theta_{13}$ vs $\Delta m_{23}^2$ plane, assuming $\delta_{CP} = 0$ and normal hierarchy, for three different choices of the systematic errors. Right plot: the same sensitivity computed in the $\delta_{CP}$ vs $\sin^2 2\theta_{13}$ plane, assuming $\Delta m_{23}^2 = 2.5 \cdot 10^{-3} \text{eV}^2$ and normal hierarchy.

A factor 20 improvement with respect to the Chooz limit.

The commissioning of the neutrino beam line successfully started on April, 24, 2009. Data taking is scheduled to start end 2009, integrating the first year $0.1 \text{MW} \cdot 10^7 \text{s}$ protons, allowing for a $\sin^2 2\theta_{13}$ sensitivity of $\sin^2 2\theta_{13} \simeq 0.1$ (90%CL, $\Delta m_{23}^2 = 2.5 \cdot 10^{-3} \text{eV}^2$, $\delta_{CP} = 0$, normal hierarchy.).

The T2K setup has been designed to be scalable [33]. The J-PARC beam intensity can be upgraded up to 1.6 MW and a new water Čerenkov detector with a fiducial 25 times bigger than Super Kamiokande, Hyper Kamiokande [33], can be build in the Kamioka region.

### 6.2 NOνA

The NOνA experiment [35] will run at an upgraded NuMI neutrino beam ($6.5 \cdot 10^{20} \text{pot/year}$, corresponding to a beam power of 700 kW; $E_{\nu} \sim 2 \text{ GeV}$ and a $\nu_e$ contamination less than 0.5%) at baseline of 810 Km, 14 mrad off-axis. The start-up phase of the experiment is funded and the fully approval is expected within 2009. The far detector will be a 15 kt “totally active” tracking liquid scintillator, scheduled to be fully operational by the end of 2013. The close detector will be a 215 ton replica of the far detector, placed 14 mrad off the NuMI beam axis at a distance of 1 km from the target. NOνA plans to run 3 years in neutrino mode and 3 years in antineutrino mode. Since NOνA will reach similar $\theta_{13}$ sensitivities of T2K with several years of delay, cfr. Fig. 11, the focus of the experiment...
is to provide data on the neutrino mass hierarchy, where NO\text{\textnu}A has a clear advantage with respect to T2K thanks to the longer baseline. These searches require a statistically significant antineutrino run. In doing that NO\text{\textnu}A can also provide first indications about the range of \(\delta_{\text{CP}}\) and informations about \(\theta_{13}\) complementary to T2K.

As a second phase, the NuMI beam intensity could be increased to 1.2 MW (“S\text{\textnu}MI”) or to 2.3 MW (“Project X”) in case the new proton driver of 8 GeV/c and 2 MW will be built at FNAL.

7 Reactor Experiments

Reactor experiments can measure \(\theta_{13}\) by detecting \(\bar{\nu}_e\) disappearance at the atmospheric \(\Delta m^2\). The oscillation disappearance \(P_{\bar{\nu}_e\bar{\nu}_e}\) can be expressed as:

\[
1 - P_{\bar{\nu}_e\bar{\nu}_e} \simeq \sin^2 2\theta_{13} \sin^2 (\Delta m_{31}^2 L/4E) + (\Delta m_{21}^2/\Delta m_{31}^2)^2 (\Delta m_{31}^2 L/4E)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}
\]

showing a direct connection between \(P_{\bar{\nu}_e\bar{\nu}_e}\) and \(\theta_{13}\), with no interference by \(\delta_{\text{CP}}\) and \(\text{sign}(\Delta m_{23}^2)\).

The deep difference between the appearance formula Eq. 2 and the disappearance Eq. 3 suggests that the two experimental approaches are truly complementary. This is illustrated in Fig. 8 where the nominal, final, sensitivity of T2K is compared with the sensitivities of

\[\text{Figure 8: 90\% CL sensitivity of T2K, from [33], Double Chooz, from [36], and Daya Bay, from [37]. Also shown are the combinations of T2K with Double Chooz and with Daya Bay, as computed with Globes [38].}\]
Figure 9: Left panel: signal and backgrounds events for T2K, computed for $\sin^2 2\theta_{13} = 0$, $\delta_{CP} = 0$, $\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV$^2$ and normal hierarchy, from [33]. Right panel: number of disappeared events in Double Chooz under the same conditions. Also shown statistic and expected systematic errors, together with systematic errors as big as the former Chooz experiment. The signal is compared with the expected background rate, before and after the subtraction of the close detector data. Elaborated from [36].

The reactor experiments Double Chooz and Daya Bay. While the appearance sensitivity is modulated by the unknown value of $\delta_{CP}$, the disappearance sensitivity is flat. Their combination provides a powerful sensitivity plot where the $\delta_{CP}$ modulation is reduced and the overall sensitivity increased.

Appearance experiments are limited by statistics and background rates, while reactor experiments are limited by systematic errors, as illustrated by Fig.9 where are compared the signal distributions for T2K and Double Chooz computed for $\sin^2 2\theta_{13} = 0.1$.

### 7.1 Double Chooz

The Double Chooz experiment [36] will be installed near the Chooz two-core (4.27+4.27 GW) nuclear power plant. The far detector, a 8.3 t gadolinium loaded liquid scintillator detector, will be placed in the existing site of the previous Chooz experiment, 1.05 km from the reactor cores, at a depth of about 300 m.w.e. The close detector, identical to the far detector, will be placed at about 400 m from the reactor cores (not at the exact relative distance of the far detector), at a depth of 115 m.w.e. The experiment aims to an overall systematic error of 0.6%, the far detector is expected to begin data taking end of 2009, while the close detector should be put in operation by end of 2011. The $\theta_{13}$ sensitivity of the experiment as function of time is shown in Fig.10 left.

[on the other hand reactor experiments, having no sensitivity to the atmospheric parameters, need the information of an accelerator experiment to delimit the $\Delta m_{23}^2$ range where they probe $\theta_{13}$]
Figure 10: Left panel: expected $\sin^2 2\theta_{13}$ sensitivity, 90% CL, of the Double Chooz experiment, computed for $\Delta m_{23}^2 = 2.5 \cdot 10^{-3} \text{eV}^2$, year zero is expected to be end 2009, from [36]. Right panel: the same for the Daya Bay experiment, from [37], where year zero is expected to be summer 2011.

7.2 Daya Bay

The Daya Bay experiment [37] will receive neutrino by two nuclear plants: Daya Bay and LingAo located in the south of China. The two nuclear plants are about 1100 m apart. Each nuclear plant has two cores running. Another two cores, called LingAo II, are expected to be commissioned by the end of 2010. The thermal power of each core is 2.9 GW, hence the existing total thermal power is 11.6 GW, and will be 17.4 GW after 2010. The basic experimental layout of Daya Bay consists of three underground experimental halls, one far and two near, linked by horizontal tunnels. Each near hall will host two 20 t gadolinium doped liquid scintillator detectors, while the far hall will host four such detectors.

The experiment aims to an overall systematic error of 0.38% (for a comparison of the systematic errors of Double Chooz and Daya Bay see [39]), the far detectors are expected to begin data taking mid of 2011. The $\theta_{13}$ sensitivity of the experiment as function of time is shown in Fig. 10 right.

8 Guessing the Future

It is of some interest to have a look to the expected sensitivities of accelerator and reactor experiments in the near future. Fig. 11 shows the evolution of the $\theta_{13}$ sensitivities as a function of the time. From the plot one can derive that in the next 5 years or so the $\theta_{13}$ parameter will be probed with a sensitivity about 25 times better than the present limit.

Since the T2K $\theta_{13}$ sensitivity depends from the unknown $\delta_{CP}$ parameter and from the
Figure 11: Evolution of experimental $\sin^2 2\theta_{13}$ sensitivities as function of time. All the sensitivities are taken from the proposals of the experiments. For T2K it is assumed a beam power of 0.1 MW the first year, 0.75 MW from the third year and a linear transition in between. NO$\nu$A sensitivity is computed for $6.5 \times 10^{20}$ pot/yr, 15 kton detector mass, neutrino run. Accelerator experiments sensitivities are computed for $\delta_{CP} = 0$ and normal hierarchy, for all the experiments $\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV$^2$. The sensitivity curves are drawn starting after six months of data taking.
Figure 12: Evolution of experimental $\sin^2 2\theta_{13}$ sensitivities of T2K and the reactor experiments Double Chooz and Daya Bay as function of time, under the same assumptions of Fig. 11. The T2K sensitivity is computed with GLoBES [38], using the GLoBES library, and shown as a band of values computed for different values of $\delta_{\text{CP}}$ and for normal (NH) and inverted (IH) hierarchy.

From the plot some considerations can be taken:

- Double Chooz is very competitive in the first years of operation, when the information of the close detector probably will not be available.

- The time evolution of beam power of T2K is crucial. It is impossible to state now which time evolution will have the J-PARC neutrino beam line, based on a totally new accelerator complex, so the sensitivity shown here is just a personal educated guess.

- Also for Daya Bay the schedule is critical. Very important will be also the goal of very small systematic errors claimed by the experiment.

This discussion is based on sensitivities, where no signal in the detectors is assumed. In case of $\theta_{13}$ in the reach of those experiments, their information will be truly complementary to measure the true value of the parameter, for a discussion under this hypothesis see for instance [40].
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