Theta 13 Determination with Nuclear Reactors

F. Dalnoki-Veress for the Double-Chooz Project
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1
D-69117, Heidelberg, Germany

Recently there has been a lot of interest around the world in the use of nuclear reactors to measure θ_{13} , the last undetermined angle in the 3-neutrino mixing scenario. In this paper the motivations for θ_{13} measurement using short baseline nuclear reactor experiments are discussed. The features of such an experiment are described in the context of *Double Chooz*, which is a new project planned to start data-taking in 2008, and to reach a sensitivity of $\sin^2(2\theta_{13}) < 0.03$.

1 Current State of Neutrino Physics

The past few decades have seen much progress in the field of neutrino physics. We now believe that active neutrinos mix in three flavours as quarks do in the quark sector, and that as a consequence the neutrinos must have mass. However, neutrinos mix with very different mixing angles from the quark sector since we know two of the mixing angles are large, whereas the mixing angle in the quark sector is exceedingly small. In the three neutrino mixing[a] scenario the mixing between the mass (ν_i where i=1,2,3) and flavour eigenstates (ν_α where alpha represents the 3 active lepton flavours) can be parameterized in terms of a unitary matrix often called the U_{PMNS} mixing matrix ($\mathcal{M}$ is the Majorana phase matrix). Nevertheless, the underlying symmetry behind the structure of this matrix and its relation to the CKM matrix is entirely unknown:

$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & & \\ & c23 & s23 \\ & -s23 & c23 \end{pmatrix}}_{\theta_{23}=\theta_{atmospheric}\sim 45^\circ} \underbrace{\begin{pmatrix} c13 & & s13e^{-i\delta} \\ & 1 & \\ -s13e^{i\delta} & & c13 \end{pmatrix}}_{\theta_{13}=\theta_{reactor}\leq 14.9^\circ} \underbrace{\begin{pmatrix} c12 & s12 & \\ -s12 & c12 & \\ & & 1 \end{pmatrix}}_{\theta_{12}=\theta_{solar}\sim 28^\circ-39^\circ} \mathcal{M} \quad (1)$$

[a] The assumption in this note is that only 3 neutrino types exist. If MiniBoone confirms the existence of a fourth neutrino the current scenario will need to be re-evaluated

Three types of experiments have been performed over the last 30 years: the pioneering solar neutrino measurements which first identified problems in the neutrino sector, atmospheric neutrino experiments, and short and long baseline nuclear reactor experiments. These three types of experiments essentially measure different components of the neutrino mixing matrix and the factorized form of the neutrino mixing matrix can be used to identify these different components. The three mixing angles are labelled θ_{sol} and θ_{atm} according to the dominant type of experiment that these angles are measured with. The third type of experiment is the the short baseline neutrino experiments which measure the final angle θ_{13} in the 3 neutrino mixing scenario. Using the mixing matrix the three flavour neutrino mixing probability can be written as:

$$P_{(\nu_\alpha \to \nu_\beta)} = \delta_{\alpha\beta} - 2\Re \sum_{j>i} U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j} \left(1 - exp^{(i\Delta m^2_{ji} L/2E)}\right) \quad (2)$$

$$where,\ \Delta m^2_{ji} = m^2_j - m^2_i \quad (3)$$

Therefore, an experiment measuring only one type of neutrino is sensitive to all 3 neutrino mass eigenstates through the U_{PMNS} neutrino mixing matrix. The degree of sensitivity depends on the type of experiment and the (L/E) distance between the neutrino source and detector.

Neutrino oscillations are then described by three mixing angles (θ_{12}, θ_{23}, θ_{13}), a CP violating phase (δ_{CP}) and two quadratic mass splittings (Δm^2_{12} and Δm^2_{23}). Solar neutrino data combined with the results of the KamLAND long baseline reactor experiment suggest $\Delta m^2_{12} = \Delta m^2_{sol} \sim 6.9^{+2.6}_{-1.5} \times 10^{-5}$, whereas atmospheric neutrino detectors and K2K (a long baseline accelerator experiment) have measured $\Delta m^2_{23} = \Delta m^2_{atm} = \pm 2^{+1.2}_{-0.9} \times 10^{-3} \sim \Delta m^2_{13}$. An ambiguity exists in the sense that it is not known whether m_1 (normal hierarchy) or m_3 (inverted hierarchy) state is the lowest neutrino mass eigenstate. Future generations of experiments especially double beta decay and long baseline accelerator experiments will attempt to resolve this. Crucial to this picture of neutrino mass mixing is the θ_{13} mixing angle which is not known and has only been constrained by reactor experiments such as Chooz and Palo Verde to be $<14.9^\circ$ (3σ). For this reason it is imperative to measure θ_{13} in the next generation of experiments.

1.1 Measurement of Theta 13

There are two types of experiments that will be sensitive to θ_{13}: the accelerator and nuclear reactor experiments. The accelerator experiments produce pions and kaons which primarily decay to produce ν_μ's. These experiments are typically long baseline experiments (LBL) optimized to the distance where there is maximum conversion of ν_μ to other flavours. Using the formula above (2) and the approximation that Δm^2_{atm}=Δm^2_{13}, θ_{sol}=θ_{12}, and θ_{atm}=θ_{23} the conversion probability is written [2]:

$$\begin{aligned} P_{\nu_\mu \to \nu_e} &\simeq \sin^2 2\theta_{13} \sin^2 \theta_{atm} \sin^2(\Delta m^2_{atm} L/4E) && (4)\\ &\mp \alpha \sin 2\theta_{13} \sin \delta_{CP} cos\theta_{13} \sin 2\theta_{sol} \sin 2\theta_{atm} (\Delta m^2_{atm} L/4E) \sin^2(\Delta m^2_{atm} L/4E) && (5)\\ &+ \alpha \sin 2\theta_{13} \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{sol} \sin 2\theta_{atm} \cos(\Delta m^2_{atm} L/4E)(\Delta m^2_{atm} L/4E)\\ &\quad \sin(\Delta m^2_{atm} L/4E)\\ &+ \alpha^2 \cos^2 \theta_{atm} \sin^2 2\theta_{sol} (\Delta m^2_{atm} L/4E)^2\\ &\quad where\ \alpha = \Delta m^2_{sol}/\Delta m^2_{atm} \simeq 0.029 \end{aligned}$$

The (+) sign in equation (5) refers to anti-neutrino oscillations and the (−) sign refers to neutrino oscillations. One notices that there are ambiguities in the sense that there are parameter correlations and degeneracies due to different combinations of parameters. For example, the survival probability is the same if a substitution of $\theta_{23} \to (\frac{\pi}{2}) - \theta_{23}$ is made, or one can vary δ and θ_{13} to give the same overall survival probability.

Table 1: Proposed sites around the world for a next generation nuclear reactor neutrino project to measure θ_{13} [5].

Site/Project	Reactor Power (GW)	Baseline Near/Far (m)	Overburden Near/Far (m.w.e.)	Det. Volume Near/Far (t)
Double-Chooz (France)	8.5	150/1050	60/300	10/10
KR2DET (Russia)	1.5	115/1000	600/600	45/45
Diablo Canyon (USA)	7	400/1800	100/700	25/50
Angra (Brazil)	4	350/1350	60/600	50/50
Braidwood (USA)	7	200/1800	250/250	25/50
KASKA (Japan)	24	350/1300	140/600	8.5/8.5
Daya Bay (China)	11	300/1500	200/1000	20/40

In nuclear reactor neutrino experiments the oscillation probability is quite different [b]:

$$P_{\overline{\nu_e}\to\overline{\nu_e}} \simeq \underbrace{1-\sin^2 2\theta_{13}\sin^2(\Delta m^2_{atm}L/4E)}_{\theta_{13}\, oscillations} + \alpha^2 \underbrace{(\Delta m^2_{atm}L/4E)\cos^4\theta_{13}\sin^2 2\theta_{sol}}_{\theta_{sol}\, influence} \quad (6)$$

Here only the first two terms contribute since α is small. Furthermore, for small (L/E) the second term does not contribute since the solar oscillation depletion occurs at much longer baselines because of the small Δm^2_{sol}. Therefore the survival probability amounts to the first term of $P_{\overline{\nu_e}\to\overline{\nu_e}}$, and reduces to the familiar two neutrino oscillations survival probability formula. Comparing the reactor neutrino survival probability formula to the LBL probabilities, one notices that the CP violating parameter δ_{CP} does not appear. This is the strength of reactor experiments since these experiments allow θ_{13} to be measured independent of δ_{CP} without the ambiguities which are present in LBL experiments. The CP asymmetry in LBL experiments may be expressed as [4]:

$$\begin{aligned} A_{CP} &= \frac{P_{\nu_\mu\to\nu_e} - P_{\overline{\nu_\mu}\to\overline{\nu_e}}}{P_{\nu_\mu\to\nu_e} + P_{\overline{\nu_\mu}\to\overline{\nu_e}}} \\ &= \left(\frac{\Delta m^2_{12} L \sin 2\theta_{12}}{4E_\nu}\right) \times \frac{\sin\delta_{CP}}{\sin\theta_{13}} \end{aligned} \quad (7)$$

Consequently, determination of θ_{13} in nuclear reactor experiments may also be useful for LBL experiments in tuning their energy to maximize the δ_{CP} asymmetry.

2 Theta 13 Reactor Experiments

In the last few years there has been great interest in the measurement of θ_{13} using nuclear reactors. In fact an international working group has been formed to study the feasibility of such an experiment [2]. Currently, there are several possible sites identified around the world for a future reactor neutrino experiment. Table 1 shows a summary of the possible sites and their specific characteristics. One of the most promising projects is *Double-Chooz*, a experiment to measure θ_{13} to be constructed at the Chooz site. The basic design and features of all the projects are similar to one another and will be illustrated with Double-Chooz.

[b] Neglecting terms of second order in α

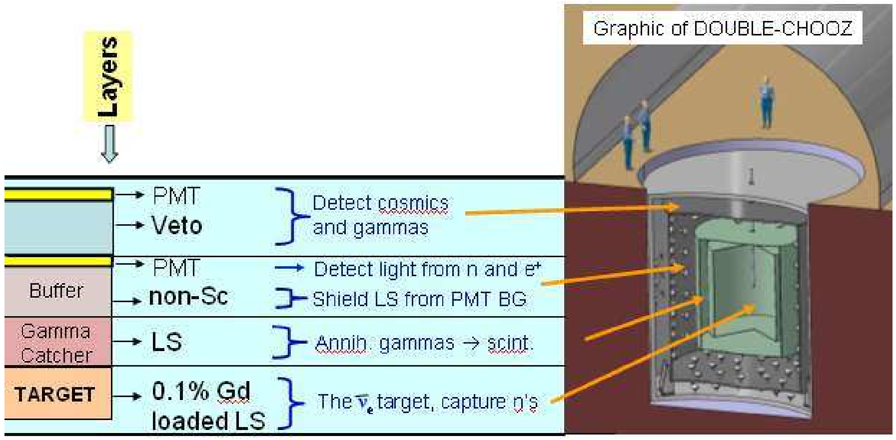

Figure 1: Artist conception of the *Double-Chooz* project showing the layers of the various components (left) of the detector [3]

3 Double-Chooz: An Example of Generic Design

The basic structure of *Double-Chooz* is illustrated in Figure 1. The important features of the design are:

- Gd loaded liquid scintillator (LS) central target defining the fiducial volume
- LS surrounding target to catch annihilation gammas (Gamma Catcher)
- Non-scintillating buffer to shield target from the photomultipliers (PMT's)
- Passive or active veto to detect cosmics
- Two detectors to cancel reactor related systematics
- Deep underground to decrease cosmogenic backgrounds

Details of the *Double-Chooz* project are described in the next section [c].

3.1 Anti-Neutrino Calorimetry

Anti-neutrinos are produced via the beta decay of the nuclear fuel used in the reactors. The antineutrino can react with a free proton via inverse beta decay:

$$\overline{\nu_e} + p \longrightarrow e^+ + n$$

The anti-neutrino energy threshold for the inverse beta reaction is 1.8 MeV. At this energy the positron annihilates at rest and produces 2 back-to-back gammas. The neutrino flux coming from the nuclear reactor is an exponentially decaying function of neutrino energy. Meanwhile, the cross-section of inverse-beta decay is an exponentially increasing function of energy so that the detected flux is a spectra peaking at approximately 3.5-4 MeV (see Figure 2).

[c]Most of the information in the next section is taken from the Double Chooz Letter of Intent [3]

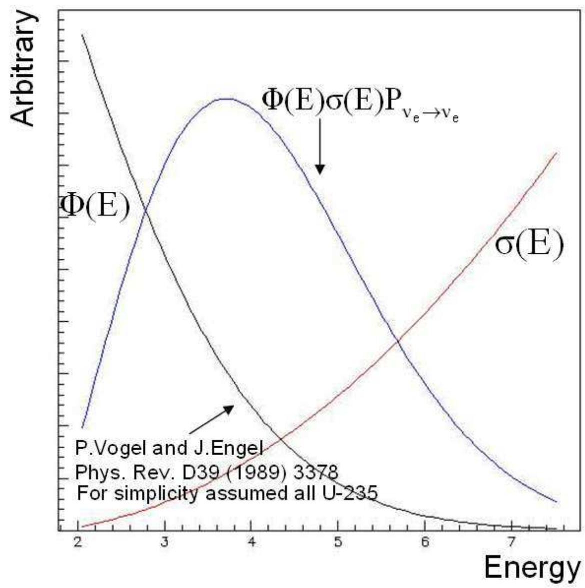

Figure 2: Figure showing the neutrino flux (calculated for ^{235}U only) and the cross-section for inverse beta decay as a function of energy and the positron spectrum.

In all of the new generation nuclear reactor projects the main target for the anti-neutrinos is a Gd doped LS volume (see Figure 1). Natural Gd has a very high neutron capture cross-section (49000 barn averaged over the isotopes [6]) and produces gammas peaking at ∼8 MeV when the excited states decay. Therefore, a specific signature for the detection of an electron antineutrino is the detection of prompt gamma's from the annihilation of the positron and the delayed capture of a neutron several tens of μs later. The gammas are detected by the central LS target, and the surrounding LS known as the 'Gamma-Catcher'. It should be mentioned that the neutrons produced in the target may also be captured in the free-H present in the LS in both the target and the Gamma-catcher, and this would create uncertainty in determining the neutrino target volume. However, the neutron capture gamma spectrum for H is very different from Gd in that the H high energy tail does not exceed ∼4 MeV. Therefore, the target fiducial volume can be selected by accepting events of energy greater than 6 MeV. This is demonstrated in Figure 3, where the neutron capture gamma spectrum is shown for *Double-Chooz* and the separation between the H and Gd spectra is evident.

The presence of the Gamma-Catcher ensures that the positron energy is fully contained, because all the light from the positron annihilation is detected. An improvement over previous experiments is the inclusion of a non-scintillating buffer to shield the gamma catcher and central target from the light produced by the PMT beta-gammas. Surrounding the buffer is a cylinder of ∼800 PMT's that detect the light from the positron annihilation and Gd gammas.

3.2 Two Identical Detectors for Uncertainty Cancellation

Antineutrinos are produced by nuclear reactors due to the beta decay of the fission daughters of 4 main isotopes (^{235}U,^{238}U, ^{239}Pu, and ^{241}Pu). In actual fact there are hundreds of different beta decay spectra to account for in modelling the total anti-neutrino flux, although the agreement between theory and experiment is approximately 4%, it is not precise enough for the new generation of short baseline nuclear reactor experiments. Thus, one of the fundamental limitations of previous experiments is the knowledge of the nuclear reactor neutrino flux. To improve on this systematic, the new generation of short baseline reactor neutrino experiments

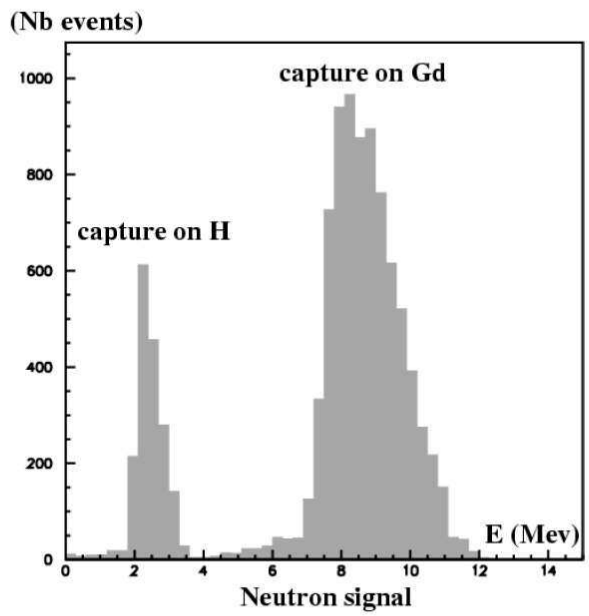

Figure 3: The gamma spectrum for neutron capture on H and on Gd showing the clear separation between the two spectra. Selecting energies exceeding 6 MeV will ensure that the neutrino target volume is well defined [3].

will use two detectors [1], one at approximately 100-200 m (Near Detector) and another detector at ∼1-1.2 km tuned to be at the first θ_{13} oscillation maximum. The near detector measures the un-oscillated neutrino spectrum and flux. Therefore, the nuclear reactor related uncertainties such as neutrino flux, structure of the core, will not be a limiting factor. The target volume for the near and far detector for *Double-Chooz* is planed to be 12.7 m^3 and is expected to give a statistical error <0.4% for the data-set of interest. Furthermore, the detectors will be identical so that many detector related efficiencies should cancel. Uncertainties such as scintillator density, fraction of free protons and hydrogen atom density will all cancel, since it is planned to fill both the near and far detector at the same time from the same batch of liquid scintillator. The important quantity is the relative systematic error between the near and far detector. This systematic has been estimated to be ∼0.6%.

3.3 Further Decrease of Systematics

The new generation of nuclear reactor neutrino experiments, such as *Double-Chooz* require an extremely small uncertainty to be sensitive to the subdominant θ_{13} oscillations. This requires not only cancellation of the detector and reactor related uncertainties, but also a carefully performed analysis not to introduce efficiencies and unnecessary cuts, since these all have accompanying uncertainties. In the Chooz experiment many of the dominant uncertainties were due to cuts applied when events were reconstructed. For *Double-Chooz* it has been decided not to apply any reconstruction cuts and this has decreased the number of cuts from 7 to 3. The remaining systematics related to the cuts are shown in Table 2. When all the analysis cuts and uncertainties are taken into account the final uncertainty is expected to be $\sim \pm 0.4(\text{stat}) \pm 0.6(\text{syst})\%$.

3.4 Background Reduction

The primary feature that distinguishes proposed projects around the world is the size of the fiducial volume. Groups propose anti-neutrino targets ranging from 10-50 m^3, determining a limit of $\sin^2\theta_{13} < 0.01 - 0.03$. However, the size of the fiducial target is not the only significant

Table 2: Uncertainties in the analysis cuts and efficiencies for the *Double-Chooz* experiment [3].

	Chooz	*Double-Chooz*
Proton Density	0.8 %	0.2 %
Neutron Efficiency	0.85 %	0.2 %
Neutron Energy Cut	0.4 %	0.2 %

feature that determines the final limit, since high statistics in the far detector is only useful if the background is low. Anti-neutrino detection only requires two logical requirements:

- Condition 1: Two pulses within 200 μs
- Condition 2: Second pulse must have E>6 MeV

Therefore, the backgrounds to this signal are accidental and correlated coincidences produced by natural radioactivity and cosmic ray induced events. The effect of cosmic rays can be sufficiently reduced by constructing the detectors deep underground to reduce the cosmic ray flux. In addition, in the *Double-Chooz* design there is a muon veto anti-coincidence shield. The muon veto consists of a LS buffer surrounded and optically separated from the PMT support structure. Surrounding the buffer there are additional PMTs which point inward so that cosmic ray muons can be tagged when these traverse the buffer. Therefore, by careful material selection, placing the detectors underground, and implementing an efficient muon veto the goal of *Double-Chooz* is to reduce the background to 1% of the signal. Some of the components of the background are:

- *Accidental background produced by* ^{232}*Th,* ^{238}*U,* ^{40}*K present in the detector materials.* The concentration of Th/U in the scintillator and acrylic vessel must be less than 10^{-12} and 10^{-10} respectively to ensure this background is negligible.
- *Correlated events due to cosmic ray spallation on* ^{12}*C in the LS.* Cosmic ray spallation on the LS can produce various short-lived isotopes such as ^{9}Li, ^{11}Li, and ^{8}He. These isotopes subsequently beta decay and can produce neutrons. In some of these cases the two pulses will have the same time structure as an anti-neutrino event. The cross-section of ^{8}He+^{9}Li has been measured by the NA54 [7] experiment at CERN.
- *Correlated background due to cosmic ray spallation outside the detector.* In this case the spallation events produce fast neutrons and the initial muon is not detected by the veto. These neutrons travel to the central target, and scatter on nuclei to produce fast protons which in turn generate scintillation light and look like positrons. The spallation neutron may then be captured in the target. The timing of such an event looks identical to anti-neutrino capture. The background for these events can be calculated using Monte Carlo methods and are expected to be <1/day.

The near detector is constructed with an artificial overburden of 60-80 m.w.e. so that the cosmic ray induced backgrounds are much higher. Fortunately, the increase in background is compensated by an increase in the signal due to the proximity of the near detector, so that the background is still < 1% of the signal. Furthermore, nuclear reactors tend to be cycled 'on' and 'off' when maintenance is done, or when fuel rods are changed, so that this will allow a 'beam-off' measurement to be done. In this way the background can be independently measured.

3.5 θ_{13} Sensitivity

The *Double-Chooz* sensitivity is calculated by doing a χ^2 fit of the expected number of events for various oscillation scenarios compared to the no-oscillation case. This analysis takes into account the relative normalization error, energy and spectral shape uncertainty, fluctuation in the core and background subtraction error. The $\sin^2(2\theta_{13})$ limit for no-oscillations is a strong function of Δm^2_{atm} in the sense that if Δm^2_{atm} is higher but no events are observed, the $\sin^2(2\theta_{13})$ limit is pushed lower. Recently SK presented a new analysis to estimate Δm^2_{atm} by reconstructing the energy and path length (using direction with respect to zenith angle) of atmospheric neutrinos. They proved from the (L/E) analysis that the data follows the 'dip' expected due to θ_{sol} oscillations and extracted Δm^2_{atm}=$2.4^{+0.6}_{-0.5}\times10^{-3}$ eV^2, an increase from the value presented at Neutrino 2002 in Munich. The no oscillation sensitivity for *Double-Chooz* is presented in Figure 4 as a function of Δm^2_{atm}, the shaded regions shows the two SK analyses. The sensitivity of the various other proposed reactor experiments to θ_{13} ranges from $\sin^2(2\theta_{13})<0.01$-0.03. In the case of discovery, a non-vanishing $\sin^2(2\theta_{13})=0.05(0.04)$ at 3σ could be measured in 3 years of data running for Δm^2_{atm}=2.0×10^{-3} eV^2(2.4×10^{-3} eV^2).

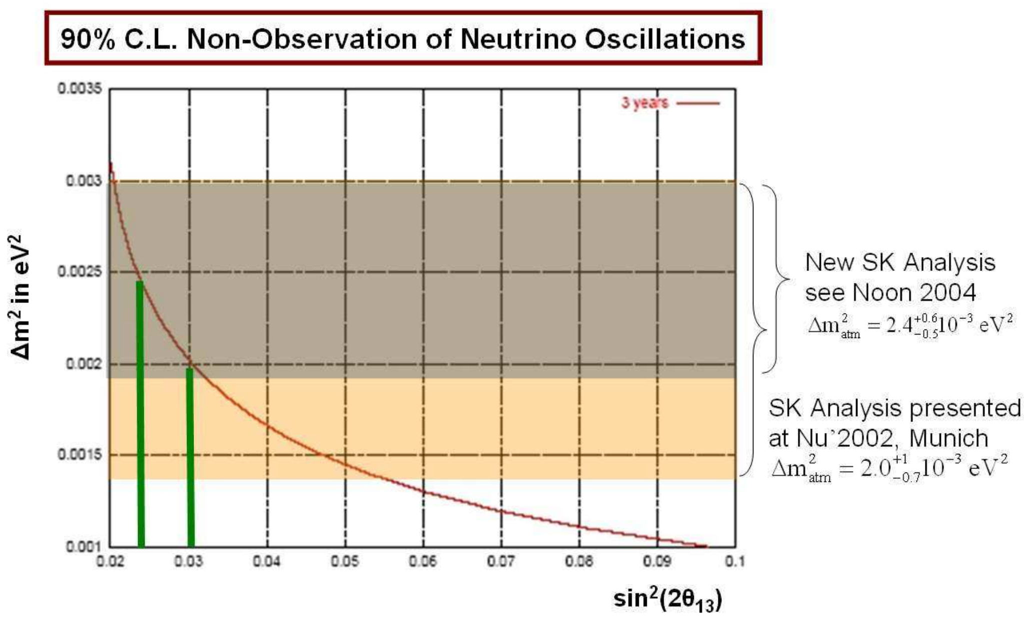

Figure 4: The 90 % C.L. upper limit that can be placed on $\sin^2(2\theta_{13})$ as a function of Δm^2_{atm} for a 3 year data set [3].

4 Conclusions

The past few years have seen a lot of progress in a new generation of nuclear reactor experiments specifically designed to measure θ_{13}. The design requires careful control of systematics by requiring two detectors, a large overburden, and a baseline for the far detector tuned to be at the first maximum of the sub-dominant θ_{13} oscillations. This allows us to neglect matter oscillations and make a pure measurement of $\sin^2(2\theta_{13})$. Several sites around the world are being investigated (see Table 1). Among the most promising is the *Double-Chooz* project, a project planned to be constructed at the old Chooz detector site. *Double-Chooz* plans to set a limit of $\sin^2(2\theta_{13})<0.03$ after 3 years of running.

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