APS Report on Reactor Neutrino Physics, Section II

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1 A Reactor Neutrino Oscillation Experiment to Measure θ_{13}: Design Concepts and Considerations

For over 50 years reactor neutrino experiments have played an important role in the development of neutrino physics. From the first detection of the free antineutrino by Reines and Cowan in 1956 [1] to the observation of reactor antineutrino disappearance at KamLAND the inverse beta-decay reaction on protons in liquid scintillator has been used to observe and count antineutrino interactions and determine the flux of reactor $\overline{\nu}_e$ as a function of distance from the source. In principle, the detector technology used today in the KamLAND experiment is still very much the same as in Reines' original reactor neutrino experiment. With a systematic uncertainty of about 6% the precision of reactor neutrino flux measurements is similar to the current precision of solar neutrino flux measurements. Only one experiment, the Chooz reactor neutrino experiment [2], has performed a better absolute measurement of the reactor antineutrino flux with a residual systematic error of 2.7%. Figure **??** shows a summary of absolute reactor $\overline{\nu}_e$ flux measurements.

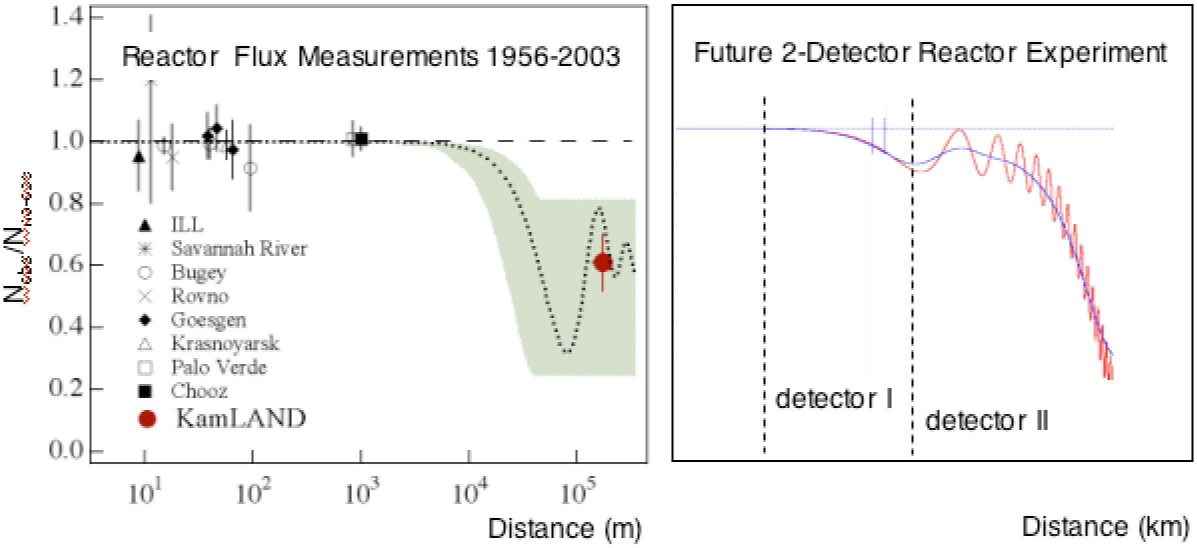

Figure 1: Absolute reactor antineutrino flux measurements in the past (left panel) and proposed future reactor neutrino oscillation experiment with multiple detectors for a relative measurement of the antineutrino interaction rate to discover subdominant oscillations and measure θ_{13}. The right panel shows the survival probability P_{ee} for a 4 MeV $\overline{\nu}_e$ (red) and averaged over the reactor $\overline{\nu}_e$ spectrum (blue).

The primary goal of a next-generation reactor neutrino oscillation experiment is to discover and measure the neutrino mixing angle θ_{13} and – together with accelerator experiments – help determine the mass hierarchy and constrain the CP-violating phases in the neutrino mixing matrix. A limit of $\sin^2 2\theta_{13} \leq 0.01$ would future efforts in neutrino oscillation physics and determine the feasibility of the search for leptonic CP violation. See Section **??** for a complete discussion of the physics opportunities of a next-generation oscillation experiment.

The search and measurement of θ_{13} at the 1% level will be an extraordinary experimental challenge.

To achieve this sensitivity and exploit the long-term physics potential of a θ_{13} reactor neutrino oscillation experiment a new experimental concept and new measures in the design of the antineutrino detectors are required.

In this section we discuss general issues that enter the design considerations and concepts of a reactor neutrino oscillation experiment to measure θ_{13}. Methods for mitigating the dominant systematic error are described and the qualitative features of various classes of θ_{13} reactor experiments are discussed. The relative importance of these issues is discussed in Section **??** on issues relevant for evaluating θ_{13} reactor neutrino experiments. We present the various design concepts for θ_{13} experiments that have been developed by the community over the course of the past year and discussed in a series of workshops on *Future Low-Energy Reactor Neutrino Experiments*.

1.1 Strategies to Improve on Past Reactor Neutrino Oscillation Experiments

Past and present reactor neutrino experiments have searched for signatures of neutrino oscillation by making an absolute measurement of the $\overline{\nu}_e$ flux from single or multiple reactors at distances ranging from a few meters to hundreds of kilometers. The precision of these measurements has been limited by the statistics of $\overline{\nu}_e$ interactions as well as the systematic uncertainties in the measurement. The dominant systematics are:

1. fiducial volume and efficiency of neutron detection
2. correlated backgrounds from muon interactions
3. theoretical uncertainty in the spectrum
4. flux uncertainty in the $\overline{\nu}_e$ source

To discover subdominant oscillation effects beyond the current precision of absolute $\overline{\nu}_e$ flux measurements a new concept is needed. A next- generation reactor $\overline{\nu}_e$ oscillation experiment will use two or multiple detectors to determine the $\overline{\nu}_e$ survival probability P_{ee} from a relative measurement of the $\overline{\nu}_e$ interaction rate and spectrum at different distances from the $\overline{\nu}_e$ source (see Figure **??**). The two detectors will be placed as close as possible to the reactor to maximize the signal statistics while optimizing the sensitivity to the subdominant oscillation signal.

Baseline Optimization: The optimum distances for the detectors is determined by the oscillation frequency in the (1,3) channel which depends on the mass splitting $\Delta m_{13} = \Delta m_{12} + \Delta m_{23} \simeq \Delta m_{23}$ for $\Delta m^2_{12} \simeq 10^{-5}$ eV^2 and $\Delta m^2_{23} \simeq 10^{-3}$ eV^2. Hence, the frequency of the (1,3) oscillation and the distances of the detectors will primarily depend on the atmospheric mass splitting Δm^2_{23}. For $\Delta m^2_{23} \simeq 2 \times 10^{-3}$ eV^2 and a mean energy of $E_{\overline{\nu}_e}$= 3.5 MeV the oscillation wavelength in the (1,3) channel is ∼4 km. The first minimum in the survival probability occurs at a distance of ∼2 km from a reactor. The simplest approach to measuring θ_{13} is to use the first detector as a *near detector* to normalize the $\overline{\nu}_e$ flux from the reactor while the second detector – also referred to as the *far detector* – is placed at a distance that maximizes its sensitivity to a suppression in the $\overline{\nu}_e$ interaction rate and/or a distortion in the observed $\overline{\nu}_e$ spectrum. This distance corresponds approximately to the position of the first minimum in the survival probability P_{ee}. One should note that the observation of a relative suppression of the interaction rate between a near and far detector is a disapperance signal while the observation of a relative distortion in the observed spectra can provide a unique signature of the (1,3) oscillation. However, for small to medium-sized detectors the statistical significance of the oscillation signal is dominated by the difference in the interaction rate. In general, for a rate-based two-detector experiment an optimal distance of ~ 1.7 km for the far detector is found [3]. Details of such optimizations are discussed in [3, 5]. It is possible to think of other detector configurations or multiple-detector schemes that optimize the experiment not to the difference in the total interaction rate but to spectral distortions in the far detector. Generally, these approaches require much larger detectors.

Reactor Flux Uncertainty: A relative measurement between multiple detectors will largely eliminate the error in the reactor $\overline{\nu}_e$ flux. Usually, the reactor $\overline{\nu}_e$ flux is predicted from the thermal power of the reactor and the known spectra of the isotopes involved in the neutrino producing fission processes. The total number of reactor antineutrinos and their energy spectrum can be calculated to about 2% and 2.5% respectively. This error enters any absolute flux measurement that compares the observed $\overline{\nu}_e$ interaction rate in the detector to the predicted reactor $\overline{\nu}_e$ flux. In a relative measurement this uncertainty is typically reduced to ∼0.2%. At multi-core sites the residual error comes from the superposition of $\overline{\nu}_e$ fluxes at different distances to the detectors.

Target Volume: In the past reactor neutrino experiments with a total volume ranging from a few tons (Chooz) to a 1kt (KamLAND) have been built. The large size of KamLAND is required to collect sufficient event statistics from neutrino sources some 180 !km away. A future reactor neutrino experiment to measure θ_{13} at a distance of $\mathcal{O}(1$ km$)$ from a reactor complex require event statistics in excess of $\sim 30,000$ events in the far detector to reach a statistical error of $\sigma_{stat} \leq 0.5\%$ in the rate. A search for spectral distortions will require even larger event rates. For a rate-based θ_{13} reactor experiment detector sizes of 25-50 t and for a shape measurement a fiducial volume in excess of 100 t are needed. The choice of a powerful reactor complex with multiple cores will increase the event statistics. Typically, two core systems have a thermal power ranging from 5-8 GW_{th}. While multi-core systems help with the event rate they essentially eliminate the possibility of making a background measurement in the neutrino detectors during any reactor-off period. This feature helped the previos Chooz experiment [2] to determine and subtract a 9.5% background, presumable due to muon-induced spallation backgrounds. Future reactor neutrino experiments are unlikely to have this capability. Figure 2 shows the expected number of events as a function of distance and volume for a Chooz-like detector.

Calibration of Relative Detector Acceptance: The novel concept of using multiple detectors for a relative measurement of the $\overline{\nu}_e$ interaction rate requires a very good understanding of the relative acceptance of the two detectors. Several issues determine the relative detector acceptance of a 2- or multi-detector system:

1. fiducial volume
2. neutron detection efficiency (in presence of backgrounds)
3. relative energy scale (for spectrum measurement)
4. accidental and correlated backgrounds

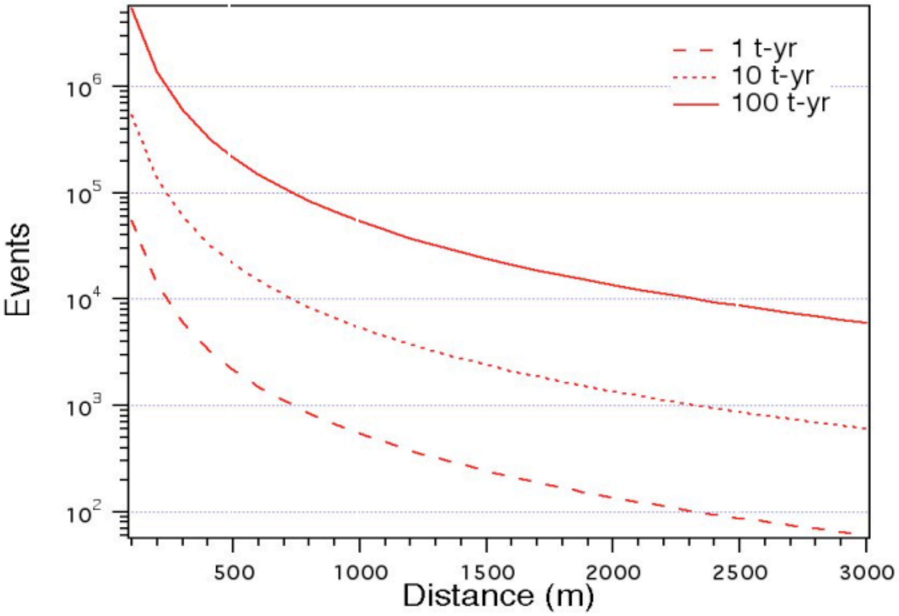

Figure 2: Expected number of events in a Chooz-like detector at a reactor complex with a thermal power of 6.5 GW$_{th}$.

In general, it will be necessary to understand the efficiency of $\overline{\nu}_e$ detection $\epsilon_{\overline{\nu}_e}$, as a function of energ $E_{\overline{\nu}_e}$, event position in the target volume $\overrightarrow{r}$, detector i, and detector position $\overrightarrow{D}$ with respect to the reactor. For mountainous underground sites the detector position determines the overburden and shielding from cosmic rays as well as the natural background around the detectors.

$$N_{\overline{\nu}_e} = N_{\overline{\nu}_e}[E_{\overline{\nu}_e}, \epsilon_{\overline{\nu}_e}, \overrightarrow{r}, \overrightarrow{D}, i] \tag{1}$$

Several strategies and techniques have been proposed to understand the relative detector acceptance. They are summarized in Table 1. A multi-layer detector with a Gd-doped inner liquid scintillator detector surrounded by a scintillating catcher region and a mineral oil buffer allows in principle the detection of the $\overline{\nu}_e$ coincidence signal without a fiducial volume or energy threshold cut. This eliminates two important detector systematics.

The idea of swapping detectors to make a measurement of the $\overline{\nu}_e$ rate and spectrum in both detectors at the same distance from the reactor is both a logistical and technical challenge for underground detectors. One of the concerns is that the detector response itself may change during this operation and make it impossible determine the relative detector acceptance without absolute calibrations before and after the move. Depending on the specific site of the proposed experiment one will have to decide whether such a procedure is practical or not. Preliminary studies show that a combination of the tabulated techniques may lead to an effective systematic error of ~0.8% in the calibration of the relative detector acceptance.

Table 1: Methods for the relative calibration of detector acceptance.

Issue	Method
target volume	flow and weight measurements, multi-layer scintillator detector no fiducial volume cut in Gd-scintillator
neutron detection efficiency	swapping detectors, source calibration
energy scale	swapping detectors, extensive calibrations with sources relative calibration with neutron-capture peak
geometrical detector effects	identical design

While many of the systematic issues we expect to encounter in a precision θ_{13} reactor neutrino oscillation have been studied in the previous Chooz, Palo Verde, and KamLAND experiments we expect to encounter additional experimental challenges in the quest to push the sensitivity of a future reactor neutrino oscillation experiment. A redundant set of calibrations and techniques to determine the relative detector acceptance are required. It will be necessary to design an experimental program that eliminates the possibility of a “single-point failure” in both the measurement, the characterization of the detector response, and the analysis of the data. In the light of these considerations we require a future reactor neutrino experiment to have

1. an extensive calibration program to determine the absolute detector response over the reactor $\overline{\nu}_e$ energy range
2. redundant strategies for mitigating the systematic error in the relative measurement including the swapping of the detectors.

Only an experiment with redundant methods to deal with systematic errors will be able to achieve the ambitious design goal of a sensitivity of $\sin^2 2\theta_{13} \leq 0.01$. For a rate- and shape based measurement most of the systematic error sources are identical. In a shape-based measurement, however, the absolute calibration of the energy scale and its non-linearity require special studies.

Homogeneous versus modular detectors: The detector design requires the choice between a homogeneous, single-detector concept (like Chooz and KamLAND) or a modular detector system. Single detectors minimize the surface area for intrinsic backgrounds relative to the fiducial volume. At a potentially much higher cost, modular detectors have the advantage of increased mobility and easier testing. In contrast to a single, large detector a modular system will allow one to build and prototype and evaluate it in the underground facility prior to completing the construction of the entire volume. Modular detectors also create a scalable system that can be expanded to reach the desired sensitivity and physics goals. For example, one can imagine a phased approach that would allow the construction of a timely medium-scale experiment to make a rate-based search for θ_{13} while providing the possibility of expansion for a shape-based, high-sensitivity measurement of θ_{13} once it has been shown to be non-zero.

Over the course of the past year several groups have proposed a variety of detector concepts. The design and size of these concepts depend largely on constraints imposed by the underground laboratory. A generic optimization of the detector has not been done yet, and, in fact, may be impossible. However, it appears that a multi-layer detector with a Gd-doped liquid scintillator target may be the design concept of choice to be able to make a measurement without fiducial volume and energy cut.

Backgrounds: Accidental and correlated backgrounds have presented a serious challenge to all past reactor neutrino experiments. In the Chooz experiment a 9.5% background [2] measured during the reactor-off time was subtracted from the candidate event set to obtain the final event set. This allowed the Chooz experiment to obtain an absolute precision of 2.7% on the reactor $\overline{\nu}_e$ flux measurement. This background was most likely due to muon-induced spallation products and accidentals in the lower energy region of the spectrum. Future reactor neutrino oscillation experiments are likely to be located at reactor complexes with multiple cores (to increase the event statistics) and won't have the ability to make an independent measurement of these backgrounds. Careful material selection and detector design can be used to reduce the accidental backgrounds. Muon-induced spallation backgrounds are best reduced by a deep location of the detector. Scaling the observed number of backgrounds in the Chooz experiment to the requirements for a future experiment we obtain the signal to muon-related background ratio for a spherical 25-ton liquid scintillator as a function of overburden (see Figure 3).

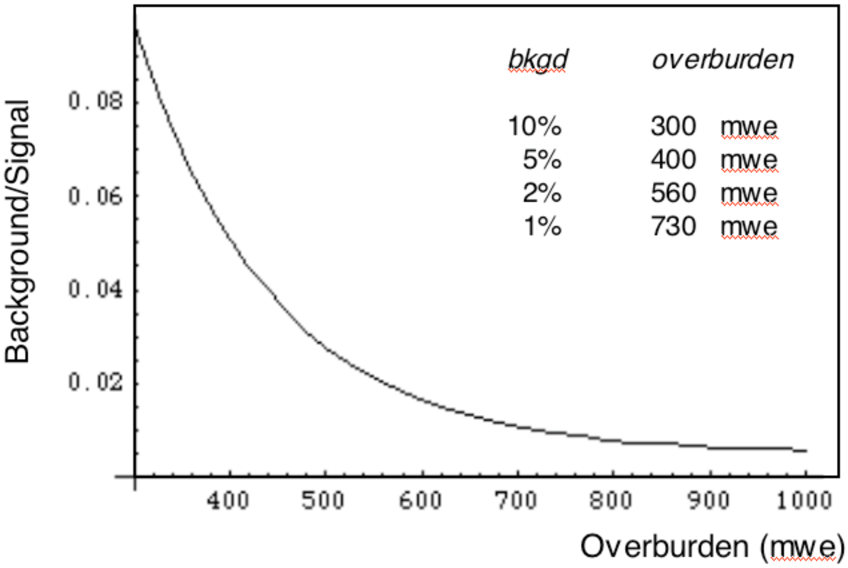

Figure 3: Signal to background ratio in a typical spherical 25-ton detector of a next-generation reactor neutrino experiment for a Chooz-like mountainous underground detector site.

Muons produce spallation backgrounds in the inner detector or fast neutrons in the rock that form a correlated background to the $\overline{\nu}_e$ candidate event signal. A high-efficiency, extended muon tracking system surrounding the liquid scintillator can be used to tag muons that enter the detector and pass through rock and shielding in the vicinity of the target. The purpose of such a muon tracking system is two-fold: (1) It can add to the effective depth of the detector by vetoing muons and (2) help understand the rate and spectral shape of correlated backgrounds by tagging muon-related backgrounds. The effective signal to background ratio depends on both the overburden as well as muon rejection and can only be determined from detailed simulations for a specific experiment. It is desirable to place the detectors as deep as possible to minimize the muon-related backgrounds in the detector.

In summary, Table 2 shows the principal contributions to the systematic error in a next-generation reactor neutrino oscillation experiment to measure θ_{13}:

Table 2: Projected systematic error budget in a next-generation reactor neutrino experiment.

Effect	Error Estimate	Method
reactor flux uncertainty	$\leq 0.2\%$	relative measurement at different distances
detection efficiency	$\leq 0.8\%$	calibration of relative det. efficiency
target volume	$\leq 0.3\%$	no fiducial volume cut in Gd scintillator, flow and weight measurement of target
backgrounds	$\leq 1.0\%$	sufficient overburden, active and passive shielding
Total Systematics	$\sim$1%	

2 Classes of θ_{13} Reactor Neutrino Oscillation Experiments

Studies towards a future reactor neutrino experiment in Europe, the US, Japan, and China have resulted in a number of proposals for a next-generation θ_{13} experiments [11, 9, 10]. We distinguish between three classes of experiments varying in cost, time scale and sensitivity. They are commonly referred to as small, medium, and large-scale θ_{13} projects.

Small: Sensitivity of $\sin^2 2\theta_{13} \sim 0.04$
As there is no prediction for the size of θ_{13} it may very well be that θ_{13} is just below the current Chooz limit [2]. In this case small-scale experiments with a 3-4× improved sensitivity over the Chooz experiment might have the opportunity to find indications for a non-zero θ_{13} at the $\sim 3\sigma$ level. After 3 years of data taking such experiments may set a limit of $\sin^2 2\theta \leq 0.03$ at the 90% CL.

CEA Saclay and College de France have proposed to build a small-scale, 2-detector oscillation experiment using two identical 10-ton detectors, one at 0.2 km and the other one at 1.05 km. The plan is to re-use the existing underground laboratory of the original Chooz experiment for a new 2-detector experiment. In this proposal a near detector will be placed in a shallow underground site under man-made overburden at a distance of about 200 m. A far detector identical to the near detector will be placed in the existing underground laboratory at 1.05 km. The Double-Chooz project is under review in France, Germany, and Italy and support from international collaborators is sought by the existing proto-collaboration. While this project cannot reach the desired sensitivity of $\sin^2 2\theta_{13} \sim 0.01$ the existing underground laboratory at Chooz allows this project to proceed on a relatively fast time scale. If approved, the Double-Chooz project is expected to start taking data in 2008/2009. Details of the project can be found at [11].

Medium: Sensitivity of $\sin^2 2\theta_{13} \sim 0.01$
A measurement or search for θ_{13} at the 1% level is of particular interest in a systematic study of neutrino oscillation parameters. It is the measurement of a fundamental neutrino mixing parameter with discovery potential and long-term impact. The discovery of θ_{13} or a limit at the 1% level will set the stage for a future program in neutrino oscillation physics. Together with the results from accelerator-based neutrino experiments a precise measurement of $\sin^2 2\theta_{13}$ can help determine the mass hierarchy and constrain the parameter space for CP-violation in the lepton sector.

Concepts for an oscillation experiment with a sensitivity of $\sin^2 2\theta \leq 0.01$ are being studied at several reactor sites. US groups have led the investigation at Braidwood in Illinois, the Diablo Canyon nuclear power plant in California, and the Daya Bay reactor complex in China [9, 10]. In comparison to small reactor θ_{13} experiments the design concepts usually include larger detectors (25-100 tons), located in deeper (230-1200 mwe) underground laboratories at optimized distances from the reactor, with reduced backgrounds, and integrated calibration and muon tracking systems. In comparison to the small-scale experiment with a sensitivity goal of $\sin^2 2\theta_{13} \sim 0.03$ medium-sized experiments require improvements and optimization in the detector design as well as the experimental layout to reach a sensitivity of $\sin^2 2\theta_{13} \leq 0.01$. Perhaps most importantly, sufficient overburden and active reduction of backgrounds are required to achieve a sensitivity of 1%. The basic experimental parameters of the different proposals with US involvement are summarized in Table 3.

Table 3: Basic design parameters of the proposed θ_{13} reactor experiments.

Proposal	Baseline (Near/Far)	Overburden (Near/Far)	Detector Size (Near/Far)	Sensitivity ($\sin^2 2\theta_{13}$)	Ref.
Double Chooz	0.2/1.05	50/300 mwe	10/10 t	0.03	[11]
Braidwood	0.2/1.7	450/450 mwe	25/50 t	0.015	[9]
Diablo Canyon	0.4/1.7	150/750 mwe	50/100 t	0.015	[10]
Daya Bay	0.3/1.7	230/1100 mwe	25/50 t	0.012	

The Ultimate θ_{13} Experiment? Beyond 100 Tons or a Sensitivity of $\sin^2 2\theta_{13} \ll 0.01$
Considering the experimental challenges involved in reaching $\sin^2 2\theta \leq 0.01$ it is difficult to imagine at present reactor neutrino oscillation experiments with a sensitivity of $\sin^2 2\theta \ll 0.01$. To improve on the current precision of absolute reactor $\overline{\nu}_e$ flux measurements and reach $\sin^2 2\theta_{13} \sim 0.01$ yet unknown challenges will have to be overcome. While it still needs to be demonstrated that a large-scale reactor neutrino oscillation experiment can improve on a sensitivity of $\sin^2 2\theta_{13} \leq 0.01$ large-scale experiments with a fiducial volume of > 100 tons offer additional advantages. They have the possibility to observe relative distortions in the observed neutrino spectra at the two detectors and provide unambiguous evidence for non-zero θ_{13} and subdominant oscillation. Furthermore, a multi-detector setup with three or more detectors has the potential to maximize the experiment's statistical sensitivity to both the rate and shape difference, and may verify the oscillation signal at different baselines. While it is not practical to consider an experiment with a truly continuos, variable baseline we can entertain the possibility of having multiple detector halls at different baselines to map out the survival probability P_{ee}.

We envision that a large reactor neutrino oscillation experiment could be built in a second phase to a successful medium-sized modular experiment that discovers non-zero θ_{13}.

Using generic assumptions about the detector design and systematic errors, the ultimate θ_{13} sensitivity of various, simple 2-detector systems has been studied by Huber et al. [3, 4]. Figure **??** gives an indication of the magnitude of the detector size and precision needed to reach a specific sensitivity in $\sin^2 2\theta_{13}$. This figure does not and cannot reflect more important qualitative improvements one can make to an oscillation experiment by placing multiple detectors at different distances or analyzing the spectral shape to demonstrate the observation of a subdominant oscillation signal.

2.1 Evaluating Different θ_{13} Experiments

Every experimental proposal will necessarily be a compromise to accommodate either constraints from the reactor site or local topography, the existing infrastructure, time scale and cost. Proposals will also balance different physics objectives such as the measurement of θ_{13} and $\sin^2 \theta_W$. Without repeating the experimental issues outlined above we can ask what are the guiding principles that will allow the comparison and evaluation of the eventual scientific impact of different θ_{13} experiments? There are four principal issues that determine the sensitivity and impact of a reactor θ_{13} experiment:

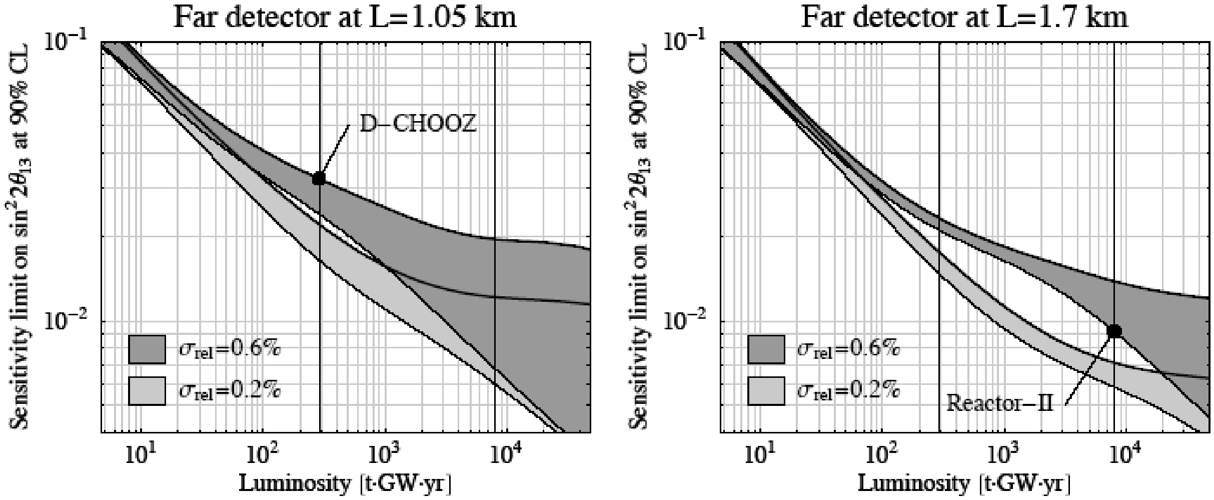

Figure 4: Sensitivity of reactor neutrino experiments to $\sin^2 2\theta_{13}$ as a function of the integrated luminosity. Figure adapted from [3]. The left panel shows the projected sensitivity of the Double-Chooz experiment, a small-scale experiment at a distance of 1.05 km. The right panel shows the sensitivity of medium or large scale experiments. Figure adapted from Ref. [4].

1. signal rate and fiducial volume
2. signal to background ratio and background estimation
3. calibration of relative detector acceptance
4. qualitative signature of non-zero θ_{13}: rate suppression *versus* oscillation signature

Backgrounds: Correlated backgrounds are one of the principal challenges in a precision reactor neutrino experiment. It is unlikely that a direct measurement of the backgrounds will be possible in a future reactor oscillation experiment. Instead these backgrounds will have to be determined from correlating muon events and correlated event signals, or from simulations. Without further knowledge of the spectrum of backgrounds the signal to background ratio limits the ultimate sensitivity of a reactor neutrino measurement of θ_{13}. Below we provide a comparison of the expected muon-related backgrounds in the US-led proposals for medium-sized experiments at the Braidwood and Daya Bay reactor sites.

We use the results of [6, 7, 8] to calculate the muon flux, neutron flux, and isotope production in underground liquid scintillators at mountainous and flat sites. The simulation corresponds to a good approximation to the topography at the Daya Bay reactor complex and the Braidwood power plant. Figure 5 shows our simulation of the mountain near Daya Bay as a four-sided pyramid. Table 4 shows the results for three different geometries, a flat geometry at 450 mwe and two different configurations with mountains. The muon flux at the far detector for the simulated mountain is about 8 times lower than the flat geometry and the neutron flux and isotope production are lower by a factor of 6. This is due to the energy dependence of the isotope production. Figures 7 and 6 shows the results of the muon and neutron flux calculations.

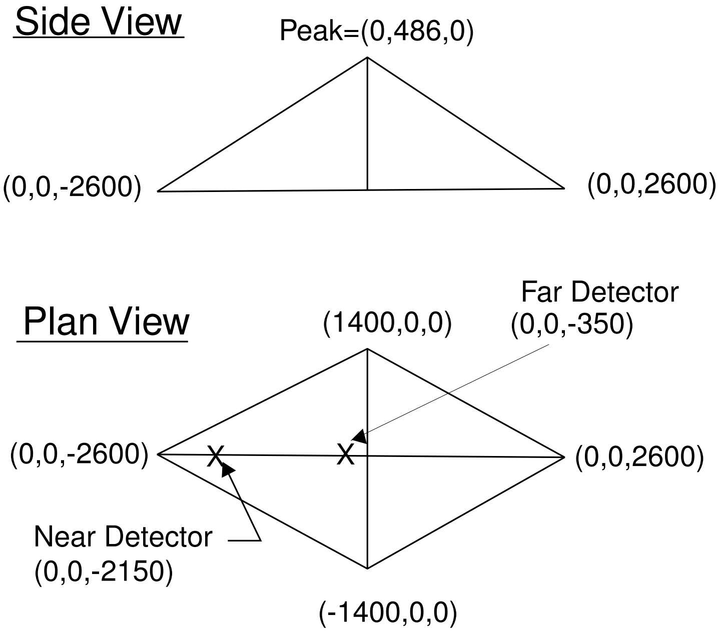

Figure 5: Simulation of the mountain near the Daya Bay nuclear power plant as a four-sided pyramid. The figure shows the location of the detectors with respect to the mountain peak. In this coordinate system the reactor is at (0,0,-2550).

Table 4: Comparison of neutron rates and cosmogenics for three different geometries. The flat site corresponds to the parameters of the Braidwood site, the mountains with 230 and 1100 mwe are a good approximation to the overburden at Daya Bay.

	flat, 450 mwe	mountain, 230 mwe	mountain, 1100 mwe
muon flux ($m^{-2}s^{-1}$)	0.194	1.63	0.024
neutron rate (ton^{-1} day^{-1})	161	824	30.0
$^{8}He+^{9}Li$ (ton^{-1} day^{-1})	0.0076 ± 0.026	0.4 ± 0.4	0.014 ± 0.002

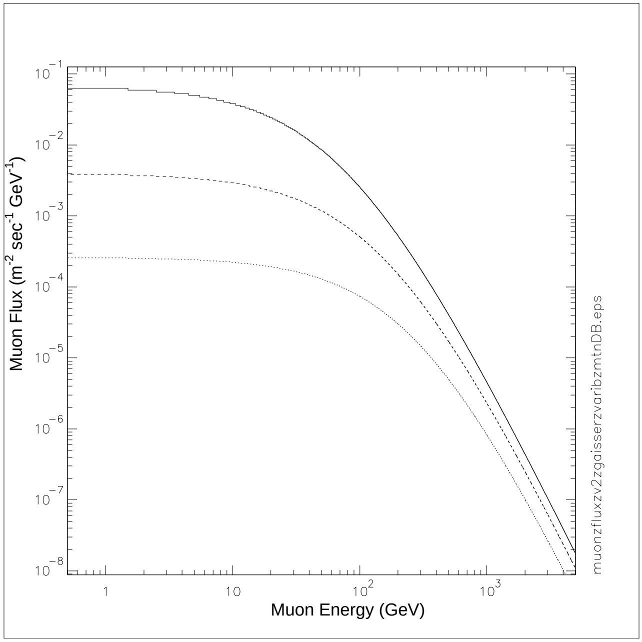

Figure 6: Muon flux as a function of energy computed for three different geometries. The upper curve is the muon flux for the near detector in a mountain with 230 mwe overburden, the middle curve for 450 mwe in a flat geometry, and the lower curve is for a detector at vertical depth of 1100 mwe in the pyramidal mountain.

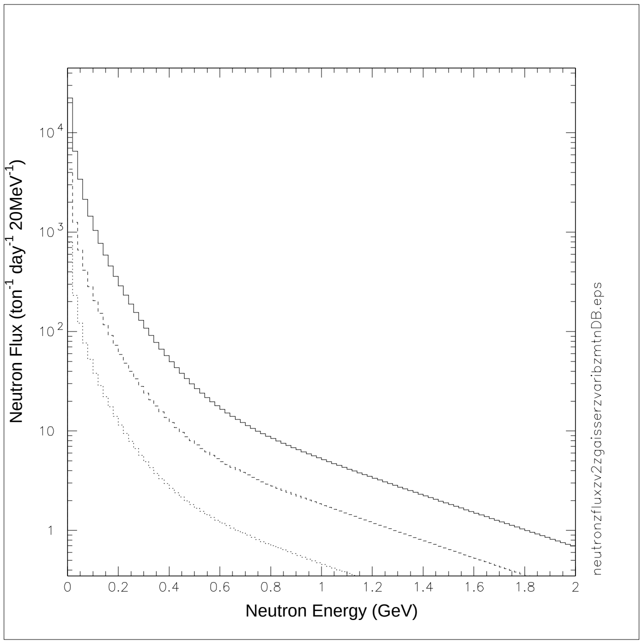

Figure 7: Neutron flux as a function of energy computed for three different geometries. The upper curve is the muon flux for the near detector in a mountain with 230 mwe overburden, the middle curve for 450 mwe in a flat geometry, and the lower curve is for a detector at vertical depth of 1100 mwe in the pyramidal mountain.

Calibrations: An extensive program of absolute and relative calibrations with sufficient degree of redundancy will be required to monitor and calibrate the detector response over a period of months and years. In part, the data themselves – spallation products in particular – will be used to assess the detector stability and the residual systematic error. Time-dependent effects as observed in the Chooz experiment will have to be characterized sufficiently. A well-defined calibration program in both hardware and methods needs to be an integral part of any experimental concept for a future reactor neutrino oscillation experiment. Only a very well-characterized detector will allow us to observe a non-zero θ_{13} based on a relative difference in the observed $\overline{\nu}_e$ interaction rate.

Oscillation Signature: The observation of non-zero θ_{13} is experimentally extremely challenging but would have profound consequences on any future program in neutrino oscillation physics. The measurement of θ_{13} is an essential input to the global evaluation of neutrino oscillation parameters including the mass hierarchy and CP-violating effects. As such, a successful θ_{13} experiment requires (1) clear evidence that oscillation in the (1,3) channel has been observed and (2), eventually, a precise determination of $\sin^2 2\theta_{13}$. As a result, one cannot underestimate the important of a direct observation of oscillatory effects either in form of spectral distortions or as a rate change for (more than 2) different baselines.

3 Time Scale, Costs, and the Global Situation

Critical to all efforts to measure θ_{13} with reactor neutrinos is an underground laboratory to shield the antineutrino detectors from cosmic rays and cosmic ray muon-induced spallation products that can mimick the coincidence structure of $\overline{\nu}_e$ interactions. This requirement is common to all proposals for a future reactor neutrino oscillation experiment. The overburden requirement for the $\overline{\nu}_e$ detectors varies depending on the power of the reactor, the distance of the detector from the reactor, and details of the detectors design. In any experiment the effective signal to background ratio depends critically on the amount of overburden, the topology of the site, and the muon veto and tracking systems. Unless an existing underground laboratory can be found at the right distance from a nuclear power plant significant civil construction efforts are necessary to create the environment to perform this experiment. Conceptual design studies by several groups have investigated the feasibility of constructing vertical shafts into the ground or horizontal tunnels into mountains to obtain the required overburden. The results of these preliminary investigations are summarized in the White Paper of the International θ_{13} Working Group [5].

Several US groups are involved in the international effort to find a suitable power plant for this experiment and the design effort. The Braidwood and Diablo Canyon site in the US, Daya Bay in China, and Chooz in France are being investigated as possible options. Braidwood and Diablo Canyon would offer the opportunity for a US-led experiment while an experiment at Daya Bay would be based on a partnership between the Institute of High Energy Physics (IHEP) in Beiing and the US. A Letter of Intent has been prepared for the Double-Chooz experiment in France and US support for this experiment is sought by the Double-Chooz proto-collaboration.

For a greenfield site in the US the civil construction costs for the underground laboratory are estimated to be of the order of \$20-30M. This is comparable to the costs for three medium-sized 25-ton detectors. An evaluation of two possible reactor sites (Braidwood in Illinois and Diablo Canyon in California) suggest that the construction of a suitable underground laboratory will take about 18-36 months depending on the type of excavation necessary and method used. An experiment using vertical shafts can possibly be built faster than a single tunnel experiment at the expense of additional cost. We expect that the civil construction at the two sites under investigation in the US will take about two years. The time scale and possible milestones for a US-led experiment are shown in Figure 8.

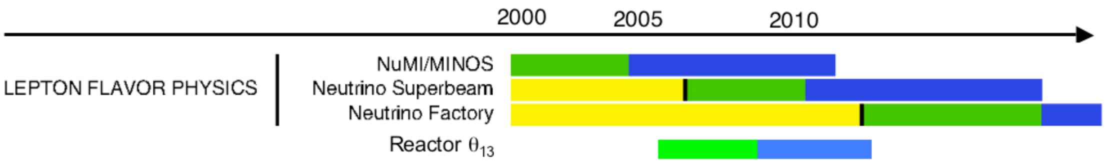

Figure 8: Projected time scale and roadmap for a θ_{13} reactor experiment in the US. Figure adapted from Ref. **??**

Besides the US-led studies at Braidwood and Diablo Canyon a R&D partnership has been formed between several institutions in the US and IHEP to study the possibility of a future reactor neutrino experiment at the Daya Bay nuclear power plant in Hong Kong. In this case the US groups would likely be responsible for the design and construction of the antineutrino detectors, or subsystems thereof, while the civil construction of the underground laboratory would be undertaken by IHEP and other institutions in China.

In France CEA Saclay and College de France have proposed the Double-Chooz experiment. This proposal intends to make use of the existing underground laboratory near the Chooz nuclear power plant for the far detector and to build an additional near detector next to the power plant. The project received scientific approval in France in March 2004 and a proto-collaboration consisting of groups in Italy, Germany, and France has been formed. Construction of the far detector can commence as early as 2006 assuming that the respective funding agencies in France and Germany will approve the proposal in 2004/2005. Together with EDF (Electricite de France), the Double-Chooz collaboration is studying the possibility of building an underground covern at a depth of ~ 8 m with additional overburden in form of a man-made mountain. The cost for this construction is likely to be covered by EDF. Without the civil construction cost for the near detector the Double-Chooz experiment is estimated at about Euro 10M. First results from both the near and far detector can be expected in 2008/2009. With this ambitious time scale the Double-Chooz experiment is likely to set the time scale for the worldwide search for θ_{13}.

4 Conclusions

A precision reactor neutrino oscillation experiment to discover and measure θ_{13} is undoubtedly the top priority of a neutrino program at nuclear reactors. To exploit the full physics potential in combination with future accelerator-based long-baseline experiments it is desirable to reach a sensitivity of $\sin^2 2\theta_{13} \leq 0.01$. This requires a new experimental concept and new measures in the design of the detectors. A relative measurement between two or multiple detectors is necessary to eliminate the dominant systematic errors in an absolute measurement of the reactor antineutrino interaction rate and reduce the residual systematic error in the observed relative interaction rate to less than 1%. Optimization of the detector baselines, the detector size, and careful choice of a suitable underground location with sufficient overburden are required to achieve this goal.

If θ_{13} is close to the present bound the proposed Double-Chooz experiment in France will be able to probe its value as early as 2009. Costs as well as time scale are an important consideration for a next-generation reactor neutrino experiment as well as the overall physics potential. It may be possible to pursue other physics opportunities such as the measurement of $sin^2\theta_W$ with an experiment that is designed to measure θ_{13}. However, it is clear that the design of a future reactor experiment has to be optimized for the oscillation measurement to be able to achieve a sensitivity of $\sin^2 2\theta_{13} \leq 0.01$. We recommend that every effort be made to proceed quickly with a precision reactor neutrino measurement at the level of $\sin^2 2\theta_{13} \leq 0.01$ as it sets the stage for the planning of a successful long-term program in neutrino oscillation physics.

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