Neutrinos at 1%: A Reactor Based Measurement of θ_{13}

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Received on 2 December, 2003

Past studies of neutrinos and the recent results on neutrino mixing have opened up many new possibilities as well as the understanding that neutrino mixing is very different from the better known quark mixing. The last remaining unmeasured component of the neutrino mixing matrix (U_{e3}) also provides a window to understanding neutrino matter effects, the mass hierarchy, and the possibility of measuring leptonic CP violation. A discussion of the benefits and difficulties of pursuing such a measurement with reactor neutrinos will be presented. In addition, possible sites for such an experiment will be discussed, including a location in Brazil.

1 Introduction to Flavor Mixing

The process of flavor oscillation arises from the fact that the flavor eigenstates and the mass eigenstates appear not to be the same. By considering the flavor and mass states to be rotated with respect to each other by an angle θ, one can decompose a neutrino flavor state into a linear combinations of mass states (ν_i). In the case of only 2 eigenstates, this is represented as

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta \quad (1)$$
$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta. \quad (2)$$

We are familiar with this rotation of bases in the quark sector where an analog to the equations above were the origin of Cabibbo Mixing[1] between d and s quarks resulting in the 2-by-2 mixing matrix

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}. \quad (3)$$

This formalism has been further extended to include 3 flavor mixing by Kobayashi and Maskawa[2]. The 3-by-3 mixing matrix is usually referred to as the Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (4)$$

Over the last decade, much experimental effort has gone into measuring the individual elements of the CKM matrix. To very high precision, the values show that the diagonal elements are very close to 1 while the off-diagonal elements are very close to zero. The implication of this is that the flavor basis and the mass basis are very nearly identical.

In the neutrino sector, a similar 3-by-3 mixing matrix has been constructed. This is usually referred to as the MNS[3] matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}. \quad (5)$$

While the age of neutrino oscillation measurements is currently very young, all of the elements of the MNS mixing matrix have been coarsely extracted from current measurements to about 30-40% precision. The current mean values are

$$|U_{mean}| = \begin{pmatrix} 0.8 & 0.57 & 0.0 \\ 0.45 & 0.5 & 0.7 \\ 0.34 & 0.6 & 0.68 \end{pmatrix}. \quad (6)$$

Notice that the structure of this matrix differs greatly from the CKM matrix which was primarily diagonal. In the MNS matrix, all elements, with the exception of U_{e3}, appear to be of order unity. Thus, contrary to the quark sector in which the flavor and mass bases were nearly identical, the neutrino flavor and mass bases are very nearly orthogonal.

2 The Significance of U_{e3}

On examination of the experimentally determined values of the MNS matrix in Eq. 6, one quickly notices that the value for U_{e3} is far different from all the other elements. The current best limits from experiment provide an upper bound of $|U_{e3}| < 0.22$. To understand better the significance of this, we can look at the Chau-Keung[4] parameterization of the MNS matrix in which the matrix is broken down into 2-by-2 rotational matrices through three Euler angles with a single imaginary phase. Using the angles θ_{ij} to refer to the mixing angles between the neutrino mass states and the conventions that $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$ we get

$$U_{MNS} = U_{23}U_{13}U_{12} \tag{7}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{8}$$

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{-i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{-i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{-i\delta} & c_{23}c_{13} \end{pmatrix}. \tag{9}$$

We can first conclude that θ_{13} is small since $U_{e3} = \sin\theta_{13}e^{i\delta}$. Perhaps more interesting, however, is that the imaginary phase δ, which would be responsible for CP violation in the lepton sector, is also present. In fact, any physical process for which this leptonic CP violating term would be present also contains the multiplicative factor of $\sin\theta_{13}$. Thus a non-zero value of θ_{13} is required for any leptonic CP violation to be observed. Recognition of this fact has focused significant attention on our ability to measure a non-zero value of θ_{13} through neutrino oscillation measurements.

3 Neutrino Oscillation

If we return briefly to Eqs. 1 and 2, in which the flavor states were expressed as a linear combination of the mass states, and express the propagation of a neutrino in time as $\nu(t) = e^{-iEt}\nu(0)$. Then, beginning with a pure neutrino flavor state (ν_e), the probability of finding a second neutrino flavor (ν_μ) is just

$$P(\nu_e \to \nu_\mu) = \langle\nu_\mu(0)|\nu_e(t)\rangle = \sin^2\theta\cos^2\theta\left|e^{-iE_2t} - e^{-iE_1t}\right|^2 \tag{10}$$

$$= \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\frac{L}{E}\right). \tag{11}$$

Equation 11 is the standard oscillation equation for any two neutrino mixing. The parameter θ is referred to as the mixing angle and the factor $\sin^2(2\theta)$ is merely the amplitude of the oscillation. A value of zero for $\sin^2(2\theta)$ would imply that no oscillations would occur. The second factor defines the oscillation itself. The frequency of the oscillation is governed by the difference between the squared masses of the two mass states: $\Delta m^2_{12} = \left|m_1^2 - m_2^2\right|$ (eV^2). The propagation of the oscillation is dependent on L/E where L is the distance from the source to the detector in kilometers and E is the energy of the neutrino in GeV.

The current best results from experiments (primarily Super-Kamiokande and SNO) have established two Δm^2 values relating to the two primary oscillations which have been observed: the solar neutrino deficit (ν_e disappearance) $\Delta m^2_{solar} \simeq 5\times10^{-5}$eV^2 and the atmospheric neutrino deficit (ν_μ disappearance) $\Delta m^2_{atm} \simeq 2\times10^{-3}$eV^2. It is important to note that in the standard neutrino picture with 3 neutrino flavors, there are only two independent mass differences since the third can be related to the other two by $\Delta m^2_{13} = \Delta m^2_{12} + \Delta m^2_{23}$. There is evidence from LSND which suggests an additional much larger $\Delta m^2 > 0.1$eV^2 for the process $\bar{\nu}_\mu \to \bar{\nu}_e$. However, since this is not confirmed by the KARMEN[5] experiment and would require new physics which has not been observed, it will not be considered for this discussion. It is usually accepted notation to refer to the smaller mass difference as being between mass states ν_1 and ν_2, thus $\Delta m^2_{12} \equiv \Delta m^2_{solar}$. However, it is important to realize that there exists no evidence yet to establish the hierarchy of the mass states. Therefore, we do not know if the masses of the two close mass states (ν_1 and ν_2) are lower (*normal hierarchy*) or higher (*inverted hierarchy*) than ν_3.

Most neutrino experiments have analyzed and reported their data based on two flavor oscillations. One can ask whether the results would change if they were interpreted within full three flavor mixing. However, due to the large difference between the two mass differences (almost two orders of magnitude), it turns out that the two oscillations can be treated as almost completely independent. As an example, consider the case of electron neutrino survival. Under full three flavor mixing, the probability of survival can be written as

$$P(\nu_e \to \nu_e) = 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(1.27\Delta m^2_{12}\frac{L}{E}\right) - \sin^2(2\theta_{13}) \sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right). \quad (12)$$

This equation is plotted in Fig. 1 as a function of L/E. One can easily see that the two oscillation frequencies are well separated. What is also apparent, however, is the significant affect of the different mixing angles on the amplitudes of the oscillation. To be able to properly understand the magnitude of the oscillations, one must account for all three mixing angles. The following equations show various flavor oscillation transitions under full three flavor mixing (excluding CP violation), but restricted to only the large Δm^2_{atm}:

$$P(\nu_e \to \nu_\mu) = P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right) \quad (13)$$

$$P(\nu_e \to \nu_\tau) = P(\nu_\tau \to \nu_e) = \sin^2(2\theta_{13}) \cos^2(\theta_{23}) \sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right) \quad (14)$$

$$P(\nu_\mu \to \nu_\tau) = P(\nu_\tau \to \nu_\mu) = \sin^2(2\theta_{23}) \cos^4(\theta_{13}) \sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right) \quad (15)$$

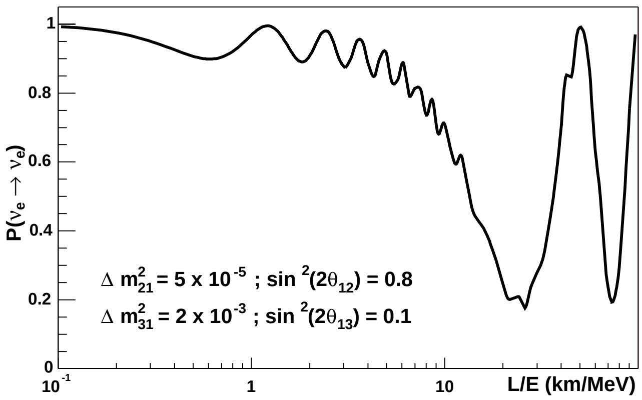

Figure 1. The survival probability of $\bar{\nu}_e$ as a function of L/E. This is a graphical representation of Eq. 12 where the values for the mixing angles and mass differences are set to the current best evidence from experimental results. The value of $\sin^2(2\theta_{13})$ is chosen to be the maximum allowed by the current exclusion limit.

4 Measurement of θ_{13} with Accelerator Neutrinos

There exist several current accelerator based neutrino beam projects: NuMI/MINOS at Fermilab, K2K in Japan, and CERN-to-Gran Sasso (CNGS). The accelerators at these laboratories create a neutrino beam by colliding intense accelerated proton beams with a fixed dense target to create and focus a pion beam which decays in flight. This results in a relatively pure ν_μ beam of a few GeV which can then be detected at distances up to 1000km away by detectors with sufficient mass. The current set of accelerator based experiments are primarily looking for ν_μ disappearance at the first oscillation maximum of the atmospheric Δm^2. Thus from Eqs. 15 and 13 we can simply write this as

$$P(\nu_\mu \to \nu_\mu) = 1 - \left(\sin^2(2\theta_{23}) \cos^4(\theta_{13}) + \sin^2(2\theta_{13}) \sin^2(\theta_{23})\right) \sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right). \quad (16)$$

Unfortunately, given our current knowledge of the mixing angles, the first amplitude term will dominate: $\sin^2(2\theta_{23})\cos^4(\theta_{13}) \sim 1$ while $\sin^2(2\theta_{13})\sin^2(\theta_{23}) < 0.05$. This means that extracting the value for $\sin^2(2\theta_{13})$ from this process will be extremely difficult.

However, by recalling that $\sin^2(\theta_{23}) \sim 1$ and looking at Eq. 13, we note that if a future experiment could isolate the exclusive process $\nu_\mu \to \nu_e$, the amplitude of any measured oscillation would directly yield the magnitude of $\sin^2(2\theta_{13})$.

This is the intent of the two proposed future long baseline projects NuMI/Off-Axis and JPARC-SK. These experiments are designed to look for neutrino interactions with an electron in the final state, as opposed to a muon, from an accelerator based ν_μ beam at the optimal L/E for the atmospheric Δm^2. This measurement will be complicated by the fact that several background sources exist. The standard accelerator based neutrino beam contains a small (∼1%) contamination of ν_e due to decays of kaons and muons off the proton target. There are also small contributions of final state electrons from ν_τ interactions in which a highly energetic τ decays via $\tau \rightarrow e^- \bar{\nu}_e \nu_\tau$. In addition, depending on the granularity of the detector, there are many processes which can produce showers which look very similar to electron signatures (*e.g.* $\nu N \rightarrow \nu N \pi^0$ where $\pi^0 \rightarrow \gamma\gamma$).

While such backgrounds may make measuring a small oscillation effect difficult, they are by no means impossible to measure or control. However, when one includes the possible effects of leptonic CP violation or matter effects, the ability to extract a value for $\sin^2(2\theta_{13})$ becomes significantly more difficult. This subject is explored in much more detail in [6] and others. For the purposes of this discussion, it is sufficient to say that all three of these effects (flavor oscillation, CP violation, and matter effects) can enhance or diminish an observed $\nu_\mu \rightarrow \nu_e$ signal. This results in an eight-fold ambiguity in the extraction of $\sin^2(2\theta_{13})$ from a single long baseline measurement of $P(\nu_\mu \rightarrow \nu_e)$.

In order to resolve these degeneracies, one would have to make use of the various different dependences on flavor, energy and baseline. Clearly matter effects will be most strongly dependent on the length of the baseline, but detectors for these experiments are large (∼50 ktons) so moving them is impossible. Matter effects will also have opposing effects on neutrinos and anti-neutrinos so measurements of both $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at a single experiment would provide useful information. However, CP violation also provides an energy dependent separation between the two oscillation probabilities depending on the actual value of the complex phase δ. Thus any real attempt to completely resolve these degeneracies would most likely require at least 2 experiments which are running at different energies and baseline distances. In addition, each experiment would likely have to measure both observables $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$.

This presents a long and expensive future program. Given the required detector sizes and required granularity to detect electron signals, these future accelerator based experiments are expected to cost ∼$200 million or more. In addition, the construction of these detectors takes 5-10 years and each one of the oscillation measurements would probably require at least 3-5 years worth of running time. However, θ_{13} could be zero, or small enough that no oscillation signals would be detected, in which case degeneracies would no longer be a concern.

5 Measurement of θ_{13} with Reactor Neutrinos

Recently, a lot of discussion has focused on the possible alternative of measuring θ_{13} with neutrinos from nuclear reactors. Nuclear reactors provide an isotropic source of pure electron anti-neutrinos ($\bar{\nu}_e$). There is a long history of neutrino experiments associated with reactors. Some of them have indeed been searches for evidence of neutrino oscillation by looking for disappearance effects. In the absence of matter effects, the survival probability of electron anti-neutrinos $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ is governed by the same equation as electron neutrinos (Eq. 12). It was pointed out previously in Fig. 1 that a judicious choice of L/E could isolate the effects of one or the other of the Δm^2 oscillations. Thus, by staying at small L/E (*i.e.* ignoring the small Δm^2_{12}) Eq. 12 reduces to

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \sin^2\left(1.27 \Delta m^2_{atm} \frac{L}{E}\right). \tag{17}$$

Any observed deficit in neutrino flux would be a direct measurement of θ_{13}. In addition, any such measurement would not suffer from the ambiguities which are seen in accelerator measurements. Neutrinos generated in nuclear reactors are at very low energy and are only detectable in the range 1-10 MeV. The optimal baseline for the first oscillation is therefore in the range of 1-4 km, depending on the exact value of Δm^2_{atm}. This distance is much too short for any matter effects to begin. In addition, disappearance processes are not affected by CP violation without a corresponding violation of CPT . Therefore, any measurement of θ_{13} from reactor neutrinos would be clean and unambiguous.

One should not mistake this to imply that such a measurement would be easy. In fact, until the recent results from KamLAND[7] which detected effects of the Δm^2_{12} oscillation at an average baseline of 180km, no reactor neutrino experiment had been able to detect signs of oscillations. The current world's limit on $\sin^2(2\theta_{13})$ comes from the CHOOZ reactor experiment ($\sin^2(2\theta_{13}) < 0.2$ at $\Delta m^2_{atm} = 0.002$)[8]. This measurement was limited by a systematic error of about 3% relating to the uncertainty in the reactor power.

Fundamentally, all reactor neutrino experiments have used a similar design. A single detector, placed at a given baseline distance from the reactor core, is used to measure the absolute flux and energy spectrum of $\bar{\nu}_e$. This spectrum is then compared to the theoretically predicted flux and spectrum based on the reactor's operating power and the radioactive decay of the reactor's fuel components. Given that the reactor fuel composition changes over time as it is consumed and that the radioactive decay spectra of the individual components are known to finite precision, the predicted flux and energy spectrum can not be determined to better than 2-3%. Any next generation measurement of $\sin^2(2\theta_{13})$ will have to make an order of magnitude improvement in our current sensitivity in order to make it worth the attempt. That implies a

90% confidence limit of $\sin^2(2\theta_{13}) < 0.02$ or perhaps a 3σ measurement if $\sin^2(2\theta_{13}) > 0.05$. Making such a measurement will require finding a way to limit the systematics to the order of 1%. A method for doing this is discussed in the next section.

6 Experimental Design

An international working group, with members from Europe, North America, Russia and Japan, has been discussing methods to make a higher precision measurement of $\sin^2(2\theta_{13})$ using reactor neutrinos. As conceived, the uncertainty in reactor flux and spectrum could be avoided by simultaneously measuring neutrinos from a reactor at two identical detectors which are placed at different baseline distances. The ratio of these two measurements would then be independent of any uncertainties in the source. Ideally, one detector would be placed as close to the reactor as possible to maximize the total neutrino flux and minimize any oscillation, while the second detector would be placed at the first oscillation maximum. By comparing the ratio of the measured fluxes to the expected fall off ($\propto 1/L^2$) a non-zero $\sin^2(2\theta_{13})$ could be detected. In addition, if enough statistics are present, relative spectral distortions could be detected. An example of two such measured energy spectra is shown in Fig. 2.

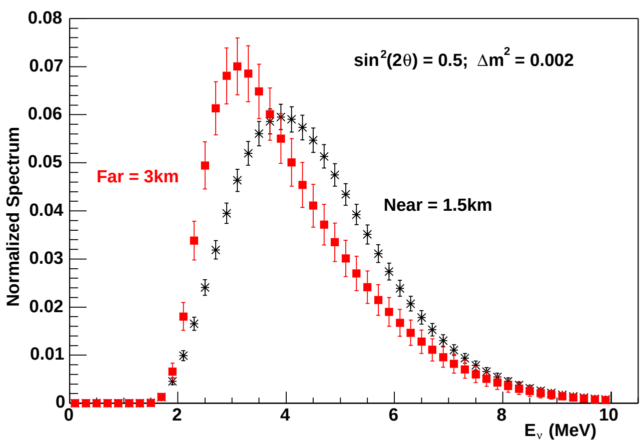

Figure 2. Comparison of the expected measured neutrino energy spectra at baseline distances of 1.5 and 3 kilometers. Oscillations as defined in Eq. 17 are assumed with the parameters set to $\Delta m^2 = 0.002$ and $\sin^2(2\theta_{13}) = 0.5$ (which is 2 and a half times the current limit in order to magnify the effect). Each shown spectrum is normalized to the total number of events at that location and the error bars represent the statistical uncertainty for a luminosity of 600 GW-ton-years at the specified baseline distance.

In fact, an interesting observation has been made by M. Lindner *et al.* [9]. They have pointed out that the comparison of spectral shapes between the two detectors will have even less dependence on systematic effects than the total flux ratio. Thus for high enough statistics, the spectral shape measurement can actually achieve almost two orders of magnitude improvement in $\sin^2(2\theta_{13})$ sensitivity. This is demonstrated in Fig. 3 where systematic errors have been classified into two categories: those which relate to overall normalization between the detectors (σ_{norm}) and those which are uncorrelated bin-to-bin (σ_{cal}). One can see that as total luminosity increases, the sensitivity improves directly with statistics until about 2-400 GW-ton-years at which point the systematics begin to restrict the total flux ratio. However, after 3000 GW-ton-years, the energy spectra comparison has finally gained enough statistics to allow the measurement to be insensitive to σ_{norm}. The ultimate sensitivity is heavily dependent on the choice of the uncorrelated bin-to-bin systematic error. The value chosen here ($\sigma_{cal} = 0.5\%$) appears reasonable.

One can wonder if the systematic error for the relative normalization between the detectors ($\sigma_{norm} = 0.8\%$) was reasonably chosen in the above analysis. It is possible to make an estimate of what is attainable by looking at the results of the Bugey experiment[10] which actually had three detectors. The Bugey detectors were located at very short distances (15m, 40m and 95m) and therefore are not relevant to the atmospheric Δm^2. However, they did attempt a comparative measurement between their 15m and 40m detectors. In Table I, the systematic errors for a single detector measurement (Absolute Normalization) and for the two detector comparative measurement (Relative Normalization) are listed.

The absolute systematics are consistent with other similar reactor measurements. When looking at the systematic errors in the relative measurement, one notes that these are dominated by neutron and positron detection efficiencies. It is important to realize that Bugey used segmented detectors constructed out of stacked rectangular tubes containing liquid scintillator. The neutron detection efficiency was due mainly to losing neutrons down the gaps between the rectangular tubes. The positron detection efficiency was similarly dominated by interactions with the walls of the rectangular tubes. Thus, by avoiding segmented detectors and using a monolithic design as in the case of CHOOZ and KamLAND, these errors can reasonably be reduced (the CHOOZ experiment lists an overall detection efficiency of 1.5% for a single detector measurement). The systematic error on the solid angle refers to the fact that the detectors were at such short baselines that the dimension of the reactor core was visible in the angular distribution of the detected neutrino events. Given the small size of these detectors, many events were lost out the sides of the detectors. This provided a difference between the two detectors because of the differing baselines. However, the much larger distances involved in any future two detector measurement (minimum 200m for a near detector) and the much larger detector sizes imply that any such angular based systematics should be negligible.

That leaves a systematic error on the number of target protons (target mass) as the dominant error. Again, the use of a monolithic design should improve this. But, it is clear that care in design, construction, and filling of the two detectors will have to be used to ensure that this error can be minimized when relating the measurements of the two detectors. Given the above discussion, and the observation that

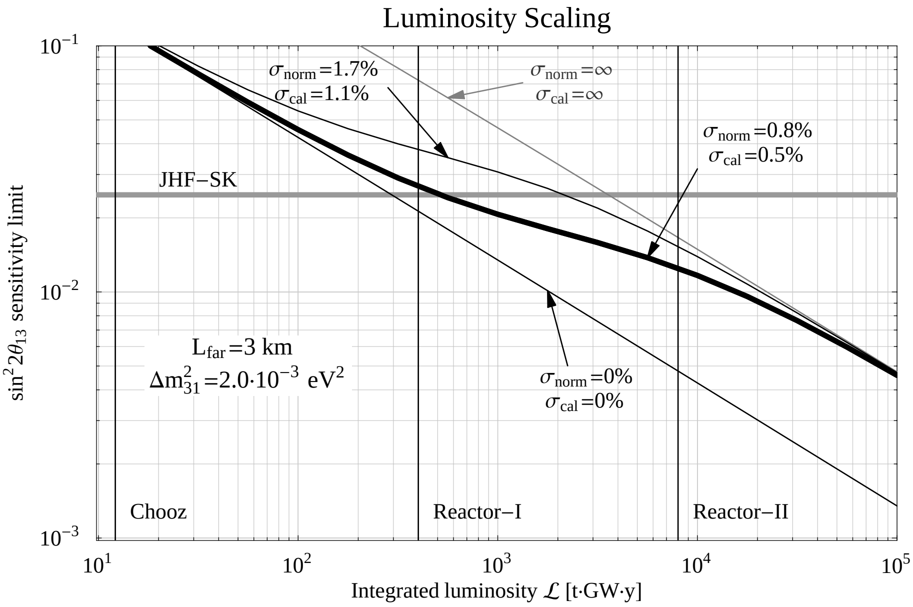

Figure 3. The sensitivity to $\sin^2 2\theta_{13}$ at 90% CL as a function of the integrated luminosity. This plot is taken from [9] and shows the effect of different values of the normalization error $\sigma_{\rm norm}$ and the energy calibration error $\sigma_{\rm cal}$. The oscillation was assumed to have $\Delta m^2_{31} = 2 \times 10^{-3}$ eV^2 and the far detector was placed at 3 kilometers from the source.

TABLE I. Breakdown of systematic errors from the Bugey experiment[10]. The absolute normalization refers to the percentage errors when a single detector measurement was made. The relative normalization refers to those errors which remained when a comparison of two detectors was made.

Error Source	Absolute Normalization (%)	Relative Normalization (%)
Neutrino Flux	2.8	-
νP Cross Section	0.2	-
Solid Angle	0.5	0.5
Target Protons	1.9	0.6
Neutron Detection	3.2	1.5
Positron Detection	0.9	0.9
Selection Correlation	1.0	-
Signal/Background	25@15m 2.2@40m	0.7@95m
Total	5.0	2.0

Bugey was able to achieve a total relative error of 2%, it seems reasonable to presume that an overall systematic error of less than 1% in a two detector measurement can be achieved.

7 Requirements for an Experimental Site

As was observed in Fig. 3, one of the most critical factors in the sensitivity to $\sin^2(2\theta_{13})$ is overall luminosity. This is a product of the power of the reactor (GW), the mass of the detectors (tons) and the length of time for the experiment (years). To a certain extent, these three components can be played against each other. However, given that both length of time and detector size require money, it is useful to maximize the reactor power if possible. Most modern reactors produce between 3-4GW$_{th}$ of power per core. Many reactor facilities have two or three cores on a single site. There is a trade-off in the additional luminosity, however. Each reactor shuts down periodically to replenish fuel. At a single reactor facility, this provides an opportunity to measure the non-reactor based backgrounds. However, at a multiple reactor facility, companies tend to avoid having all reactors off simultaneously. Thus the backgrounds must be extrapolated from the reduced flux running, introducing an additional error source into the measurement.

The primary source of backgrounds come from cosmic muons. While external vetoes can be constructed to remove these signals from the data stream, the overall rate at the surface is prohibitive. Therefore, any detector must be placed under a significant overburden. In order to keep any background corrections small, and by extension their contribution to the systematic errors small, the background rate at the far detector needs to be less than 1%. This implies an overburden of at least 300m of water equivalent (mwe). Further consideration of backgrounds from muon induced production of radioactive isotopes which can produce correlated events mimicking the neutrino signal (such as ^{8}He, ^{9}Li and ^{11}Li) have suggested that a larger overburden, perhaps as much as 500 mwe, may be required.

To achieve these levels of overburden, extensive excavations may be required. Any reactor facility under consideration must have geological conditions that are conducive to such a construction effort. This means that the ground underneath must be stable enough to support boring shafts 200m down and building caverns, or there need to be surrounding hills which are high enough and can support horizontally excavated tunnels. The latter possibility is generally preferred since the costs of tunneling into a hillside are expected to be less than for boring a shaft. However, that requires that hills exist at the optimal distance for the oscillation measurement. Fig. 4 shows a calculation of sensitivity to $\sin^2(2\theta_{13})$ as a function of baseline distance for 3 different values of Δm^2_{atm}.

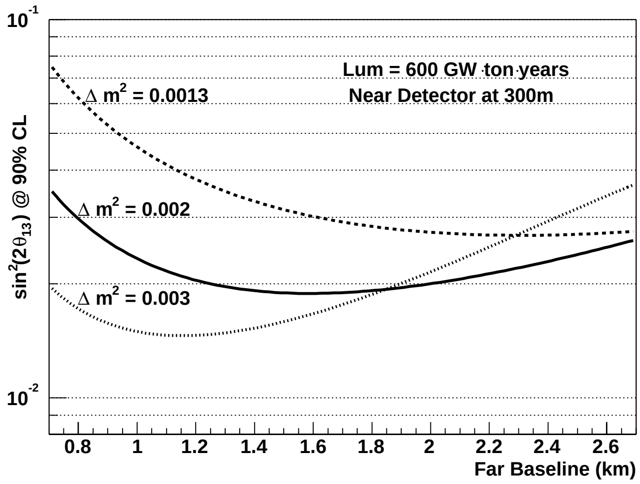

Figure 4. Statistical sensitivity to $\sin^2(2\theta_{13})$ as a function of baseline distance to the far detector. The statistical power is calculated for a luminosity of 600 GW-ton-years and a 1% systematic limit bin-to-bin. Curves are shown for three values of Δm^2 representing the best fit and the upper and lower limits of the 90% allowed region from the Super-Kamiokande experiment.

One can see that for the current best fit of Super-Kamiokande ($\Delta m^2_{atm} = 0.002$), the optimal baseline distance for the far detector is about 1.6km. However, the dependence is relatively flat and any location between 1.3km and 2km would provide reasonable sensitivity while maintaining flexibility to various values of Δm^2.

In addition to the usual nuclear reactor facilities in the U.S. and France, locations as diverse as Siberia, Japan, and Taiwan have been considered for this experiment. Each of these has different advantages. Many have shown distinct difficulties either in finding adequate detector locations, or more commonly, in finding adequate communication and access from the nuclear reactor facility itself. In the next section, we will discuss one very promising reactor facility located at Angra dos Reis, Brazil.

8 An Experiment at Angra dos Reis

Angra dos Reis is located about 150km south of Rio de Janeiro. The nuclear facility contains two operational reactors. The Angra-I reactor is an older low power (about 1.5 GW$_{th}$) reactor that is not frequently operated. The Angra-II reactor, on the other hand, was brought on-line in 2000 and is consistently operated at about 4.1 GW$_{th}$. The reactors are located on the coast and the reactor company controls a strip of land that stretches inland about 1-1.5km and is approximately 4 or 5 km along the coast. All experimental constructions which will be considered here would be situated within the reactor company's site boundaries.

Much of this terrain is mountainous granite with multiple peaks in the 200-600m region. This allows good background reduction to be achieved for an experimental hall with relatively cheap civil construction by tunneling sideways into such a mountain. Also within the site boundaries there exists a town, Praia Brava, which houses most of the 2 or 3 thousand people who work at the reactor facility and also contains a hotel and stores. Such already existing infrastructure could make using this facility more attractive.

The company which runs Angra is state owned and operated. One of the unique features of attempting this experiment in Brazil is that the presidents of both the electric power company and it's daughter nuclear power company are former particle physicists who used to do experiments at CERN. As a result, they are very receptive to communications from members of the Brazilian physics community and have been very helpful in providing resources and access to the facility. A one day site visit has already been performed to evaluate the viability of performing the experiment there. Significant assistance was provided by the director of operations from the reactor facility and we spent significant time with the director of civil construction on the site. With their help, we were able to explore all the possible experimental site locations and arrive at a solution which was acceptable to both the reactor facility and the experimental needs. The reactor company has agreed to supply full detailed cost estimates of any civil construction plan that we provide by using their detailed knowledge of the site geology and known contractors.

A topographic map of the site, as supplied by the reactor company, is shown in Fig. 5. The concentric circles are at 500m radial intervals from the primary Angra-II reactor core. The near site location is 300-350m from the core. It has the possibility to gain about 15-20m of rock overburden (30-50 mwe). The far site location would exist under a 240m hill at about 1350m from the reactor core. Access to the far site would come from a 420m tunnel which starts from the

Figure 5. A topographic map of the nuclear reactor site at Angra dos Reis. The concentric circles are at 500 meter radial intervals from the core of Angra-II. Proposed locations for the near and far detector experimental halls as well as the far detector access tunnel are shown.

western edge of the hillside. This location is easily accessible from the town of Praia Brava and would be very near to the current location of their sewage treatment plant.

It is envisaged to place identical 50 ton fiducial detectors at each location. Exact detector designs have not yet been developed, but it is currently assumed that such detectors would build off of the developments from other groups. Most likely a 3 volume detector would be optimal: a central liquid scintillator volume that would be doped with gadolinium (target); a surrounding volume of liquid scintillator without gadolinium (gamma catcher); a non-scintillating buffer to shield the radioactivity of the photo-tubes which would be installed at the outer edge of this volume. An active muon shield would then be required to surround this system. A spherical detector with an active target of 50 tons would have a total diameter of approximately 7.3 meters. The access tunnels and experimental halls have been designed to accommodate these dimensions.

Preliminary estimations have been performed of the signal and background rates for the given detector configuration. The detector at the far location is expected to receive about 120 signal events per day, while the near site would be expected to receive about 3000. Some very preliminary background estimations suggest that the far detector would expect less than 10 Hz uncorrelated backgrounds which would easily be vetoed by an active muon shield and about 1-2 correlated background events per day from muon induced radioactive isotopes. Similarly the near detector would expect an uncorrelated background rate of about 830Hz (yielding an active live time of 63% after muon vetoing) and a correlated background of approximately 150 events per day. Having a signal to noise rate of about 100 in the far detector and 20 in the near detector should allow reasonable background rejection while maintaining statistical sensitivity. Fig. 6 (left) shows the expected statistical sensitivity as a function of time, for the best fit value and 90% allowed limits of Δm^2 from Super-Kamiokande. As can be seen, a limit of $\sin^2(2\theta_{13}) < 0.02$ at 90% confidence level can be achieved within 3 years. Also in Fig. 6 (right) is shown the complete limit and 3σ discovery potential for a 3 year run over all $\sin^2(2\theta_{13})$ and Δm^2.

9 Conclusions

The field of neutrino experimentation has made huge strides in the past few years. We now know that neutrinos oscillate and that they have mass. We are able to construct a comprehensive three flavor framework of neutrinos which is similar to our understanding of quarks. However, it is clear that the behavior of neutrinos within that framework is fundamentally different from what we have experienced in other areas. One of the most significant goals of any future neutrino program is the measurement of the parameter θ_{13}. A non-zero value of this parameter will open the door to many interesting effects such as leptonic CP violation, matter effects, and the ability to distinguish the neutrino mass hierarchy. A reactor experiment offers a straight forward and cost effective method to measure or constrain this parameter. The sensitivity will be comparable to proposed accelerator based experiments without the difficulties caused by ambiguities between the different effects. In the event that both reactor and accelerator experiments are performed, the reactor experiment's complementarity will allow the degeneracies to be broken and additional measurements to be made.

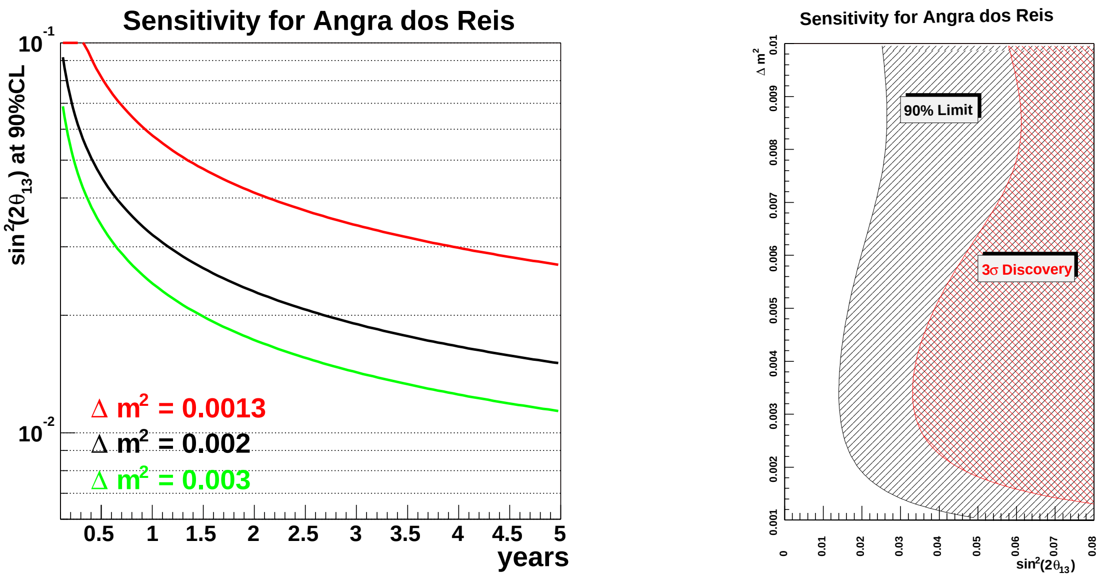

Figure 6. Expected sensitivity to $\sin^2(2\theta_{13})$ which could be achieved by an experiment at Angra dos Reis. The plot on the left shows the sensitivity as a function of years of running for three different values of Δm^2. On the right, the full coverage of Δm^2 vs. $\sin^2(2\theta_{13})$ is shown assuming three years of data taking. Curves for both the limit at 90% confidence level and the discovery at 3 σ are shown. The current limit at 90% confidence is $\sin^2(2\theta_{13}) < 0.2$.

While many locations for a reactor experiment are under investigation, a very favorable site is located in Brazil at Angra dos Reis. The communication that is already established with the reactor company and the surrounding topography make the experimental case very sound. In addition, this experiment provides an opportunity for the Brazilian community to host and perform cutting edge neutrino research at a relatively cheap cost. The international working group is currently working on the draft of a white paper which will contain the current best knowledge on the issues pertaining to a reactor based measurement of θ_{13}. This document is expected to be released by the end of 2003.

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