1 Beyond θ_{13}

In this section, we review other physics possibilities using anti-electron neutrinos from a nuclear reactor. These include a measurement of the weak mixing angle, improved limits on neutrino magnetic moments, an improved measurement ofΔm^2_{12}, tests of CPT symmetry, searches for sterile neutrinos, and studies of nearby supernova.

1.1 $\sin^2\theta_W$

A precision measurement of $\sin^2\theta_W(Q^2 = 4\ \mathrm{MeV}^2)$ can be performed at a reactor-based experiment using the near detector of an experiment designed to measure θ_{13}. This is motivated experimentally by the NuTeV anomaly, a 3σ deviation of $\sin^2\theta_W$ from the Standard Model prediction [1], measured in deep inelastic neutrino scattering. It is also motivated theoretically, as a precision study at $Q^2 \approx 0$. The two existing low Q^2 measurements are from atomic parity violation[2], which samples $Q^2 \sim 0$; and SLAC E158, a Møller scattering experiment at average $Q^2 = 0.026\ \mathrm{GeV}^2$ [3]. These results are in agreement with the Standard Model, as shown in Fig. 1. They are, however, subject to different radiative corrections than neutrino scattering. Thus, this measurement is attractive if the errors can be shown to be comparable to those measured at the NuTeV, APV, and E158 experiments.

The technique we employ uses the rate of the purely leptonic $\bar{\nu}e$ scattering to measure $\sin^2\theta_W$. We normalize the $\bar{\nu}e$ "elastic scatters" (ES) using the $\bar{\nu}p$ "inverse beta decay" (IBD) events, to reduce the error on the flux. The measurement is performed in the region of $3 \leq E_{vis} \leq 5$ MeV, where E_{vis} is the visible energy. This is a region between two potential backgrounds: radioactive contaminants and unassociated neutrons. Another crucial aspect is that the detector is located beneath an overburden of at least 300 mwe (meters, water-equivalent).

The details of the proposed measurement are described in reference [5]. Here we provide an brief overview of the ideas.

For the purposes of this calculation we employ spherical scintillator oil detectors subdivided into three regions. The central region, of radius 190 cm, contains Gd-doped scintillator. The fiducial volume will be confined to 150 cm, corresponding to 13 tons. This is surrounded by an undoped scintillator region extending to a radius of 220 cm. This, in turn, is surrounded by a pure oil region out to a radius of 290 cm, which acts as a buffer between the active detector and the phototubes. This design was chosen as a "test model" to demonstrate the feasibility of the measurement and does not represent highly specific requirements. We assume two near and four far detectors. Further design information and assumptions for efficiencies are given in reference [5].

As the model for this study we use the Braidwood setup, consisting of two 3.6 GW

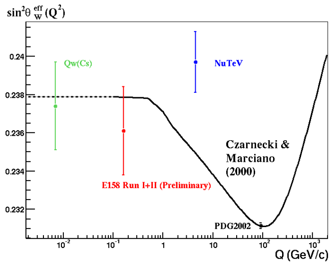

Figure 1: Measurements of $\sin^2\theta_W$ as a function of Q; from reference [4]. The curve shows the Standard Model expectation.

reactors. The near detectors are located at 224 m from the cores. We assume 900 live days of running.

This style of detector has been optimized to reconstruct $\bar{\nu}p$ events, which dominate the rate when the reactor is running. This design is also optimal for measuring $\sin^2\theta_W$ to high precision. Initially, one might think otherwise for two reasons. First, $\bar{\nu}p$ events events represent a potential background, but this background can be controlled, as long as the experiment is efficient for triggers on H as well as Gd neutron captures. Second, high-energy-muon-induced (HEMI) isotopes are the most significant background. This could be reduced by running on a non-carbon-based target, or by employing a large overburden. As we show in reference [5], the benefits of measuring the $\bar{\nu}e$ and $\bar{\nu}p$ events in the same detector, which requires a carbon-based target, far outweigh the drawbacks.

NuTeV has made a 0.75% measurement, including statistics and systematics, of the weak mixing angle. To match this, one needs to measure the $\bar{\nu}e$ absolute rate within the 3 to 5 MeV visible energy window with a 1.2% uncertainty. With this in mind, one must have at least 10,000 ES events. Furthermore, systematics must be controlled at the $< 1\%$ level.

By choosing a lower limit of 3 MeV visible energy, we cut most backgrounds from contamination. This is because the energetic α signals quench, producing less than 1 MeV. This leaves only the $\beta + \gamma$ decays; of these, only one branch of the Th chain contributes. Contamination from the acrylic vessels are not an issue due to the severe fiducial volume cut. Therefore, only dissolved contaminants in the oil and Gd contribute. We assume the oil and Gd are purified to KamLAND levels, resulting in a total background of 100 events (although a contamination up to two orders of magnitude higher can be tolerated).

The largest background is the HEMI isotopes. We assume 300 mwe overburden. At 450 mwe, which may be an option, the rate of production of these isotopes will be cut by a factor of two. This is therefore a somewhat conservative assumption. We assume that those β decays which are accompanied with a neutron can be vetoed. We also assume that HEMI events with an accompanying neutron can be vetoed. The result is an estimated 1458 events.

Statistical error on the signal	0.95%
Statistical error $\bar{\nu}p$ background subtraction	0.34%
Statistical error on U and Th background	0.09%
Statistical error on muon-induced isotopes	0.34%
Systematic error on muon-induced isotopes	0.46%
Statistical error on the normalization	0.10%
Systematic error on electron-to-free-proton ratio	0.60%
Systematic error on the Gd capture fraction	0.30%
Total error	1.3%

Table 1: Fractional errors on the number of $\bar{\nu}e$ scattering events based on assumptions presented in ref. [5].

The environmental background rates can be measured *in situ* if the near and far detectors are built as similarly as possible. We assume that the Gd-doped scintillator is mixed in a single batch so that contaminants are the same in all detectors. The overburdens may not be identical, but in the flat environment of Braidwood they will be very similar. The rate of HEMI events can be calibrated by comparing the cosmic muon rates. Then the background in the 3 to 5 MeV window can be measured in the far detector and subtracted from the near detector.

The fractional error on the number of $\bar{\nu}e$ events, for sources contributing $> 0.1\%$ to the total, are listed in Table 1. We estimate that this analysis has statistical and systematic errors which are roughly equal. Therefore increased statistics yields further improvement.

The total error which is obtained in the event rate is 1.3%. This translates to an error on $\sin^2\theta_W$ of $\delta(\sin^2\theta_W)$=0.0019. This is comparable to the NuTeV error of 0.0017. This error is lower than the published SLAC E158 and APV errors. This error can be made equal to NuTeV by running for 1800 days. Based in this, we conclude that this measurement is both feasible and exciting, and should be considered as an interesting addition to a future θ_{13} experiment.

1.2 Precision Measurement of Δm_{12} with a Second Generation Long Baseline Reactor Experiment

1.2.1 Introduction

The first results from the KamLAND [7] experiment have had the largest impact on the allowed regions of parameter space in the 'solar sector' than perhaps any other single experiment. Figure 2, from Ref. [6], shows the available LMA space with and without the

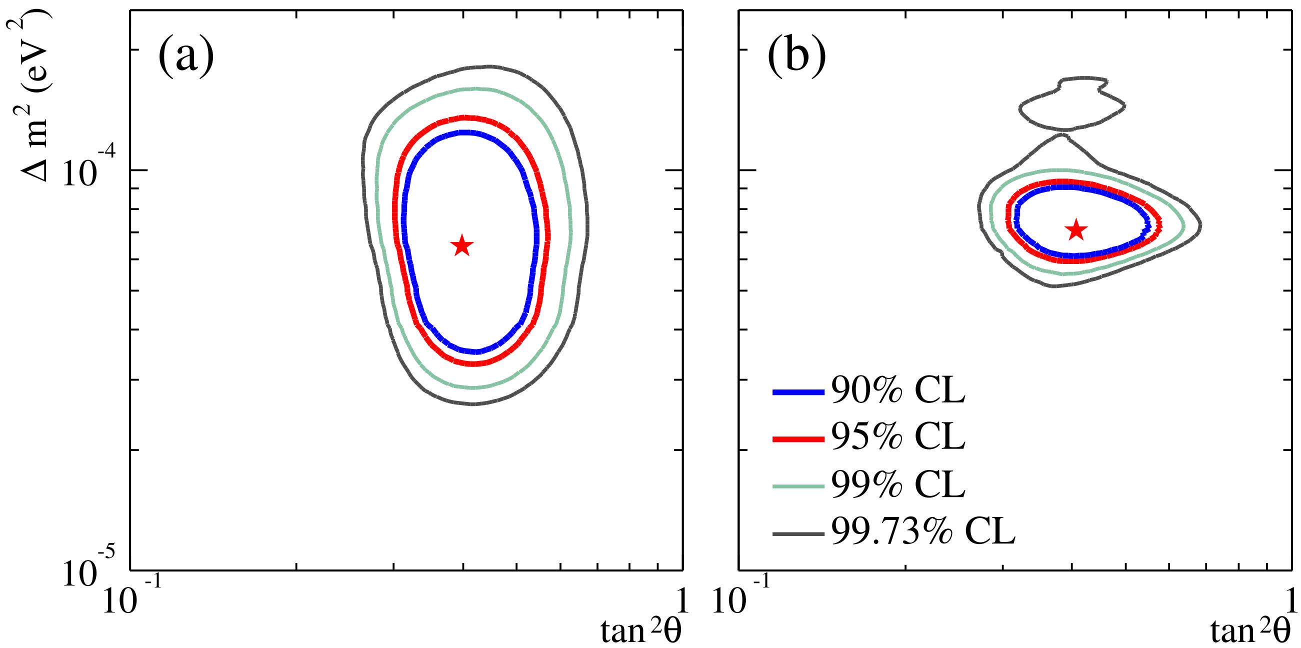

Figure 2: Allowed region of (1,2) sector parameter space based upon solar (left panel) and solar+KamLAND measurements (right panel), taken from Ref. [6].

KamLAND results. The driving uncertainties on the KamLAND results are statistical—their first results were a disappearance measurement based upon the observation of just 54 events—and the systematic uncertainties on knowledge of the detector response. In addition, there is also the systematic uncertainties resulting from knowledge of the reactor fluxes (roughly 2%), neutrino spectra (2.5%) and cross sections (0.2%). With the plans for a reactor measurement intended to measure the (1,3) survival probability to 1%, it is worth exploring whether a new (1,2) sector experiment can be done to improve on KamLAND's measurements.

1.2.2 Physics Motivation

Improvements in the precision of the (1,2) sector mixing parameters are interesting both from the standpoint of neutrino physics and solar astrophysics. Aside from the advantages of a precision measurement of the mixing parameters in this sector—which may at least constrain some current or future Grand Unified Theories—the comparison of reactor antineutrino experiments with those made by current and future solar neutrino experiments provides a unique test of the oscillation model itself. The reactor and solar experiments differ in almost every relevant way: the baselines are vastly different, the lepton numbers are reversed, and the MSW effect is the primary transformation mechanism for one (solar) and completely unimportant for the other (reactor).

In addition to tests of neutrino physics, reactor measurements in the (1,2) sector provide strong constraints on solar physics: independent knowledge of the mixing angles allows us to predict the total fluxes of the low energy solar neutrinos based on measurements of the exclusive ν_e flux (and in the absence of inclusive neutral current measurements). Reference [8] describes how improvements in the KamLAND measurements improve our knowledge of the *pp* neutrino fluxes in conjunction with solar measurements. Even for the higher energy solar neutrinos (^{8}B and hep), comparisons of the predicted total flux based upon the ν_e flux and reactor-based (1,2) measurements to the measured total active flux with neutral currents allow tests for sterile neutrinos.

Somewhat ironically, a measurement in the (1,2) sector with smaller uncertainties could also provide an indirect measure of θ_{13} when combined with solar neutrino measurements (see Chapter **??**). Because the solar transformation changes from matter-enhanced oscillations at high energies to vacuum-dominated transformation at low energies, the low and high energy solar data allows a measurement of θ_{12} which is only weakly correlated with θ_{13}. This fact, in combination with a precision terrestrial measurement of (1,2) disappearance like that made by KamLAND, can lead to a restriction on the size of θ_{13}.

1.2.3 Potential Experiment

Clearly, to be worthwhile, any new reactor-based (1,2) sector measurement must do substantially better than the KamLAND experiment has already done. A new experiment could have several advantages. A single baseline, rather than the multiple baselines KamLAND uses due to the multiple reactors, could make a spectral distortion clearer. In addition, if a new (1,2) sector reactor experiment were run in conjunction with a short baseline θ_{13} experiment, many of the uncertainties on reactor fluxes, cross sections, and efficiencies are substantially reduced. If a θ_{13} experiment were built which achieved the goal of 1%-scale systematic uncertainties on the normalization between near and far, this would be a factor of five or so better than what KamLAND has published to date.

Figure 3 shows the energy spectrum of the survived $\bar{\nu_e}$'s at four different baselines for a single reactor location. We see that at roughly 70 km, the suppression is largest, assuming the current best fit parameters shown in Figure 2).

There are two substantial hurdles which would still need to be overcome, even if the expected 1% uncertainties in the differential efficiencies between near and far detectors was achieved. The first is still statistics—a detector placed near the center of the 70 km first minimum would still need to comparably large to KamLAND, of order 1 kTon. Figure 4 shows the event rates for a 1 kTon detector as a function of baseline for oscillated and

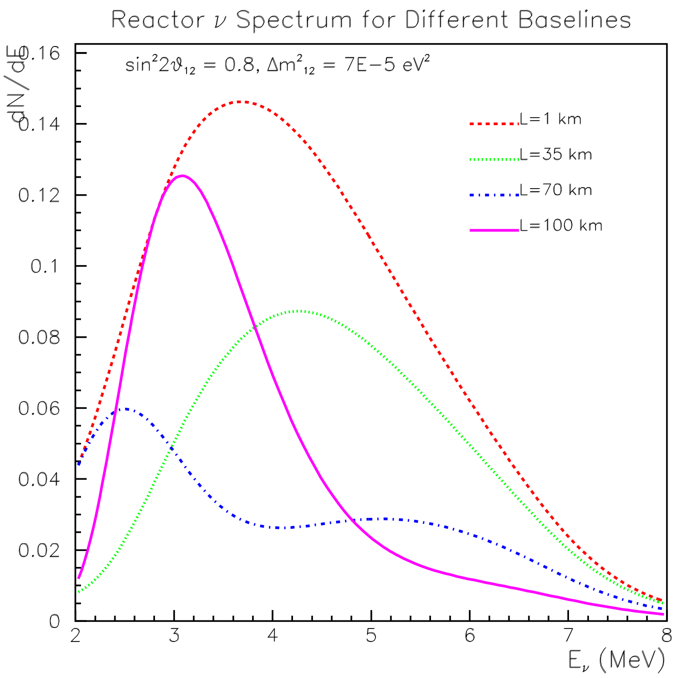

Figure 3: Neutrino energy spectrum for different baselines with distortions due to oscillation in the (1,2) sector.

unoscillated scenarios, using the fluxes as expected for the Braidwood reactor site (6.2 GW). We can see that near 70 km, in 1 kTon-year a detector would see roughly 20 events, relative to the expected rate of roughly 50 per kTon year. In fact, because of the $1/L^2$ reduction in the flux, the optimal baseline for measuring a deficit is not at 70 km where the largest suppression from oscillation is, but actually closer to 50 km, where an oscillated rate of 100 events can be compared to just 40 observed events per kTon-year. To retain the systematic advantages of identical near and far detectors, a 'detector' for a measurement in the (1,2) sector would likely have to be made out of several modules built to the design of the (1,3) sector detectors.

The second major hurdle is a consequence of the first: with the low statistics signal, backgrounds must be very carefully controlled, and therefore a site in which the overburden was substantial would be required for the measurement to be made. Even at an overburden as large as that of the KamLAND experiment (2700 m.w.e), the backgrounds could dominate the systematic uncertainties. It is likely that such an experiment would therefore not only require an efficient veto but perhaps one which could track cosmic rays to aid in rejection of spallation products and cosmogenic neutrons. In addition, the detector materials and construction would likely have much stronger purity requirements than might be needed for the θ_{13} measurement.

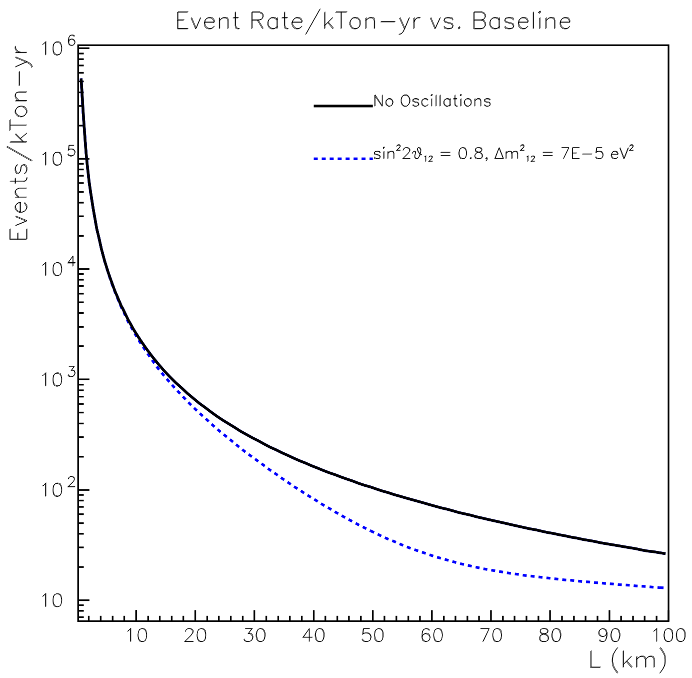

Figure 4: Event rate as a function of baseline for (1,2) oscillated and unoscillated scenarios.

1.3 Sterile Neutrinos

Reactor experiments have the potential to explore and constrain the existence of sterile neutrinos. The presence of sterile neutrinos in addition to the three active flavors has been considered in order to explain the LSND signal together with the other solar, atmospheric, accelerator and reactor data.

Mixing of the electron neutrino with a sterile state would affect the disappearance of $\bar{\nu}_e$ in reactors.

The survival probability of $\bar{\nu}_e$ at nuclear reactors is given by:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4\sum_{a>b} |U_{1a}|^2 |U_{1b}|^2 \sin^2\left(\frac{\Delta m_{ab} L}{4E}\right)$$

For a baseline around 1km, the mass splitting relevant for atmospheric neutrinos, $\Delta m^2_{atm} = m_3^2 - m_1^2 \simeq 2\times 10^{-3}$, gives the dominant contribution in the three flavors case. In the presence of a sterile neutrino with some not too small mixing with ν_e, this is corrected by the contribution of the new $\Delta m_s^2 = m_4^2 - m_1^2$, if this is in the right range:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{atm} L}{4E}\right) - \sin^2 2\theta_s \sin^2\left(\frac{\Delta m_s L}{4E}\right)$$

If Δm_s^2 is ~ 1 eV, as motivated by trying to accommodate the LSND experiment with the rest of the neutrino data, the Δm_s^2 oscillations are averaged out over km distances and the last term has a small, constant contribution to the survival probability. The experiment would in this case get a measurement of θ_{13} if $\theta_{13} \gtrsim .01$. In order to distinguish a constant contribution in the energy spectrum, the mixing angle θ_s would have to be larger than what is required by the LSND data. The contribution of such a sterile neutrino in a reactor experiment would become measurable if a detector would be placed at a very short distance from the reactor (~ 10 m). In this case the Δm_s^2 oscillation becomes the dominant one and the experiment would get a measurement of θ_s if $\sin^2 2\theta_s \gtrsim .01$.

Solar and atmospheric data do not favor the presence of a sterile neutrino, but still allow it at a few percent level. If Δm_s^2 is of the order of Δm_{atm}^2, both Δm^2's would contribute to the survival probability in a reactor experiment and it would be hard to measure them separately. This would be possible if the mass scales are still sufficiently different to give a significant distortion in the energy spectrum. If no oscillation effect is observed, the mixing angle limit obtained would apply to each of the two mixing angles, θ_{13} and θ_s.

It would also be possible to constrain the existence of a sterile neutrino by adding reactor data to all the rest of the neutrino data and trying to perform an "unitarity check" for a three flavor mixing matrix. This would be possible with a combination of precise disappearance and appearance experiments and checking if $P(\nu_e \to \nu_e) + P(\nu_e \to \nu_\mu) + P(\nu_e \to \nu_\tau)$ adds up to 1.

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