Comparisons of Reactor Experimental Scenarios

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1 Introduction

This memo gives the results from an investigation of the measurement sensitivities for various multi-detector, reactor experiments. The first section starts by comparing generic two and three detector scenarios as a function of position and systematic uncertainties. A comparison is then made of several of the proposed experiments using the parameters given in their publications. The following section then investigates the two parameter (Δm^2 and $\sin^2 2\theta_{13}$) measurement capability for two and three detector scenarios.

2 Sensitivity Estimates for Two and Three Detector Scenarios

This section gives a set of sensitivity studies using a full energy dependent fitting program that includes systematic uncertainties on various quantities. For these studies, it is assumed that there is an uncertainty of 2% on the power from each reactor and an uncertainty of 2% on the reactor flux times cross section which is common among all detectors. In addition, there is a common systematic uncertainty on the background, sys_bkgnd, whose value is given in the Table 2. For each detector, it is assumed that there is an uncorrelated uncertainty on the detection efficiency, sys_eff. Since this efficiency is uncorrelated, the effective overall uncertainty is $\sqrt{N_{Det}} sys\_eff$.

For each Δm^2, the program uses a χ^2 formed using the expected number of events in 100 0.1 MeV energy bins along with a possible oscillation signal . The systematic uncertainties are included by adding fit parameters ($d^{xsec}, d^{Bkgnd}, d_j^{Near}$, and d_j^{Far}) for each uncertainty with an appropriate constraining term associated with the assumed uncertainty. The sensitivity to oscillations is found using Minuit to do a multi-parameter fit to $\sin^2 2\theta$ and the systematic error parameters. Eq. 1 and 2 give the input parameters to the χ^2 calculation and Eq. 3 displays the formula for the χ^2 evaluation.

$$\begin{aligned} N_{i,j,k}^{Near} &= N_{i,j,k}^{Far} \left(Ebin_i, NearDetector_j, Reactor_k\right) \left(1 + d_k^{Reactor}\right) \left((1 + d_j^{Near}\right) \quad (1) \\ N_{i,j,k}^{Far} &= N_{i,j,k}^{Far} \left(Ebin_i, FarDetector_j, Reactor_k\right) \left(1 + d_k^{Reactor}\right) \left((1 + d_j^{Far}\right) \end{aligned}$$

Common Parameters for Runs

Reactor 1	$x = -150$ m $y = 0$ m 3.5 GW
Reactor 2	$x = 150$ m $y = 0$ m 3.5 GW
Near Det.	$x = 0$ m $y = 200$ m $z = -100$ m 50 tons 2,555,400 evnts
Data Event Eff. Far Det.'s	900 days 0.75 $z = -100$ m
Bkgnd Rate	0.2 evts/ton/day 9030 /50 tons / 900 days
Syst. xsec Syst. Power	0.02 0.02

Table 1: Common parameters used in scenario runs. Runs use two reactors with one near detector and either one or two far detectors.

$$
\begin{aligned}
P_{i,j,k}^{OscNear} &= \text{Osc. Prob. for } \Delta m^2, \sin^2 2\theta, E = Ebin_i \text{ and } L = Distance(NearDector_j - Reactor_k) \\
P_{i,j,k}^{OscFar} &= \text{Osc. Prob. for } \Delta m^2, \sin^2 2\theta, E = Ebin_i \text{ and } L = Distance(FarDector_j - Reactor_k)
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
\chi^2 = & \sum_{i,j,k} \frac{(N_{i,j,k}^{ObsFar} - N_{i,j,k}^{Far}(1 - P_{i,j,k}^{OscFar})(1 + d^{xsec}) - N_{i,j}^{FarBkgnd}(1 - d^{Bkgnd}))^2}{N_{i,j,k}^{Far} + N_{i,j}^{FarBkgnd}} \\
& + \sum_{i,j,k} \frac{(N_{i,j,k}^{ObsNear} - N_{i,j,k}^{Near}(1 - P_{i,j,k}^{OscNear})(1 + d^{xsec}) - N_{i,j}^{NearBkgnd}(1 - d^{Bkgnd}))^2}{N_{i,j,k}^{Near} + N_{i,j}^{NearBkgnd}} \\
& + \left(\frac{d^{xsec}}{\delta_{xsec}}\right)^2 + \left(\frac{d^{Bkgnd}}{\delta_{Bkgnd}}\right)^2 + \sum_j \left(\frac{d_j^{Near}}{\delta_{eff}}\right)^2 + \sum_j \left(\frac{d_j^{Far}}{\delta_{eff}}\right)^2 + \sum_k \left(\frac{d_k^{Reactor}}{\delta_{power}}\right)^2
\end{aligned} \tag{3}
$$

Various scenarios are presented in Table 2 using the overall parameters given in Table 1. The main systematic uncertainty associated with the measurement is the relative near to far efficiency. For a setup with moveable detectors this is assumed to be 0.23% and for fixed detectors 0.8%. As can be seen from the results, the single position scenarios with moveable detectors have the best sensitivity especially if one matches the total tonnage necessary for multiple position setups. The longer distance scenarios, as expected, have better coverage for the low $\Delta m^2 = 1 \times 10^{-3}$ eV^2 case.

Far Det. 1 (50 tons)	Far Det. 2 (50 tons)	sys_bkgnd	sys_eff	No. of events N_{Far1}	N_{Far2}	$\sin^2 2\theta$ (90% CL) for Δm^2 (eV^2) 1×10^{-3}	2×10^{-3}	3×10^{-3}
1200 m	—	0.14	0.008	134,400	—	0.146	0.047	0.031
		0.035	0.008			0.110	0.038	0.027
		0.035	0.0023			0.054	0.017	0.011
(100 tons)		0.035	0.0023			0.036	0.012	0.008
1200 m	1800 m	0.14	0.008	134,400	65,440	0.090	0.033	0.025
		0.14	0.0023			0.061	0.021	0.014
		0.035	0.008			0.060	0.025	0.022
		0.035	0.0023			0.034	0.013	0.010
1200 m	2400 m	0.035	0.008	134,400	40,900	0.049	0.025	0.022
		0.035	0.0023			0.031	0.014	0.011
1200 m	3600 m	0.035	0.008	134,400	23,240	0.043	0.030	0.026
		0.035	0.0023			0.032	0.016	0.011
1500 m	—	0.035	0.008	89,907	—	0.081	0.032	0.027
		0.035	0.0023			0.044	0.016	0.012
(100 tons)		0.035	0.0023			0.029	0.011	0.009
1500 m	2000 m	0.035	0.008	89,907	54,807	0.052	0.024	0.021
		0.035	0.0023			0.031	0.012	0.010
1500 m	3000 m	0.035	0.008	89,907	29,465	0.043	0.025	0.025
		0.035	0.0023			0.029	0.014	0.012
1800 m	—	0.035	0.008	65,440		0.066	0.030	0.027
		0.035	0.0023			0.039	0.016	0.013
(100 tons)		0.035	0.0023			0.026	0.011	0.009
1800 m	2700 m	0.035	0.008	65,440	34,240	0.043	0.024	0.023
		0.035	0.0023			0.028	0.013	0.013

Table 2: Results for various scenarios using the common parameters listed in above table. Each far detector is assumed to have a fiducial mass of 50 tons. sys_bkgnd is the systematic uncertainty in the background and sys_eff is the uncertainty on the overall efficiency for each detector.

These longer distance scenarios also make stronger demands on statistics and thus are better with larger detectors.

The same calculation has been applied to the experimental setups being put forward by various collaborations. Table 3 gives a comparison including some options for multiple far detectors. Again the moveable detector scenarios (Braidwood and Wolf Creek) give the best sensitivity. It is not clear for Diablo Canyon if the far detector can be moved to the near site. Also, the near detector position at 500m for Diablo Canyon does reduce its sensitivity. The other proposals are worse by more than a factor of two.

Experiment (L_{Far} m)	Detectors	sys_eff (%)	No. of Events Near	Far (each)	Bkgnd	$\sin^2 2\theta$ (90% CL) for Δm^2 (eV^2) 1×10^{-3}	2×10^{-3}	3×10^{-3}
Braidwood ($L_{near}=200$ m)								
(1800 m)	3 @ 25 ton	0.23	1.8M	34K	4.5K	0.031	0.013	0.011
(1800 m)	5 @ 25 ton	0.23	1.8M	34K	4.5K	0.025	0.010	0.009
(1800 m)	5 @ 25 ton	0.8	1.8M	34K	4.5K	0.037	0.016	0.015
(1500 m)	5 @ 25 ton	0.23	1.8M	46K	4.5K	0.028	0.010	0.008
Wolf Creek ($L_{near}=250$ m)								
(1500 m)	3 @ 25 ton	0.23	660K	25K	4.5K	0.051	0.019	0.014
(1500 m)	5 @ 25 ton	0.23	660K	25K	4.5K	0.041	0.015	0.011
(1500 m)	2 @ 100 ton	0.8	2.64M	100K	18K	0.054	0.022	0.017
Diablo Can.($L_{near}=400$ m)								
(1800 m)	3 @ 25 ton	0.8	507K	30K	4.5K	0.040	0.019	0.017
(1800 m)	5 @ 25 ton	0.8	507K	30K	4.5K	0.036	0.018	0.015
CHOOZ II ($L_{near}=200$ m)								
(1050 m)	2 @ 8.5 ton	0.8	750K	34K	352	0.124	0.038	0.025
Kashiwazaki ($L_{near}=325$ m)								
(1300 m)	3 @ 8.5 ton	0.8	386K	49K	1.4K	0.056	0.022	0.018
(1500 m)	2 @ 100 ton	0.8	2.64M	100K	18K	0.054	0.022	0.017
Daya Bay($L_{near}=300$ m)								
(1800 m)	6 @ 8.5 ton	0.8	285K	22K	1.5K	0.044	0.021	0.018
(1800 m)	6 @ 8.5 ton	0.23	285K	22K	1.5K	0.032	0.014	0.012
(1800 m)	12 @ 8.5 ton	0.8	285K	22K	1.5K	0.032	0.015	0.013
(1800 m)	12 @ 8.5 ton	0.23	285K	22K	1.5K	0.024	0.010	0.009
Brazil ($L_{near}=325$ m)								
(1350 m)	2 @ 50 ton	0.8	1M	68K	9K	0.071	0.025	0.019

Table 3: Sensitivities for various proposed experiments. The results assume 3 years of running. Except where noted the experimental parameters and errors are given in Table 1.

Far Det. 1 (50 tons)	Far Det. 2 (50 tons)	sys_eff	For $\Delta m^2 = 0.002$ eV^2 and $\sin^2 2\theta = 0.04$ $\delta(\Delta m^2)$ eV^2	$\delta\left(\sin^2 2\theta\right)$
1200 m	—	0.008	0.0014	0.034
(100 tons)		0.0023	0.0009	0.024
1200 m	1800 m	0.008	0.0005	0.012
		0.0023	0.0004	0.010
1200 m	2400 m	0.008	0.0003	0.011
1500 m	—	0.008	0.0008	0.017
(100 tons)		0.0023	0.0005	0.012
1500 m	2000 m	0.008	0.0004	0.011
1500 m	3000 m	0.008	0.0003	0.011
1800 m	—	0.008	0.0005	0.014
(100 tons)		0.0023	0.0004	0.008
1800 m	2400 m	0.008	0.0003	0.011
1800 m	3000 m	0.008	0.0003	0.011

Table 4: Oscillation parameter measurement errors for $\Delta m^2 = 0.002$ eV^2 and $\sin^2 2\theta = 0.04$. The last two columns give the 1 σ errors. The rows marked as (100 tons) have 100 fiducial tons of detector at the given location.

3 Measurement Capabilities for Two and Three Detector Scenarios

In this section, the measurement capabilities of a given scenario are investigated. These capabilities are related to using multiple detector positions to show oscillatory behavior if an oscillation signal is observed. For this study, a figure of merit for seeing oscillatory behavior is given by how well Δm^2 is measured.

Tables 4 and 5 give the 1 σ error estimates for measurements of the oscillation parameters assuming the given underlying values. In most cases the detectors are assumed to be 50 tons except for the two detector scenarios listed as (100 tons). The systematic error on the background is assumed to be 3.5% and the other errors and setup parameters are as given in Table 1.

As can be seen from the tables, the three detector scenarios do have some advantage for this type of measurement but only very slightly. With the statistics available with 50 or 100 ton detectors, the energy dependence does not provide much additional information. So, a large single detector at one far position gives almost equivalent information to two smaller detectors.

Far Det. 1 (50 tons)	Far Det. 2 (50 tons)	sys_eff	For $\Delta m^2 = 0.002$ eV^2 and $\sin^2 2\theta = 0.02$ $\delta(\Delta m^2)$ eV^2	$\delta\left(\sin^2 2\theta\right)$
1200 m	—	0.0023	0.0024	0.033
(100 tons)		0.0023	0.0019	0.025
1200 m	1800 m	0.008	0.0006	0.011
1200 m	2400 m	0.008	0.0006	0.011
1500 m	—	0.0023	0.0014	0.016
(100 tons)		0.0023	0.0010	0.012
1500 m	2000 m	0.008	0.0007	0.011
1800 m	—	0.0023	0.0009	0.011
(100 tons)		0.0023	0.0007	0.008
1800 m	2400 m	0.008	0.0005	0.010

Table 5: Oscillation parameter measurement errors for $\Delta m^2 = 0.002$ eV^2 and $\sin^2 2\theta = 0.02$. The last two columns give the 1 σ errors. The rows marked as (100 tons) have 100 fiducial tons of detector at the given location.

4 Conclusions

For these studies, it is assumed that the systematic error on the relative detector efficiency is 0.8% for non-moveable detectors and 0.23% for moveable detectors. For these assumptions, a 100 ton (or four 25 ton) set of moveable detectors is about a factor of two better in sensitivity than 100 tons of fixed detectors at two locations. For seeing oscillatory behavior (measuring Δm^2 for these studies), the multiple far location scenarios have a slight advantage but not at a significant level. The bottom line is that the best sensitivity is found to be associated with on far location with multiple detectors that can be moved to the near site for cross calibration.