Lawrence Berkeley National Laboratory

Title
The future of reactor neutrino experiments: A novel approach to measuring theta13

Permalink
https://escholarship.org/uc/item/8vh776c3

Authors
Heeger, Karsten M.
Freedman, Stuart J.
Luk, Kam-Biu

Publication Date
2003-08-24

The Future of Reactor Neutrino Experiments: A Novel Approach to Measuring θ_{13}

Karsten M. Heeger[*], Stuart J. Freedman[†*] and K.-B. Luk[†*]

[*]*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[†]*University of California at Berkeley, Berkeley, CA 94720, USA*

Abstract. Results from non-accelerator neutrino oscillation experiments have provided evidence for the oscillation of massive neutrinos. The subdominant oscillation, the coupling of the electron neutrino flavor to the third mass eigenstate, has not been measured yet. The size of this coupling U_{e3} and its corresponding mixing angle θ_{13} are critical for CP violation searches in the lepton sector and will define the future of accelerator neutrino physics. The current best limit on U_{e3} comes from the CHOOZ reactor neutrino disappearance experiment. In this talk we review proposals for future measurements of θ_{13} with reactor antineutrinos.

Recent results from atmospheric, solar, and reactor neutrino experiments [1] have provided evidence for the mixing of massive neutrinos. The phenomenon of neutrino mixing is characterized by the coupling between the neutrino flavors ($\nu_{e,\mu,\tau}$) and mass eigenstates ($\nu_{1,2,3}$), and the associated mixing angles. Past and present neutrino oscillation experiments have determined two of the three mixing angles in the neutrino mixing matrix, U_{MNSP}, of three active species. The coupling of the electron neutrino flavor to the third mass eigenstate, U_{e3}, is yet to be determined. Equation 2 shows a parametrization of U_{MNSP} and the experimental input to this matrix.

$$U_{MNSP} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \tag{1}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\text{PRESENT: atmospheric } \nu \\ \text{FUTURE: accelerator } \nu}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_D} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_D} & 0 & c_{13} \end{pmatrix}}_{\substack{\text{reactor } \nu \\ \text{reactor and accelerator } \nu}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{solar } \nu \\ \text{solar } \nu}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta/2} \end{pmatrix}}_{\substack{0\nu\beta\beta \\ 0\nu\beta\beta}} \tag{2}$$

The current best upper limit on U_{e3} comes from the CHOOZ reactor neutrino disappearance experiment [4]. In contrast to the surprisingly large mixing of the other neutrino states, the U_{e3} coupling was found to be small [4]. The discovery of subdominant effects in $\overline{\nu}_e \rightarrow \overline{\nu}_{\mu,\tau}$ oscillations and a non-zero U_{e3} coupling would have a profound impact on neutrino physics. It determines whether CP violation can play a significant role in lepton mixing; if U_{e3} is zero, CP is conserved.

CP violation is a well-established phenomenon in the quark sector but leptonic CP violation is as yet unknown. CP violation in the lepton sector could have cosmological implications far beyond the phenomenon on neutrino oscillations. It may be the only way

to explain the observed matter-antimatter asymmetry in the Universe. In this context a successful θ_{13} experiment has the potential to define the direction of neutrino research and the neutrino program at accelerators for the next decade and beyond. The small size of θ_{13} compared to the other neutrino mixing angles may also point us to an underlying symmetry in theoretical neutrino mass models.

Nuclear reactors are an abundant source of $\overline{\nu}_e$ and have been the site of several experiments. From the discovery of the free antineutrino by Reines and Cowan in 1956 [3], to the first discovery of reactor $\overline{\nu}_e$ disappearance at KamLAND in Japan in 2002 [2], reactor neutrino experiments have played a central role in the history of neutrino physics. Almost five decades after the discovery of the neutrino, reactor neutrino experiments have – together with solar neutrino studies – provided evidence for the mixing of massive neutrinos. Reactor neutrino experiments study antineutrinos with an average energy of 4 MeV produced in the fission reactions in the core of a nuclear reactor. Reactor antineutrinos are usually detected through the inverse β-decay reaction on protons $\overline{\nu}_e + p \rightarrow e^+ + n$. The coincidence signal from the prompt positron and the delayed neutron capture allows the unique identification of electron antineutrinos.

The observation of neutrino flavor transformation in the atmospheric and solar neutrino experiments have allowed us to measure the oscillation parameters, including the square of the mass differences between the neutrino mass eigenstates. We expect to observe the signatures of neutrino oscillations associated with these mass states in accelerator and reactor neutrino experiments. In 2002, the KamLAND experiment made the first measurement of the disappearance of reactor $\overline{\nu}_e$ at an average distance of 180 km from the source and confirmed the dominant oscillation effect observed in solar neutrinos. Past reactor experiments such as CHOOZ and Palo Verde have studied the flux of reactor $\overline{\nu}_e$ at distances of ~ 1 km from the reactor cores. These experiments did not observe a flux suppression and limited the subdominant mixing associated with θ_{13} to $sin^2 2\theta_{13} < 0.9$ [4]. Combined analyses of the result from reactor and solar neutrino experiments now place a limit of $sin^2 2\theta_{13} < 0.6$ on the subdominant $\overline{\nu}_e \rightarrow \overline{\nu}_{\mu,\tau}$ oscillation. The goal of the next generation reactor neutrino oscillation experiment is the discovery of this subdominant neutrino oscillation and the first measurement of θ_{13}.

Over a distance of a few kilometers the survival probability of reactor $\overline{\nu}_e$ is well described by the approximate expression

$$P_{ee} \simeq 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right) \cos^4 \theta_{13} \sin^2 2\theta_{12} \qquad (3)$$

which is dominated by the frequency associated with the atmospheric mass splitting $\Delta m_{13} = \Delta m_{12} + \Delta m_{23} \simeq \Delta m_{23}$. A next-generation reactor experiment with 2 or more antineutrino detectors can make a precise measurement of the relative change in rate and shape of the energy spectrum and detect the signature of θ_{13} in the relative spectral distortion. The relative measurement between multiple detectors will make this experiment largely independent of the absolute reactor $\overline{\nu}_e$ flux, absolute detector systematics, and uncertainties in the cross-section.

Principle features of a suitable reactor site are a powerful reactor (or multiple cores) and overburden in excess of 300 mwe to shield the antineutrino detectors from cosmic
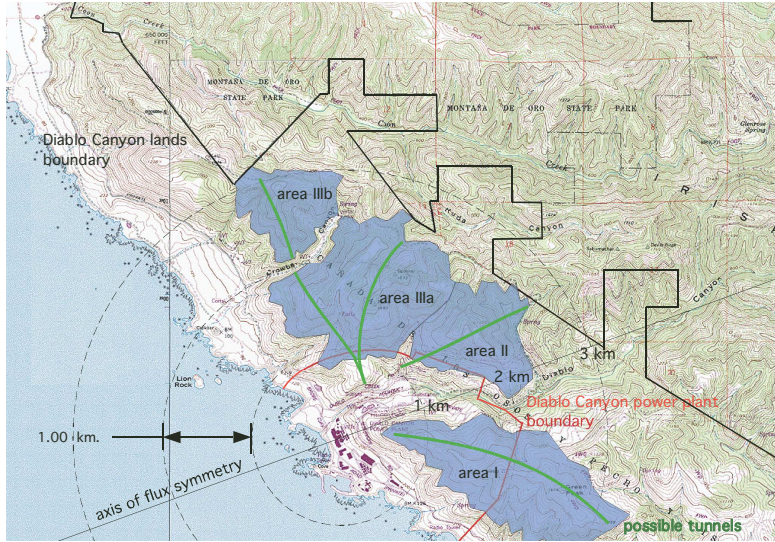
FIGURE 1. Topographic map of the site of the Diablo Canyon nuclear power plant in San Luis Obispo County, CA, USA. The land boundary as well as the power plant site boundary are indicated. The shaded areas identify regions with sufficient overburden for the placement of antineutrino detectors. The green lines illustrate the location of possible horizontal tunnels ranging in distance between 600 m to 3.2 km from the reactor cores of the power plant. At these locations we find an overburden of 300-600 mwe.

rays. Multiple reactor cores may lead to interference effects and reduce the ultimate sensitivity of an experiment. The construction of a horizontal tunnels or a vertical shafts are usually required to obtain this overburden. The variable baseline provided by horizontal tunnels is useful for optimizing the baseline of the two detectors and to demonstrate the neutrino oscillation effect with measurements at various locations along the tunnel. A tunnel may also be used to facilitate the relative calibration of the detectors at one location.

A number of reactor sites worldwide are currently under evaluation by different experimental groups [6]. For an overview of the current activities see [7] and references therein. One of the promising sites in the US is the Diablo Canyon nuclear power plant in central California. Two cores separated by ~ 100 m provide a total thermal energy of 6.2 GW$_{th}$. Nearby coastal mountains provide good overburden and make the plant an almost ideal site for a reactor neutrino experiment. Horizontal tunnels in the coastal mountains may provide overburden of 300-400 mwe at distances of 0.6-1 km and 600-800 mwe at < 3.2 km. The general layout and topography of the site allows the construction of a kilometer-long tunnel for two movable detectors. An overview map of the site is shown in Figure 1.

The physics potential of a next-generation reactor neutrino measurement has been discussed in [5] and references therein. The ultimate sensitivity of such an experiment will strongly depend on the layout of the experiment including the distances from the reactor cores, the overburden, the size of the detectors and their mobility. With a sensitivity of up to $\sin^2 2\theta_{13} = 0.01$ [5] a reactor neutrino measurement of θ_{13} is comparable to next-generation accelerator experiments. The difference between a low-energy, short-baseline reactor neutrino experiment and a longer-baseline accelerator
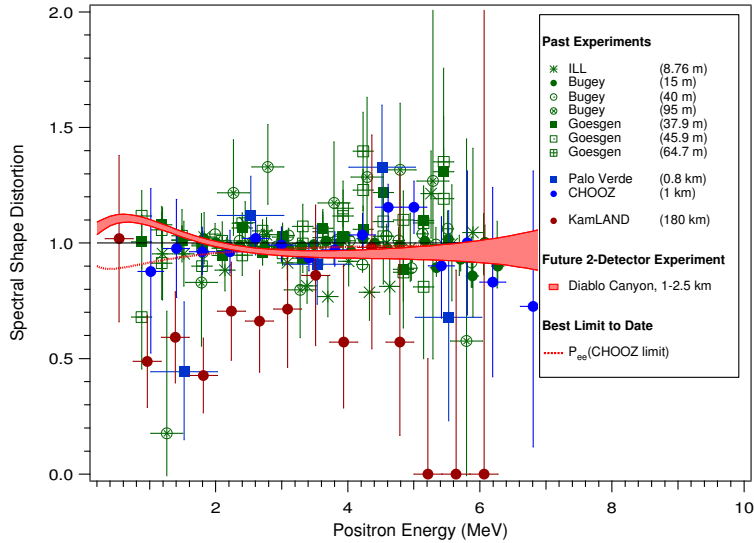
FIGURE 2. Expected statistical precision of a next-generation 2-detector reactor neutrino oscillation experiment compared to the results from past and present single-detector reactor neutrino experiments. This figure shows the ratio of the measured positron spectrum to the unoscillation spectrum for single-detector experiments and the ratio between the near and far detector for the proposed 2-detector experiment at Diablo Canyon. The errors are statistical.

experiment in which matter effects play a role make these approaches complementary. The combined interpretation of the reactor and accelerator experiments will provide the best sensitivity to θ_{13} and δ_{CP}. The expected statistical accuracy of a next-generation reactor neutrino experiment is illustrated in Figure 2.

In summary, next-generation reactor neutrino experiments have the potential to discover the neutrino mixing angle θ_{13} and define the roadmap of accelerator neutrino studies for the next decade and beyond. A discovery or a new limit on θ_{13} would determine the prospects for measuring leptonic CP violation. Through this effect we might find that neutrinos may play a significant role in the evolution of the early Universe and can in fact explain the long-standing mystery of the baryon asymmetry in the Universe.

REFERENCES

1. Fukuda, Y. et al. (Super-Kamiokande Collaboration), *Phys.Rev.Lett.82* (1999); Ahmad, Q.R. et al. (SNO Collaboration), *Phys.Rev.Lett.89:011301* (2002); Eguchi, K. et al. (KamLAND Collaboration), *Phys.Rev.Lett.90:021802* (2003)
2. Eguchi, K. et al. (KamLAND Collaboration), *Phys.Rev.Lett.90:021802* (2003)
3. Cowan, C.L. et al., *Science 124, 103* (1956)
4. Appollonio, M. et al., *Eur.Phys.J.C27:331-374* (2003)
5. Huber, P. et al., *arXive: hep-ph/030323* (2003)
6. Martemianov, V. et al., *arXive: hep-ph/0305295* (2003); Yasuda, O., *arXive: hep-ph/0305295* (2003); Suekane, F. et al., *arXive: hep-ex/0306029* (2003); Shaevitz, M.H. and Link, J.M., *arXive: hep-ex/0306031* (2003); Goodman, M., *arXive: hep-ex/0307017* (2003)
7. http://theta13.lbl.gov/ (2003)