Title

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Authors

Heeger, Karsten M.
Freedman, Stuart J.
Kadel, Richard W.
et al.

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Measurement of θ_{13} with Reactor Neutrinos

K.M. Heeger[a], S.J. Freedman[bc], R.W. Kadel[a], K.-B. Luk[ab]

[a]Lawrence Berkeley National Laboratory, Physics Division, Berkeley, CA 94720, USA

[b]University of California at Berkeley, Physics Department, Berkeley, CA 94720, USA

[c]Lawrence Berkeley National Laboratory, Nuclear Science Division, Berkeley, CA 94720, USA

Recent experimental results have provided unambiguous evidence that neutrinos have a small but finite mass and mix from one type into another. The phenomenon of neutrino mixing is characterized by the coupling between the neutrino flavor ($\nu_{e,\mu,\tau}$) and mass eigenstates ($\nu_{1,2,3}$) and the associated mixing angles. Previous neutrino oscillation experiments have determined two of the three mixing angles in the neutrino mixing matrix, U_{MNSP}. Using multiple neutrino detectors placed at different distances from a nuclear power plant, a future reactor neutrino experiment has the potential to discover and measure the coupling of the electron neutrino flavor to the third mass eigenstate, U_{e3}, the last undetermined element of the neutrino mixing matrix.

1. Introduction

Reactor neutrino experiments have played an important role in the history of neutrino physics. From the first direct detection of the antineutrino by Reines and Cowan in 1956 to the recent measurements at Palo Verde, Chooz, and KamLAND. Experiments with reactor antineutrinos have led to the discovery of the neutrino, the first observation of reactor $\overline{\nu}_e$ disappearance, and most recently to the measurement of spectral distortion, a unique signature of neutrino oscillation. Reactor neutrino experiments have also allowed us to place the best constraints on the neutrino magnetic moment.

Non-accelerator neutrino experiments have provided unambiguous evidence for the flavor transformation and mixing of massive neutrinos. Neutrino mixing is a result of the coupling between the neutrino flavor and mass eigenstates. The size of this effect is described by the neutrino mixing angles. The recent discoveries of solar neutrino flavor transformation at SNO, the observation of atmopsheric neutrino oscillation, and the precise measurement of reactor neutrino oscillation parameters have determined two of the three mixing angles in the neutrino mixing matrix U_{MNSP}.

The third mixing angle, θ_{13}, is yet unknown. The current best upper limit comes from the CHOOZ reactor antineutrino disappearance experiment [2]. The discovery of subdominant effects in $\overline{\nu}_e \rightarrow \overline{\nu}_{\mu,\tau}$ oscillation and the precise measurement of θ_{13} would have profound impact on neutrino physics. A successful experiment has the potential to define future research in neutrino oscillation physics for the next decade and beyond. The mixing angle θ_{13} is one of the parameters of the Standard Model and it may help us understand the underlying structure of neutrino mixing. Its size determines whether CP violation may play a significant role in the lepton sector. CP violation is a well-established phenomenon in the quark sector but yet unknown in the lepton sector. Neutrino oscillation and CP violation in the lepton sector may lead to leptogenesis and ultimately explain the observed matter-antimatter (i.e. baryon asymmetry) in the Universe.

Precision measurements of neutrino oscillation parameters play an important role in understanding the physics of massive neutrinos. Oscillation measurements determine the fundamental neutrino mixing parameters and help us answer fundamental questions related to the physics at high mass scales, the physics of flavor, and unification. A measurement of θ_{13} may help us answer some of the central questions in neutrino oscillation physics:

- Why are the neutrino mixing angles large, maximal, and small?
- Is there CP, T, or CPT violation in the lepton sector?
- Can the mixing of massive neutrinos and CP violation explain the baryon asymmetry in the Universe?
- Is there a connection between the lepton and baryon sector in particle physics?

2. A Multi-Detector Reactor Neutrino Oscillation Experiment

Reactor neutrino experiments study $\overline{\nu}_e$ with an average energy of $\sim$ 4 MeV produced in the fission reactions in the core of a nuclear reactor. Reactor $\overline{\nu}_e$ 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 $\overline{\nu}_e$ events. In the past several experiments have measured the absolute reactor neutrino flux to search for neutrino oscillation. The idea of a 2-detector reactor neutrino experiment to measure θ_{13} was first discussed by Mikealyan et al. [3]. Since then a number of groups have investigated the concept of multi-detector experiments for a relative measurement of the $\overline{\nu}_e$ interaction rate at different distances from a reactor to measure the neutrino mixing angle θ_{13} [4].

A future θ_{13} reactor neutrino oscillation experiments will use two or perhaps multiple liquid scintillator detectors placed at distances between 0.1-3 km from a nuclear reactor to measure the rate and energy spectrum of $\overline{\nu}_e$ interactions at different distances from the $\overline{\nu}_e$ source. A change in the observed $\overline{\nu}_e$ interaction rate due to the $\overline{\nu}_e$ survival probability

$$P_{ee} \simeq 1 - \sin^2 2\theta_{13} \sin^2(\frac{\Delta m^2_{atm} L}{4E}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(\frac{\Delta m^2_{solar} L}{4E})$$

would be an indication of subdominant $\overline{\nu}_e \rightarrow \overline{\nu}_{\mu,\tau}$ oscillation. A relative measurement between two detectors largely eliminates the dominant systematics that limit absolute measurements such as the detection efficiency, the fiducial volume of the detectors, and the reactor flux systematics.

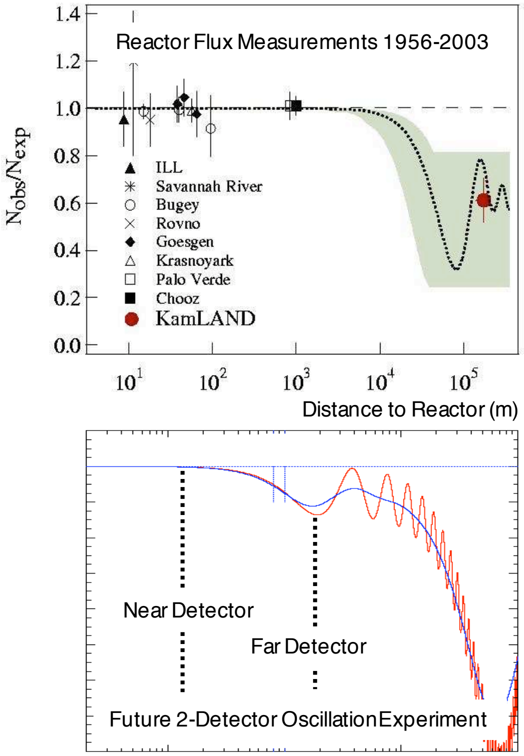

Figure 1. Upper panel: Measurement of the absolute $\overline{\nu}_e$ flux at different distances from reactors [1]. Lower Panel: A future 2-detector reactor experiment can precisely measure the subdominant θ_{13} oscillation from a relative measurement of the $\overline{\nu}_e$ rate at two different distances from the reactor.

A θ_{13} reactor experiment requires the construction of underground detector halls and access tunnels or shafts for the placement of at least two medium-sized liquid scintillator detectors with a fiducial volume of 10-50 t depending on the size of the reactor complex. Overburden in excess of several hundred meters water equivalent (mwe) is required to reduce cosmic-ray related backgrounds, in particular the creation of β-delayed neutron emitters that form a background to the $\overline{\nu}_e + p \rightarrow e^+ + n$ coincidence signal. Tunnels of up to 3 km in length or vertical shafts of 70-200 m in depth are to be built to access the underground detector halls.

3. A Horizontal Tunnel Laboratory

We have performed design and engineering studies on a future reactor neutrino experiment at the Diablo Canyon nuclear power plant in California, and more recently at the Daya Bay power plant near Hong Kong, China [5]. A horizontal tunnel can provide good overburden and access to the underground detector halls. The nearby coastal mountains provide overburden of up to 1200 meters water equivalent (mwe). Negotiations with the reactor operators are underway to develop a proposal for the construction of a next-generation neutrino oscillation experiment to search for θ_{13} with a sensitivity of $\sin^2 2\theta_{13} \leq 0.01$ at 90% C.L..

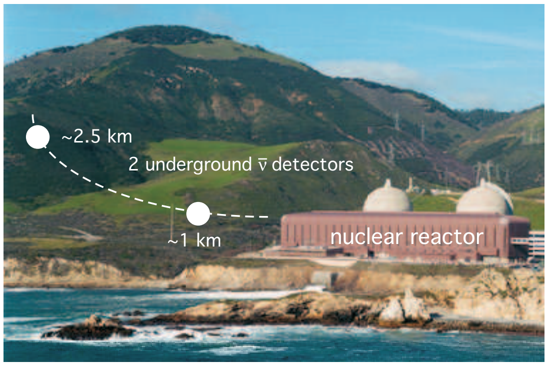

Figure 2. Concept of a 2-detector neutrino oscillation experiment at the Diablo Canyon nuclear power plant in California.

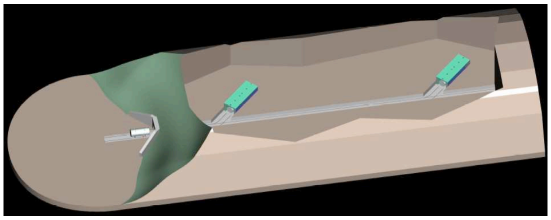

Figure 3. A horizontal tunnel with detector halls allows the placement of multiple detectors at suitable distances from the reactor. A tunnel provides easy access and sufficient overburden.

4. Summary

A future reactor experiment with multiple detectors will allow a measurement of θ_{13} with no ambiguities due to matter effects and better precision than other proposed experiments. At distances of 1-2 km matter effects have negligible effects on the propagation of reactor $\overline{\nu}_e$. With a proposed sensitivity of $\sin^2 2\theta_{13} \leq 0.01$ a reactor experiment will provide important input to future oscillation studies at accelerators. In combination with the results from long-baseline accelerator neutrino experiments the precision measurement of θ_{13} with reactor neutrinos may allow us to resolve the hierarchy of the spectrum of neutrino mass states and constrain the effects of CP violation in the lepton sector [6,7]. 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.

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