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TOWARDS A PRECISION MEASUREMENT OF θ_{13} WITH REACTOR NEUTRINOS: INITIATIVES IN THE UNITED STATES

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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. In this paper we describe recent efforts in the US towards a next-generation experiment to measure θ_{13} with reactor neutrinos.

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 atmospheric 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}.

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

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

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 ~ 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 determine 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

$$P_{ee} \simeq 1 - \sin^2 2\theta_{13} \sin^2 (\frac{\Delta m^2_{atm} L}{4E}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (\frac{\Delta m^2_{sol} L}{4E}) \quad (3)$$

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.

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.

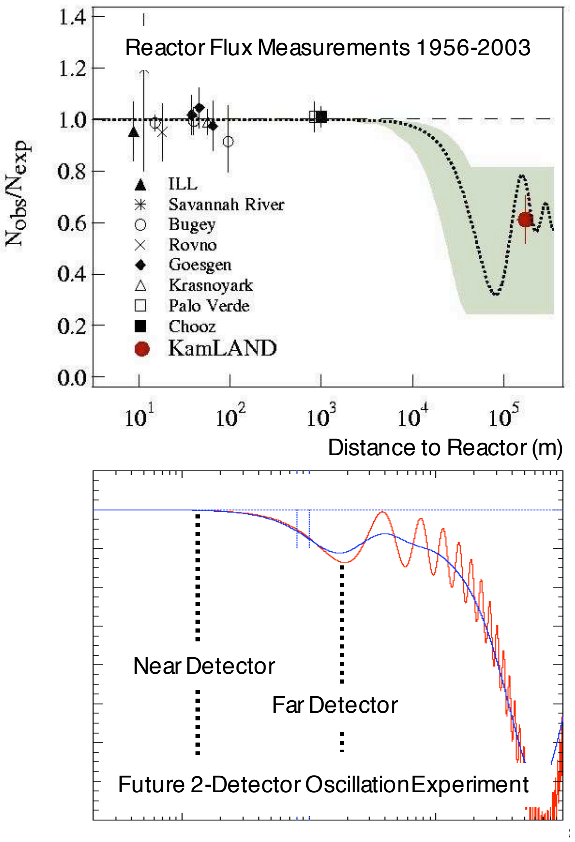

Figure 1. Upper panel: Past measurements of the absolute $\overline{\nu}_e$ flux at different distances from reactors. Lower Panel: Survival probability of $\overline{\nu}_e$ measured as a function of distance from the reactor. The red curve is for a mono-energetic $\overline{\nu}_e$ at the average energy, and the blue curve is the result smeared by the expected reactor anti-neutrino energy spectrum. 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.

3. Initiatives for a Next-Generation Reactor Neutrino Oscillation Experiment in the United States

A reactor θ_{13} experiment requires the use of multiple underground neutrino detectors at distances of 0.1-3 km from a power plant. The design of the experimental facilities depends critically on the topography of the reactor site. A variety of concepts involving vertical shafts or horizontal tunnels have been considered by numerous groups worldwide. In the recent past the following two proposals have been pursued in the US, one using a horizontal tunnel laboratory underneath a mountain and the other one based on two vertical shafts at different distances from a power plant.

3.1. *A Horizontal-Tunnel Neutrino Laboratory at Diablo Canyon*

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]. 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..

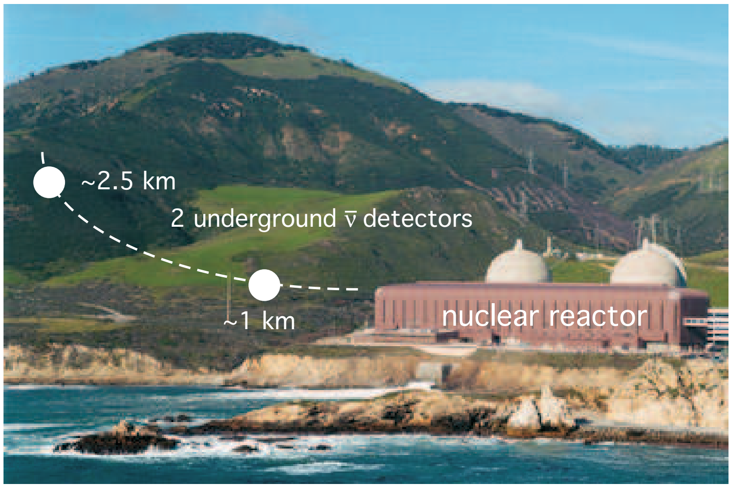

Figure 2. Concept of a 2-detector neutrino oscillation experiment at the Diablo Canyon nuclear power plant in California. A relative measurement of the reactor $\overline{\nu}_e$ interaction rate and energy spectra at different distances allows the observation of subdominant oscillation effects in $\overline{\nu}_e \rightarrow \overline{\nu}_{\mu,\tau}$.

A horizontal tunnel can provide good overburden and easy access to the underground detector halls with many advantages . At Diablo Canyon and Daya Bay nearby coastal mountains provide overburden of up to 1200 meters water equivalent (mwe). Horizontal tunneling is a well-established technology and used worldwide for the construction of road tunnels. Horizontal tunnels with roads or rails that connect the underground detector

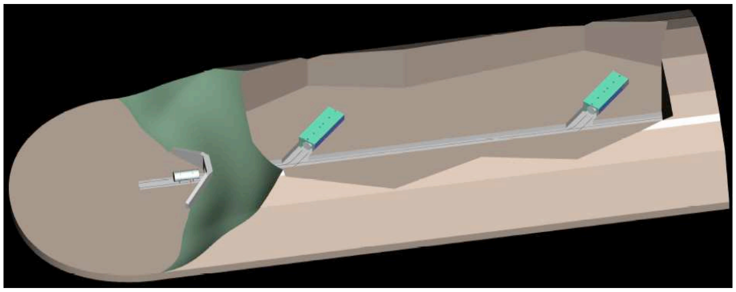

Figure 3. A horizontal tunnel with detector halls allows the placement of multiple detectors at suitable distances from the reactor. A tunnel provides easy access and sufficient overburden.

halls provide an easy method of interchanging the location of the detectors and moving them to different baselines. This will help control some of the critical experimental systematics:

The measurement of θ_{13} relies on the determination of of the neutrino interaction rate in multiple detectors at different baselines and will depend on the detector target mass, the distance of the detector from the nuclear reactor, the detection efficiency, and indistinguishable cosmic-ray induced backgrounds. Small variations in the target mass of the detectors can lead to apparent differences in the observed event rate. Many strategies have been proposed to improve on this systematic error but a residual error will remain. Interchanging detector positions is a powerful method to calibrate signal variations due to differences in the detector target mass.

Cosmic-ray induced spallation backgrounds are dependent on the overburden at a particular detector location. For all mountainous reactor sites the cosmic-ray induced background is position and baseline dependent. Only the relative calibration of detectors at the same location in the presence of the same backgrounds will allow one to make an absolute comparison of the neutrino signal rate. Moving and interchanging detector locations will be critical for measuring the same signal to background ratio in different detectors. We are actively considering an experimental design that allows the movement and exchange of detectors at different baselines so that the relative neutrino detection efficiencies of the detectors can be calibrated in the presence of the same neutrino flux and the same backgrounds. This concept of a relative detector calibration will automatically account for detector systematics such as variations in the target mass. An extensive calibration program using passive and active sources as well as the neutron capture signal on Gd will allow us to determine critical parameters of the detector response such as attenuation lengths and absolute energy calibration before and after the move. Movable detectors and a comprehensive calibration program may provide the only guarantee that a change in the observed event rate in detectors at different baselines is due to neutrino oscillation and not due to systematics in the target mass, the determination of backgrounds, or the relative detector efficiencies.

3.2. *An Underground Neutrino Experiment at Braidwood*

Another US initiative focuses on the design of an underground laboratory at the Braidwood power plant in Illinois [6]. At Braidwood a two-core reactor complex provides a total average thermal power of about 6.5 GW_{th}. This proposal uses two vertical shafts for the placement of underground neutrino detectors at distances of 0.1-0.2 km and 1.5-1.8 km from the reactor complex. Underground halls at the bottom of these shafts allow the placement of two spherical detectors with diameters of up to 6 m. Cranes and surface transportation may allow the interchange of the detectors between the near and far detector sites. Construction methods and the local geology allow vertical shafts to be built with a depth of up to 120 m which provides < 450 mwe (meter-water-equivalent) of overburden for both the near and the far detector. The homogeneous geology and flat topography ensure that the flux of cosmic rays and cosmic-ray associated backgrounds will be the same at the near and far detector sites. The signal-to-background ratio, however, changes as the flux of reactor $\overline{\nu}_e$ falls off as $1/r^2$ with the distance of the reactor. With this design a sensitivity of $\sin^2 2\theta_{13} \leq 0.01 - 0.02$ at the 90% C.L. may be achievable. Other physics studies such as the measurement of $\sin^2 \theta_W$ may also become possible [7].

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

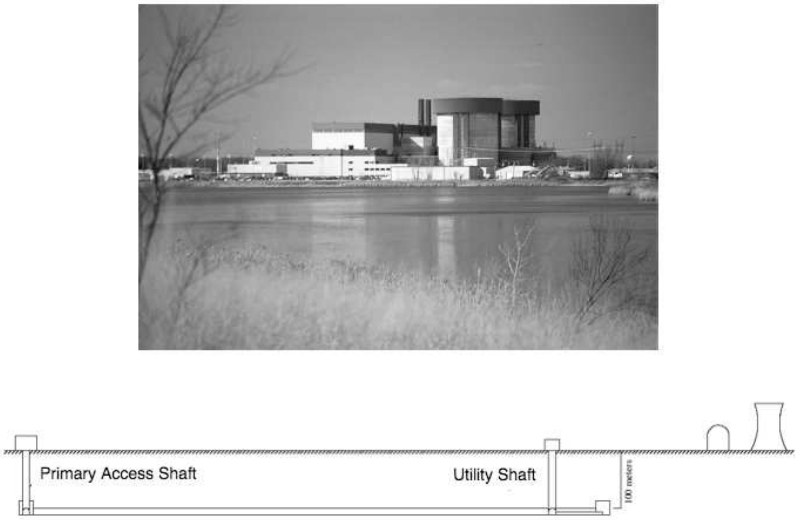

Figure 4. Proposal for an underground neutrino laboratory at the Braidwood nuclear power plant in Illinois using vertical access shafts.

CP violation in the lepton sector [8,9]. 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.

Acknowledgements

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