WHITE PAPER REPORT on Using Nuclear Reactors to Search for a value of θ_{13}

January 2004

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January 26, 2004

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Executive Summary

Purpose of this White Paper

There has been superb progress in understanding the neutrino sector of elementary particle physics in the past few years. It is now widely recognized that the possibility exists for a rich program of measuring CP violation and matter effects in future accelerator ν experiments, which has led to intense efforts to consider new programs at neutrino superbeams, off-axis detectors, neutrino factories and beta beams. However, the possibility of measuring CP violation can be fulfilled only if the value of the neutrino mixing parameter θ_{13} is such that $\sin^2(2\theta_{13})$ greater than or equal to on the order of 0.01. The authors of this white paper are an International Working Group of physicists who believe that a timely new experiment at a nuclear reactor sensitive to the neutrino mixing parameter θ_{13} in this range has a great opportunity for an exciting discovery, a non-zero value to θ_{13}. This would be a compelling next step of this program. We are studying possible new reactor experiments at a variety of sites around the world, and we have collaborated to prepare this document to advocate this idea and describe some of the issues that are involved.

Purpose of the Experiment

In the presently accepted paradigm to describe the neutrino sector, there are three mixing angles. One is measured by solar neutrinos and the KamLAND experiment, one by atmospheric neutrinos and the long-baseline accelerator projects. Both angles are large, unlike mixing angles among quarks. The third angle, θ_{13}, has not yet been measured to be nonzero but has been constrained to be small in comparison by the CHOOZ reactor neutrino experiment.

The basic feature of a new reactor experiment is to search for energy dependent $\bar{\nu}_e$ disappearance using two (or more) detectors, to see $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance. The detectors need to be located underground in order to reduce backgrounds from cosmic rays and cosmic ray induced spallation products. The detectors need to be designed identically in order to reduce systematic errors to 1% or less. Control of the relative detector efficiency, fiducial volume, and good energy calibration are needed.

A measurement of or stringent limit on θ_{13} would be crucial as part of a long term program to measure CP parameters at accelerators, even though a reactor $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance experiment does not measure any CP violating parameter. A sufficient value of θ_{13} measured in a reactor experiment would strongly motivate the investment required for a new round of accelerator ν experiments. A reactor experiment's unambiguous measurement of θ_{13} would also strongly support accelerator measurements by helping to resolve degeneracies and ambiguities. The combination of measurements from reactors and neutrino results from accelerators will allow early probes for CP violation without the necessity of long running at accelerators with anti-neutrino beams.

Anticipated Sensitivity

The best current limit on θ_{13} comes from the CHOOZ experiment and is a function of Δm^2_{atm}, which has been measured using atmospheric neutrinos by Super-Kamiokande and others. The latest reported value of Δm^2_{atm} from Super-Kamiokande is $1.2 < \Delta m^2_{atm} < 3.0 \times 10^{-3}\text{eV}^2$ with a best fit reported at 2.0. The CHOOZ limits for Δm^2_{atm} of 2.6 and $2.0 \times 10^{-3}\text{eV}^2$ are $\sin^2(2\theta_{13}) <$ 0.14 and 0.20. Global fits using the solar data limit the value for small Δm^2_{atm} to less than 0.12. In order to improve on the CHOOZ experiment, a new reactor experiment needs more statistics and better control of systematic errors. The relative sensitivity at low Δm^2_{atm} can be improved by locating the far detector further than 1 km. Increased statistics can be achieved by running longer, using a larger detector, and judicious choice of a nuclear reactor. The dominant systematic errors in an absolute measurement of the reactor neutrino flux, such as cross-sections, flux uncertainties, and the absolute target volume, will be largely eliminated in a relative measurement with two or multiple detectors. Good understanding of the relative detector response and the backgrounds is required for a precise relative measurement of the reactor neutrino flux and spectrum. Experiments are being considered which increase the luminosity from the CHOOZ value of 12 t GW y (ton-Gigawatt-years) to 400 t GW y or more. This will allow a mixing angle sensitivity of $\sin^2(2\theta_{13}) > 0.01$. For example, 400 t GW y would be obtained with a 10 (40) ton far detector, and a 14 (3.5) GW reactor in 3 years. One design consideration of the new experiment is the possibility for upgrades to achieve even greater luminosity and sensitivity. The ability to phase upgrades to achieve a luminosity of 8000 t GW y is being considered.

Major Challenges

A new reactor experiment will build on the experience of several previous reactor experiments, such as CHOOZ, Palo Verde and KamLAND (described in Section 4 of this white paper). These experiments had different goals, mostly being designed for signals due to large mixing. Important experience on calibration, control of systematic errors and the reduction of background has also been obtained by the Super-Kamiokande, SNO and Borexino collaborations.

A next-generation reactor experiment will be designed to make a precision measurement of the reactor electron anti-neutrino survival probability at different distances from the reactor and search for subdominant oscillation effects associated with the mass splitting of the m_1 and m_3 mass eigenstates. A measurement at the $\mathcal{O}(1\%)$ level will require careful control of possible systematic errors. Most of the technical requirements of this experiment are well understood but the details of the detector design still need to be optimized. Some of the open questions under consideration are the following: liquid scintillator loaded with 0.1% of gadolinium has been used in the past, but there are concerns regarding its stability in solution and possible attenuation length degradation which need to be fully understood. If movable detectors are chosen, there must be confidence that moving the detector does not introduce additional time-dependent effects. The use of a second detector will certainly help to control many systematic errors, but also will present a challenge in maintaining a known relative calibration over time. Another challenge is reduction of cosmic ray associated backgrounds such as neutrons and ^{9}Li spallation and their accurate estimation. The reduction of gamma ray background is also important because it will affect the ability to reduce the threshold to below 1 MeV. These and other design issues are discussed in Sections 5-8 of this white paper.

Experimental Prospects

The International Working Group has held two workshops (April 30-May 1, 2003 at the University of Alabama and October 9-11, 2003 at Technical University of Munich) and we are planning a third one (March 20-22, 2004 at Niigata University.) During the past year, the International Working Group has identified a large number of reactors as possible sites for a new experiment. Many of these sites are discussed in Section 9, and a few are described in more detail in seven Appendices. These include the Angra reactor in Brazil; the possibility of a new experiment at CHOOZ, called Double-CHOOZ (or CH$\theta_{13}\theta_{13}$Z); Daya Bay near Hong Kong in China, Diablo Canyon in California; a reactor in Illinois; the reactor complex at Kashiwazaki in Japan, and the Krasnoyarsk reactor underground at Zhelezhnogorsk in Russia.

It is not the role of this document to provide a cost estimate or schedule for any of the experiments which will be proposed. But it is appropriate to try to set the scale of the endeavor in order to compare to other kinds of initiatives in neutrino physics. A two-detector system as described in this document seems to cost in the range \$5M to \$15M. The civil construction costs to place these detectors underground will be very site dependent and require a detailed engineering cost estimate as described in Section 11. Estimates are in the range of several tens of millions of dollars, depending on site condition and tunnel length. Since reactors with an underground site already exist, such as those at CHOOZ and Krasnoyarsk, there is a strong incentive to consider those sites for the earliest experiment, though there may be physics trade-offs which must be considered. Some of the envisioned reactor experiments might start taking data in 2007-2008. First results could be achieved as early as 2009.

None of these efforts has yet resulted in a proposal to a funding agency, but site specific proposals and R&D proposals will be submitted during 2004. This white paper is a step in that direction. Given the importance of the measurement of θ_{13} and the enthusiasm of the proponents, we are hopeful that two or more of these experiments will move forward on a favorable time scale.