CHOOZ AND PERRY: NEW EXPERIMENTS FOR LONG BASELINE REACTOR NEUTRINO OSCILLATIONS

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Abstract

We discuss the Chooz experiment, a long baseline search for neutrino vacuum oscillations, which will utilize a gadolinium-loaded liquid scintillation detector one km from a large nuclear power station. The 300-mwe underground site of the detector reduces cosmic ray muons, the main source of background in this type of experiment, by a factor of 300, thereby allowing clean detection of antineutrinos from the reactor. The experimental goal is to probe \( \Delta m^2 \) values down to \( 1 \times 10^{-3} \text{eV}^2 \) for large values of \( \sin^2 2\theta \) and mixing angles to 0.08 for favorable regions of \( \Delta m^2 \). A subsequent experiment which will have a 13 km baseline at the former IMB site in Ohio and which can reach \( \Delta m^2 \geq 8 \times 10^{-5} \text{eV}^2 \) is also briefly described.

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1 Introduction

A central issue in particle physics, astrophysics and cosmology is the question of whether or not the rest masses of the neutrinos are exactly zero. In the minimal $SU(2)_L \otimes U(1)$ standard electroweak model, all neutrinos are massless and lepton number is exactly conserved. Despite longstanding success, however, the standard model is incomplete and inadequate, with many parameters left unspecified and a physically unreasonable global symmetry needed to enforce exact lepton number conservation.

The standard model, therefore, generally is agreed to need significant extensions. Although the nature of the necessary modifications is unclear, most proposed extensions of the standard model allow finite neutrino mass and many others require it. Experimental searches for neutrino mass are therefore important both to test the standard model and to guide theorists seeking a better model. Clear experimental evidence for finite neutrino mass would herald a new era of physics “beyond the standard model”.

Furthermore, if the neutrinos are experimentally proven to have mass, not only would there be deep implications for our theoretical ideas on particle physics and on the unification of forces, but also for our understanding of essential astrophysical phenomena such as the energy generating mechanism of the Sun, the final stages of stellar evolution, and the history of the Universe itself. Thus, the experimental search for finite neutrino mass could well provide the key to a rich domain of new phenomena.

We discuss here an incisive new experiment combining and extending proven methods of particle detection and background rejection to search with order-of-magnitude improved sensitivity for the phenomenon of neutrino oscillations. If discovered, such oscillations would provide clear proof of the existence of finite neutrino mass.

This area is ripe for a new and potentially definitive experiment, in that experimental hints for the existence of neutrino oscillations come from two distinct sets of observations: a long series of unexpectedly low results in measurements of the terrestrial flux of solar neutrinos; and the observation of an anomaly in the flux of cosmic-ray produced muon neutrinos observed by deep underground detectors. Achieving sensitivity to the neutrino mass scales indicated by these hints requires a new generation of long baseline neutrino oscillation experiments such as the Chooz experiment.
2 Reactor Neutrino Oscillation Experiments

Nuclear power reactors provide intense, well-understood sources of low energy $\nu_e$'s. Not only is the neutrino energy spectrum known to an accuracy of a few percent, but the neutrino flavor composition (pure $\nu_e$) and angular distribution (isotropic) of the reactor neutrino beam are known essentially perfectly, unlike accelerator neutrino beams. Thus, reactors provide nearly ideal sources for neutrino oscillation experiments.

Over the years, therefore, a number of neutrino oscillation searches have been performed. Table 1 compares some of these experiments, as well as three future experiments. The best existing limits from a reactor neutrino oscillation measurement come from an experiment at Gösgen in Switzerland which was 65 meters from the reactor and achieved a $\Delta m^2$ sensitivity approaching $\sim 10^{-2}$ eV$^2$ [1]. A more stringent limit in $\Delta m^2$ has been obtained recently by a Kurchatov Institute group [2], but the sensitivity in mixing was not as good ($\sin^2 2\theta \sim .50$).

The Gösgen experiment measured the $\nu_e$ spectrum at three distances up to 64.7 m from the reactor by using the inverse beta decay reaction $\nu_e + p \to e^+ + n$. The reactor had a thermal power of 2800 MW, while the detector provided a target mass of 320 kg and yielded a neutron detection efficiency of 21.7%. The results of the Gösgen experiment as well as several other reactor neutrino oscillation experiments are summarized on the exclusion plot shown in Fig. 1, where, for example, the area above and to the right of the curve labelled “Gösgen” is the region of the $\Delta m^2$ vs. $\sin^2 2\theta$ phase space where neutrino oscillations would have been detected had they been present. The minimum detectable $\Delta m^2$ for maximal mixing was $1.9 \times 10^{-2}$ eV$^2$.

3 Description of the Chooz Experiment

The Chooz experiment is a highly sensitive neutrino oscillation search using an underground facility near a nuclear power station in France. The experiment will look for the flux reduction and spectral distortion which would signal the existence of vacuum oscillations of the electron antineutrino beam emitted by the reactors. The limits on neutrino oscillations expected are shown in Fig. 1 by the curves labelled “Chooz”. For maximal mixing, the experiment will detect oscillations for values of $\Delta m^2 > 1 \times 10^{-3}$ eV$^2$, an
order-of-magnitude improvement over currently available limits. The experiment will also provide an excellent testing ground for methodology for the future Perry experiment (see Table 1 and ref. [3]). An overview of the Chooz experiment is shown in Fig. 2.

4 Neutrino Source and Site

The neutrino source is a pair of reactors at the Chooz B nuclear power station in the Ardennes region of northeastern France. Each of the PWR reactors will have a thermal power of 4.2 GW and is scheduled for startup by the end of 1995. An essential feature of the experimental site is the availability of a tunnel with an overburden of 115 m of rock, equivalent to 300 m of water. Building the neutrino detector in this tunnel will provide the cosmic-ray shielding needed to preserve the signal/noise ratio against a one hundred-fold neutrino flux reduction with respect to previous experiments. The advantages of such a site are made clear in Fig. 3.

5 The Detector

The neutrino detector is shown in Fig. 4, while its principal design parameters are exhibited in Table 2. The neutrino target will be contained in a 5.5-m-diameter cylindrical steel tank shielded locally by about 75 cm of low radioactivity material. The tank will contain three concentric liquid scintillation detectors: an outer 90-ton veto counter; an intermediate 17-ton optically separated event containment detector; and a central acrylic vessel containing five tons of a specially developed gadolinium-loaded liquid scintillator. The outer two vessels will contain a high flash point pure hydrocarbon scintillator also specially developed at Drexel for this experiment.

Scintillation photons from particle interactions in the two inner detectors will be collected by 160 eight-inch photomultiplier tubes and processed by fast multi-hit TDC’s and fast waveform digitizers. The detector will have good energy resolution, with about 76 photoelectrons detected per MeV of ionization energy deposited. Scintillation light from the veto counter will be collected by an additional 40 PMT’s.

Primary shielding against background will be provided by the 300 mwe-
thick rock overburden, which will reduce the surface cosmic ray muon flux by a factor of 300, as shown in Fig. 3. The residual cosmic ray background is further suppressed by the 90-ton outer veto counter, which also provides additional shielding against ambient radioactivity.

Neutrinos above the threshold energy of 1.8 MeV will be detected by the reaction $\nu_e + p \rightarrow e^+ + n$. The observable energy from this reaction will equal the positron kinetic energy augmented by 1.022 MeV resulting from detection of the positron annihilation gamma rays. Following thermalization of the recoil neutron, an additional 8 MeV will be detected as a result of capture of the neutron by a gadolinium nucleus (time constant 28 µs). Thus, a readily recognizable delayed coincidence pulse pair will signal the neutrino interaction. The 8-MeV neutron capture event will be well separated from the beta and gamma radiation accompanying decay of members of the ubiquitous uranium and thorium decay chains and from the decay of $^{40}$K. Further significant rejection of the accidental coincidence background will be possible by software reconstruction of the positron and neutron capture vertices.

With an expected event rate of about $31 \text{ d}^{-1}$ (see Table 3), we anticipate a total running time of two years will be adequate to achieve our goal of a statistical error better than 4%. Neutrino oscillations would be uncovered by comparing the observed integral count rate with an accurately calibrated detector-efficiency Monte Carlo calculation. Information on reactor power and fuel burn-up will be available from the power station. The neutrino flux per unit power will be determined from calculations which currently are reliable to about 2%, especially at low energy, where a neutrino oscillation signal would probably be strongest. In the event of a positive signal, it would be useful to construct a close-in detector to provide a flux independent confirmation. A detector site at less than 100 m from the reactors is available if needed.

For the experiment, about five tons of Gd-loaded scintillator and 107 tons of high flash point hydrocarbon scintillator will be needed. Optimized formulations for each of these materials were developed after extensive testing at Drexel University. We thus have high performance detection media for the experiment at minimal cost. The properties of the two scintillators are listed in Table 4. Fig. 5 shows a measurement of the neutron capture time spectrum for the Gd-loaded scintillator. Similar measurements over more than a one year period show no changes in the mean capture lifetime, indicating good long-term stability of the material.
6 Conclusions and Outlook

The availability of a site near a reactor yet well-shielded from cosmic rays provides a new opportunity to extend the search for neutrino oscillations by an order of magnitude. The Chooz experiment described here will cover the region of parameter space hinted at by the anomalous atmospheric neutrino results. The experiment can be running by mid-1995, with preliminary results in hand before the end of 1996.

Extension of sensitivity by an additional order of magnitude in $\Delta m^2$ will be possible in a future experiment at the Perry reactor using the deep underground site of the former IMB experiment [3]. Many of the methods and measurements of the Chooz experiment will be directly applicable to Perry. The Perry experiment would have a fiducial volume of one kiloton and a count rate of $12 \text{ d}^{-1}$.

References

[1] G. Zacek et al., Neutrino Oscillation Experiments at the Gösgen Nuclear Power Reactor, Phys. Rev. D34 (1986) 2621.

[2] G.S. Vidyakin et al., Jour. Moscow Phys. Soc. 1 (1991) 85.

[3] R. Steinberg et al., PERRY: A Reactor Neutrino Oscillation Experiment Sensitive to $\Delta m^2 = 10^{-4} \text{ eV}^2$, in DPF92, to be published.
| EXPERIMENT   | NEUTRINO TARGET MASS | REACTOR DISTANCE (max.) | \(\Delta m^2\) (90% c.l.) |
|-------------|----------------------|-------------------------|--------------------------|
| Grenoble    | 320 kg               | 8.75 m                  | .15                      |
| Savannah River | 260 kg             | 24 m                    | .05                      |
| Gösgen      | 320 kg               | 65 m                    | .019                     |
| Krasnoyarsk | 600 kg               | 92 m                    | .014*                    |
| Rovno       | 200 kg               | 25 m                    | .06                      |
| Krasnoyarsk | 600 kg               | 230 m                   | .01                      |
| Bugey III   | 1200 kg              | 40 m                    | in progress              |
| San Onofre  | 12000 kg             | 680 m                   | \(2 \times 10^{-3}\)     |
| Chooz       | 4800 kg              | 1025 m                  | \(1 \times 10^{-3}\)     |
| Perry       | 1000 ton             | 12.9 km                 | \(1 \times 10^{-4}\)     |

Table 1: Summary of reactor neutrino oscillation experiments.

Table 2: Design parameters of the detector.
Table 3: Calculation of the neutrino event rate.
|                         | Gadolinium                      | High Flash                      |
|-------------------------|---------------------------------|---------------------------------|
| Chemical content:       |                                 |                                 |
| mineral oil             | 59.5%                           | 96.8%                           |
| aromatics and alcohols  | 40%                             | 3%                              |
| PPO, bis-MSB, etc.      | 0.4%                            | 0.2%                            |
| Gd                      | 0.1%                            | -                               |
| Compatibility           | acrylic, ABS, PVC, CF4          | acrylic, ABS, PVC, CF4          |
| Density (25°C)          | 0.869 gm cm⁻³                   | 0.854 gm cm⁻³                   |
| Volume expansion coeff. | 7.9 × 10⁻⁴K⁻¹                   | 7.4 × 10⁻⁴K⁻¹                   |
| H/C ratio               | 1.93                            | 2.07                            |
| Scintillation yield     | 42% of anthracene               | 42% of anthracene               |
| -or- 162 eV/photon      |                                 |                                 |
| Optical attenuation length | 8 m                      | 20 m                            |
| Refractive index (20°C) | 1.480±.002                      | 1.473±.002                      |
| Flash point             | 69 °C                           | 110 °C                          |
| Atomic composition:     |                                 |                                 |
| H                       | 7.00 × 10²² atoms cm⁻³          | 7.57 × 10²² atoms cm⁻³          |
| C                       | 3.62 × 10²² atoms cm⁻³          | 3.65 × 10²² atoms cm⁻³          |
| N                       | 1.41 × 10¹⁹ atoms cm⁻³          | 4.01 × 10¹⁸ atoms cm⁻³          |
| O                       | 1.08 × 10²¹ atoms cm⁻³          | 4.01 × 10¹⁸ atoms cm⁻³          |
| Gd                      | 3.33 × 10¹⁸ atoms cm⁻³          | -                               |
| Neutron capture time    | 28 µs                           | 180 µs                          |
| Gd capture fraction     | 87%                             | -                               |
| Thermal n mean capture path | 6 cm                         | 40 cm                           |

Table 4: Properties of the liquid scintillators developed at Drexel for use in the experiment.
Figure 1: Reactor neutrino oscillation limits showing 90% c.l. exclusion contours. The Chooz experiment will extend existing results by more than one order of magnitude in $\Delta m^2$. The future Perry experiment would allow an additional ten-fold sensitivity improvement.
Figure 2: Overview of the experiment. Detection of the weak neutrino signal at 1 km is made possible by the 300 meter of water equivalent shielding above the detector, which attenuates the otherwise overwhelming cosmic ray muon-induced background by a factor of 300 and by the layered design of the detector and its local shielding. The high detection efficiency for antineutrino events (more than 80%) further enhances the expected signal-to-background ratio and facilitates accurate determination of the detector efficiency, needed for accurate comparison of the measured and expected neutrino fluxes.
Figure 3: Muon depth vs. intensity and neutrino flux at various sites. At Chooz (and to a somewhat lesser extent at Perry/IMB) the low neutrino fluxes available for long baseline oscillation experiments are compensated by comparably reduced muon fluxes. Since cosmic ray muons produce the most serious backgrounds in these experiments, shallow sites such as that at San Onofre are at a serious disadvantage.
Figure 4: The Chooz detector. The neutrino target contains 4.9 tons of gadolinium-loaded liquid scintillator in which the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ takes place. The positrons and their annihilation photons are detected at zero time delay, while the neutron is detected typically between 10 and 100 $\mu$s later following thermalization and capture by a gadolinium nucleus, leading to the release of a total of about 8 MeV of $\gamma$ rays. A 300 meter of water equivalent underground location and massive gravel, steel and liquid scintillator shielding suppress the background to a few counts per day, about 10 times lower than the anticipated neutrino event rate.
Figure 5: Neutron capture time delay spectrum with a 0.12% Gd-loaded scintillator. Thermal neutron capture events produce the exponentially decaying part of the curve. A mean capture lifetime of 22.5 $\mu$s is obtained by fitting an exponential plus constant term to this region. For the Chooz scintillator, a Gd concentration of 0.1% thus will yield a capture lifetime of about 27 $\mu$s. The prompt peak, indicated by the arrow, has been shifted by delaying the signal from the neutron channel. Prompt coincidences are caused both by cosmic ray showers and by scattered gamma rays from the Cm/Be neutron source.