Neutrino Oscillations at Reactors: What Is Next?*

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Abstract—We briefly review previous and future reactor experiments aimed at searches for neutrino masses and mixing. We also consider the new idea to seek small mixing-angle oscillations in the atmospheric-neutrino-mass-parameter region at Krasnoyarsk. © 2000 MAIK “Nauka/Interperiodica”.

1. INTRODUCTION

The first long-baseline reactor experiment CHOOZ’97 [1] successfully reached the atmospheric-neutrino-mass-parameter region \( \delta m^2_{\text{atm}} \sim 10^{-3} \text{ eV}^2 \) and tested there a large portion of the area of interest in the \( \delta m^2 - \sin^2 2 \theta \) plane. No evidence for oscillations has been found. Thus, oscillations of electron neutrinos cannot dominate in the atmospheric-neutrino anomaly.

The Super-Kamiokande data on atmospheric neutrinos provide strong evidence for intensive \( v_e, v_{\mu}, v_{\tau} \) transitions [2]. In the three-active-neutrino \( (v_e, v_{\mu}, v_{\tau}) \) oscillation model considered here, we have \( v_{\tau} = v_e \).

We wish to emphasize, however, that both experiments, CHOOZ’97 and SuperKamiokande, do not rule out \( v_e \leftrightarrow v_{\mu} \) oscillations as a subdominant mode in the \( \delta m^2_{\text{atm}} \) region [3, 4].

The results of recent experiments have attracted much attention to the problem of neutrino oscillations. New physical ideas and projects of new large-scale experiments at accelerators are being vigorously discussed [4].

What new contributions can be made with reactor electron antineutrinos for exploring the problems of the electron-neutrino mass and mixing?

One line of future studies has already been announced. To probe the large-mixing-angle (LMA) MSW solution \( (\delta m^2_{\text{sol}} = 10^{-4} - 10^{-5} \text{ eV}^2, \sin^2 2 \theta \sim 0.7) \) [5] of the solar-neutrino puzzle, the projects KamLAND at Kamioka [6] and BOREXINO at Gran Sasso [7] plan to detect neutrinos from reactors operating hundred kilometers away from the detector sites.

In this article, we consider another possibility. We find that, with two-detector techniques, the sensitivity to the mixing parameter in the \( \delta m^2_{\text{atm}} \) region can be substantially increased in relation that achieved in CHOOZ. We propose a new study of the problem at the Krasnoyarsk underground (600 mwe) laboratory with detectors situated 1100 and 250 m from the reactor. The main goals of the proposed experiment are (1) to obtain deeper insight into the role of the electron neutrino in the atmospheric neutrino anomaly, (2) to obtain new information about neutrino mixing (the \( U_{e3} \) element of the neutrino mixing matrix can be measured), and (3) to ensure normalization for future long-baseline experiments at accelerators.

2. OSCILLATIONS OF REACTOR ANTINEUTRINOS

A nuclear reactor generates antineutrinos at a rate of \( N_{\bar{\nu}} \sim 1.8 \times 10^{20} \text{ s}^{-1} \) per 1 GW of thermal power. A typical reactor-\( \bar{\nu}_e \) energy spectrum normalized to one fission event is presented in Fig. 1.

These electron antineutrinos are detected via the inverse beta-decay reaction

\[
\bar{\nu}_e + p \rightarrow e^+ + n. \tag{1}
\]

The positron kinetic energy \( T \) is related to the electron-antineutrino energy \( E \) as

\[
T = E - 1.804 \text{ MeV}. \tag{1a}
\]

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The signature of electron-antineutrino absorption in a liquid-scintillator target is a spatially correlated delayed coincidence of the prompt positron and the signal from the neutron-capture gamma rays.

The probability \( P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \) for \( \bar{\nu}_e \) to survive at a distance \( R \) (m) from the source is given by the expression

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \left( 1.27 \frac{d\delta m^2}{E} R \right),
\]

where \( E(\text{MeV}) \) is the neutrino energy, \( \delta m^2 \) is the mass parameter in \( \text{eV}^2 \), and \( \sin^2 2\theta \) is the mixing parameter. The distortion of the positron energy spectrum and the deficit of the total electron-antineutrino-detection rate relative to the no-oscillation case are signatures for oscillations that are sought experimentally. The deficit of the total rate is the strongest for \( (R\delta m^2)_{\text{max}} \approx 5\text{ m eV}^2 \).

In pressurized water reactors (PWR), the electron-antineutrino spectrum and the total cross section for reaction (1) vary with the nuclear-fuel composition, (the burnup effect). The current fuel composition is provided by reactor services. When the fuel composition is known, the no-oscillation cross section \( \sigma_{\nu_e-A} \) can be calculated within the uncertainty of 2.7\%. (For more information see, for example, [8] and references therein.) With the aid of an integral-type detector, the CDF–KURCHATOV–LAPP group measured accurately the cross section at a distance of 15 m from the Bugey-5 reactor [9]:

\[
\sigma_{\text{expt}} = 5.750 \times 10^{-43} \text{ cm}^2/\text{fission} \pm 1.4\%.
\]

This highly accurate value \( \sigma_{\text{expt}} \) can be used in other experiments with reactor antineutrinos as a no-oscillation metrological reference. When it is used in practice, one must consider the differences in the fuel compositions and take into account the number of “small effects.” This increases the error up to about 2\%.

3. PAST, CURRENT, AND FUTURE EXPERIMENTS

Intensive searches for neutrino oscillations with detectors located at distances from reactors in the range between about 10 and 230 m were performed from 1980 to 1995. These “short-baseline” experiments are listed in Fig. 2 (left panel). The highest sensitivity to the mixing parameter \( (\sin^2 2\theta = 0.02) \) was achieved by the Bugey-3 group in the measurements with two identical detectors located at distances of 15 and 40 m from the reactor [9] (Fig. 3).

The CHOOZ detector used a 5-t liquid scintillator (Gd) target. It was located in an underground laboratory (300 mwe) at a distance of about 1 km from the neutrino source. The ratio \( R \) of the measured neutrino-detection rate to that expected in the no-oscillation case was (November 1997)

\[
R = 0.98 + 0.04(\text{stat.}) + 0.04(\text{syst.}).
\]

The systematic errors come mainly from the reactor properties and the absolute values of neutrino-detection efficiencies. The 90\% C.L. exclusion plot CHOOZ’97 for \( \bar{\nu}_e \) disappearance channel is presented in Fig. 3, along with the allowed \( \bar{\nu}_\mu \rightarrow \nu_e \) oscillation channel SK’73d [2] (shaded area). The experiment was contin-