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Experimental conditions for determination of the neutrino mass hierarchy with reactor antineutrinos

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Abstract

This article reports the optimized experimental requirements to determine neutrino mass hierarchy using electron antineutrinos ($\bar{\nu}_e$) generated in a nuclear reactor. The features of the neutrino mass hierarchy can be extracted from the $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$ oscillations by applying the Fourier sine and cosine transforms to the L/E spectrum. To determine the neutrino mass hierarchy above 90% probability, the requirements on the energy resolution as a function of the baseline are studied at $\sin^2 2\theta_{13} = 0.1$. If the energy resolution of the neutrino detector is less than $0.04/\sqrt{E_\nu}$ and the determination probability obtained from Bayes' theorem is above 90%, the detector needs to be located around 48–53 km from the reactor(s) to measure the energy spectrum of $\bar{\nu}_e$. These results will be helpful for setting up an experiment to determine the neutrino mass hierarchy, which is an important problem in neutrino physics.

1. Introduction

Since the measurement of the large $\sin^2 2\theta_{13}$ at RENO, Daya Bay, and Double Chooz, the precise measurement of neutrino mass hierarchy, the sign of Δm^2_{32}, has become the focus in neutrino physics [1–3]. It had been believed that the neutrino mass hierarchy can be determined through long-baseline experiments, mainly using accelerator neutrino beams. Recently, the ca-

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pability of a reactor neutrino experiment at an intermediate baseline to distinguish normal or inverted hierarchy was reported.

For an intermediate-baseline neutrino experiment, many approaches have been proposed; they can be categorized into the χ^2 analysis methods, which are discussed in Refs. [4–8], and the Fourier-transform methods [5,9,10]. The χ^2 analysis methods based on the newly adopted Bayesian approach utilize all the available information from experiments, and it is straightforward to incorporate the uncertainties in order to evaluate the sensitivity, providing robust and complementary results in the Fourier-transform methods [11]. Although the χ^2 analysis methods are attractive and interesting, the Fourier-transform methods are more intuitive. The prominent merit of the Fourier-transform methods is that the mass hierarchy can be extracted without precise knowledge of the reactor antineutrino spectrum, the absolute value of the large $|\Delta m^2_{31}|$, and the energy scale of a detector. The Fourier-transform methods were introduced to enhance and visualize the structures of mass hierarchy in the frequency spectrum, as first discussed in Ref. [12].

In principle, the mass hierarchy can be determined through precise measurements of $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$. As $|\Delta m^2_{21}|$ is very small and is only ~ 3 % of $|\Delta m^2_{31}|$, we have to measure $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$ with a precision much better than 3%. However, $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$ have been measured in many experiments with only $\gg 3\%$ precision [13].

The intermediate baseline based on reactor neutrino experiments has been explored using the precise measurement of distortions of the energy spectrum with negligible matter effect. Learned et al. proposed a new method to distinguish normal and inverse hierarchy after a Fourier transform of the L/E spectrum of reactor neutrinos [12]. They pointed out that the Fourier power spectrum has a small but not negligible shoulder next to the main peak, and its relative position could be used to extract the mass hierarchy while a non-zero θ_{13} is considered.

In this paper, we analyze the sensitivity of medium-baseline reactor antineutrino experiments to the neutrino mass hierarchy for a baseline range of 30–60 km and overall energy resolution, $\delta E/\sqrt{E_\nu}$, in the range of 0 to $0.08/\sqrt{E_\nu}$ with the Fourier-transform method. The optimal baseline length is estimated based on the expected probability of determination.

2. Detection of reactor antineutrino

In a nuclear reactor, antineutrinos are mainly produced via the β-decay of the fission products of the four types of radioactive isotopes, ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu, in the fuel. The antineutrino flux having energy E_ν in MeV with thermal power P_{th} in GW$_{th}$ is given as

$$\frac{dN}{dE_\nu} = \frac{P_{th}}{\sum_k f_k \epsilon_k}\phi(E_\nu) \times 6.24 \times 10^{21}, \tag{1}$$

where f_k and ϵ_k are the relative fission contribution and the energy released per fission of isotope k, respectively. Further, $\phi(E_\nu)$ is the number of antineutrinos produced per fission and is obtained as follows [14,16]:

$$\begin{aligned}\phi(E_\nu) = {} & f_{^{235}\mathrm{U}} e^{0.870-0.160E_\nu-0.091E_\nu^2} \\ & + f_{^{239}\mathrm{Pu}} e^{0.896-0.239E_\nu-0.0981E_\nu^2} \\ & + f_{^{238}\mathrm{U}} e^{0.976-0.162E_\nu-0.0790E_\nu^2} \\ & + f_{^{241}\mathrm{Pu}} e^{0.793-0.080E_\nu-0.1085E_\nu^2}.\end{aligned} \tag{2}$$