Fast Neutrino Oscillation in Short Baseline Reactor Antineutrino Experiments

Быстрые осцилляции нейтрино в реакторных экспериментах с короткой осцилляционной базой

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Атомные электростанции активно используются для изучения свойств нейтрино благодаря интенсивному потоку частиц, что позволяет накапливать значительную статистику. В экспериментах на короткой осцилляционной базе, где расстояние между реактором и детектором составляет меньше 100 м, важно учитывать размытие пройденного расстояния, чтобы избежать переоценки чувствительности детектора к нейтринным осцилляциям.

В данной работе представлены результаты учета размытия для осцилляционной базы в 15 м и проведено сравнение с точечной моделью.

Nuclear power plants are actively used to study the properties of neutrinos due to the intense $\overline{\nu}_e$ flux, which makes possible to accumulate significant statistics. In short baseline experiments, where the distance between the reactor and the detector is less than 100 meters, it is important to take into account the smearing of the oscillation base to avoid overestimating of sensitivity to fast neutrino oscillations.

This work presents the results of accounting for this smearing for a 15 m oscillation baseline and compares them with a point-like model.

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Introduction

Properties of neutrino have been studied for the last half-century. The discovery of neutrino oscillation confirmed the fact that neutrinos have mass.

Nuclear power plants (NPPs) are ideal artificial source of antineutrinos. Intensity of these sources is $2 \cdot 10^{20}$ $\overline{\nu}_e$/sec/GW. Also, energies of reactor antineutrinos are below 12 MeV, making it possible to detect $\overline{\nu}_e$ via the inverse beta decay ($p + \overline{\nu}_e \rightarrow e^+ + p$). NPPs are used to measure oscillation parameters of survival probability of $\overline{\nu}_e$. The oscillation baseline, distance

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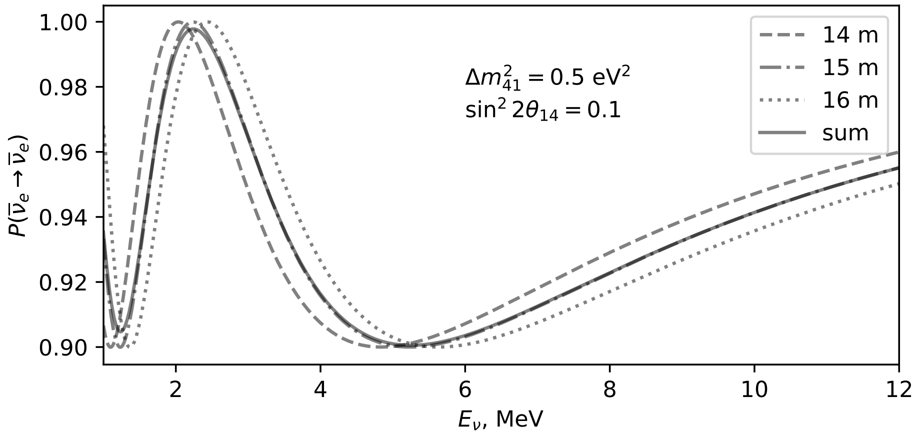

Fig. 1. Survival probability of electron antineutrino for distances: 14 m (gray dashed dotted line), 15 m (gray dashed line), and 16 m (gray dotted line). Weighted sum of survival probability is shown (black solid line).

between reactor and detector, varies from several kilomiters to hundreds of kilomiters for three-flavor oscillation experiments. At the same time, the short baseline reactor experiments (baseline ~ 100 m) can be used for precise measurements of the $\overline{\nu}_e$ spectra of nuclear fuel.

First measurements of the $\overline{\nu}_e$ spectra were provided in 1980th. Measured spectra was used in several experiments to predict number of $\overline{\nu}_e$, but they have observed deficit of $\overline{\nu}_e$ events. This deficit is known as the reactor antineutrino anomaly [1]. Historically, the first explanation of RAA was given in the terms of sterile neutrinos. Sterile neutrinos interact gravitationally only and can mix with active neutrinos.

Nowadays, the significance of the RAA decreases with updated measerements of $\overline{\nu}_e$ spectra, but sterile neutrinos make sense as a search for the physics beyond the Standard Model.

Neutrino oscillation

Usually, neutrino oscillation is described within the 3ν oscillation framework. In the case of short baseline experiments, it is possible to use the 2ν approximation. The following formula is used to describe the survival probability of electron antineutrinos in the case of fast oscillation

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \frac{1}{4}\sin^2 2\theta_{14} \sin^2\left(\frac{\Delta m^2_{41}}{4E_\nu}L\right), \qquad (1)$$

where θ_{14} is a mixing angle between the first and forth massive states, Δm^2_{41} is the difference of squared masses, E_ν is the energy of neutrino, L is the distance traveled by antineutrino between the birth and detection points. The typical oscillation over the energy of neutrino is shown in figure 1.

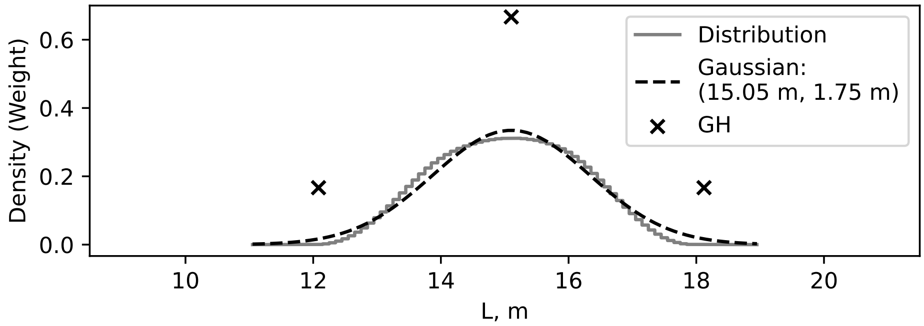

Fig. 2. Distribution of distances between reactor and detector (gray solid line) and fit by the Gaussian distribution (black dashed line). Weights of Guassian-Hermitian (GH) are demonstrated (black crosses). The distance between geometrical centers of detector and reactor is 15 m.

Experimental setup

A toy model of the short baseline experiment was used to study fast oscillation. The sizes and power of the reactor are taken from typical commercial version. The reactor is cylinder with height of 4 m and radius of 2 m, the thermal power is 3 GW. Nuclear fuel is uniformly distributed in the volume of the reactor. The spectrum of $\overline{\nu}_e$ is formed from spectra of isotopes with the following fission fractions: ^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu $\sim 0.58 : 0.08 : 0.29 : 0.05$.

The detector is sphere with a radius of 1 m, filled with liquid scintillator. It contains $2.7 \cdot 10^{29}$ protons. The energy resolution of detector is 16.5% for 1 MeV. The response of the detector takes into account only energy resolution. However, in the real experiment, it is crucial to concider the non-linearity of liquid scintillator.

The oscillation baseline is equal to 15 m. The effective time of collecting events is 36.4 days. The total number of observed $\overline{\nu}_e$ events is $1.7 \cdot 10^6$ events under assumption of no oscillation effect.

Distribution

To determine the smearing of oscillation baseline, the following Monte-Carlo experiment was conducted. The point of birth is uniformly randomized in the cylindrical volume of the reactor. The point of detection is uniformly randomized within the spherical volume of the detector. Finally, the position of the detection point is additionally randomized within a „resolution“ sphere with radius of 10 cm. The previous steps are repeated 10^8 times. The distribution of distances is obtained and fitted with a Gaussian-like function.

To account for the smearing of oscillation baseline, the distribution is divided into 6 points and integrated using Gaussian-Hermite quadrature. The distribution of distances and its fit are illustrated in the figure 2. Non point sizes of reactor and detector lead to oscillation baseline smearing. Baseline smearing causes supression of observed oscillation. If smearing is not accounted in analysis, it may cause missfitting of observation. Effect of suppressed oscillation is illustrated in the figure 1.

Analysis

The toy experiment is modeled using the following function

$$N_k^{\mathrm{IBD}} = N^{\mathrm{global}} C_{kj} \frac{N_p}{4\pi L^2} \int\limits_{-1}^{1} d\cos\theta \int_{E_j}^{E_{j+1}} dE_\nu \frac{d\sigma(E_\nu, \cos\theta)}{d\cos\theta} \int_{x_0}^{x_1} dx f(x) P(E_\nu, x) \frac{W_{\mathrm{th}}}{\sum\limits_i f_i E_i} \sum_i f_i S_i(E_\nu), \qquad (2)$$

where N^{global} is a scale factor, N_p is a number of target protons, L is the distance between the centers of reactor and detector, C_{ij} is an element of the resolution matrix, $f(x)$ is a distribution of the traveled distance by $\overline{\nu}_e$, W_{th} is a thermal power of the reactor, f_i is the fission fraction of isotope i, E_i is the fission energy of isotope i, S_i is a spectrum of $\overline{\nu}_e$. x_0 and x_1 denote the minimum and maximum traveled distance by $\overline{\nu}_e$.

The analysis of sensitivity is obtained through Gaussian approximation of CL_s [2]. The analysis operates with the following χ^2

$$\chi^2(\mu, \mathbf{d}, N^{\mathrm{global}}) = (\mu - \mathbf{d})(V^d_{\mathrm{stat}} + V^d_{\mathrm{syst}})^{-1}(\mu - \mathbf{d}), \qquad (3)$$

where μ is a vector of modeled IBD events, $\mathbf{d}$ is a vector of observed data. The matrices V^d_{stat} and V^d_{syst} represent statistical and systematic uncertainties, respectively.

The sensitivity of the toy experiment is demonstrated in figure 3. It is sensitive to the parameters of sterile neutrino in the region $10^{-2}\ \mathrm{eV}^2 \lesssim \Delta m^2_{41} \lesssim 10\ \mathrm{eV}^2$ over two orders of sterile amplitude $\sin^2 2\theta_{14}$. Further accumulation of data will expand sensitivity to lower values of the amplitude $\sin^2 2\theta_{14}$. However, taking into account the smearing of the oscillation baseline decreases the sensitivity in the area of large sterile mass splitting.

Conclusion

Hypothetical sterile neutrinos are arises with $\Delta m^2_{41} \sim 7\ \mathrm{eV}^2$ [3]. Commercial reactors are very large but this fact does not significantly change sensitivity. The presence of baseline smearing can diminish sensitivity, especially in regions of large sterile mass splitting.

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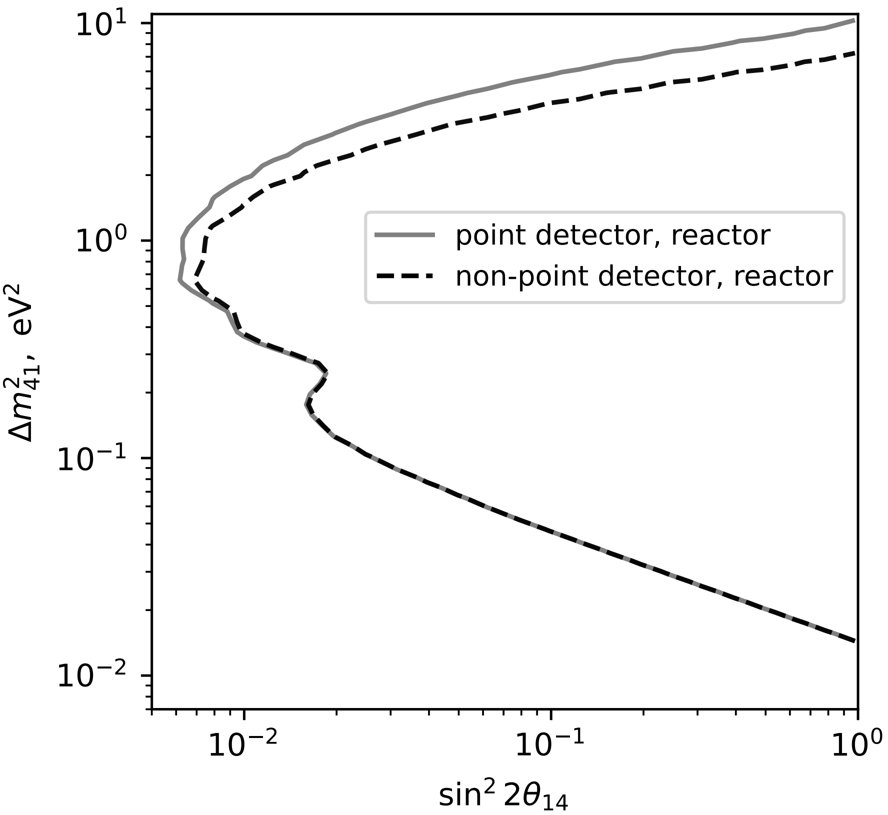

Fig. 3. Sensitivity of the toy experiment. The sensitivity of the point (gray solid line) and continuous (black dashed line) detectors and reactors are shown.

REFERENCES

1. *Mention G., Fechner M., Lasserre T., Mueller T.A., Lhuillier D., Cribier M., Letourneau A.* Reactor antineutrino anomaly // Physical Review D. — 2011. — . — V. 83, no. 7. — URL: http://dx.doi.org/10.1103/PhysRevD.83.073006.

2. *Qian X., Tan A., Ling J., Nakajima Y., Zhang C.* The Gaussian CL method for searches of new physics // Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. — 2016. — 8. — V. 827. — P. 63–78. — URL: http://dx.doi.org/10.1016/j.nima.2016.04.089.

3. *Serebrov A.P., Samoilov R.M., Chaikovskii M.E., Zherebtsov O.M.* Result of the Neutrino-4 Experiment and the Cosmological Constraints on the Sterile Neutrino (Brief Review) // JETP Letters. — 2022. — . — V. 116, no. 10. — P. 669–682. — URL: http://dx.doi.org/10.1134/S002136402260224X.