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Effect of the reactor antineutrino anomaly on the first Double-Chooz results

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We investigate the possible effects of short-baseline $\bar{\nu}_e$ disappearance implied by the reactor antineutrino anomaly on the Double-Chooz determination of ϑ_{13} through the normalization of the initial antineutrino flux with the Bugey-4 measurement. We show that the effects are negligible and the value of ϑ_{13} obtained by the Double-Chooz collaboration is accurate only if $\Delta m^2_{41} \gtrsim 3\ \mathrm{eV}^2$. For smaller values of Δm^2_{41} the short-baseline oscillations are not fully averaged at Bugey-4 and the uncertainties due to the reactor antineutrino anomaly can be of the same order of magnitude of the intrinsic Double-Chooz uncertainties.

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The first results [1] of the Double-Chooz experiment [2] led to the following result for the amplitude of long-baseline $\bar{\nu}_e$ disappearance:

$$\sin^2 2\vartheta_{13}^{\mathrm{DC}} = 0.085 \pm 0.029 \pm 0.042. \tag{1}$$

This amplitude enters in the effective long-baseline (LBL) survival probability of $\bar{\nu}_e$ in the case of three-neutrino mixing (see Ref. [3]),

$$P^{\mathrm{DC}}_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\vartheta_{13}^{\mathrm{DC}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right), \tag{2}$$

which has been assumed in the analysis of the data by the Double-Chooz collaboration [1]. Here we adopt the standard parameterization of the mixing matrix, with $|U_{e3}| = \sin\vartheta_{13}$.

An essential ingredient in the extraction of the value of $\sin^2 2\vartheta_{13}^{\mathrm{DC}}$ from the data is the normalization of the initial flux prediction on the value measured by the Bugey-4 experiment [4], since the first results of the Double-Chooz experiment have been obtained with the far detector only [1]. This normalization is important because the recent recalculations of the reactor $\bar{\nu}_e$ flux [5,6] indicate a value which is larger than that measured by Bugey-4 and other short-baseline reactor antineutrino experiments, leading to the reactor antineutrino anomaly [7]. The ratio of observed and theoretically predicted $\bar{\nu}_e$ flux for the Bugey-4 experiment is [7]

$$\frac{\phi^{\mathrm{obs}}_{\text{Bugey-4}}}{\phi^{\mathrm{the}}_{\text{Bugey-4}}} = 0.942 \pm 0.042, \tag{3}$$

and the average ratio of observed and theoretically predicted $\bar{\nu}_e$ fluxes in short-baseline reactor antineutrino experiments is [8]

$$\frac{\phi^{\mathrm{obs}}_{\mathrm{SBL}}}{\phi^{\mathrm{the}}_{\mathrm{SBL}}} = 0.946 \pm 0.024, \tag{4}$$

which is a 2.2σ effect. Several experiments which could check the reactor antineutrino anomaly have been proposed and some are already under preparation [9–18].

In this letter we investigate if the short-baseline $\bar{\nu}_e$ disappearance implied by the reactor antineutrino anomaly has an effect in the determination of ϑ_{13}, in spite of the normalization of the initial antineutrino flux with the Bugey-4 measurement.

In general, the $\bar{\nu}_e$ flux measured in the Double-Chooz far detector is given by

$$\phi^{\mathrm{LBL}}_{\bar{\nu}_e} = \phi^0_{\bar{\nu}_e} P^{\mathrm{LBL}}_{\bar{\nu}_e\to\bar{\nu}_e}, \tag{5}$$

where $\phi^0_{\bar{\nu}_e}$ is the $\bar{\nu}_e$ flux produced by the reactor and $P^{\mathrm{LBL}}_{\bar{\nu}_e\to\bar{\nu}_e}$ is the effective LBL $\bar{\nu}_e$ survival probability.

In the simplest framework of 3 + 1 neutrino mixing, which can accommodate short-baseline neutrino oscillations together with the well-established atmospheric (long-baseline) and solar neutrino oscillations (see the recent Refs. [8,19–23], and references therein), the effective long-baseline $\bar{\nu}_e$ survival probability is given by [24]

$$P^{\mathrm{LBL}}_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \cos^4\vartheta_{14} \sin^2 2\vartheta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \frac{1}{2}\sin^2 2\vartheta_{14}, \tag{6}$$

where the oscillations due to $\Delta m^2_{41} \gg \Delta m^2_{31}$ have been averaged and we adopted a parameterization of the four-neutrino mixing matrix in which $|U_{e3}| = \sin\vartheta_{13}\cos\vartheta_{14}$ and $|U_{e4}| = \sin\vartheta_{14}$.

We can calculate the value of $\sin^2 2\vartheta_{13}$, taking into account the reactor antineutrino anomaly, by noting that in the analysis of the Double-Chooz collaboration the $\bar{\nu}_e$ flux measured in the far detector has been fitted with

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$$\phi_{\bar{\nu}_e}^{\mathrm{LBL}} = \phi_{\bar{\nu}_e}^{\mathrm{SBL}} P_{\bar{\nu}_e \to \bar{\nu}_e}^{\mathrm{DC}}. \tag{7}$$

where $\phi_{\bar{\nu}_e}^{\mathrm{SBL}}$ is the short-baseline $\bar{\nu}_e$ flux inferred from the Bugey-4 measurement, taking into account the differences between the Bugey and Chooz reactors. In the framework of $3+1$ neutrino mixing, the short-baseline $\bar{\nu}_e$ flux is given by

$$\phi_{\bar{\nu}_e}^{\mathrm{SBL}} = \phi_{\bar{\nu}_e}^{0}(1 - A_{\mathrm{B4}} \sin^2 2\vartheta_{14}), \tag{8}$$

where A_{B4} is the average of $\sin^2(\Delta m_{41}^2 L/4E)$ in the Bugey-4 experiment. The value of this quantity is plotted in Fig. 1 as a function of Δm_{41}^2. One can see that $\sin^2(\Delta m_{41}^2 L/4E)$ is fully averaged ($A_{\mathrm{B4}} \simeq 1/2$) for $\Delta m_{41}^2 \gtrsim 3\ \mathrm{eV}^2$, but for smaller values of Δm_{41}^2 the average A_{B4} can be significantly different from $1/2$.

Let us first consider the case of $\Delta m_{41}^2 \gtrsim 3\ \mathrm{eV}^2$, for which $A_{\mathrm{B4}} \simeq 1/2$. In this case, from Eqs. (5), (6), and (8), the $\bar{\nu}_e$ flux measured in the Double-Chooz far detector can be written as

$$\phi_{\bar{\nu}_e}^{\mathrm{LBL}} = \phi_{\bar{\nu}_e}^{\mathrm{SBL}} \left[1 - \frac{\cos^4\vartheta_{14} \sin^2 2\vartheta_{13}}{1 - \frac{1}{2}\sin^2 2\vartheta_{14}} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E} \right) \right]. \tag{9}$$

Comparing Eq. (7) with $P_{\bar{\nu}_e \to \bar{\nu}_e}^{\mathrm{DC}}$ given by Eq. (2) and (9), we obtain

$$\sin^2 2\vartheta_{13} = \sin^2 2\vartheta_{13}^{\mathrm{DC}} \frac{1 - \frac{1}{2}\sin^2 2\vartheta_{14}}{\cos^4\vartheta_{14}}, \tag{10}$$

which gives the connection between $\vartheta_{13}^{\mathrm{DC}}$ and the pair ϑ_{13}, ϑ_{14} for $\Delta m_{41}^2 \gtrsim 3\ \mathrm{eV}^2$.

Equation (10) shows that in principle, normalizing the initial neutrino flux at a value measured by a short-baseline experiment as the Bugey-4 experiment is not sufficient to take into account the effects of short-baseline oscillations. However, in practice the correction is small because the reactor antineutrino anomaly implies that ϑ_{14} is small, which leads to

$$\left(1 - \frac{1}{2}\sin^2 2\vartheta_{14}\right) / \cos^4\vartheta_{14} = 1 + \mathrm{O}(\vartheta_{14}^4). \tag{11}$$

In this case, the long-baseline Double-Chooz data determine the value of $\sin^2 2\vartheta_{13}$ independently from the value of $\sin^2 2\vartheta_{14}$, which is determined by the short-baseline reactor antineutrino anomaly.

Let us now consider values of A_{B4} different from $1/2$, which can be realized if $\Delta m_{41}^2 \lesssim 3\ \mathrm{eV}^2$, and as one can see from Fig. 1. In this case, the contribution of $\phi_{\bar{\nu}_e}^{\mathrm{SBL}}$ to $\phi_{\bar{\nu}_e}^{\mathrm{LBL}}$ cannot be factorized as in Eq. (9). Therefore, in order to find the value of $\sin^2 2\vartheta_{13}$ given by Double-Chooz data, we must fit these data. We performed an approximate fit, extracting the necessary information from the figures in Ref. [1]. The results are shown in Fig. 2, where we plotted the value of $\sin^2 2\vartheta_{13}$ as a function of $\sin^2 2\vartheta_{14}$ for different values of A_{B4}. Figure 2 also shows the best-fit value of $\sin^2 2\vartheta_{14}$ and its 1σ, 2σ and 3σ allowed ranges obtained from the fit of short-baseline reactor antineutrino data [22]. One can see that the deviation of $\sin^2 2\vartheta_{13}$ from $\sin^2 2\vartheta_{13}^{\mathrm{DC}}$ in the allowed-band of $\sin^2 2\vartheta_{14}$ is negligible for $A_{\mathrm{B4}} = 1/2$, according to the discussion above. On the other hand, the deviation of $\sin^2 2\vartheta_{13}$ from $\sin^2 2\vartheta_{13}^{\mathrm{DC}}$ can be relatively

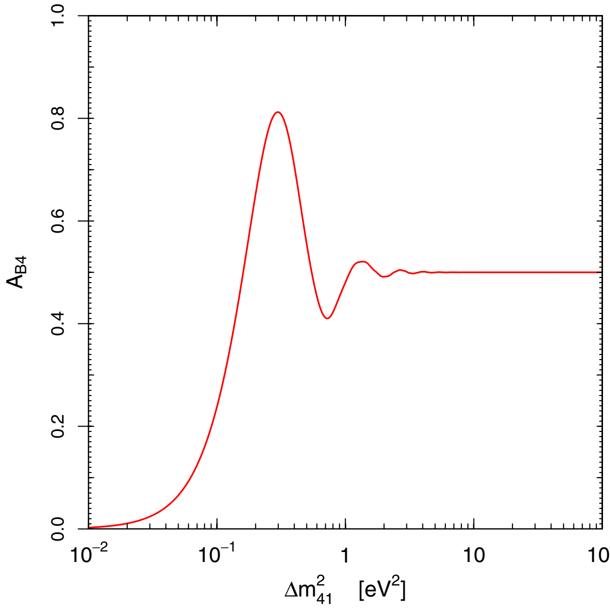

FIG. 1 (color online). Averaged value of $\sin^2(\Delta m_{41}^2 L/4E)$ in the Bugey-4 experiment as a function of Δm_{41}^2.

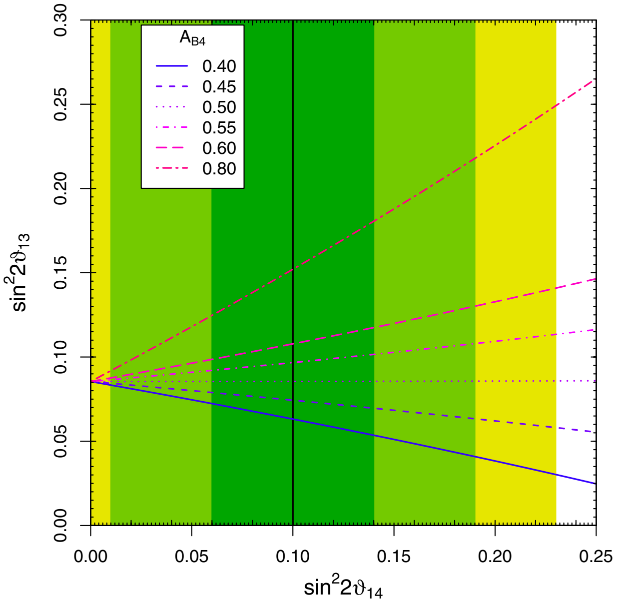

FIG. 2 (color online). $\sin^2 2\vartheta_{13}$ as a function of $\sin^2 2\vartheta_{14}$ obtained from Eq. (10) and the best-fit value of the Double-Chooz measure in Eq. (1) for different values of A_{B4}. The vertical solid black line gives the best-fit value of $\sin^2 2\vartheta_{14}$ obtained from the fit of short-baseline reactor antineutrino data [22]. The colored vertical bands show the corresponding 1σ, 2σ, 3σ allowed ranges.

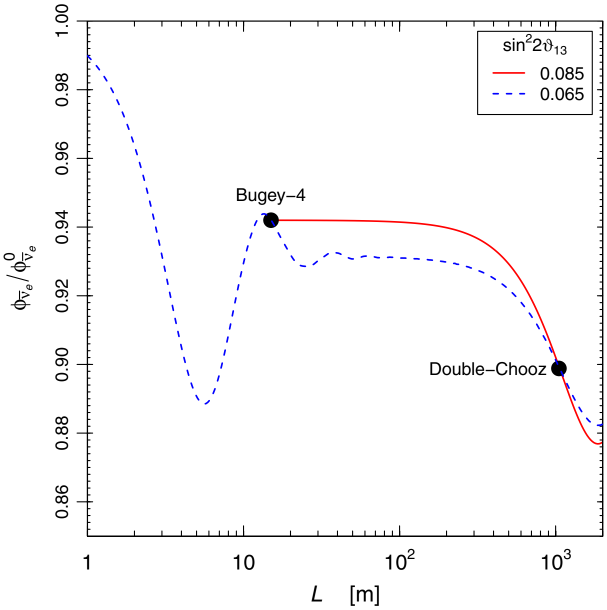

FIG. 3 (color online). Relative suppression of the averaged reactor electron antineutrino flux as a function of distance. The red, solid curve is calculated using the three-neutrino mixing survival probability in Eq. (2) with $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2 and the Double-Chooz best-fit value of $\sin^2 2\vartheta^{\mathrm{DC}}_{13}$ in Eq. (1) and by normalizing the flux at the value measured by the Bugey-4 experiment at $L = 15$ m. The blue, dashed curve is calculated with the four-neutrino mixing survival probability (see Eq. (2.8) of Ref. [24]) and $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\vartheta_{13} = 0.065$, $\Delta m^2_{41} = 0.8$ eV^2 and $\sin^2 2\vartheta_{14} = 0.14$. The values of $\sin^2 2\vartheta_{13}$ and $\sin^2 2\vartheta_{14}$ have been chosen in order to fit both the Bugey-4 and Double-Chooz data points.

large for values of A_{B4} different from 1/2. Therefore, the uncertainty due to short-baseline oscillations must be taken into account in the extraction of $\sin^2 2\vartheta_{13}$ from the Double-Chooz data if $\Delta m^2_{41} \lesssim 3$ eV^2.

The cause of the deviation of $\sin^2 2\vartheta_{13}$ from $\sin^2 2\vartheta^{\mathrm{DC}}_{13}$ when the short-baseline oscillations are not fully averaged at Bugey-4 is illustrated in Fig. 3, where we plotted the relative decrease of the averaged reactor electron antineutrino flux as a function of distance. The red, solid curve shows the suppression of the Bugey-4 flux for larger distances calculated using the three-neutrino mixing survival probability in Eq. (2) with the Double-Chooz best-fit value of $\sin^2 2\vartheta^{\mathrm{DC}}_{13}$ in Eq. (1). The blue, dashed curve is calculated with the four-neutrino mixing survival probability (see Eq. (2.8) of Ref. [24]) and oscillation parameters chosen in order to fit both the Bugey-4 and Double-Chooz data points. One can see that since the short-baseline oscillations are not fully averaged at Bugey-4, the residual short-baseline oscillations at larger distances contribute to the suppression of the flux and the fit of the Double-Chooz data point requires a value of $\sin^2 2\vartheta_{13}$, which is smaller than $\sin^2 2\vartheta^{\mathrm{DC}}_{13}$.

In the following we estimate the uncertainty of the determination of $\sin^2 2\vartheta_{13}$ from Double-Chooz data implied by the fit of short-baseline reactor antineutrino data [22].

Figure 4 shows the value of $\sin^2 2\vartheta_{14}$ as a function of Δm^2_{41} obtained from the fit of short-baseline reactor antineutrino data (see Ref. [22]). Note that Fig. 4 is obtained from a one-dimensional χ^2 analysis of short-baseline reactor antineutrino data for each fixed value of Δm^2_{41}. Hence, it is different from the usual two-dimensional χ^2 analyses which give allowed regions in the $\sin^2 2\vartheta_{14}$-Δm^2_{41} plane (as, for example, Fig. 1 of Ref. [22]). The rapid decrease of the best-fit value of $\sin^2 2\vartheta_{14}$ for $\Delta m^2_{41} \lesssim 0.2$ eV^2 reflects the fact that the oscillation explanation of the reactor antineutrino anomaly requires larger values of Δm^2_{41}.

Figure 5 shows the value of $\sin^2 2\vartheta_{13}$ as a function of Δm^2_{41} obtained from our approximate fit of Double-Chooz data and $\sin^2 2\vartheta_{14}$ in Fig. 4. One can see that the deviation from $\sin^2 2\vartheta^{\mathrm{DC}}_{13}$ is smaller than about 1% for $\Delta m^2_{41} \gtrsim 3$ eV^2, in agreement with the discussion above. On the other hand, the deviation of $\sin^2 2\vartheta_{13}$ from $\sin^2 2\vartheta^{\mathrm{DC}}_{13}$ can be relatively large for smaller values of Δm^2_{41}, reaching about 40% at 2σ for $\Delta m^2_{41} \simeq 0.3 - 0.4$ eV^2.

Finally, using the constraints on Δm^2_{41} and $\sin^2 2\vartheta_{14}$ obtained from a two-dimensional χ^2 analysis of short-baseline reactor antineutrino data [22], for the best-fit value of $\sin^2 2\vartheta_{13}$ in our approximate fit of Double-Chooz data we obtain

$$\sin^2 2\vartheta_{13} = 0.084^{+0.025}_{-0.010}. \qquad (12)$$

Here, the uncertainties are only those due to the analysis of short-baseline reactor antineutrino data. Hence, they must be added to the intrinsic Double-Chooz uncertainties in Eq. (1).

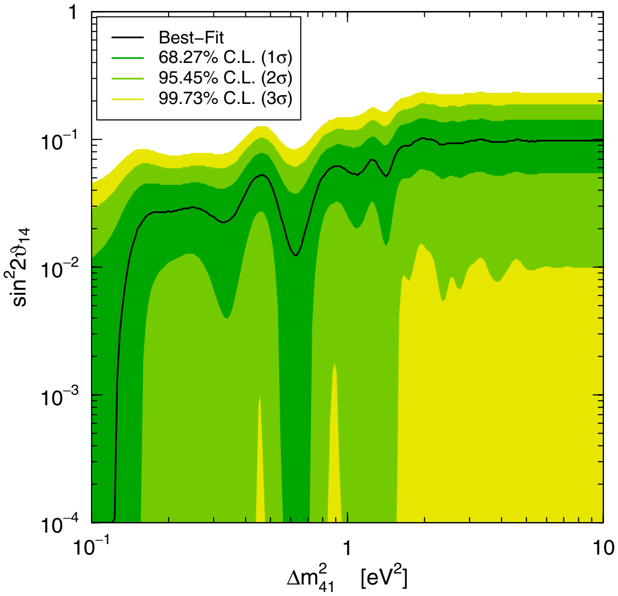

FIG. 4 (color online). $\sin^2 2\vartheta_{14}$ as a function of Δm^2_{41} obtained from the fit of short-baseline reactor antineutrino data (see Ref. [22]).

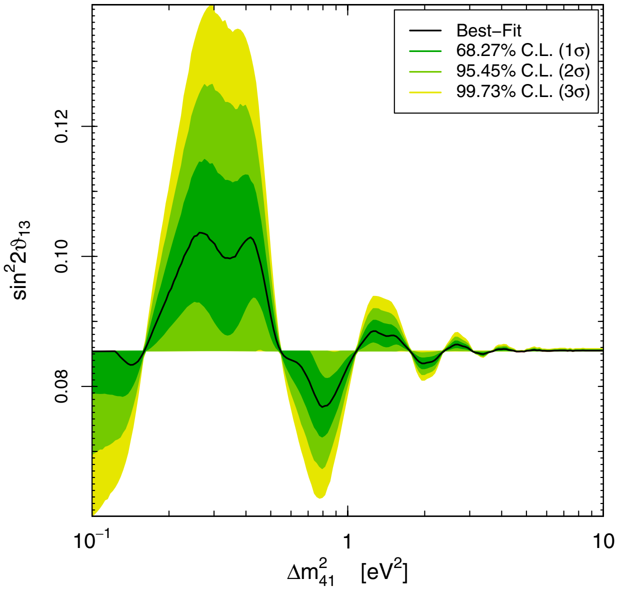

FIG. 5 (color online). $\sin^2 2\vartheta_{13}$ as a function of Δm^2_{41} obtained from the best-fit value of the Double-Chooz measure in Eq. (1) and $\sin^2 2\vartheta_{14}$ in Fig. 4.

The result in Eq. (12) shows that the uncertainties on the determination of $\sin^2 2\vartheta_{13}$ due to the reactor antineutrino anomaly are comparable with the intrinsic Double-Chooz uncertainties in Eq. (1). Therefore, the reactor antineutrino anomaly must be taken into account in the extraction of the value of $\sin^2 2\vartheta_{13}$ from Double-Chooz data.

In conclusion, we have shown that if the short-baseline oscillations indicated by the reactor antineutrino anomaly exists, in order to obtain the value of ϑ_{13} in long-baseline reactor neutrino oscillation experiments it is not sufficient to normalize the flux at a value measured by a short-baseline experiment, because the short-baseline oscillations may be not fully averaged at such reference point. In the case of the first results of the Double-Chooz experiment [1], the flux has been normalized at the value measured by the Bugey-4 experiment [4], for which the short-baseline oscillations are fully averaged only for $\Delta m^2_{41} \gtrsim 3\ \text{eV}^2$. We have shown that for smaller values of Δm^2_{41} the corrections due to short-baseline oscillations must be taken into account and that a neutrino oscillation analysis of the reactor antineutrino anomaly indicates that these corrections may be relevant.

Let us finally note that in the long-baseline reactor experiments with a near detector which is farther from the reactor than about 100 m (RENO [25], Daya Bay [26], Double-Chooz [2]) short-baseline oscillations are fully averaged for $\Delta m^2_{41} \gtrsim 0.1\ \text{eV}^2$. Therefore, even if the reactor antineutrino anomaly is due to short-baseline oscillations, the value of $\sin^2 2\vartheta_{13}$ can be extracted accurately from the data by comparing the near and far detection rates using the three-neutrino mixing survival probability in Eq. (2), independently of the reactor antineutrino anomaly. However, if Δm^2_{41} is sufficiently small, the medium-baseline $\bar{\nu}_e$ flux measured in the near detector could be smaller than that measured in the Bugey-4 experiment and in other short-baseline reactor experiments (see Ref. [7]). This would be a confirmation of the reactor antineutrino anomaly.

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