First Double-Chooz Results and the Reactor Antineutrino Anomaly

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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 $\theta_{13}$ through the normalization of the initial antineutrino flux with the Bugey-4 measurement. We show that the effects are negligible and the value of $\theta_{13}$ obtained by the Double-Chooz collaboration is accurate only if $\Delta m^2_{41} \gtrsim 3$ eV$^2$. For smaller values of $\Delta m^2_{41}$ 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:

$$\sin^2 2\theta_{13}^{DC} = 0.085 \pm 0.029 \pm 0.042 .$$

(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]):

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}^{DC} = 1 - \sin^2 2\theta_{13}^{DC} \sin^2 \left( \frac{\Delta m^2_{41} L}{4E} \right) ,$$

(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 $|U_{e3}| = \sin \theta_{13}$.

An essential ingredient in the extraction of the value of $\sin^2 2\theta_{13}^{DC}$ from the data is the normalization of the initial flux prediction on the value measured by the Bugey-4 experiment [3], 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 recalculation of the reactor $\bar{\nu}_e$ flux [3,6] 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 [3]. The ratio of observed and theoretically predicted $\bar{\nu}_e$ flux for the Bugey-4 experiment is [3]

$$\frac{\phi_{\text{obs}}^{\bar{\nu}_e \text{-Bugey-4}}}{\phi_{\text{the-Bugey-4}}} = 0.942 \pm 0.042 ,$$

(3)

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

$$\frac{\phi_{\text{obs}}^{\bar{\nu}_e \text{-SBL}}}{\phi_{\text{the-SBL}}} = 0.946 \pm 0.024 ,$$

(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 $\theta_{13}$, 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

$$\phi_{\bar{\nu}_e}^{LBL} = \phi_{\bar{\nu}_e}^0 \cdot P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}^{LBL} ,$$

(5)

where $\phi_{\bar{\nu}_e}^0$ is the $\bar{\nu}_e$ flux produced by the reactor and $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}^{LBL}$ is the effective long-baseline (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]

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}^{LBL} = 1 - \cos^2 \theta_{14} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{41} L}{4E} \right)$$

$$- \frac{1}{2} \sin^2 2\theta_{14} ,$$

(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 $|U_{e3}| = \sin \theta_{13} \cos \theta_{14}$ and $|U_{e4}| = \sin \theta_{14}$.

We can calculate the value of $\sin^2 2\theta_{13}$ 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

$$\phi_{\bar{\nu}_e}^{LBL} = \phi_{\bar{\nu}_e}^{SBL} \cdot P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}^{DC} .$$

(7)
where \( \phi^\text{SBL}_{\bar{\nu}_e} \) 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

\[
\phi^\text{SBL}_{\bar{\nu}_e} = \phi^0_{\bar{\nu}_e} \left(1 - A_{B4} \sin^2 2\vartheta_{14}\right),
\]

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

Let us first consider the case of \( \Delta m^2_{41} \gtrsim 3\text{eV}^2 \), for which \( A_{B4} \approx 1/2 \). In this case, from Eqs. 6, 7 and 8, the \( \bar{\nu}_e \) flux measured in the Double-Chooz far detector can be written as

\[
\phi^\text{LBL}_{\bar{\nu}_e} = \phi^\text{SBL}_{\bar{\nu}_e} \left[1 - \frac{\cos^4 \vartheta_{14} \sin^2 2\vartheta_{13}}{1 - \frac{1}{2} \sin^2 2\vartheta_{14}} \sin^2 \left(\frac{\Delta m^2_{41} L}{4E}\right)\right].
\]  

Comparing Eq. 7 with \( P^\text{DC}_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \) given by Eq. 4 and Eq. 9, we obtain

\[
\sin^2 2\vartheta_{13} = \sin^2 2\vartheta_{13}^\text{DC} \frac{1 - \frac{1}{2} \sin^2 2\vartheta_{14}}{\cos^4 \vartheta_{14}},
\]

which gives the connection between \( \vartheta_{13}^\text{DC} \) and the pair \( \vartheta_{13}, \vartheta_{14} \) for \( \Delta m^2_{41} \gtrsim 3\text{eV}^2 \).

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 \( \vartheta_{14} \) is small, which leads to

\[
(1 - \frac{1}{2} \sin^2 2\vartheta_{14}) / \cos^4 \vartheta_{14} = 1 + O(\vartheta_{14}^4).
\]

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 \( \Delta m^2_{41} \lesssim 3\text{eV}^2 \), as one can see from Fig. 1. In this case the contribution of \( \phi^\text{SBL}_{\bar{\nu}_e} \) to \( \phi^\text{LBL}_{\bar{\nu}_e} \) 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. 10. 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 1\( \sigma \), 2\( \sigma \) and 3\( \sigma \) 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 \( \sin^2 2\vartheta_{13}^\text{DC} \) in the allowed band of \( \sin^2 2\vartheta_{14} \) is negligible for \( A_{B4} = 1/2 \), according to the discussion above. On the other hand, the deviation of \( \sin^2 2\vartheta_{13} \) from \( \sin^2 2\vartheta_{13}^\text{DC} \) can be relatively large for values of \( A_{B4} \) different from...
FIG. 3. Relative suppression of the averaged reactor electron antineutrino flux as a function of distance. The solid red curve is calculated using the three-neutrino mixing survival probability in Eq. (2) with $\Delta m^2_{31} = 2.4 \times 10^{-3} \text{eV}^2$ and the Double-Chooz best-fit value of $\sin^2 2\theta_{13}^{DC}$ in Eq. (1) and by normalizing the flux at the value measured by the Bugey-4 experiment at $L = 15\text{m}$. The blue dashed curve is calculated with the four-neutrino mixing survival probability in Eq. (6) with $\Delta m^2_{41} = 0.8 \text{eV}^2$ and $\sin^2 2\theta_{14} = 0.14$. The values of $\sin^2 2\theta_{13}$ and $\sin^2 2\theta_{14}$ have been chosen in order to fit both the Bugey-4 and Double-Chooz data points.

1/2. Therefore, the uncertainty due to short-baseline oscillations must be taken into account in the extraction of $\sin^2 2\theta_{13}$ from the Double-Chooz data if $\Delta m^2_{31} \lesssim 3 \text{eV}^2$.

The cause of the deviation of $\sin^2 2\theta_{13}$ from $\sin^2 2\theta_{13}^{DC}$ 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 solid red 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 $\sin^2 2\theta_{13}^{DC}$ in Eq. (1). The blue dashed curve is calculated with the four-neutrino mixing survival probability in Eq. (6) 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 $\sin^2 2\theta_{13}$ which is smaller than $\sin^2 2\theta_{13}^{DC}$.

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

Figure 4 shows the value of $\sin^2 2\theta_{14}$ as a function of $\Delta m^2_{31}$ obtained from the fit of short-baseline reactor antineutrino data (see Ref. [22]). Figure 5 shows the value of $\sin^2 2\theta_{13}$ as a function of $\Delta m^2_{41}$ obtained from the best-fit value of the Double-Chooz measure in Eq. (1) and $\sin^2 2\theta_{14}$ in Fig. 4.
\[ \sin^2 2\theta_{13} - \Delta m^2_{41} \] plane (as for example Fig. 1 of Ref. [22]). The rapid decrease of the best-fit value of \( \sin^2 2\theta_{13} \) for \( \Delta m^2_{41} \lesssim 0.2 \text{eV}^2 \) reflects the fact that the oscillation explanation of the reactor antineutrino anomaly requires larger values of \( \Delta m^2_{41} \).

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

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

\[
\sin^2 2\theta_{13} = 0.084_{-0.010}^{+0.025}. \tag{12}
\]

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).

The result in Eq. (12) shows that the uncertainties on the determination of \( \sin^2 2\theta_{13} \) 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 \( \sin^2 2\theta_{13} \) 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 \( \theta_{13} \) 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 [11], 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 \( \Delta m^2_{41} \) 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 [24], Daya Bay [26], Double-Chooz [21]) 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 \( \sin^2 2\theta_{13} \) 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 \( \Delta m^2_{41} \) 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. [23]). This would be a confirmation of the reactor antineutrino anomaly.