Large Short-Baseline $\bar{\nu}_\mu$ Disappearance

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We analyze the LSND, KARMEN and MiniBooNE data on short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations and the data on short-baseline $\nu_e$ disappearance obtained in the Bugey-3 and CHOOZ reactor experiments in the framework of 3+1 antineutrino mixing, taking into account the MINOS observation of long-baseline $\bar{\nu}_\mu$ disappearance and the KamLAND observation of very-long-baseline $\nu_e$ disappearance. We show that the fit of the data implies that the short-baseline disappearance of $\bar{\nu}_\mu$ is relatively large. We obtain a prediction of an effective amplitude $\sin^2 2\theta_{\mu e} \gtrsim 0.1$ for short-baseline $\bar{\nu}_\mu$ disappearance generated by $0.2 \lesssim \Delta m^2 \lesssim 1\text{eV}^2$, which could be measured in future experiments.

The MiniBooNE experiment [1] measured recently a signal of $\nu_\mu \rightarrow \nu_e$ transitions at the same ratio of distance (L) and energy (E) of that observed in the LSND experiment [2]. This is a strong indication in favor short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions, which depend just on the ratio $L/E$ (see Refs. [3, 10]).

In Ref. [11] we discussed the interpretation of the MiniBooNE and LSND signals in a minimal framework of short-baseline oscillations of antineutrinos with a two-neutrino-like transition probability which depends on an effective mixing angle and an effective squared-mass difference, such as that obtained in the case of four-neutrino mixing (see Refs. [3, 6, 8, 9]). The oscillations of antineutrinos may be different from those of neutrinos [12], since the MiniBooNE experiment with a neutrino beam did not observe a signal of short-baseline $\nu_\mu \rightarrow \nu_e$ oscillations [13] compatible with the MiniBooNE and LSND measurements of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. Other hints in favor of CPT-violating different values of the effective squared-mass differences and mixings of neutrinos and antineutrinos come from the comparison of the data on long-baseline $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance in the MINOS experiment [14] and from a neutrino oscillation analysis [15] of the electron neutrino data of the Gallium radioactive source GALLEX [16] and SAGE [17] experiments and the electron antineutrino data of the reactor Bugey-3 [18] and Chooz [19] experiments. Moreover, if only antineutrino oscillation data are considered, the strong tension between the data of short-baseline disappearance and appearance experiments in 3+1 [6, 20, 21] and 3+2 [22, 23] mixing schemes is relaxed [24], because the crucial data of the CDHSW experiment [25] constrain only short-baseline $\nu_\mu$ disappearance and the strong constraint coming from Super-Kamiokande atmospheric neutrino data has been evaluated assuming equal disappearance of $\nu_\mu$ and $\bar{\nu}_\mu$.

In Ref. [11] we considered the constraints on short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations coming from the data of the KARMEN experiment [26] and the data of the Bugey-3 [18] and Chooz [19] experiments. The KARMEN experiment [26] did not observe short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at a distance which was about half that of LSND, with the same neutrino energy spectrum. Hence, the KARMEN data constrain the parameter space of neutrino mixing which can explain the LSND and MiniBooNE signals. The data of the Bugey-3 [18] and Chooz [19] experiments provide the most stringent constraints on short-baseline disappearance of reactor $\nu_e$'s. For simplicity, we considered the case in which the probability of $\nu_e$ disappearance is equal to the probability of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, $P_{\nu_\mu \rightarrow \nu_e} = 1 - P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}$. This is the limit of the model-independent inequality $P_{\nu_\mu \rightarrow \nu_e} \leq 1 - P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}$ which follows from simple particle conservation.

In this paper we improve the calculations presented in Ref. [11] by considering the constraints on the mixing of $\bar{\nu}_\mu$ following from the observation of long-baseline $\bar{\nu}_\mu$ disappearance in the MINOS experiment [14]. In principle, there could be also a constraint coming from the data of the Super-Kamiokande atmospheric neutrino experiment [27], but since the Super-Kamiokande detector cannot distinguish neutrinos from antineutrinos the extraction of such a constraint would require a detailed analysis of Super-Kamiokande atmospheric neutrino data which is beyond our possibilities. As we will see in the following, the MINOS measurement of long-baseline $\bar{\nu}_\mu$ disappearance is sufficient to obtain a significant constraint on the mixing of $\bar{\nu}_\mu$ which allows us to infer interesting predictions on the short-baseline disappearance of $\bar{\nu}_\mu$'s.

The MINOS constraints on the mixing of $\bar{\nu}_\mu$ can be quantified only by considering a specific neutrino mixing scheme. Here, we adopt the simplest 3+1 four-neutrino mixing scheme (see Refs. [3, 6, 8, 9]) of antineutrinos in which there are three independent squared-mass differ-
1. $\Delta m^2_{31}$ which generates the very-long-baseline disappearance of $\bar{\nu}_e$ observed by the KamLAND reactor experiment [28].

2. $\Delta m^2_{31}$ which generates the long-baseline disappearance of $\bar{\nu}_e$ observed by the MINOS accelerator experiment [14] and the oscillations of atmospheric $\bar{\nu}_\mu$'s.

3. $\Delta m^2_{31}$ which generates the short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations observed by the LSND [2] and MiniBooNE [1] accelerator experiments.

In this scheme the effective transition and disappearance probabilities in short-baseline experiments are given by

$$P_{\bar{\nu}_e \rightarrow \nu_\beta}^{SBL} = \sin^2 2\theta_{\alpha \beta} \sin^2 \left( \frac{\Delta m^2 L}{4E} \right),$$

$$P_{\bar{\nu}_e \rightarrow \nu_\alpha}^{SBL} = 1 - \sin^2 2\theta_{\alpha \alpha} \sin^2 \left( \frac{\Delta m^2 L}{4E} \right),$$

with $\alpha \neq \beta$ and $\Delta m^2 = \Delta m^2_{31}$ for simplicity. The effective mixing parameters $\Delta m^2$ and $\theta$'s.

The best-fit values of the effective oscillation amplitudes corresponding to $|U_{e4}|^2$ and $|U_{\mu4}|^2$ in Eq. (11) are

$$\Delta m^2_{ee} = 0.45 \text{ eV}^2, \quad |U_{e4}|^2 = 0.0042, \quad |U_{\mu4}|^2 = 0.79,$$

for $\chi^2_{\text{min}} = 82.0, \quad \text{NDF} = 83, \quad \text{GoF} = 51\%,$

where NDF is the number of degrees of freedom and GoF is the goodness-of-fit. Hence the global fit is acceptable. Moreover, the parameter goodness-of-fit is 28%, which is reasonable.

The best-fit values of the effective oscillation amplitudes corresponding to $|U_{e4}|^2$ and $|U_{\mu4}|^2$ in Eq. (11) are

$$\sin^2 2\theta_{ee} = 0.013, \quad \sin^2 2\theta_{\mu \mu} = 0.017, \quad \sin^2 2\theta_{e \mu} = 0.65,$$

with MINOS data release [29]. A more precise analysis of the MINOS energy spectrum of $\bar{\nu}_e$ events taking into account the effect of $|U_{\mu4}|^2$ will be presented elsewhere [32].
and $B$ together with the marginal $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$'s for $\sin^2 2\theta_{\mu\mu}$, $\sin^2 2\theta_{ee}$, and $\sin^2 2\theta_{\mu\mu}$.

Figure 1 is similar to Fig. 7 of Ref. [11]. In Fig. 1 the constraint on $|U_{\mu 4}|^2$ from MINOS data shifts the allowed interval of $\sin^2 2\theta_{\mu\mu}$ towards slightly smaller values with respect to those in Fig. 7 of Ref. [11], where the upper bounds on $\sin^2 2\theta_{ee}$ are given only by the reactor constraints on $|U_{e 4}|^2$, allowing $|U_{\mu 4}|^2$ to be as large as unity. However, the change in the allowed intervals of $\Delta m^2$ and $\sin^2 2\theta_{ee}$ with respect to those obtained in Ref. [11] is rather small: from the marginal $\Delta \chi^2$'s in Fig. 1 we obtain

$$2 \times 10^{-3} \lesssim \sin^2 2\theta_{ee} \lesssim 4 \times 10^{-2},$$

(14)

$$0.2 \lesssim \Delta m^2 \lesssim 1 \text{ eV}^2 \quad \text{or} \quad \Delta m^2 \simeq 6 \text{ eV}^2,$$

(15)

at 95% C.L. (to be compared with $2 \times 10^{-3} \lesssim \sin^2 2\theta_{ee} \lesssim 5 \times 10^{-2}$ and $0.2 \lesssim \Delta m^2 \lesssim 2 \text{ eV}^2$ obtained in Ref. [11]).

Figure 2 shows the allowed regions in the $\sin^2 2\theta_{ee} - \Delta m^2$ plane, together with the $3\sigma$ exclusion curve obtained from the reactor Bugey-3 and Chooz data. One can see that $\sin^2 2\theta_{ee}$ is approximately bounded to be smaller than the limit imposed by the reactor data. Taking into account the approximation

$$\sin^2 2\theta_{ee} \simeq 4|U_{e 4}|^2,$$

(16)

which is valid for the small values of $|U_{e 4}|^2$ allowed by KamLAND data (Eq. (9)), the lower limits on $\sin^2 2\theta_{ee}$ follow from the need to have a value of $\sin^2 2\theta_{\mu\mu} = 4|U_{e 4}|^2|U_{\mu 4}|^2$ in the range in Eq. (14) with $|U_{\mu 4}|^2$ limited to be smaller than unity by $\chi^2_{\text{MINOS}}$ in Eq. (7). From the marginal $\Delta \chi^2$ in Fig. 2 we obtain

$$7 \times 10^{-3} \lesssim \sin^2 2\theta_{ee} \lesssim 6 \times 10^{-2},$$

(17)

at 95% C.L.
\[ \sin^2 2\theta_{ee} \Delta m^2 \]

\[ \sin^2 2\theta_{\mu\mu} \Delta m^2 \]

\[ \Delta \chi^2 = \chi^2 - \chi_{\text{min}}^2 \]

FIG. 2. Allowed regions in the \( \sin^2 2\theta_{ee} - \Delta m^2 \) and \( \sin^2 2\theta_{\mu\mu} - \Delta m^2 \) planes and marginal \( \Delta \chi^2 \) for \( \sin^2 2\theta_{ee} \) and \( \sin^2 2\theta_{\mu\mu} \). The best-fit point is indicated by a cross. The thin dash-dotted line in the \( \sin^2 2\theta_{ee} - \Delta m^2 \) plane represents the 3σ exclusion curve obtained from the reactor Bugey-3 and Chooz data.

Figure 2 shows also the allowed regions in the \( \sin^2 2\theta_{\mu\mu} - \Delta m^2 \) plane and the marginal \( \Delta \chi^2 \) for \( \sin^2 2\theta_{\mu\mu} \), which gives

\[ \sin^2 2\theta_{\mu\mu} \gtrsim 0.1, \quad (18) \]

at 95% C.L.. This result is interesting, because it implies that the short-baseline disappearance of \( \bar{\nu}_\mu \)'s is rather large and could be measured in future experiments [34–36]. The preferred region in Fig. 2 lies around the best-fit point in Eq. (13) which corresponds to a rather large value of \( \sin^2 2\theta_{\mu\mu} \). Notice that such large values of \( \sin^2 2\theta_{\mu\mu} \) are not constrained by MINOS data, because they correspond to values of \( |U_{e4}|^2 \) close to 1/2. MINOS data constrain small values of \( \sin^2 2\theta_{\mu\mu} = 4|U_{\mu4}|^2 (1 - |U_{e4}|^2) \) in conjunction with the need to have a value of \( \sin^2 2\theta_{ee} = 4|U_{e4}|^2 |U_{\mu4}|^2 \) in the range in Eq. (14) with a small \( |U_{e4}|^2 \simeq \sin^2 2\theta_{ee}/4 \) from Eq. (17).

It is interesting to notice that in Fig. 2 large values of \( \sin^2 2\theta_{\mu\mu} \) are excluded for \( \Delta m^2 \gtrsim 1 \text{eV}^2 \) by the constraints imposed by MiniBooNE \( \bar{\nu}_\mu \) data, which are included in the analysis according to the method described in Ref. [11] taking into account the \( \bar{\nu}_\mu \) disappearance given by Eq. (2). This is in agreement with the MiniBooNE exclusion curve for \( \bar{\nu}_\mu \) disappearance in Fig. 3 of Ref. [37].

In conclusion, we have analyzed the data of short-baseline antineutrino oscillation experiments taking into account the constraints on the mixing of \( \bar{\nu}_\mu \) given by the observation of long-baseline \( \bar{\nu}_\mu \) disappearance in the MINOS experiment [14] in the framework of 3+1 antineutrino mixing. The LSND [2] and MiniBooNE [1] signals...
in favor of short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations are compatible with the constraints given by the data of the KARMEN [26] short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ experiment, the Bugey-3 [18] and Chooz [19] short-baseline $\bar{\nu}_e \rightarrow \bar{\nu}_e$ experiments, the MINOS [14] long-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ experiments and the KamLAND [28] very-long-baseline $\nu_\tau \rightarrow \nu_\tau$ experiment. Our analysis predicts that the short-base dis-
appearance of $\bar{\nu}_\mu$ is rather large and could be measured in future short-baseline $\bar{\nu}_\mu$ disappearance experiments sensitive to values of $\Delta m^2$ in the sub-eV$^2$ region [34–36].

Although the numerical results obtained in this paper depend on the chosen framework of 3+1 antineutrino mixing, the prediction of large $\bar{\nu}_\mu$ disappearance in short-base experiments is a general consequence of the LSND and MiniBooNE signals in favor of short-base oscillations. In fact, since the mixing of $\bar{\nu}_e$ with the massive neutrino(s) responsible for short-base oscillations is constrained to be small by the short-base reactor $\bar{\nu}_e$ data, taking into account the KamLAND measurement of a large very-long-base $\bar{\nu}_e$ disappearance, the mixing of $\bar{\nu}_\mu$ with the massive neutrino(s) responsible for short-base oscillations must be relatively large. The MINOS measurement of long-base $\bar{\nu}_\mu$ disappearance implies that $\bar{\nu}_\mu$ must have also a relatively large mixing with the massive neutrino(s) responsible for long-base oscillations. Therefore since $\bar{\nu}_\mu$ have relatively large mixing with the two sets of massive neutrinos whose squared-mass difference generate short-base oscillations, the amplitude of short-base $\bar{\nu}_\mu$ disappearance must be large. The numerical predictions for such amplitude in mixing schemes more complicated than the simplest framework of 3+1 antineutrino mixing considered here will be presented elsewhere [32].

Note Added

After the completion of this work, a very interesting new evaluation of the $\bar{\nu}_e$ fluxes produced in nuclear reactors has been published in Ref. [39]. The increase of about 3% of the flux normalization with respect to the standard evaluation used in the analysis of all experimental data (see Ref. [41]) has several implications for the interpretation of neutrino oscillation data and may lead to a reactor antineutrino anomaly [40]. Such an increase of the reactor $\bar{\nu}_e$ fluxes tends to decrease the tension between the putative lack of $\bar{\nu}_e$ and $\nu_\mu$ short-base disappearance and the LSND and MiniBooNE signals of short-base $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations in CPT-invariant 3+1
neutrino mixing schemes \cite{3, 6, 24, 21, 38, 42, 43}, reducing the need to treat the oscillations of neutrinos and antineutrinos separately \cite{11}. Figure 3 illustrates the change by comparing the regions in the $\sin^2 2\theta_{\mu\nu} - \Delta m^2$ plane allowed at 99\% C.L. by LSND \cite{2} and MiniBooNE \cite{1} $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ data with the 99\% C.L. exclusion curve obtained from MiniBooNE $\nu_\mu \rightarrow \nu_e$ data \cite{13}. KARMEN $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ data \cite{20}, CDHSW $\nu_\mu \rightarrow \nu_e$ data \cite{22}, atmospheric neutrino data \cite{35} and Bugey-3 \cite{18} and Chooz $\nu_e \rightarrow \nu_e$ data with the standard reactor $\bar{\nu}_e$ fluxes and the new reactor $\bar{\nu}_e$ fluxes. One can see that the change is very small. The parameter goodness-of-fit shifts from 0.0048\% to 0.0064\%. Since the new reactor $\bar{\nu}_e$ fluxes do not allow us to reconcile the data in the framework of CPT-invariant 3+1 neutrino mixing, the analysis of the antineutrino data presented in this paper remains valid. More detailed implications of the new reactor $\bar{\nu}_e$ fluxes will be discussed elsewhere \cite{32}. 

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