Electron antineutrino disappearance at KamLAND and JUNO as decisive tests of the short baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance anomaly

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The IsoDAR antineutrino source, which produces a flux from ^{8}Li isotope decay at rest, when paired with the proposed Jiangmen Underground Neutrino Observatory detector, has unprecedented sensitivity to $\bar{\nu}_e$ disappearance for oscillations at high Δm^2. Assuming charge conjugation, parity transformation, and time reversal (CPT) invariance, the sensitive region for $\bar{\nu}_e$ disappearance can be used to restrict the allowed parameter space of a $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance signal. The 5σ sensitivity of this experiment covers the entire $\bar{\nu}_\mu \to \bar{\nu}_e$ allowed parameter space from a combined fit to short-baseline experiments. This represents a decisive test of the LSND neutrino experiment and MiniBooNE antineutrino appearance signals within all models that are CPT invariant. Running IsoDAR at KamLAND restricts a large part of the appearance signal region in a similar way.

I. INTRODUCTION

Within a model with charge conjugation, parity transformation, and time reversal (CPT) invariance, the allowed parameter space for $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance oscillations must be contained within the parameter space allowed for $\bar{\nu}_e$ disappearance, as can be seen from the following chain of reasoning:

(1) CPT invariance requires that $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations and $\nu_e \to \nu_\mu$ oscillations must be identical.

(2) The probability for ν_e disappearance must be larger than the probability for $\nu_e \to \nu_\mu$ oscillations.

(3) CPT invariance requires that the probability of $\bar{\nu}_e$ disappearance be the same as the probability for ν_e disappearance.

Thus, if the sensitive region of a $\bar{\nu}_e$ disappearance experiment entirely covers the parameter space for a $\bar{\nu}_\mu \to \bar{\nu}_e$ signal region, then either a signal must be observed with mixing angle such that $\sin^2 2\theta_{\bar{e}e} > \sin^2 2\theta_{\bar{\mu}e}$, or all models based on oscillations that assume CPT invariance must be ruled out as an explanation for the $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance signal. We will use this argument to show how the JUNO (Jiangmen Underground Neutrino Observatory) and KamLAND detectors can be used to address existing short baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance signals.

The world's data on $\bar{\nu}_\mu \to \bar{\nu}_e$ appearancefrom short-baseline experiments can be combined to yield a "global $\bar{\nu}_e$ appearance" allowed region, using the code from Ref. [1]. Three experiments contribute. The liquid scintillator neutrino detector (LSND) experiment observed a $> 3\sigma$ excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam that can be interpreted as $\bar{\nu}_\mu \to \bar{\nu}_e$ signal at the mass splitting of $\Delta m^2 > 0.01$ eV^2 [2]. The complementary KARMEN experiment failed to observe $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations [3], and this represents an important constraint. These studies were followed by the MiniBooNE experiment, which employed both ν_μ and $\bar{\nu}_\mu$ beams. For this discussion, we consider only the antineutrino running, which can be directly compared to KARMEN and LSND with no assumptions concerning CP violation. MiniBooNE observed an excess of $\bar{\nu}_e$ events [4]. Figure 1 shows the 99% confidence level (C.L.) allowed region for appearance from a joint fit to the data sets (purple), where Δm^2 is plotted versus $\sin^2 2\theta_{\mu e}$.

Also relevant to this discussion are recent analyses of $\bar{\nu}_e$ disappearance signals from reactors [5] that have reported a signal at $> 2\sigma$. The light gray region of Fig. 1 shows the 99% allowed region for this disappearance in terms of Δm^2 versus $\sin^2 2\theta_{ee}$ from Ref. [5]. This is called the "reactor anomaly."

These two results are inconsistent with a three-neutrino model [7], but can be explained if one or more non-interacting ("sterile") neutrinos are introduced [1,6,7]. Other data which are included in the sterile neutrino global fits include low-level signals for ν_e appearance from sources [8,9], constraints in ν_e oscillations from comparisons of KARMEN and LSND cross-section measurements [10], and a large number of null signals from ν_μ oscillation experiments [1]. The Δm^2 versus $\sin^2 2\theta_{ee}$ allowed region at 99% C.L. for the $\bar{\nu}_e/\nu_e$ disappearance parameters from a combined fit to all oscillation data is indicated by the dark gray region [6], which we will call the "global fit" 99% C.L. allowed region.

II. ISODAR@KAMLAND

The IsoDAR@KamLAND experiment [11] is proposed to decisively address the global fit. This experiment pairs the IsoDAR source with the KamLAND detector. IsoDAR makes use of the same cyclotron design as the injector cyclotron for DAEδALUS to accelerate protons to 60 MeV/n. The protons impinge on a Beryllium target that produces copious neutrons. The target is surrounded by
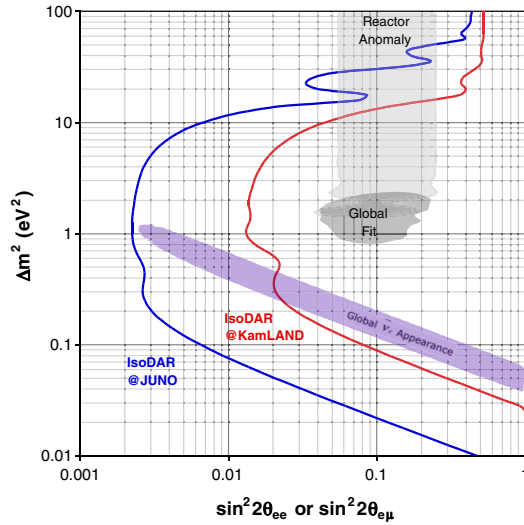
FIG. 1 (color online). Allowed regions and sensitivities for various experiments. The red and blue solid curves indicate Δm^2 vs. $\sin^2 2\theta_{ee}$ boundaries where the null oscillation hypothesis can be excluded at 5σ with IsoDAR@KamLAND and IsoDAR@JUNO experiments respectively for five-year data runs. Also, shown by the light (dark) gray areas are the 99% allowed regions for the reactor anomaly [5] (global oscillation fit [6]). Finally, the purple region corresponds to the Δm^2 vs. $\sin^2 2\theta_{e\mu}$ allowed region at 99% C.L. from a combined fit to all $\bar{\nu}_e$ appearance data [1].

a 99.99% isotopically pure ^{7}Li sleeve, where neutron capture on the ^{7}Li results in ^{8}Li production. The ^{8}Li isotopes then undergo β decay at rest to produce an isotropic $\bar{\nu}_e$ flux with an average energy of ~6.5 MeV and an endpoint of ~13 MeV.

In a liquid scintillator detector, events are observed through inverse beta decay, $\bar{\nu}_e + p \rightarrow e^+ + n$, which is easily tagged through positron (prompt-light)–neutron-capture coincidence. The energy of the neutrino can be reconstructed from the visible energy of the positron: $E_\nu = E_{e^+} + 0.8$ MeV. For KamLAND, the energy resolution of $6.4\%/\sqrt{E(\text{MeV})}$ is assumed in the sensitivity calculations [11]. The position can be reconstructed using the timing of arrival of the scintillation light at the photomultiplier tubes. Thus, this interaction allows for accurate reconstruction of L/E. The vertex resolution for KamLAND is assumed to be 12 cm$/\sqrt{E(\text{MeV})}$ [11]; however, the resolution is small compared to the variation of the extent of the neutrino source, which leads to an uncertainty in the neutrino flight path of 40 cm.

The analysis to obtain the oscillation sensitivity follows the method of Ref. [12] assuming a 5% normalization uncertainty and a 90% detection efficiency. Since L and E can be precisely measured, this analysis exploits the L/E dependence of the possible oscillation probability, $P = 1 - \sin^2 2\theta \sin^2[1.27\Delta m^2(L/E)]$, to estimate the $\Delta m^2 - \sin^2 2\theta$ regions where the null oscillation hypothesis can be excluded at the 5σ confidence level.

Less than one year of running this experiment, using the 1 kton KamLAND liquid scintillator detector, will indicate a signal if the global fit is due to oscillations, and with five years of running, will achieve the sensitivity at 5σ shown in Fig. 1 (red line). This result directly addresses the reactor disappearance signal up to $\Delta m^2 \sim 10$ eV^2. (The higher Δm^2 region is not accessible unless IsoDAR normalization, which is presently assumed to be 5% [11], can be greatly improved.)

This experiment also makes strong statements concerning the sterile neutrino model for the global fit (dark gray region). If no signal is observed, then the sterile neutrino model for this region is decisively ruled out. The value of running for five years or more, if an oscillation signal is observed, is that the L/E pattern can be mapped out to determine the number of sterile neutrinos involved in the oscillation [11].

New in this paper, we point out that the IsoDAR@KamLAND 5σ sensitivity also covers a substantial region of the $\bar{\nu}_e$ appearance anomaly. As shown in Fig. 1, after five years of running, the region with $\sin^2 2\theta_{e\mu} > 0.02$ will be explored. Thus this experiment can be used to explore a series of hypotheses. If a signal is observed, then the result may lie in the global fit allowed region, consistent with all of the allowed anomalies interpreted within a sterile neutrino model. Alternatively, the signal may be inconsistent with the global fit hypotheses, but lie within the global $\bar{\nu}_e$ appearance allowed region, indicating that the reactor anomaly is not due to oscillations, but that the LSND and MiniBooNE signals do arise from oscillations. Lastly, if no signal is observed, then according to the argument at the start of the report, $\sin^2 2\theta_{e\mu} > 0.02$ can be excluded in all models that respect
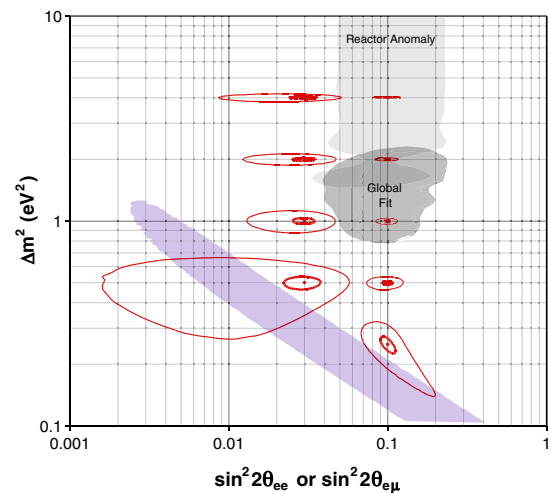

FIG. 2 (color online). Measurement capability of IsoDAR@ KamLAND for five years of running overlaid on the reactor anomaly (light gray) and global fit (dark gray) Δm^2-$\sin^2 2\theta_{ee}$ and the global $\bar{\nu}_e$ appearance (purple) Δm^2-$\sin^2 2\theta_{\mu e}$ allowed regions. 1 and 5σ measurement contours are indicated for various underlying true sets of parameters.

CPT. In Fig. 2, we present the measurement capability for five years of IsoDAR@KamLAND for various true values of the oscillation parameters.

III. ISODAR@JUNO

The IsoDAR source can also be paired with the 20 kton JUNO (formerly, Daya Bay II) detector. This is a liquid scintillator detector proposed for a reactor-based determination of the mass hierarchy [13]. To calculate the sensitivity, we repeat the analysis of IsoDAR@KamLAND described in the previous section, assuming that an IsoDAR antineutrino source is run with this much larger and more precise experiment.

The design of JUNO remains under discussion. For this analysis, we used the following parameters. The active target consists of an acrylic sphere of 34.5 m in diameter. The resulting fiducial volume is 20 ktons. The photomultiplier tubes are located at a diameter of 37.5 m. Beyond this is a 1.5 m veto region. This is assumed to be surrounded by rock. The depth is expected to be similar to that of KamLAND, $\sim$2000 m.w.e. The JUNO detector is being carefully designed to achieve excellent energy resolution of $3\%/\sqrt{E}$. We assume that the vertex resolution is the same as for KamLAND. The source requires substantial iron and concrete shielding to contain the neutrons that escape the ^{7}Li sleeve, which limits the proximity of IsoDAR to any large detector. For these studies, we assume a five-year run with an IsoDAR cyclotron source that accelerates deuterons. The deuteron option gives an enhanced rate ($\times$2.7) of antineutrino production as compared to the proton option described in Ref. [11] and also has a smaller size. For this analysis, we assume that the center of the source is located 5.0 m from the edge of the active region of JUNO. This leads to 27.5×10^6 inverse beta decay events reconstructed in the JUNO detector, assuming no oscillation.

Figure 1 shows the sensitivity curve for IsoDAR@JUNO (blue line), which completely covers the "global $\bar{\nu}_e$ appearance" region at greater than the 5σ CL. If no oscillation signal is observed, then all present anomalies, including LSND, will be excluded at 5σ as an indication of neutrino oscillations. Thus, this fits the call to decisively address all of the present high Δm^2 anomalies.

On the other hand, if an oscillation signal is observed, then precision measurements of the L/E dependence will allow the oscillations to be studied and quantified as shown in Fig. 3. The upper plot shows the oscillation signal for a point in the global fit allowed region, which would fit models if all of the present anomalies are verified as oscillations. The lower plot shows the signal for a
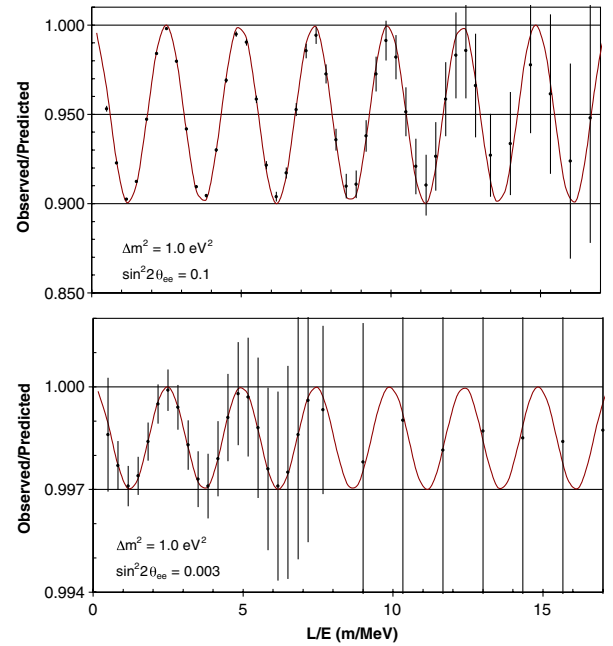

FIG. 3 (color online). The L/E dependence of the oscillation signature after five years of IsoDAR@JUNO running for $\Delta m^2 = 1.0 \text{ eV}^2$ and $\sin^2 2\theta = 0.1$ (top)–a solution within the Global Fit allowed region–and $\sin^2 2\theta = 0.003$ (bottom)–a solution within the Global $\bar{\nu}_e$ Appearance allowed region. The black points are the simulated data and the solid curve is the oscillation probability with no smearing in the reconstruction of position and energy.

solution within the global $\bar{\nu}_e$ appearance allowed region, which would fit models if only the LSND-MiniBooNE (antineutrino) anomalies are verified.

IV. CONCLUSION

In this paper, we have shown that IsoDAR@JUNO $\bar{\nu}_e$ disappearance experiment has sensitivity to cover the entire short-baseline appearance allowed region at 5σ. This allows for a decisive test of the question of whether the LSND signal arises from oscillations. We also show that IsoDAR@KamLAND can address a substantial region of the allowed space. These are elegant experiments because the only assumption is that *CPT* is a valid symmetry.

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