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 JUNO (Jiangmen Underground Neutrino Observatory) detector, has unprecedented sensitivity to $\bar{\nu}_e$ disappearance for oscillations at high $\Delta m^2$. Assuming CPT invariance, the sensitive region for $\bar{\nu}_e$ disappearance can be used to restrict the allowed parameter space of a $\bar{\nu}_e \to \bar{\nu}_e$ 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 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.

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I. INTRODUCTION

Within a model with 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 $\nu_e$ 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 $\nu_e$ 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 $\sin^2 2\theta_{ee} > \sin^2 2\theta_{\mu e}$, 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 $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance from 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 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 $\nu_\mu$ 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]. Fig. 1 shows the 99% confidence level (CL) allowed region for appearance from a joint fit to the data sets (purple), where $\Delta m^2$ 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 $\Delta m^2$ versus $\sin^2 2\theta_{ee}$ from Ref. [5]. This is called

![Graph](https://via.placeholder.com/150)
the “Reactor Anomaly.”

These two results are inconsistent with a three-neutrino model \[3\], but can be explained if one or more noninteracting (“sterile”) neutrinos are introduced \[1\] \[3\] \[7\]. Other data which are included in the sterile neutrino global fits include low-level signals for \(\nu_e\) appearance from sources \[5\] \[9\], constraints in \(\nu_e\) oscillations from comparisons of KARMEN and LSND cross-section measurements \[10\], and a large number of null signals from \(\nu_{\mu}\) oscillation experiments \[1\]. The \(\Delta m^2\) versus \(\sin^2 2\theta_{ee}\) allowed region at 99% CL for the \(\nu_e/\nu_e\) disappearance parameters from a combined fit to all oscillation data is indicated by the dark gray region \[7\], which we will call the “Global Fit” 99% CL 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 DAE5ALUS to accelerate protons to 60 MeV/n. The protons impinge on a Beryllium target that produces copious neutrons. The target is surrounded by a 99.99% isotopically pure \(^7\)Li sleeve, where neutron capture results in \(^8\)Li production. The \(^8\)Li isotopes then undergo \(\beta\) decay at rest to produce an isotropic \(\bar{\nu}_e\) flux with an average energy of \(\sim 6.5\) MeV and an endpoint of \(\sim 13\) MeV.

In a liquid scintillator detector, events are observed through inverse beta decay (IBD), \(\bar{\nu}_e + p \rightarrow e^+ + n\), 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: \(E_p = E_{e^+} + 0.8\) 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 (PMTs). Thus, this interaction allows for accurate reconstruction of \(L/E\). The vertex resolution for KamLAND is assumed to be \(12\text{cm}/\sqrt{E(\text{MeV})}\) \[11\]; 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. \[13\] 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 5\(\sigma\) confidence level.

In 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 5\(\sigma\) 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 \(\Delta m^2\) 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 report, we point out that the IsoDAR@KamLAND 5\(\sigma\) 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 \(\sin^2 2\theta_{ee} > 0.02\) 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, \(\sin^2 2\theta_{ee} > 0.02\) can be excluded in all models that respect \(CPT\). In Fig. 2 we present the measurement capability for five years of IsoDAR@KamLAND for various true values of the oscillation parameters.

FIG. 2: Measurement capability of IsoDAR@KamLAND for five years of running overlaid on the Reactor Anomaly (light gray) and Global Fit (dark gray) \(\Delta m^2-\sin^2 2\theta_{ee}\) and the Global \(\bar{\nu}_e\) Appearance (purple) \(\Delta m^2-\sin^2 2\theta_{ee}\) allowed regions. 1 and 5\(\sigma\) measurement contours are indicated for various underlying true sets of parameters.
KamLAND, by rock. The depth is expected to be similar to that of
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active target consists of an acrylic sphere of 34.5 m in di-
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Global $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance allowed region. The black points are
energy.

### 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 deter-
mination of the mass hierarchy [12]. To calculate the sen-
sitivity, we repeat the analysis of IsoDAR@KamLAND
described in the previous section, assuming that an Iso-
DAR 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 ac-
tive target consists of an acrylic sphere of 34.5 m in di-
ameter. The resulting fiducial volume is 20 ktons. The
PMTs 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 substan-
tial 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 as-
sume 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. [13] 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 $27.5 \times 10^6$ IBD
events reconstructed in the JUNO detector, assuming no
oscillation.

Fig. 3 shows the sensitivity curve for IsoDAR@JUNO
(blue line), which completely covers the “Global $\bar{\nu}_e$ Ap-
pearance” region at greater than the 5$\sigma$ CL. If no os-
cillation signal is observed, then all present anomalies,
including LSND, will be excluded at 5$\sigma$ as an indication
of neutrino oscillations. Thus, this fits the call to deci-
sively address all of the present high $\Delta m^2$ 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 veri-
fied as oscillations. The lower plot shows the signal for a solution within the Global $\bar{\nu}_e$ Appearance allowed region,
which would fit models if only the LSND-MiniBooNE (an-
tineutrino) anomalies are verified.

### IV. CONCLUSION

In this paper, we have shown that IsoDAR@JUNO $\bar{\nu}_e$
disappearance experiment has sensitivity to cover the en-
tire short-baseline appearance allowed region at 5$\sigma$. 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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[1] J. M. Conrad, C. M. Ignarra, G. Karagiorgi, M. H. Shae-
vitz and J. Spitz, Adv. High Energy Phys. 2013, 163897
(2013) arXiv:1207.4765 [hep-ex].
[2] A. Aguilar et al. [LSND Collaboration], Phys. Rev. D 64,
112007 (2001).
[3] B. Armbruster et al. [KARMEN Collaboration], Phys.
Rev. D 65, 112001 (2002) [hep-ex/0203021].
[4] A. A. Aguilar-Arevalo et al. [MiniBooNE Collaboration],
[5] G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier and A. Letourneau, Phys. Rev. D 83, 073006 (2011).

[6] M. Sorel, J. M. Conrad and M. Shaevitz, Phys. Rev. D 70, 073004 (2004).

[7] C. Giunti, M. Laveder, Y. F. Li and H. W. Long, “A Pragmatic View of Short-Baseline Neutrino Oscillations,” arXiv:1308.5288 [hep-ph].

[8] J. N. Abdurashitov et al. [SAGE Collaboration], Phys. Rev. C 80, 015807 (2009).

[9] F. Kaether, W. Hampel, G. Heusser, J. Kiko and T. Kirsten, Phys. Lett. B 685, 47 (2010).

[10] J. M. Conrad and M. H. Shaevitz, Phys. Rev. D 85, 013017 (2012) [arXiv:1106.5552 [hep-ex]].

[11] A. Bungau, et al., Phys. Rev. Lett. 109, 141802 (2012) [arXiv:1205.4419 [hep-ex]].

[12] Y. -F. Li, J. Cao, Y. Wang and L. Zhan, Phys. Rev. D 88, 013008 (2013) [arXiv:1303.6733 [hep-ex]].

[13] S. K. Agarwalla, J. M. Conrad and M. H. Shaevitz, JHEP 1112, 085 (2011) [arXiv:1105.4984 [hep-ph]].