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How accurately can one test CPT conservation with reactor and solar neutrino experiments?

John N. Bahcall [a], V. Barger [b], Danny Marfatia [c]

[a] *Institute for Advanced Study, Princeton, NJ 08540, USA*
[b] *Department of Physics, University of Wisconsin-Madison, WI 53706, USA*
[c] *Department of Physics, Boston University, Boston, MA 02215, USA*

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Abstract

We show that the combined data from solar neutrino experiments and from the KamLAND reactor neutrino experiment can establish an upper limit on, or detect, potential CPT violation in the neutrino sector of order 10^{-20} to 10^{-21} GeV. © 2002 Elsevier Science B.V. All rights reserved.

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A number of previous authors have discussed the possibility of observing hypothesized CPT violation through neutrino oscillation phenomena [1–6]. Stimulated by this fascinating possibility, we investigate here a related question: how accurately can one use solar and reactor neutrino measurements to set an upper limit on CPT violation in the neutrino sector? In this Letter, therefore, we assume CPT violation is small and determine the upper limit that can be set on the magnitude of possible violations of CPT using existing solar neutrino data and reactor neutrino data that will soon be available [7]. Of course, CPT violation may be detected if differences between neutrino and antineutrino propagation are observed that are larger than the sensitivity limit derived here.

Solar neutrino experiments give information about the propagation characteristics of neutrinos, primarily concerning the two mass eigenstates with the smallest absolute difference in their masses. Reactor experiments, such as KamLAND [7], can give similar information about antineutrinos. Similar particle energies (1–10 MeV) are involved in both sets of experiments.

If CPT is conserved, then the survival probabilities as a function of energy, $P(E)$, must be identical in vacuum for neutrinos and for antineutrinos. The reader will easily recognize that the identity of the survival probabilities for neutrinos and antineutrinos is a special case of the general result of CPT conservation: $P_{\alpha,\beta} = P_{\bar{\beta},\bar{\alpha}}$.

We shall show below that solar neutrino experiments [8] plus the reactor experiment KamLAND [7] will, taken together, be sufficiently accurate to test sig-

E-mail addresses: jnb@sns.ias.edu (J.N. Bahcall), barger@pheno.physics.wisc.edu (V. Barger), marfatia@physics.bu.edu (D. Marfatia).

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nificantly the equality of survival probabilities and, if CPT is conserved, to set a stringent upper limit on some conjectured forms of the violation.

First, we want to make some order of magnitude comparisons in order to motivate the fact that the KamLAND/solar neutrino data are precise enough to give interesting limits on CPT. The best established limit on CPT violation in the baryon sector is the well-known upper limit on the mass difference between K and $\overline{\mathrm{K}}$ [9]:

$$|m_{\mathrm{K}} - m_{\overline{\mathrm{K}}}| < 4.4 \times 10^{-19}\ \mathrm{GeV} \quad (90\%\ \mathrm{C.L.}). \tag{1}$$

How does this upper limit on the K–$\overline{\mathrm{K}}$ mass difference compare with the characteristic range of sensitivity of solar neutrino and reactor neutrino experiments?

Two energy parameters naturally affect the sensitivity of solar and reactor neutrino probes of CPT violation. The first parameter is just the time available for rare processes to occur, which is inversely proportional to the separation, L, between the source of the reactor neutrinos and the detector. The energy scale which results from this consideration is

$$\delta\mathrm{CPT} \sim \hbar c/L \sim 10^{-21}(200\ \mathrm{km}/L)\ \mathrm{GeV}, \tag{2}$$

where for specificity we have used the characteristic reactor-detector distance that applies to KamLAND, $L \sim 200$ km. The sensitivity also depends upon the frequency of the neutrino oscillations, which is determined by the neutrino energy and the difference of squared neutrino masses. Thus we have a second parameter affecting the sensitivity of CPT measurements involving solar neutrinos,

$$\delta\mathrm{CPT} \sim \delta m^2/E \lesssim 10^{-19}\ \mathrm{GeV}. \tag{3}$$

In obtaining the numerical form of Eq. (3), we used $\delta m^2 < 4 \times 10^{-4}\ \mathrm{eV}^2$ for solar neutrino oscillations [10].

Comparing the dimensional estimates of δCPT from Eqs. (2) and (3) with the K–$\overline{\mathrm{K}}$ mass difference, we see that solar and reactor neutrino observations can indeed set a sensitive upper limit on (or perhaps measure) CPT violation. The δCPT sensitivity for solar and reactor neutrinos is expected to be one or two orders of magnitude more sensitive than the existing upper limit to the K–$\overline{\mathrm{K}}$ mass difference.

The basic strategy we use in evaluating the sensitivity of solar neutrino and reactor experiments to CPT violation is to first suppose that CPT is exactly conserved. Then we find the maximum difference between the allowed survival probabilities for neutrinos and antineutrinos that is consistent with the expected experimental uncertainties. To be conservative and specific, we adopt for solar neutrinos the currently allowed region (in δm_ν^2 and $\sin^2 2\theta_\nu$ space) permitted by existing experiments [10] (see also [11]). For the KamLAND experiment, we assume that the parameter space that will be found for antineutrino oscillations is a fraction [12] $\epsilon \leqslant 1$ of the allowed solar neutrino parameter space. We assume that the correct solar neutrino solution is the favored LMA solution, since if CPT is conserved KamLAND will be sensitive to antineutrino oscillations only if the LMA solution has been chosen by nature.

We characterize the general sensitivity of reactor and solar neutrino experiments to CPT violation by the quantity

$$\langle\Delta\mathrm{CPT}\rangle = 2\frac{|\langle P_{\nu\nu}(E,L) - P_{\bar{\nu}\bar{\nu}}(E,L)\rangle|}{\langle P_{\nu\nu}(E,L) + P_{\bar{\nu}\bar{\nu}}(E,L)\rangle}. \tag{4}$$

Here both $P_{\nu\nu}(E,L)$ and $P_{\bar{\nu}\bar{\nu}}(E,L)$ are computed for the same experimental situation, but with different values for (δm_ν^2, $\sin^2 2\theta_\nu$) and for ($\delta m_{\bar{\nu}}^2$, $\sin^2 2\theta_{\bar{\nu}}$). The average in Eq. (4) is carried out over reactor distances L and over all neutrino and antineutrino energies E.

An experimental upper limit on $\langle\Delta\mathrm{CPT}\rangle$ can be used to test arbitrary future conjectures of CPT violation. Practically speaking, $\langle\Delta\mathrm{CPT}\rangle$ is the number of events observed in a reactor (antineutrino) oscillation minus the number of events that would have been observed if neutrinos and antineutrinos had exactly the same oscillation parameters, divided by the average number of neutrino and antineutrino events.

We have evaluated numerically the maximum value of $\langle\Delta\mathrm{CPT}\rangle$ that results from the mismatch of the average survival probabilities computed from two different points within the same allowed neutrino and antineutrino oscillation regions, both of which are assumed coincident with the current 3σ allowed parameter domain for solar neutrinos ($\epsilon = 1$). We find for 10^6 randomly sampled pairs,

$$\langle\Delta\mathrm{CPT}\rangle \leqslant 1.1 \quad (3\sigma\ \mathrm{limit}). \tag{5}$$

The maximum value is achieved for the pairs of neutrino parameters, $\delta m_\nu^2 = 3.3 \times 10^{-5}\ \mathrm{eV}^2$, $\sin^2 2\theta_\nu = 0.98$; $|\delta m_{\bar{\nu}}^2| = 6.4 \times 10^{-5}\ \mathrm{eV}^2$, $\sin^2 2\theta_{\bar{\nu}} = 0.6$, which lie near the boundary of the currently allowed solar neutrino oscillation region. Matter effects that simulate CPT violation, and which arise from the different interaction strengths of neutrinos and antineutrinos with electrons in the earth, would contribute ~ 0.1 to $\langle \Delta\mathrm{CPT} \rangle$.

We have tested the sensitivity of the upper limit given in Eq. (5) to the assumed size, characterized by ϵ, of the allowed parameter domain for the KamLAND experiment. Even choosing ϵ as small as 0.25 does not appreciably change the upper limit that is obtainable for $\langle \Delta\mathrm{CPT} \rangle$. Note that this bound applies for any source of CPT violation, Lorentz symmetry violating or preserving. It is argued in Ref. [13] that CPT violation necessarily implies violation of Lorentz invariance.

To illustrate the power of the combined KamLAND reactor and solar neutrino experiments, we consider an effective interaction which has been discussed by Coleman and Glashow [2], and by Colladay and Kostelecky [14], that violates both Lorentz invariance and CPT invariance. The interaction is of the form

$$\mathcal{L}(\Delta\mathrm{CPT}) = \bar{\nu}_L^{\alpha} b_{\mu}^{\alpha\beta} \gamma_{\mu} \nu_L^{\beta}, \tag{6}$$

where α, β are flavor indices, L indicates that the neutrinos are left-handed, and b is a Hermitian matrix. We discuss the special case with rotational invariance in which b_0 and the mass-squared matrix are diagonalized by the same mixing angle. We also assume that there are only two interacting neutrinos (or antineutrinos) and follow previous authors in defining η as the difference of the phases in the unitary matrices that diagonalize δm^2 and the CPT odd quantity δb, which is the difference between the two eigenvalues of b_0.

When the relative phase $\eta = 0$, the expression for the survival probabilities of neutrino and antineutrinos take on an especially simple form, see [3]. We find the upper limit that could be established for δb if the allowed antineutrino oscillation region determined by KamLAND were equal to the current allowed solar neutrino oscillation region. In agreement with an approximate analytic solution for this case of the form given in Eq. (2), we find by a numerical exploration that

$$\delta b < 1.6 \times 10^{-21}\ \mathrm{GeV}, \quad \eta = 0 \quad (3\sigma\ \text{limit}). \tag{7}$$

It will be difficult to improve this limit by an order of magnitude because earth matter effects, which simulate Lorentz non-invariant CPT violation, are comparable to intrinsic CPT violation for

$$\delta b \sim \sqrt{2}\, G_F N_e \approx 1.5 \times 10^{-22}\ \mathrm{GeV}, \tag{8}$$

where N_e is the electron number density in the earth's crust.

If the relative phase $\eta = \pi/2$, the neutrino masses and the CPT violating term appear in important terms in the expressions for the survival probabilities in the form $[(\delta m^2/E) + 2\delta b]$. We again explore numerically an assumed KamLAND allowed region equal to the current allowed region for solar neutrino oscillations. We find

$$\delta b < 3.1 \times 10^{-20}\ \mathrm{GeV},$$
$$\eta = \pi/2 \quad (3\sigma\ \text{limit}), \tag{9}$$

in good agreement with the dimensional estimate given in Eq. (3). The limit in Eq. (9) could be improved by about a factor of three if solar neutrino experiments exclude $\delta m_{\nu}^2 > 10^{-4}\ \mathrm{eV}^2$ and KamLAND also finds $|\delta m_{\bar{\nu}}^2| < 10^{-4}\ \mathrm{eV}^2$.

We conclude that the combined data from solar and reactor neutrino experiments can test accurately the conservation of CPT in the neutrino sector. If a reactor experiment like KamLAND finds antineutrino survival probabilities outside the range expected for neutrinos (based on solar neutrino experiments, cf. Eqs. (5), (7) and (9), then this will be evidence for a violation of CPT.

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