Hint of CPT Violation in Short-Baseline Electron Neutrino Disappearance

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Abstract. We analyzed the electron neutrino data of the Gallium radioactive source experiments and the electron antineutrino data of the reactor Bugey and Chooz experiments in terms of neutrino oscillations. We found a hint of a CPT-violating asymmetry of the effective neutrino and antineutrino mixing angles.

The GALLEX [1–3] and SAGE [4–7] Gallium solar neutrino experiments have been tested with intense artificial $^{51}$Cr and $^{37}$Ar radioactive sources placed inside the detectors. The results of these “Gallium radioactive source experiments” indicate a ratio $R$ of measured and predicted $^{71}$Ge event rates which is smaller than unity:

\[
R_{\text{GALLEX-Cr}1}^B = 0.953 \pm 0.11, \quad (1)
\]
\[
R_{\text{GALLEX-Cr}2}^B = 0.812^{+0.10}_{-0.11}, \quad (2)
\]
\[
R_{\text{SAGE-Cr}}^B = 0.95 \pm 0.12, \quad (3)
\]
\[
R_{\text{SAGE-Ar}}^B = 0.791^{+0.084}_{-0.078}. \quad (4)
\]

The average ratio is [8]

\[
R_{\text{Ga}}^B = 0.86^{+0.05}_{-0.05}. \quad (5)
\]

Thus, the number of measured events is about 2.8$\sigma$ smaller than the prediction. This is the “Gallium anomaly” [8–16].

As indicated by the “$B$” subscript, the ratios in Eqs. (1)–(5) have been calculated with respect to the rate estimated using the best-fit values of the cross sections of the detection process

\[
\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^- \quad (6)
\]

calculated by Bahcall [17] for $^{51}$Cr and $^{37}$Ar neutrinos. The uncertainties of these cross sections are not taken into account in the experimental ratios in Eqs. (1)–(4). These uncertainties are large [17–19], because only the cross section of the transition from the ground state of $^{71}$Ga to the ground state of $^{71}$Ge is known with precision from the measured rate of electron capture decay of $^{71}$Ge to $^{71}$Ga. Electron neutrinos produced by $^{51}$Cr and $^{37}$Ar radioactive sources can
be absorbed also through transitions from the ground state of $^{71}$Ga to two excited states of $^{71}$Ge at 175 keV and 500 keV, with cross sections which are inferred using a nuclear model from $p + ^{71}$Ga $\rightarrow ^{71}$Ge $+ n$ measurements [20].

Hence, at least part of the deficit of measured events with respect to the prediction could be explained by an overestimation of the transitions to the two excited states of $^{71}$Ge [6, 7, 21]. However, since the contribution of the transitions to the two excited states of $^{71}$Ge is only 5\% [17], even the complete absence of such transitions would reduce the ratio of measured and predicted $^{71}$Ge event rates to about 0.91 $\pm$ 0.05, leaving an anomaly of about 1.7\% [14].

We think that for a correct assessment of the statistical significance of the Gallium anomaly simple approaches based on either accepting the Bahcall cross section without taking into account its uncertainty or suppressing without theoretical motivations the transitions to the two excited states of $^{71}$Ge are insufficient. A correct assessment of the statistical significance of the Gallium anomaly can be done by taking into account the large uncertainties of the transitions to the two excited states of $^{71}$Ge [17–19]. The most reliable estimate of these transitions and their uncertainties have been done by Haxton in Ref. [19], leading to cross sections for $^{51}$Cr and $^{37}$Ar neutrinos which are larger than the Bahcall cross sections [8]. This leads to an enhancement of the Gallium anomaly. However, since uncertainties of the cross sections are large, a correct assessment of the statistical significance of the Gallium anomaly requires an accurate statistical treatment.

In Ref. [8] we calculated the average ratio $R_{Ga}^{Ga}$ of measured and predicted $^{71}$Ge event rates using the Haxton cross sections and their uncertainties:

$$ R_{Ga}^{Ga} = 0.76^{+0.09}_{-0.08}. \quad (7) $$

We found that the probability of $R_{Ga}^{Ga} < 1$ is 99.86\% (3.0\% anomaly), slightly larger than the probability of $R_{B}^{Ga} < 1$, which is 99.75\% (2.8\% anomaly).

For the four individual Gallium radioactive source experiments, using the same method, we obtained [8]

$$ R_{GALLEX-Cr1}^{GALLEX-Cr} = 0.84^{+0.13}_{-0.12}, \quad (8) $$

$$ R_{GALLEX-Cr2}^{GALLEX-Cr} = 0.71^{+0.12}_{-0.11}, \quad (9) $$

$$ R_{SAGE-Cr}^{SAGE-Cr} = 0.84^{+0.14}_{-0.13}, \quad (10) $$

$$ R_{SAGE-Ar}^{SAGE-Ar} = 0.70^{+0.10}_{-0.09}. \quad (11) $$

Since the Gallium anomaly is confirmed by the new statistical analysis which takes into account the uncertainty of the detection cross section, it is plausible that it is due to a physical mechanism. In the following, we consider the possibility of electron neutrino disappearance due to short-baseline oscillations [9–15, 22] (another explanation based on quantum decoherence in neutrino oscillations has been proposed in Ref. [23]).

We consider the electron neutrino survival probability

$$ P_{\nu_e \rightarrow \nu_e}^{SBL}(L, E) = 1 - \sin^2 2\theta, \sin^2 \left( \frac{\Delta m^2 L}{4E} \right), \quad (12) $$

where $\theta$ is the mixing angle, $\Delta m^2$ is the squared-mass difference, $L$ is the neutrino path length and $E$ is the neutrino energy. This survival probability is effective in short-baseline (SBL) experiments in the framework of four-neutrino mixing schemes (see Refs. [24–27]), which are the simplest extensions of three-neutrino mixing schemes which can accommodate the two measured small solar and atmospheric squared-mass differences $\Delta m^2_{\text{SOL}} \approx 8 \times 10^{-5}$ eV$^2$ and $\Delta m^2_{\text{ATM}} \approx 2 \times 10^{-3}$ eV$^2$ and one larger squared-mass difference for short-baseline neutrino
Eq. (13) gives the fit of the four data in Eqs. (8)–(11). In fact, the best-fit values of the oscillation parameters are

\[
\sin^2 2\theta_{\nu, \text{bf}} = 0.46, \quad \Delta m^2_{\nu, \text{bf}} = 2.24 \text{ eV}^2.
\]  

The null hypothesis of no oscillations is disfavored at 99.95% C.L. (3σ) by \(\Delta \chi^2 = 15.4\). This indication in favor of neutrino oscillations is slightly stronger than the indication in favor of the Gallium anomaly obtained from Eq. (7) (3σ), because neutrino oscillations give different values for the ratio \(R\) in GALLEX and in the two SAGE experiments, which allow for a better fit of the four data in Eqs. (8)–(11). In fact, the best-fit values of the oscillation parameters in Eq. (13) give \(R^{\text{GALLEX-Cr1}} = 0.77\), \(R^{\text{SAGE-Cr}} = 0.76\) and \(R^{\text{SAGE-A}} = 0.75\).

From Fig. 1 one can see that the marginal distributions of \(\sin^2 2\theta_{\nu}\) and \(\Delta m^2\) indicate that, at 3σ,

\[
\sin^2 2\theta_{\nu} \gtrsim 0.1, \quad \Delta m^2 \gtrsim 0.2 \text{eV}^2.
\]  

These bounds indicate that the short-baseline disappearance of electron antineutrinos is larger than that of electron antineutrinos, which is bounded by the results of reactor neutrino experiments [12–14, 28, 29]. Our analysis of the data of the Bugey and Chooz reactor antineutrino experiments in terms of the effective short-baseline electron antineutrino survival probability

\[
P^{\text{SBL}}_{\bar{\nu}_e \rightarrow \bar{\nu}_e}(L, E) = 1 - \sin^2 2\theta_{\bar{\nu}} \sin^2 \left(\frac{\Delta m^2_{\bar{\nu}} L}{4E}\right),
\]  

where \(\theta_{\bar{\nu}}\) is the effective antineutrino mixing angle and \(\Delta m^2_{\bar{\nu}}\) is the effective antineutrino squared-mass difference, gives the best-fit values [14]

\[
\sin^2 2\theta_{\bar{\nu}, \text{bf}} = 0.042, \quad \Delta m^2_{\bar{\nu}, \text{bf}} = 1.85 \text{ eV}^2.
\]  

Figure 1. Results of the fit of the data of the Gallium radioactive source experiments [8]. The best-fit point is indicated by a cross.

Figure 2. Results of the fit of the data of reactor and Tritium \(\beta\)-decay experiments [14]. The best-fit point is indicated by a cross.
Figure 2 shows the allowed regions in the $\sin^2 2\beta$ plane [30]. The best-fit point is shown by a cross.

Figure 3. Allowed regions in the $A_{\sin^2 2\theta}^{\text{CPT}}$ -- $A_{\Delta m^2}^{\text{CPT}}$ plane [16].

Figure 4. Marginal $\Delta \chi^2$ for $A_{\sin^2 2\theta}^{\text{CPT}}$ [16].

Figure 2 shows the allowed regions in the $\sin^2 2\theta$ -- $\Delta m^2$ plane and the marginal $\Delta \chi^2$'s, obtained taking into account also the constraints on the mixing given by the results of the Mainz and Troitsk Tritium $\beta$-decay experiments [14].

CPT symmetry implies that the survival probabilities of neutrinos and antineutrinos are equal (see Ref. [30]), i.e. $\sin^2 2\theta_{\nu} = \sin^2 2\theta_{\bar{\nu}}$ and $\Delta m^2_{\nu} = \Delta m^2_{\bar{\nu}}$. Figs. 1 and 2 show that $\sin^2 2\theta_{\nu}$ is likely to be larger than about 0.1, whereas $\sin^2 2\theta_{\bar{\nu}}$ is likely to be smaller than about 0.1. The incompatibility of neutrino and antineutrino data in the case of CPT symmetry is quantified by a 0.2% parameter goodness-of-fit [31]. Hence, we have a hint of CPT violation in short-baseline $\nu_e$ and $\bar{\nu}_e$ disappearance [16] which could be complementary to that found recently in the MINOS long-baseline $\nu_{\mu}$ and $\bar{\nu}_{\mu}$ appearance experiment [32].

Analyzing the Gallium data and the reactor plus Tritium data in terms of the CPT mass and mixing asymmetries

$$A_{\Delta m^2}^{\text{CPT}} = \Delta m^2 - \Delta m^2_{\nu},$$

$$A_{\sin^2 2\theta}^{\text{CPT}} = \sin^2 2\theta_{\nu} - \sin^2 2\theta_{\bar{\nu}},$$

we obtained the best-fit values [16]

$$A_{\sin^2 2\theta}^{\text{CPT}}^{\text{bf}} = 0.42, \quad A_{\Delta m^2}^{\text{CPT}}^{\text{bf}} = 0.37 \text{eV}^2.$$ (19)

The allowed regions in the $A_{\sin^2 2\theta}^{\text{CPT}}$ -- $A_{\Delta m^2}^{\text{CPT}}$ plane are shown in Fig. 3. We used a logarithmic scale for $A_{\sin^2 2\theta}^{\text{CPT}}$, considering only the interval $10^{-3} \lesssim A_{\sin^2 2\theta}^{\text{CPT}} \lesssim 1$ which contains all the allowed regions. For $A_{\Delta m^2}^{\text{CPT}}$, we used an antisymmetric logarithmic scale, which allows us to show both positive and negative values of $A_{\Delta m^2}^{\text{CPT}}$, enlarging the region of small values of $A_{\Delta m^2}^{\text{CPT}}$ between 0.1 and 1 eV^2.

The best-fit value ($A_{\Delta m^2}^{\text{CPT}}$)_{bf} of the mass asymmetry is small, but Fig. 3 shows that in practice any value of the mass asymmetry is allowed, with a slight preference for positive values. On the other hand, we obtain a very interesting result for the mixing asymmetry: the best-fit value ($A_{\sin^2 2\theta}^{\text{CPT}}$)_{bf} is large and positive and Fig. 3 shows that zero or negative values are disfavored.
From Fig. 3 one can see that the smallest value of $A_{\sin^2 2\theta}^{\text{CPT}}$ included in the $3\sigma$ allowed region is about 0.005 at $A_{\Delta m^2}^{\text{CPT}} \simeq -0.15$ eV$^2$. However, since in practice $A_{\Delta m^2}^{\text{CPT}}$ is not bounded, the statistically reliable limits on $A_{\sin^2 2\theta}^{\text{CPT}}$ are given by the marginal $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$ function for $A_{\sin^2 2\theta}^{\text{CPT}}$, depicted in Fig. 4. One can see that $A_{\sin^2 2\theta}^{\text{CPT}} > 0.055$ at $3\sigma$.

The marginal $\Delta \chi^2$ of a null asymmetry ($A_{\sin^2 2\theta}^{\text{CPT}} = 0$) is 12.0, with an associated p-value of 0.05%. Hence, there is an indication of a positive asymmetry $A_{\sin^2 2\theta}^{\text{CPT}}$ at a level of about $3.5\sigma$.

The indication in favor of a CPT asymmetry that we have found is robust, because it is obtained by confronting the observations on the disappearance of electron neutrino and antineutrino, which should be equal if the CPT symmetry is not violated. We considered the simplest case of a difference of the effective squared-masses and mixings of neutrinos and antineutrinos. The analysis of the data in the framework of other, more complicated, models would lead to a similar indication of a CPT asymmetry in the space of the parameters of the specific model under consideration.

The short-baseline disappearance of electron neutrinos can be tested in the future with new Gallium radioactive source experiments, as that proposed in Ref. [15]. The Borexino collaboration is studying the possibility of a radioactive source experiment [33] which could provide a “smoking gun” signal by measuring the oscillation pattern inside the detector. By using radioactive sources of electron neutrinos and antineutrinos it may be possible to test the CPT asymmetry. Some possible measurements with radioactive sources and different detector types has been recently discussed in Ref. [34].

Other experiments under study which can test the CPT asymmetry by measuring the disappearance of both electron neutrinos and antineutrinos with sources which emit well-known neutrino and antineutrino fluxes and detection processes with well-known cross sections are near-detector beta-beam [35] and neutrino factory [36,37] experiments.

In conclusion, we have found an indication of a CPT-violating asymmetry in the short-baseline disappearance of electron neutrinos and antineutrinos by confronting the neutrino data of the Gallium radioactive source experiments and the antineutrino data of the reactor Bugey and Chooz experiments. Considering the simplest case of a difference of squared-masses and mixings of neutrinos and antineutrinos, we found that the squared-mass asymmetry is practically not bounded, whereas the mixing asymmetry is positive with a statistical significance of about $3.5\sigma$.

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