RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 49, NUMBER 2 FEBRUARY 1994

Improved limits on time-reversal-violating, tensor weak couplings

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(Received 9 August 1993)

Improved upper limits are derived on the possible existence of the T-violating (time-reversal) part of the tensor weak coupling constants, C_T and C'_T. The previous measurements of the electron-neutrino directional correlation in the nuclear beta decay of ^{6}He are analyzed for sensitivity to T-violating couplings. The results of the analysis are presented in the context of previous beta decay limits on T-violating tensor couplings and compared to somewhat similar limits from precision electric dipole moment experiments.

PACS number(s): 11.30.Er, 23.40.Bw, 12.15.Ji

Thirty years ago, CP violation (charge conjugation-parity) was discovered to occur in the decay of neutral kaons [1]. Since that time the neutral kaon observations have become quite precise [2]. However, the underlying mechanism behind the observed CP-violation is still not theoretically understood [3]. This lack of understanding is due, at least in part, to the absence of confirming data on CP violation or equivalent T violation (time-reversal) from systems other than neutral kaons.

The equivalence of T violation and CP violation is generally assumed on the basis of the CPT theorem [4], which states that under certain very general conditions, CPT is conserved for all interactions. In fact, the neutral kaon data give experimental confirmation that CPT is conserved, thus demonstrating T violation, at the same level as CP violation, independent of the CPT theorem [5].

A wide variety of systems (high energy, nuclear, atomic, solid-state) have been used to experimentally search for CP and T violations, all except neutral kaons without avail [6]. In particular, T-violating weak interaction couplings have been tightly constrained by experiments using nuclear beta decay [7,8]. A 1985 analysis [9] by Skalsey and Hatamian used nuclear beta decay data to set the first limits on T-violating tensor couplings (defined below) in the charged weak current. These limits were obtained from beta longitudinal polarization (P_L) measurements. The leading order sensitivity of P_L is to T-conserving quantities. The T-violating tensor limits were obtained by considering Coulomb correction terms [10] to P_L (i.e., terms due to the nuclear Coulomb field that are dependent on the quantity αZ; α—the fine structure constant, and Z—the daughter nuclear charge) in Gamow-Teller decays. In this paper, improved limits on T-violating tensor couplings are derived from the electron-neutrino (e-ν) directional correlation results as measured [11] in the pure Gamow-Teller decay of ^{6}He.

The most general form for the current-current weak interaction, beta decay Hamiltonian is usually written [12] as

$$H_w = \frac{G_w}{\sqrt{2}} \sum_j (\bar{\Psi}_p O_j \Psi_n)[\bar{\Psi}_e O_j (C_j + C'_j \gamma_5)\Psi_\nu] + \text{H.c.} \tag{1}$$

where G_w is the overall weak interaction coupling constant, $j = S, V, T, A$ (scalar, vector, tensor, axial vector couplings), and

$$O_S = 1, \quad O_V = \gamma_\mu, \\ O_T = -\frac{i}{2\sqrt{2}}(\gamma_\mu\gamma_\lambda - \gamma_\lambda\gamma_\mu), \quad O_A = -i\gamma_\mu\gamma_5. \tag{2}$$

The pseudoscalar coupling, $O_p = \gamma_5$, vanishes in lowest order since O_p couples to the relativistic components of nucleon wave functions. Vector and scalar contribute to Fermi decays (with spin $S_{e\nu} = 0$), and axial vector and tensor contribute to Gamow-Teller decays ($S_{e\nu} = 1$). A nonzero imaginary part for any C_j or C'_j would be evidence for T violation, in particular, in this work, $\text{Im}C_T$ and $\text{Im}C'_T$. The limitation of only five permissible couplings arises from requiring rotational and Lorentz invariance.

The standard electroweak model reduces Eq. (1) to the well-known "$V-A$" (vector minus axial vector), two-component massless neutrino theory with

$$C_V = C'_V, \quad C_A = C'_A \ , \tag{3}$$

$$|C_S| = |C'_S| = |C_T| = |C'_T| = \text{Im}C_V = \text{Im}C_A = 0 \ . \tag{4}$$

Any inequality in Eq. (3) would imply a right-handed current admixture (sometimes called "$V + A$") to the usual, totally left-handed $V-A$ current. Experimental limits on right-handed quantities can be found in Ref. [13]. Upper limits on the numerous equations in Eq. (4) have been determined under a variety of assumptions about the behavior of non-$V-A$ couplings. A least-squares adjustment of the real part of all the beta decay coupling constants [$\text{Re}(C_j)$ and $\text{Re}(C'_j)$] and compilation of relevant experimental data are presented in Ref. [12]. The imaginary parts (T violating) of the various couplings [$\text{Im}(C_j)$ and $\text{Im}(C'_j)$] are experimentally excluded: V and A in Ref. [7]; T in Ref. [9]; and finally improved limits on S are considered in a recent paper [8]. The same general method used in Ref. [8] to improve the limits on scalar couplings is applied here to improve the limits in Ref. [9] on T-violating tensor couplings.

The quantity of interest here and in Ref. [8] is the directional correlation between e and ν in nuclear beta decay, traditionally [10] called a. Measurements of a involve detecting nuclear recoils or β-delayed particle emissions. To constrain tensor T-violating couplings, analysis of a pure Gamow-Teller decay (e.g., ^{6}He β^- decay) is appropriate, for which a is [10]

$$a = -\frac{1}{3}\frac{|C_A|^2 + |C_A'|^2 - |C_T|^2 - |C_T'|^2 - \frac{\alpha Z m}{P_e} 2\,\mathrm{Im}(C_T C_A^* + C_T' C_A'^*)}{|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2} \tag{5}$$

where m and P_e are the electron mass and momentum.

This most general form for a can be simplified considerably with a few reasonable approximations and arguments. First, recalling Eq. (3), we set $C_A = C_A'$ (no right-handed currents). This assumption makes the Coulomb correction term to a (i.e., the term with αZ) identical to the term limited in Ref. [9]:

$$\mathrm{Im}(C_T C_A'^* + C_T' C_A^*) = -0.063 \pm 0.052. \tag{6}$$

(As in Ref. [9], all errors quoted in this paper are 1σ.) Evaluating, we find that the Coulomb correction term in Eq. (5) makes a negligible contribution to the subsequent analysis, primarily because the coefficient of the imaginary term in Eq. (5) is less than 10^{-2} for ^{6}He decay. Finally, Eq. (5) reduces to the somewhat simplified form of

$$a = -\frac{1}{3}\frac{1 - \frac{|C_T|^2}{2|C_A|^2} - \frac{|C_T'|^2}{2|C_A|^2}}{1 + \frac{|C_T|^2}{2|C_A|^2} + \frac{|C_T'|^2}{2|C_A|^2}}. \tag{7}$$

Equation (7) can be equated to the experimental data obtained from ^{6}He decay [11]:

$$a(^6\mathrm{He}) = -0.3343 \pm 0.0030, \tag{8}$$

to yield the limits:

$$|C_T|^2 + |C_T'|^2 = -0.0048 \pm 0.0143, \tag{9}$$

where $|C_A|^2 = 1.593$. To interpret Eq. (9) in terms of imaginary tensor couplings, we must account for the real parts of C_T and C_T'. The analysis of Ref. [12] summarizes the least squares adjustment procedure for all the real parts of the coupling constants using data until 1984. The most recent updated values include:

$$\mathrm{Re}C_T = \mathrm{Re}C_T' = 0.000 \pm 0.048, \tag{10}$$

taken from Table II of Ref. [8].

Combining Eqs. (9) and (10) yields:

$$[\mathrm{Im}C_T]^2 + [\mathrm{Im}C_T']^2 = -0.0048 \pm 0.0147, \tag{11}$$

directly limiting T-violating tensor couplings.

Notice that the central value in Eq. (11) is in a physically unallowed region (i.e., negative) even for T-violating couplings. A similar situation was encountered in the analysis in Ref. [8], but in our case since the central value is much closer to zero compared to the standard error, we simply take the square root of the error in Eq. (11) to yield:

$$|C_T| \le 0.121; |C_T'| \le 0.121 \tag{12}$$

For comparison, Fig. 1 displays the previous limits from Ref. [9] [Eq. (6) here] and the new limits derived in this paper [Eq. (11)]. Clearly, a substantial reduction has been obtained in the range of permitted values for T-violating tensor couplings.

In conclusion, much tighter limits on T-violating tensor couplings have been obtained from considering e-ν correlation measurements from ^{6}He decay. The limiting values are comparable in magnitude to the limits on the analogously defined T-violating scalar couplings [8,14] and complement those results. The major impact of the new, tighter tensor limits is to eliminate the possibility of large, but canceling values for ImC_T and ImC_T' as permitted by the previous limits.

The limits presented in Fig. 1 can also be compared

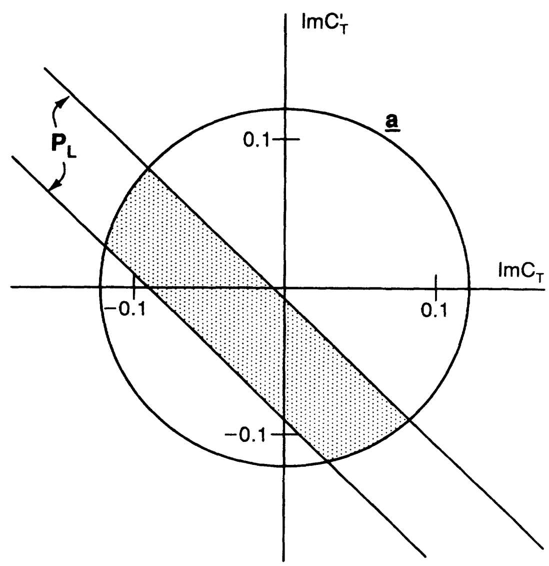

FIG. 1. Improved limits on T-violating tensor couplings. The area between the two straight parallel lines gives the permitted values for ImC_T and ImC_T' from the 1985 analysis [9] of P_L measurements [Eq. (6)], in principle, the area extending to infinity in two directions. The circle denotes the constraints [Eq. (11)] arising from the present analysis of the ^{6}He a measurement [11]. The shaded intersecting region is the present best direct limits on the permitted values for T-violating tensor couplings.

with the results of atomic electric dipole moment (EDM) experiments. Limits on T-violating, electron-nucleon tensor interactions, with C_T defined similarly to Eq. (1), have been obtained from ^{199}Hg atoms [15]:

$$C_{Tn}\langle\sigma_n\rangle + C_{Tp}\langle\sigma_p\rangle = (-1.2 \pm 2.5) \times 10^{-7}, \qquad (13)$$

where $\langle\sigma_n\rangle$ and $\langle\sigma_p\rangle$ are the expectation values for the Pauli spin operators for the neutrons and protons in the ^{199}Hg nucleus. Recently, an improved ^{199}Hg EDM measurement has been reported [16] that sets the upper limit $C_T < 2 \times 10^{-8}$ at 95% confidence. The ^{199}Hg EDM measurements are sensitive to a *neutral* current tensor coupling between electrons and nucleons; the nuclear beta decay limits derived in this paper apply to a *charged* current. Hence, the extremely precise limits given by the EDM data cannot be directly compared [17] to the beta decay results in Fig. 1, which are then the best direct limits on T-violating tensor couplings in the form of Eq. (1).

The author wishes to acknowledge helpful discussions with R. S. Conti, D. W. Gidley, G. W. Ford, and R. R. Lewis. Support for this work has come from the NSF Grant PHY-9119899 and the Office of the Vice President for Research of the University of Michigan.

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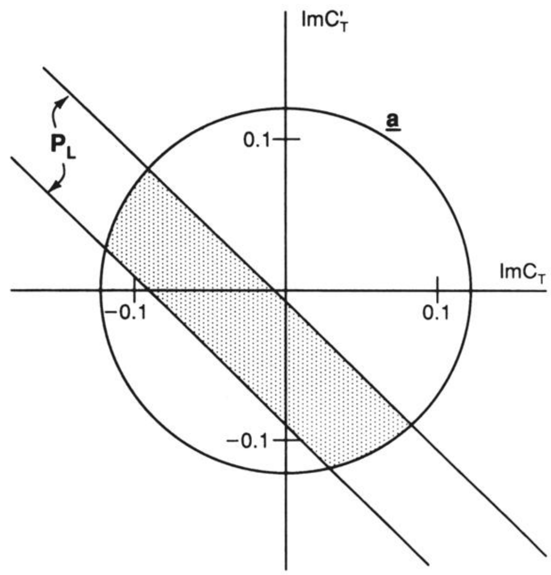

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