Upper limit on T nonconserving tensor couplings in nuclear beta decay

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Upper limits are derived for the first time on charged, tensor coupling constants that violate time reversal invariance (T). Various previous measurements of beta polarization from nuclear decays are analyzed. The best limit is $\mathrm{Im}(C_T C_A'^* + C_T' C_A^*) = -0.063 \pm 0.052$, a factor of 5 more precise than the present limit on analogously-defined, scalar T-violating terms. Finally, the relation of tensor couplings to searches for scalar couplings is discussed. No T violations are inferred.

Since the discovery[1] in 1964 that the combined parity-charge conjugation invariance principle (CP) is violated in the decay of neutral kaons, there has been considerable theoretical and experimental effort to illuminate the mechanism of CP violation. Presently, this mechanism is not understood theoretically as there are several models of CP violation that describe all data equally well.[2] Numerous experiments have been performed in different systems ($K^{\pm}$, η, Λ^0, nuclear, atomic) searching for CP violations[2,3] and closely related experiments[4,5] searching for violations of time reversal invariance (T). The close relation is the theorem[6] requiring CPT invariance for all relativistic field theories. Observation of CP violation as well as T violation,[7] however, remains exclusive to kaon decay.

In this paper we discuss previous experiments in nuclear beta decay that place limits on T violation and, in particular, we consider the effects of a charged tensor coupling contributing to the beta decay process. There are no previously published limits on T-violating tensor couplings in beta decay processes. Tensor interactions in quantum field theories currently are not popular due to the difficulty in producing a theory that is renormalizable.[8] Gravity is a tensor force and undeniably exists; the present inability to renormalize a tensor interaction will not necessarily exclude the existence of such forces. Therefore, we believe the possibility of T-violating tensor couplings deserves scrutiny. Recent results from atomic physics experiments have set limits on a T-violating, neutral current, tensor coupling constant by precisely measuring the electric dipole moments of heavy atoms.[9] In nuclear beta decay, a charged, rather than neutral, tensor coupling would be much more likely to contribute to any observed T violation. The usual practice in nuclear beta decay T tests is to neglect the possibility of tensor couplings[5] and exclude them from the analysis. This is not necessary for beta decay experiments measuring other T-odd coupling constants (e.g., scalar admixtures[5] or V,A interference[4]) with ≥ 0.05 accuracy, as will be shown below.

The measured quantity which will be of interest is the beta particle's longitudinal spin polarization:

$$P_L \equiv \langle \hat{\sigma} \cdot \hat{\mathbf{v}} \rangle = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \cong \mp \left| \frac{\mathbf{v}}{c} \right| = \mp \beta , \qquad (1)$$

where $\hat{\sigma}$ are the Pauli spin matrices, $\mathbf{v}$ is the beta particle velocity, and $N_\uparrow$ ($N_\downarrow$) is the number of betas with spin parallel (antiparallel) to their velocity. The longitudinal polarization is approximately $+\beta$ and $-\beta$ for positrons and electrons, respectively, from nuclear beta decay.[10] While not of the usual form of triple vector angular correlations used to investigate T violation (e.g., Ref. 5: $\hat{\sigma} \cdot \hat{\mathbf{J}} \times \hat{\mathbf{v}}$, where $\hat{\mathbf{J}}$ is nuclear spin), limits can be obtained from beta longitudinal polarization measurements. A more precise expression has been derived which includes Coulomb final-state contributions and the effect of scalar (S) and tensor (T, but only the T which appears in subscripts) couplings mixing with the dominant vector and axial vector ($V-A$) couplings:[11]

$$P_L = \frac{G\beta}{1 + b\dfrac{m_e}{E}} , \qquad (2)$$

where, for the case of pure Gamow-Teller decay (axial vector coupling only):[12]

$$G\xi \equiv \pm 2\,\mathrm{Re}(C_T C_T'^* - C_A C_A'^*) + \frac{\alpha Z m_e}{P_e} 2\,\mathrm{Im}(C_T C_A'^* + C_T' C_A^*) ; \qquad (3a)$$

$$b\xi \equiv \pm 2[1-(\alpha Z)^2]^{1/2} \mathrm{Re}(C_T C_A^* + C_T' C_A'^*) ; \qquad (3b)$$

$$\xi \equiv |C_T|^2 + |C_A|^2 + |C_T'|^2 + |C_A'|^2 ; \qquad (3c)$$

$\mathbf{P}_e$ and E are the electron momentum and energy; α is the fine structure constant; and Z is the atomic number of the daughter nucleus. The upper (lower) sign is for electron (positron) decay and C_i are the leptonic coupling constants for the various weak interactions [$C_V = C_V' \equiv 1$, $C_A = C_A' = -1.254(6)$].[13] The term "b" in Eq. (3b) is usually referred to as "Fierz interference." An important point is that the existence of an imaginary part of any C_i is T violating. This feature appears in the expression for G [Eq. (3a)] as "Coulomb terms" (i.e., dependent on the quantity αZ). Note that Eq. (2) reduces to Eq. (1) under the assumptions of (1) T invariance (which implies that all coupling constants and therefore the Hamiltonian are real), (2) no scalar or tensor admixtures to ($V-A$), and (3) $C_A = C_A'$. We will employ several methods for extracting limits on T violation. These use (1) absolute polarization measurements on electrons from the nuclear beta de-

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cay of high-Z nuclei (e.g., ^{153}Sm), which gives the best present limit, and (2) results from a new polarization comparison technique using positrons from two nuclei, one low-Z and one high-Z, but at the same energy.

The Fierz interference term, b in Eq. (3b), is not sensitive to T violation since it depends only on real parts. Previous experiments in nuclear beta decay have set limits on Fierz interference in pure Gamow-Teller decay:[14]

$$|b_{GT}| \lesssim 0.02 \ . \tag{4}$$

In the case of absolute electron polarization measurements, the determination of G requires knowledge of b, as shown in Eq. (2). The advantage of the polarization comparison technique can be seen in the following equation, valid for comparing the polarization from two pure Gamow-Teller decays:

$$\frac{P_L^{(1)}-P_L^{(2)}}{P_L^{(2)}} \cong \frac{P_L^{(1)}-P_L^{(2)}}{\beta} \simeq \pm \left[\frac{\alpha m_e}{|C_A|^2 P_e}(Z_2-Z_1)\mathrm{Im}(C_T C_A'^* + C_T' C_A^*) + \{[1-(\alpha Z_2)^2]^{1/2} - [1-(\alpha Z_1)^2]^{1/2}\} \frac{m_e}{|C_A|^2 E}\mathrm{Re}(C_T C_A^* + C_T' C_A'^*) \right] , \tag{5}$$

ignoring terms of $O(b^2)$ and assuming $C_T, C_T' \ll C_A = C_A'$ here and below. Note that the second term, containing the real part, has a Z dependence that makes it small compared to the first term. Hence, when comparing polarization measurements the uncertainty in b_{GT} hardly affects the limits obtainable on T-violating terms.

The effect on T-violation limits due to the uncertainty in b_{GT} can also be neglected in the absolute polarization measurements by comparing high-Z and low-Z results (e.g., ^{32}P). Since the various absolute electron polarization measurements were performed with different electron energies, Eq. (5) does not apply. In this case, we obtain, assuming that it is permissible to neglect the Z dependence of b:

$$\frac{P_L^{(1)}}{\beta^{(1)}} - \frac{P_L^{(2)}}{\beta^{(2)}} = (G^{(1)} - G^{(2)}) + b m_e \left[\frac{G^{(2)}}{E^{(2)}} - \frac{G^{(1)}}{E^{(1)}} \right] . \tag{6}$$

Since $|b| \lesssim 0.02$ for Gamow-Teller decay,[14] the second term in Eq. (6) can be safely ignored for all practical applications, which leaves

$$\frac{P_L^{(1)}}{\beta^{(1)}} - \frac{P_L^{(2)}}{\beta^{(2)}} \cong G^{(1)} - G^{(2)} = \frac{\alpha m_e}{|C_A|^2 P_e}(Z_1 - Z_2) \times \mathrm{Im}(C_T C_A'^* + C_T' C_A^*) \ . \tag{7}$$

All the equations derived thus far are in the allowed decay approximation; this is subject to "recoil order" corrections[15] due to effects such as recoiling of the nucleus and higher-order forbiddenness. As an example, the well-known "weak magnetism" term arises in the recoil order analysis. This correction term and others have been discussed extensively in the literature.[15] In particular, theoretical recoil order analysis of longitudinal beta polarization has shown[16,17] that the polarization is typically changed by about one part in 10^3 from β. These effects are completely negligible for the analysis of present experimental data, unless there is a considerable enhancement of recoil order effects in the decays studied. However, if we were to assume an order of magnitude enhancement in the recoil order contribution above the usual values, our final limit would be increased by only 30% of its value. We also point out that the Coulomb contributions to the recoil order corrections have been analyzed and produce even smaller effects on the polarization.[17] These will also be ignored in the rest of our analysis.

Experimentally, there have been over 100 measurements of absolute electron polarization from nuclear beta decay. Most use forbidden, rather than allowed, decays due to the usually longer lifetimes in forbidden decay. Many of these measurements must also be correlated, in some sense, since they are frequently performed on the same instrument by the same investigators. We will selectively present those results which give the best limits on T violation. In particular, ^{153}Sm has the highest Z, allowed decay where electron polarization has been measured.[18] All but one of the intense beta branches contributing in this decay are pure Gamow-Teller transitions. The one exception is an allowed mixed transition where the Fermi matrix element is much smaller than the Gamow-Teller matrix element ($\lesssim 1\%$ from Fermi beta decay systematics[19]), since the Fermi transition is isospin hindered. Consequently, we treat ^{153}Sm as a pure Gamow-Teller decay. The most precise measurements of electron polarization from ^{153}Sm were performed by Van Klinken,[18] with uncertainties (in P_L/β) of 0.016 and 0.020 at 261 and 172 keV energy, respectively. Using these measurements in Eqs. (2) and (3) to set limits on T violating, imaginary tensor couplings yields the averaged result

$$\mathrm{Im}(C_T C_A'^* + C_T' C_A^*) = -0.063 \pm 0.055 \ , \tag{8}$$

where uncertainty in the Fierz interference term increases the error by 25%.

The above-mentioned uncertainty can be removed from the analysis by comparing absolute electron polarization measurements from low-Z and high-Z nuclei. We use the pure Gamow-Teller decay of ^{32}P for comparison to the ^{153}Sm decay. Several measurements of the electron polarization from ^{32}P decay have been performed as summarized in Ref. 20. We use the ^{32}P results of Brosi *et al.*[21] and Ullman *et al.*[22] for comparison to ^{153}Sm. Using Eq.

(7) we obtain

$$\mathrm{Im}(C_T C_A'^* + C_T' C_A^*) = -0.094 \pm 0.073 \ .$$

Relative beta polarization measurements, as opposed to absolute measurements, can also be used to derive limits on T violation. The first demonstration of a new technique for positron polarimetry[23] has produced a polarization comparison with uncertainty of 0.011 [in $\Delta P/P$, Eq. (5)] for the pure Gamow-Teller decays, ^{22}Na and ^{68}Ga. Using Eq. (5), we obtain

$$\mathrm{Im}(C_T C_A'^* + C_T' C_A^*) = -0.058 \pm 0.159 \ . \qquad (9)$$

Combining this positron result with the best electron result [Eq. (8)] gives

$$\mathrm{Im}(C_T C_A'^* + C_T' C_A^*) = -0.063 \pm 0.052 \ , \qquad (10)$$

the best present limit on T violating, charged tensor couplings. Since this limit depends critically on the ^{153}Sm data, the previously discussed problem of Fermi mixing in this decay is now examined further. To increase the uncertainty in Eq. (10) from 5.2% to 5.3% would require the Fermi matrix element to be one-fifth the size of the Gamow-Teller matrix element, which is at least an order of magnitude larger than expected.[19] We conclude that the effect of Fermi mixing is entirely negligible.

A recent experiment at Princeton, using polarized ^{19}Ne decay, searched for imaginary scalar couplings as a test of time reversal invariance.[5] The result of this experiment was

$$\mathrm{Im}(C_S C_A'^* + C_S' C_A^*) = +0.382 \pm 0.256 \ . \qquad (11)$$

In their analysis, the assumption is made that $C_T = C_T' = 0$ for both real and imaginary parts of C_T and C_T'. The validity of this assumption was not made clear. Limits on Fierz interference in Gamow-Teller decay restrict the real parts,[14] and now our new limit, Eq. (10), restricts the imaginary parts. We have reanalyzed the ^{19}Ne result, without neglect of C_T and C_T', and find

$$\mathrm{Im}(C_S C_A'^* + C_S' C_A^*) = +0.409 \pm 0.260 \ . \qquad (12)$$

There is negligible difference between Eqs. (11) and (12); thus a correct accounting of C_T hardly affects the results of the Princeton experiment. Limits on imaginary scalar couplings [$\mathrm{Im}(C_S C_V)$] can also be obtained by considering beta polarization measurements using pure Fermi or mixed decays.[11,24]

In conclusion, limits on charged tensor couplings that violate T invariance (imaginary couplings) can be extracted from beta polarization measurements. Curiously, longitudinal polarization is manifestly T even in leading order. It is through the correction terms due to the nuclear Coulomb field that T sensitivity is obtained. There is, at this time, no indication of the presence of such tensor couplings. The uncertainty is a factor of 5 better than the analogous limits on imaginary scalar couplings. The imaginary tensor coupling limits are also about the same size as the real tensor coupling limits (Fierz interference). Prospects for improving the limits on imaginary tensor couplings are good. A precise polarization comparison [$\sigma(\Delta P/P) = 0.5\%$] of ^{178}Ta and ^{18}F would reduce the uncertainty in Eq. (10) by a factor of 3.

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