Experimental test of time reversal invariance using beta-polarization-gamma angular correlations in beta decay

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A measurement of the transverse beta spin polarization in a β-γ nuclear cascade gives information on time reversal invariance. Results from a preliminary experiment, using ^{203}Hg decay, are presented. The one previous experimental investigation, which used ^{198}Au decay, is also reanalyzed in light of more recent information on Mott scattering polarization analysis. No time reversal violations are indicated in either experiment.

I. INTRODUCTION

There has been a recent upsurge of theoretical interest in descriptions of *CP* violation;[1] *CP* is closely related to time reversal invariance (T) through the *CPT* theorem. There is also the older question of the observed *CP* violation[2] and T violation[3] in neutral kaon decay. These phenomena have been observed only in neutral kaons and there are several current theoretical models[1] that describe all data equally well. This has motivated us to look for other experiments where *CP* and T violations might be directly observed. In this article we reanalyze the results of a nuclear beta decay T test[4,5] in light of more recent information on Mott scattering beta polarization analysis,[6–8] and present the results of a preliminary remeasurement using a different nucleus.[9]

Curtis and Lewis[10] first pointed out that it is possible to perform a T test in nuclear beta decay by measuring a beta-gamma angular correlation and looking for a transverse spin polarization of the beta particle. They showed in this case that the beta-gamma angular correlation function for a first-forbidden, nonunique beta decay is of the form:[4,10]

$$W(\hat{\mathbf{p}},\hat{\sigma},\hat{\mathbf{k}})=1+\tfrac{1}{2}A_{22}[3(\hat{\mathbf{p}}\cdot\hat{\mathbf{k}})^2-1]+F(\hat{\sigma}\cdot\hat{\mathbf{k}})(\hat{\mathbf{p}}\cdot\hat{\mathbf{k}})+G(\hat{\sigma}\cdot\hat{\mathbf{p}}\times\hat{\mathbf{k}})(\hat{\mathbf{p}}\cdot\hat{\mathbf{k}})\ , \quad (1)$$

where $\hat{\mathbf{p}}$ and $\hat{\sigma}$ are the beta direction and spin, respectively, and $\hat{\mathbf{k}}$ is the gamma ray direction. A_{22} is the amplitude of the beta-gamma directional correlation, and F measures transverse beta polarization in the plane and G that perpendicular to the plane of the beta and gamma momenta. Determination of F is sensitive to the type of weak interaction coupling ($V-A$ or scalar-tensor); presence of a nonzero G indicates violation of T, neglecting possible final state effects. Shortly after the Curtis and Lewis article, a Letter[4] by Simms and Steffen (hereafter SS) was published, followed by a comprehensive article,[5] in which the measurements of F and G were reported for ^{198}Au decay. These appear to be the only such measurements for any nucleus.

The value of G is proportional to a T-violating complex coupling:[10]

$$G\propto\frac{M(\mathbf{r})M(\boldsymbol{\sigma}\times\mathbf{r})\mathrm{Im}(C_VC_A^*+C_V'C_A'^*)}{[M(\mathbf{r})]^2+\eta[M(\boldsymbol{\sigma}\times\mathbf{r})]^2}\ , \quad (2)$$

where the C's are leptonic couplings for vector and axial vector interactions, $M(\mathbf{r})$ and $M(\boldsymbol{\sigma}\times\mathbf{r})$ are first-forbidden nuclear matrix elements, and $\eta=O(1)$. It is the quantity $\mathrm{Im}[C_VC_A^*+C_V'C_A'^*]$ that is related to T violation. This term gives rise to a non-Hermitian Hamiltonian that does not conserve T. The matrix elements $M(\mathbf{r})$ and $M(\boldsymbol{\sigma}\times\mathbf{r})$ appear in leading order for first-forbidden decay only in β transitions with $\Delta J=1$.[11] Consequently, we have chosen to use the decay of ^{203}Hg ($\Delta J=1$) for our measurement since the previously used ^{198}Au decay has $\Delta J=0$.

II. THE PREVIOUS EXPERIMENT

The technique used by us and by SS to measure the transverse beta polarization is "Mott scattering:" elastic, large-angle scattering of electrons from high-Z nuclei.[12] Thin Au foils typically provide the target nuclei. The Mott scattering polarization analyzing power is given by:

$$S_{an}=A/P\ , \quad (3a)$$

where P is the transverse beta polarization and A is the observed right-left scattering asymmetry:

$$A=\frac{N_R-N_L}{N_R+N_L}\ . \quad (3b)$$

S_{an} is tabulated for elastically scattered electrons from infinitely thin foils as a function of beta energy and scattering angle by Sherman[13] and by Lin.[8] The energy-averaged analyzing power used by SS is[14]

$$\bar{S}_{an}=0.38\ . \quad (4)$$

It is clear from more recent investigations of Mott scattering, in particular Brosi *et al.*[6] at high energy (616 keV) and Van Klinken[7] at low energy (264 keV and lower), that the contribution from multiple, inelastic electron-electron collisions in the 1.47 mg/cm^2 Au scattering foil used by SS significantly reduces the value in Eq. (4). We have recalculated the energy-averaged analyzing power appropriate for the SS investigation and find:

$$\bar{S}_{\text{recalc}}=0.18\pm0.03\ , \tag{5}$$

about a factor of 2 degradation.

Relating the measured transverse polarizations to the quantities F and G is done through Eq. (1). Note in the correlation $G(\hat{\sigma}\cdot\hat{\mathbf{p}}\times\hat{\mathbf{k}})(\hat{\mathbf{p}}\cdot\hat{\mathbf{k}})$, that the beta and gamma directions have a cross product and then a dot product between them. To maximize the resulting quantity $\sin\theta_{\beta\gamma}\cos\theta_{\beta\gamma}$, the angle $\bar{\theta}_{\beta\gamma}=135°$ was chosen by SS, giving a factor of -0.500 between G and the measured transverse polarization.[4] Actually, finite detector size reduces the factor -0.500 to some degree. We have calculated the proper factor for SS by averaging over detector angles and obtain -0.436 ± 0.003, a relatively small correction to -0.500.

Corrected values for F and G can now be calculated and compared to theoretically expected values, viz.,[15]

$$\left.\begin{aligned} F_{\text{obs}}&=-0.053\pm0.026 \\ G_{\text{obs}}&=-0.145\pm0.039 \end{aligned}\right\} \text{ for } {}^{198}\text{Au}\ . \tag{6}$$

By "theoretically expected values" we mean there are final state interaction effects (sometimes called "Coulomb" effects) that have a polarizing effect on the β particle and thereby give rise to small, nonzero values. These can mimic a T-odd effect in the case of G since the final state effects, electromagnetic in origin, do *not* violate T.

This effect of final state interactions on F and G can be found (assuming the usual V-A coupling and no T violations) using the "ξ approximation"[16] for first-forbidden beta decay (see the Appendix). The ξ approximation relates, in a simple way, the β-γ directional correlation to the expected values for F and G.[3,16,17] Using the well-established β-γ directional correlation for ^{198}Au decay[17] we find:

$$\left.\begin{aligned} F_{\text{theo}}&=-0.014 \\ G_{\text{theo}}&=+0.007 \end{aligned}\right\} \text{ for } {}^{198}\text{Au}\ . \tag{7}$$

Thus, it turns out that our corrections do not alter the conclusions reached by SS (Refs. 4 and 5) but only revise the numerical quantities presented by them. Our special interest is in the value of G, the T-odd correlation coefficient, and whether it differs from the theoretically-predicted value. This difference,

$$G_{\text{obs}}-G_{\text{theo}}=-0.152\pm0.039 \text{ for } {}^{198}\text{Au}\ , \tag{8}$$

is a 3.9σ disagreement. But as SS assert (their result had a 4.1σ difference), "Within limits of error . . . agree satisfactorily."[5] We concur with their conclusion that this difference is probably experimental in origin, but we also feel it is of interest to reinvestigate the G term using a different nucleus to enhance the T-violation sensitivity and at a hopefully much better level of precision.

III. THE NEW EXPERIMENT

A preliminary experiment to repeat the SS investigation has been performed using an existing Mott scattering apparatus. We have converted this to a T-test experiment by adding two plastic scintillator gamma-ray detectors, appropriate shielding, and a $\approx300\ \mu$Ci ^{203}Hg source. The geometry of our apparatus, similar in principle to that of SS, is shown in Fig. 1. Our new design has a four detector arrangement that is used to minimize instrumental asymmetries and compensate for drift instabilities in, for example, detector gains. SS used only two detectors and moved the γ detector to generate an asymmetry. In our arrangement the four possible combinations of β-γ coincidence counting rates $R_{\beta\gamma}$ are measured simultaneously. Two polarization asymmetries, defined as in Eq. (3b), are formed:

$$\begin{aligned} A_1&=\frac{R_{11}-R_{21}}{R_{11}+R_{21}}\ , \\ A_2&=\frac{R_{12}-R_{22}}{R_{12}+R_{22}}\ , \end{aligned} \tag{9}$$

effectively one asymmetry for each γ detector. The asymmetry due to a T-violating polarization changes sign between A_1 and A_2. Instrumental asymmetries will not change sign between A_1 and A_2, so forming

$$A=\frac{A_1-A_2}{2} \tag{10}$$

cancels instrumental asymmetries leaving the true asymmetry. Since A_1 and A_2 are obtained simultaneously, a polarization "reversal" occurs on the average at one-half the data rate, which greatly minimizes the effects of any drift instabilities. The cancellation of instrumental asymmetries in A_1 and A_2 has occurred in our preliminary experiment using this technique. We also periodically exchange the position of the two γ detectors to average out

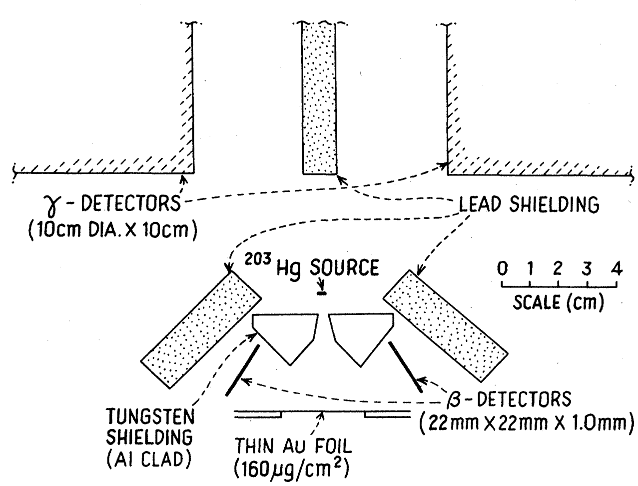

FIG. 1. Schematic diagram of the T-test apparatus. Two β detectors and two γ detectors, all made from plastic scintillator, are positioned to measure the T-odd angular correlation $(\hat{\sigma}\cdot\hat{\mathbf{p}}\times\hat{\mathbf{k}})(\hat{\mathbf{p}}\cdot\hat{\mathbf{k}})$. Betas that are emitted downward and Mott scatter in the Au foil are detected in back-angle thin scintillator detectors. This determines the transverse spin polarization. Gamma detectors are placed above the source so $\bar{\theta}_{\beta\gamma}=135°$.

differences in their efficiency. The analyzing power has been calculated in the same manner as before:[7,8]

$$\bar{S}_{an}=0.20\pm0.03 \ . \tag{11}$$

Also, the finite detector angles dilute the $\sin\theta_{\beta\gamma}\cos\theta_{\beta\gamma}$ factor from -0.500 to -0.422 ± 0.004.

Careful investigations on the origins of noise and backgrounds in this system have been performed. These include: (1) cosmic-ray background, (2) accidental, random coincidences due to finite coincidence resolving time ($\tau_{\rm res}=7$ nsec), (3) the scattering of gamma rays, (4) the scattering of beta particles from surfaces other than the Au scattering foil, and (5) the presence of conversion and Auger lines in the beta spectrum and x-ray lines in the gamma spectrum.

Corrections have been applied to the data to account for these backgrounds. The accidental, random coincidence background is counted during data acquisition. A 50 nsec delayed γ signal is used for coincidence with the β signal in exactly the same manner as prompt β-γ coincidences are counted. This directly measures the rate of accidental coincidences which is then subtracted from the observed coincidence rate. Corrections for the effect of scattered betas and gammas and the effect of cosmic-ray events are made by periodically running the system with no Au scattering foil in place. The primary noise contribution is due to scattered betas. The signal/noise that is observed is 8/1 and the prompt β-γ true coincidence rate is 10 Hz. After 20 days of continuous running we have obtained the result:

$$G_{\rm obs}=+0.018\pm0.032 \text{ for } {}^{203}\text{Hg} \ . \tag{12}$$

This result has been corrected for further calculated systematic effects that do not cancel in Eq. (10): (1) depolarization of betas in the 6 mg/cm^2 source,[18] (2) bremsstrahlung of betas, and (3) the β-γ directional correlation.[19] Effects due to spin precession of the daughter nucleus before gamma emission or spin precession of the beta particle in-flight in the earth's or atomic electrons magnetic fields are negligibly small. As a final check for instrumental effects we also periodically replace the Au scattering foil with an Al foil. This reduces the polarization sensitivity by about a factor of 10 (Ref. 7). No asymmetry has likewise been observed with the Al replacement.

We have applied the ξ approximation, as used before, to ^{203}Hg decay to get the expected value of the final state interaction effects:

$$G_{\rm theo}=-0.002\pm0.002 \text{ for } {}^{203}\text{Hg} \ . \tag{13}$$

The uncertainty here is due to conflicting measurements of the β-γ directional correlation[19] (see Fig. 1 of Ref. 19), the input data used by the ξ approximation to predict $G_{\rm theo}$ (see the Appendix). No uncertainty is assigned to the ξ approximation and its use here. It is assumed that the experimental uncertainty in the β-γ directional correlation dominates the error in $G_{\rm theo}$. This error is more than an order of magnitude below our experimental result and so refined estimates of $G_{\rm theo}$ will probably not significantly change our final result:

$$G_{\rm obs}-G_{\rm theo}=+0.020\pm0.032 \text{ for } {}^{203}\text{Hg} \ . \tag{14}$$

Our result, consistent with zero, indicates no violation of time-reversal invariance. The level of sensitivity to the T-violating coupling $\mathrm{Im}(C_V C_A^* + C_V' C_A'^*)$ [see Eq. (2)] obtained in this experiment is far poorer than that obtained for exactly the same coupling in a recent polarized ^{19}Ne T test.[20] Because, even in the optimal case where the nuclear matrix elements $M(\boldsymbol{\sigma}\times\mathbf{r})=M(\mathbf{r})$ in ^{203}Hg decay, our limit on the coupling is still at least an order of magnitude larger than the limit $[|\mathrm{Im}(C_V C_A^* + C_V' C_A'^*)| < 0.003]$ obtained in the allowed decay of ^{19}Ne (Ref. 20). This might seem to discount the significance of our result; there are two reasons why this new result is still of interest: (1) The investigation of the 4σ T-violating signal of SS has been a major motivation for this work. (2) Forbidden beta decay may have enhancement mechanisms for T-violating signals.

IV. CONCLUSION

Transverse lepton polarization has been an observable in four previous T tests, including SS. One is in kaon decay,[21] another one in muon decay[22] and the final one in ^{19}Ne decay.[23] No positive results for T violation have been found in any of the above, nor anywhere except with neutral kaons.[3] The possibility that lepton (electron) polarization may be an observable with enhanced sensitivity to T-violating effects over previous T tests is discussed by Holstein in the case of ^{19}Ne decay.[24] The 3.9σ SS result is also theoretically tantalizing, but most probably experimental in origin. We intend to continue our ^{203}Hg experiment in a new, dedicated apparatus where we plan to reach the $(2-3)\times10^{-3}$ level and hopefully resolve these questions.

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APPENDIX

The "ξ approximation" is a high-Z nuclear approximation since the quantity $\xi\equiv\alpha Z/2R$ is supposed to satisfy $\xi>1$ for the approximation to work well. This is also sometimes called the "quasiallowed" approximation. The ξ approximation expresses the beta spin correlation coefficients, F and G as functions of the relatively-easily measured β-γ directional correlation A_{22}.[4,16]

$$F=-\frac{3}{2}\frac{\lambda_6}{\lambda_2}\frac{A_{22}}{p} \ , \quad G=\frac{9}{8}\alpha Z\frac{\lambda_8}{\lambda_2}\frac{A_{22}}{p} \ , \tag{A1}$$

where $\lambda_i = \lambda_i(Z,p)$ are Coulomb coefficients defined in Ref. 16, $\alpha = \frac{1}{137}$, Z-daughter nucleus atomic number, and p is the magnitude of the momentum. It is not clear from from the available experimental data[19,25] if ^{203}Hg decay satisfies the ξ approximation. Consequently, the value for G_{theo} derived for ^{203}Hg decay [Eq. (13)] is only a crude approximation, but appropriate for this work due to the size of the experimental uncertainty.

[1] L. Wolfenstein and D. Chang, *Intense Medium Energy Sources of Strangeness—1983* (University of California, Santa Cruz), Proceedings of a Workshop on Intense Medium Energy Sources of Strangeness, AIP Conf. Proc. No. 102, edited by T. Goldman, H. E. Haber, and H. F-W. Sadrozinski (AIP, New York, 1983).

[2] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. **13**, 138 (1964).

[3] K. R. Shubert *et al.*, Phys. Lett. **31B**, 662 (1970); R. C. Casella, Phys. Rev. Lett. **21**, 1128 (1968).

[4] P. C. Simms and R. M. Steffen, Phys. Rev. Lett. **1**, 289 (1958).

[5] P. C. Simms and R. M. Steffen, Phys. Rev. **118**, 768 (1960).

[6] A. R. Brosi, A. I. Galonsky, B. H. Ketelle, and H. B. Willard, Nucl. Phys. **33**, 353 (1962).

[7] J. Van Klinken, Nucl. Phys. **75**, 161 (1966).

[8] S. R. Lin, Phys. Rev. **133**, A965 (1964).

[9] M. Skalsey, R. Conti, and T. A. Girard, Bull. Am. Phys. Soc. **28**, 715 (1983).

[10] R. B. Curtis and R. R. Lewis, Phys. Rev. **107**, 543 (1957).

[11] M. Morita, *Beta Decay and Muon Capture* (Benjamin, Reading, Mass., 1973), p. 167; C. S. Wu and S. A. Moszkowski, *Beta Decay* (Wiley, New York, 1966), p. 78; E. J. Konopinski, *The Theory of Beta Radioactivity* (Oxford University, London, 1966), p. 201.

[12] N. F. Mott and H. S. W. Massey, *Theory of Atomic Collisions* (Oxford University, London, 1949).

[13] N. Sherman, Phys. Rev. **103**, 1601 (1956).

[14] P. C. Simms, Ph.D. dissertation, Purdue University, 1958 (unpublished).

[15] This assumes that corrections applied to the data by SS, not clearly spelled out, will scale with the revised analyzing power. Most types of corrections (e.g., β scatterings from chamber walls, scattered high energy γ rays firing the β detector, aluminum foil normalization, etc.) will scale in this way. However, there are corrections (e.g., source depolarization which is very small for the SS ^{198}Au sources) where the scaling is inappropriate. We assume the first type of corrections dominate. The final results of the SS investigation are taken to be the transverse polarizations quoted in the abstract of Ref. 5, not the apparently incorrect values in Table I of Ref. 5.

[16] T. Kotani and M. Ross, Phys. Rev. Lett. **1**, 140 (1958); Prog. Theor. Phys. **20**, 643 (1958); Phys. Rev. **113**, 622 (1959).

[17] R. M. Steffen, Phys. Rev. **118**, 763 (1960).

[18] B. Blake and B. Muhlschlegel, Z. Phys. **167**, 584 (1962).

[19] J. M. Wyrick and A. H. Weber, Phys. Rev. C **8**, 1955 (1973).

[20] A. L. Hallin *et al.*, Phys. Rev. Lett. **52**, 337 (1984).

[21] M. K. Campbell *et al.*, Phys. Rev. Lett. **47**, 1032 (1981); Phys. Rev. D **21**, 1750 (1980); **27**, 1056 (1983).

[22] F. Corriveau *et al.*, Phys. Lett. **129B**, 260 (1983).

[23] M. B. Schneider, *et al.*, Phys. Rev. Lett. **51**, 1239 (1983).

[24] B. R. Holstein, Phys. Rev. C **28**, 342 (1983).

[25] J. J. Van Rooijen, J. Geus, H. A. Helms, and J. Blok, Nucl. Phys. **A167**, 421 (1971).