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# Fermi–Gamow-Teller interference in $^{56}$Co decay

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A measurement of the circular polarization of the $\gamma$ rays following the $\beta$ decay of $^{56}$Co reveals an anisotropy coefficient of $A = 0.017(13)$. A Fermi to Gamow-Teller ratio, $M_F C_V / M_{GT} C_A = -0.13(2)$, was derived demonstrating a sizable interference between the two amplitudes.

[NUCLEAR STRUCTURE Fermi and Gamow-Teller amplitudes in $^{56}$Co $\beta$ decay.]

The study of the interference term between Fermi and Gamow-Teller amplitudes in nuclear $\beta$ decay provides a sensitive test of time-reversal invariance in semileptonic weak interactions. A breakdown of time-reversal invariance would manifest itself in an imaginary part of this interference term. With this in mind, we have reexamined the allowed $\beta$ decay of $^{56}$Co for which several contradictory experimental results have been reported. The work by Ambler *et al.*,[1] using a low temperature nuclear polarization technique, gives a vanishing interference. The same conclusion of zero interference has been reported by Pingot[2] based on a measurement of the circular polarization correlation in $^{56}$Co decay. In striking disagreement with these results, Behrens,[3] Mann *et al.*,[4] and Bhattacherjee *et al.*[5] have reported evidence for a nonzero interference term. The purpose of the present study is to resolve the existing inconsistency and to assess the suitability of the $\beta$ decay of $^{56}$Co for a test of time-reversal invariance.

In our work we make use of the $\beta$-$\gamma$ circular polarization correlation. As documented in previous experiments by Boehm and Wapstra[6] and Schopper,[7] the circular polarization of a $\gamma$ ray emitted following $\beta$ decay is analyzed in a given direction with respect to the coincident $\beta$ particle. Spin dependent forward Compton scattering on magnetized iron provides the $\gamma$ ray polarization analyzing power. The anisotropy of right handed circularly polarized $\gamma$ rays as a function of the angle $\theta$ between the $\beta$ particle and $\gamma$ ray is defined by

$$W(\theta) = 1 + A\,(v/c)\cos(\theta) \quad ,$$

where $v/c$ is the $\beta$ velocity. For a mixed Fermi and Gamow-Teller transition, characterized by the amplitude ratio

$$Y = M_F C_V / M_{GT} C_A \quad ,$$

where $C_V$ and $C_A$ denote the usual vector and axial vector coupling constants, the coefficient $A$ is related to $Y$ by

$$A = \frac{\sqrt{3}}{6}\frac{1}{1+Y^2}\left(\frac{I_2}{[(I_1+1)I_1]^{1/2}} + 4Y\right)F_1(L,L,I_2,I_1) \quad .$$

The $F_1$ coefficient[8] for a particular $\gamma$ ray transition depends on the initial and final state spins $I_1$ and $I_2$, and the multipole order $L$ of the $\gamma$ ray, which here is assumed to be pure. Standard $V$-$A$ time-reversal invariant theory is assumed for the present treatment. In the case of $^{56}$Co (spin sequence $4(\beta^+)4(\gamma)2(\gamma)0$], we have

$$A = -(0.08327 + 0.7448Y)/(1+Y^2) \quad , \tag{1}$$

which is shown in Fig. 2.

For our experiment a circular polarization analyzer consisting of a forward scattering analyzer magnet, a NaI, and a plastic scintillation counter with 180 cm long light pipes was used. Our system is similar to that described in Refs. 6 and 7. Sources of approximately 100 $\mu$Ci were prepared by depositing $^{56}CoCl_2$ in aqueous solution onto 0.5 mg/cm$^2$ Mylar foil. For the estimated maximum source thickness of 1$\mu$g/cm$^2$ of our $^{60}$Co source ($^{56}$Co and $^{58}$Co sources had smaller surface thicknesses) scattering in the source can be neglected.[9] Two slightly different source holder geometries were used for the first and second sets of data, allowing a test of the effect of scattering.

The experimentally measured quantity $(N^+ - N^-)/(N^+ + N^-)$ is related to the anisotropy coefficient $A$ by

$$(N^+ - N^-)/(N^+ + N^-) = A\,(v/c)\epsilon\langle P\cos(\theta)\rangle \ ,$$

where $N^+(N^-)$ is the number of coincidence counts with the magnetization of the analyzer along (opposing) the direction of the $\gamma$ rays. $\epsilon$ is the ratio of the true to total (including $\gamma$-$\gamma$ and accidental) coincidences and $\langle P\cos(\theta)\rangle$ is the effective circular polarization efficiency of the analyzer system.

The polarization efficiency $\langle P\cos(\theta)\rangle$ was determined by performing the experiment with $^{60}$Co [spin sequence $5(\beta^-)4(\gamma)2(\gamma)0$], assuming the measured value for $A$ of $-0.334(10)$.[10] The $\gamma$-detector lower energy threshold was placed above the positron annihilation peak from $^{56}$Co and the upper threshold was placed just above the scattered 1.33 MeV $\gamma$ rays from $^{60}$Co, as shown in Fig. 1. The thresholds remained the same throughout the experiments. For $^{60}$Co and $^{56}$Co, a combination of two $\gamma$'s in the spin sequence $4^+(\gamma)2^+(\gamma)0^+$ was analyzed. [In both $^{60}$Co and $^{56}$Co the nuclei do not undergo depolarization in the cascade (see Ref. 11).] A small correction of 4% for the energy dependence of the polarization efficiency between $^{60}$Co and $^{56}$Co was necessary. The polarization efficiency for the combination of scattered 1.17 and 1.33 MeV $\gamma$ rays for these thresholds was measured to be $1.50(13)\times10^{-2}$. A further check of the polarization efficiency was carried out with the help of the $\beta$ decay of $^{58}$Co [spin sequence $2(\beta^+)2(\gamma)0$].

The first set of data with $^{56}$Co (36 days of running) was taken simultaneously with two $\beta$-detector thresholds. For all of the runs the magnet field was switched every 40 seconds. The data were written onto a disk and analyzed continuously by computer. Corrections for linear, quadratic, and higher order drifts, all of them small, were applied. In spite of careful magnetic shielding and compensation fields, small residual $\beta$ singles asymmetries of $-1.9(4)\times10^{-5}$ and $-2.8(3)\times10^{-5}$ for the high (600 keV) and low (550 keV) $\beta$ thresholds were present (the $\beta$ threshold was kept above the 440 keV end point of a possible 0.8% branch to the 3.1 MeV state in $^{56}$Fe). The $v/c$ averaged over the accepted spectra were 0.93 and 0.92 for these thresholds. A typical $\beta$ spectrum is shown in Fig. 1. The average $\beta$ count rates were $4.6\times10^4$ and $5.1\times10^4$ sec$^{-1}$, respectively. The $\gamma$ singles asymmetry was $0.5(1.1)\times10^{-5}$, with an average $\gamma$ singles rate of 4600 sec$^{-1}$. The coincidence count rates were 21 and 23 sec$^{-1}$. The coincidence asymmetries for the two thresholds were found to be $1.7(1.7)\times10^{-4}$ and $2.4(1.6)\times10^{-4}$, respectively. The coincidence data were analyzed by normalizing to the product of the singles counts. With a time resolution of 7 nsec the accidental rate was 7%, and the $\gamma$-$\gamma$ coincidence rate was 18%. The results are shown in Table I.

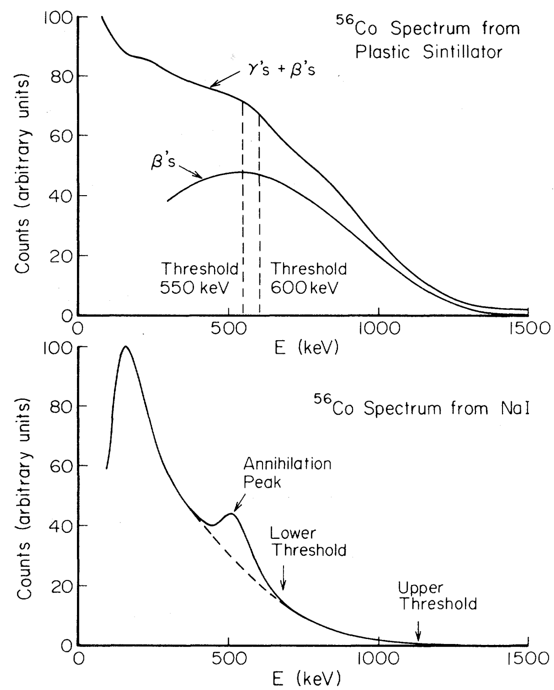


FIG. 1. $^{56}$Co spectra in the detectors of the polarization analyzer indicating the positions of the discriminator thresholds.

TABLE I. Experimental results.

| Experimental conditions | $\left\langle \frac{v}{c} \right\rangle$ | $A$ | $Y$ |
|---|---|---|---|
| First geometry, high $\beta$ threshold | 0.93 | $0.017 \pm 0.017$ | $-0.135 \pm 0.03$ |
| Second geometry, low $\beta$ threshold | 0.92 | $0.023 \pm 0.016$ | $-0.143 \pm 0.03$ |
| Second geometry, low $\beta$ threshold | 0.91 | $0.001 \pm 0.025$ | $-0.112 \pm 0.04$ |
| Combined result | · · · | $0.017 \pm 0.013$ | $-0.13 \pm 0.02$ |

A second set of data was accumulated with several changes in the experimental setup. As mentioned above, the source holder was changed to reduce $\beta$ scattering. The $\beta$-detector magnetic shielding was increased, which lowered the singles asymmetry to $0.97(23) \times 10^{-5}$. The $\beta$-singles rate was $7.2 \times 10^4$ $sec^{-1}$ with the threshold at 450 keV ($v/c = 0.91$). The $\gamma$ detector was changed from a 12.5 cm × 12.5 cm NaI with a 5 cm thick Pb collimator with a 5 cm aperture to a 5 cm × 5 cm NaI. This lowered the counting rate but improved the resolution of the $\gamma$ detector and also defined the scattering angles better. The $\gamma$-singles asymmetry was $-0.9(1.9) \times 10^{-5}$ at a count rate of 1100 $sec^{-1}$. After 40 days of running at a rate of 7 coincidences $sec^{-1}$, the normalized coincidence asymmetry was $0.1(2.3) \times 10^{-4}$.

In Table I, in addition to the asymmetries $A$, we also show the corresponding value for $Y$ using Eq. (1). Combining the results of the low $\beta$-threshold experiments we conclude that $A = 0.017(13)$. This value is plotted in Fig. 2. The resulting value $Y = -0.13(2)$ agrees well with those of Refs. 3–5, confirming the sizable interference between Fermi and Gamow-Teller amplitudes. The result of Ref. 2, $A = -0.085(3)$, does not agree with our findings. However, it should be emphasized that the data for $^{56}Co$ presented in this reference shows an excessively small value of $\chi^2 = 0.06$ per degree of freedom, signaling a deficiency in their counting system.

The allowed decay of $^{56}Co$ is of interest because of its unusually large log$ft$ of 8.7, but allowed shape and absence of $\beta$-$\gamma$ directional correlation. Owing to the suppression of the dominant Gamow-Teller amplitude, one is sensitive to small Fermi matrix elements. For the Fermi matrix element we find from our measurement, $M_F = 0.49(8) \times 10^{-3}$, which is of the expected order of magnitude for this mass region.

Thus it appears that $^{56}Co$ is a good candidate for tests of time-reversal invariance. An earlier experiment by Calaprice *et al.*[12] can now be unambiguously interpreted. Using our value for $Y$, one obtains for the relative phase angle $\phi$, between the vector and axial vector couplings, a value of $\phi = 182(5)$ deg, consistent with time-reversal invariance. Further tests on the reality of the coupling constants are now being conducted in our laboratory.

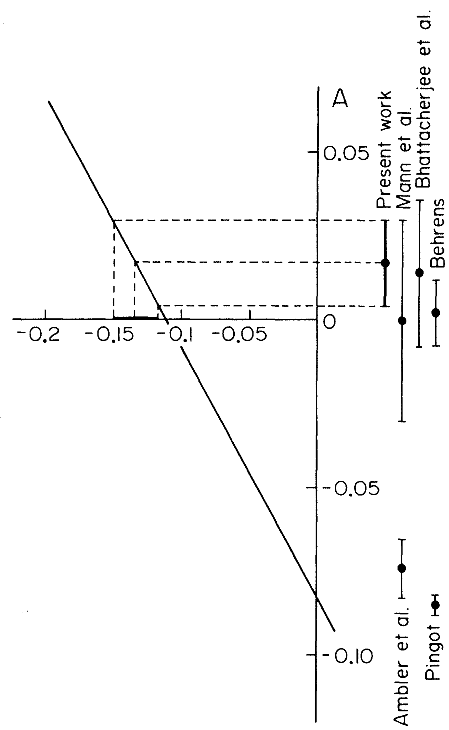


FIG. 2. Circular polarization anisotropy $A$ vs Fermi to Gamow-Teller ratio $Y$. The drawn line corresponds to Eq. (1). The experimental values for $A$ are depicted on the right side of the figure, with references given in the text.

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