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Beta asymmetries in the decay of polarized ^{56}Co

W. P. Lee,[*] A. M. Sabbas,[†] M. E. Chen,[‡] P. S. Kravitz,[§] L. M. Chirovsky,[§] J. L. Groves,[**] and C. S. Wu
Physics Department, Columbia University, New York, New York 10027

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Allowed isospin-hindered positron decay from polarized ^{56}Co has been studied using a β-particle detection assembly mounted on a ^{3}He/^{4}He dilution refrigerator, and the asymmetry parameter was found to be $A_\beta = +0.359 \pm 0.009$. Assuming the standard $V-A$ weak interaction theory and time-reversal invariance, the Fermi to Gamow-Teller interference ratio, $y = C_V M_F / C_A M_{\rm GT}$, is then -0.091 ± 0.005. Our high precision result is in reasonable agreement with most of the previously reported results, but is in serious disagreement with an earlier measurement by Pingot, who found $y = +0.002 \pm 0.004$.

I. INTRODUCTION

The study of β-decay asymmetries from polarized nuclei provided the first experimental evidence of fundamental symmetry violations of parity (P) and charge conjugation (C) in weak interactions.[2] For isospin-hindered, allowed β decay ($\Delta J = 0$, $J \neq 0$, $\Delta T = \pm 1$, parity change: no), the measured asymmetry can be used to determine the Fermi to Gamow-Teller mixing ratio, $y = C_V M_F / C_A M_{\rm GT}$, which must be zero if the isospin selection rule is strictly obeyed. A nonzero value of y therefore implies the existence of an isospin impurity, and thus, may reveal important information regarding the charge-dependent nature of the nuclear forces.[3] Furthermore, accurate values of y are essential for experimental tests of time-reversal invariance (TRI) in the β-decay process, since any possible T-violating amplitude is directly proportional to the magnitude of y.[4]

Two experimental methods applicable to nuclear β decay give information concerning y: (1) β-asymmetry measurements from polarized nuclei (β asymmetry) and (2) β-γ circular polarization correlations in unpolarized nuclei (β-γ correlation).[5] The β-asymmetry method is experimentally difficult since the β-emitting nuclei must be polarized, yet the β-particle trajectories must be undeflected. However, the potential sensitivity of the β-asymmetry method to y is quite large. The correlation method has the advantages that no polarization fields are necessary and the measurements can be carried out at room temperature. However, the β-γ correlation technique suffers from the fact that the signal-to-background ratio is typically 20 times smaller than in the β-asymmetry method.

Most previous determinations of y use the correlation technique; the results for all isotopes studied up to 1975 have been tabulated by Raman, Walkiewicz, and Behrens.[6] In the case of ^{56}Co, seven independent measurements[1,7–12] have previously been reported, and the results for y are in poor agreement. (See Fig. 1.) Whereas the most precise result reported[1] ($y = +0.002 \pm 0.004$) is consistent with the isospin selection rule, all other five less accurate measurements[8–12] using the same β-γ correlation method give quite large negative values for y. (See Fig. 1.) Also, there has been one β-asymmetry measurement[7] made previously, and the result reported ($y = -0.013 \pm 0.012$) is consistent with a vanishing value for y.

In order to resolve the serious discrepancy among the previous measurements of y in ^{56}Co and in other isotopes, and to carry out T-invariance tests of the weak interaction, we have developed a nuclear orientation facility for precise measurements of β-decay asymmetries from polarized nuclei.[13] As a test of the apparatus we have carried out an extensive study of the β-particle angular distribution from polarized ^{60}Co over a wide range of angles, and the results were in excellent agreement with the usual $V-A$ weak interaction theory.[14] In the present paper, we report the β-asymmetry measurements made with this facility on polarized ^{56}Co nuclei, from which the Fermi/Gamow-Teller ratio, y, will be deduced and compared with the previous results. A short account of this work has previously been published in the form of a Letter.[15]

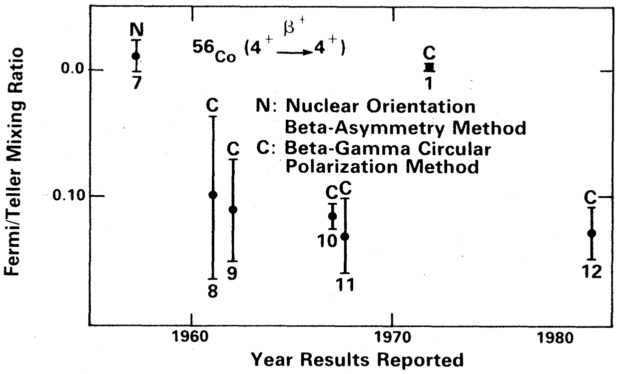

FIG. 1. Plot of all values for the Fermi/Gamow-Teller mixing for ^{56}Co previously reported other than in this work. The numbers that label the data points refer to the associated references: 1, Pingot; 7, Ambler *et al.*; 8, Daniel *et al.*; 9, Mann *et al.*; 10, Behrens; 11, Bhattacherjee; 12, Markey and Boehm.

II. THEORETICAL FORMULATIONS

The decay scheme of ^{56}Co is complicated,[16] and only a partial scheme relevant to the experiment is shown in Fig. 2. The β decay under study is the $4^+ \to 4^+$ positron transition with a maximum energy of 1459 keV. The 847 keV transition from 2^+ to 0^+, the 1238 keV transition from 4^+ to 2^+, and the 2598 keV transition from 3^+ to 2^+ are the three most intense γ transitions with branching ratios of 100%, 68%, and 17%, respectively.

The general theoretical formulations for the angular distribution of radiation emitted from oriented nuclei have been given in detail in Ref. 17. Here we will only present those formulas appropriate to the ^{56}Co case. Assuming the usual T-invariant $V-A$ interaction and neglecting the second-forbidden contributions, the β-particle angular distribution from polarized ^{56}Co can be expressed as

$$W_\beta(\theta)=1+B_1Q_1\frac{1.1547y-0.1291}{1+y^2}(v/c)\cos\theta \; . \qquad (1)$$

Here B_1 is the first order nuclear orientation parameter; Q_1 is the solid-angle correction factor which is 0.997 for our experimental setup; v/c is the ratio of the β-particle velocity, v, to the speed of light, c; θ is the angle between the β-particle emission direction and the polarization axis, the direction of the hyperfine field at the nucleus; and $y=C_VM_F/C_AM_{\rm GT}$ is the Fermi/Gamow-Teller mixing ratio. Equation (1) is also often expressed in another notation where

$$W_\beta(\theta)=1+A_\beta PQ_1(v/c)\cos\theta \; . \qquad (2)$$

Here P is the degree of nuclear polarization and A_β is the β-asymmetry parameter. For ^{56}Co, P is related to B_1 by

$$P=-\frac{(J+1)^{1/2}}{(3J)}B_1=-0.6455B_1 \; , \qquad (3)$$

and A_β is a function of y only with

$$A_\beta=\frac{0.2000-1.7889y}{1+y^2} \; . \qquad (4)$$

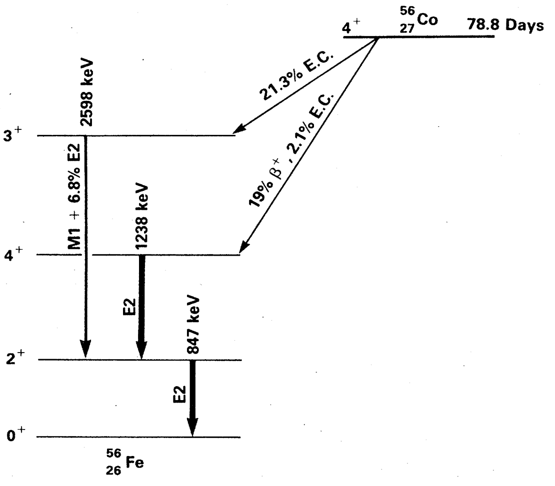

FIG. 2. Partial decay scheme for $^{56}_{27}$Co.

For the 847 keV ($2^+ \to 0^+$), 1238 keV ($4^+ \to 2^+$), and 2598 keV ($3^+ \to 2^+$) γ rays, the angular distribution has the general form

$$W_\gamma(\theta)=1+B_2U_2A_2Q_2P_2(\cos\theta) \\ +B_4U_4A_4Q_4P_4(\cos\theta) \; . \qquad (5)$$

In the above, B_2 and B_4 are the nuclear orientation parameters of order 2 and 4, respectively; U_2 and U_4 are the deorientation coefficients; A_2 and A_4 are the angular distribution coefficients; Q_2 and Q_4 are the geometry correction factors; and P_2 and P_4 are the ordinary Legendre polynomials. In this experiment, the measured γ-ray angular distribution is used to determine the nuclear polarization, P, and the polarization angle, θ, needed in the extraction of the β-asymmetry parameter, A_β. Even though Ohya *et al.*[18] have recently determined the U_2A_2 and U_4A_4 values for most of the γ rays of ^{56}Co, we chose to use the 2598 keV peak to determine the magnitude of the sample polarization rather than using the more intense 847 keV and 1238 keV γ rays. The U_2A_2 and U_4A_4 values for the 2598 keV γ ray can be unambiguously calculated and the flat background easily subtracted. The values of the relevant coefficients for the 2598 keV γ ray are

$$U_2=0.9044, \quad U_4=0.6087 \; ;$$

$$A_2=0.7985, \quad A_4=0.0471 \; .$$

Also, for the experimental setup used for detecting γ rays, $Q_2=0.977$ and $Q_4=0.928$. Therefore, for the 2598 keV γ ray, Eq. (5) reduces to

$$W_\gamma(\theta)=1+0.7056B_2P_2(\cos\theta) \\ +0.0298B_4P_4(\cos\theta) \; . \qquad (6)$$

III. EXPERIMENTS

Nuclear polarization was produced by using the hyperfine structure method. The ^{56}Co activity (~ 20 μCi) was first electroplated and then thermally diffused into a 25 μm-thick ferromagnetic host foil of 2V permendur (49% Co, 49% Fe, 2% V). The thermal treatment procedure was carefully controlled so that the 2V-permendur foil was magnetically well annealed and the source activity was diffused to a depth of about 1 μm from the front surface. The distribution of the diffused activity in the 2V permendur was measured by electropolishing successive 0.1 μm layers of the front surface of the foil away until all of the activity was removed. We found that for the sources used in these measurements about two thirds of the diffused activity was within 1 μm of the front surface. The 2V-permendur source was then mounted on a closed, double-loop magnetic circuit powered by two independent pairs of superconducting coils, and subsequently cooled to temperatures of about 0.020 K with a ^{3}He/^{4}He dilution refrigerator. A nuclear polarization of approximately 60% was obtained for ^{56}Co at the minimum operating temperature of the refrigerator.

An outstanding feature of our nuclear polarization cryostat is that the polarization axis can be rotated freely over almost the entire 360 angular range in the plane of the source foil simply by adjusting the relative magnetizing currents in the two independent magnetic loops. Also, the leakage magnetic field in the region between the source and the detector is confined such that the β-particle trajectories are deflected by less than 2 deg from the original emission direction for all settings of polarization angle. Accurate detection of β particles was therefore possible at almost any angle from the polarization axis. Detailed descriptions of the nuclear polarization apparatus and the source preparation procedures have been published.[13]

The β particles were detected by an 80 mm^2×5 mm Si(Li) semiconductor detector mounted on the 77 K tail inside the cryostat. At the operating temperature of 100 K, the detector had an energy resolution of about 3 keV FWHM for the 122 keV γ rays from ^{57}Co. An aluminum shutter was mounted between the source and the β detector that could be opened or closed from outside the cryostat. The shutter had a thickness of 0.36 cm (960 mg/cm^2) which was sufficient to absorb the most energetic β particles (1.5 MeV) emitted by the source, thus enabling the γ background to the detector to be accurately measured. A Ge(Li) detector was mounted outside the cryostat for the γ-radiation measurements. The Ge(Li) detector axis was oriented perpendicular to the Si(Li) detector axis, with both axes in the same horizontal plane and intersecting at the center of the source.

The experimental data were collected in two runs with different sources. In one run (source I) 15 μCi of ^{56}Co were diffused into a 2V-permendur host foil. In a second run (source II) 15 μCi of ^{56}Co and 5 μCi ^{60}Co were simultaneously diffused into the 2V-permendur host foil. The original plan for including the ^{60}Co activity in source II was to use the well-known ^{60}Co γ-ray anisotropies to determine the polarization of the ^{60}Co activity. However, the determination of the peak area for the two ^{60}Co γ rays was more difficult than expected, primarily because of the large polarization-dependent background resulting from the many high-energy ^{56}Co γ rays. Since the background was not linear on both sides of the ^{60}Co peaks, the calculated peak areas were very sensitive to the method used for background subtraction. Consequently, in the final analysis reported here, the 2598 keV γ-ray data from the ^{56}Co activity were used for the polarization measurements.

In each run data were collected that could be used to determine: (1) the polarization, P, of the ^{56}Co nuclei; (2) the polarization angle, θ, between the hyperfine field at the ^{56}Co nuclei and the emission direction of the detected β particles; and (3) the β-asymmetry parameter, A_β. Each direction of polarization was established by applying current to one of the magnetic loops described earlier. The polarization directions studied were approximately 20°, 90°, 200°, and 270°. The data collected at 20° and 200° were used to determine A_β, whereas the data obtained at 90° and 270° were used to identify systematic instrumental errors. Accurate values of the polarization angles were determined from the 2598 keV γ-ray data. In 2V permendur the hyperfine field is opposite to the applied field;[19] thus, all the angles listed are between the hyperfine field direction and the β-emission direction.

At each setting of the polarization angle equal amounts of data were taken at a "cold" temperature setting where the source nuclei were polarized and at a "warm" temperature setting where the source nuclei were unpolarized. Here, the "cold" temperature is the lowest stable source temperature obtainable with our dilution refrigerator ($\sim$0.020 K) and the "warm" temperature is 4.2 K, at which the source polarization is negligible. Other than the difference in temperature, these spectra were collected under identical conditions. The "warm" data were used to normalize the "cold" data and thus remove any nonpolarization dependent contributions to the β-asymmetry measurements.

At each source temperature three different spectra were accumulated using the internal Si(Li) β detector. Spectra were taken with the aluminum shutter for β particles in the "open" position and in the "closed" position. The spectra taken with the Ge(Li) detector were the γ spectra used to determine the direction of the source polarization. Also, at both "cold" and "warm" source temperatures, frequent calibrations of the Si(Li) detector were made using a ^{57}Co source mounted externally and the 511 keV annihilation radiation from ^{56}Co β^+ particles. All the spectra collected can then be conveniently labeled as follows: $S^{\text{cold}}_{\text{close}}(\theta_\beta)$, $S^{\text{cold}}_{\text{open}}(\theta_\beta)$, $S^{\text{cold}}_{57}(\theta_\beta)$, $G^{\text{cold}}_{\text{close}}(\theta_\gamma)$, $S^{\text{warm}}_{\text{close}}(\theta_\beta)$, $S^{\text{warm}}_{\text{open}}(\theta_\beta)$, $S^{\text{warm}}_{57}(\theta_\beta)$, $G^{\text{warm}}_{\text{close}}(\theta_\gamma)$. The angles θ_β and θ_γ refer to the angles between the nuclear polarization axis and the axes of the Si(Li) detector and the Ge(Li) detector, respectively. In our experimental arrangement, θ_β and θ_γ were related by

$$|\cos\theta_\beta| = (1-\cos^2\theta_\gamma)^{1/2}\cos 10^\circ \,. \tag{7}$$

Some additional spectra were taken with the Ge(Li) detector with the 2V-permendur source foil at the "cold" temperature and with a large current (2 A) in the magnetizing coils of the double magnetic loop. The large magnetizing currents were applied to ensure that the polarization axis was along the external field direction. The data collected with the large applied fields were used to determine P, B_1, B_2, and B_4 in Eqs. (1), (2), and (6).

Four Si(Li) detector spectra taken at the "cold" temperature with the source polarized are superimposed and plotted in Fig. 3. The stability of the energy scale is demonstrated by the coincidence of the Compton edges of the 847, 1238, and 511 keV annihilation γ rays among the various spectra. The β asymmetry is most evident by comparing the shutter-open spectra, $S^{\text{cold}}_{\text{open}}(20^\circ)$ and $S^{\text{cold}}_{\text{open}}(200^\circ)$, taken at opposite polarization directions. The two shutter-closed, γ-background spectra taken at the opposite angles are, within experimental accuracy, identical, as expected.

In Fig. 4, spectra taken with the same magnetizing-field setting but at different temperatures are compared. The β asymmetry is now evident between the cold spectrum and the warm spectrum, $S^{\text{cold}}_{\text{open}}(20^\circ)$ and $S^{\text{warm}}_{\text{open}}(20^\circ)$, respectively. The γ anisotropy in the shutter-closed spectra is a superposition of all the γ rays emitted by the ^{56}Co nuclei that are scattered in the Si(Li) detector.

Some β spectra obtained by subtracting the shutter-closed, γ-background spectra from the corresponding

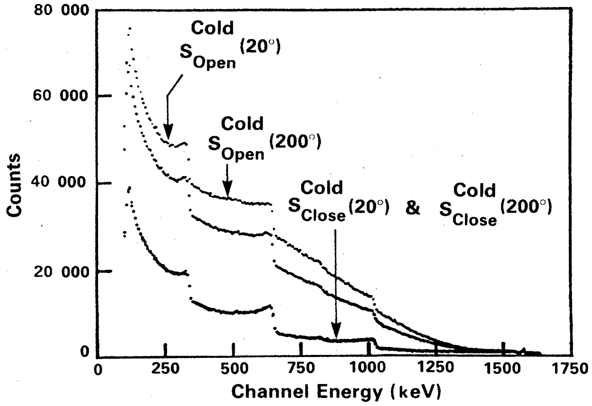

FIG. 3. Comparison of the spectra obtained using the Si(Li) detector with $\theta_\beta=20°$ and 200° and the aluminum shutter opened and closed.

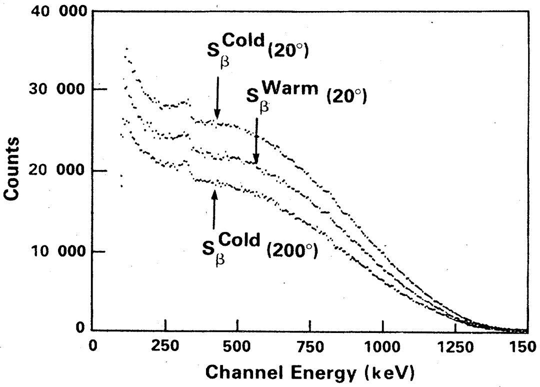

FIG. 5. Comparison of the β spectra [the Si(Li) spectra after γ-background subtraction] for $\theta_\beta=20°$ and 200° and the sample warm (4 K) and cold (~ 0.02 K). The $S_\beta^{\text{warm}}(200°)$ spectrum was indistinguishable from the $S_\beta^{\text{warm}}(20°)$ spectrum shown.

shutter-open spectra are shown in Fig. 5. In general, all the β spectra obtained are quite smooth with the exception of a small peak at the Compton edge of the 511 keV γ rays. The spectra taken with the source polarized in opposite directions, $S_\beta^{\text{cold}}(20°)$ and $S_\beta^{\text{cold}}(200°)$, are distinctly asymmetric with respect to the warm, unpolarized spectrum, $S_\beta^{\text{warm}}(20°)$, which is located approximately midway between the two polarized spectra over the entire β energy range.

IV. DATA ANALYSIS AND RESULTS

The data analysis procedure was the same for both experimental runs. The angular distribution, $W_\gamma(\theta)$, for the 2598 keV γ ray was determined at each polarization setting using

$$W_\gamma(\theta)=N_\gamma^{\text{cold}}(\theta)/N_\gamma^{\text{warm}}(\theta)\ , \tag{8}$$

where $N_\gamma(\theta)$ is the area under the 2598 keV peak in the Ge(Li) spectra after corrections for the source decay and dead-time effects. The values of $W_\gamma(\theta)$ taken with large applied magnetizing currents and, therefore, known polarization directions were used to determine the nuclear orientation parameters B_2 and B_4. The resulting values of B_2 and B_4 were then used in Eq. (6) to find the polarization angle θ for all the spectra collected. Also, the corresponding values of B_1, or equivalently, the degree of polarization, P, were obtained using the tables in Ref. 17. Our data give a negative sign for B_1 (positive P) for $y \le 0$ as expected theoretically and in agreement with most of the circular polarization measurements previously reported. Then, the magnetic moment ^{56}Co is positive.

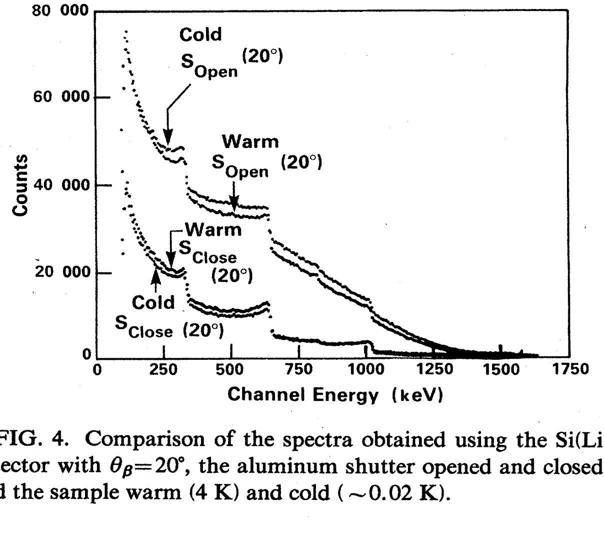

FIG. 4. Comparison of the spectra obtained using the Si(Li) detector with $\theta_\beta=20°$, the aluminum shutter opened and closed, and the sample warm (4 K) and cold (~ 0.02 K).

The background-free β spectrum at each polarization angle was obtained by taking the difference between the shutter-open and the corresponding shutter-closed spectra, with appropriate corrections. The β-particle angular distribution, $W_\beta^{\text{ex}}(\theta_\beta,n)$ was then independently obtained at each angle θ_β and channel n by normalizing the cold, polarized spectrum with respect to the warm, unpolarized one.

Many systematic effects such as the γ absorption in the shutter, positron annihilation in the detector, backscattering of betas from the front surface of the Si(Li) detector, and a small deterioration of the Si(Li) detector due to radiation damage were all taken into account in the determination of $W_\beta^{\text{ex}}(\theta_\beta,n)$. A detailed description of the correction procedure for these systematic effects has been described in the recent report on ^{58}Co.[20] The only differences between the ^{58}Co and ^{56}Co cases are minor changes in the input parameters associated with each correction because of the different energy region of interest between the two isotopes. All these corrections were made on each individual spectrum, and each correction had a very similar impact on the cold and the corresponding warm β spectrum. Consequently, since $W_\beta^{\text{ex}}(\theta_\beta,n)$ was obtained from a ratio of a cold spectrum to the corresponding warm β spectrum, the corrections had a small effect on the $W_\beta^{\text{ex}}(\theta_\beta,n)$ values.

The experimental β-asymmetry spectra, $A_\beta^{s}(\theta_\beta,n)$, was then calculated for each angle and each energy bin using

$$A^s_\beta(\theta_\beta,n)=\frac{W^{\rm ex}_\beta(\theta_\beta,n)-1}{v(n)/c}\ , \tag{9}$$

where $v(n)$ is the velocity of the betas in energy bin n. In Fig. 6, the values of $A^s_\beta(\theta_\beta,n)$ obtained in a single run are plotted against the energy for three different polarization angles. As expected, within experimental errors, $A^s_\beta(\theta_\beta,n)$ is independent of the energy over almost the entire energy region for all the three angles shown. Also, $A^s_\beta(\theta_\beta,n)$ is, on the average, zero at 90°, and is approximately the same in magnitude but opposite in sign at opposite angles of 20° and 200°, in excellent agreement with the theoretical expectations.

The values of $A^s_\beta(\theta_\beta,n)$ were weight-averaged over the energy region between 500 and 900 keV to obtain a single average value $A^s_\beta(\theta_\beta)$ for each angle in both runs. For the combined ^{56}Co and ^{60}Co source run, the lower energy limit of 500 keV is well above the ^{60}Co β-particle endpoint energy of 314 keV, and consequently, the presence of ^{60}Co does not constitute a "contamination" problem for the determination of $A^s_\beta(\theta_\beta)$. The values of $A^s_\beta(\theta_\beta)$, polarization P_1, and $\cos\theta_\beta$ determined for both runs are listed in Table I. Also listed are the values for the β-asymmetry parameter, A_β, determined at each angle from the relation

$$A_\beta=\frac{A^s_\beta(\theta_\beta)}{F_m Q_1 P\cos\theta_\beta}\ . \tag{10}$$

Here Q_1 is the detector solid angle correction factor defined earlier. F_m is a correction factor that compensates for the attenuation of the measured β-asymmetry parameter because of a finite thickness of the source foil. F_m was determined for the ^{56}Co sources used in these measurements by Monte Carlo techniques.

A Monte Carlo program was written that takes into account the profile of the ^{56}Co activity in the permendur foil and the geometry of the experimental setup. Modified Mott-Born scattering formulas and cross sections for both small- and large-angle scattering of positrons emitted by ^{56}Co were included. The Monte Carlo simulations indicate that the value of A_β measured in our geometry is 98% of the value that would be obtained for a zero thickness foil. That is, $F_m=(0.98\pm0.01)$.

The final values obtained for A_β are listed in Table I. The polarization, P, and the cosine of the emission direction were obtained from the γ data as discussed in the text. The four values obtained for A_β are in reasonably good agreement. Averaging over the four values of A_β, our final result is

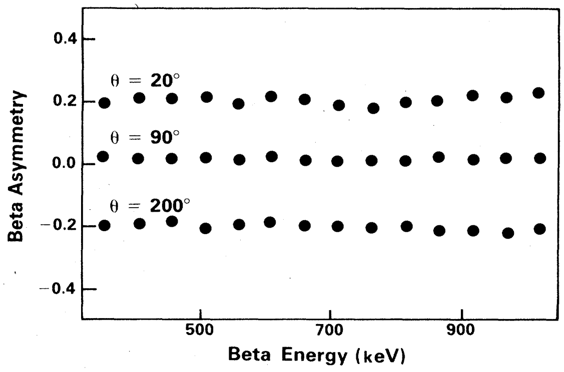

FIG. 6. Plot of $A^s_\beta(\theta_\beta,n)$ vs the beta particle kinetic energy ($\propto n$) for three values of θ_β.

$$A_\beta=+0.359\pm0.009\ ,$$

which corresponds to a F/GT ratio of

$$y=-0.091\pm0.005$$

for the β^+ decay of ^{56}Co. The contributions to the error in the final value for A_β are listed in Table II.

In addition, our results give a positive value for the magnetic moment of ^{56}Co. A negative value for the magnetic moment would give a value of $y=+0.3$, in sharp disagreement with the circular polarization results.

V. DISCUSSION

Referring to Fig. 1, our result for y is in satisfactory agreement with all previous β-γ circular polarization correlation measurements, except that of Ref. 1, which reported a value of y consistent with zero with a very small error bar ($y=+0.002\pm0.004$). Also, our result is in disagreement with a β-asymmetry measurement[7] made shortly after the discovery of parity violation in β decay. We have carried out two independent runs with separately prepared sources. In each run, data were taken at opposite polarization angles near 0° and 180° for the determination of the β-asymmetry parameter, A_β, and at 90° and 270° for identification of any serious instrumental errors. The unwanted γ-ray background response in the β detector was unambiguously differentiated from the desired β spectrum over almost the entire β-particle energy range.

TABLE I. ^{56}Co experimental results.

Run	P	$\cos\theta$	$A_\beta(\theta_\beta)$	A_β
One	0.614±0.007	+0.961±0.012	+0.202	+0.350
		−0.955±0.012	−0.201	+0.350
Two	0.592±0.011	+0.969±0.014	+0.211	+0.374
		−0.949±0.014	−0.199	+0.361
		Final $A_\beta=0.359\pm0.009^{\rm a}$		

[a] The error listed includes contributions from all the sources of error listed in Table II. The final value for A_β is an average of the four measurements listed.

TABLE II. Sources of experimental error in A_β. The errors listed for A_β are those that would result from each source alone.

Source of error	Percent error in A_β
Statistics	1.1%
Polarization, P	1.9%
Geometry, $\langle \cos\theta \rangle$	1.3%
Multiple scattering in the source[a]	0.4%
Beta-ray detector deterioration[a]	0.2%
Positron annihilation in the detector[a]	0.1%
Backscattering from the Si(Li) detector[a]	0.1%
	Total 2.6%

[a] The error estimates for these corrections to the data are approximately one third of the total change in A_β that resulted from each of the corrections.

Instead of using the conventional "field-up" and "field-down" difference technique, we used the "normalization" technique between the cold, polarized data and the warm, unpolarized data to determine the β asymmetry independently at each polarization angle. The analyzed results were not only compatible with the theoretical expectations for all the four angles measured, but were also in excellent agreement with each other between the two experimental runs. From Eq. (4), it can be seen that to have $y=0$, A_β should be equal to 0.2, which is only about one half the size of A_β that we observed. Consequently, we conclude that there is a large Fermi and Gamow-Teller mixing in the ^{56}Co β decay.

Using the $ft_{1/2}$ value given in Ref. 6, the present result for y yields a nonvanishing Fermi matrix element of

$$|M_F| = (3.5 \pm 0.3) \times 10^{-4} .$$

This value of M_F corresponds to an isospin impurity amplitude of

$$|\alpha| = (1.8 \pm 0.2) \times 10^{-4} ,$$

and a charge-dependent nuclear matrix element of

$$|\langle H_{\rm CD} \rangle| = (0.99 \pm 0.11) \text{ keV} ,$$

in the first-order perturbation treatment.

The theoretical calculation of $\langle H_{\rm CD} \rangle$ has been made by Yap[21] for several different isotopes, including ^{56}Co, using a parametrized phenomenological charge-dependent nuclear potential in addition to the Coulomb interactions. In the framework of his theoretical analysis, the present $\langle H_{\rm CD} \rangle$ result is consistent with the existence of a small amount (approximately a few percent) of charge dependence of nuclear forces.

However, it should be noted that in the present discussions the second forbidden contributions from the d-wave ($L=2$) leptons are neglected. Because of the nuclear structure complexities, accurate theoretical estimates of these contributions to the Fermi matrix element are not yet available. In view of the small value of M_F under consideration here, the possibility that it may originate from the second forbidden effects cannot be ruled out.

Finally, Calaprice *et al.*[4] have performed an experiment to test the validity of time reversal invariance (TRI) in β decay, in which they measured the β-γ angular correlation in aligned ^{56}Co nuclei. Assuming, in general, that TRI does not hold so that $y = |y| e^{i\phi}$, and using our value of y, their measurements lead to a result for the phase angle, $\phi = 183° \pm 7°$, consistent with no T violation.

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[*] Present address: Physics Department, University of California, Irvine, CA 92717.

[†] Present address: Siemens Gammasonics, Des Plaines, IL 60018.

[‡] Present address: Brookhaven National Laboratory, Upton, NY 11973.

[§] Present address: AT&T Bell Laboratories, Murray Hill, NJ 07974.

[**] Present address: Schlumberger-Doll Research, Ridgefield, CT 06877.

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