calculated effective decay lengths agree within about 0.2 mm. Variations of the above control sample were also studied. Considering the consistency of all the data for both τ and control events we have assigned a systematic uncertainty of 0.3 mm to the decay path measurement.

Taking the τ mass to be[3] 1.782 GeV, and the average beam energy for this experiment of 14.5 GeV, we find for the lifetime

$$\tau_\tau = (4.9 \pm 2.0) \times 10^{-13} \text{ sec}.$$

Here we have used the weighted mean decay path from Table I, and have added the 0.3-mm systematic uncertainty in quadrature with the statistical error given there. The prediction from τ-μ universality is given by

$$\tau_\tau = (m_\mu / m_\tau)^5 \tau_\mu b_e = (2.8 \pm 0.2) \times 10^{-13} \text{ sec},$$

where b_e is the branching fraction for $\tau \to e\nu\bar{\nu}$, 0.176 ± 0.016.[4] Previous published measurements include values of[5] $(4.6 \pm 1.9) \times 10^{-13}$ and[6] $(-0.25 \pm 3.5) \times 10^{-13}$ sec, consistent with the result reported here.

This work was supported in part by the Department of Energy under contracts No. DE-AC02-76ER02114, No. DE-AC03-76SF00515, and No. DE/AC02-76ER00881, by the National Science Foundation under Contracts No. NSF-PHY80-06504, No. NSF-PHY79-20020, and No. NSF-PHY79-20821, and by the Istituto Nazionale di Fisica Nucleare.

[(a)]Permanent address: CERN, Geneva, Switzerland.

[(b)]Present address: Cyclotron Laboratory, Harvard University, Cambridge, Mass. 02438.

[(c)]Present address: 20 Caine Road, Hong Kong, B. C. C.

[(d)]Present address: SRI International, Menlo Park, Cal. 94025.

[(e)]Present address: Mechanical Engineering Department, Stanford University, Stanford, Cal. 94305.

[1]MAC Collaboration, in Proceedings of the International Conference on Instrumentation for Colliding Beams, edited by W. Ash, Stanford Linear Accelerator Center Report No. SLAC-PUB-2894, 1982 (to be published).

[2]Sphericity is defined in, for example, G. Hanson *et al.*, Phys. Rev. Lett. 35, 1609 (1975).

[3]W. Bacino *et al.*, Phys. Rev. Lett. 41, 13 (1978).

[4]C. A. Blocker *et al.*, Stanford Linear Accelerator Center Report No. SLAC-PUB-2820, 1981 (unpublished).

[5]G. J. Feldman *et al.*, Phys. Rev. Lett. 48, 66 (1982).

[6]J. G. Branson (TASSO Collaboration), in *Proceedings of the 1981 International Symposium on Lepton and Photon Interactions at High Energies, Bonn, 24–29 August 1981*, edited by W. Pfeil (Physikalisches Institut, Universität Bonn, Bonn, Germany, 1981).

Fermi–Gamow-Teller Mixing in the Allowed Isospin-Hindered Positron Decay of ^{56}Co

J. L. Groves, W. P. Lee,[(a)] A. M. Sabbas, M. E. Chen, P. S. Kravitz, L. M. Chirovsky,[(b)] and C. S. Wu

Physics Department, Columbia University, New York, New York 10027

(Received 23 March 1982)

A new high-precision measurement of the asymmetry coefficient, A_β, for the positron decay of polarized ^{56}Co is reported: $A_\beta = +0.359 \pm 0.009$. If one assumes the $V-A$ form of the weak interaction and time-reversal invariance, the Fermi–Gamow-Teller mixing ratio, $y = C_V M_F / C_A M_{GT}$, is then -0.091 ± 0.005. Since y is nonzero and isospin is not conserved, ^{56}Co β^+ decay is a good candidate for sensitive time-reversal invariance tests of the weak interaction.

PACS numbers: 23.40.Hc, 27.40.+k

The allowed isospin-hindered ($J^\pi \overset{\beta^\pm}{\to} J^\pi$, $T \to T \pm 1$) β transitions in nuclei[1] are of particular interest for studies of isospin conservation of nuclear forces[2] and for time-reversal invariance (TRI) tests of the weak interaction.[3] Fermi transitions require $\Delta T = 0$, and consequently, a nonzero value of the Fermi to Gamow-Teller mixing ratio,[1] $y = C_V M_F / C_A M_{GT}$, violates isospin conservation. In TRI tests in nuclear β decay, the magnitudes of T-odd correlations are proportional to y. Furthermore, Barroso and Blin-Stoyle[3] have suggested that possible T-nonconserving effects in allowed isospin-hindered β transitions may be amplified by a factor of 10^2. Consequently, precise measurements of y for these β transitions are of fundamental importance.

The mixing ratio, y, has previously been measured for ^{56}Co($4^+ \overset{\beta^+}{\to} 4^+$, 1→2) by several groups using both the asymmetry of the angular distribution of β particles from oriented nuclei (NO),[4] and the asymmetry of the β-γ circular polarization correlation methods (CP).[5-11] The reported results are in very poor agreement. References 4 and 10 report values of y consistent with zero (+0.001 ± 0.004) whereas the weighted average of all other previous measurements of y is -0.120 ± 0.010.[5-9,11] Both experimental methods are difficult and require very careful attention to possible systematic errors for high-precision measurements. We report here the results of a precise measurement of y using the nuclear orientation method. During the analysis of the experimental data, several possible sources of error were investigated and estimated. Our final result for ^{56}Co is $y = -0.091 \pm 0.005$ where the error listed includes all the sources considered. Except for the early NO measurement[4] and the deviant CP measurement,[10] our value for y is in reasonable agreement with previous CP measurements. Thus, the NO and CP experimental methods give consistent results.

We have developed a nuclear orientation facility designed primarily for precision measurements of the angular distribution of β particles from polarized nuclei. The sample cooling is provided by a ^{3}He/^{4}He dilution refrigerator. Nuclei are polarized by magnetic saturation of ferromagnetic host foils at temperatures below 0.020 K. Previous studies with this facility include a measurement over a wide range of angles of the directional distribution of β particles from polarized ^{60}Co.[12] The observed angular distribution and the asymmetry factor $\{A_\beta(^{60}\text{Co}) = -1.01 \pm 0.02\}$ were in excellent agreement with the theoretical predictions of $1 + \alpha(v/c)\cos\theta$ dependence and $A_\beta(^{60}\text{Co}) = -1.0$ for the allowed Gamow-Teller decay of ^{60}Co.

The ferromagnetic host foils for ^{56}Co used in this study were prepared by diffusing ^{56}Co atoms into 25.4-μm-thick Permendur (49% Co, 49% Fe, 2% V) foils following a carefully studied procedure that resulted in foils that were magnetically soft and simultaneously had ^{56}Co atoms restricted to a region within 1 μm of the front surface.[13] Two different sources were prepared for this experiment. Source foil I contained approximately 15 μCi of ^{56}Co. Source foil II contained 15 μCi of ^{56}Co plus 5 μCi of ^{60}Co.

Two intersecting closed magnetic loops were used to carry the magnetic flux to the Permendur source foils and this minimized the magnetic fields in the region between the source and the β detector and permitted a wide range of polarization angles, θ. With the Permendur magnetically saturated, and θ set at the worst-case situation (90°), a 100-keV outgoing β particle was deflected by less than 2°. The hyperfine field at the ^{56}Co nucleus in the Permendur foil was measured using the NMR/ON technique and found to be 285 kG.

The β particles were detected using a Si(Li) crystal mounted inside the Dewar vacuum of the dilution refrigerator. The Si(Li) detector and preamplifier front end were cooled to 100 K for optimum performance. A total of 1.1 mg/cm^2 of material was between the source foil and the active part of the Si(Li) detector. A Ge(Li) detector was mounted outside the cryostat at 90° with respect to the source–Si(Li) detector axis and was used to observe the angular distribution of the γ radiation emitted by the source foils. An aluminum shutter (0.96 g/cm^2) that could be mechanically operated from outside the cryostat was mounted so that it could be moved in front of the Si(Li) detector to block the β particles, thus permitting determinations of the γ background in the Si(Li) detector.

The angular distribution of β radiation from ^{56}Co can be written[14]

$$W_\beta(\theta, v) = 1 + A_\beta P(v/c) Q \cos\theta, \qquad (1)$$

where P is the nuclear polarization $(\langle J_z \rangle / J)$, A_β is the β-asymmetry coefficient, v/c is the ratio of the β velocity to the speed of light, Q is the solid-angle correction factor (0.997), and θ is the angle between the polarization axis and β-emission direction. We measured $W_\beta(\theta, v)$ as a function of v (512 channels) for four values of θ. We used the resulting data to search for systematic errors, to study the applicable small corrections to the data, and finally to obtain a value for A_β.

The data accumulation procedures for the two sources were the same. Seven different spectra were collected at each setting of the polarization angle. The spectra were labeled $S_{\beta+\gamma}{}^{\text{cold}}$, $S_\gamma{}^{\text{cold}}$, $S_{\beta+\gamma}{}^{\text{warm}}$, $S_\gamma{}^{\text{warm}}$, $S_\gamma{}^{\text{cal}}$, $G_\gamma{}^{\text{cold}}$, and $G_\gamma{}^{\text{warm}}$, where S and G refer to spectra taken with the Si(Li) and the Ge(Li) detectors, respectively. The superscript "cold" indicates that the spectrum was taken when the ^{56}Co nuclei were polarized at the dilution refrigerator's operating temperature (≃ 0.020 K); the superscript "warm" indicates that the spectrum was obtained with unpolarized ^{56}Co nuclei at 4.2 K. Otherwise corresponding "cold" and "warm" spectra for a particular polarization setting were taken under identical experimental conditions. The subscripts "$\beta+\gamma$"

and "γ" denote spectra taken with the aluminum shutter open and closed, respectively. The spectra labeled S_γ^{cal} were taken with external ^{57}Co and ^{58}Co sources for energy calibration of the β spectra.

The data were collected so that A_β could be independently determined at each polarization angle. We wanted to look for systematic effects that might be a function of θ and to assess the effects of a series of corrections to the observed β spectra. First the spectra were examined for missing data and for energy shifts using the frequently obtained S_γ^{cal} spectra and a pulser peak above the β^+-spectrum end point. No energy shifts were observed. Next, each spectrum was multiplied by a weighting factor to remove the effect of radioactive decay. Pure β^+ spectra, S_β, were obtained from the shutter-open and shutter-closed spectra using $S_\beta = S_{\beta+\gamma} - aS_\gamma$ where $a = 1.055$ to correct for the attenuation of the γ background because of the thickness of the shutter. Then, the experimental directional distribution $W_\beta(\theta, v)$ was obtained for each value of θ by dividing S_β^{cold} by S_β^{warm}, and the asymmetry parameter was calculated from

$$A_\beta(\theta, v) = \frac{W_\beta(\theta, v) - 1}{P(v/c)Q\cos\theta}. \qquad (2)$$

The nuclear polarization, P, and $\cos\theta$ given in Table I for each run were determined from an analysis of the angular distribution of 2598-keV $(3^+ \to 2^+)$ γ radiation from ^{56}Co observed with the Ge(Li) detector.[15] Also listed are the values of A_β obtained from the data before any additional corrections. These "uncorrected" values of A_β were obtained by taking the weighted average of $A_\beta(\theta, v)$ given by Eq. (2) over the β^+ spectrum from 500 to 900 keV.

Next several corrections to the β^+ spectra and their effects on $A_\beta(\theta, v)$ were investigated. The Si(Li) detector was observed to deteriorate slowly as the exposure to positrons increased. As a result, the number of counts in each of the energy bins, after radioactive decay corrections, very slowly decreased (0.01%/h) as the exposure of the detector increased. The β^+ spectra were corrected by normalization to zero exposure time. Compton scattering of the 511-keV γ rays in the Si(Li) detector following annihilation of the detected β^+ particles distorts the observed β^+ spectra and, consequently, a correction was made to the β^+ spectra based on the energy-loss probability for Compton scattering of 511-keV photons in silicon. The backscattering of β^+ particles from the Si(Li) detector was corrected for with a method described by Charoenkwan.[16] A correction for multiple-scattering effects in the source foil was also made. The procedure used was to estimate the attenuation of A_β for our source configuration by Monte Carlo techniques. Input to the Monte Carlo simulation included the activity profile in the source foil, the experimental arrangement, and the scattering cross sections for both small- and large-angle scattering of the positrons emitted by ^{56}Co. The correction was made by taking the average of $A_\beta(\theta, v)$ over the region of interest (500 to 900 keV) after all previous corrections had been included and then dividing this average by the attenuation factor from the Monte Carlo simulation.

The final results obtained for the two different source preparations are listed in Table I. The values listed for A_β were obtained by averaging over the energy range from 500 to 900 keV. Only the data taken with polarization angles near 0° or 180° were used to determine A_β. Our final value after averaging over all the runs and after the data corrections is $A_\beta = 0.359 \pm 0.009$. If we assume time-reversal invariance (TRI) and the $V-A$ form of the weak interaction, A_β for ^{56}Co can

TABLE I. ^{56}Co asymmetry measurement results.

Source	$\cos\theta$	P	A_β Before corrections	A_β After corrections
I	-0.955 ± 0.012	0.614 ± 0.007	$+0.333$	$+0.350$
	$+0.961 \pm 0.012$	0.614 ± 0.007	$+0.353$	$+0.350$
II	-0.949 ± 0.014	0.592 ± 0.011	$+0.331$	$+0.361$
	$+0.969 \pm 0.014$	0.592 ± 0.011	$+0.367$	$+0.374$
			Final $A_\beta = +0.359 \pm 0.009$ [a]	

[a] The error listed includes estimates of the errors associated with all the corrections to the data that are discussed in the text.

TABLE II. Summary of all measurements of y for ^{56}Co.

Ref.	Method[a]	A_β	$\tilde{A}_\beta$	y
4	O	$+0.22\pm0.02$	-0.074 ± 0.009	$+0.013\pm0.012$
5,7	C	$+0.37\pm0.12$	-0.01 ± 0.05	-0.10 ± 0.07
6	C	$+0.39\pm0.07$	0.00 ± 0.03	-0.11 ± 0.04
8	C	$+0.40\pm0.02$	$+0.002\pm0.010$	-0.115 ± 0.014
9	C	$+0.43\pm0.05$	$+0.014\pm0.022$	-0.13 ± 0.03
10	C	$+0.195\pm0.007$	-0.085 ± 0.003	$+0.002\pm0.004$
11	C	$+0.42\pm0.04$	$+0.014\pm0.013$	-0.13 ± 0.02
Present work	O	$+0.359\pm0.009$	-0.015 ± 0.004	-0.091 ± 0.005

[a]Here O means that A_β was determined from the asymmetry of positrons emitted by polarized ^{56}Co nuclei. y and $\tilde{A}_\beta$ were then calculated from A_β. C indicates that $\tilde{A}_\beta$ was measured in a beta-gamma circular polarization correlation study of ^{56}Co. y and A_β were then calculated from $\tilde{A}_\beta$.

be written

$$A_\beta=\frac{0.2000-1.789y}{1+y^2}, \qquad (3)$$

which gives $y=-0.091\pm0.005$ for ^{56}Co.

We are in quite reasonable agreement (see Table II) with all the previous results except for those of Ambler *et al.*[4] and Pingot.[10] The results reported by Ambler *et al.*[4] were from a very early measurement of A_β for ^{56}Co that used adiabatic demagnetization for cooling. Problems with fringing fields, temperature variations, and positron detection add considerable uncertainty to the value of A_β reported. However, the measurements reported by Pingot[10] are irreconcilable with our results. Under the assumption of TRI, $\tilde{A}_\beta$ from Pingot[10] implies an A_β 45% smaller than we observe. Also, Pingot's results are in striking disagreement with the other β-γ circular polarization correlation measurements on ^{56}Co.

A theoretical calculation of the Fermi contribution to the β^+ decay of ^{56}Co has been carried out by Yap[17] using a Coulomb potential and a phenomenological, charge-dependent, nuclear potential. The adjustable parameters in the model for the nuclear potential are not well known but can be used to predict a range of values for the Fermi nuclear matrix element, M_F, for ^{56}Co.[17] Our result for y gives a Fermi contribution ($M_F=3.5\times10^{-4}$)[18] consistent with Yap's[17] calculation.

In conclusion, ^{56}Co has significant Fermi-Gamow-Teller mixing and, consequently, is a good candidate for TRI tests of the weak interaction. In a previously reported TRI test using ^{56}Co, Calaprice *et al.*[19] found $2|y|\sin\varphi/(1+|y|^2)=-0.011\pm0.022$ where $y=|y|e^{i\varphi}$. With our results for y, $\varphi=183\pm7°$ consistent with no T nonconservation.

The authors wish to thank Professor J. M. Daniels of the University of Toronto for helpful discussions while on sabbatical leave in our laboratory. We also acknowledge the support of the National Science Foundation for this project.

(a)Present address: TRIUMF, University of British Columbia, Vancouver, British Columbia, V6T 2A3, Canada.

(b)Present address: Bell Telephone Laboratories, Murray Hill, N.J. 07974.

[1]M. Morita, *Beta Decay and Muon Capture* (Benjamin, Reading, Mass., 1973).

[2]S. D. Bloom, Nuovo Cimento 32, 1023 (1964).

[3]A. Barroso and R. J. Blin-Stoyle, Phys. Lett. 45B, 178 (1973).

[4]E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. 108, 503 (1957).

[5]H. Daniel, M. Kuntze, and O. Mehling, Z. Naturforsch. 160, 1118 (1961).

[6]L. G. Mann, S. D. Bloom, and R. J. Nagel, Phys. Rev. 127, 2134 (1962).

[7]H. Daniel, O. Mehling, P. Schmidlin, D. Schotte, and E. Thummernicht, Z. Phys. 179, 62 (1964).

[8]H. Behrens, Z. Phys. 201, 153 (1967).

[9]S. K. Bhattacherjes, S. K. Mitra, and H. C. Padhi, Nucl. Phys. A96, 81 (1967).

[10]O. Pingot, Nucl. Phys. A174, 627 (1971).

[11]J. Markey and F. Boehm, private communication.

[12]L. M. Chirovsky, W. P. Lee, A. M. Sabbas, J. L. Groves, and C. S. Wu, Phys. Lett. 94B, 127 (1980).

[13]The magnetic properties of Permendur will be reported elsewhere.

[14]K. S. Krane, Los Alamos Scientific Laboratory Re-

port No. LA-4677, 1971 (unpublished).

[15] *Table of Isotopes*, edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978), 7th ed.

[16] P. Charoenkwan, Nucl. Instrum. Methods 34, 93 (1965).

[17] C. T. Yap, Nucl. Phys. A100, 619 (1967).

[18] S. Raman, T. A. Walkiewicz, and H. Behrens, At. Data Nucl. Data Tables 16, 451–494 (1975).

[19] F. P. Calaprice, S. J. Freedman, B. Osgood, and W. C. Thomlinson, Phys. Rev. C 15, 381 (1977).

Coincident Electrofission Cross Section for ^{238}U from 5 to 11.7 MeV

D. H. Dowell,[a] L. S. Cardman, P. Axel, G. Bolme, and S. E. Williamson[b]

Department of Physics and Nuclear Physics Laboratory, University of Illinois at Urbana-Champaign, Champaign, Illinois 61820

(Received 8 March 1982)

The ^{238}U$(e, e'f)$ cross section was measured for excitations between 5 and 11.7 MeV. The sum of the $E2$ and $E0$ strength functions was extracted with the aid of available ^{238}U(γ, f) data. The present results show that the $E2/E0$ strength in the fission channel is spread almost uniformly from 7 to 11.7 MeV. The $E2/E0$ strength that is found in the fission channel corresponds to 10% of the isoscalar $E2$ sum rule; if the fission probability is 0.22, this energy region contains 45% of this sum.

PACS numbers: 25.85.Ge, 24.30.Cz, 27.90.+b

There have been conflicting reports[1-9] about the magnitude, energy dependence, and fission probability of the isoscalar electric quadrupole giant resonance (GQR) in ^{238}U. The spectra of inelastically scattered protons,[1] alpha particles,[5,6,8] and ^{6}Li ions[7] have a broad bump at energies which vary for the different experiments but are generally in the range between 9 and 13 MeV. This enhanced inelastic scattering was interpreted as a concentration of $E2$ strength by interpolating a "background" in the 9- to 13-MeV excitation-energy region on the basis of the inelastic scattering observed at higher and lower energies. This procedure has been used[10,11] to identify concentrated $E0$ strength near $80A^{-1/3}$ MeV and $E2$ strength near $65A^{-1/3}$ MeV for many nuclei with A between 50 and 209. The separation of $E0$ and $E2$ strength followed the pioneering (α, α') experiments at scattering angles as low as 3° by Youngblood and his collaborators.[12] Our results, which have a better signal-to-noise ratio than did previous experiments for the sum of $E2$ and $E0$ strengths, show a relatively energy-independent distribution of the $E2/E0$ strength between 7 and 11 MeV. Our results make it clear that the assumed background in the (p, p'), (α, α'), and $(^{6}\mathrm{Li}, ^{6}\mathrm{Li}')$ experiments overestimated the $E2/E0$ strength from 9 to 11 MeV compared to the $E2/E0$ strength from 7 to 9 MeV. This discrepancy raises the question of whether the $E2/E0$ strength is as concentrated in energy as is assumed for nuclei with A between 50 and 209. The background in inelastic hadron scattering comes from an unknown combination of multistep nuclear excitations and direct excitations of higher multipolarity states. Because these backgrounds involve nuclear excitation, they cannot be removed by coincident measurement of the nuclear decay. In contrast, the $(e, e'f)$ cross sections which we measure are due to single-step nuclear excitations that include only low multipoles.

The previous reports of anomalously high[2,3] and low[5,6] fission probability of the GQR in ^{238}U can be clarified by our findings. High fission probability was inferred from electrofission (e, f) experiments[2,3] which can provide reliable information about $E2$ strength only if accurate virtual-photon spectra are known and if accurate absolute cross sections are available both for $E1$ photofission and for electrofission. The large $E2$ component claimed[2,3] has been contradicted by experiments[9] which measured (e^{+}, f) as well as (e^{-}, f). Our results cast doubt on the high fission probability partly because the reported energy concentration[2,3] conflicts with our results, and partly because our data are consistent with equal $E1$ and $E2$ fission probabilities. This equality of fission probability for 1^{-} and 2^{+} states is expected because the density of fission transition states at high energy is not related to the energies of the lowest fission barriers of states with different spins and parities. The argument in Ref. 3 that