Test of time-reversal invariance in the beta decay of ^{56}Co†

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A limit on time reversal noninvariance is obtained by measuring the β-γ angular correlation in the decay of oriented ^{56}Co. From a search for a correlation of the form $E_1(\hat{J}\cdot\hat{k})(\hat{J}\cdot\hat{p}\times\hat{k})$, where $\hat{J}$, $\hat{p}$, and $\hat{k}$ are unit vectors in the direction of the orientation axis, positron momentum, and photon momentum, respectively, we obtain $E_1 = 2y\sin\phi/(1+y^2) = -0.011 \pm 0.022$, where $ye^{i\phi} = C_V M_F / C_A M_{GT}$.

[RADIOACTIVITY ^{56}Co: measured $\beta\gamma$ correlations from oriented nuclei, inferred limit on time reversal violation.]

I. INTRODUCTION

Since 1964 when CP violation in the decay of the K_L was established by Christensen *et al.*[1] there have been many attempts to detect the effects of the implied time-reversal violation in low energy phenomena.[2] To date these searches have yielded no positive results, and for tests involving the β decay of the neutron[3] and ^{19}Ne (Ref. 4) the limits on T violation are quite small, nearly at the level of the implicit violation in K_L decay. It has long been appreciated, however, that without a good idea of the mechanism for T violation, present results do not rule out the existence of large effects in other systems.

Our present study of ^{56}Co was motivated by the possibility that significant T violation might appear through mechanisms to which previous experiments were not sensitive. One possibility is that T violation is present in second class[5] contributions to β decay.[6] Since the neutron and ^{19}Ne decays involve transitions within isospin multiplets, the sensitivity to T violating second class currents is only through kinematically suppressed terms.[7] However, ^{56}Co decay proceeds between two different isospin multiplets ($T=1 \rightarrow T=2$) and there is no requirement that the dominant contributions to the decay be entirely first class. In particular, for $\Delta T = 1$ decays the form factors of the axial vector current could be a sum of first and second class terms but, owing to the conserved vector current theory,[8] those for the vector current are solely first class.

The β decay of ^{56}Co is allowed by spin-parity and isospin, yet the decay is very inhibited, $\log ft = 8.62$. If this inhibition does not extend to T-violating matrix elements then one might expect an enhancement of a T-violating angular correlation. This strategy has been successfully applied to selection of systems for the study of P violation in nuclei[2] and has already been employed in searches for T violation in γ decay.[9] In a recent paper, Barroso and Blin-Stoyle[10] have suggested a specific mechanism for the amplification of T violation in isospin hindered decays.

Another motivation, that we shall discuss later, comes from one possible interpretation of previous β asymmetry and β-γ circular polarization correlation measurements in ^{56}Co.

In the present study we searched for a T-violating β-γ correlation from aligned ^{56}Co. The transitions of interest are indicated in Fig. 1. The theoretical expression for the β-γ correlation from aligned nuclei was worked out some time ago.[11,12] For the $4^+(\beta)4^+(\gamma)2^+$ spin sequence of ^{56}Co decay, we obtain from Ref. 11,

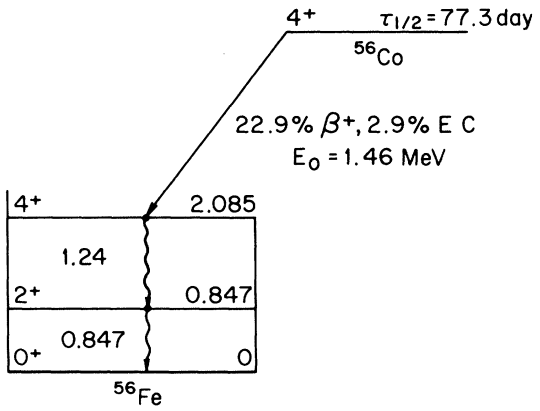

FIG. 1. Partial decay scheme for ^{56}Co showing the β and the two γ transitions used in our analysis. Not shown are many higher levels which feed these levels by electron capture and subsequent γ emission.

$$W(\hat{J},\hat{p},\hat{k}) \propto 1 - 1.3431\,\frac{(\frac{17}{20}+y^2)}{(1+y^2)}\,R_2P_2(\hat{J}\cdot\hat{k}) - 0.9132\,\frac{(\frac{1}{2}+y^2)}{(1+y^2)}\,R_4P_4(\hat{J}\cdot\hat{k}) + E_1\frac{v}{c}\,\frac{1}{\sqrt{80}}\,[1.3431\,R_2P_2'(\hat{J}\cdot\hat{k}) + 0.9132\,R_4P_4'(\hat{J}\cdot\hat{k})]\,(\hat{J}\cdot\hat{p}\times\hat{k})\,, \tag{1}$$

where $\hat{J}$, $\hat{p}$, and $\hat{k}$ are unit vectors in the directions of the orientation axis, the positron momentum, and the photon momentum, respectively; $P_i(\hat{J}\cdot\hat{k})$ and $P_i'(\hat{J}\cdot\hat{k})$ are the ith order Legendre polynomial and its derivative; and $ye^{i\phi} = C_V M_F / C_A M_{GT}$ (y real) with M_F and M_{GT} being the Fermi and Gamow-Teller matrix elements and C_V and C_A the vector- and axial-vector-coupling constants. The numerical factors in Eq. (1) arise from angular momentum algebra for the relevant spin sequence. The parameter R_k is the statistical tensor of the inital state,

$$R_k = \sum_m (-1)^m C(JJk; m, -m)a(m)\,, \tag{2}$$

where $a(m)$ is the population of the mth nuclear sublevel.

The second two terms in Eq. (1) correspond to the ordinary γ-ray anisotropy and the last term if present (i.e., $E_1 \neq 0$) would indicate a violation of T symmetry. The most significant T-violating correlation involves the combination $(\hat{J}\cdot\hat{k})\,(\hat{J}\cdot\hat{p}\times\hat{k})$. We note that while Eq. (1) implies T violation if the Fermi and Gamow-Teller contributions are relatively complex, the experimental detection of a $(\hat{J}\cdot\hat{k})\,(\hat{J}\cdot\hat{p}\times\hat{k})$ correlation signals T violation in general assuming the weak interaction can be treated to first order in perturbation theory and neglecting the final state interaction.

It should be noted that Eq. (1) is valid for the β-γ correlation associated with either the 1.24- or 0.847-MeV γ rays in ^{56}Co decay (see Fig. 1). In this "stretched" electric quadrupole γ-ray transition, $4^+ \to 2^+ \to 0^+$, the angular distributions of these two γ rays are identical and depend only on the alignment transferred to the 4^+ level in ^{56}Fe by the β decay.[13] We utilize this fact by combining both β-γ correlations to set a limit on E_1.

In the allowed approximation of the vector–axial-vector (V-A) theory, a calculation of the time-reversal parameter gives[11]

$$E_1 = 2y\sin\phi/(1+y^2)\,; \tag{3}$$

a more complete calculation, including recoil effects and final state electromagnetic corrections, has been given by Holstein.[7] In the notation where the nuclear form factors a and c are identified with $C_V M_F$ and $C_A M_{GT}$, and b and d are the weak magnetism and second class tensor form factors, respectively, the T-violating part is

$$E_1^{TRV} = \frac{2\,\mathrm{Im}a^*}{a^2+c^2}\left(c - \frac{1}{3}\frac{E_0}{M}(c-d-b) + \frac{1}{3}\frac{E}{M}(7c-b-d)\right), \tag{4}$$

whereas the T-conserving final state contribution is

$$E_1^{EM} = \frac{\alpha Z E^2}{2Mp}\,\frac{\mathrm{Re}a^*}{a^2+c^2}\left((c+b-d) - \frac{m_e^2}{E^2}(3c+b+d)\right). \tag{5}$$

In the above, p and E are the momentum and energy of β, M is the nuclear mass, α is the fine structure constant, and Z is the charge of the daughter nucleus.

Normally one would expect the E/M recoil terms of E_1 to be relatively insignificant compared with the leading c form factor. However, in a hindered decay such as the ^{56}Co where we have $c \approx 10^{-3}$, the recoil terms could very well be dominant if the b and d form factors are not hindered by the nuclear effects which hinder c. In spite of this possibility, there seems to be no evidence for such relative enhancement in the ^{56}Co decay. In particular, the β spectrum has essentially the allowed shape[14] and the β-γ correlation is isotropic.[15] Including only terms of first order in E/M, and neglecting a relative to c, the former sets an upper limit $b/Ac \lesssim 100$ whereas the latter yields $(b/Ac + d/Ac) = 3 \pm 6$, where A is the nucleon number.

In the impulse approximation b is given by the sum of matrix elements of the spin and orbital angular momentum operators whereas c is a matrix element of the spin operator. Thus, to the extent that the orbital part of b may be neglected, the ratio b/Ac is state independent and by the definitions of Holstein one expects $b/Ac \cong 3.8$.[16] This ratio could very well be much larger if the orbital part of b is not hindered by the nuclear structure effects which hinder the spin operator. However, barring a fortuitous cancellation of the b and d terms, or a cancellation due to E^2/M^2 terms, the result of the β-γ correlation indicates that there is no enhancement of the ratio b/Ac relative to the value 3.8 while the spectrum shape permits a larger value. A more precise measurement of the spectrum would help to clarify this matter but the present evidence from both experiments is consistent with an essentially "allowed" decay.

If we include only the leading terms we can use

the result of the β-γ correlation experiment to calculate the electromagnetic final state term E_1^{EM}. Again for a hindered decay this could be much larger than normally expected but with the limit $(b/Ac - d/Ac) \leq 10$, and with $y = -0.115$ (see discussion below), we obtain from Eq. (5) the small value $E_1^{EM} \leq 2 \times 10^{-4}$. Although higher order effects may change this estimate, it is 100 times smaller than our experimental error and is therefore neglected in the following analysis.

In Eq. (1) we have omitted alignment tensors with odd rank because to a good approximation these are zero for our particular method of nuclear orientation. The absence of terms such as $R_1[3(\hat{p}\cdot\hat{k})(\hat{J}\cdot\hat{k}) - (\hat{p}\cdot\hat{J})]$ is an important feature of the present experiment since their effect, combined with the attendant magnetic deflection of the β particles due to the holding field, would be to produce a spurious asymmetry which simulates a time-reversal asymmetry.

II. EXPERIMENTAL METHODS

Alignment of a 3.5-μCi source of ^{56}Co ($t_{1/2} = 77$ day) was achieved by the low temperature ferromagnetic crystal method of Grace *et al.*[17] The ^{56}Co sample was produced by the reaction ^{56}Fe$(p,n)^{56}$Co, chemically purified to remove the iron,[18] and then implanted[19] with 70 keV energy into a single crystal of cobalt (hcp). Chemical separation of the ^{56}Fe was necessary to avoid excessive damage to the crystal during the implantation. For our sample, the total dose of implanted mass-56 atoms was 10^{15} atom/cm^2. The cobalt crystal has the shape of a thin wafer 5 mm $\times$ 5 mm $\times \frac{1}{4}$ mm with the implantation area being 4 mm $\times$ 4 mm.

In a single crystal of hexagonal close packed cobalt there is no net magnetization in the absence of an external field, but all the magnetic domains are aligned parallel or antiparallel to the crystal c axis. Hence, alignment of the implanted ^{56}Co obtains through the interaction of the ^{56}Co magnetic moment ($|\mu| = 3.822\mu_N$)[20] with the crystal hyperfine field ($H_{eff} = -227$ kG)[21] at low temperatures without the need for an external polarizing field. As noted before, this technique is particularly useful for the present measurement in which alignment, but not polarization, is required because it eliminates the need for an external magnetic field. An external field in the presence of odd alignment terms could produce spurious T-violating asymmetries.

The implanted atoms are stopped within 200–300 Å of the surface and to assure that they are situated in a good single crystal structure careful attention was given to the surface polish. The cobalt crystal was first soldered to a copper rod (see below) and the surface of the crystal was then mechanically polished with 23-μm and then 8-μm silicon carbide paper. This was followed by an electropolish in a solution of chromic and phosphoric acids. The crystal structure was then examined by studying the backscatter channeling pattern of α particles.[22] The intensity of backscatters decreased by 98% when the beam was directed along the a axis, indicating good single crystal structure. A 20 Å thick amorphous surface layer was observed but since this is much smaller than the range of the implanted ions it is very likely that the ^{56}Co atoms were situated in single crystal cobalt. This was confirmed by the γ-ray anisotropy for ^{56}Co which was observed to be consistent with the expected hyperfine field and temperature. With a separate cobalt crystal we also repeated the original experiment of Grace *et al.*[17] That is, we exposed this crystal to reactor neutrons which produced ^{60}Co throughout the crystal. When cooled, this sample gave a γ-ray anisotropy consistent with the same field and temperature as for the ^{56}Co.

A schematic diagram of the apparatus is shown in Fig. 2. The source crystal was soldered to a copper holder using bismuth-cadmium solder. This was done in a helium atmosphere to avoid oxidizing the surface. This holder was screwed to a copper rod which was connected by a tin heat switch to a bundle of 35 000 No. 40 wires upon which a 630-g cerium magnesium nitrate (CMN) salt pill had been grown from solution.[23] The salt was precooled to 100 mK by a ^{3}He-^{4}He dilution refrigerator. Then the salt was thermally isolated from the refrigerator by a lead heat switch and demagnetized from a field of 12 kG. In this way the source was cooled to a temperature of 6 mK.

The temperatures were measured with 100 Ω Speer carbon resistors. These were calibrated using the nuclear magnetic resonance susceptibility of copper at low temperatures and ^{3}He vapor pressure thermometry above 0.4 K. The nuclear alignment for the data analysis was determined by direct observation of the γ-ray anisotropy from the decay of ^{56}Co. Four shorted superconducting coils shielded the source crystal from the small field due to the residual field in the superconducting solenoid.

Positrons were detected at 90° to the alignment axis with a 1-cm^2 by 3-mm thick Si(Li) detector mounted inside the cryostat 2 cm from the source. The β detector was heated and operated at a temperature of about 70 K. It was thermally isolated from the source with three layers of 0.0063-mm thick aluminized Mylar heat shields. An Ortec model 125 preamplifier was placed outside the

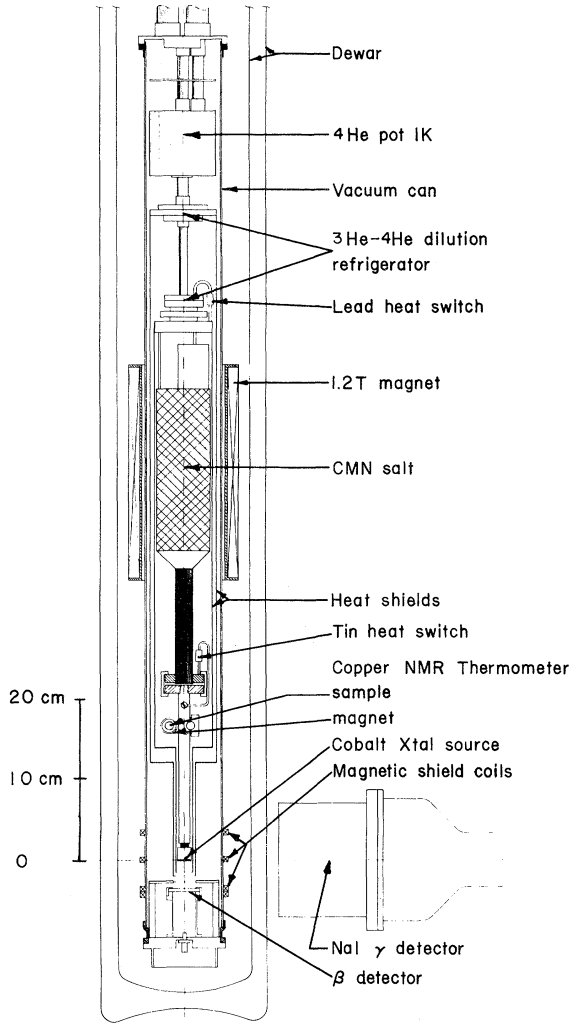

FIG. 2. A schematic representation of the cryogenic apparatus.

cryostat and connected to the Si(Li) detector by 180 cm of 93-Ω RG 62 coaxial cable (total capacitance 80 pF). Electronic noise was typically equivalent to 100–200 keV and the β-γ coincidence time resolution was ~30 nsec. Two 13- by 10-cm NaI(Tl) detectors were mounted outside the cryostat in the plane of the source crystal at angles of $+45°$ and $-45°$ to the c axis as shown in Fig. 3. These angles maximize the dominant T-violating correlation $(\hat{J}\cdot\hat{k})(\hat{J}\cdot\hat{p}\times\hat{k})$. A difference in the β-γ coincidence rates for the 1.24- or 0.847-MeV γ ray associated with the two γ detectors in the presence of nuclear alignment would signal the correlation of interest. A third detector at 180° monitored the γ-ray anisotropy and provided checks on the experiments. All three γ detectors were 13 cm from the source.

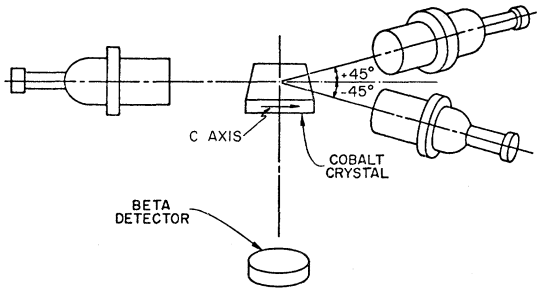

FIG. 3. A schematic representation of the detector geometry showing the three NaI γ detectors in the horizontal plane of crystal at angles of $-45°+45°$, and 180° to the c axis of the cobalt crystal. The β detector is located below the crystal.

The counting electronics shown schematically in Fig. 4 was designed to minimize the effect of systematic differences between the γ detectors. A fast signal from each γ detector was amplified and then discriminated at a level just below 0.511 MeV. The $\pm45°$ γ discriminator pulses were timed to coincide for prompt γ-γ events with the 180° detector and then mixed in a "fast fan in." Coincidences between the resulting signal and a fast discriminator signal from the β detector were detected with a time-to-pulse height converter followed by a single channel analyzer. The lower level discriminator for the β detector was set at ~0.6 MeV. With a 60-nsec window set around the

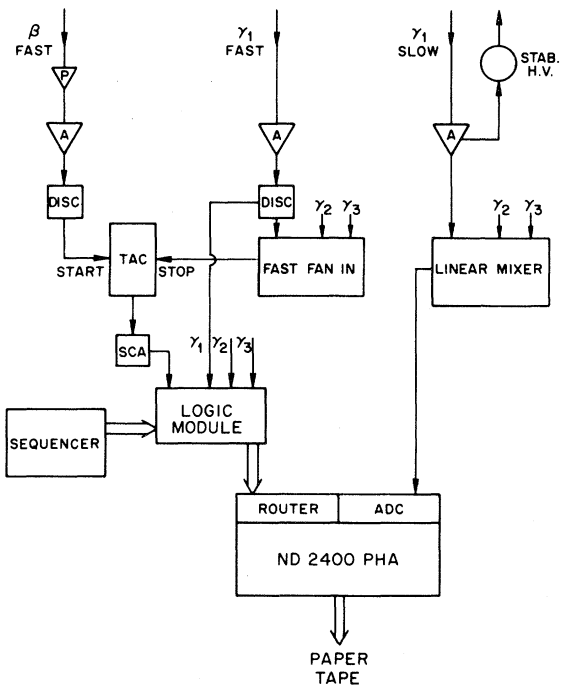

FIG. 4. A block diagram of the counting electronics.

30-nsec coincidence peak the true to random ratio for β-γ coincidences was better than 50 to 1 and no correction for accidental coincidences was made.

The energy signals from the γ detectors were mixed after amplification and digitized in a single amplitude-to-digital converter of a ND2400 pulse height analyzer. The discriminator pulse from each γ detector was used to route the corresponding energy signal into one of four 128-channel memory arrays. Singles and β-γ coincidence γ spectra were collected in separate arrays during alternate 1- and 10-sec periods, respectively. The counting periods were controlled by a crystal oscillator referenced sequencer. An anticoincidence circuit in the router eliminated γ-γ coincidences which would yield ambiguous detector identification and incorrect energies in the present system.

Runs lasted about a week each, with data being written on paper tape and the memory cleared twice each day. The gains of the γ detectors were stabilized during each run by Spectrostat[24] gain stabilizing power supplies that monitored the position of the 0.511-MeV line. Each run began with the source cool and data were taken while the source slowly warmed at a rate of about 1 mK per day. For the last half of each run the source was warmed above ~100 mK, at these temperatures the nuclear alignment was negligible.

III. RESULTS

The photopeak intensities of the 1.24- and 0.847-MeV γ rays in the singles and β-γ coincidence spectra were determined by summing between limits determined from the centroid and width of the peak in the corresponding singles spectra for each detector. This procedure corrected for small gain shifts that were not compensated for by the Spectrostat power supplies. A typical singles and β-γ coincidence spectrum is shown in Fig. 5.

The experimental E_1 parameter is approximately given by

$$E_1\epsilon(T)\approx\frac{N_c^+-N_c^-}{N_c^++N_c^-}, \tag{6}$$

where $N_c^\pm$ is the β-γ coincidence rate in one of the lines for the $\pm 45°$ γ detector. The quantity $\epsilon(T)$ is a temperature dependent quantity obtained from the coefficient of E_1 in Eq. (1) applied to the experimental geometry correcting for the finite solid angles of the γ and β detector and inserting the average value of v/c for the β energies observed. Corrections for β backscattering (~24%) and γ coincidences with Compton scattered electrons in the

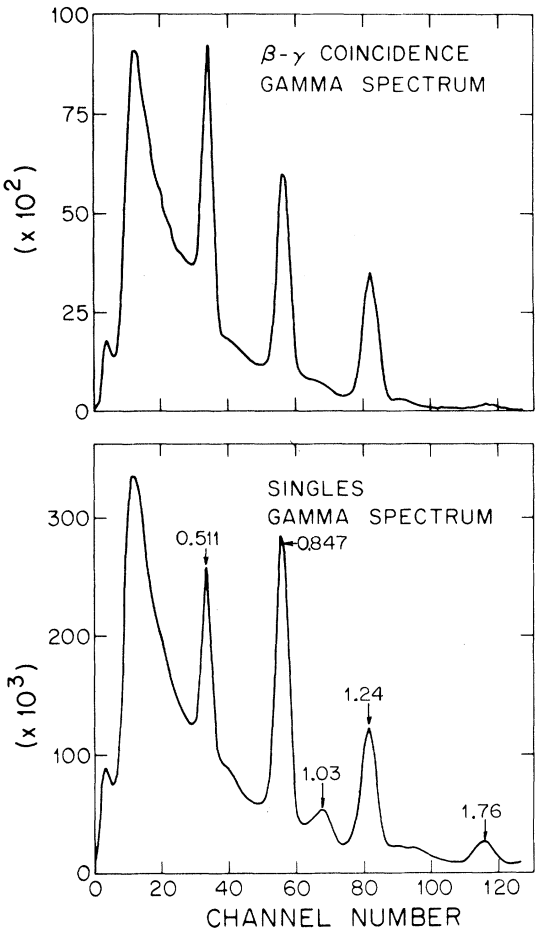

FIG. 5. The γ spectra for β-γ coincidences and for γ singles are shown in the two graphs. The 0.511-MeV peak from β annihilation and the 0.847- and 1.24-MeV γ peaks are clearly visible on the coincidence spectrum. The 1.03- and the 1.76-MeV γ peaks from electron capture are also visible in the singles spectra.

β detector were also included in $\epsilon(T)$ (5% for the 1.24 MeV and 14% for the 0.847-MeV γ rays). The approximation in Eq. (6) arises from neglecting the small (and insignificant) noncancellation of the γ anisotropy in the denominator of the right hand side. The quantity $\epsilon(T)$ then represents the sensitivity of the present experiment for determining the E_1 parameter including the effect of the nuclear alignment and the various corrections. At high temperatures $\epsilon\approx 0$ and at 7 mK $\epsilon\approx -0.045$ for the 1.24-MeV γ ray.

The determination of E_1 by means of Eq. (6) is subject to a number of spurious asymmetries. In particular, a difference in the γ detector efficiencies or a difference in the efficiencies of electronic coincidence detection produces a false effect. Owing to the γ anisotropy term $R_2P_2(\cos\theta)$, a spurious asymmetry also arises if the two γ de-

tectors are not symmetrically located at ±45° with respect to the alignment direction.

The asymmetry due to differences in the detector efficiencies can be eliminated by normalizing the coincidence rates with the singles γ rates but this procedure does not alter the effect due to asymmetric coincidence electronics. Normalizing with the singles rates also eliminates the detector alignment problem, provided the β-γ coincidence and the γ singles anisotropies are identical. Unfortunately, the γ singles and coincidence anisotropies are not the same in this case; the singles anisotropy is changed by the 1.24- or 0.847-MeV γ rays which arise from decays of higher levels in ^{56}Fe populated by electron capture decays. The data were therefore analyzed with the expression

$$\Delta = \frac{N_c^+ - N_c^-}{N_c^+ + N_c^-} - \zeta \frac{N_s^+ - N_s^-}{N_s^+ + N_s^-}, \tag{7}$$

where E_1 is determined from the temperature dependence of Δ by a fit to the equation $\Delta = \epsilon(T)E_1 + K$. The constant K allows for differences in the detector efficiencies and the singles asymmetry $(N_s^+ - N_s^-)/(N_s^+ + N_s^-)$ is used to cancel the angular misalignment effect; the factor ζ takes account of the difference between the γ singles and β-γ coincidence anisotropies; it is determined experimentally with the 180° detector to be 1.2 ± 0.2 and 1.4 ± 0.2 for the 1.24- and 0.847-MeV γ rays, respectively. For most runs the angular alignment was very accurate and because the singles anisotropy for the ±45° detectors is small, the error in ζ is negligible. As a test, in one run the detectors were set at +35° and −55° and the misalignment asymmetry was found to cancel within statistical errors.

Since E_1 is determined from the temperature dependence of the count rates it is important that there be no movement of the source with temperature. The error associated with source movement was judged to be negligible by analyzing the singles asymmetry of the 0.511-MeV annihilation γ rays in the ±45° detectors. Roughly half of those originate from the source crystal and, as these are emitted isotropically independent of temperature, the observed rates are a measure of the source stability.

The data for each run were fitted according to Eq. (7) and an experimental value for E_1 was determined. The combination of rates on the right hand side of Eq. (7) for the 1.24-MeV γ-ray line obtained during one run is shown in Fig. 6 along with the corresponding β-γ coincidence rate in the 180° detector. The rate in the 180° detector shows the effect of the γ-ray anisotropy but no temperature dependence is visible in the data corresponding to Eq. (7).

The experimental values for E_1 obtained from four runs are shown in Table I. Combining these results we obtain $E_1 = -0.011 \pm 0.022$.

In order to interpret this result in the allowed approximation in terms of the phase angle ϕ one needs an independent determination of y [see Eq.

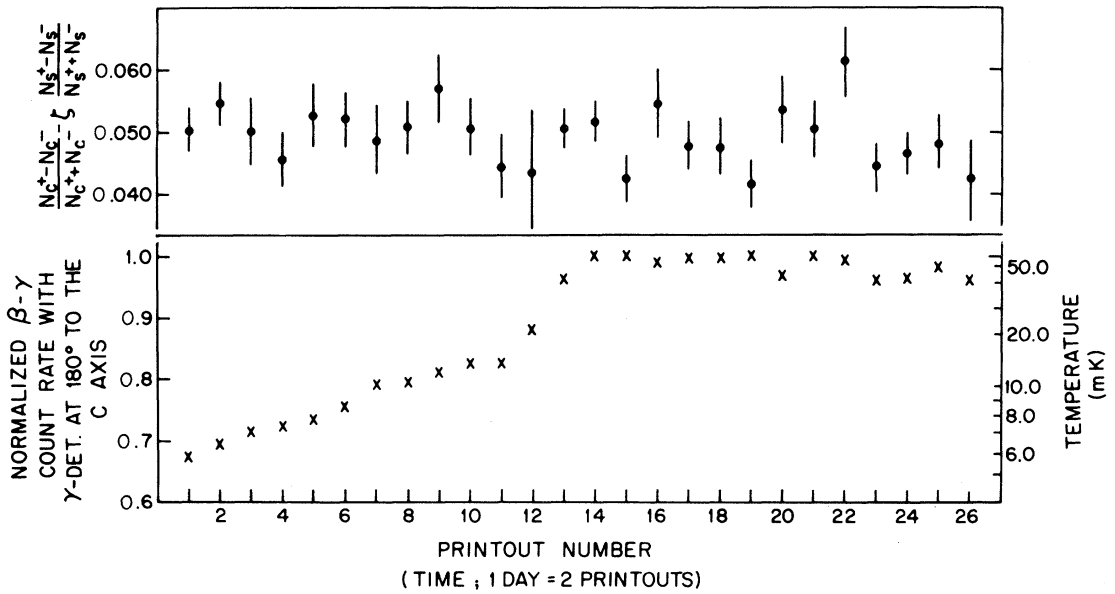

FIG. 6. Data associated with the 1.24-MeV γ ray are presented for one demagnetization. The data presented above demonstrates the lack of alignment dependence to the correlation measured.

TABLE I. Measurements of the correlation parameter E_1.

Run	E_1(0.847 MeV γ)	E_1(1.24 MeV γ)
1	-0.058 ± 0.075	-0.019 ± 0.087
2	$+0.229 \pm 0.260$	$+0.253 \pm 0.263$
3	$+0.011 \pm 0.037$	-0.065 ± 0.042
4	$+0.066 \pm 0.081$	$+0.017 \pm 0.083$

(3)]. The γ-ray anisotropy itself depends on y, but only weakly. A much better determination comes from measurements of the β asymmetry from a polarized sample or from the β-γ circular polarization (CP) correlation. Without the assumption of T invariance (and in the allowed approximation) the β asymmetry is given by

$$A = \frac{1}{1+y^2}\left[\frac{1}{(J+1)} + 2\left(\frac{J}{J+1}\right)^{1/2} y\cos\phi\right] \tag{8}$$

and the β-γ CP correlation by

$$\tilde{A} = \frac{\sqrt{3}}{6}\frac{1}{1+y^2}\left(\frac{2}{[J(J+1)]^{1/2}} - 4y\cos\phi\right). \tag{9}$$

In principle, then, these two measurements are sufficient to determine both y and ϕ.

The β asymmetry has been measured only once with the result, $A = +0.221 \pm 0.021$.[25] The β-γ CP correlation has been measured several times[26] and there is a serious inconsistency between the two most precise values, $\tilde{A} = 0.002 \pm 0.010$ (Ref. 27) and $\tilde{A} = -0.085 \pm 0.003$ (Ref. 28). When the result of Refs. 25 and 28 are combined we find $y \approx 0$ and ϕ is left undetermined. With this value for y our experiment places no limit on ϕ. However, the combination of Refs. 25 and 27 gives $y \approx -1$ and $\phi \approx 90°$ and thus implies maximal T violation. Our result for E_1 is inconsistent with the latter values since $y \approx -1$ in Eq. (3) gives $\phi = 181° \pm 2°$.

If ϕ is assumed to be close to 180° then the result $\tilde{A} = 0.002 \pm 0.010$ implies $y = -0.115^{+0.014}_{-0.013}$ and our value for E_1 yields $\phi = 183° \pm 6°$.

We note that the combination of these various experimental results relies on the allowed approximation and in the case of the highly hindered decay of ^{56}Co forbidden contributions may be significant. Nevertheless, our null result for T

TABLE II. Tests of time-reversal invariance in β decay.

Decay	$J_i \to J_f$ $T_i \to T_f$	Logft	Correlation	Experiment	Ref.	y	Ref.	ϕ (deg)
$n \to pe^-\bar{\nu}$	$\frac{1}{2}^+ \to \frac{1}{2}^+$ $\frac{1}{2} \to \frac{1}{2}$	3.03	$D\hat{J}\cdot\left(\frac{\vec{v}}{c}\times\hat{q}\right)$	$D = -0.14 \pm 0.20$ $+0.04 \pm 0.05$ $+0.01 \pm 0.01$ -0.0011 ± 0.0017	a b c d	0.469 ± 0.004	j	180.14 ± 0.22
$^{19}\text{Ne} \to {}^{19}\text{Fe}^+\nu$	$\frac{1}{2}^+ \to \frac{1}{2}^+$ $\frac{1}{2} \to \frac{1}{2}$	3.24	$D\hat{J}\cdot\left(\frac{\vec{v}}{c}\times\hat{q}\right)$	$D = +0.002 \pm 0.014$ $+0.002 \pm 0.004$	e f	0.625 ± 0.004	k	180.2 ± 0.4
$^{52}\text{Mn} \to {}^{52}\text{Cr}\ e^+\nu$	$6^+ \to 6^+$ $1 \to 2$	5.5	$E_1\hat{J}\cdot\left(\frac{\vec{v}}{c}\times\hat{k}\right)(\hat{J}\cdot\hat{k})$	$E_1 = 0.09 \pm 0.16$	g	-0.144 ± 0.006	l	162 ± 35
$^{58}\text{Co} \to {}^{58}\text{Fe}\ e^+\nu$	$2^+ \to 2^+$ $2 \to 3$	6.6	$E_1\hat{J}\cdot\left(\frac{\vec{v}}{c}\times\hat{k}\right)(\hat{J}\cdot\hat{k})$	$E_1 = 0.13 \pm 0.30$	h	-0.0063 ± 0.0056	m	Undetermined
$^{56}\text{Co} \to {}^{56}\text{Fe}\ e^+\nu$	$4^+ \to 4^+$ $1 \to 2$	8.7	$E_1\hat{J}\cdot\left(\frac{\vec{v}}{c}\times\hat{k}\right)(\hat{J}\cdot\hat{k})$	$E_1 = -0.011 \pm 0.022$	i	0.003 ± 0.004 $-0.115^{+0.014}_{-0.013}$	n o	Undetermined 183 ± 6

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violation in ^{56}Co is independent of this assumption although assumptions of this kind are required to interpret our result in terms of a limit on the phase angle ϕ. In the allowed approximation our limit on T violation is inconsistent with the large T violation implied by the combination of the results of Refs. 25 and 27.

The ^{56}Co result also provides an upper limit for a charge dependent potential which is even under parity and odd under time reversal. Such an interaction could produce a $T=2$ isospin impurity in the predominantly $T=1$ ^{56}Co initial state which in turn would contribute to the imaginary part of the Fermi form factor.

Denoting the interaction by H_c^{odd} and expressing the ^{56}Co state in terms of its isospin components as

$$|^{56}\text{Co}\rangle = [(1-\alpha^2)]^{1/2}\,|4^+, T=1\rangle + \alpha\,|4^+, T=2\rangle \tag{10}$$

we note that the amplitude α of the $T=2$ isospin impurity is given, in first order perturbation theory, by the expression

$$\alpha = \frac{\langle 4^+, T=1\,|H_c^{\text{odd}}|\,4^+, T=2\rangle}{\Delta E}. \tag{11}$$

The $T=2$ impurity of interest is the analog of the 4^+, $T=2$ final state of ^{56}Fe. This analog state has not been identified in ^{56}Co (Ref. 30) but according to Coulomb energetics it is expected at an excitation of 5.65 MeV. For our purpose, this is an adequate estimate for the energy difference ΔE. The Fermi form factor "a" is the matrix element of the isospin raising operator $\langle ^{56}\text{Fe}\,|\,T_+\,|\,^{56}\text{Co}\rangle$, and by Eq. (10) this is 2α, assuming the ^{56}Fe final state to be a pure $T=2$ state.

The determination of $\langle H_c^{\text{odd}}\rangle$ is made complicated by the inconsistency of the β-γ (CP) experiments and their implication for the magnitude of y. However, all data are consistent with $|y| \ll 1$ and in this limit the β-γ (CP) measurements determine $y\cos\phi$, that is, the real part of y. On the other hand, it is the imaginary part of y which is determined by the time-reversal correlation parameter E_1 and on the assumption that this is due to a purely imaginary Fermi form factor a^i and that the Gamow-Teller form factor c is purely real we can determine both from E_1 and the ft value. With $\log ft = 8.7$ and $E_1 = -0.011 \pm 0.022$ we obtain $|c| = 3.5\times10^{-3}$ and $|a^i| = (1.9\pm3.5)\times10^{-5}$. Combining the latter with $a^i = 2\alpha$, $\alpha = \langle H_c^{\text{odd}}\rangle/\Delta E$ and $\Delta E = 5.65$ MeV we obtain $\langle H_c^{\text{odd}}\rangle = 54 \pm 110$ eV, as a limit for the T-violating charge dependent interaction.

In Table II we summarize all the angular correlation tests of time-reversal invariance in nuclear β decay. The experiments on the neutron and ^{19}Ne $\Delta T=0$ mirror decays have been improved over the years with the result that no violation is seen within an error of a few tenths of a percent. More precise results are still needed to detect an effect equivalent to the size of the CP violation, however.

Of the $\Delta T=1$ decays, the old experiment on the ^{58}Co decay is not sensitive to a T violation since the mixing ratio y is consistent with zero. The ^{52}Mn time-reversal experiment of the same period, when combined with a recent determination of y for a measurement of the β asymmetry, sets a limit of 35° on the phase. Finally the present experiment on ^{56}Co sets a limit of 6° or no limit at all, depending on which β-γ (CP) experiment one accepts. To improve the present status of tests of T invariance in $\Delta T=1$ decays it would be useful to repeat the ^{52}Mn time-reversal experiment, by methods employed for the present ^{56}Co experiment. Also, to clarify the implications on the present experiment it would be worthwhile to repeat the β-γ (CP) and β asymmetry angular correlations. Based on the current data, however, we conclude that there is no evidence for a violation of time-reversal symmetry in $\Delta T=1$ decays.

Finally, we note that the nucleus ^{134}Cs is a very favorable case for a test of time-reversal invariance[28,29] because y is relatively large (0.208 ± 0.009) (Ref. 27) and because the decay is greatly hindered ($\log ft = 8.8$).

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