a critical reading of the manuscript.

---

†This work was partially supported by Conselho Nacional de Pesquisas and Financiabora de Estudos e Projetos, Brasil.

*Foundacão de Amparo a Pesquisa do Estado de São Paulo scholarship.

[1] S. S. Hanna, J. R. Calarco, E. Kuhlmann, E. Ventura, and D. G. Mavis, in *Proceedings of the International Symposium on Highly Excited States in Nuclei, Jülich, Federal Republic of Germany, 1975,* edited by A. Faessler, C. Mayer-Boericke, and P. Turek (Kernforschungsanlage Jülich GmbH, Jülich, Federal Republic of Germany, 1975); N. Shikazano and T. Terasawa, Nucl. Phys. A250, 260 (1975).

[2] W. W. Gargaro and D. S. Onley, Phys. Rev. C 4, 1032 (1971).

[3] I. C. Nascimento, E. Wolynec, and D. S. Onley, Nucl. Phys. A246, 210 (1975).

[4] E. Wolynec, G. Moscati, O. D. Gonçalves, and M. N. Martins, Nucl. Phys. A244, 205 (1975).

[5] E. Wolynec, G. Moscati, J. R. Moreira, O. D. Gonçalves, and M. N. Martins, Phys. Rev. C 11, 1083 (1975).

[6] As a rough estimate, we have evaluated the mean life for γ de-excitation using the single-particle model and the mean life for α emission by the Geiger-Nuttal law.

[7] V. L. Telegdi and M. Gell-Mann, Phys. Rev. 91, 169 (1953).

[8] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Reading, Mass., 1975), Vol. 2.

Time Reversal Test in ^{57}Fe†

N. K. Cheung, H. E. Henrikson, E. J. Cohen,* A. J. Becker,‡ and F. Boehm
California Institute of Technology, Pasadena, California 91125

(Received 28 June 1976)

The linear polarization of the $E2$-$M1$ 122-keV γ ray of ^{57}Fe following the electron capture decay of polarized ^{57}Co was measured with a Compton polarimeter. An average time-reversal–noninvariant counting asymmetry of $(-0.4\pm 0.8)\times 10^{-5}$ was obtained. This corresponds to a phase angle between the $E2$ and $M1$ matrix elements of $\sin\eta = (-3.1 \pm 6.5)\times 10^{-4}$, consistent with time-reversal invariance.

The phenomenon of CP nonconservation has so far been observed only in the neutral K meson system. A compilation of the CP-nonconserving parameters furthermore reveals that the observed CP-nonconservation is mainly due to a CPT-conserving, T-nonconserving interaction.[1] This raises the question of whether one expects to observe T nonconservation in other systems, especially in the broad class of nuclear phenomena.

In the particular case of electromagnetic transitions, time-reversal noninvariance will manifest itself by the presence of a relative phase η other than 0 or π between reduced matrix elements of interfering multipoles in a mixed transition. Experimental limits on $\sin\eta$ so far are a few parts in 10^3, and are close to the limits of P-even, T-odd observables predicted by the classes of $\Delta Y = 0$ millistrong and electromagnetic theories proposed to account for the observed CP nonconservation.[2,3] It is thus of interest to push down the experimental limit by an order of magnitude to clarify this situation. The purpose of this Letter is to describe the results of a new experiment which provides a considerably lower limit on T nonconservation in nuclear physics.

Experimental measurements of η must involve at least three vectors, such as the nuclear polarization $\vec{J}$, the γ-ray momentum $\vec{k}$, and the γ-ray linear or circular polarization $(\vec{E}, \vec{P}_\gamma)$. Recent experiments using angular correlation techniques measured T-odd quantities of the form $(\vec{J}\cdot\vec{k}_1\times\vec{k}_2)\times(\vec{k}_1\cdot\vec{k}_2)$,[4-6] $\vec{k}_1$ and $\vec{k}_2$ being γ-ray momenta in a cascade. Polarization of the initial state was achieved by either capture of polarized thermal neutrons or low-temperature nuclear orientation. The precision obtainable by this method was limited by the inherent low count rate in a coincidence experiment. If, however, the linear polarization $\vec{E}$ is determined in addition to the direction of a γ ray, terms of the form $(\vec{J}\cdot\vec{k}\times\vec{E})(\vec{J}\cdot\vec{k})\times(\vec{J}\cdot\vec{E})$ can be measured. By measuring the absorption of linearly polarized recoiless γ rays in a magnetic medium, several authors[7-9] have established good limits on $\sin\eta$. This method is unfortunately hampered by multiple scattering, Faraday rotations, and large final-state effects.

We report here a new approach to the measurement of the quantity $(\vec{J}\cdot\vec{k}\times\vec{E})(\vec{J}\cdot\vec{k})(\vec{J}\cdot\vec{E})$ based on nuclear polarization by means of low temperature and strong magnetic field. The case chosen is

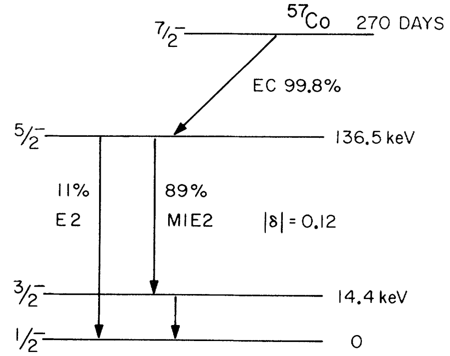

FIG. 1. Decay scheme of ^{57}Co.

the 122-keV $M1$-$E2$ transition in ^{57}Fe emitted following the electron capture of ^{57}Co. The decay scheme is shown in Fig. 1. Nuclear orientation of ^{57}Co in iron is well understood from a previous work.[10]

The angular and linear polarization distribution for a mixed electromagnetic transition from oriented nuclei can be written as a sum of three terms[11, 12]:

$$W(\theta,\varphi)=W_1(\theta)+W_2(\theta,\varphi)+W_3(\theta,\varphi), \tag{1}$$

where θ is the angle between the momentum vector $\vec{k}$ of the γ ray and the orientation axis $\vec{J}$, and φ is the angle between the linear polarization vector $\vec{E}$ and the plane formed by $\vec{J}$ and $\vec{k}$. $W_1(\theta)$ is the usual directional distribution term if the linear polarization is not measured. $W_2(\theta,\varphi)$ is the usual T-even linear polarization distribution term and $W_3(\theta,\varphi)$ is the T-odd linear polarization term of particular interest to us. Explicitly, W_3 is given by

$$W_3(\theta,\varphi)=\sum_{k=\mathrm{odd}} Q_k B_k U_k A_{k2}'(-2i)\left(\frac{(k-2)!}{(k+2)!}\right)^{1/2} P_k^{\,2}(\cos\theta)\sin 2\varphi, \tag{2}$$

with

$$A_{k2}'=-iE_p f_k F_k|\delta|(\sin\eta)/(1+|\delta|^2). \tag{3}$$

In Eqs. (2) and (3), B_k is a function of $\mu H/kT$ characterizing the nuclear polarization, U_k is the deorientation parameter, A_{k2}' is the angular distribution coefficient, $P_k^{\,2}$ is the associated Legendre polynominal of order $(k,2)$, Q_k is the solid angle correction, and f_k and F_k are the usual coefficients in an electromagnetic transition.[11, 12]. $\delta \equiv|\delta|e^{i\eta}$ is the complex mixing ratio for the mixed transition and E_p is the efficiency for measuring linear polarization. Note that the lowest nonvanishing term in W_3 is proportional to $\sin^2\theta\cos\theta \times \sin 2\varphi$ which is in turn proportional to the T-odd quantity $(\vec{J}\cdot\vec{k}\times\vec{E})(\vec{J}\cdot\vec{k})(\vec{J}\cdot\vec{E})$. The magnitude of this term is a maximum for $\theta=\theta_{\max}=54.7°$ and $\varphi=\pm 45°$.

A 2-mCi source was prepared by diffusing ^{57}Co into an iron disk 3.2 mm in diameter and 12.7 μm thick at 890°C in a hydrogen atmosphere. The annealed disk was soldered with gallium in the horizontal plane to the tip of a cold finger, the upper end of which was screwed into the mixing chamber of the ^{3}He-^{4}He dilution refrigerator, details of which are described by Becker, Henrikson, and Cook.[13] The source was located at the center of two pairs of superconducting magnet coils in a Helmholtz-like geometry providing the relatively small magnetic field (2 kG) to magnetically saturate the iron disk. ^{57}Co nuclei were oriented by the large hyperfine field of the polarized electrons (287 kG).[14]

A Compton polarimeter was used to measure the linear polarization of the γ rays. It consists of an aluminum scatterer and four NaI(Tl) detectors to observe the 90° Compton-scattered γ rays. The experimental setup is shown schematically in Fig. 2. The angle between $\vec{k}$ and the polarization axis, θ, was set at 54.7°. The NaI(Tl) detectors No. 1, 2, 3, and 4 were set up at $\varphi=45°$, 135°, 225°, and 315°, respectively. By switching the external magnetic field (thereby flipping $\vec{J}$), the count rates for $\theta=\theta_{\max}$ and $\theta=\pi-\theta_{\max}$ were compared. For each detector,

$$\frac{W(\theta_{\max},\varphi)-W(\pi-\theta_{\max},\varphi)}{W(\theta_{\max},\varphi)+W(\pi-\theta_{\max},\varphi)}=-0.0164Q_3B_3P_3^{\,2}(\cos\theta_{\max})\sin 2\varphi\,\sin\eta\,E_p/D, \tag{4}$$

where $D=1+0.0058Q_4B_4P_4(\cos\theta_{\max})$. Because the pure $E2$ 136-keV line (11% intensity) cannot be resolved from the 122-keV line (89% intensity), D was replaced by $D'=1.124-0.039Q_4B_4P_4(\cos\theta_{\max})$. With four NaI detectors placed symmetrically around the scatterer, most of the first-order systematic errors such as those due to deviations from the precise scattering angles can be eliminated.

A Ge(Li) detector was set up at 180° from the polarimeter (Fig. 2) to measure the source tem-

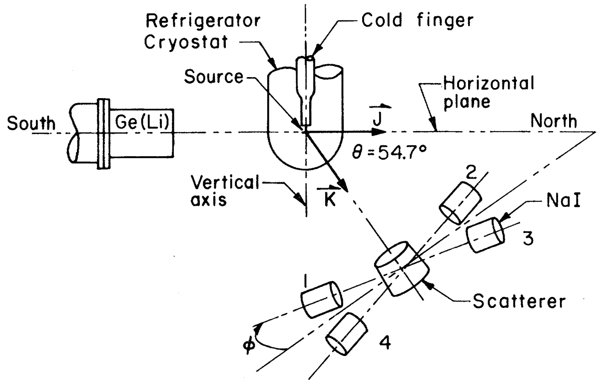

FIG. 2. Schematic diagram of experimental setup.

perature and to monitor the stability of the system against temperature changes, drifts in electronics, etc. The temperature was measured every 24 hr from the directional distribution of the 136-keV γ ray using the Ge(Li) detector. The nuclei were oriented parallel ($\theta = 0°$) and then perpendicular ($\theta = 90°$) to the axis of this detector. From these count rates, $\mu H/kT$ was evaluated. All B_k values can then be determined.[10]

The polarization efficiency E_p of the polarimeter can be determined with an incident beam of known polarization, such as the photons from the oriented ^{57}Co nuclei. In this case E_p can be deduced by measuring the quantity

$$\frac{W(\theta=90°,\varphi=0°)-W(\theta=90°,\varphi=90°)}{W(\theta=90°,\varphi=0°)+W(\theta=90°,\varphi=90°)} = E_p\frac{0.492B_2Q_2-0.024B_4Q_4}{1.124-0.034Q_2B_2-0.014Q_4B_4}. \qquad (5)$$

The result at $T = 16.5$ mK is $E_p = -0.456 \pm 0.009$. This was checked by a Monte Carlo calculation and also by measuring the 121–280-keV cascade polarization-directional correlation in the ^{75}Se decay in a manner similar to that described by Van den Bold, van de Geijn, and Endt.[15]

With this new level of precision, care must be exercised to identify and eliminate different systematic effects, four of which will be briefly discussed:

(i) The asymmetry due to the influence of switching magnetic field on the photomultipliers was eliminated by inserting 30 cm of light pipe between the NaI crystal and the photomultiplier.

(ii) Immediately after a temperature measurement, each NaI detector registered a large asymmetry of $\sim 8\times10^{-4}$. The asymmetries for successive 12-hr runs then decreased gradually provided that no more temperature measurements were made. This was thought to be caused by the remanent magnetization in the 90° direction resulting from the foil having been magnetized in this direction for temperature measurement. To verify this a controlled magnetic field of a few gauss was applied in the 90° direction in addition to the 0°–180° switching field and the same result as that obtained after a temperature measurement was reproduced. With the cause of this asymmetry established, the iron foil was carefully demagnetized in the 90° direction by a sinusoidal magnet current of 0.25 Hz with a logarithmic decaying envelope.

(iii) A residual magnetization in the vertical direction (perpendicular to the plane of the disk) also contributed to an asymmetry in the count rate of individual NaI detectors. Unlike case (ii), by taking the average of four detectors, the asymmetries cancelled out. To further reduce this asymmetry, the iron disk was demagnetized in the vertical direction using a vertical field before a long series of runs was started.

(iv) A 12-hr periodic drift in count rate was observed giving rise to spurious asymmetries. This was due to the liquid nitrogen boiling off, causing the center of gravity of the cryostat to change, and hence causing a slight movement which changed the solid angle of the polarimeter. This drift was eliminated by fastening the cryostat to the polarimeter.

At an average temperature of 17.6 mK ($B_3 = 0.33$), 27 runs, each of 12-hr duration, were made, giving a mean raw asymmetry $A' = (-0.35 \pm 0.74)\times10^{-5}$. This raw asymmetry was corrected for the x rays which contributed to 6% of the area of the 90° Compton-scattered peak, giving a corrected asymmetry of $A = (-0.37 \pm 0.78)\times10^{-5}$. This corresponds to the final result $\sin\eta = (-3.1 \pm 6.5)\times10^{-4}$, with χ^2 per degree of freedom of 0.95, $P(\chi_\nu^2 > 0.95) = 0.55$.

At this level of asymmetry, attention must be paid to any nuclear and atomic effects that might mask the genuine effect we are seeking. One possibility was the rotation of the polarization vector $\vec{E}$ as the γ ray passed through a ferromagnetic medium, giving rise to a net asymmetry. Using the experimental value of Bock and Luksch,[16] it was estimated that this would contribute an asymmetry of $\sim 6\times10^{-7}$, which is an order of magnitude below the precision of the present experiment and can thus be neglected.

More important is the final-state interaction arising from higher-order terms of the transition operator, as a result of which the mixing ratio δ is modified by an extra phase ξ to $\delta' = \delta e^{i\xi} = |\delta| e^{i(\xi+\eta)}$. Hence, the measured quantity will be $\sin(\xi+\eta)$ rather than $\sin\eta$. Goldwire and Hannon[17] have made detailed calculations of the phase ξ arising from internal conversion and Thomson scattering of the atomic electrons. Their results for a 122-keV $M1$-$E2$ transition are $\xi(\text{conversion}) = -7.7\times10^{-4}$ and $\xi(\text{Thomson}) = +1.7\times10^{-4}$, yielding $\xi_{\text{total}} = (-6.0\pm0.4)\times10^{-4}$, where the error is the cumulative computational error as cited in Ref. 17. However, in view of the present experimental precision, no conclusion can be drawn as to the presence of the final-state interactions. If one accepts the above value of ξ, the measured value then becomes $\sin\eta = (2.9\pm6.6)\times10^{-4}$. Before one can use the computed value of ξ with confidence it is important that an independent experimental check on the calculations be carried out.

In view of the present experimental result, it is unlikely that the observed *CP* nonconservation is due to the classes of millistrong and electromagnetic theories, although the precision is still not sufficient to draw any conclusion with certainty. The new level of precision achieved in the present experiment indicates that the single-counting linear polarization technique is a powerful tool for studying small *T*-odd asymmetries.

We would like to thank Dr. H. C. Goldwire and Dr. J. P. Hannon for communicating their results to us prior to publication, and Dr. P. Herczeg for helpful discussions. D. Cook and E. Seltzer's contribution in the early part of the experiment is gratefully acknowledged.

---

†Work supported by the U. S. Energy Research and Development Administration under Contract No. AT-[04-3]-63.

*Present address: Jet Propulsion Laboratory, Pasadena, Calif. 91103.

‡Present address: Physics Department, Columbia University, New York, N. Y. 10027.

[1] See, for example, the review by K. Kleinknecht, to be published.

[2] R. J. Blin-Stoyle, *Fundamental Interactions and the Nucleus* (North-Holland, Amsterdam, 1973).

[3] A. Richter, in *Interaction Studies in Nuclei*, edited by H. Jochum and B. Ziegler (North-Holland, Amsterdam, 1975).

[4] M. J. Holmes, W. D. Hamilton, and R. A. Fox, Nucl. Phys. A199, 401 (1973).

[5] M. I. Bulgabov *et al.*, Yad. Fiz. 18, 12 (1973) [Sov. J. Nucl. Phys. 18, 6 (1974)].

[6] K. S. Krane, B. T. Murdoch, and W. A. Steyert, Phys. Rev. C 10, 840 (1974).

[7] O. C. Kistner, Phys. Rev. Lett. 19, 872 (1967).

[8] M. Atac, B. Chrisman. P. Debrunner, and H. Frauenfelder, Phys. Rev. Lett. 20, 691 (1968).

[9] E. Zech, F. Wagner, H. J. Hoerner, and P. Kienle, in *Hyperfine Structure and Nuclear Radiations* (North-Holland, Amsterdam, 1968), p. 314; E. Zech, Z. Phys. 239, 197 (1970).

[10] E. J. Cohen, A. J. Becker, N. K. Cheung, and H. E. Henrikson, Hyperfine Interact. 1, 193 (1975).

[11] R. M. Steffen, LASL Report No. LA-4565-MS, 1971 (unpublished).

[12] R. M. Steffen and K. Alder, *The Electromagnetic Interactions in Nuclear Spectroscopy* (North-Holland, Amsterdam, 1975), p. 505.

[13] A. J. Becker, H. E. Henrikson, and D. C. Cook, Nucl. Instrum. Methods 108, 291 (1973).

[14] G. N. Ras, in Proceedings of the International Meeting on Hyperfine Interactions, University of Leuven, Leuven, Belgium, 10–12 September 1975 (to be published).

[15] H. J. Van den Bold, J. van de Geijn, and P. M. Endt, Physica (Utrecht) 24, 23 (1958).

[16] P. Bock and P. Luksh, Lett. Nuovo Cimento 2, 1081 (1971).

[17] H. C. Goldwire and J. P. Hannon, to be published.