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Time-reversal test and nuclear-structure study using $^{110}Ag^{m}$ †

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The decay of oriented $^{110}Ag^{m}$ has been studied through singles and coincidence counting. The nuclear polarization was obtained by using a dilution refrigerator and the hyperfine field in iron. Ge(Li) singles spectra yielded the following $E2/M1$ mixing ratios: $\delta(447\text{ keV}) = -0.40 \pm 0.06$, $\delta(678\text{ keV}) = -0.36 \pm 0.03$, $\delta(687\text{ keV}) = -1.65 \pm 0.09$, $\delta(707\text{ keV}) = -1.42 \pm 0.07$, $\delta(1384\text{ keV}) = -0.39 \pm 0.02$, $\delta(1505\text{ keV}) = -1.09 \pm 0.09$. In a time-reversal invariance test the phase angles η of the mixing ratio $\delta = |\delta| e^{i\eta}$ were measured through the observation of γ-γ directional correlations in the daughter ^{110}Cd. Three NaI detectors allow six coincidence combinations to be measured for both the 1505-658 keV and the 1384-(885)-658 keV cascades. We found $\sin\eta(1505\text{ keV}) = (1.5 \pm 2.2) \times 10^{-3}$ and $\sin\eta(1384\text{ keV}) = (-1.7 \pm 5.1) \times 10^{-3}$, consistent with time-reversal invariance. The g factor of the 658 keV state in ^{110}Cd was determined to be 0.28 ± 0.05.

[RADIOACTIVITY $^{110}Ag^{m}$ (oriented); measured $I_\gamma(\theta = 90°, T)$. ^{110}Cd; deduced γ mixing. ^{110}Cd; measured $\gamma\gamma$ coin, time-reversal test; deduced mixing ratio phase angles, 1505 and 1384 keV γ rays; 658 keV level deduced g.]

INTRODUCTION

Symmetries have always played a central role in the development of physics, since they and their related conservation laws are used frequently to simplify physical problems. Among such symmetries, of particular importance are parity (P), charge conjugation (C), and time reversal (T). Before 1956 the evidence for invariance under P, C, T transformations was thought to be extremely strong. All tests in atomic, nuclear, and particle physics indicated validity of the symmetries. However, as Lee and Yang[1] considered theoretically, and Wu[2] unequivocally demonstrated in 1957, both parity and charge conjugation invariances are violated in weak interactions, which are responsible for nuclear β-decays. Since then, the investigation of the symmetry laws satisfied by the nuclear Hamiltonian has received greater attention.

In 1964 Christenson *et al.*[3] observed evidence for CP violation in the decay of the long-lived neutral K meson. Assuming CPT invariance in all interactions, the observed CP violation implied a T violation. Subsequently, data on the kaon system were used to show a T violation independent of CPT conservation.[4-6] The presence of the CP violation in neutral kaon decay prompted a number of investigations to determine the origin of the T-violating part of the Hamiltonian. However, at the present the T-violating terms in neutral kaon decay have not been identified and several interactions remain as possible sources of the T-violating effects.[7]

In a mixed-multipole electromagnetic transition in the nucleus, a consequence of T invariance is that the reduced matrix elements are real (in the absence of a final state interaction). However, the phase angle η of the mixing ratio δ would be different from 0 or π if T is violated.[8] A term proportional to $\sin\eta$, and therefore sensitive to time reversal to first order, must contain three vectors, and change sign under the T operation. The quantities which can be measured are polar vectors characterizing the photon momentum $\vec{k}$, axial vectors characterizing the nuclear spins $\vec{J}$ and the photon spin $\vec{S}$, and the plane of linear polarization $\vec{\epsilon}$. The transformations of these quantities under time reversal operations are $\vec{J} \to -\vec{J}$, $\vec{k} \to -\vec{k}$, $\vec{S} \to -\vec{S}$, and $\vec{\epsilon} \to \vec{\epsilon}$. Appropriate combinations of these quantities which are odd under T and even under P have been discussed by Jacobsohn and Henley[9] and have been tabulated by Boehm.[10]

The more recent experiments usually involve a measurement of two of the above mentioned quantities from polarized nuclei (from which the third vector $\vec{J}$ is determined). One type of experiment[11] searches for T-odd quantities of the form $(\vec{\epsilon} \cdot \vec{k} \times \vec{J})(\vec{k} \cdot \vec{J})(\vec{\epsilon} \cdot \vec{J})$. In this case, an orientation tensor of the third rank is required, and the γ-ray linear polarization must be measured. In another type of experiment, T-odd quantities of the form $(\vec{J} \cdot \vec{k}_1 \times \vec{k}_2) \cdot (\vec{k}_1 \cdot \vec{k}_2)$ are sought. For instance, the γ-γ directional correlation from an initial state polarized by the capture of a polarized neutron has been measured several times.[12-14] Additionally, coincidence asymmetries have been sought in β-γ-γ triple correlations from unpolarized nuclei,[15-17] a method equivalent to a polarized-nuclei γ-γ correlation because the β-particles are used to specify the nuclear spin direction. In general, methods employing dynamic polarization have been limited statistically by the low rate of accumulation of events. However, nuclear orientation obtained by using a ^{3}He-^{4}He dilution refrigerator can be employed advantageously, since a direction in space can be fixed essentially indefinitely for large numbers of nuclei.[18-21] The present work measures $\sin\eta$ by looking at γ-γ directional correlations from ^{110}Ag^m nuclei polarized using such a dilution refrigerator.

In conjunction with this time-reversal test, it was possible to employ the ultralow-temperature nuclear orientation to obtain relatively easily the $E2/M1$ mixing ratios for eight γ rays in the daughter nucleus ^{110}Cd. Also, an important aspect of the T-violation study was the measurement of the magnetic moment for the 658 keV first excited state in ^{110}Cd.

Directional correlations from oriented nuclei

The general theory for directional correlations from oriented nuclei has been described in Ref. 22, and the relevant details will be summarized briefly here. With the polarization axis $\hat{J}$ chosen as the z axis, θ_1 and θ_2 describing, respectively, the polar angles of emission of $\gamma_1(\hat{k}_1)$ and $\gamma_2(\hat{k}_2)$ with respect to $\hat{J}$, and ϕ being the azimuthal angle between the $(\hat{k}_1, \hat{J})$ and $(\hat{k}_2, \hat{J})$ planes, the directional correlation may be written as

$$W(\theta_1\theta_2\phi) = \sum_{\lambda_1\lambda\lambda_2} Q_\lambda(\gamma_1)Q_{\lambda_2}(\gamma_2)B_{\lambda_1}(J)A_\lambda^{\lambda_2\lambda_1}(\gamma_1) \times A_{\lambda_2}(\gamma_2)H_{\lambda_1\lambda\lambda_2}(\theta_1\theta_2\phi). \quad (1)$$

Here, B_{λ_1} is the orientation parameter which depends on J and the populations $P(m)$ of the m sublevels of the nucleus, A_{λ_2} is the directional distribution coefficient for the second γ-ray and depends on the spins of the intermediate and final states, and Q_λ and Q_{λ_2} are the solid-angle corrections for the finite size of the detectors. The generalized angular distribution coefficient $A_\lambda^{\lambda_2\lambda_1}(\gamma_1)$ for $I_0 \xrightarrow{\gamma_1} I_1$ is given for T even $(\lambda_1+\lambda+\lambda_2 = \text{even})$ by

$$A_\lambda^{\lambda_2\lambda_1} = \frac{F_\lambda^{\lambda_2\lambda_1}(LLI_1I_0) + 2|\delta|\cos\eta F_\lambda^{\lambda_2\lambda_1}(LL'I_1I_0) + |\delta|^2 F_\lambda^{\lambda_2\lambda_1}(L'L'I_1I_0)}{(1+|\delta|^2)} \quad (2)$$

and for T odd $(\lambda_1+\lambda+\lambda_2 = \text{odd})$ by

$$A_\lambda^{\lambda_2\lambda_1} = \frac{2i|\delta|\sin\eta}{1+|\delta|^2} F_\lambda^{\lambda_2\lambda_1}(LL'I_1I_0), \quad (3)$$

where δ is the γ-ray mixing ratio using the phase convention of Ref. 23. The generalized F coefficients $F_\lambda^{\lambda_2\lambda_1}$ have been tabulated for cases relevant to T-violation studies in Ref. 24.

The angular function $H_{\lambda_1\lambda\lambda_2}$ is given by[24]

$$H_{\lambda_1\lambda\lambda_2}(\theta_1\theta_2\phi) = \sum_{q\ge 0} \begin{Bmatrix} 2-\delta_{q0} \\ -2i \end{Bmatrix} \langle\lambda_1 0 \lambda q|\lambda_2 q\rangle (-)^\lambda \left(\frac{2\lambda+1}{2\lambda_2+1}\right)^{1/2} \left(\frac{(\lambda-q)!(\lambda_2-q)!}{(\lambda+q)!(\lambda_2+q)!}\right)^{1/2} \times P_\lambda^q(\cos\theta_1)P_{\lambda_2}^q(\cos\theta_2) \begin{Bmatrix} \cos q\phi \\ \sin q\phi \end{Bmatrix}. \quad (4)$$

Of the two pairs of quantities in braces, the upper member refers to cases in which $\lambda_1+\lambda+\lambda_2$ is even, while the lower member is for odd values of that sum; the latter case is the one of interest for studies of time-reversal invariance. For γ-ray directional distributions (no polarizations measured), λ and λ_2 are restricted to even values, and hence λ_1 must be odd for studies of T violation (i.e., the initial state must be polarized).

The directional correlation function then may be written as

$$W = W_0 + W_T + W', \quad (5)$$

where W_0 is the "normal" or T-conserving term (λ_1 = even), W_T is the T-violating term (λ_1 = odd), and an additional term W' has been included to account for a polarization-sensitive, T-nonviolating effect arising from a precession perturbation of the intermediate state. By periodically reversing the direction of the nuclear polarization, one can measure the asymmetry a, defined by

$$a = [W(\uparrow) - W(\downarrow)]/[W(\uparrow) + W(\downarrow)]. \quad (6)$$

$W(\uparrow)$ and $W(\downarrow)$ indicate the measured correlation with nuclear spin up and down, respectively. Since the λ_1-odd terms in W_T change sign under this reversal while the λ_1-even terms in W_0 do not, this asymmetry may be written, assuming $W_T, W' \ll W_0$, as

$$a \sim (W_T + W')/W_0 \equiv a_T + a' . \tag{7}$$

The quantity W' signifies the polarization-sensitive effect which simulates T violation and is due to an intermediate state interaction, resulting in an azimuthal shift $\Delta\phi$. Fortunately, this asymmetry can be measured relatively accurately when a T-violating effect cannot contribute, i.e., at high temperatures when the nuclear orientation is small.

The lowest nonvanishing term in W_T, corresponding to $(\lambda_1 = 1,\ \lambda = \lambda_2 = 2)$, is proportional to

$$W_T \sim W_T(\lambda_1 = 1,\ \lambda = \lambda_2 = 2)$$
$$\propto Q_2(\gamma_1)Q_2(\gamma_2)B_1(J)F_2^{21}(\gamma_1)\frac{2|\delta|\sin\eta}{1+|\delta|^2}$$
$$\times A_2(\gamma_2)(\hat{J}\cdot\hat{k}_1\times\hat{k}_2)(\hat{k}_1\cdot\hat{k}_2). \tag{8}$$

In order to make a sensitive test of T, one must try to make W_T as large as possible.

To maximize $(\hat{J}\cdot\hat{k}_1\times\hat{k}_2)(\hat{k}_1\cdot\hat{k}_2)$, the geometry was chosen[18] such that $\theta_1 = \theta_2 = 90°$, $\phi = \pm 45°$ or $\pm 135°$, i.e., the detectors are in the plane perpendicular to $\hat{J}$ and are 45° or 135° apart. In choosing the best nucleus to be studied, it is important to note that the term $|\delta|/(1+|\delta|^2)$ has a maximum value of 0.5 when $|\delta| = 1$. Of course,

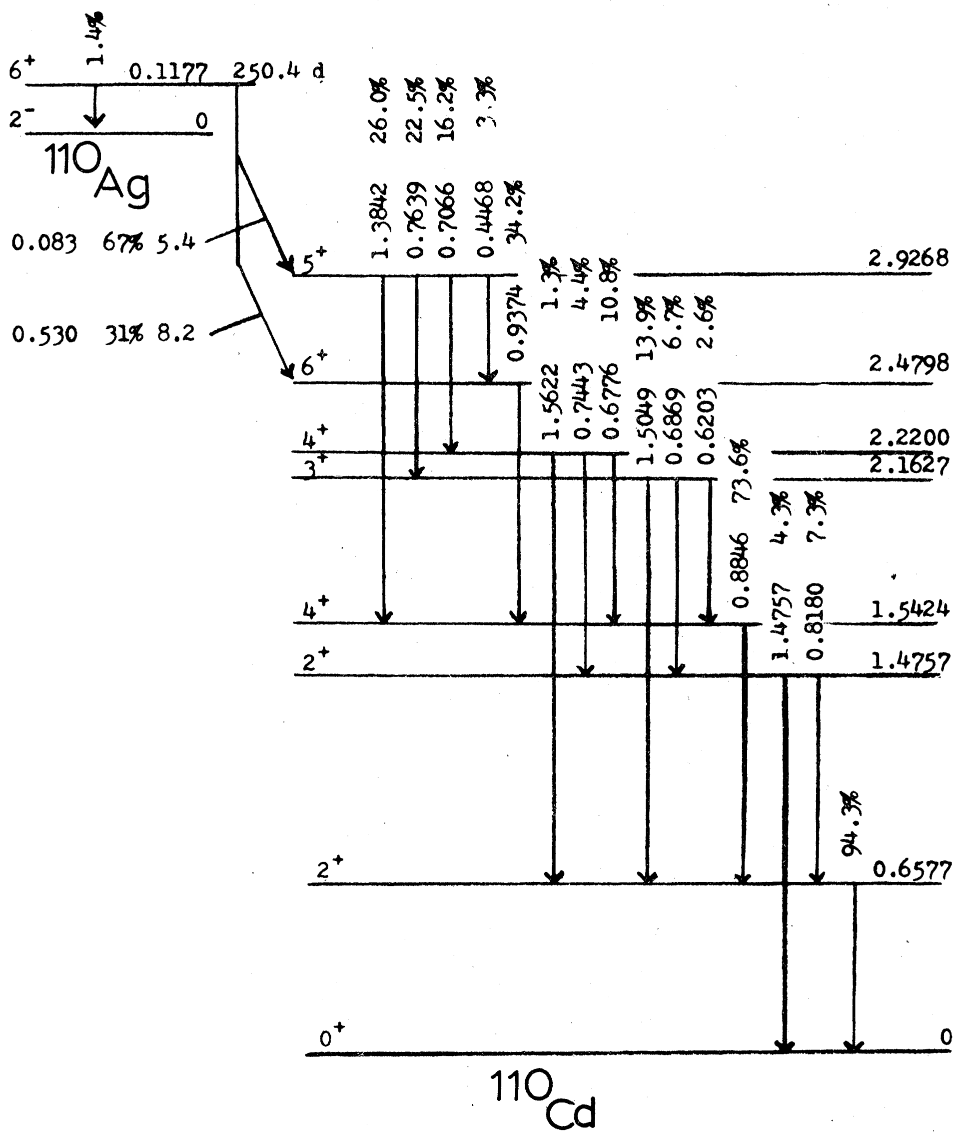

FIG. 1. Decay scheme of $^{110}Ag^m$.

important additional criteria arise from the fact that the degree of polarization obtainable depends on the magnetic moment of the parent nucleus, the hyperfine field in the host material, and the temperatures that are available. Also, it is important to choose a nucleus with a strongly fed cascade, a convenient half-life, and readily detectable γ rays.

After an extensive search of the literature, the parent isotope $^{110}Ag^m$ was chosen. The decay scheme is shown in Fig. 1. The 250.4 day 6^+ isomeric state of $^{110}Ag^m$ has a magnetic moment of $3.6\mu_N$ and the hyperfine field values reported[25,26] were between -250 and -447 kG, corresponding to effective splittings $\Delta \equiv \mu H/Jk = 5.5$ and 9.8 mK, respectively. Even with the lower number, an appreciable orientation is within the capability of our dilution refrigerator. The cascades that are appropriate for the T-violation studies are the 1505–658 keV and 1384–(885)–658 keV ones of the daughter ^{110}Cd.

Source preparation

One of the most difficult tasks of this experiment was the source preparation. Iron was chosen to be the host since it yields a large hyperfine field and also is magnetically soft, thereby allowing an easy reversal of the direction of polarization. However, relatively little is known about the Ag-Fe system, and widely differing values have been reported for the effective hyperfine field of $^{110}Ag^m$ in iron. The work of Ref. 25, using an ion-implanted source, yielded a hyperfine field of -250 kG. In Ref. 26, a hyperfine field of -447 kG was reported for a melted source. A possible reason for the difference is that Ag does not readily dissolve in iron, with concentration limits of about 10^{-5} mentioned in the literature. Thus for the T-violation test to be meaningful, careful attention had to be given to developing an effective source-preparation technique to produce both a high-activity source and one with a large hyperfine field at the Ag nuclei.

The final source-preparation technique involved several steps. High specific activity (18.7 mCi/mg) $^{110}Ag^m$ in a 1 N HNO_3 solution was mixed into fine iron powder to form a slurry, which then was dried and reduced in an H_2 atmosphere. The powder then was pressed into a pellet and melted in an induction furnace under an argon atmosphere. The next, very important step was to quench the molten Ag-Fe source ("splatcool") and form it into the shape of a wire without annealing. A simple quenching device was used in which the molten pellet was suspended on a "trap door" over a mineral oil bath and dropped in. This quenching technique worked very well and produced a dramatic increase in the hyperfine field. One explanation for the quenching and cold-forming requirements is that the Ag dissolves well in molten iron, but slow cooling and/or later annealing allow loosely bound Ag atoms to migrate to nearby imperfections.

For a $^{110}Ag^m$ source, heating comes mainly from the self absorption of β rays. Since the β energies for $^{110}Ag^m$ are low, the source strength was not limited by the refrigeration capability but by the high-count-rate performance of the electronics, and for this experiment was about 50 μCi.

Cryogenic apparatus

Figure 2 shows the geometry of the source region and a portion of the cryostat. The source was soldered vertically to the tip of a copper source rod using indium solder. The semiflexible source rod was made up of a bundle of formvar-coated copper wires in a brass tube such that the wire bundle had a small amount of lateral adjustability, which was helpful for the final source centering. Thermal contact to the ^{3}He-^{4}He mixture was provided by about 4×10^3 cm^2 of surface area of sintered copper powder.

Also schematically shown in Fig. 2 is the superconducting solenoid which was used to provide the vertical polarizing field on the source. A field of 4 kG was used throughout the experiment, sufficient to saturate the iron host. Since the influence of reversing the 4 kG polarizing field on the photomultipliers could cause a systematic

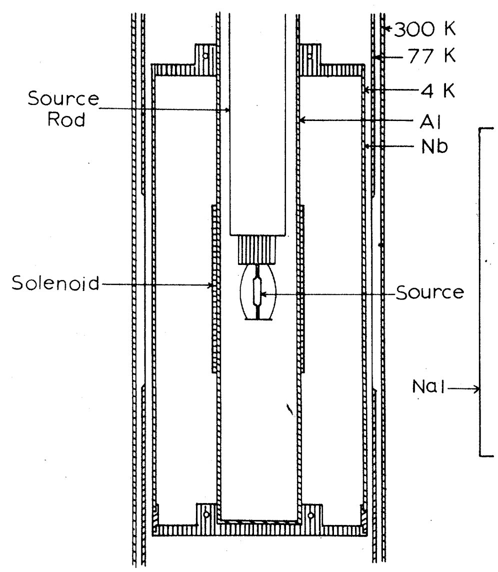

FIG. 2. Geometry of the source region.

false effect, the wire source and the solenoid had a thin superconducting niobium cup placed around them to contain the field. A Gaussmeter placed at the face of the NaI detector registered only a 0.01 G change for a 8 kG sweep of the field at the source. No gain or count-rate changes correlated with field direction were observed with the niobium shield in place.

Detectors and instrumentation

For the time-reversal test three 7.5×7.5 cm NaI detectors were used to provide high photopeak efficiency for the coincidence measurements. Since the aim was to obtain the best possible statistics, Ge(Li) detector resolution was sacrificed for NaI detector efficiency. As noted above, to maximize $(\hat{J}\cdot\hat{k}_1\times\hat{k}_2)(\hat{k}_1\cdot\hat{k}_2)$, the detectors were placed in the plane perpendicular to the polarization axis $\hat{J}$ and were at $\phi=0°$, $\pm 135°$. The source-detector distance was 5.4 cm for all three detectors, a value determined by the restrictions of the maximum integral count rate (about 200 kHz) each detector channel could sustain without substantial pulse pileup.

For each cascade, all six coincidence possibilities for the three detectors were obtained simultaneously, i.e., $A(\gamma_1)B(\gamma_2)$, $B(\gamma_1)A(\gamma_2)$, $B(\gamma_1)C(\gamma_2)$, $C(\gamma_1)B(\gamma_2)$, $C(\gamma_1)A(\gamma_2)$, and $A(\gamma_1)C(\gamma_2)$. Of the four combinations in which there is a $\pm 135°$ angle between the detectors, the sign of the asymmetry a_T due to a T violation should be positive for two of them and negative for the other two. With this symmetric detector method one can average the asymmetries observed from these four coincidences to remove, at least to first order, systematic effects such as the miscentering of the source. As a further experimental check, no time-reversal effect is expected for coincidences between the two detectors with $\phi=90°$.

Since the upper limit on the source strength and counting rate was imposed by detector pulse pileup and electronics considerations rather than by the refrigerator's capacity, the effective management of high count-rates in the electronics required some special attention. A block diagram of the electronics is shown in Fig. 3. A pulse in the 1384–1505 keV region of any detector that was in coincidence with a 658 keV γ ray in either of the other detectors was allowed through a linear gate, given an ID tag identifying

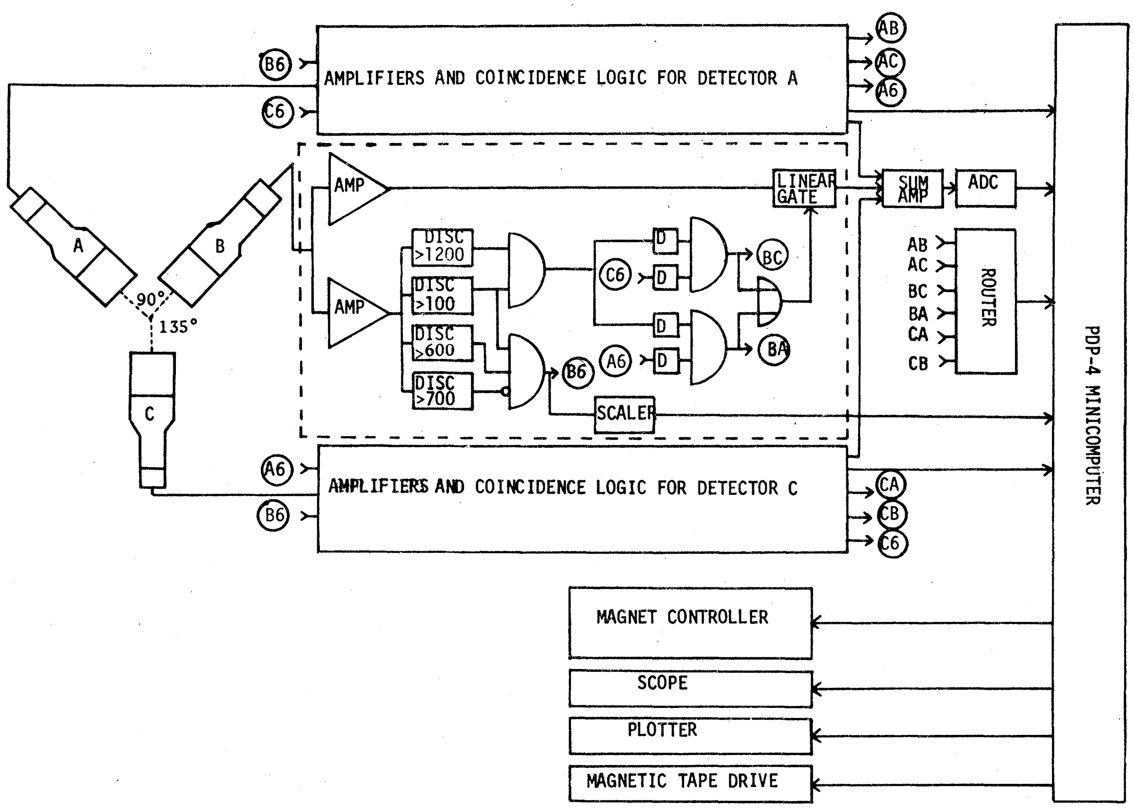

FIG. 3. Block diagram of the electronics used in the time-reversal experiment.

which detectors it belonged to, and then sent through a summing amplifier into an analog-to-digital converter (ADC) interfaced to a PDP-4 computer which put it into the proper memory slot. The 658 keV singles of each detector were also recorded by computer-readable scalers to monitor the general health of the experiment. In order to average out the effects of drifts in the electronics, the polarizing field direction had to be switched as often as was practical. A magnet controller circuit was built which interfaced the power supply for the magnet to the PDP-4 computer to switch the field direction automatically. To minimize the effect of temperature variations on the photomultiplier gain, the detectors and their photomultipliers were enclosed in a temperature-stabilized box during the entire time-reversal run.

Data were accumulated in and the experiment was controlled by a PDP-4 minicomputer-based data acquisition system. With the magnetic field directed upward, for example, six coincidence spectra were accumulated for 50 min, following which the computer turned off the ADC and the monitor scalers, sent out magnet power supply control commands to gradually reverse the field direction, wrote the data on magnetic tape, did a minimal on-line analysis, and then restarted the run in the other field direction after a 10 min waiting period. The final data analysis was done on an IBM 360 computer.

Data analysis

The "difference spectra technique" was used in the data analysis. Rather than computing the areas of the peaks from the coincidence spectrum itself, a field-down spectrum was subtracted from a field-up one for the same detector combination. With this approach the asymmetry of the background beneath the peak of interest also was determined.

Before the difference spectrum was calculated, the centroids of the predominant 1384 keV peaks were found, and the spectra were aligned according to this centroid to take care of any small gain shifts. In order to remove systematic linear drifts in the count rate and to correct for radioactive decay, a spectrum was compared with the average of the preceding and the following spectra. Throughout the experiment, the count rates were reasonably stable so that no higher-order-trend removal techniques were required.

The difference spectra were then examined. No evident structure was found except in the 1384 and 1505 keV peak region, indicating that the asymmetry of the backgrounds beneath the peaks was negligible. Then the counts in two windows centered on the centroids of the 1384 and 1505 keV peaks were summed to give the areas of the peaks in the difference spectrum. To avoid a sharp cutoff and the arbitrariness of giving one channel full weight and the one next to it zero weight, the counts in channels on either side of each window were also added with a linearly decreasing weight. The areas of the peaks in the difference spectrum were then normalized with the corresponding areas in the sum spectrum to give the measured asymmetry [Eq. (6)]. Several corrections were made to the asymmetry:

1. Each coincidence peak was considered to sit on a linear background.
2. Since the NaI detectors have relatively poor resolution, some of the 764 keV γ rays were also included in the 658 keV gate. Thus part of the 1505 keV γ rays in the coincidence spectrum actually came from 764-1505 keV coincidence. This was corrected for during the analysis.
3. A 5% correction was made to compensate for the true-to-chance coincidence ratio of 20.

The 658 keV singles count rates served as monitors of systematic problems but were not used to normalize or adjust the results.

RESULTS AND DISCUSSION

Nuclear orientation of $^{110}Ag^m$

The orientation parameters $B_{\lambda_1}(J)$ in Eq. (1) are functions of the temperature, the effective hyperfine field of $^{110}Ag^m$ in Fe, and the magnetic moment of $^{110}Ag^m$. They can be determined by measuring the directional distributions of γ rays emitted from oriented $^{110}Ag^m$. The directional distribution is given by

$$W'(\theta)=\sum_{\lambda_1=\text{even}} Q_{\lambda_1}B_{\lambda_1}U_{\lambda_1}A_{\lambda_1}P_{\lambda_1}(\cos\theta). \qquad (9)$$

Here, Q_{λ_1} is the solid-angle correction for the single detector, θ is the angle between the nuclear orientation direction and the observed γ ray, $P_{\lambda_1}(\cos\theta)$ is the Legendre polynomial of order λ_1, U_{λ_1} describes the deorientation of the decaying level due to unobserved preceding radiations, and A_{λ_1} is given by

$$A_{\lambda_1}=\frac{F_{\lambda_1}(LLJ_fJ_i)+2F_{\lambda_1}(LL'J_fJ_i)|\delta|\cos\eta+|\delta|^2F_{\lambda_1}(L'L'J_fJ_i)}{(1+|\delta|^2)}, \qquad (10)$$

where the F_{λ_1}'s are the usual F coefficients for electromagnetic transitions. For a mixed γ-ray transition, A_{λ_1} depends on the mixing ratio δ in addition to the spins of the initial and final states (J_i and J_f).

The geometry of the source region was identical to that for the T-invariance test. A Ge(Li) detector was used to observe the γ rays which were emitted perpendicularly ($\theta = 90°$) to the polarization axis. Fifteen γ rays were resolved. The intensities of these γ-ray peaks were compared with those from "warm" runs taken when the source was at about 1° K, yielding the value $W'(90°)$ for each line. For some of the pure $E2$ transitions, since the A_{λ_1}, U_{λ_1}, and Q_{λ_1} coefficients are all known, Eq. (9) then was used to determine the orientation parameters B_{λ_1}. After the B_{λ_1}'s were determined, the A_{λ_1}'s for the mixed transitions were calculated, and the mixing ratios δ determined using Eq. (10).

The $E2/M1$ mixing ratios for six γ-ray transitions were measured to a good accuracy and are listed in Table I. Also shown in Table I are the same δ's as measured by Ruhter and Camp,[27] Krane and Steffen,[23] and Johnston and Stone.[28] In most cases, the selection of which of the two solutions obtained for δ from Eq. (10) was not possible from the available experimental data, so the values shown in Table I are the ones in closest agreement with those from the references. It must be noted, however, that for the 1505 keV γ ray, Ruhter and Camp[27] have strongly opted for the other solution than had Krane and Steffen,[23] and our value shown is equivalent to the former's number.

It is important to comment that the nuclear orientation measurement actually yielded values only for $\lambda_1 = 2$. Since $W'(\theta)$ involves even λ_1's, the (small) $\lambda_1 = 4$ term had to be included. The method used was essentially a bootstrapping technique in which initially, the $\lambda_1 = 4$ term was assumed to be zero, and the data were used to find a value for the $\lambda_1 = 2$ term. This term then permitted an analytic calculation of the corresponding $\lambda_1 = 4$ term. Next, assuming this new $\lambda_1 = 4$ term, a new $\lambda_1 = 2$ term was found from the data. This process was repeated until the change in either term upon recalculation was negligible.

g factor of the 658 keV state in ^{110}Cd

The corrected experimental asymmetries for the 1505-658 keV and the 1384-(885)-658 keV cascades are listed in Table II. As discussed above, a nonnegligible but uncertain amount of precession effect was expected to appear in the asymmetries. In order to measure just this effect, data were taken at 4 K for 3 weeks, and warm asymmetries were obtained as listed in Table II. At 4 K any T-violating effect is negligible since $W_T \propto B_{\lambda_1} \simeq 0$. At warm temperatures, Eq. (7) becomes

$$a \equiv \frac{W(\uparrow) - W(\downarrow)}{W(\uparrow) + W(\downarrow)} \sim \frac{W_T + W'}{W_0} \sim \frac{W'}{W_0} = \frac{W_0(\phi + \Delta\phi) - W_0(\phi - \Delta\phi)}{W_0(\phi + \Delta\phi) + W_0(\phi - \Delta\phi)} . \qquad (11)$$

From the measured warm asymmetries, the precession angle $\Delta\phi$ can be determined using the above equation.

The average warm asymmetry of the four

TABLE I. $E2/M1$ mixing ratios for ^{110}Cd γ rays.

E_γ (keV)	This work	Ruhter and Camp [a]	Krane and Steffen [b]	Johnston and Stone [c]
447	−0.40 ± 0.06	−0.33 ± 0.05	−0.45 ± 0.20	
620	−1.2 ± 0.5 −0.7 ± 0.3	−0.70 ± 0.04	−0.80 ± 0.50	
678	−0.36 ± 0.03	−0.32 ± 0.05	−0.25 ± 0.20	−0.44 ± 0.05
687	−1.65 ± 0.09	−1.27 ± 0.38	$-1.1\ ^{+0.8}_{-0.4}$	−1.80 ± 0.05
707	−1.42 ± 0.07	−1.10 ± 0.20	−1.0 ± 0.3	−0.58 ± 0.02
818	−1.2 ± 0.5	−1.44 ± 0.10	−1.20 ± 0.15	−1.36 ± 0.10
1384	−0.39 ± 0.02	−0.44 ± 0.02	−0.37 ± 0.03	−0.46 ± 0.01
1505	−1.09 ± 0.09	−1.13 ± 0.20	−0.55 ± 0.10	−1.26 ± 0.06 −0.48 ± 0.03

[a] W. D. Ruhter and D. C. Camp, Bull. Am Phys. Soc. 22, 566 (1977).
[b] K. S. Krane and R. M. Steffen, Phys. Rev. C 2, 724 (1970).
[c] P. D. Johnston and N. J. Stone, Nucl. Phys. A206, 273 (1973).

TABLE II. Corrected experimental asymmetries (×10^3).

1505-658 keV cascade						
Pair No.	1: $B(1)C(2)$	2: $A(1)B(2)$	3: $B(1)A(2)$	4: $C(1)B(2)$	5: $C(1)A(2)$	6: $A(1)C(2)$
Angle (ϕ)	−135°	−90°	90°	135°	−135°	135°
T = 14 mK	−0.731 ± 0.209	−0.194 ± 0.217	−0.123 ± 0.259	0.963 ± 0.361	−0.879 ± 0.348	0.955 ± 0.194
T = 4 K	−2.219 ± 0.207	0.032 ± 0.251	0.182 ± 0.191	2.202 ± 0.236	−1.819 ± 0.228	1.730 ± 0.201
1384-(885)-658 keV cascade						
Pair No.	1: $B(1)C(2)$	2: $A(1)B(2)$	3: $B(1)A(2)$	4: $C(1)B(2)$	5: $C(1)A(2)$	6: $A(1)C(2)$
Angle (ϕ)	−135°	−90°	90°	135°	−135°	135°
T = 14 mK	−0.645 ± 0.183	−0.092 ± 0.185	−0.226 ± 0.237	1.074 ± 0.314	−0.974 ± 0.310	0.846 ± 0.166
T = 4 K	−2.574 ± 0.174	0.235 ± 0.244	−0.003 ± 0.163	2.287 ± 0.205	−1.782 ± 0.187	1.553 ± 0.163

coincidences at 135° for the 1505-658 keV cascade was $(-1.98 \pm 0.11) \times 10^{-3}$, corresponding to a precession angle of $\Delta\phi = (0.19 \pm 0.01)°$. From this result, and assuming a static magnetic interaction, the g factor of the 658 keV state in ^{110}Cd can be deduced using the Larmor precession equation

$$\Delta\phi \sim g\mu_N H\tau/\hbar \ . \qquad (12)$$

Here, $H = (-348 \pm 10)$ kG is the effective hyperfine field at the Cd nucleus in an Fe lattice,[29] and $\tau = (7.2 \pm 0.7)$ ps is the mean life of the 658 keV state.[30] The g factor then was determined to be

$$g(658 \text{ keV}) = 0.28 \pm 0.05,$$

consistent with, but more accurate than, the value reported in Ref. 31.

The average warm asymmetry for the 1384-(885)-658 keV cascade was $(-2.02 \pm 0.09) \times 10^{-3}$, corresponding to a precession angle of $(0.34 \pm 0.01)°$. If a simple subtraction is made of the precession angle for the 658 keV state from this value, the precession angle for the 1542 keV state turns out to be $(0.15 \pm 0.02)°$. Since neither g nor τ is known for this level, this precession angle cannot be used further.

The asymmetries of the two coincidence pairs at 90° for both cascades were consistent with zero, indicating that, in fact, nuclear spin precession was the dominant cause of these warm asymmetries.

Phase angles for the 1505 and 1384 keV γ rays

The average cold asymmetries a of the four coincidence pairs at 135° for the 1505-658 and 1384-(885)-658 keV cascades were $(-0.87 \pm 0.12) \times 10^{-3}$ and $(-0.82 \pm 0.11) \times 10^{-3}$, respectively. Using the assumption that the angles of precession were temperature-independent below 4 K, the equivalent asymmetries a' at 14 mK due to the precession effects were calculated from the 4 K values and were found to be $(-0.96 \pm 0.05) \times 10^{-3}$ and $(-0.86 \pm 0.03) \times 10^{-3}$, respectively, for the two cascades. The asymmetries a_T due to the T-violating effect then can be calculated using Eq. (7):

$$a_T = a - a' = (0.10 \pm 0.14) \times 10^{-3}, \quad (1505\text{-}658 \text{ keV}),$$
$$= (0.04 \pm 0.11) \times 10^{-3}, \quad (1384\text{-}(885)\text{-}658 \text{ keV}).$$

As indicated by Eq. (8), the determination of the phase angle η from a_T requires the knowledge of other factors. Particularly important are the orientation parameter B_1 and the mixing ratio δ. Thus the prior directional distribution measurement was essential for the accurate determination of these values.

However, two difficulties arise in trying to find the B_1 for the T-invariance part of the experiment from the B_2 from the directional distribution part. First, there was a possible source temperature difference between the two runs. The temperature in the source and mixing-chamber region of the dilution refrigerator was monitored continuously by a CMN thermometer coupled to a SQUID detector. Since the direction of the applied magnetic field was switched regularly during the T-invariance test, but was held constant during the directional distribution run, in the former case each field reversal created some hysteresis heating in the source, an effect probably accentuated by the absence of any annealing of the iron host after its being melted, quenched, and formed. Thus the source temperature was not constant but would increase during the field change, quickly decrease immediately thereafter, and then slowly return to its original value. To minimize this effect, the data accumulation was not restarted until the sample had cooled back down appreciably so that the temperature variation within each run was less than 0.5 mK.

The average temperature (and hence the average orientation parameters) was used for the data analysis. Since there was no evidence from the thermometer that this magnetic hysteresis heating depended on the direction of the polarization, it should not have given rise to a false asymmetry. In addition, however, the effect of this hysteresis or of any possible small magnetic anisotropy in the iron host was removed by the simultaneous detection of the different γ-ray combinations in the three detectors. The average orientation parameter B_2 during the time-reversal runs was determined to be 0.93 ± 0.02.

The other difficulty in finding B_1 from B_2 is in the assumption that all the $^{110}Ag^m$ nuclei experience the same hyperfine field. More likely, especially in view of the range of reported effective H_{hf} values, there is a distribution of fields within the source. To check the effect of such a distribution, a calculation was made in which the B_2 parameter was assumed to have arisen from a source in which most of the $^{110}Ag^m$ nuclei experienced the largest H_{hf} reported in the literature (−447 kG) and the rest experienced $H_{hf} = 0$. Then the average B_1 parameter was calculated from B_2 using the same model. From this worst-case estimate a 10% error was introduced in the previously determined B_1 value.

Under these considerations, the phase angles were determined to be

$$\sin\eta = (1.5 \pm 2.2) \times 10^{-3}, \quad (1505 \text{ keV } \gamma \text{ ray}),$$

$$\sin\eta = (-1.7 \pm 5.1) \times 10^{-3}, \quad (1384 \text{ keV } \gamma \text{ ray}).$$

Both values are consistent with time-reversal invariance.

Hannon and Trammel[32] have pointed out that the effects originating in the atomic electron shell can introduce, via internal conversion and scattering processes, a phase difference irrespective of T violation. This phase difference can be as large as 10^{-3} when the γ ray energy is less than 100 keV. However, for the higher-energy transitions used in our correlation experiment, these effects are expected to be much smaller and are not considered likely to represent any significant contribution.

Our results do not show a violation of T invariance. The measured values for $\sin\eta$ reached an extremely high accuracy with the directional-correlation approach for a T-violation test in nuclear γ decays.[12-17] The precision is also of the same order of magnitude to that obtained with the Mössbauer or linear polarization technique [$\sin\eta = (-0.3 \pm 0.7) \times 10^{-3}$,[11] $\sin\eta = (1.0 \pm 1.7) \times 10^{-3}$,[33] $\sin\eta = (0.7 \pm 2.4) \times 10^{-3}$ [34]]. Furthermore, the sensitivity of a given experiment depends on presently unknown nuclear matrix elements. Theoretical estimations are essential before the implications of a certain experiment can be fully realized. Unfortunately, these estimations are rather crude and highly model dependent.

To account for the CP and T violations in the neutral kaon decay, numerous microscopic theories have been proposed.[7] These can be grouped into millistrong, electromagnetic, milliweak, and superweak theories, which would predict an amplitude of a T-odd part in the nuclear wave functions of roughly 10^{-3}, 10^{-3}, $10^{-3} - 10^{-7}$, and 10^{-9} respectively.[35] One promising study of T violation is the measurement of the electric dipole moment of the neutron. The latest limit for the neutron dipole moment is $< 3 \times 10^{-24}$ e cm,[36] which tends to rule out millistrong, electromagnetic, and milliweak theories, and thus supports the superweak theories. Furthermore, the most accurate current experimental values for η_{+-} and η_{00} in Kaon decay are also in good agreement with the predictions of the superweak theory.[37]

The existence of a nonzero neutron dipole moment violates T and P, whereas in nuclear γ decays T-odd P-even observables are measured. However, after the efforts of almost one and a half decades, the accuracy for the T-violation tests in γ decays has been improved only from 10^{-2} to 10^{-3}. It would be very difficult to improve yet another order of magnitude. Unless some novel technique can be devised, it would be impossible to detect a T violation in nuclear γ decays as predicted by the superweak theory.

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