Beta-Gamma-Gamma Correlation in ^{56}Mn: A Test of Time-Reversal Invariance*

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A test of time-reversal invariance was performed by measuring the imaginary part $|\delta| \sin\eta$ of the mixing ratio $\delta = |\delta| e^{i\eta}$ between $E2$ and $M1$ reduced matrix elements through the observation of two β-γ-γ cascades in ^{56}Mn. The imaginary part was found to be $(-8.1\pm4.8)\times10^{-3}$ for the 1.81-MeV transition, and $(-7.1\pm 3.7)\times10^{-3}$ for the 2.12-MeV transition. In order to eliminate instrumental asymmetries, the difference between the two values was taken, $\Delta(|\delta| \sin\eta) = (1\pm6)\times10^{-3}$. With an average mixing ratio for the two transitions, $\langle|\delta|\rangle = 0.23$, the difference in phases is $\Delta \sin\eta \approx \Delta\eta \approx (0.4\pm2.6)\times10^{-2}$, giving no evidence for time-reversal violation.

THE discovery[1] of the two-pion decay mode of the $K_L{}^0$ meson has led to theoretical and experimental reexamination of time-reversal (T) invariance. The present work was stimulated by the suggestion of Bernstein, Feinberg, and Lee[2] that T invariance could be violated in the electromagnetic interaction; it is based on the fact that the reduced matrix elements for γ transitions can always be chosen to be real if T invariance holds.[3] T invariance thus implies that, for a mixed γ transition, the mixing ratio δ is real. If δ is written as $|\delta| e^{i\eta}$, where η is the phase angle between matrix elements for competing multipole modes, then a deviation of $\sin\eta$ from zero implies a violation of T invariance. (Deviations due to non-Hermiticity have been estimated to be extremely small.[4]) Relevant experiments were first proposed by Lee and Yang[5]; the theory was later worked out in more detail.[6–8] Actual experiments have been performed with $\beta\gamma\gamma$ cascades,[9,10] with γ-γ cascades from oriented nuclei,[11] and with Mössbauer techniques.[12,13] The lowest limit has been obtained with the latter approach. However, a negative result with one particular transition does not make other experiments unnecessary; the sensitivity of a given experiment depends on unknown nuclear matrix elements. A variety of transitions in various nuclides must be studied in order to hunt for possible effects. It is for this reason that we publish the present β-γ-γ data even though they do not give as low a limit as some of the other experiments.

We selected ^{56}Mn for our experiment because it has two mixed transitions with different sign of the mixing ratio. Each transition gives a value for $|\delta| \sin\eta$. If an observed asymmetry in this quantity is due to an experimental effect, it should be the same for both cascades; if, on the other hand, it is caused by a T violation, it is unlikely that both cascades (with different mixing ratios) will give the same value. Therefore, the *difference* of the quantities $|\delta| \sin\eta$ for the two cascades gives a measure for T conservation that is largely independent of the unavoidable experimental asymmetries.

^{56}Mn ($T_{1/2}=2.58$ h) decays to ^{56}Fe by three principal branches, two of which are β-γ-γ cascades that follow the spin sequence $3^+\to2^+\to2^+\to0^+$. In each of these two, a mixed $E2$-$M1$ transition (2.12 or 1.81 MeV) is preceded by an allowed Gamow-Teller β decay (0.75 or 1.05 MeV endpoint) and followed by a pure $E2$ transition (0.845 MeV). In such a cascade, T violation could show up as an asymmetry of the triple correlation of the directions, $\hat{k}_\beta$, $\hat{k}_1$, and $\hat{k}_2$, of the β and two γ's. The probability function is

$$W_{\beta\gamma\gamma} = W_{\gamma\gamma}(1+\epsilon\lambda/|\lambda|) = W_{\gamma\gamma}(1\pm\epsilon), \qquad (1)$$

where ϵ contains $\sin\eta$, λ changes sign under T, and $W_{\gamma\gamma}$ is the γ-γ correlation function;

$$\begin{aligned}
\epsilon &= -0.245\,|\lambda|\,(v/c)\,|\delta|\,\sin(\eta)/W_{\gamma\gamma},\\
\lambda &= (\hat{k}_1\cdot\hat{k}_2)(\hat{k}_\beta\cdot\hat{k}_1\times\hat{k}_2),\\
W_{\gamma\gamma} &= 1+|\delta|^2 + A_{22}P_2(\hat{k}_1\cdot\hat{k}_2) + A_{44}P_4(\hat{k}_1\cdot\hat{k}_2), \qquad (2)\\
A_{22} &= 0.250+0.732\,|\delta|\,\cos\eta - 0.077\,|\delta|^2,\\
A_{44} &= 0.327\,|\delta|^2.
\end{aligned}$$

Here, v/c is the ratio of the speed of the β to that of

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light and the P_l's are Legendre polynomials; δ is the ratio of $E2$ to $M1$ reduced matrix elements; $\delta=\langle\| E2 \|\rangle/\langle\| M1 \|\rangle = |\delta| e^{i\eta}$. The mixing ratios are known from earlier experiment as[14–16] $|\delta|\cos\eta = +0.18\pm0.03$ and -0.28 ± 0.03 for the 1.81- and 2.12-MeV transitions, respectively.

Any difference in the probability of $\hat{k}_\beta$ being up or down relative to the direction $\hat{k}_1\times\hat{k}_2$ is maximized when $|\hat{k}_1\times\hat{k}_2|=|\hat{k}_1\cdot\hat{k}_2|=(\frac{1}{2})^{1/2}$ and $|\lambda|=\frac{1}{2}$. Experimentally, this difference would be very difficult to measure because of differences in detector solid angles, efficiencies, spectral responses, and backgrounds. Therefore, a ratio of probabilities is formed in which many experimental factors cancel and the asymmetry terms $1\pm\epsilon$ do not. Such a ratio can be found by using four fixed detectors arranged as shown in Fig. 1; two γ detectors, labeled L and R are separated by 135° at the source; two β detectors labeled Up and Dn are up and down relative to the $+z$ axis which is perpendicular to the plane of the γ detectors. Four sets of triple coincidences can be recorded, one set for each possible combination of signs of $\hat{k}_{\beta z}$ and $(\hat{k}_1\times\hat{k}_2)_z$. For two of the four types of triple coincidences, the sign of λ is positive and for the other two, it is negative. The four numbers of true coincidences can be combined in a ratio in which all detector efficiencies and spectral fractions cancel. From this ratio $(1+\epsilon)^2/(1-\epsilon)^2$ one can obtain ϵ. The true coincidence efficiencies do not cancel in that ratio, but they and their ratio are estimated to be unity to less than a few parts in 10^4. Moreover, the corresponding systematic error nearly cancels in the difference of ϵ's for the two cascades.

Unfortunately, ϵ is about 100 times smaller than $\sin\eta$ for each cascade in ^{56}Mn, so a determination of $\sin\eta$ to $\pm10^{-2}$ means a measurement of ϵ to $\pm10^{-4}$, which requires a minimum total number of triple coincidences of 10^8. The connection between the experimental value of ϵ and the value of $\sin\eta$ is

$$\epsilon=-\frac{0.123\langle v/c\rangle Q_1Q_{22}|\delta|\sin\eta}{1+|\delta|^2+A_{22}Q_{22}P_2(\frac{3}{4}\pi)+A_{44}Q_{44}P_4(\frac{3}{4}\pi)}. \quad (3)$$

The Q's are geometrical attenuation coefficients due to the solid angles subtended by the detectors at the source.[17]

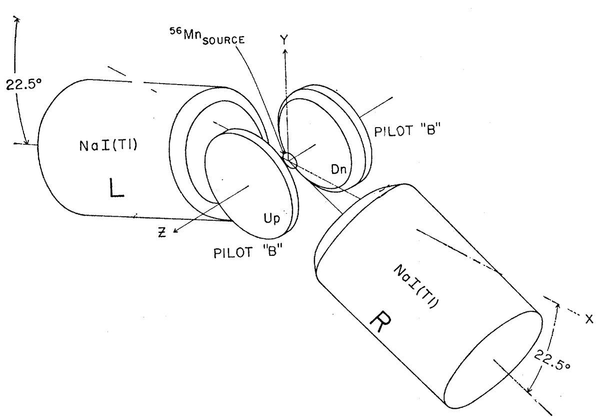

FIG. 1. Detector geometry.

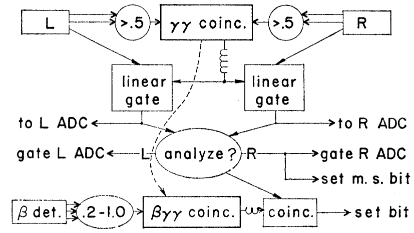

FIG. 2. Partial block diagram of logic circuitry. Only one of the two β-γ-γ coincidence circuits is shown.

The detector solid angles were chosen to maximize the statistical accuracy in ϵ in a given counting time. The γ detectors were NaI(Tl) crystals, 5.1×7.5 cm with 6.3-mm (45°) beveled edges, mounted on high quantum-efficiency RCA 8575 photomultipliers. The crystals were faced with β absorbers of 1.2-g/cm^2 Be. The β detectors were discs of Pilot B plastic, 4.4×0.6 cm with 3.2-mm (45°) beveled edges, mounted on Philips 56AVP tubes by 2.5-cm-long Lucite light pipes. The fractional solid angle subtended at the source was 0.200 ± 0.008 for a β detector and 0.073 ± 0.001 for a γ crystal, giving $Q_1=0.80$ and $Q_{22}=0.72$. We neglected the $A_4Q_{44}P_4$ term in ϵ. Averaged over the appropriate β spectra, the ratios $\langle v/c\rangle$ were 0.81 and 0.82 for the 2.12- and 1.81-MeV branches.

Several Mn sources were used, each of which had 25–60-μg/cm^2 layers of metallic Mn evaporated in a 6.3-mm-diam spot onto 6-μg/cm^2 Al substrates on both sides of the strips of quarter-mil Mylar, 12 cm in length. Multiple scattering in the sources was negligible, the mean scattering angle being less than 12° for the lowest-energy β rays accepted (200 keV). Sources were inserted in the University of Illinois Triga Mark II reactor and exposed to a flux of about 1.8×10^{12} neutrons/cm^2 sec for periods ranging 20 min–1 h. Our maximum source strengths were about 100 μC. More active sources caused severe gain shifts and anode fatigue in the RCA 8575's. Within 1 h after irradiation, the sources were placed in position, and coincidence data were taken for periods 3–8 h.

A skeletal block diagram of the electronics appears in Fig. 2; we show only one of the two β-γ-γ coincidence circuits. Precoincidence pulse-height discrimination was used to limit the range of energies for which fast timing pulses would be passed to the fast coincidence circuits. For γ rays, the range was 0.5 MeV and above, and for β's, it was 0.2–1.0 MeV. Timing jitter in the output

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TABLE I. Summary of results.[a]

	Cascade I	Cascade II	Difference (II−I)
Energy of mixed transition	1.81 MeV	2.12 MeV	
$\|\delta\|\cos\eta$, the real part of mixing ratio	0.18 ± 0.03	-0.28 ± 0.03	
ϵ, the triple-correlation asymmetry term	$(-4.3\pm2.5)\times10^{-4}$	$(-3.8\pm2.0)\times10^{-4}$	$(0.4\pm3.2)\times10^{-4}$
$\|\delta\|\sin\eta$, the imaginary part of mixing ratio	$(-8.1\pm4.8)\times10^{-3}$	$(-7.1\pm3.7)\times10^{-3}$	$(1\pm6)\times10^{-3}$
$\sin\eta$	$(-4.5\pm2.7)\times10^{-2}$	$(-2.6\pm1.4)\times10^{-2}$	$(0.4\pm2.6)\times10^{-2}$
η	$(-4.5\pm2.7)\times10^{-2}$	$\pi+(2.6\pm1.4)\times10^{-2}$	

[a] Total number of true coincidences (β-γ-γ): 2.4×10^8. Number of runs: 300.

of each integral or differential discriminator was only a few nanoseconds, because each was strobed by a fast pulse derived from the same detector, from an anode trigger set around 0.1 MeV. Twofold coincidence circuits were used throughout. Resolving times (2τ) were 12 nsec for γ-γ and 17 nsec for β-γ-γ. We checked β-γ-γ coincidence efficiencies several times during data taking; the efficiency ratio was within 2×10^{-4} of unity.

Double-delay–line-clipped pulses from both L and R were sampled for 50 nsec at their peaks following each γ-γ coincidence. The two linear pulses entered a Nuclear Data 1024 channel dual ADC, both halves of which were gated off. One ADC would be gated on if the pulse height in it was "probably" due to either the 1.81- or 2.12-MeV γ's (1.3 MeV$\leq$energy loss), and if, at the same time, the pulse height of the other counter was "probably" due to the 0.845-MeV γ (0.6 MeV$\leq$energy loss $\leq$1.0 MeV). The circuits which made this decision are represented in Fig. 2 by the element labeled "analyze?". Analyzed pulse-height spectra each occupied 64 channels—the least significant 6 bits of a 10-bit memory address. The most significant bit was set if the pulse height of interest occurred in detector R. Other address bits were set if there were a β_{Up} or a β_{Dn} in coincidence with the γ-γ coincidence, or if certain delayed-coincidence events occurred.

Delayed-coincidence counting of false coincidence rates was done concurrently with prompt-coincidence counting by means of the same coincidence circuits. Here we used a method of double pulsing which permitted measurement of prompt γ-γ–accidental β, and accidental γ-γ–prompt β, where the β was in coincidence with either the early or the late γ. These "partly prompt–partly false" rates were about one hundreth of the triple-prompt rates and about 50 times the triple-false rate. Consequently, it was sufficient to compute the triple-false rate, and the difference in prompt- and delayed-coincidence resolving times, which was measured and found to be less than $\frac{1}{2}\%$, introduced negligible systematic error in the determination of the asymmetry terms in the correlations. Accidental slow coincidences did not exist. Trigger dead times and gates were adjusted so that ambiguous or erroneous routing was avoided. Four racks of modular electronics were separated according to function and powered separately to minimize interaction. Care was taken to avoid any influence of β and β-γ-γ circuits on the γ, γ-γ and analog circuits, except for the setting of a memory-address bit, which affected the pulse-height spectra negligibly. By placing 6.3-mm Lucite slabs between the source and β detectors, we found that triple-coincidence background, due to Compton scattering, bremsstrahlung, and annihilation, following pair production, was about 1% of the true triples, and was the same within statistics for the four types of coincidences. We estimate the possible error in ϵ due to background to be less than 5×10^{-5}.

Moving the source diagonally off center by 6 mm produced no noticeable effect in the determination of ϵ. During the course of the experiment we frequently interchanged the counters and/or the associated logic circuitry.

A total of 300 irradiation-counting cycles produced the following total number of prompt triples: 1.4×10^8 under the 1.81-MeV peak and 1.0×10^8 under the 2.12-MeV peak. Data were analyzed in three steps by a FORTRAN program. First, accidental counts were subtracted, next the 1.81- and 2.12-MeV photopeaks were separated, and finally ϵ and its statistical error were calculated for each transition. We obtained numbers of true coincidences of four types from the data stored in the multichannel analyzer. Separation of the photopeaks is crucial in the data analysis; our program took advantage of the fact that the high-energy edge of the 2.12-MeV photopeak has a negligible contribution from the 1.81-MeV photopeak for each γ spectrum. The program used the difference between the γ-γ spectrum and the normalized spectrum of β_{Up}-γ-γ plus β_{Dn}-γ-γ coincidences for both γ phototubes in computing the number of 2.12-MeV γ rays (Compton spectra) under the 1.81-MeV photopeaks and the number of 1.81-MeV γ's (high-energy edges of the photopeaks) under the 2.12-MeV photopeaks in the coincidence spectra. This computation was done for each run separately, and ϵ was then calculated for each run.

Statistical errors in ϵ were calculated from statistical errors in the true coincidences. The statistical errors from photopeak-separation uncertainties were included. We noted that the 2.12-MeV branch, for which the photopeak is practically free from 1.81-MeV γ's, gave unity for the value of χ^2 (about the mean ϵ), divided by the number of runs.

The average values of ϵ for the 1.81- and 2.12-MeV mixed γ transitions are $(-4.3\pm2.5)\times10^{-4}$ and $(-3.8\pm2.0)\times10^{-4}$, respectively. In Table I, these results are translated into values of $|\delta|\sin\eta$, $\sin\eta$, and η. We feel that our nonzero values of ϵ arise from asymmetries in experimental conditions, and that the difference in asymmetries give a more bias-free measure of a possible T-violation effect. A nonzero difference would imply that nonvanishing asymmetry terms are actually present and that T invariance is violated. We find a difference, $\Delta\epsilon=(0.4\pm3.2)\times10^{-4}$, and conclude *that no evidence for time-reversal violation is present.*

The standard deviation in the experimental value of the asymmetry difference can be translated into an error in the determination of the phase η. The difference in imaginary parts of the mixing ratio is about 19 times ϵ; $\Delta(|\delta|\sin\eta)\cong(1\pm6)\times10^{-3}$. Although the difference $\Delta\sin\eta$ in imaginary parts of the complex phase is not proportional to $\Delta(|\delta|\sin\eta)$ because $|\delta|$ is not the same for both cascades, we can use the average mixing ratio $\langle|\delta|\rangle=0.23$ in order to estimate it and find $\Delta\eta\cong\Delta\sin\eta\cong(0.4\pm2.6)\times10^{-2}$.

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Properties of P^{30} Levels from the Reaction $Si^{29}(p,\gamma)P^{30}$. II

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A previous investigation of the γ-ray decay schemes of 7 resonances in the reaction $Si^{29}(p,\gamma)P^{30}$ in the range $E_p=700$–1750 keV has been extended to 24 resonances in the range $E_p=300$–1800 keV. The new decay scheme studies were conducted with a 40-cc Ge(Li) detector. The spins, parities, isobaric spins, lifetimes, and transition multipolarity mixings for many resonances and bound states of P^{30} have been determined from an extensive series of angular-correlation, linear-polarization, and Doppler-shift-attenuation measurements. New resonance information includes the discovery that resonances previously reported at $E_p=1505$, 1748, and 1772 keV are each doublets. The latter two have components at 1746 and 1749, and at 1773 and 1775 keV, respectively. The 1505-keV "resonance" was found to be a doublet with a separation of 0.7 ± 0.1 keV by means of high-resolution elastic-scattering measurements. Unique spin assignments for 15 and parity assignments for 11 resonance levels were obtained. The observed resonance strengths $(2J+1)\Gamma_\gamma\Gamma_p/\Gamma$ vary between 0.077 and 14 eV. Several unusually broad odd-parity resonances were observed which have large reduced widths for p-wave and f-wave capture. The strong contribution of $1f_{7/2}$, $2p_{3/2}$, and $2p_{1/2}$ orbitals to the configuration of states near $E_x=7$ MeV in P^{30} is revealed. The influence of isobaric spin on the level structure and γ-ray decay properties is apparent. The 2^- resonances at $E_p=1470$ and 1686 keV and the 4^- doublet at 1505 keV are identified as T-admixed pairs. Significant revisions of the decay schemes of the 1.45-, 2.94-, 4.14-, 4.50-, and 4.92-MeV levels have resulted from the 40-cc Ge(Li) spectra. The "4.92-MeV level" is shown to be a doublet with components at 4.921 ± 0.002 and 4.945 ± 0.005 MeV. By combining results of the angular-correlation, linear-polarization, and lifetime measurements, the following J^π assignments are derived for bound levels: $0.71(1^+)$, $1.45(2^+)$, $1.97(3^+)$, $2.54(3^+)$, $2.72(2^+)$, $2.84(3^+)$, $2.94(2^+)$, $3.02(1^+)$, $4.14(2^-)$, $4.18(2^+)$, $4.23(4^-)$, $4.43(2^+)$, $4.47(0^+)$, $4.50(1^+)$, $4.62(3^-)$, $4.92(5^-$ or $3^-)$, and $4.94(1)$. Previous $T=1$ assignments for the bound levels at $E_x=0.68$, 2.94, 4.18, 4.47, and 4.50 MeV are strongly supported by the data. Prominent "analog-to-antianalog" $M1$ transitions similar to those in other s-d shell nuclei are observed. An average isospin impurity of 7% for levels below 7 MeV in P^{30} is derived from the set of $E1$ transition rates. On the average, the $E2$ transition rates have strengths slightly less than one Weisskopf unit. However, strong $E2$ enhancement is observed for the $2.94\rightarrow0.68$, $2.54\rightarrow0$, and $2.72\rightarrow0$ transitions which have strengths of 21, 15, and 9 Weisskopf units, respectively. Several of the observed odd-parity resonance and bound levels appear to correspond to $T=1$ and $T=0$ members of a two-nucleon spectrum with major components $(s_{1/2}f_{7/2})$, $(d_{3/2}f_{7/2})$, and $(s_{1/2}p_{3/2})$.

I. INTRODUCTION

In an earlier paper[1] (hereafter referred to as I), we reported the results of a study of the γ-ray decay schemes of seven resonances between $E_p=700$–1750 keV in the reaction $Si^{29}(p,\gamma)P^{30}$ using large NaI(Tl) detectors and a 2-cc Ge(Li) detector. The decay schemes of the 7 resonances and of 15 bound levels below 5 MeV in P^{30} were presented. Resonance strengths, energies of bound levels with accuracies varying between ±2 and ±4 keV, and a new Q value of 5.597 ± 0.003 MeV for the reaction were also reported.

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