Circular Polarization of Gamma Radiation Following Allowed Beta Transitions*†

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(Received March 23, 1959)

The degree of circular polarization of gamma rays following allowed beta transitions has been investigated as a function of the angle $\Theta_{\beta\gamma}$ between beta-particle momentum and gamma direction and as a function of the energy of the beta particle. The anisotropy of the beta-gamma circular polarization correlation observed for pure Gamow-Teller transitions ($\Delta I=1$) is used to determine the validity of $C_A'=C_A$. The experimental results for Co^{60} and Na^{22} are $W(\Theta_{\beta\gamma})=1-(0.345\pm0.019)(v/c)\cos\Theta_{\beta\gamma}$ and $W(\Theta_{\beta\gamma})=1+(0.35\pm0.02)(v/c)\cos\Theta_{\beta\gamma}$, respectively. These values yield $C_A'=(1\pm0.2)C_A$.

The degree of circular polarization of the gamma rays following mixed beta transitions ($\Delta I=0$) confirms the existence of V-A interference terms. For Sc^{46} and Na^{24} the beta-gamma circular polarization correlations, $W(\Theta_{\beta\gamma})=1+(0.24\pm0.02)(v/c)\cos\Theta_{\beta\gamma}$, and $W(\Theta_{\beta\gamma})=1+(0.07\pm0.03)(v/c)\cos\Theta_{\beta\gamma}$, were observed. From these measurements the ratios of Fermi to Gamow-Teller components for the Sc^{46} beta transition, $(M_F/M_{GT})^2=0.13\pm0.04$, and for the Na^{24} beta transition, $(M_F/M_{GT})^2=0.002\pm0.010$, were determined.

1. INTRODUCTION

As a consequence of the nonconservation of parity in weak interactions[1–3] the gamma radiation following nuclear beta decay is, in general, circularly polarized.[4,5]

Measurements of the degree of this circular polarization give the same information about the coupling constants as do experiments with polarized initial nuclear states. The first measurement of a beta-gamma circular polarization correlation was reported by Schopper[6] and numerous experiments of this kind on allowed as well as on first-forbidden beta transitions have since been performed.[7–14] In this paper measurements on the pure Gamow-Teller transitions of Co^{60} and Na^{22} are presented which give further evidence that the violation of parity conservation in beta decay is complete, thus giving strong support to the two-component neutrino theory. Measurements on the mixed Fermi and Gamow-Teller transition of Sc^{46} ($\Delta I=0$) confirm the existence of a Fermi Gamow-Teller interference term, which excludes the possibility of complete violation of time-reversal invariance. In addition, these measurements provide a rather accurate determination of the relative magnitudes and of the signs of the Fermi and the Gamow-Teller matrix elements in the Sc^{46} beta transition.

The angular distribution of circularly polarized gamma rays with helicity $\mathcal{H}$ emitted after an allowed beta transition is given by[4,5]:

$$W(\Theta_{\beta\gamma})=1+\mathcal{H}A\,(v/c)\cos\Theta_{\beta\gamma}, \tag{1}$$

where $\Theta_{\beta\gamma}$ measures the angle between the directions of the gamma rays and the beta particles of velocity v. For a beta-gamma cascade $I_1 \xrightarrow{\beta} I_2 \xrightarrow{\gamma} I_3$, involving a gamma transition of pure multipolarity L, the factor A which measures the degree of circular polarization can be expressed as:

$$A=\frac{2}{L+1}\left[\mu(I_1,I_2)b_{\mathrm{GT}}+\delta_{I_1I_2}\times\left(\frac{I_2+1}{I_2}\right)^{\frac{1}{2}}b_{\text{F-GT}}\right]\frac{1}{1+b/W}, \tag{2}$$

$$\xi=(|C_S|^2+|C_V|^2+|C_S'|^2+|C_V'|^2)M_F^2+(|C_T|^2+|C_A|^2+|C_T'|^2+|C_A'|^2)M_{\mathrm{GT}}^2, \tag{3}$$

$$\xi b_{\mathrm{GT}}=\left[\mathrm{Re}(C_T{}^*C_T'-C_A{}^*C_A')-\frac{Ze^2}{\hbar cp}\mathrm{Im}(C_T{}^*C_A'+C_T'{}^*C_A)\right]M_{\mathrm{GT}}^2, \tag{4}$$

$$\xi b_{\text{F-GT}}=\left[\mathrm{Re}(C_T{}^*C_S'+C_T'{}^*C_S-C_A{}^*C_V'-C_A'{}^*C_V)\pm\frac{Ze^2}{\hbar cp}\mathrm{Im}(C_A{}^*C_S'+C_A'{}^*C_S-C_T{}^*C_V'-C_T'{}^*C_V)\right]M_FM_{\mathrm{GT}}, \tag{5}$$

* This work was supported by the U. S. Atomic Energy Commission.

† Preliminary results of this work were reported at the Rehovoth Conference on Nuclear Structure, September 1957, and at the 1958 spring meeting of the American Physical Society, Washington, D. C. [Bull. Am. Phys. Soc. 3, 205 (1958)].

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$$\xi b=\pm 2\left[1-\left(\frac{Ze^2}{\hbar c}\right)^2\right]^{\frac{1}{2}} \mathrm{Re}[(C_S C_V^* + C_S' C_V'^*) M_F^2 + (C_T C_A^* + C_T' C_A'^*) M_{GT}^2], \quad (6)$$

$$\mu(I_1,I_2)=\begin{cases}1, & I_2=I_1-1\\ -1/I_2, & I_2=I_1\\ -(I_2+1)/I_2, & I_2=I_1+1.\end{cases}$$

The usual notation (e.g., Lee and Yang[1]) is used. The upper signs refer to β^- decay, the lower signs refer to β^+ decay. Adopting the presently accepted relative proportions of the various coupling constants C_j ($j=S,T,V,A$):

(a) $C_A \gg C_T$, $C_A' \gg C_T'$ (neutrino recoil experiments[15]),
(b) $C_V \gg C_S$, $C_V' \gg C_S'$ (neutrino recoil experiments[16]),
(c) $b \simeq 0$ (absence of Fierz interference terms[17–20]),
(d) C_A/C_V = real number, C_A'/C_V' = real number (time-reversal invariance of the beta interaction[21]),

the expressions for the Gamow-Teller term b_{GT} and for the interference term $b_{F\text{-}GT}$ can be greatly simplified:

$$b_{GT}=-C_A C_A'/(C_A^2+C_A'^2), \quad (7)$$

$$b_{F\text{-}GT}=-\frac{C_A C_V'+C_A' C_V}{C_A^2+C_A'^2+(C_V^2+C_V'^2)y^2}y, \quad (8a)$$

$$y=M_F/M_{GT}. \quad (8b)$$

The results of many parity experiments suggest that $C_j'=\pm C_j$; this relationship is a necessary condition for the validity of the two-component neutrino theory,[22–24] since the operator $C_j \pm C_j' \gamma_5$ then degenerates into $C_j(1\pm\gamma_5)$ which converts a 4-component wave function of a massless particle into a two-component wave function describing a particle of helicity $\mathcal{H}=\mp 1$ and its antiparticle of helicity $\mathcal{H}=\pm 1$.

Part of the purpose of the present work was to arrive at a reasonably accurate experimental verification of $C_A'=C_A$. At the time this investigation was started, measurements of the angular distribution of beta particles emitted from polarized nuclei[3,25–27] and observations of the longitudinal polarization of beta particles[28–33] were consistent with $C_A'=(0.4\text{–}2.5)C_A$. After completion of this work greatly improved longitudinal polarization measurements on the P^{32} and Co^{60} electrons were reported by several authors.[34–38] These recent results indicate $C_A'=(0.8\text{–}1.25)C_A$. The considerably more difficult experiments on pure Fermi transitions[39–42] yield $C_V'=(0.4\text{–}2.5)C_V$.

2. APPARATUS AND EXPERIMENTAL PROCEDURE

The degree of circular polarization P_c ($P_c>0$ for $\mathcal{H}>0$) of the gamma radiation was measured by observing the Compton scattering on polarized electrons. The scattering cross section $d\sigma$ of this process,[43–46] and hence the intensity of the scattered radiation of momentum $\mathbf{k}$ depends on P_c, on the scattering angle θ, and on the angle ψ between the initial photon of momentum $\mathbf{k}_0$ and the electron spin $\mathbf{S}$ ($m=c=\hbar=1$):

$$d\sigma=\tfrac{1}{2}e^4(k/k_0)^2(\phi_0+fP_c\phi_c)d\Omega, \quad (9)$$

$$\phi_0=1+\cos^2\theta+(k_0-k)(1-\cos\theta), \quad (10)$$

$$\phi_c=-(1-\cos\theta)[(k_0+k)\cos\theta\cos\psi + k\sin\theta\sin\psi\cos\varphi], \quad (11)$$

f is the fraction of electrons which are polarized and φ is the angle between the $(\mathbf{k}_0,\mathbf{k})$ plane and the $(\mathbf{k},\mathbf{S})$ plane. Polarized electrons are available in magnetized iron.

The circular polarization analyzer used in the beta-gamma correlation measurements described in this paper is shown in Fig. 1. It is similar to arrangements used by Schopper[6,12] and by Boehm and Wapstra.[7]

The fraction of polarized electrons in the magnetized iron was determined from a precise measurement of the average magnetic induction B in the inner iron cylinder:

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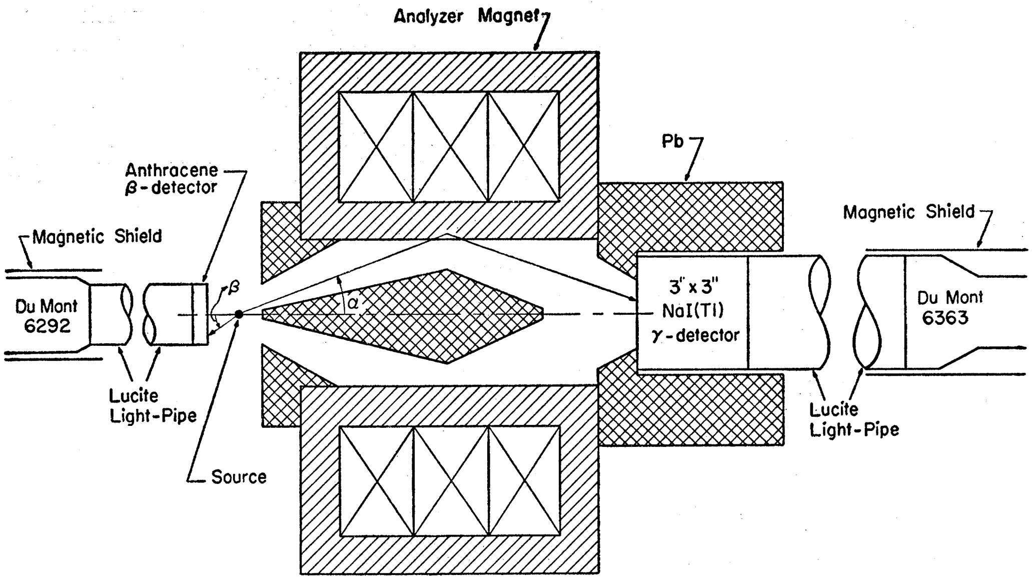

FIG. 1. Beta-gamma circular polarization correlation analyzer.

$B=H+4\pi 2\mathfrak{S}\beta N+\Delta B$, where H is the magnetic field, β the Bohr magneton, and N the number of iron atoms per unit volume. ΔB is the small ($\sim$3%) contribution to B from the orbital motion of the electrons.[47] The *differential* polarization efficiency $\epsilon(k_0,\alpha)$ of the analyzer for gamma radiation, emitted by a (point) source at an angle α with respect to the axis of the analyzer magnet, is defined by

$$P_c\epsilon(k_0,\alpha)\ \sin\alpha d\alpha=\frac{N_-^{\alpha}-N_+^{\alpha}}{N_-^{\alpha}+N_+^{\alpha}}\sin\alpha d\alpha, \qquad (12)$$

where N_-^{α} (N_+^{α}) is the gamma counting rate observed with the electron spins pointing toward (away from) the source, and P_c is the polarization of the radiation emitted in the direction α. The quantity $\epsilon(k_0,\alpha)$ was obtained by applying Eq. (9) to the geometry of the analyzer magnet and by integration over the finite size of the NaI(Tl) gamma detector. The absorption of gamma radiation before and after scattering, and the polarization dependence of the absorption processes, as well as the plural scattering in the iron, were taken into account in these computations. Fortunately, it was found that, whereas the plural scattering gives an appreciable contribution to the intensity of the scattered radiation (depending on energy and angle from 10 to 30%), its influence on the polarization efficiency is small (1 to 2%).[48]

In a beta-gamma correlation experiment P_c is not a constant, but varies with the angle $\Theta_{\beta\gamma}$ between beta particle and gamma-ray momentum. For allowed beta decays, according to Eq. (1), $P_c=-\mathcal{H}A\,(v/c)\cos(\alpha-\beta)$, if the beta particle is emitted in the direction of the β counter at an angle β with respect to the axis of the magnet. Furthermore, the finite size of the beta detector introduces a spread of P_c for each angle α. By (graphical) integration of $[\cos(\alpha-\beta)]\epsilon(k_0,\alpha)$ over the angle α (finite length of scattering magnet) and over β (finite size of the beta detector) the *effective* polarization efficiency $E(k_0)$ of the analyzer for a beta-gamma circular polarization correlation experiment is obtained:

$$E(k_0)P_c(\Theta')=\frac{C_+-C_-}{C_++C_-}=\delta, \qquad (13)$$

where Θ' is the angle between the axes of the beta detector and the gamma detector, and C_+ and C_- are the beta-gamma coincidence counting rates observed for the electrons in the iron scatterer polarized away from, and towards the source, respectively. It should be kept in mind that the effective polarization efficiency $E(k_0)$ of the equipment so obtained is only correct if $P_c(\Theta_{\beta\gamma})$ is proportional to $\cos\Theta_{\beta\gamma}$. The computation of $E(k_0)$ is estimated to be accurate to about 3%.

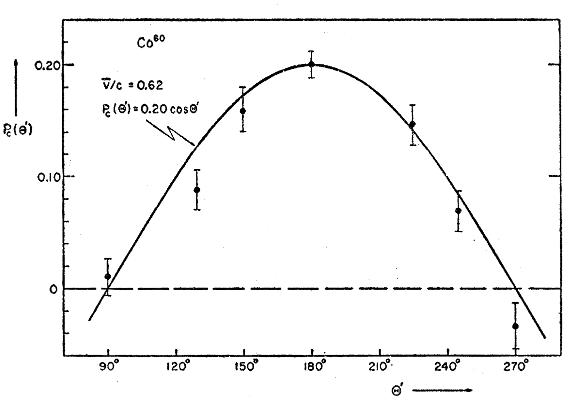

FIG. 2. Circular polarization $P_c(\Theta')$ of gamma rays following the beta decay of Co^{60} as a function of the angle Θ'.

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The measurements of the coincidence counting rates were made with a coincidence spectrometer of the usual fast-slow type.[49] The magnetization was reversed every 15 minutes and the data recorded automatically. The effect of the stray magnetic field on the photomultipliers was reduced by shielding, such that the changes in single counting rates upon reversal of the magnetization was less than 0.1%. All the data were corrected for the presence of gamma-gamma coincidences. The sources which were less than 1 mg/cm^2 thick were deposited on aluminized Mylar foils of 0.9 mg/cm^2 thickness.

3. EXPERIMENTAL RESULTS

A. Pure Gamow-Teller Transitions

a. Measurements on Co^{60}

The $5^+ \xrightarrow{\beta^-} 4^+ \xrightarrow{\gamma_1} 2^+ \xrightarrow{\gamma_2} 0^+$ cascade of Co^{60} is particularly suited for precise beta-gamma circular polarization correlation measurements. In fact, it was the first decay investigated in this manner.[6] Since both gamma transitions are pure multipoles of the same order ($L=2$) and the nuclear spin change ΔI is equal to L in both gamma transitions, the beta-gamma circular polarization correlation of the β-γ_2 pair is the same as that of the β-γ_1 pair.[5]

Partly as a check of the performance of the equipment the $\Theta_{\beta\gamma}$ dependence [compare Eq. (1)] of the circular polarization P_c of the Co^{60} gamma rays was measured (Fig. 2). The integral discriminator in the beta channel was set to accept all beta particles with energies larger than 95 kev, corresponding to an average value of $(v/c)_{Av}=0.62$ for the Co^{60} beta particles. The point at $\Theta'=180°$, where P_c was measured most accurately, was used to construct the $\cos\Theta'$ curve, which is shown as a solid line in Fig. 2. An attempt to investigate the v/c dependence of P_c was made by measuring the degree of circular polarization P_c^π at $\Theta'=180°$ as a function of the beta-particle energy. The energy width of the window in the beta channel was $\Delta E=50$ kev. The results of these measurements, corrected for the scattering of the beta particles in air and for backscattering in the beta scintillation crystal, are shown in Fig. 3. In view of the large corrections which must be applied at low beta energies the measurements were not extended to beta energies under 100 kev. Thus the range of v/c is rather limited ($v/c=0.55$ to 0.79) and it is difficult to draw any *definite* conclusions as to the dependence of P_c on v/c. The experimental points of Fig. 3 agree, within limits of error, with $P_c^\pi=-Av/c$. Recently, beta-gamma circular polarization correlation experiments with a magnetic beta spectrometer were reported,[50] which seemed to indicate a circular polarization of $P_c^\pi=0.33\pm0.06$, independent of v. On the basis of the experimental results presented here a constant value of P_c^π, although it cannot be excluded entirely, seems to be rather improbable. Furthermore, the majority of the points in Fig. 3 are lower than 0.33 ± 0.06, the value quoted in reference 50. Similarly, measurements of Appel, Schopper, and Bloom[12] at $(v/c)_{Av}=0.57$ give a value of $\bar{P}_c^\pi=-A(v/c)_{Av}=-0.19\pm0.01$, which is also considerably below the value of reference 50. In view of these inconsistencies more experiments, in particular in the low beta-energy region, are required to determine the v/c dependence of P_c. In the following we assume Eq. (1) to be valid.

A least-square fit of the experimental points of Fig. 3 to $P_c^\pi=-Av/c$ yields the following value for A:

$$A=-0.345\pm0.019,$$

in excellent agreement with the result of Appel, Schopper, and Bloom[12] (compare Table I).

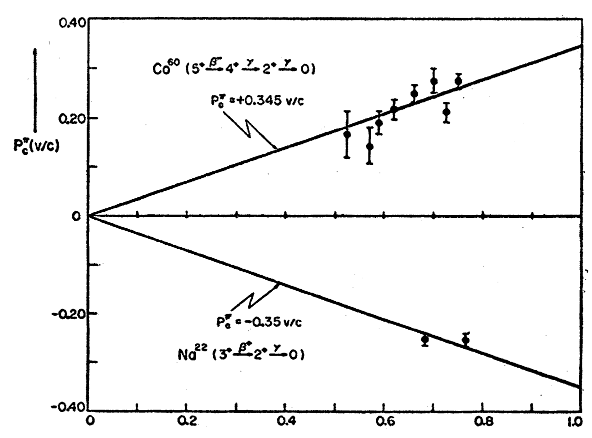

FIG. 3. Circular polarization $P_c^\pi(v/c)$ of gamma rays of Co^{60} and Na^{22} at $\Theta'=180°$ as a function of v/c of the beta particles.

TABLE I. Summary of beta-gamma circular polarization correlation data.

β emitter	ΔI	Anisotropy coefficient A	Reference
Co^{60} (β^-)	1	$-0.41\ \pm0.07$	Schopper[6]
		$-0.40\ \pm0.09$	Boehm and Wapstra[7]
		$-0.38\ \pm0.04$	Steffen[8]
		$-0.32\ \pm0.07$	Lundby *et al.*[9]
		-0.344 ± 0.09	Debrunner and Kundig[10]
		-0.335 ± 0.018	Appel *et al.*[12]
		-0.345 ± 0.019	Present work
Na^{22} (β^+)	1	$+0.39\ \pm0.08$	Schopper[6]
		$+0.295\pm0.054$	Appel *et al.*[12]
		$+0.35\ \pm0.02$	Present work
Na^{24} (β^-)	0	-0.068 ± 0.047	Schopper[51]
		$+0.07\ \pm0.04$	Boehm and Wapstra[7]
		$+0.05\ \pm0.04$	Steffen[8]
		$+0.07\ \pm0.03$	Present work
Sc^{46} (β^-)	0	$+0.33\ \pm0.04$	Boehm and Wapstra[7]
		$+0.23\ \pm0.06$	Steffen[8]
		$+0.29\ \pm0.11$	Lundby *et al.*[14]
		$+0.24\ \pm0.04$	Jungst and Schopper[52]
		$+0.24\ \pm0.02$	Present work

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b. Measurements on Na^{22}

The positron decay of Na^{22} is followed by a 1.28-Mev gamma ray: $3^+ \xrightarrow{\beta^+} 2^+ \xrightarrow{\gamma} 0$ and is suited for beta-gamma circular polarization correlation measurements. The presence of the annihilation radiation, however, requires special precautions. The discriminator in the gamma channel was set to accept gamma rays above 0.52-Mev energy. The response of the NaI(Tl) scintillation detector to the gamma radiation scattered from the magnetized iron was thus different from the previous measurements, where the discriminator setting was lower. This fact was taken into account in computing the polarization efficiency $E(k_0)$ of the analyzer. A Lucite absorber in front of the analyzer magnet prevented positrons from being annihilated in the magnetized iron cylinder. From the results of the Na^{22} measurements, which are included in Fig. 3, one deduces

$$A = +0.35 \pm 0.02.$$

c. Discussion

According to Eqs. (2) and (7), the anisotropy coefficient A for the Gamow-Teller transitions Co^{60} and Na^{22} is given by

$$A = \mp \tfrac{2}{3} \frac{C_A'/C_A}{1+(C_A'/C_A)^2}.$$

The upper sign is valid for the β^- emitter Co^{60}, the lower for the β^+ emitter Na^{22}. Figure 4 shows a representation of A as a function of the coupling constant ratio C_A'/C_A, together with the experimental values determined for Co^{60} and Na^{22}. From this graph the relationship between C_A' and C_A can be determined:

$$C_A' = (1.0 \pm 0.2) C_A.$$

The error (standard error) of this ratio, although it seems to be one of the most accurate determinations of its kind at present, is relatively large, because of the insensitivity of A to variations of C_A'/C_A, if the latter is near unity. It seems rather difficult at present to improve on the experimental determination of C_A'/C_A by orders of magnitude, since all parity-effect measurements suffer from the same difficulty.

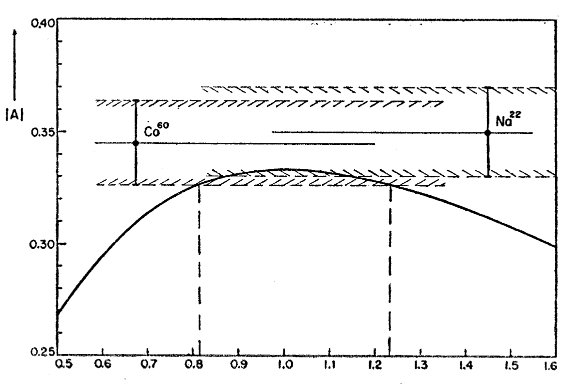

FIG. 4. The anisotropy coefficient A for Co^{60} and Na^{22} as a function of C_A'/C_A.

B. Mixed Fermi and Gamow-Teller Transitions

Once the coupling constants C_A, C_A', C_V, and C_V' are known, the measurement of the beta-gamma circular polarization correlation provides a rather sensitive method of determining the relative contributions of the Fermi and the Gamow-Teller component to an allowed beta transition of $\Delta I = 0$. In the following we assume that the relations $C_A' = C_A$ and $C_V' = C_V$ hold exactly. Admittedly, the experimental verification of $C_V' = C_V$ is even poorer than the one of $C_A' = C_A$. The results of longitudinal polarization measurements of beta particles in pure or almost pure Fermi transitions yield $C_V' = (0.4 \text{ to } 2.5) C_V$.

a. Measurements on Na^{24}

The β^- decay of Na^{24} is followed by two gamma rays of equal multipolarity: $4^+ \xrightarrow{\beta} 4^+ \xrightarrow{\gamma_1} 2^+ \xrightarrow{\gamma_2} 0^+$.

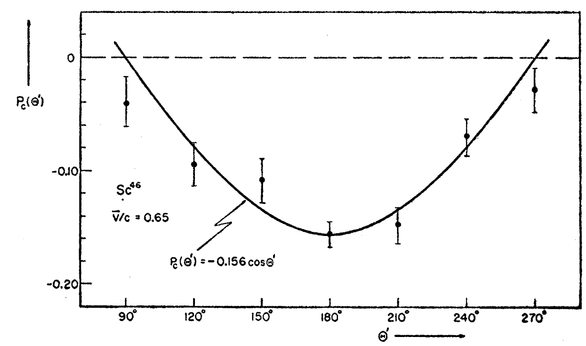

FIG. 5. Circular polarization $P_c(\Theta')$ of gamma rays following the beta decay of Sc^{46} as a function of the angle Θ'.

The circular polarization measurements on Na^{24} were performed with an integral discriminator in the β channel accepting β particles of energies above 0.80 Mev $[(v/c)_{Av} = 0.94]$. The experimentally determined value of $P_c^{\pi} = -0.065 \pm 0.028$ yields

$$A = +0.07 \pm 0.03.$$

In view of the small anisotropy of the Na^{24} beta-gamma circular polarization correlation no attempt was made to investigate the $\cos\Theta_{\beta\gamma}$ dependence or the variation of P_c with v/c. The result quoted above agrees with the measurements reported by Boehm and Wapstra,[7] but not with the measurements of Schopper[51] (compare Table I).

b. Measurements on Sc^{46}

This nuclide is of particular interest, since the circular polarization measurements on Sc^{46} established the

[51] H. Schopper, quoted in reference 3.

presence of V-A interference terms with certainty,[7,11] thus excluding the possibility of complete violation of time reversal invariance (C_V/C_A = imaginary).

With the integral discriminator in the β channel at 0.095 Mev the $\cos\Theta_{\beta\gamma}$ dependence of P_c was measured (Fig. 5). The results of an attempt to verify the v/c dependence of P_c, using a window of 50 kev in the β channel, are shown in Fig. 6. The experimental points are consistent with $P_c = \text{const}\,v/c$.

From these measurements the value of the anisotropy factor A of Sc^{46} is extracted:

$$A = +0.24 \pm 0.02.$$

The agreement with the work of the CERN group[14] and

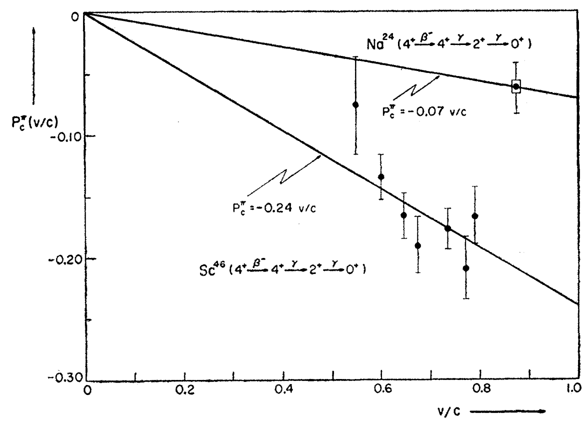

FIG. 6. Circular polarization $P_c^\pi(v/c)$ of gamma rays of Sc^{46} and Na^{24} at $\Theta' = 180°$ as a function of v/c of the beta particles.

with the results of Jungst and Schopper[52] is excellent. The value of A found in this investigation, however, is considerably smaller than the result of Boehm and Wapstra[7] (compare Table I).

c. Discussion of Results

According to Eq. (8) the coefficient A for a $\Delta I = 0$ β^- transition can be written as

$$A = +\frac{1}{L+1}\left[+\frac{1}{I_2} - \left(\frac{I_2+1}{I_2}\right)^{\frac{1}{2}} \frac{C_A C_V y}{C_A^2 + C_V^2 y^2}\right].$$

According to the most recent measurements on the

[52] W. Jungst and H. Schopper, Z. Naturforsch. **13a**, 505 (1958).

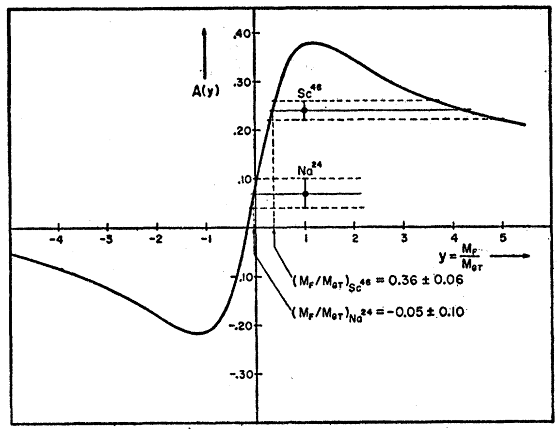

FIG. 7. The anisotropy coefficient $A(y)$ for mixed transitions ($\Delta I = 0$) as a function of the matrix element ratio $y = M_F/M_{GT}$.

decay of the free neutron, $C_V = -1.19 C_A$, and A can be expressed as a function of $y = M_F/M_{GT}$ only. $A(y)$ is represented as solid line in Fig. 7, together with the experimental values for Na^{24} and Sc^{46}. The values of y determined for these two nuclides are indicated in Fig. 7. The second set of solutions, $y > 1$, are discarded as very improbable. The contribution of the Fermi component to the beta transition of Na^{24} is very small: $M_F^2 = (0.0025 \pm 0.0100) M_{GT}^2$. The isotopic spin of the Na^{24} ground state is $T = 1$, whereas the isotopic spin of the Mg^{24} state which is populated by the Na^{24} beta decay is $T = 0$. By virtue of the isotopic-spin selection rules beta decay by a Fermi transition is forbidden between states with $\Delta T = 1$. Considering the fact that isotopic spin should be a good quantum number for nuclides of mass numbers as small as 24, the absence (within experimental error) of a Fermi component in the Na^{24} beta decay agrees with theoretical expectations. In the Sc^{46} beta decay, on the other hand, the contribution of the Fermi component cannot be neglected: $M_F^2 = (0.13 \pm 0.04) M_{GT}^2$. This is an indication that the application of the isotopic spin concept to nuclear states with as many as 46 nucleons yields unsatisfactory results.

ACKNOWLEDGMENTS

The author is greatly indebted to Mr. P. Alexander for his help in constructing the analyzer magnet and to Mrs. D. G. Speer for her help in reading and processing the large amount of automatically accumulated data.