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Circular Polarization Measurements in the β Decay of V^{48}, Co^{56}, Fe^{59}, and Cs^{134}*

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The β-γ circular-polarization angular correlation has been measured for V^{48}, Co^{56}, Fe^{59}, and Cs^{134} using the Livermore apparatus described previously. Since all of these decays (with one exception) are characterized by $\Delta J=0$, $J\neq 0$, and $\Delta T\approx 1$, they possess the necessary elements for testing isospin conservation in allowed β decay. The measured asymmetry parameters are: -0.066 ± 0.035 for V^{48}, 0.00 ± 0.03 for Co^{56}, -0.074 ± 0.022 for Cs^{134}, and -0.23 ± 0.05 and 0.01 ± 0.10, respectively, for the 462-keV and 271-keV, β branches in Fe^{59}. These results are consistent in all cases with a very small Fermi matrix element and therefore support the validity of isospin conservation, with the doubtful exception of the 271-keV β-decay branch of Fe^{59}. However, in this case the extreme difficulty of disentangling the 271-keV branch from the 462-keV branch, which is pure Gamow-Teller $[3/2^-(\beta)5/2^-(\gamma)7/2^-]$, renders this exception rather uncertain. In the case of V^{48} our result is in disagreement with that of Boehm and Wapstra, who found evidence for sizable interference, but is in better agreement with the result of Daniel and Kuntze, who find evidence for small interference. Our Co^{56} result is in excellent agreement with the work of Daniel and Kuntze. Our result for the low-energy branch of the Fe^{59} decay ($\Delta J=0$) is in accord with the work of Forster and Sanders, the accuracy being, however, very poor in both measurements. With regard to the high-energy branch ($\Delta J=1$), our result is lower by a factor of two than that of Forster and Sanders.

Our Cs^{134} result shows definite interference, but because of the large *ft* value the Fermi matrix element is still very small, in keeping with the other findings at this laboratory.

I. INTRODUCTION

THE measurements reported in this paper are part of a continuing program at this laboratory in which the asymmetry parameter in the angular correlation between β rays and circularly polarized γ rays is measured. Previous reports[1–3] give a complete description[3] of the techniques and apparatus used in the present experiments as well as complete references[3] to related work at other laboratories. Our technique is a somewhat modified version of the one introduced by Schopper[4] and by Boehm and Wapstra.[4] In brief, the method uses Compton scattering from magnetized iron in order to detect circular polarization in γ rays.

The principal result of this work is a determination of the relative magnitudes of the Fermi and Gamow-Teller contributions in mixed β decays ($\Delta J=0$), under the assumption that the $A-V$ theory[5] of β decay is valid. Since in this theory the Fermi type of β decay can occur only between states having the same isospin ($\Delta T=0$), these results have a direct bearing on its validity as well as on the question of the isospin as a good quantum number.[3,6–8] Hence, it is of importance that two of the nuclides reported here (Co^{56} and Cs^{134}) have very large β-decay *ft* values, since this means that the Gamow-Teller matrix elements are unusually small. Thus, in these cases even a small Fermi matrix element, due to a small isospin impurity in one of the relevant states, may result in a relatively large contribution to the β decay and would be easily detectable. This appears to have happened for both Co^{56} and Cs^{134}.

The following relation between the asymmetry parameter and the nuclear constants was obtained[3] from the work of several authors[9–11]:

$$A=\mp\frac{\sqrt{3}/6}{1+\delta^2}\left(\frac{1}{1+y^2}\right)\left[\frac{I_f(I_f+1)-I_i(I_i+1)+2}{[I_f(I_f+1)]^{1/2}}\pm 4y\right]$$
$$\times[F_1(\lambda,\lambda,I_{ff}I_f)+\delta^2F_1(\lambda+1,\lambda+1,I_{ff}I_f)+2\delta F_1(\lambda,\lambda+1,I_{ff}I_f)]. \quad (1)$$

The upper sign applies for β^- decay and the lower sign for β^+ decay. This formula is identical with Eq. (2′) in reference 3 with the added restriction that only the two γ-ray multipoles of lowest possible order are assumed to contribute. We have used δ for the ratio of the γ-ray matrix elements of $2^{\lambda+1}$ pole to 2^{λ} pole, and $y\equiv C_VM_V/C_AM_A$.

II. SOURCES

V^{48} and Co^{56} were produced in the Crocker Laboratory 60-in. cyclotron by the $(d,2n)$ reaction on natural titanium and iron foils, respectively. Carrier free separations were carried out using ion exchange techniques.[12,13] The Fe^{59} and Cs^{134} were purchased from commercial suppliers. All sources were mounted on uncoated Mylar films of 1 mg/cm² by solution evaporation.

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[1] S. D. Bloom, L. G. Mann, and J. A. Miskel, Phys. Rev. Letters **5**, 326 (1960).

[2] L. G. Mann, S. D. Bloom, and R. J. Nagel, Nuclear Phys. (to be published).

[3] S. D. Bloom, L. G. Mann, and J. A. Miskel, Phys. Rev. **125**, 2021 (1962).

[4] H. Schopper, Nuclear Instr. **2**, 158 (1958). Earlier references as well as a detailed description of the basic method may be found here.

[5] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).

[6] C. C. Bouchiat, Phys. Rev. **118**, 540 (1960).

[7] P. S. Kelly and S. A. Moszkowski, Z. Physik **158**, 304 (1960).

[8] J. Bernstein and R. Lewis, Phys. Rev. **112**, 232 (1958).

[9] K. Alder, B. Stech, and A. Winther, Phys. Rev. **107**, 728 (1957).

[10] Y. V. Gaponov and V. S. Popov, Nuclear Phys. **4**, 453 (1957).

[11] J. D. Jackson, S. B. Treiman, and H. W. Wyld, Jr., Phys. Rev. **106**, 517 (1957).

[12] U. Schindewolf and J. W. Irvine, Anal. Chem. **30**, 906 (1958).

[13] J. L. Hague, E. E. Maczkowske, and H. A. Bright, J. Research Natl. Bur. Standards **53**, 353 (1954).

TABLE I. The measured asymmetry parameter A in the angular correlation between β rays and circularly polarized γ rays. The asymmetry parameter in the last column is obtained by a renormalization of the relative asymmetry parameter so that the average of the Co^{60} and Na^{22} magnitudes equals 1/3.

Nuclide	Raw effect[a] $(N_n-N_s)/(N_n+N_s)$	f_{PA}	f_{PE}	Correction factors[b] f_{BS}	f_{VC}	f_{RC}	f_{GG}	f_{NP}	Total[c] correction f_T	Relative[d] asymmetry parameter A_r	Asymmetry parameter A
V^{48}	-0.068 ± 0.034	1.00	1.00	1.01	1.22	1.03	1.18	1.50	2.25	-0.15 ± 0.08	-0.066 ± 0.035
Co^{56}	-0.004 ± 0.023	1.00	1.00	1.00	1.11	1.26	1.35	1.55	2.93	-0.01 ± 0.07	0.00 ± 0.03
Cs^{134}	-0.077 ± 0.023	1.00	1.35	1.01	1.23	1.04	1.04	1.20	2.18	-0.17 ± 0.05	-0.074 ± 0.022
Average Co^{60} and Na^{22} (absolute magnitudes)										0.76 ± 0.10	1/3

[a] Statistical errors only (standard deviation).

[b] These correct for the following effects: f_{PA}—coincidences involving annihilation radiation; f_{PE}—energy dependence of the polarization detection efficiency; f_{BS}—back scattered β particles; f_{VC}—dependence of the polarization on velocity of the β ray; f_{RC}—accidental coincidences; f_{GG}—coincidences between two γ rays; f_{NP}—coincidences which do not involve scattering from magnetic iron.

[c] The product of all the individual correction factors.

[d] The product of f_T and the raw effect.

III. RESULTS

As in our previous work, the difference in the β-γ coincidence rates for opposite magnetic field directions was compared with the average of the Co^{60} and Na^{22} values, which number was used as a calibration standard in order to determine the asymmetry parameter. In all of the present work the iron scattering cylinder was 3/8 in. thick. Also, all sources were contained in a helium atmosphere.[3]

The data are given in Tables I and II. The "raw effect" is the difference between the north-field and south-field counting rates divided by the sum of those rates. The correction factors have all been discussed in detail previously. The asymmetry parameters appear in the last column.

For Fe^{59}, given in Table II, the procedure for obtaining the asymmetry parameters from the raw data is not as straightforward as in the other cases. This is because it is impossible to observe the low-energy β spectrum, which has a mixed character ($\Delta J=0$), without detecting at the same time the higher energy spectrum, which is assumed to be pure Gamow-Teller ($\Delta J=1$). Hence, two sets of data are necessary (actually three sets were used); one, with the β-detection threshold at 270 keV, gives the polarization of γ rays associated with the high-energy (462-keV) β spectrum only, and the other, with a lower threshold, contains the effect of the 271-keV β spectrum.

To separate these two spectra properly, we first compare each set of data with the Na^{22} and Co^{60} average to get the average polarization P_γ of those γ rays detected at each β threshold. All the correction factors except f_{VC} are used in this calculation. Explicitly,

$$P_\gamma=\left[\frac{1/3}{0.76}\right]_{Co^{60}-Na^{22}}\times\left[\frac{N_n-N_s}{N_n+N_s}f_{T'}\right]_{Fe^{59}}. \tag{2}$$

This P_γ can then be expressed as a properly weighted average of the A's associated with the two β spectra, as follows (for the β threshold at 115 keV):

$$P_\gamma=\left\{0.54A_{462}\left[\alpha\frac{\bar{v}_{462}}{c}\right]_{115}\right.$$
$$\left.+0.46A_{271}\left[\beta\frac{\bar{v}_{271}}{c}\right]_{115}\right\}\frac{1}{0.54\alpha+0.46\beta}. \tag{3}$$

Here the factors 0.54 and 0.46 are the relative intensities of the two β spectra, α and β are the fractions of the 462- and 271-keV spectra, respectively, that are accepted by the discriminator setting, and $\bar{v}/c$ is the ratio of the average speed of the β particles accepted to the speed of light. Solving this equation simultaneously for each set of data gives the results in the last two columns of Table II. The accuracy is seen to be quite poor, due to cancellation effects.

TABLE II. The measured asymmetry parameter in the angular correlation between β rays and circularly polarized γ rays for Fe^{59} β decay.

Raw effect[a] $(N_n-N_s)/(N_n+N_s)$	Threshold for β detection (keV)	f_{PE}	Correction factors[b] f_{BS}	f_{RC}	f_{GG}	f_{NP}	Total[b] correction $f_{T'}$	Degree[c] of γ polarization P_γ	Asymmetry[d] parameters A_{462}	A_{271}
-0.221 ± 0.044	270	1.13	1.01	1.10	1.02	1.45	1.86	-0.176 ± 0.035	-0.23 ± 0.05	
-0.118 ± 0.026	115	1.07	1.01	1.08	1.01	1.50	1.77	-0.090 ± 0.020		0.09 ± 0.14
-0.133 ± 0.033	70	1.07	1.01	1.08	1.01	1.50	1.76	-0.102 ± 0.025		-0.05 ± 0.13
Average									-0.23 ± 0.05	0.01 ± 0.10

[a] Statistical errors only (standard deviation).

[b] See Table I; f_{VC} is not included here.

[c] Based on the values in Table I for Na^{22} and Co^{60}, which were used to normalize the results in this table.

[d] See text for the relation between P_γ and the A's.

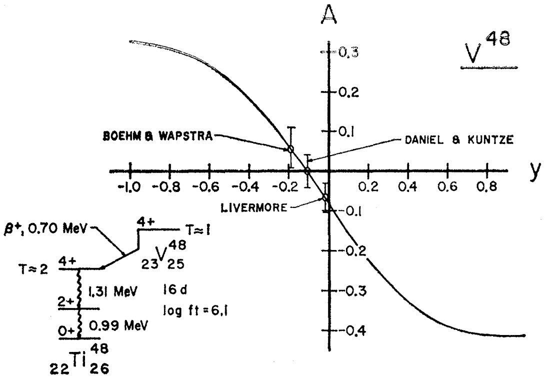

FIG. 1. Experimental results for A, the asymmetry parameter, in the case of V^{48}. The curve is the theoretical relation between A and $y \equiv C_V M_V / C_A M_A$ [Eq. (1)].

All the results are compared with Eq. (1) in Figs. 1 through 5, where the results of other measurements are also given.[14–16] In the case of V^{48} (Fig. 1) there may be evidence of the kind of disagreement that has characterized several of these measurements in the past.[3] However, in the case of Co^{56} (Fig. 2) the agreement between our work and the work of Daniel and Kuntze is essentially complete. Fe^{59} contain two β spectra that were measured, one mixed ($\Delta J = 0$) and the other pure Gamow-Teller ($\Delta J = 1$). Accordingly two theoretical curves are given (in Figs. 3 and 4), one of A vs y which applies to the mixed spectrum, and the other of A vs δ which applies to the pure Gamow-Teller spectrum. In the case of the pure Gamow-Teller transition, our results differ quite largely from the results of Forster and Sanders[17] (see Fig. 3), but because of the steep dependence of A on δ, the multipole mixing ratio, the conclusions to be drawn are essentially the same. In the case of the low-energy transition, which is mixed (see Fig. 4), our results are in satisfactory agreement with Forster and Sanders, but because of the large errors the amount of interference is not very precisely determined.

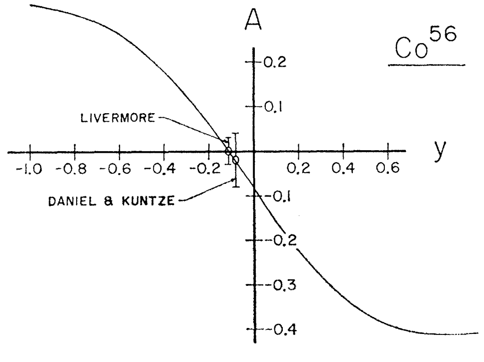

FIG. 2. Experimental results for Co^{56}. The curve is the theoretical relation between A and $y \equiv C_V M_V / C_A M_A$ [Eq. (1)].

TABLE III. Ratios of the Fermi and Gamow-Teller contributions in the β decay of V^{48}, Co^{56}, Fe^{59}, and Cs^{134}. The $A-V$ theory [Eq. (1)] was used to relate A and the ratio $C_V M_V / C_A M_A$.

Nuclide	Reference	A	$C_V M_V / C_A M_A$
V^{48}	Boehm and Wapstra[a]	$+0.06 \pm 0.04$	-0.20 ± 0.07
	Daniel and Kuntze[b]	0.00 ± 0.04	-0.11 ± 0.05[c]
	Present results	-0.066 ± 0.035	-0.02 ± 0.05
Co^{56}	Daniel *et al.*[d]	-0.02 ± 0.06	-0.08 ± 0.08[c]
	Present results	0.00 ± 0.03	-0.11 ± 0.04
Fe^{59} (462-keV β)	Present results	-0.23 ± 0.05	...[e]
	Forster and Sanders[f]	-0.46 ± 0.08	...[e]
(271-keV β)	Present results	$+0.01 \pm 0.10$	$+0.28^{+0.25}_{-0.20}$
	Forster and Sanders[f]	-0.04 ± 0.11	$+0.17 \pm 0.25$
Cs^{134}	Present results	-0.074 ± 0.022	$+0.22 \pm 0.04$

[a] See reference 16.
[b] See reference 14.
[c] Due apparently to a numerical error these results are given a + sign by Daniel *et al.*
[d] See reference 15.
[e] This β spectrum is pure Gamow-Teller ($\Delta J = 1$). The γ ray has $\delta = -0.26 \pm 0.05$, giving approximately $(7 \pm 2)\%$ $E2$ and 93% $M1$ from the Livermore results, and $\delta = -0.04$, giving $<1\%$ $E2$, from the results of Forster and Sanders.
[f] See reference 17.

In Table III all of the measurements on these nuclides are summarized. It is seen that with our results a near-zero Fermi component seems clearly indicated only in the case of V^{48}. However, the unusually small size of the Gamow-Teller matrix elements in Co^{56} and Cs^{134} is chiefly responsible for the large ratios shown in Table III, as will be discussed. It seems most likely that the accuracy of the Fe^{59} measurement is simply not good enough to warrant any strong conclusions.

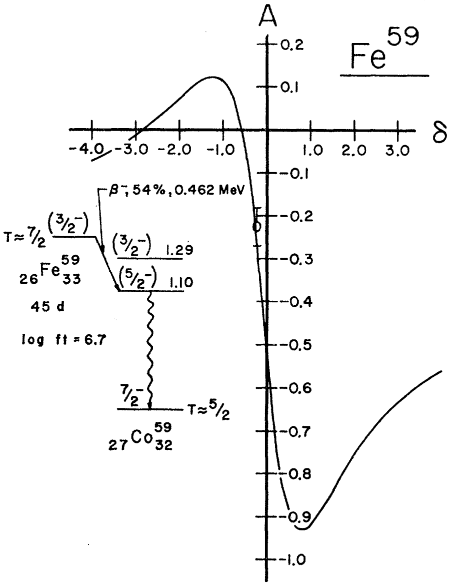

FIG. 3. Experimental results for the 462-keV β branch of Fe^{59}. In this case A is a function of the $E2/M1$ amplitude ratio (δ) only, since the fact that $\Delta J = 1$ in the β transition precludes any Fermi contribution. The curve is obtained from Eq. (1).

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[14] H. Daniel and M. Kuntze, Z. Physik **162**, 229 (1961).
[15] H. Daniel, M. Kuntze, and O. Mehling, Z. Naturforsch, **169**, 1118 (1961).
[16] F. Boehm and A. H. Wapstra, Phys. Rev. **109**, 456 (1958).
[17] H. H. Forster and N. L. Sanders, Nuclear Phys. **15**, 683 (1960).

TABLE IV. Impurity coefficients α_{pd} (α_{dp}) describing admixing into the parent (daughter) state of the analog state of the daughter (parent) in the case of positron (electron) decay.

Nuclide	Logft	Isospin Parent	Isospin Daughter	Impurity admixture
V^{48}	6.1	1	2	α_{pd}, 1×10^{-3}
Co^{56}	8.7	1	2	α_{pd}, 3×10^{-4}
Fe^{59} (271-keV β)	5.9	7/2	5/2	α_{dp}, 2×10^{-4}
Cs^{134}	8.8	12	11	α_{dp}, 5×10^{-2}

IV. DISCUSSION

In assessing the validity of the isospin concept, a more directly significant quantity than the ratios shown in Table III is the actual magnitude of the Fermi matrix elements. These can be obtained from the ft values and the above ratios.[3] By assuming that the Fermi matrix element is due entirely to an admixture in the daughter (or parent) of the analog state of the parent (or daughter),[3,18] we can then determine the amount of these isospin impurities. The results of this analysis are shown in Table IV. Only in the case of Fe^{59}, for which the accuracy is very limited, is there an appreciable mixture. Co^{56} and Cs^{134} are seen to contain a very small impurity in spite of the fact that the ratio C_VM_V/C_AM_A is unusually large. This happens because the large ratio is due to an unusually small value of M_A rather than a large value of M_V. To our knowledge there have been no attempts to calculate the Fermi matrix elements for these nuclides.

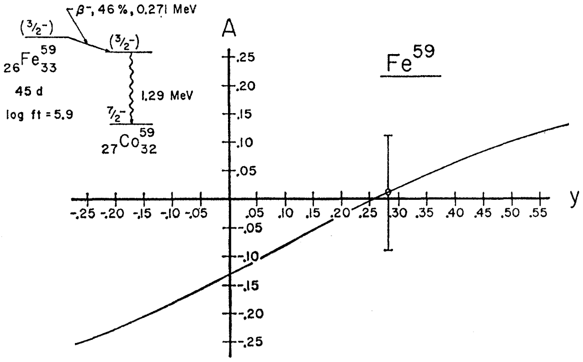

FIG. 4. Experimental result for the 271-keV β branch of Fe^{59}. The curve is the relation in Eq. (1) between A and $y\equiv C_VM_V/C_AM_A$.

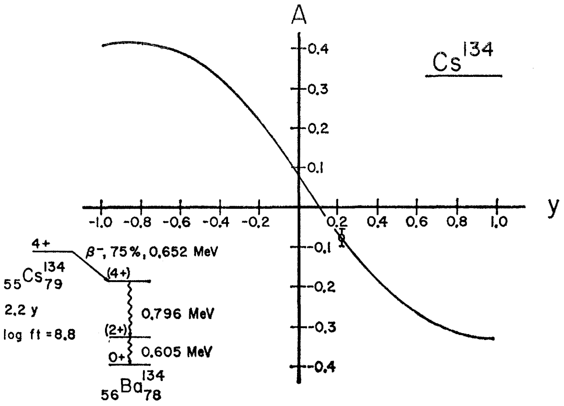

FIG. 5. Experimental result for Cs^{134}. The curve is the relation in Eq. (1) between A and $y\equiv C_VM_V/C_AM_A$.

These data sometimes give useful information about nuclear spins. In both V^{48} and Co^{56} the spins 3^+ and 5^+ for the ground states would lead to -0.416 and $+0.33$, respectively, for A, using Eq. (1). Since in these cases there would be no question of β-decay mixing, and the γ-ray mixing is probably very small ($E2$ vs $M3$), the predictions should be quite reliable. The data, therefore, are strong evidence against these spins. In Co^{56} the spin of 4 has been measured directly, but in V^{48} only indirect measurements are available.[19] The above argument applies equally well to Cs^{134}, except in this case it is the spins of the levels at 0.605 and 1.401 MeV in Ba^{134} that are less directly measured. Here the spin of 3^+ for the 1.401-MeV level and dipole radiation would lead to $A=-0.50$, which again strongly disagrees with the data.

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[18] W. P. Alford and J. B. French, Phys. Rev. Letters **6**, 119 (1961).

[19] See K. Way *et al.*, *Nuclear Data Sheets*, Nuclear Data Project, National Academy of Sciences, National Research Council. (U. S. Government Printing Office, Washington, D. C.).