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Circular Polarization Measurement of Gamma Rays Following Beta Decay of Al^{24} and Na^{24} to Determine the Meson Exchange Effect*

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We have measured and compared the β circularly polarized γ angular correlations for Al^{24} and Na^{24}, as suggested by Bouchiat, in order to determine the size of the Fermi matrix elements M_π due to meson exchange and $a_0(1)\sqrt{2}$ due to isospin impurities. The polarimeter was a cylindrical magnet that produces 19 000 G in the form of a square wave oscillating at 140 cps. At this frequency the 2.1-sec half-life presents no new problem except one of source handling. A pneumatic tube was used to transport sources between the polarimeter and the UCLA cyclotron internal beam. The results (using superscripts + and − to denote Al^{24} and Na^{24}, respectively) are A^+ (the circular polarization asymmetry parameter) $=-0.084\pm0.054$, $A^-=0.091\pm0.017$, $M_F{}^+=(0.06\pm5.4)\times10^{-3}$, and $M_F{}^-=(0.8\pm1.7)\times10^{-3}$. From $M_\pi=\frac{1}{2}(M_F{}^- - M_F{}^+)$ and $a_0(1)\sqrt{2}=\frac{1}{2}(M_F{}^- + M_F{}^+)$, we get $M_\pi=(0.4\pm3)\times10^{-3}$ and $a_0(1)\sqrt{2}=(0.4\pm3)\times10^{-3}$ in this isobaric triplet. With the CVC conserved vector-current hypothesis M_π should be zero.

INTRODUCTION

It has been suggested by Bouchiat[1] that a comparison of the angular correlations between β rays and circularly polarized γ rays in the decays of Al^{24} and Na^{24} to the 4.12-MeV state in Mg^{24} can provide a sensitive test of the conserved vector-current theory of β decay,[2] independent of the details of the nuclear model used in calculations.[1,3] The problems encountered in measurements of γ-ray circular polarization have been discussed elsewhere.[4–6] In essence, the measurement consists of a comparison of scattered γ-ray intensities for Compton scattering from electrons aligned either parallel to or antiparallel to the incident γ-ray direction. Magnetized iron is used as a source of partially polarized electrons. Generally the change in count rate upon reversing the magnetic field is $<1\%$. In the present work Al^{24} presented the more difficult experimental problem because of its short (2.1 sec) half-life and the need to reject strong positron branches which decay to higher excited states in Mg^{24}. Figure 1 shows the relevant decay scheme data.[3,7–9]

In other circular polarization measurements at Livermore we have alternated the magnetic-field direction as rapidly as possible in order to avoid what we believe to be very severe instrumental-stability requirements.[4] For the present experiment we used a new magnet[10] in a system similar to that described previously.[4] This magnet produces a square wave of flux (19 000 G) at 140 cps, with complete flux reversal

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[1] Claude C. Bouchiat, Phys. Rev. Letters 3, 516 (1959).

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

[3] E. L. Haase, H. A. Hill, and D. B. Knudsen, Phys. Letters **4**, 338 (1963).

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

[5] E. L. Haase, Ph.D. thesis, Princeton University, Technical Report PUC-1962-71, 1962 (unpublished).

[6] H. Schopper, Nucl. Instr. Methods **3**, 158 (1958).

[7] C. Broude and H. E. Gove (to be published).

[8] A. Scott and R. Polichar (to be published).

[9] N. Glass and J. R. Richardson, Phys. Rev. **98**, 1251 (1955).

[10] R. E. Pechacek, L. G. Mann, S. D. Bloom, and R. M. Rodrigues, Rev. Sci. Instr. **35**, 58 (1964).

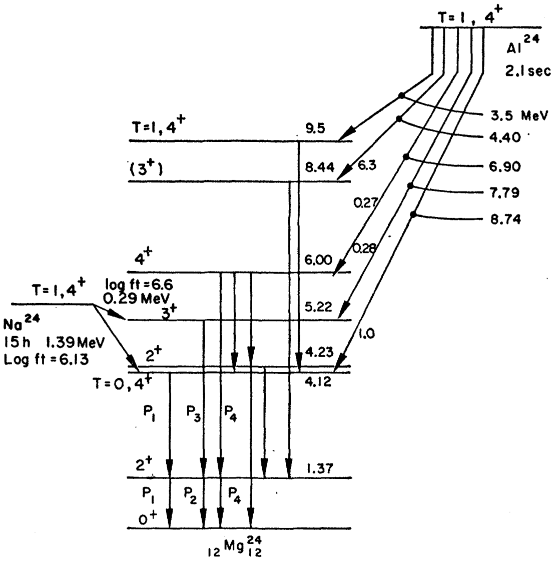

FIG. 1. Decay scheme data used in this work. Polarizations of γ rays are denoted by *P*. Intensities shown in the Al^{24} β decay are normalized to the β branch of highest energy, 8.74 MeV (about 8% of the total Al^{24} decay).

in 0.4 msec. Beta, gamma, and β-γ coincidence pulses associated with opposite field directions are stored in separate scalers. In this method all possible drifts of the electronics, variations in source strengths, etc., have a negligible effect on the measurement. Consequently the new problems introduced by the 2.1-sec half-life are purely source handling problems.

The alternative to this procedure consists of counting for periods of the order of 10 min at each field direction. The data are printed out before each field reversal. When this method is used with sources of short half-life ($\tau \ll 10$ min), the number of coincidences associated with opposite field directions must be properly normalized to the singles counts in order to correct for variations in source strengths. Haase[5] has discussed this in detail as it applies to the Al^{24} measurement.

SOURCES

To produce Al^{24} by the reaction $Mg^{24}(p,n)Al^{24}$, a 10-mil natural magnesium foil was bombarded by 25-MeV protons in the UCLA Spiral-Ridge Cyclotron. This foil was mounted on a nylon "rabbit" which was transferred periodically via a pneumatic tube[11] between the cyclotron internal beam and the polarization equipment outside the cyclotron shielding. Six seconds were used for the counting and the irradiation periods and 1 sec for each transit. The cyclotron oscillator was switched off during the counting periods to eliminate unnecessary background. Sodium 24 was produced in the Livermore Pool-Type Reactor by neutron capture in NaF powder.

Besides Al^{24}, appreciable amounts of Al^{25} and Al^{26} were produced by the (p,n) reaction in Mg^{25} and Mg^{26}, and Mg^{23} was produced by the reaction $Mg^{24}(p,np)Mg^{23}$. These activities reached equilibrium within a minute after starting a run, and they contributed about 30% of all the pulses in the γ discriminator. They produced no coincidences because the β discrimination level was greater than twice their maximum β-decay energy. Sodium 25 and 24 were also produced by the $(p,2p)$ reactions, in amounts that contributed $\approx 1\%$ of the γ-ray pulses. The pulse rate from the β discriminator was observed to decay with the 2.1-sec half-life of Al^{24} by using an RIDL pulse-height analyzer in the multiscaler mode.

EXPERIMENT

Scintillation detectors were used in a conventional fast-slow coincidence system.[10] The detectors were $1\frac{3}{4}$- $\times 1\frac{3}{4}$-in.-diam plastic for β rays and 3- $\times$3-in. NaI(Tl) for γ-rays, coupled to 6810 A photomultipliers. The system was designed to handle very high rates in the beta detector. The *RC*-clipped β pulses were 14 nsec wide at half-maximum height. Discriminator and scaler dead times were 90 nsec. In order to achieve the highest possible β-ray count rates in the Al^{24} measurement the average current in the 6810 A was kept as low as possible by reducing the gain. At the gain used, about 3 MeV of energy in the β detector produced a 1-V pulse at the 6810-A output, the minimum pulse height required to fully actuate the coincidence circuit. No additional amplification was used after the photomultipliers. The fast coincidence resolving time (2τ) was approximately 9 nsec. Magnetic shielding and small bucking coils reduced the effects of leakage flux on the counting rates to $<10^{-3}$ and eliminated the need for light pipes on the photomultipliers. This was especially desirable in the γ-ray detector because the greater light collection without light pipes results in faster triggering of the coincidence circuit. [The limiting factor in our coincidence resolving time is the speed of the NaI(Tl) γ-ray detector, which is much slower than the β-ray detector.]

In the Al^{24} experiment the β discriminator was set at 6.3 MeV. This eliminated all β-ray branches except the 8.74 and 7.79 MeV, and a negligible amount of the 6.90-MeV branches. However, at the high β pulse rates used there was a possibility that lower energy positrons might produce an appreciable number of coincidences through "pile up" on other pulses.[3,5] The small width (14 nsec) of the β pulses and short resolving time of the fast coincidence circuit should reject most of these coincidences. The fast coincidence circuit rejects pileup pulses because of the relatively large (≈ 3 MeV) energy required to produce a coincidence output. Two or more β pulses smaller than 3 MeV must occur within at most 5 nsec of each other in order to actuate the β side of the coincidence circuit.

The amount of this pileup was measured as a function of the β pulse rate using the simple β-γ cascade of 3.8-

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[11] A. Scott and R. Polichar (to be published).

min V^{52} (2.73-MeV β^-).[12] We estimated that β pulses from V^{52} would be as likely to pile up to give a resultant pulse of >3.9 MeV as the pulses from the 4.5-MeV branch of Al^{24} would be to give a resultant of >6.3 MeV, the β discriminator level used throughout the Al^{24} correlation experiment. Pulses from lower energy branches of Al^{24} and from the other contaminants present were smaller and less likely than the 4.5-MeV branch to produce pileup. The maximum β count rate above 2.0 MeV for the source activities used in the Al^{24} experiment was 5×10^6 counts/sec (A, Fig. 2). With the same β count rate above 0.71 MeV in the V^{52} pileup test, the coincidence rate with the β discriminator set at 3.9 MeV was approximately 1 per second (B, Fig. 2). As the maximum total coincidence rate was 30 counts/sec for the 6.3-MeV β discriminator setting in the Al^{24} experiment and since the pileup rate decreases as the square of the source strength, we estimate a conservative upper limit of a 3% correction to the actual coincidence rate. The experimental polarization asymmetry of all the Al^{24} positrons above 2.0 MeV was measured to be $+0.036\pm0.075$ (cf. line 7, Table I). The upper limit of 3% pileup coincidences with this asymmetry would yield a maximum correction of 4% to the observed asymmetry of the 8.86-MeV branch of Al^{24}.

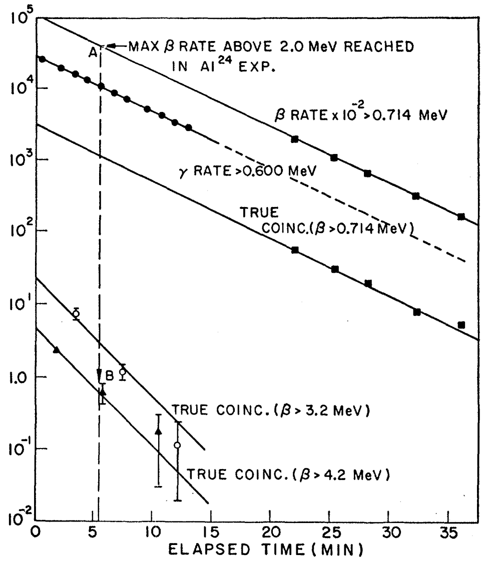

FIG. 2. Pulse rates from V^{52} in the equipment used for circular polarization measurements on Al^{24}. The arrow indicates the point where the V^{52} β-ray intensity was equal to the initial intensity (A) of β rays above 2.0 MeV in our Al^{24} sources. The point B shows a maximum pileup coincidence rate of $\approx10^{-3}$ times the true rate in this source. The lines represent half-lives of 3.8 and 1.9 sec, for single events and double (pileup) events, respectively.

The treatment of data was identical to that used in Ref. 4. The coincidence asymmetry, defined as the difference in total coincidences for opposite field directions divided by the sum, is corrected for several background effects for which the asymmetry is zero. This corrected asymmetry is compared with that of Co^{60}, which is used as a calibration standard. In Table I the corrections are shown as the number of coincidences, in percent of the total, due to each effect (lines 3–5). The uncertainty in each correction introduces an error in the asymmetry that is much smaller than the statistical error. The only correction factor that was not measured directly involves γ rays which produce coincidences without scattering from the inner surface of the magnet, but this effect largely cancels out in the normalization to Co^{60}. The coincidence rates were also corrected by factors of $\lesssim0.1\%$ for differences in time duration of the two field orientations, source decay, scaler dead-time differences, and magnetic-field effects on the photomultiplier gains. The first three of these effects cancel out completely and could have been ignored.[4] This cancellation in the asymmetry occurs for all effects which do not depend on the magnetic-field direction. Tests with the field off have shown conclusively that the instrumental asymmetry is $<0.01\%$.

TABLE I. Results of the circular polarization measurements on Al^{24} and Na^{24}.

	Al^{24}	Na^{24}	Co^{60}
1. Total coinc.	1 763 153	26 052 717	10 732 073
2. $a_{obs}(\%)$[a]	-0.092 ± 0.075	0.128 ± 0.020	-0.369 ± 0.031
3. Accidental coinc. (% of total)	15.0 ± 0.3	4.6 ± 0.03	2.2 ± 0.2
4. γ-γ coinc. (%)	23.7 ± 1.3	23.5 ± 0.3	16.0 ± 0.5
5. Other coinc. (%)[b]	28 ± 10	28 ± 10[c]	28 ± 7[c]
6. $a_{corr}(\%)$	-0.19 ± 0.16	0.242 ± 0.037	-0.63 ± 0.06
7. A[d]	-0.084 ± 0.054	0.091 ± 0.017	$(-1/3)$
8. $M_F\times10^3$	$+0.06\pm5.4$	$+0.8\pm1.7$	
9. M_π[e] Present work	0.0004 ± 0.003		Mean
Haase *et al.*	0.001 ± 0.003		0.0007 ± 0.002
10. $a_0(1)\sqrt{2}$[f] Present work	0.0004 ± 0.003		Mean
Haase *et al.*	0.001 ± 0.003		0.0007 ± 0.002

[a] The difference in coincidences for opposite field directions divided by the total.
[b] Coincidences which do not involve γ rays scattered from magnetized material.
[c] Based on the theoretical polarization detection efficiencies and the known polarizations.
[d] Asymmetry parameter in the β-γ circular polarization correlation.
[e] The Fermi matrix element due to meson exchange, $=(M_F^- - M_F^+)/2$.
[f] The Fermi matrix element due to isospin impurities, $=(M_F^- + M_F^+)/2$.

The data are shown in Table I. Maximum counting rates at the start of each counting period for Al^{24} were 25×10^3 γ rays, 33×10^3 β rays, and 30 coincidences per sec; a good day gave 1.5×10^5 coincidences. The γ-ray discriminator was maintained at 600 keV (to reject annihilation radiation) by frequent checks with the 605-keV γ rays from Cs^{134}. The ratio of β to γ rates then was used as a very sensitive method of maintaining a constant β discriminator level of 6.3 MeV. The Compton edge of the intense 7.07-MeV γ ray in Al^{24} was clearly visible in the β detector when the β rays were removed by absorption. This, along with the Co^{60} γ rays, was used to calibrate the β discriminator.

We used the data in Refs. 3 and 7–9, with the formulas of Gaponov and Popov[13] to calculate the effects

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[12] Produced in the UCLA Engineering Department Reactor.

[13] Yu. V. Gaponov and V. S. Popov, Nucl. Phys. 4, 453 (1957).

on the asymmetry from the other branches (Fig. 1). The only appreciable correction ($\approx 20\%$ of the observed asymmetry) comes from the 7.79-MeV β branch. We used $P_2=P_3=0.25$, based on pure $E2$ radiations[7] in a 4-3-2-0 spin sequence, and $P_1=P_4$ because these cascades have the same spins and multipolarities. The observed asymmetry (line 6, Table I) is proportional to the average of the asymmetries produced by each γ ray,[14] weighted by the relative intensities of each γ ray in the decay scheme and by the detection probabilities (the differential Compton-scattering cross sections at the angle of scattering in our magnet, $\approx 53°$). This gives the following expressions, which equal the corrected asymmetries (line 6) in Table I:

$$K(0.482P_1+0.013)f(\Omega_\beta) \qquad \text{for Al}^{24};$$

$$K\left(0.533-\frac{v}{c}A^{\mathrm{Na}}\right)f(\Omega_\beta) \qquad \text{for Na}^{24};$$

$$K\left(0.476-\frac{v}{c}A^{\mathrm{Co}}\right)f(\Omega_\beta)=-0.109Kf(\Omega_\beta) \qquad \text{for Co}^{60}.$$

The function $f(\Omega_\beta)$ is the average value of the cosine of the angle between the β-ray and γ-ray directions[6] ($0.72<f<0.79$ in the present work) and v/c is the average value of the β-ray velocity divided by the speed of light. K is the degree of electron alignment in the magnet (≈ 0.08).

To determine the corrections for coincidences resulting from γ rays not scattered from magnetized material, the a_{obs} for Co^{60} (line 2, Table I) was corrected for accidental and γ-γ coincidences (lines 3 and 4, Table I) and compared with the above expression for Co^{60}. A similar procedure, with $A^{\mathrm{Na}}=0.091\pm0.015$, was used for Na^{24} to give a rough check of the Co^{60} result. If this effect were completely independent of γ-ray energy we could ignore it, because it cancels out in the normalization to the Co^{60} standard, as do the factors K and $f(\Omega_\beta)$. Extensive measurements with this magnet,[15] and also with our previous magnet,[4] have shown that it is actually a slowly varying function of the difference between the scattered γ-ray energy and the γ discriminator level. For a change of 100 keV in this energy difference the number of unwanted γ rays changes 11%. In the present experiments the γ discriminator was ≈ 170 keV below the scattered energy for Na^{24} and Al^{24}, and ≈ 130 keV below the scattered energy for Co^{60}.

RESULTS

The results are shown in lines 7–10 of Table I, the errors being over-all standard deviations determined largely by the counting statistics. The values of A agree with the theoretical values for pure Gamow-Teller β decay of $+\frac{1}{12}$ for Na^{24} and $-\frac{1}{12}$ for Al^{24}. They also agree with the measurements of Haase *et al.*[3] The Fermi matrix elements M_F were obtained from the experimental values of A and the theoretical relation between A and $y=C_VM_F/C_AM_{GT}$, as in Ref. 1. We used[16,1] $C_A/C_V=-1.2$ and $M_{GT}=+0.061$ for Na^{24} and -0.061 for Al^{24}. Assuming $|M_F|\ll|M_{GT}|$, this gives

$$M_F{}^-=(A^- -\tfrac{1}{12})/10.2 \quad \text{for} \quad \text{Na}^{24}$$

and

$$M_F{}^+=(-A^+ -\tfrac{1}{12})/10.2 \quad \text{for} \quad \text{Al}^{24},$$

where the superscripts $-$ and $+$ denote β^- and β^+ decay, respectively.

The quantities $M_\pi=(\frac{1}{2})(M_F{}^- - M_F{}^+)$ and $a_0(1)\sqrt{2}=(\frac{1}{2})(M_F{}^- + M_F{}^+)$ of lines 9 and 10 of Table I are the contributions to M_F due to meson exchange effects and isotopic spin impurities, respectively.[1] Our value of M_π is consistent with the conserved vector-current theory prediction of zero meson-exchange contributions to β decay. The value of M_π does not necessarily disagree with the conventional β decay theory, since the meson-exchange contribution in that theory may also be significantly smaller than the standard deviation of these experiments. The combined value for $a_0(1)\sqrt{2}$ of <0.003 indicates that Bouchiat's estimate[1] of 0.013 is much too large.

Recent calculations of M_F by Blin-Stoyle and Novakovic[17] include a charge-dependent nuclear force in addition to the Coulomb effects considered by Bouchiat. For a charge dependence of a few percent their results agree with our value of $a_0(1)\sqrt{2}$ and also with the observed[4] values of M_F in Ar^{41}, Sc^{44}, and Mn^{52}. They also make an estimate of $M_\pi\approx 0.003$ for Na^{24}, assuming the vector current is not conserved. This suggests that a reduction of the error in our experiment by a factor of ≈ 5 would be very desirable.

ACKNOWLEDGMENTS

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[14] H. A. Tolhoek, Rev. Mod. Phys. 28, 277 (1956).

[15] L. G. Mann and D. C. Camp (to be published).

[16] M. E. Rose, *Nuclear Spectroscopy,* edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), p. 827.

[17] R. J. Blin-Stoyle and L. Novakovic (to be published).