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Circular Polarization Measurement of Gamma Rays Following Beta Decay of Al²⁴ and Na²⁴ to Determine the Meson Exchange Effect*

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We have measured and compared the β circularly polarized γ angular correlations for Al²⁴ and Na²⁴, 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 19000 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 Al²⁴ and Na²⁴, respectively) are A^+ (the circular polarization asymmetry parameter) = -0.084 ± 0.054 , $A^-=0.091\pm0.017,\ M_F^+=(0.06\pm5.4)\times10^{-3},\ {\rm and}\ M_F^-=(0.8\pm1.7)\times10^{-3}.\ {\rm From}\ M_\pi=\frac{1}{2}(M_F^--M_F^+)\ {\rm and}\ M_{\pi}=\frac{1}{2}(M_{\pi}^--M_{\pi}^-)$ $a_0(1)\sqrt{2} = \frac{1}{2}(M_F - + M_F^+)$, we get $M_{\pi} = (0.4 \pm 3) \times 10^{-3}$ and $a_0(1)\sqrt{2} = (0.4 \pm 3) \times 10^{-3}$ in this isobaric triplet. With the CVC conserved vector-current hypothesis M_{π} should be zero.

INTRODUCTION

T has been suggested by Bouchiat¹ that a comparison of the angular correlations between β rays and circularly polarized γ rays in the decays of Al²⁴ and Na²⁴ to the 4.12-MeV state in Mg24 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 Al²⁴ 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 Mg24. 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 magnet¹⁰ in a system similar to that described previously.4 This magnet produces a square wave of flux (19000 G) at 140 cps, with complete flux reversal

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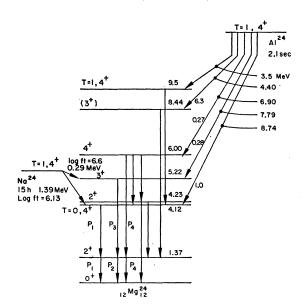


Fig. 1. Decay scheme data used in this work. Polarizations of γ rays are denoted by P. Intensities shown in the Al²⁴ β decay are normalized to the β branch of highest energy, 8.74 MeV (about 8% of the total Al²⁴ decay).

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. Haase⁵ has discussed this in detail as it applies to the Al²⁴ measurement.

SOURCES

To produce Al²⁴ by the reaction Mg²⁴(p,n)Al²⁴, 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 tube¹¹ 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 Al²⁴, appreciable amounts of Al²⁵ and Al²⁶ were produced by the (p,n) reaction in Mg²⁵ and Mg²⁶, and Mg²³ was produced by the reaction Mg²⁴(p,np)Mg²³. 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 Al²⁴ 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 $1\frac{3}{4}$ × $1\frac{3}{4}$ -in.-diam plastic for β rays and 3-×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 Al²⁴ 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 Al²⁴ 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 (\approx 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-

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

min V⁵² (2.73-MeV β^-).¹² We estimated that β pulses from V⁵² 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 Al²⁴ correlation experiment. Pulses from lower energy branches of Al24 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 Al²⁴ experiment was 5×106 counts/sec (A, Fig. 2). With the same β count rate above 0.71 MeV in the V⁵² 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 Al²⁴ 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 Al24 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 Al24.

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 Co⁶⁰, 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 statis-

TABLE I. Results of the circular polarization measurements on Al24 and Na24.

	A124	Na ²⁴	$C_{O^{60}}$
1. Total coinc.	1 763 153	26 052 717	10 732 073
2. $a_{\text{obs}}(\%)^{a}$	-0.092 ± 0.075	0.128 ± 0.020	-0.369 ± 0.033
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°	28±7°
6. acorr (%)	-0.19 ± 0.16	0.242 ± 0.037	-0.63 ± 0.06
7. Ad	-0.084 ± 0.054	0.091 ± 0.017	(-1/3)
8. $M_F \times 10^3$	$+0.06\pm5.4$	$+0.8 \pm 1.7$	(-, -,
9. M_{π^0} Present work	0.0004 ± 0.003		Mean
Haase et al.	0.001	± 0.003	0.0007 ± 0.003
 a₀(1) √2^f Present w 	ork 0.000	04 ± 0.003	Mean
Haase et a		± 0.003	0.0007 ± 0.00

The difference in coincidences for opposite field directions divided by the total. b Coincidences which do not involve γ rays scattered from magnetized

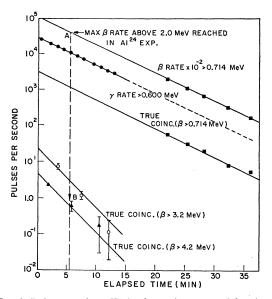


Fig. 2. Pulse rates from V52 in the equipment used for circular polarization measurements on Al24. The arrow indicates the point where the V⁵² β -ray intensity was equal to the initial intensity (A) of β rays above 2.0 MeV in our Al²⁴ sources. The point B shows a maximum pileup coincidence rate of $\approx 10^{-3}$ 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.

tical 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 Co⁶⁰. The coincidence rates were also corrected by factors of $\gtrsim 0.1\%$ 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%.

The data are shown in Table I. Maximum counting rates at the start of each counting period for Al²⁴ were 25×10^3 y rays, 33×10^3 β rays, and 30 coincidences per sec; a good day gave 1.5×10⁵ coincidences. The γ-ray discriminator was maintained at 600 keV (to reject annihilation radiation) by frequent checks with the 605-keV γ rays from Cs¹³⁴. 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 Al²⁴ was clearly visible in the β detector when the β rays were removed by absorption. This, along with the Co⁶⁰ 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 Popov¹³ to calculate the effects

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, $=(M_F^-+M_F^+)/2$.

 $^{^{12}\ \}mathrm{Produced}$ 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 radiations⁷ 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, $\approx 53^{\circ}$). This gives the following expressions, which equal the corrected asymmetries (line 6) in Table I:

$$K(0.482P_1+0.013)f(\Omega_{\beta})$$
 for Al²⁴;

$$K\left(0.533-A^{\text{Na}}\right)f(\Omega_{\beta})$$
 for Na²⁴;

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

The function $f(\Omega_{\beta})$ is the average value of the cosine of the angle between the β -ray and γ -ray directions⁶ (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 $a_{\rm obs}$ for Co⁶⁰ (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 Co⁶⁰. A similar procedure, with $A^{\text{Na}} = 0.091 \pm 0.015$, was used for Na²⁴ to give a rough check of the Co⁶⁰ result. If this effect were completely independent of γ -ray energy we could ignore it, because it cancels out in the normalization to the Co⁶⁰ 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 Na²⁴ and Al^{24} , and $\approx 130 \text{ keV}$ 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 Na²⁴ and $-\frac{1}{12}$ for Al²⁴. 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 Na²⁴ and -0.061 for Al²⁴. Assuming $|M_F| \ll |M_{GT}|$, this gives

$$M_F = (A - \frac{1}{12})/10.2$$
 for Na²⁴

and

$$M_F^+ = (-A^+ - \frac{1}{12})/10.2$$
 for Al²⁴,

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. 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 of 0.013 is much too large.

Recent calculations of M_F by Blin-Stoyle and Novakovic¹⁷ 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 observed⁴ values of M_F in Ar⁴¹, Sc⁴⁴, and Mn⁵². They also make an estimate of $M_\pi \approx 0.003$ for Na²⁴, 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.

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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).