Gamma-Gamma Directional Correlations in ^{144}Nd

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The γ-γ directional correlations of the 779–617-keV γ cascade and 814–697-keV γ cascade in ^{144}Nd following the decay of ^{144}Pm($t_{1/2}$=349 day) were measured using a 10.6-cm^3 Ge(Li) detector and a 3×3-in. NaI(Tl) detector in conjunction with a multichannel analyzer in the standard fast-coincidence configuration. The results obtained are consistent with most-probable spin assignments (with second choice in the parentheses) to the various levels as 2^+ for 1510 keV, 4^+ (6^+) for 1791 keV, 3 (5) for 2093 keV, 4^+ for 2203 keV, and 5^- for the ground state of ^{144}Pm. The possible value of the quadrupole content for the 779-keV γ ray is found to be in the range 11 to 20% or 61 to 80%, while for the 814-keV γ ray, the possible value of the quadrupole content is in the range 36 to 94%.

I. INTRODUCTION

The level scheme of ^{144}Nd has been investigated by several authors by studying the n-capture spectra[1-5] and by studying the electron capture[6-13] and β^- decays[9,14-16] of ^{144}Pm and ^{144}Pr, respectively. As a summary of these data, a level scheme has appeared in the *Table of Isotopes*.[17] This is essentially the same as the one proposed recently by Raman[13] and shown in Fig. 1, except that no level at 1560 keV has been found by Raman.

By combining the experimental data with the theoretical predictions of Heyde and Brussaard[18] spins and parities have been assigned to different levels as shown in Fig. 1. The less-certain assignments are indicated by parentheses. The ground-state and the first-excited-state spins are well established as 0^+ and 2^+, respectively, because of the fact that ^{144}Nd is an even-even nucleus and that the 697-keV γ transition is $E2$. The results[6-10] of γ-γ correlations and the measured K conversion coefficients are consistent with assignments of 4^+ and 6^+ to the levels at 1314 and 1791 keV, respectively. The level found[12,13] at 1510 keV gives rise to an 814-keV γ transition leading to the well-known 2^+ state at 697 keV.[12,13] The 1510-keV level has been tentatively assigned a 3^- value by identifying the 814-keV γ ray with the 810-keV γ ray observed in inelastic α scattering.[19] On the other hand, if the 1510-keV level is identified with the theoretically predicted[18] level at 1509, it should be assigned a value of 2^+. The level at 2093 keV has been tentatively assigned a value of 5^- because of the presence of a 779-keV γ ray from this level to the 4^+, 1314-keV level and the nature of the transition from ^{144}Pm to this level.

The aim of the present work was to investigate the γ-γ directional correlations for the 779- to 617-keV and 814- to 697-keV γ cascades so that some definite spins could be assigned to the 1510- and 2093-keV levels.

II. EXPERIMENTAL PROCEDURE

The radioisotope ^{144}Pm was produced by the reaction ^{145}Nd(p, $2n$)^{144}Pm. A sample consisting of 58 mg of enriched ^{145}Nd (85–95% enriched) was exposed for 1 h in an 18.5±0.5-MeV proton beam at 83.3 μA in the Oak Ridge National Laboratory 218-cm cyclotron. The experiments were started after a waiting period of 8 months so as to let the short-lived activities decay. The presence of ^{143}Pm($t_{1/2}$=265 day) impurity did not interfere with the correlation measurements.

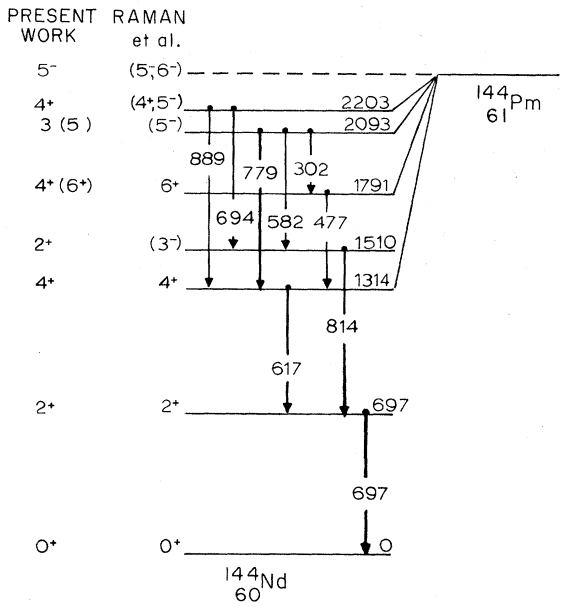

FIG. 1. Decay scheme of ^{144}Pm as suggested by Raman (Ref. 13).

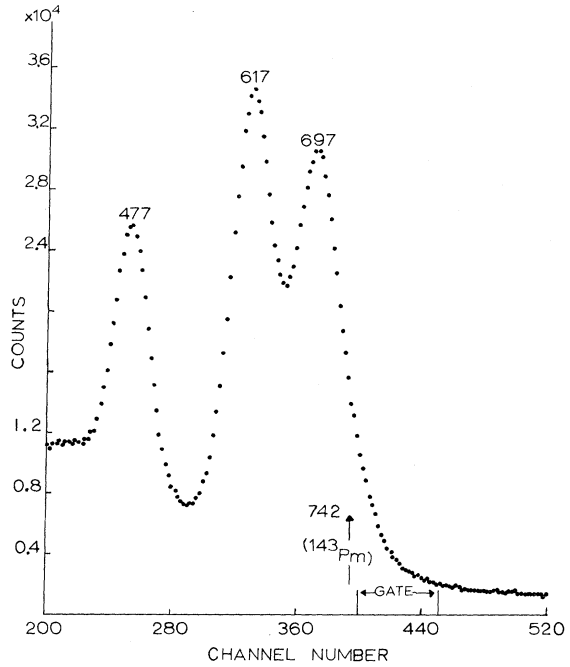

FIG. 2. Singles γ spectrum of ^{144}Nd obtained with a 3 × 3-in. NaI(Tl) detector.

A 10.6-cm^3 coaxial Ge(Li) detector and a 3×3-in. NaI(Tl) detector were used in conjunction with a multichannel analyzer in the standard fast-coincidence configuration. The singles spectra obtained by using the two detectors are shown in Figs. 2 and 3. The coincidence spectra were obtained by gating the NaI(Tl) detector in the following regions: (a) 750 to 800 keV, (b) 800 to 850 keV, and (c) 830 to 860 keV; and by gating the Ge(Li) detector for the 779- and the 814-keV γ rays. These observations confirmed the previous assignment by Raman[13] that the 814-keV γ ray is in coincidence with the 697-keV γ ray, while the 779-keV γ ray is in coincidence with the 617-keV γ ray.

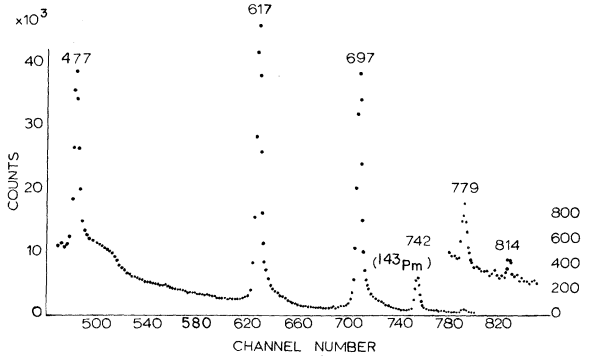

FIG. 3. Singles γ spectrum of ^{144}Nd obtained with a 10.6-cm^3 Ge(Li) detector.

Because of the weak intensities of the 779- and 814-keV γ rays (the γ rays of interest), it was decided to set the NaI(Tl) detector gate to cover the region from 750 to 860 keV; thereby getting coincidences with both the 617- and 697-keV γ rays simultaneously in the Ge(Li) detector as shown in the coincidence spectrum in Fig. 4. There will always be some contribution to the 814-697-keV coincidences from the 779-697-keV coincidences. A proper correction was applied as discussed later. For the γ-γ directional correlations, the Ge(Li) detector was always fixed at one position, while the NaI(Tl) detector was moved to different angles. The data were collected at four different angles, 90, 120, 150, and 180°, counting for 10 min at each angle and repeating it for 100 sets. Accidental-coincidence data were taken at frequent intervals. The decentering of the source was less than 1%. Also, in order to make sure that there was no appreciable contribution to the gate from the 697-keV γ rays, the gate settings were checked frequently. Corrections were applied to the resulting total coincidences at each angle to account for (a) the accidental coincidences, (b) the Compton scattering, and (c) the background.

The coincidence spectrum data collected in the multichannel analyzer were read out on paper tape, and transferred to IBM cards and then to magnetic tape. The data were analyzed by using the IBM 360 computer.

A least-squares fit of the data was made to the function $w(\theta) = a_0 + a_2 \cos^2\theta + a_4 \cos^4\theta$ for the purpose of plotting $w(\theta)$ versus θ as shown in Figs. 5 and 6. For the purpose of interpretation, a least-squares

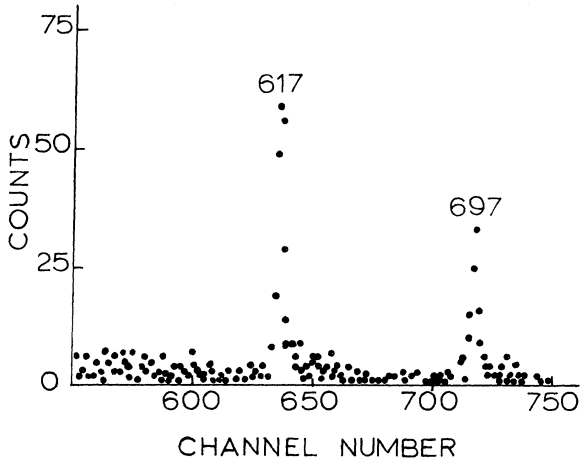

FIG. 4. Coincidence spectrum in Ge(Li) detector with NaI(Tl) detector gated at the energy range 750 to 860 keV.

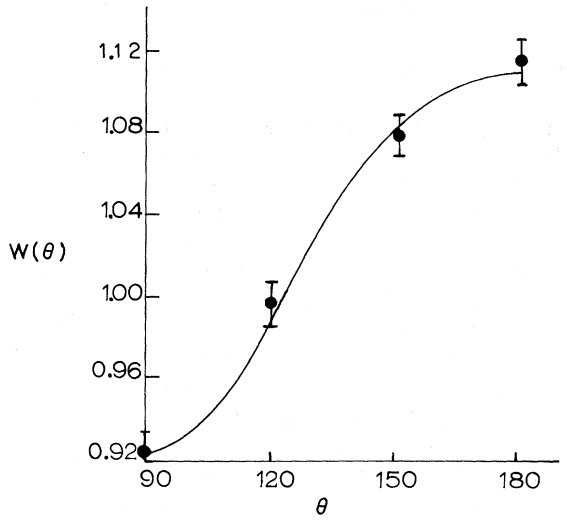

FIG. 5. The plot of $w(\theta)$ versus θ for the 779-617-keV γ cascade. The continuous curve is the least-squares fit to the experimental points.

fit was made to $W'(\theta) = A_0' + A_2' P_2(\cos\theta) + A_4' P_4(\cos\theta)$, and the normalized coefficients $A_2 = A_2'/A_0'$ and $A_4 = A_4'/A_0$ were obtained. The coefficients were corrected for the finite angular resolution of the detectors.[20,21]

III. RESULTS AND INTERPRETATION

A. 779-617-keV γ Cascade

The results obtained for this cascade are

$$W(\theta) = 1 + (0.156 \pm 0.01) P_2(\cos\theta) - (0.039 \pm 0.014) P_4(\cos\theta).$$

The spins of the 697- and 1314-keV levels have been confirmed as 2^+ and 4^+, respectively, while

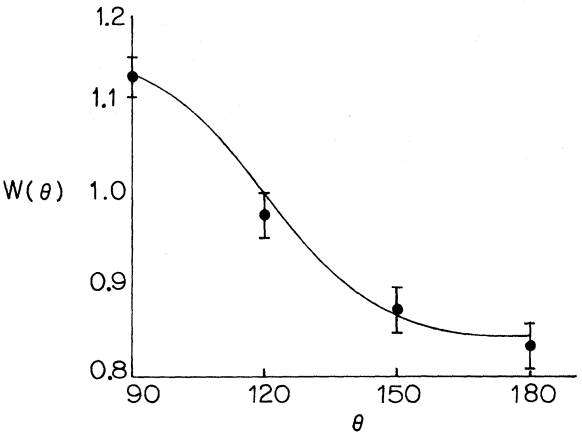

FIG. 6. The plot of $w(\theta)$ versus θ for the 814-697-keV correlation (uncorrected). The continuous curve is the least-squares fit to the experimental points.

the spin of the 2093-keV level has been suggested to be 6^+ by Santhanam[12] or 5^- by Raman.[13] The negative sign of the A_4 coefficients eliminates the assignment of any even spin to the 2093-keV level. Hence this level must be assigned a spin value of 3 or 5, while any higher odd spin will require the 779-keV γ ray to be octupole radiation.

If we assume the spin sequence for this cascade to be 5(dipole + quadrupole)4(quadrupole)2, the experimental values of the coefficients yield for the 779-keV γ ray a mixing ratio of

$$\delta_{779} = -1.25 \text{ to } -2.0,$$

or the fraction of the quadrupole content for the 779-keV γ ray is

$$Q_{779} = \delta_{779}^2/(1 + \delta_{779}^2) = 0.61 \text{ to } 0.80.$$

Thus, the 779-keV γ ray will be a mixture of (61 to 80)% quadrupole, while the rest is dipole. On the other hand, if we assume the spin sequence for this cascade to be 3(dipole + quadrupole)4(quadrupole)2, the results are

$$\delta_{779} = +0.35 \text{ to } 0.5,$$

which corresponds to

$$Q_{779} = 0.11 \text{ to } 0.2.$$

Thus, the 779-keV γ ray will be a mixture of (11 to 20)% quadrupole. In making the above calculations, we have taken into account estimates of any contributions from the 697-keV γ ray due to any slight gate shifting.

B. 814-697-keV γ Cascade

The coincidences obtained at 679 keV shown in Fig. 4 are not only due to the 814-697-keV γ cascade, but also are from the 779-(617 unobserved)-697-keV γ cascade. Thus the combined correlation is

$$W(\theta) = 1 - (0.248 \pm 0.017) P_2(\cos\theta) + (0.108 \pm 0.029) P_4(\cos\theta).$$

To obtain the correlation function for the 814-697-keV γ cascade requires the knowledge of the exact amount of contribution from the other cascade. Employing the method used by Arya,[22] it was found that for the 814-697-keV γ cascade the A_2 coefficient remains negative, while the A_4 coefficient remains large and positive. Since the spins of the ground-state and 697-keV levels are established to be 0^+ and 2^+, respectively, the positive value of A_4 eliminates an assignment of 3^- or any other odd spin to the 1510-keV level. The only possible spin assignment to the 1510-keV level which will be consistent with the rest of the decay scheme is 2^+. This value also agrees with the theoretically

predicted[18] value for the level at 1509 keV.

The above corrections, together with some contribution from the 697-keV γ transitions between the 2203- and 1510-keV levels, does not change the sign of the A_4 coefficient. Thus, taking A_4 to be a positive coefficient, the extreme range of values for the quadrupole content of the 814-keV γ ray from this experiment is (36 to 94)%; i.e.,

$$Q_{814} = 0.36 \text{ to } 0.94 .$$

IV. CONCLUSION

The γ-γ directional correlations of the 779-617-keV γ cascade and 814-697-keV γ cascade are consistent with either a 3 or 5 spin assignment to the 2093-keV level and a 2^+ assignment to the 1510-keV level. Taking into account the present results and assuming the decay scheme by Raman[13] to be firmly established, several other conclusions could be drawn concerning the spin assignment to the other levels. The existence of the weak 582-keV γ transition between the 2093- and 1510-keV levels leaves 3 as the only possible spin for the 2093-keV level. In that case, out of the two possible spins (6^- or 5^-) for the ground state of ^{144}Pm, 5^- is the correct value. Furthermore, the 302-keV γ transition (though very weak) from the 2093-keV state (3) to the 1791-keV state (6^+) will not be possible unless the 1791-keV state is 4^+. Even though a 6^+ value has been assigned to the 1791-keV state on the basis of conversion coefficient and γ-γ correlations, the experimental data do not completely exclude the 4^+ assignment if we take the 477-keV γ ray to be a mixture of dipole and quadrupole. Thus, we may conclude that spin 3 is more probable than 5 for the 2093-keV level, and 4^+ is more probable than 6^+ for the 1791-keV state. The assignment of 2^+ to the 1510-keV level leads to the assignment of 4^+ to the 2203-keV level instead of 5^-, because of the presence of the 694-keV transition between the 2203- and 1510-keV states.

The most-probable spin assignments, with second choices in the parentheses, to various levels are 2^+ for 1510 keV, 4^+ (6^+) for 1791 keV, 3 (5) for 2093 keV, 4^+ for 2203 keV, and 5^- for the ground state of ^{144}Pm, as shown in Fig. 1. Also the 779- and 814-keV γ rays are found to be mixtures of dipole and quadrupole, with the 779-keV γ ray having (11 to 20)% [or (61 to 80)%] quadrupole content and the 814-keV γ ray having (36 to 94)% quadrupole content.

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