Lifetimes of ground-band states in ^{150}Nd

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Members of the ground-state band of ^{150}Nd to spin 8^+ have been Coulomb excited with 149-MeV ^{40}Ar ions, and the lifetimes of these states have been measured by the Doppler-shift recoil distance method. The half-lives of the 2^+, 4^+, 6^+, and 8^+ states are 1.44 ± 0.07 ns, 63.0 ± 3.2 ps, 12.4 ± 1.1 ps, and 4.0 ± 0.4 ps, respectively. The observed enhancement of the experimental $B(E2)$'s over rotational values is found to be in agreement with a simple band-mixing description.

[NUCLEAR REACTIONS ^{150}Nd(^{40}Ar, ^{40}Ar$'\gamma$), $E = 149$ MeV; measured lifetimes of 2^+, 4^+, 6^+, and 8^+ ground-band states, recoil distance method; deduced $B(E2)$ values, compared with theory.]

I. INTRODUCTION

It has been demonstrated in many experiments that the reduced transition probabilities of ground-band states in well-deformed nuclei can be satisfactorily understood in terms of the rotational model. Recent measurements[1] to quite high spins ($I \leq 20$) in ^{232}Th have further reinforced the rotational description. In transitional nuclei, however, significant deviations from rotational behavior have been observed[2-4] for $B(E2)$ values of ground-band states. These deviations are often attributed to band mixing between the ground-band and low-lying vibrational bands. The observed enhancement of the $B(E2)$ values has been taken to be of the form.[5]

$$B(E2;I\to I-2) = B_0(E2;I\to I-2) \times\{1+\tfrac{1}{2}\alpha[I(I+1)+(I-2)(I-1)]\}^2, \quad (1)$$

where $B_0(E2)$ is the rigid rotor value and α is a mixing parameter.

Several explanations, some of which are equivalent or overlapping, can account for departures of $B(E2)$ values from rotational behavior, e.g., band mixing,[5] centrifugal stretching,[6,7] Coriolis antipairing,[8] or fourth-order cranking,[9] and it seems reasonable that one or more of these effects may be simultaneously contributing. To better understand this situation, we have measured the lifetimes of the first four excited states of the ground band of ^{150}Nd, a nuclide located at the abrupt onset of deformation in the rare earth region. Since very good accuracy is required in testing these theories, the Doppler-shift recoil-distance method was utilized as it is believed to provide the most accurate lifetimes in our range of interest, 10^{-12} to 10^{-10} s. The nuclide ^{150}Nd is similar to its much studied isotone ^{152}Sm and, for this reason it was felt that comparisons with ^{152}Sm would be quite valuable.

Aside from the multiple Coulomb excitation work of Fraser and Greenberg,[10,11] which has established the ground band to spin 8^+ and several low-lying vibrational states, little has been published about ^{150}Nd. This nuclide is not easily produced in nuclear reactions and the radioactive decay of ^{150}Pr has been observed[12,13] to populate only a few levels in ^{150}Nd, so the paucity of knowledge about ^{150}Nd is not surprising.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The apparatus (or so-called "plunger") employed in this work has been described by Johnson *et al.*[14] and has been used previously in the measurement of lifetimes as short as 2 ps. Since the nuclear lifetimes of interest in ^{150}Nd are anticipated to be longer than 2 ps, the same procedures followed in previous measurements were used.

The 149-MeV ^{40}Ar beam from the Oak Ridge isochronous cyclotron (ORIC) was focused through a 2.7-mm diameter tantalum collimator and a concentric annular silicon surface barrier detector onto the stretched target foil. The backscattered ^{40}Ar ions were detected by the annular detector which subtended a 159° to 175° angle. This detector was covered with a 1.77-mg/cm^2 gold foil to prevent secondary electrons from striking the detector face. A coaxial Ge(Li) detector with an efficiency of 17% for a 1.33-MeV γ ray [relative to that for a 7.6-cm × 7.6-cm NaI(Tl) detector at 25-cm distance] was placed 5.5 cm from the target at 0° with respect to the beam direction and was used to detect the emitted γ rays.

The movable stopper consisted of a thin layer of lead which was lapped to a surface-finish tolerance of ~3 μm on a thick copper end plate. The fast timing pulses from the Ge(Li) detector and the annular detector were used for the stop-start requirements of a time-to-amplitude converter (TAC). The pulse height information from the TAC, the γ-ray detector, and the heavy-ion detector was digitized by a fast analog-to-digital converter and stored on magnetic tape in the event-by-event mode using a Tennecomp TP-5000 data acquisition system.

The enriched neodymium target (96.13% ^{150}Nd) was a metal foil fabricated by the Isotopes Division at Oak Ridge National Laboratory. The foil thickness, as determined by α-particle energy loss measurements, was 2.8 mg/cm^2. This foil is somewhat thicker than is normally used in this type of measurement, and some spreading in recoil velocities is apparent in the experimental spectra of Fig. 1. However, by placing individual coincidence gates on various portions of the backscattered heavy-ion spectrum, it was determined that little error was introduced by using the average recoil velocity. The average recoil velocity imparted to the ^{150}Nd ions when the backscattered ^{40}Ar ions were detected in coincidence with γ rays was calculated to be $(0.03074 \pm 0.00007)c$ by using the energy difference between the shifted and unshifted peaks in the γ-ray spectra. This value is in excellent agreement with the value calculated from the expression of Ref. 1 which considers the recoil velocity at the front edge of the target and accounts for changes that occur as a recoiling nucleus traverses the target in a forward direction.

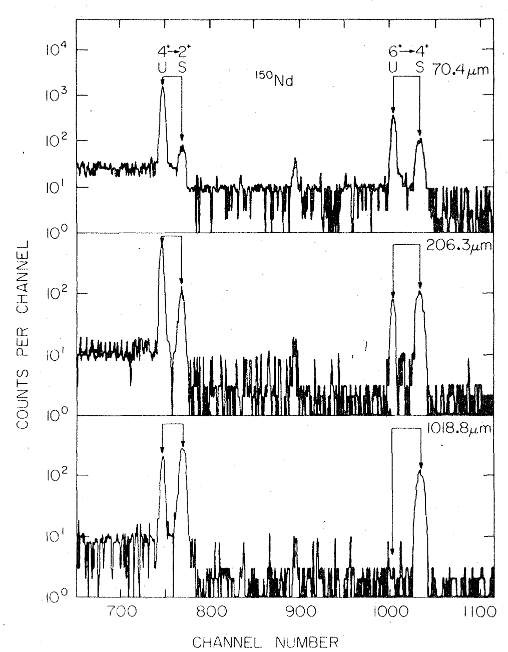

FIG. 1. Portions of the γ-ray spectra displaying the shifted and unshifted γ rays from the $4^+ \to 2^+$ and $6^+ \to 4^+$ transitions in ^{150}Nd taken at three different target-stopper separations.

γ-ray spectra for two of the transitions taken at three target-stopper separation distances are shown in Fig. 1. Because they are produced by γ-ray emission from nuclei in flight, the peaks labeled with an S are shifted with respect to the γ-ray energy of a stationary or stopped nucleus (designated with a U). The peak broadening due to the spread in recoil velocities is evident for the shifted components, but this is not a problem since the shifted and unshifted components are clearly separated at this recoil velocity. The intensities of the shifted (I_S) and unshifted (I_U) peaks are related exponentially to the half-life $t_{1/2}$ of the state by

$$\frac{I_U}{I_U + I_S} = \exp \frac{D \ln 2}{\bar{v} t_{1/2}} , \qquad (2)$$

where $\bar{v}$ is the average recoil velocity of the target nuclei along the detector axis and D is the target-stopper distance. For complete analysis several corrections[14] must be applied to the data. These corrections have been incorporated into the computer code ORACLE by Sturm and Guidry[15] and are applied for (a) the positional and velocity dependence of the solid angle for the shifted component, (b) the variation of detector efficiency with energy for the shifted and unshifted peaks, (c) the effect of feeding from higher-lying states, and (d) the effect of perturbation of the nuclear alignment from hyperfine interactions which alter the angular distributions of the γ rays. The final half-lives are then obtained from ORACLE which applies these corrections in an iterative procedure. Only in the case of the lifetime of the $2^+ \to 0^+$ transition, where the correction is 22%, does the corrected lifetime differ by greater than 5% from the uncorrected lifetime. For a given state a plot of the corrected ratio of the unshifted γ-ray intensity divided by the total γ-ray intensity as a function of the target-stopper separation then yields the nuclear half-life. Figure 2 shows the corrected lifetime data for the $4^+ \to 2^+$, $6^+ \to 4^+$, and $8^+ \to 6^+$

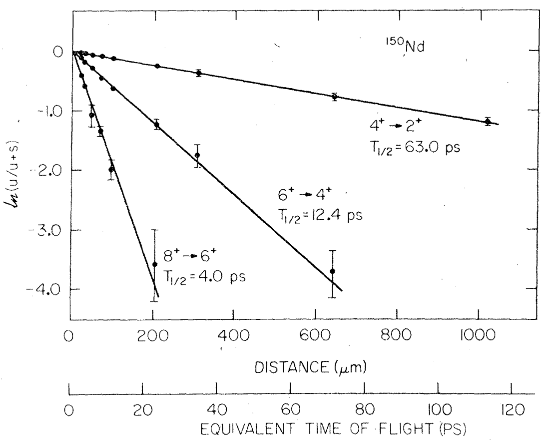

FIG. 2. Plots of ratios of unshifted to total γ-ray intensities as a function of target-stopper separation for the $4^+ \to 2^+$, $6^+ \to 4^+$, and $8^+ \to 6^+$ transitions in ^{150}Nd.

transitions in ^{150}Nd. Although the $10^+ \to 8^+$ transition was also observed as a 469-keV γ ray in this work, an unfortunate degeneracy between this γ ray and a γ ray depopulating the β-vibrational band[16] precludes a lifetime determination.

The angular distribution information used in the calculations was obtained from the semiclassical Winther-de Boer coupled equations computer code[17] assuming rigid rotor behavior. Moreover, it is assumed that the Abragam-Pound formalism[18] is a reasonable approximation for the loss of alignment of the nuclear state due to relaxation processes. In light of the work of Ward *et al.*,[19] we have adopted the values of 25 and 8 ps for the spin-independent relaxation constants τ_2 and τ_4, respectively, for the final calculation, although other values of τ_2 ($\tau_4 \approx \frac{3}{10}\tau_2$) ranging up to 1000 ps were also tried. It was observed that changing τ_2 by a factor of 10 had only a few percent influence on the calculated half-lives.

At the bombarding energy employed, the distance of closest approach between the surfaces of the target nucleus and projectile is only ~3 fm, if it is assumed that the nuclei have spherical surfaces with radii of $1.25A^{1/3}$ fm. For these conditions Coulomb-nuclear interference is expected to be present; however, our measurements were performed in coincidence with backscattered argon projectiles. Very little perturbation of the nuclear alignment is expected[20] for backward scattering angles, since classically only low impact parameters contribute in this case. Therefore, the nuclear force affects the total angular momentum distribution but does not appreciably perturb the magnetic substate distribution. We assume that the angular distributions from the Winther-de Boer program contain only small errors which are well within the error limits assigned to our measurements. Moreover, since the cascade feeding corrections were obtained using our experimental excitation probabilities, Coulomb-nuclear interference should not greatly affect our lifetime determinations.

Table I provides a summary of the half-life and $B(E2)$ values obtained in this work. The internal conversion coefficients in this table were obtained from the theoretical values of Hagar and Seltzer[21] for the K, L, and M shells and from the values of Dragoun, Plajner, and Schmutzler[22] for higher-lying shells. Statistical errors as well as systematic and indeterminate errors (e.g., uncertainties in the γ-ray angular distributions and internal conversion coefficients) are included in the error limits given.

III. DISCUSSION

In Table I we present a comparison of the experimental $B(E2)$ values with rotational calculations. Note that our value for $B(E2; 2^+ \to 0^+)$ is in excellent agreement with the precision (α, α') Coulomb excitation measurements of Ahmed *et al.*[23] and Shaw.[24] This is a significant result in that the half-life of this state (1.44 ± 0.07 ns) is considerably longer than the range of half-lives for which the recoil-distance technique is usually employed. Since the corrections to the data can

TABLE I. Half-life and $B(E2)$ values for ^{150}Nd.

Transition	E_γ (keV)	$T_{1/2}$ (ps)	α_T [a]	$B(E2)$ (e^2b^2)	$\frac{B(E2)_{exp}}{B(E2)_{rot}}$
$2^+ \to 0^+$	130.2	1440 ± 70	0.866	0.56 ± 0.03	(1.00) [b]
$4^+ \to 2^+$	251.2	63.0 ± 3.2	0.0927	0.82 ± 0.04	1.03 ± 0.05
$6^+ \to 4^+$	339.0	12.4 ± 1.1	0.0361	0.98 ± 0.09	1.13 ± 0.09
$8^+ \to 6^+$	409.3	4.0 ± 0.4	0.0207	1.21 ± 0.12	1.33 ± 0.13

[a] Total internal conversion coefficients are from Refs. 21 and 22.

[b] The weighted average for $B(E2; 2^+ \to 0^+)$ of 0.561 ± 0.007 e^2b^2 from the more accurate (α, α') Coulomb excitation measurements of Ahmed *et al.* (Ref. 23) and Shaw (Ref. 24) were used instead of the value from this work.

become rather large for such a case, the observed agreement is reassuring and implies that the code ORACLE applies these corrections in a realistic and correct manner.

From the data in the last column of Table I it is evident that, as the nuclear spin increases, the degree of deviation from purely rotational behavior increases. This is not a surprising pattern of behavior for 90-neutron nuclei which are generally described as "soft" rotors. As already pointed out, these soft nuclei exhibit the effects of considerable mixing of the wave functions of the ground-state band and the vibrational bands. The degree of this mixing is expressed in Eq. (1) by the parameter α which can be evaluated as shown in Fig. 3 from the slope of the fitted line while $B_0(E2)$, the rigid rotor value, can be obtained from the intercept. A weighted least squares fit to these data indicates a value for α of $(2.6 \pm 0.5) \times 10^{-3}$ and $B_0(E2) = 0.542 \pm 0.008$ $e^2 b^2$. It is interesting to note that this value of α is nearly identical to values of this mixing parameter determined[2] for the other $N = 90$ isotones ^{152}Sm and ^{154}Gd.

It has been shown[2,25] that the mixing contribution from the β vibration to the ground-state band is most dominant in this region. The contribution of β- and γ-vibrational modes to α can be estimated from the formulas[5]

$$\alpha = \alpha_0 + \alpha_2 , \qquad (3)$$

where α_0 and α_2 represent contributions from the β and γ vibrations, respectively, and

$$\alpha_0 = 2Z_0 \frac{B(E2; 0g \to 2\beta)_0}{B(E2; 0g \to 2g)_0} , \qquad (4)$$

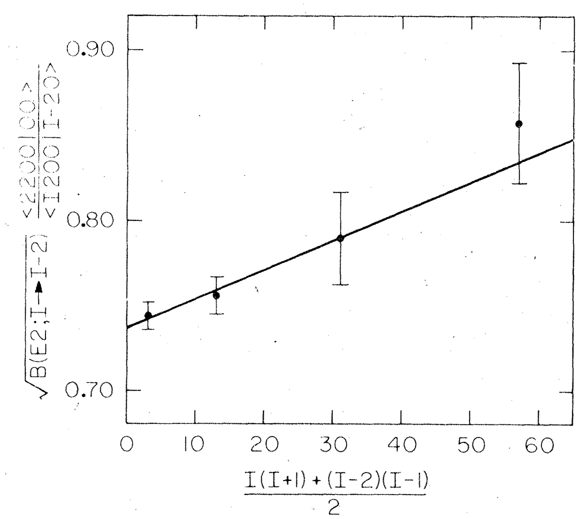

FIG. 3. Plot of $[B(E2; I \to I-2)]^{1/2}\langle 2200|00\rangle / \langle I200|I-20\rangle$ versus $\frac{1}{2}[I(I+1)+(I-2)(I-1)]$ for ^{150}Nd. The line is a weighted least squares fit to the data.

$$\alpha_2 = \tfrac{1}{6} Z_2 \frac{B(E2; 0g \to 2\gamma)_0}{B(E2; 0g \to 2g)_0} , \qquad (5)$$

where Z_0 and Z_2 are the usual mixing parameters[26,27] and the $B(E2)_0$ values are intrinsic (or unmixed) transition probabilities. The $B(E2)_0$ values to the β and γ bands were extracted[27] from the experimental values of Ahmed *et al.*[23] Using the experimental γ-ray branching ratios from our work and from Tripathi *et al.*,[16] Z_2 was calculated to be 0.078 ± 0.011 and $\alpha_2 = (0.43 \pm 0.07) \times 10^{-3}$. Unresolved γ-ray doublets in our spectra and in those of Tripathi *et al.*[16] do not allow us to accurately determine Z_0 from the γ-ray branching ratios; however, from Eq. (3), $\alpha_0 = (2.2 \pm 0.5) \times 10^{-3}$. Substituting this value of α_0 into Eq. (4), we obtain $Z_0 = 0.069 \pm 0.013$.

There are striking similarities between the properties of ^{150}Nd and the other $N = 90$ isotones ^{152}Sm and ^{154}Gd. The ground-band energy spacings are similar in these nuclei, while the β band is based at 675, 685, and 681 keV in ^{150}Nd, ^{152}Sm, and ^{154}Gd, respectively. The agreement between the Z_0 values[27,28] for these nuclei indicates that the extent of mixing of the ground-state band with the β band in these isotones is nearly identical. Our measurement of α in ^{150}Nd $[(2.6 \pm 0.5) \times 10^{-3})]$ is in excellent agreement with observations[2,28] in ^{152}Sm $[(2.1 \pm 0.6) \times 10^{-3}]$ and ^{154}Gd $[(2.6 \pm 1.0) \times 10^{-3}]$, and the enhancements of $B(E2)$ values for ground-band states are extremely similar to those reported[2] for ^{152}Sm and ^{154}Gd. Our measurements are of greater accuracy, however, and provide a better test of the applicability of the band-mixing model to these nuclei.

Deviations of the moment of inertia in the ground band of ^{150}Nd could also be attributed to centrifugal stretching,[6,7] and in this description the parameter α is obtained from the energy spacings of the ground band. From the energies of the 2^+ and 4^+ levels in ^{150}Nd a value of $\alpha = 8.2 \times 10^{-3}$ is calculated but, as observed[4,25] for ^{152}Sm and ^{154}Sm, a dramatically lower value is obtained if the spacings of higher levels are used. The implications of this behavior have been discussed by Diamond *et al.*,[4] and for the lower spin members of the ground band of ^{150}Nd the centrifugal stretching explanation must be considered to be incomplete.

In conclusion, it should be noted that the data as plotted in Fig. 3 are adequately fitted with a straight line. If, indeed, α has more than one component, more accurate measurements including states of higher spin where the deviations would be greater are necessary to observe such subtle effects.

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[1]M. W. Guidry, P. A. Butler, P. Colombani, I. Y. Lee, D. Ward, R. M. Diamond, F. S. Stephens, E. Eichler, N. R. Johnson, and R. Sturm, Nucl. Phys. A266, 228 (1976).

[2]N. Rud, G. T. Ewan, A. Christy, D. Ward, R. L. Graham, and J. S. Geiger, Nucl. Phys. A191, 545 (1972).

[3]R. M. Diamond, F. S. Stephens, K. Nakai, and R. Nordhagen, Phys. Rev. C 3, 344 (1971).

[4]R. M. Diamond, G. D. Symons, J. L. Quebert, K. H. Maier, J. R. Leigh, and F. S. Stephens, Nucl. Phys. A184, 481 (1972).

[5]G. D. Symons and A. C. Douglas, Phys. Lett. 24B, 11 (1967).

[6]R. M. Diamond, F. S. Stephens, and W. J. Swiatecki, Phys. Lett. 11, 315 (1964).

[7]A. S. Davydov and A. A. Chaban, Nucl. Phys. 20, 499 (1960).

[8]B. R. Mottelson and J. G. Valatin, Phys. Rev. Lett. 5, 511 (1960).

[9]S. M. Harris, Phys. Rev. 138, B509 (1965).

[10]I. Fraser and J. S. Greenberg, private communication reported in Ref. 11.

[11]C. M. Baglin, Nucl. Data B18, 223 (1976).

[12]T. E. Ward, N. A. Morcos, and P. K. Kuroda, Phys. Rev. C 2, 2410 (1970).

[13]S. W. Yates and A. J. Filo (unpublished).

[14]N. R. Johnson, R. J. Sturm, E. Eichler, M. W. Guidry, G. D. O'Kelley, R. O. Sayer, D. C. Hensley, N. C. Singhal, and J. H. Hamilton, Phys. Rev. C 12, 1927 (1975).

[15]R. J. Sturm and M. W. Guidry, Nucl. Instrum. Methods 138, 345 (1976).

[16]S. N. Tripathi, M. C. Schell, D. F. Coope, and M. T. McEllistrem, Bull. Am. Phys. Soc. 22, 614 (1977).

[17]A. Winther and J. de Boer, in *Coulomb Excitation*, edited by K. Alder and A. Winther (Academic, New York, 1966), p. 303.

[18]A. Abragam and R. V. Pound, Phys. Rev. 92, 943 (1953).

[19]D. Ward, H. R. Andrews, R. L. Graham, J. S. Geiger, and N. Rud, Nucl. Phys. A234, 94 (1974).

[20]M. W. Guidry (private communication).

[21]R. S. Hager and E. C. Seltzer, Nucl. Data A4, 397 (1968).

[22]O. Dragoun, Z. Plajner, and F. Schmultzler, Nucl. Data A9, 119 (1971).

[23]A. Ahmed, R. M. Ronningen, A. V. Ramayya, R. B. Piercey, H. Kawakami, C. F. Maguire, and J. H. Hamilton, Bull. Am. Phys. Soc. 22, 614 (1977).

[24]A. Shaw, as reported in Ref. 10.

[25]J. M. Domingos, G. D. Symons, and A. C. Douglas, Phys. Rev. C 10, 250 (1974).

[26]O. Nathan and S. G. Nilsson, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), p. 601.

[27]L. L. Riedinger, N. R. Johnson, and J. H. Hamilton, Phys. Rev. 179, 1214 (1969).

[28]N. Rud, H. L. Nielsen, and K. Wilsky, Nucl. Phys. A167, 401 (1971).