Lifetimes of states in the transitional nucleus ^{152}Gd

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The lifetimes of states in ^{152}Gd have been measured by the Doppler-shift recoil-distance technique. Half-lives determined for the 2^+, 4^+, 6^+, $2^{+\prime}$, and $0^{+\prime}$ states are 34.2 ± 1.5, 7.3 ± 0.4, 2.5 ± 0.5, 7.3 ± 0.6, and 37 ± 8 ps, respectively. These states were Coulomb excited with 147-MeV ^{40}Ar ions and measurements were performed in coincidence with the backscattered projectiles. Comparisons of the experimental values with calculations from the rotational, vibrational, dynamic deformation, boson expansion, and interacting boson models show that the predictions of the latter two theories provide a reasonable overall description of this nucleus, but there are some discrepancies in interband transition strengths. In the course of this work the half-life of the 6^+ state of ^{156}Gd was also redetermined as 16.7 ± 0.6 ps.

[NUCLEAR REACTIONS ^{152}Gd(^{40}Ar,^{40}Ar$'$,γ), $E=147.2$ MeV; measured lifetimes of 2^+, 4^+, 6^+, $2^{+\prime}$, and $0^{+\prime}$ states; deduced $B(E2)$ values, compared with theory.]

I. INTRODUCTION

Recently we completed a rather extensive Coulomb excitation study[1] with xenon projectiles on the even mass nuclei $^{152-160}$Gd. The objective was to trace systematically their level properties in the transition from the spherical-like member ^{152}Gd to the well-behaved rotational members ^{156}Gd and heavier. While the Coulomb excitation yields for the three heavier gadolinium isotopes were well accounted for by the use of rotational matrix elements, it was necessary to make some adjustments in the higher state elements for ^{154}Gd to fit the experimental data. This was expected since this nucleus, lying just at the onset of strong deformation (90 neutrons), has a somewhat β-soft potential and therefore is susceptible to effects such as centrifugal stretching, Coriolis antipairing, and band mixing.[2–6]

As anticipated for the yrast sequence in ^{152}Gd, the Coulomb excitation yields, calculated with the Winther-deBoer[7] program and rotational matrix elements, are in very poor agreement with the experimental yields. Even at the $6\to4$ transition the discrepancy was already more than 30 percent. Matrix elements calculated with boson models gave better fits[1]; but there was an obvious need for a direct experimental determination of ^{152}Gd matrix elements. Accordingly, we carried out the lifetime experiments described in this paper and, since only thin targets of ^{152}Gd were available, we resorted to the Doppler-shift recoil-distance technique.

II. EXPERIMENTAL RESULTS AND DATA ANALYSES

A detailed description of the recoil distance method, apparatus, and data analysis techniques is given[8–10] elsewhere. States in ^{152}Gd were Coulomb excited with a beam of 147.2-MeV ^{40}Ar ions from the Oak Ridge Isochronous cyclotron. The ^{40}Ar beam was focused through a 2.7-mm diameter tantalum collimator and a concentric annular silicon surface barrier detector onto the tightly stretched target foil. To decrease background radiation, the face of the tantalum collimator was covered with 30-mg/cm^2 lead foil. Backscattered ^{40}Ar ions were detected in the annular silicon detector which subtended an angle of 159° to 175° (average scattering angle of 165°). A 1.77-mg/cm^2 gold foil was placed over the face of this detector to prevent secondary electrons from striking it. A Ge(Li) detector with an efficiency of 16%, relative to that of a 7.6×7.6-cm NaI detector for 1332 keV at 25 cm, was located at 0° with respect to the beam direction and at a distance of 5.6 cm from the target. The resolution of this detector for 1332-keV γ rays was 1.9 keV (FWHM).

The movable stopper of the Doppler-shift apparatus consisted of a 40-μm layer of lead evaporated onto a thick copper end plate lapped to a surface finish tolerance of ~ 3 μm. Pulse height information from the time-to-amplitude converter, the γ-ray detector, and the heavy-ion detector were stored in event-by-event mode on magnetic tape.

The ^{152}Gd target used in these measurements was enriched to 42.8% in the desired mass. Although this represents more than a 200-fold improvement over the normal abundance of the mass 152, it leaves sizable abundances of the other stable gadolinium isotopes which give rise to numerous interfering lines in the γ-ray spectrum. However, by using a thin metallic target (1.09 mg/cm^2) and a high quality Ge(Li) detector, it was possible to resolve all of the ^{152}Gd lines from other ones which were significantly produced by the ^{40}Ar ions.

Data were first accumulated at six target-stopper separations ranging from 34 μm to 0.78 mm. In a final measurement, we brought the target and stopper into electrical contact, and this represented our minimum distance measurement. From the energy differences between shifted and unshifted γ-ray peaks in these spectra, we extract a value of $(0.03381 \pm 0.00007)c$ for the velocity of the recoiling ^{152}Gd nuclei. This computation is based on the expression of Quebert *et al.*[11]

To illustrate the experimental data, we show in Fig. 1 a portion of the γ-ray spectrum for four of the seven distances employed in the measurements. These show the shifted and unshifted γ-ray peaks for the $2^+ \to 0^+$ and $4^+ \to 2^+$ transitions in ^{152}Gd, as well as those for the $6^+ \to 4^+$ transition in ^{156}Gd. The latter served as a good internal calibration of our accuracy since the half-life of this transition had previously been determined[12,22] to high accuracy. An examination of the width of the shifted component (relative to the unshifted line) for each transition confirms that there is little spread in the velocities of the recoiling ions. Both the small angle for detecting the backscattered projectiles and the thin target contribute to this minimal spread.

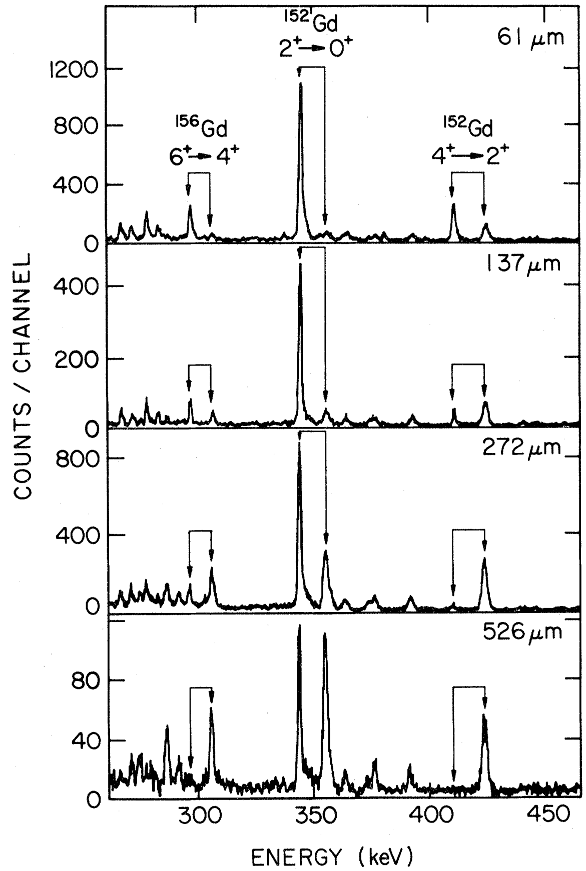

FIG. 1. Spectra of shifted and unshifted γ rays for the $2^+ \to 0^+$ and $4^+ \to 2^+$ transitions in ^{152}Gd and for the $6^+ \to 4^+$ transition in ^{156}Gd taken at four of the target-stopper separations.

The intensities of the shifted (I_s) and unshifted (I_u) peaks, corrected for the effects mentioned below, are related exponentially to the half-life, $t_{1/2}$, of the state by

$$\frac{I_u}{I_u + I_s} = \exp\left[\frac{D \ln 2}{\bar{v} t_{1/2}}\right], \tag{1}$$

where $\bar{v}$ is the average recoil velocity of the target nuclei along the detector axis and D is the target-stopper distance. In the data analysis several corrections were applied by the methods described in Refs. 8–10. These corrections, which have been incorporated into the computer code ORACLE by Sturm and Guidry,[10] were 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 were then obtained from ORACLE, which applies these corrections in an iterative procedure. For a given state, the slope of the corrected ratio $I_u/(I_u+I_s)$ vs D yields its half-life.

In Fig. 2 the ratio I_u/I_u+I_s is shown as a function of the target-stopper separation for the lowest-lying 2^+, 4^+, and 6^+ states of ^{152}Gd. These data and the assigned half-lives for the states reflect all of the corrections introduced in the analysis program. Although not shown on this plot, lifetime information was also obtained for the $2^{+\prime}\rightarrow 2^+$ and $0^{+\prime}\rightarrow 2^+$ transitions in ^{152}Gd as well as for the $6^+\rightarrow 4^+$ transition in ^{156}Gd.

The angular distribution information used in the half-life calculations was obtained from the semiclassical Winther-deBoer coupled equations computer code.[7] An exponential relaxation[13] was assumed as a reasonable approximation for the loss of alignment of the nuclear state. In light of the work of Ward *et al.*,[14] we have adopted values of 25 and 8 ps for the spin-dependent relaxation constants τ_2 and τ_4, respectively, for the final calculations. Other values of τ_2 (with $\tau_4=\frac{1}{3}\tau_2$), within a reasonable range of 20 to 40 ps, were also tried and the maximum deviation introduced to the lifetimes for the data in Fig. 2 was 3%.

III. DISCUSSION

In Table I we show the half-lives and corresponding $B(E2)$ values determined in this work for transitions in ^{152}Gd. The internal conversion coefficients of Rösel *et al.*[15] were used in computing the experimental $B(E2)$ values. Error limits assigned to the half-life and $B(E2)$ values represent both statistical and systematic contributions, including such effects as the range of reasonable relaxation constants used in the alignment attenuation corrections.

The statistical quality of the data for the $0^{+\prime}\rightarrow 2^+$ transition was not adequate for an accurate lifetime determination by the standard analysis as applied to the other transitions. However, by summing the data from all the different target-stopper distances, it was possible to obtain well-resolved shifted and unshifted γ-ray peaks and thus, to extract a meaningful lifetime for this transition ($t_{1/2}=37\pm 8$ ps). Such methods have been used before and a description has been given by Kennedy, Stuchbery, and Bolotin.[20] Until the present measurement, only limits of $0.02\leq t_{1/2}\leq 0.21$ ns had been set[21] for this transition in delayed coincidence experiments.

The gadolinium target used in our measurements contained 15% mass 156. As a consequence, we ob-

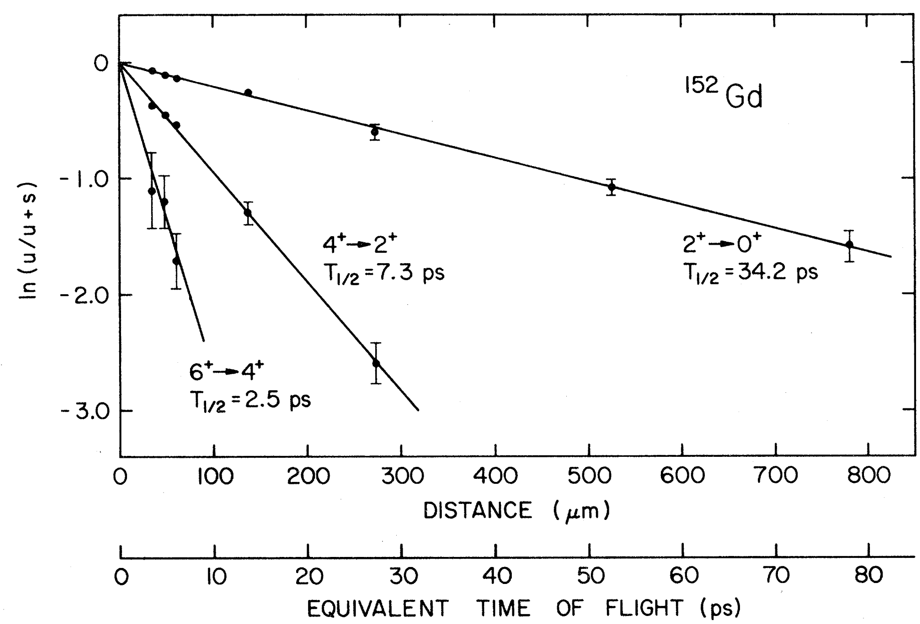

FIG. 2. Plots of ratios of unshifted to the sum of unshifted-plus-shifted γ ray intensities as a function of target-stopper separation for ground-band members of ^{152}Gd excited in the present experiments.

TABLE I. Half-life and $B(E2)$ values for transitions in ^{152}Gd.

Transition $J_i \to J_f$	E_γ[a] (keV)	$t_{1/2}(J_i)$ (ps)	$B(E2)$ (e^2b^2)
$2^+ \to 0^+$	344.3	34.2 ± 1.5[b]	0.33 ± 0.02
$4^+ \to 2^+$	411.1	7.3 ± 0.4	0.64 ± 0.04
$6^+ \to 4^+$	471.9	2.5 ± 0.5	0.95 ± 0.19
$2^{+\prime} \to 2^+$	586.3	7.3 ± 0.6	0.077 ± 0.006[c]
$0^{+\prime} \to 2^+$	271.1	37 ± 8[d,e]	0.85 ± 0.19[f]

[a]Gamma-ray energies are those from the Nuclear Data Sheets (Ref. 16). The values from the present experiments are 344.3, 411.0, 471.5, 586.3, and 271.0 keV.
[b]Previously reported values for the 2^+ state: 28.6 ± 1.9 ps by Coulomb excitation (Ref. 17); 37 ± 7 ps by delayed coincidence techniques (Ref. 18); 53 ± 9 ps by delayed coincidence techniques (Ref. 19).
[c]Assumes the branching ratio in Nuclear Data Sheets (Ref. 16), and takes into account the $M1+E0$ admixtures.
[d]Obtained by summed spectra method (see Ref. 20).
[e]Previous value: $0.02 \le t_{1/2} \le 0.21$ ns by delayed coincidence techniques (Ref. 21).
[f]Assumes the branching ratio in Nuclear Data Sheets (Ref. 16) for the $E0$ branch.

tained some lifetime data on this nucleus. The range of target-stopper distances covered provided an excellent lifetime check on the $6^+ \to 4^+$ transition, yielding a value of 16.7 ± 0.6 ps. This is in good agreement with previously determined values of 15.8 ± 0.4 ps (Ref. 12) and 17.6 ± 2.4 ps (Ref. 22).

In Table II we have compared the $B(E2)$ values for the transitions from the 2^+, 4^+, 6^+, $2^{+\prime}$, and $0^{+\prime}$ states in ^{152}Gd with the predictions of the rotational model,[23,24] vibrational model,[25] the boson expansion theory (BET),[26] the interacting boson approximation (IBA),[27] and the dynamic deformation theory (DDT).[28] In these comparisons, we used our present data for the $2^+ \to 0^+$ and $2^{+\prime} \to 0^{+\prime}$ transitions as the normalization. For the $2^{+\prime}$ state we also made use of the branching ratios and mixing ratios given in Ref. 16 and the recent work of Zolnowski, Hughes, Hunt, and Sugihara.[29]

Since ^{152}Gd is two neutrons removed from the onset of strong permanent deformation at 90 neutrons, it is not surprising that experimental $B(E2)$ values for the $4^+ \to 2^+$ and $6^+ \to 4^+$ transitions differ significantly from rotational predictions. This is in agreement with our[1] Coulomb excitation yields using ^{136}Xe projectiles. Both the BET and IBA predict $B(E2)$ values in agreement with our experimental results for these two transitions, although the well-known loss of $B(E2)$ strength in high spin states for these models appears to be setting in at the $6 \to 4$ transition. Although the vibrational model correctly predicts the $4^+ \to 2^+$ and $6^+ \to 4^+$ transitions, we observe significant strengths for such transitions as the $2^{+\prime} \to 0^{+\prime}$ and $2^{+\prime} \to 0^+$ and these are strictly forbidden in the harmonic approximation.

A point of interest is that the boson expansion model overpredicts the size of the $B(E2)$ for the $2^{+\prime} \to 2^+$ transition by about a factor of 4. This is the same situation we[30] observed recently for the nucleus ^{110}Pd. There we found that both boson models overpredict the strength of this transition as

TABLE II. Comparison of ^{152}Gd transition probabilities with theoretical values.

Transition	E_γ (keV)	$B(E2)_{exp}$ (e^2b^2)	$B(E2)_{exp}/B(E2)_{theory}$ Rotor[a]	BET[b]	IBA[c]	DDT[d]	Vib[e]
$2^+ \to 0^+$	344.3	0.33 ± 0.02	(1.00)	(1.00)	(1.00)	(1.00)	(1.00)
$4^+ \to 2^+$	411.1	0.64 ± 0.04	1.36 ± 0.06	0.98 ± 0.06	1.03 ± 0.06	0.93 ± 0.06	0.97 ± 0.06
$6^+ \to 4^+$	471.9	0.95 ± 0.19	1.83 ± 0.37	1.25 ± 0.25	1.25 ± 0.25		0.96 ± 0.20
$2^{+\prime} \to 0^{+\prime}$	315.2	0.21 ± 0.02			(1.00)		f
$2^{+\prime} \to 2^+$	586.3	0.077 ± 0.006		0.27 ± 0.03	0.47 ± 0.04	12.4 ± 1.4[g]	0.12 ± 0.01
$2^{+\prime} \to 0^+$	930.6	0.0014 ± 0.0002			0.053 ± 0.007	0.15 ± 0.02	f
$2^{+\prime} \to 4^+$	175.0	0.173 ± 0.022			1.59 ± 0.21		f
$0^{+\prime} \to 2^+$	271.1	0.85 ± 0.19		2.36 ± 0.40	1.36 ± 0.30	1.15 ± 0.26	1.29 ± 0.28

[a]Rotational model (Refs. 23 and 24).
[b]Boson expansion theory (Ref. 26).
[c]Interacting boson approximation (Ref. 27).
[d]Dynamic deformation theory (Ref. 28).
[e]Vibrational model (Ref. 25).
[f]This transition is strictly forbidden in the harmonic vibrator picture.
[g]See text for explanation of this value.

well as the $0^{+\prime}\rightarrow 2^{+}$ by similarly large factors. For the $0^{+\prime}\rightarrow 2^{+}$ transition in ^{152}Gd, however, the boson expansion model underpredicts the strength by more than a factor of 2. Taken together, the data presented here and in Ref. 30 suggest that both the BET and IBA give a qualitative reproduction of the transitions between low-spin states in transitional nuclei. However, some discrepancies are seen for interband matrix elements. It is not clear how much significance should be attached to these discrepancies. On one hand, these discrepancies involve small matrix elements and are sensitive to small changes in wave functions. On the other hand, there are several adjustable parameters in the calculations and not so many data points. In addition, there is a suggestion here, as well as in Ref. 30, that the finite dimensionality of the boson space leads to truncation effects in the calculations for the highest spins which are not present in the data. This is not surprising, by analogy to more rotational nuclei where the boson models seriously underpredict the high-spin $B(E2)$ strength due to unphysical truncation of the model space.

In column 7 of Table II, we show the comparison of experiment with the dynamic deformation theory calculations of Kumar and Gupta.[28] They did not calculate the $B(E2)$ for the $2^{+\prime}\rightarrow 2^{+}$ transition, but we have utilized Kumar's calculations[31] in ^{150}Sm (also an 88-neutron nucleus) where the $B(E2;2^{+\prime}\rightarrow 0^{+})$ and $B(E2;2^{+\prime}\rightarrow 2^{+})$ are given and their ratio is 1.45. By assuming this ratio is the same in ^{152}Gd, the value of

$$B(E2;2^{+\prime}\rightarrow 2^{+})_{\rm exp}/B(E2;2^{+\prime}\rightarrow 2^{+})_{\rm theory}$$

is deduced as 12.4 ± 1.4.

We conclude that, given the parameter adjustment latitude in the theories discussed here, a systematic analysis of transitional nuclei such as the ^{152}Gd and the ^{108,110}Pd discussed in Ref. 30 will be required before definitive conclusions about detailed predictions of these theories can be drawn.

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