only weakly excited in the (d,p) reaction. However, the present data are again inconclusive, since weakly excited states are observed in both final nuclei (Ru^{105} and Ru^{103}). The only remaining prospect for deformation is that even with the present extensive data on levels in Ru^{105}, it appears that (in contrast to the situation in Ru^{103}) the γ rays observed in Ru^{105} following the decay of Tc^{105} cannot be fitted into a consistent level scheme.[3] This result may be not inconsistent with the recent (t,p) study[16] on Ru^{104}, which finds evidence that Ru^{106} has a transitional character between a vibrational and rotational nucleus.

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PHYSICAL REVIEW C VOLUME 3, NUMBER 1 JANUARY 1971

Lifetimes of Ground-Band States in $^{148,150,152}Sm$†

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The lifetimes of a number of ground-band states in $^{148,150,152}Sm$ have been measured by the recoil-distance Doppler-shift method following Coulomb excitation by backscattered ^{40}Ar projectiles. The measured $B(E2)$ values for ^{152}Sm are larger than the rigid-rotor values; in terms of the mixing or stretching parameter α the present experiments yield $\alpha = (+2.2 \pm 0.7) \times 10^{-3}$. For $^{148,150}Sm$ the measured $B(E2)$ values are near those expected for vibrational nuclei.

INTRODUCTION

The stable samarium isotopes are well suited for the testing of current nuclear models and ideas, as they span the region from vibrators to rotors, and include soft nuclei as well as rigid ones. Much of the information on the nature of the ground band has come from studies of the energy-level spacings. The lifetimes, or $B(E2)$ values, of the excited states in the ground band constitute another source of information on the changes occuring in these levels as the spin increases.

The recoil-distance Doppler-shift method,[1] when combined with high-resolution Ge detectors and heavy-ion beams, seems ideal for determining half-lives in the 10^{-9}–10^{-12}-sec range.[2-7] However, an earlier study involving recoils from $(^{40}Ar, 4n)$ reactions indicated that the accuracy obtained might be only barely sufficient to distinguish, for example, rigid rotors from soft rotors. It would clearly help to obtain spectra with better peak-to-background ratios and to achieve larger recoil velocities. In the present study, both of these effects are obtained by producing the recoiling nuclei by means of (multiple) Coulomb excitation with ^{40}Ar beams, rather than by compound-nucleus reactions.

EXPERIMENTAL METHOD

The deexcitation transitions from the Sm targets were observed by a Ge detector set at 0° to the beam direction and operated in coincidence with the backscattered ^{40}Ar projectiles observed in a Si ring counter (142–161°). Thus, multiple excitation of the higher-spin states was maximized and a collimated beam of Sm recoils was produced with a high velocity along the beam direction. These nuclei were stopped by a lead-covered plunger attached to a precision micrometer whose position could be adjusted to ±0.003 mm. The targets were ~1-mg/cm^2 metal foils of the separated isotope stretched tightly over a holder assembly. By observation with a microscope, they appeared to be flat and parallel to the plunger surface within ±0.01 mm.

The average recoil velocity in the beam direction, $v \cos\theta_0$, is obtained from the fractional energy difference of the Doppler-shifted and unshifted lines by solving the following expression for $\beta = v/c$:

$$\frac{\Delta E}{E_0} = \left(\frac{(1-\beta^2)^{1/2}}{\beta(1-\cos\theta_c)}\right) \ln\left(\frac{(\beta+1)(1-\cos\theta_0)}{\beta\cos\theta_c - \cos\theta_0 + [(\cos\theta_0 - \beta\cos\theta_c)^2 + (1-\beta^2)\sin^2\theta_0]^{1/2}}\right) - 1 ,$$

where θ_c is the half angle of the γ-ray detector and θ_0 is the angle between the recoiling nucleus and the axis of that counter. Since all targets were nearly the same thickness, they all gave nearly the same average recoil velocity along the beam direction, namely, ~3.4% that of light.

RESULTS

Some typical spectra for ^{152}Sm are shown in Fig. 1. We have integrated the areas under the shifted and unshifted peaks, and corrected for the small change in solid angle of the Ge counter for both shifted and unshifted transitions due to the change in position of the lead plunger. An estimate was made for the effect of dispersion in the recoil velocity on the fractions of unshifted intensity. This was done by assuming that the extra width of the shifted peak relative to the unshifted one came from this source.[6] Since in the worst case the estimated error to the fraction was <1% and the effect on the half-life determination was still smaller, this effect was neglected. Small corrections were made for the differences in Ge-detector efficiency between the shifted and unshifted peaks and in effective solid angle for the shifted transitions with respect to the unshifted ones due to the motion of the recoiling nuclei. In the present case these two effects are opposite in sign and tend to cancel, but the latter dominated and leads to a net reduction of 3–4% in the intensities of the shifted transitions.

For ^{152}Sm the fraction of each transition which is unshifted is plotted in Fig. 2 versus the distance from the target. The solid lines are the calculated best fits from a computer program which allows feeding from one state higher than the one whose half-life is being determined. The amount of feeding was obtained both from the deBoer-Winther multiple-excitation program[8] and from the experimental yield of the next higher transition; these agreed within 20%, and the lifetime does not depend very critically on the value used. The calculated fit also took into account the angular distribution of the γ rays; the angular-distribution parameters A_k were evaluated from the deBoer-Winther program, again allowing for the calculated feeding from higher-lying levels. Finite-solid-angle corrections for the Ge counter were made from the tables of Black and Gruhle.[9] These angular-distribution results also had to be corrected for the attenuation caused by the interaction of the nuclear magnetic moment with the large hyperfine field arising from the unpaired electrons of the ionized product nucleus recoiling in vacuum.[10–12] Thus,

$$W(\theta, t) = 1 + A_2 Q_2 e^{-t/\tau_2} P_2(\cos\theta) + A_4 Q_4 e^{-t/\tau_4} P_4(\cos\theta) ,$$

where Q_2 and Q_4 are the finite-solid-angle coefficients, θ is the angle between the beam direction and the γ-ray detector, t is the time since the recoiling nucleus left the target, and τ_2 and τ_4 are measures of the hyperfine attenuation. Assuming a magnetic dipole interaction,[11] for which $\tau_4 = \frac{3}{10}\tau_2$, the value of τ_2 can be determined from a comparison of the angular distribution obtained from a thin self-supporting ^{152}Sm target and a lead-backed one (the latter yields an unattenuated distribution, i.e., is in agreement with that from the multiple-Coulomb-excitation program).

In Tables I and II we have listed the transitions studied, their energies in keV, the measured half-lives, values for the total conversion coefficients, and the values of $B(E2;\, I\to I-2)$ derived from the last two quantities. We believe that the systematic and instrumental errors in these measurements are small. The largest source of error in the determination of $T_{1/2}$, especially for the higher-lying transitions, is the statistical uncertainty in the peak integrations. To obtain the errors assigned to the half-life values in the tables, the 1% uncertainty in the recoil velocity and the small uncertainties due to errors in the half-life of, and feeding from, the preceding level and in the angular distribution and attenuation coefficients were combined with the statistical uncertainty in the integrations. In only one case, the $4^+\to 2^+$ transition in ^{148}Sm, did we observe interference from another line in the spectrum. In this case the $3^-\to 2^+$ transition has an energy only 19 keV less than that of the $4^+\to 2^+$ one, and so the shifted $E1$ line coincides with the unshifted $4^+\to 2^+$ component, contribution a tail of $\sim$8% to the latter. This has been subtracted, but necessarily there is a greater uncertainty in this particular result.

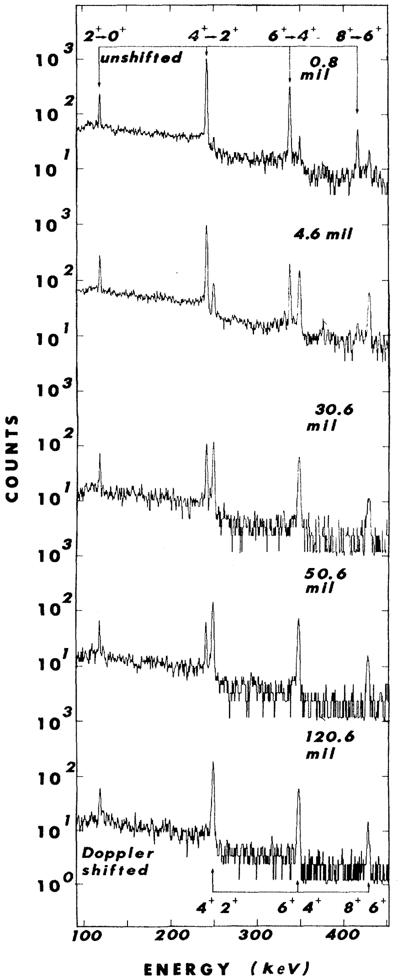

FIG. 1. Spectra from ^{152}Sm Coulomb-excited with backscattered ^{40}Ar projectiles. The lead plunger is set at the indicated distances from the target. The positions of the unshifted (shifted) lines are given at the top (bottom) of the figure.

In proceeding from the measured half-lives to $B(E2)$ values, the uncertainty (taken to be 2%) in the total conversion coefficients used introduces an additional error which is a maximum for the most highly converted transition, the $2^+\to 0^+$ in ^{152}Sm, and negligible for the highest-energy ones.

DISCUSSION

The $B(E2)$ values determined in this work are compared in Tables I and II with values calculated for the rigid rotor, or the harmonic oscillator, or the centrifugal-stretching model of Davydov and Ovcharenko,[13] all normalized to the experimental $B(E2;\, 2\to 0)$. The values for ^{148,150}Sm indicate nearly harmonic-oscillator behavior as is already suggested by their energy-level spacings. The magnitude of the $B(E2;\, 0\to 2)$ for ^{150}Sm, $(1.36\pm 0.05)\,e^2\times 10^{-48}$ cm^4, agrees reasonably well with other recent values 1.44 ± 0.15[14] and 1.29 ± 0.07,[15] although we find a somewhat larger value, 0.96 ± 0.07, for $B(E2;\, 4\to 2)$ than do the latter workers (0.82 ± 0.10). Our value for $B(E2;\, 0\to 2)$ for ^{148}Sm, $(0.76\pm 0.05)\,e^2\times 10^{-48}$ cm^4, is in agreement with two other values, namely, 0.79 ± 0.08[14] and 0.705 ± 0.025,[16] but in disagreement with a third, 0.65 ± 0.05.[15]

For ^{152}Sm the $2^+\to 0^+$ half-life was not measured in this work; the value listed in Table II is the average of two recent literature values[17,18] which are in excellent agreement. We believe that the

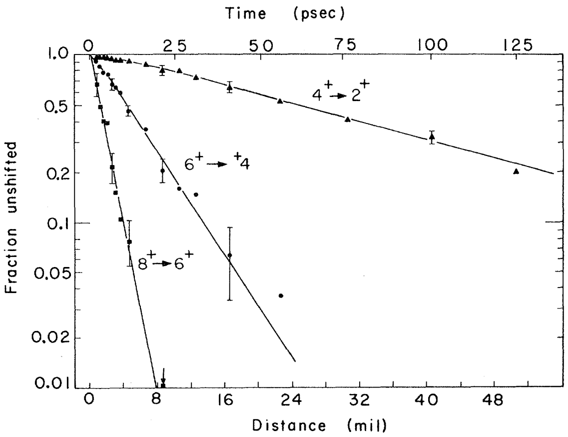

FIG. 2. The fraction of each transition in ^{152}Sm which is unshifted in energy vs the distance between target and plunger. The symbols are the experimental points; the lines are the calculated best fits allowing for one stage of feeding.

TABLE I. $B(E2)$ values for ^{150,148}Sm.

Nucleus	Transition	Energy (keV)	$T_{1/2}$ [a] (psec)	α_T [b]	$B(E2;\ I\to I-2)$ exp.	vib.
^{150}Sm	$2\to 0$	334.0	48.1 ± 1.7	0.041	0.272 ± 0.010	(0.272)
	$4\to 2$	439.4	6.35 ± 0.4	0.019	0.534 ± 0.04	0.544
^{148}Sm	$2\to 0$	550.5	7.33 ± 0.4	0.010	0.151 ± 0.010	(0.151)
	$4\to 2$	630	$2.3\ \ \pm 0.6$	0.0072	$0.25\ \ \pm 0.07$	0.302

[a] The values of $v\cos\theta_0$ found for the recoiling ^{150}Sm and ^{148}Sm nuclei were $(0.0339\pm 0.0004)c$ and $(0.0341\pm 0.004)c$, respectively.

[b] From calculations by R. S. Hager and E. C. Seltzer, California Institute of Technology Report No. CALT-63-60, 1967 (unpublished).

three ^{152}Sm $B(E2)$ values determined in this study are more accurate than an older result, $B(E2;\ 4^+\to 2^+)=(0.76\pm 0.15)\ e^2\text{b}^2$,[19] and more accurate than three recent measurements (of which two do not explicitly give $B(E2)$ values[20,21]), and the third gives $B(E2;\ 4^+\to 2^+)=(1.08\pm 0.07)\ e^2\text{b}^2$, $B(E2;\ 6^+\to 4^+)=(1.14\pm 0.11)\ e^2\text{b}^2$,[22] as all of these other measurements are heavy-ion Coulomb-excitation experiments and involve certain problems mentioned below and discussed in greater detail elsewhere.[23]

The three $B(E2)$ values given in Table II are clearly larger than those expected for a rigid rotor. The remarkable fit to the values calculated by Davydov and Ovcharenko for $\mu=0.3$ and $\gamma=10°$ is probably somewhat fortuitous, as the values of μ obtained from the ratios of the ground-band transition energies in ^{152}Sm are not constant but range from 0.40–0.28, indicating deviations from that model.

If we consider the increase in the $B(E2)$ to be of the form

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

where $B_0(E2)$ is the rigid-rotor value, the ratio of any two measured $B(E2)$ values and the square of the corresponding Clebsch-Gordan coefficients yield a determination of the mixing or stretching parameter α. The present work gives $\alpha=(+2.2\pm 0.7)\times 10^{-3}$. This value for α can be related to the increase in deformation with spin (stretching) according to

$$\Delta\beta_I/\beta\approx\alpha I(I+1)\,.$$

The value of $\Delta\beta_2/\beta$ obtained from the present work, 13×10^{-3}, is in reasonable agreement with those obtained from Mössbauer[24,25] and μ-mesonic atom[26] measurements, 8×10^{-3}, although it is not clear that these experiments are determining exactly the same quantity. However, this agreement does lend support to the concept that β is increasing with spin in ^{152}Sm. We can also try to relate this increase in deformation with spin to the mixing of the β-vibrational and ground-state bands in ^{152}Sm and to deviations from the $I(I+1)$ rule in the ground-band energies.[27,28] However, the $E2$ branching ratios from the β-band states to the ground band are not entirely consistent with such a simple β-band mixing interpretation,[23,29-32] nor are the deviations of the ground-band energies. Thus we can only say that the range of values for the increase in deformation predicted from β-band–ground-band mixing as determined from the different known branching ratios overlaps the presently measured value, and that the deviations in the ground-band energy spacings appear to require

TABLE II. $B(E2)$ values for ^{152}Sm.

Transition	Energy (keV)	$T_{1/2}$ [a] (psec)	α_T [b]	$B(E2;\ I\to I-2)$ exp.	rotor	DO [c]
$2\to 0$	121.78	1447 ± 26 [d]	1.179	0.670 ± 0.015	(0.670)	(0.670)
$4\to 2$	244.6	58.9 ± 1.8	0.109	0.989 ± 0.035	0.958	1.012
$6\to 4$	340.2	9.98 ± 0.48	0.038	1.20 ± 0.06	1.056	1.193
$8\to 6$	418.7	3.10 ± 0.30	0.021	1.39 ± 0.14	1.106	1.373

[a] The value of $v\cos\theta_0$ for the recoiling nuclei was $(0.0338\pm 0.004)c$.

[b] From calculations by H.-Chr. Pauli, private communication to J. deBoer.

[c] These values have been taken from the calculations of Davydov and Ovcharenko, Ref. 13, for $\mu=0.3$ and $\gamma=10°$. See text.

[d] Average value from Refs. 17 and 18.

a 2–3 times larger increase.

This topic is treated in greater detail in another paper involving multiple-Coulomb-excitation studies of ^{152}Sm (Ref. 23). A partial explanation may come from the mixing in of still other excited bands, for example, the γ-vibrational band and the neutron and proton pairing vibrational bands (Coriolis antipairing) among others. It is interesting to note that although neutron and proton Coriolis-antipairing, centrifugal-stretching, and fourth-order-cranking corrections all can, and probably do, contribute to the ground-band energy deviations, a number of two-parameter expressions for the energy-level spacings, each based on only one of these effects, fit the experimental data very well. An explanation may lie in the generalized-cranking-model calculations of Ma and Rasmussen,[33] where they show that under certain assumptions a more generalized expression incorporating several effects can be reduced to look like any one of the two-parameter expressions alone, but with the two parameters involved actually a function of the larger number of parameters of the original expression. They have not calculated the generalized corrections to the transition moments, and these may have a different dependence on the admixed bands than do the ground-band energy deviations. If so, comparison of the two types of measurements (and others, also) may allow unraveling of the relative importance of the various effects.

The present measurements show that application of the recoil-distance Doppler-shift method to nuclei recoiling from heavy-ion Coulomb excitation can give lifetimes of quasirotational ground-band levels with enough precision to differentiate among nuclear models for this band. This method compares very favorably with the conventional heavy-ion multiple-Coulomb-excitation method based on yield measurements and, most importantly, is subject to fewer uncertainties. In the latter case, a desired $B(E2)$ value (lifetime) may be significantly affected by (1) other $B(E2)$ values in the band, (2) higher multipole moments of the nucleus, (3) static moments, and (4) the excitation of other coupled states or bands. In many Coulomb-excitation yield experiments sufficient information is not available to make all these corrections unambiguously. With the present method none of these affect the result, apart from a small correction (which may be empirically made) due to feeding from higher states.

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PHYSICAL REVIEW C VOLUME 3, NUMBER 1 JANUARY 1971

^{210}Pb$(p, d)^{209}$Pb Reaction at 20.6 MeV*

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The ^{210}Pb$(p, d)^{209}$Pb reaction has been studied at an energy of 20.6 MeV in the angular range 13–70°. The objectives of the work were twofold. First, the fragmentation of the two-particle–one-hole $\nu_{0^+}{}^2\,\nu_{nlj}{}^{-1}$ strength up to an excitation in ^{209}Pb of 5.3 MeV was investigated and compared with the corresponding $\nu_{nlj}{}^{-1}$ strength in ^{207}Pb as reported in a recent study of the ^{208}Pb(p, d) reaction at 20 and 22 MeV. Second, the microscopic structure of the valence neutrons $\nu_{0^+}{}^2$ in the ground state of ^{210}Pb was investigated by measuring the spectroscopic factors for pickup to the six low-lying neutron single-particle states in ^{209}Pb.

1. INTRODUCTION

The neutron single-particle strengths in ^{209}Pb and the neutron single-hole strengths[1] in ^{207}Pb have been measured recently. The conclusion which comes from an over-all assessment of these data is that, with the exception of the $\frac{15}{2}^-$ level at 1428 keV[2-4] in ^{209}Pb, the relative values of the spectroscopic factors agree within ±20% with the shell-model predictions. The $1j_{15/2}$ strength is fragmented, as would be expected in view of the probable proximity of the unperturbed positions of the $1j_{15/2}$ state and the $2g_{9/2}\times 3^-$ multiplet. The $2g_{9/2}\times 3^-$ multiplet arises due to the coupling of the 3^- state of the ^{208}Pb core and the $2g_{9/2}$ single-particle orbit.

It is of great interest to investigate the next level of complexity in ^{209}Pb, namely, the 2p-1h states arising from the coupling between the valence neutron configuration in ^{210}Pb(0) and the neutron-hole excitations as observed in ^{207}Pb. The ^{210}Pb(p,d)-^{209}Pb reaction is particularly useful since it specifically excites states of this character. It is a principal objective of this work to locate states containing components with this configuration. Some of these results have been previously reported.[5] The present paper gives a more complete analysis of the data.

2. EXPERIMENTAL PROCEDURE

The measurements were carried out at the Los