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Lifetimes and electromagnetic decay properties of negative-parity states in ^{150,152,154}Sm from $(n, n'\gamma)$ measurements

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The Doppler shifts of γ rays following the decay of the 1_1^- and 3_1^- states in ^{150,152,154}Sm excited by inelastic scattering of 1.3 MeV neutrons from natural Sm_2O_3 have been measured. With the Winterbon theory to describe the slowing down process of the recoiling atoms in the bulk of the target material, nuclear lifetimes could be extracted from these data. These measured lifetimes are compared to the results of a recent investigation with the gamma-ray induced Doppler (GRID) broadening technique and have been used to clarify problems associated with the incomplete knowledge of the feeding pattern in heavy nuclei inherent in the GRID method. The large $E1$ transition rates in ^{152}Sm obtained in the previous study are confirmed; the $B(E1)$ systematics has been extended to ^{154}Sm and is interpreted within the framework of the interacting boson model.

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I. INTRODUCTION

In a recent study of lifetimes in the transitional $N = 86$–90 even-mass Sm isotopes using the gamma-ray induced Doppler (GRID) broadening method following thermal neutron capture, large $E1$ transition rates for the decay of the lowest-lying 1^- and 3^- states in ^{152}Sm were obtained. As discussed in detail by Jungclaus *et al.* [1], the principal ambiguity inherent in the analysis of GRID data in heavy nuclei is associated with the lack of knowledge of the feeding into the state under investigation. By an appropriate choice of the neutron energy, inelastic neutron scattering (INS) offers the possibility of avoiding problems from unknown feeding; i.e., the nuclei are populated just above the level under study. Therefore, we performed a Doppler-shift attenuation method (DSAM) measurement following INS [2] of the same states in order to confirm the obtained GRID lifetimes, to extend the systematics to ^{154}Sm, and to understand better the different feeding scenarios employed in [1].

II. EXPERIMENT AND ANALYSIS

The experiments were performed with the 7 MV Van de Graaff accelerator at the University of Kentucky where fast monoenergetic neutrons produced by the ^{3}H$(p,n)^3$He reaction with an energy of 1.3 MeV were scattered from a sample consisting of 33.7 g of Sm_2O_3 powder of natural composition. The γ rays from the $(n,n'\gamma)$ reaction were detected in a Compton-suppressed 51% n-type coaxial HPGe detector which was placed about 1 m from the sample. Time-of-flight suppression

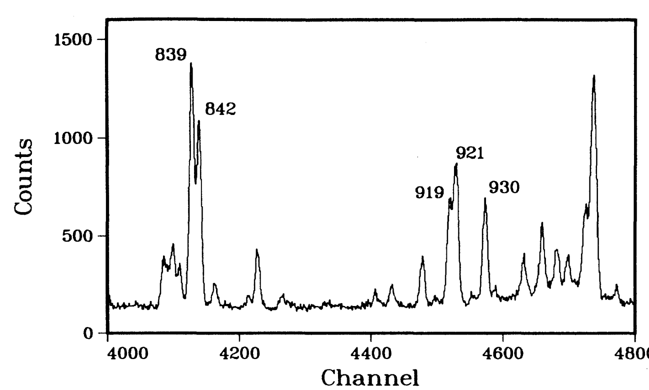

FIG. 1. A portion of the γ-ray spectrum measured following the inelastic scattering of 1.3 MeV neutrons from a Sm_2O_3 sample of natural abundance. The angle of measurement was 144°, and peaks for which Doppler shifts have been determined (see Table I) are labeled with energies in keV.

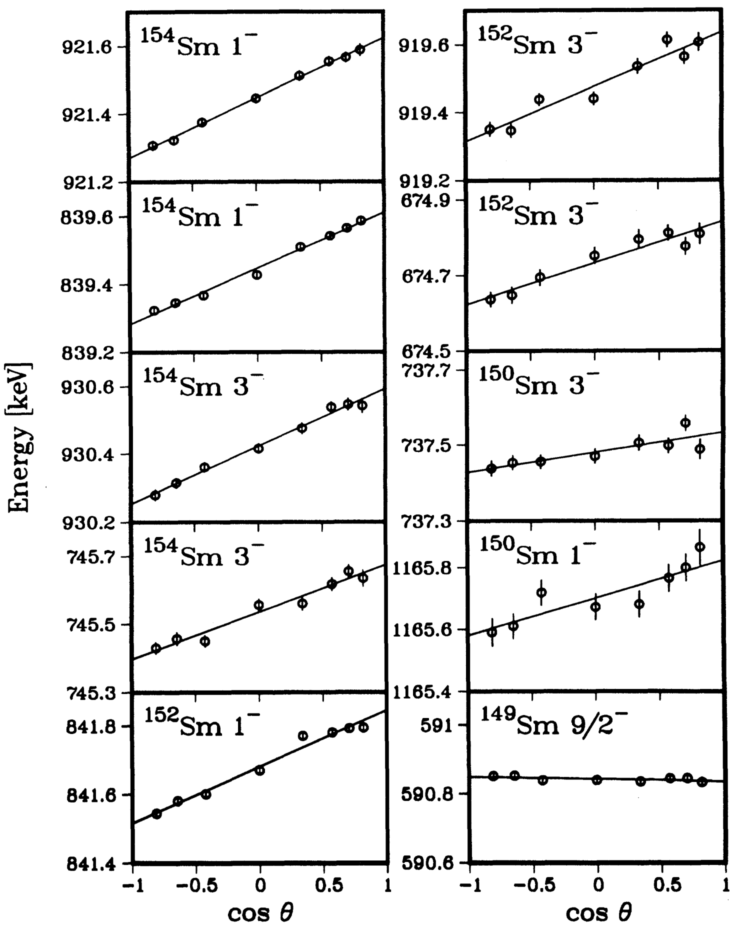

FIG. 2. Gamma-ray energy versus cosΘ plots for γ rays in Sm nuclei. Initial spins are indicated for the appropriate nuclei. For comparison, a peak in ^{149}Sm which does not exhibit a Doppler shift (τ=3 ps) is shown in the lowest right frame.

was used to further reduce the background, and radioactive ^{133}Ba, ^{60}Co, and ^{137}Cs sources were present near the detector during the measurements to provide internal energy calibration. Spectra were accumulated at eight angles, with 35° and 144° as the extremes, with respect to the incident neutrons in order to obtain the Doppler shifts for the γ rays deexciting the 1_1^- and 3_1^- states in ^{150,152,154}Sm. A very careful and consistent analysis of the spectra was crucial for the precise determination of the peak centroids, since the expected maximal Doppler shift is very small in heavy nuclei (about 300 eV for E_n=1.3 MeV), and many of the transitions of interest are

TABLE I. Lifetimes of 1_1^- and 3_1^- states in selected even-*A* Sm nuclei. The present DSAM-INS results are compared with previous GRID [1] and NRF [6] values.

Nucleus	E_x (keV)	I^π	E_γ (keV)	DSAM-INS τ (fs)	DSAM-INS $\tau_{\rm adop}$ (fs)	GRID[a] $\tau_{\rm CTF}$ (fs)	GRID[a] $\tau_{\rm Bethe}$ (fs)	GRID[a] $\tau_{\rm min}$ (fs)	GRID[a] $\tau_{\rm max}$ (fs)	NRF[b] $\tau_{\rm NRF}$ (fs)
^{148}Sm	1161	3_1^-	611			775^{+530}_{-240}	880^{+605}_{-270}	275^{+370}_{-130}	1270^{+795}_{-365}	-
^{150}Sm	1165	1_1^-	1165	84^{+37}_{-23}	84^{+37}_{-23}					68^{+7}_{-6}
			832			195^{+20}_{-15}	185^{+20}_{-15}	60(15)	235(20)	
	1071	3_1^-	737	155^{+185}_{-75}	155^{+185}_{-75}	420(25)	415^{+25}_{-20}	330(20)	650^{+40}_{-35}	-
^{152}Sm	963	1_1^-	842	29(4)	29(4)	71^{+18}_{-14}	28^{+12}_{-9}	-	285^{+50}_{-40}	39(4)
	1041	3_1^-	919	36^{+10}_{-8}	39(7)	48^{+11}_{-9}	11^{+7}_{-5}	-	283^{+35}_{-30}	-
			675	42^{+11}_{-9}						
^{154}Sm	921	1_1^-	921	30^{+4}_{-3}	29(2)					38(6)
			839	29^{+3}_{-2}						
	1013	3_1^-	930	34^{+5}_{-4}	33(4)					
			745	32^{+7}_{-6}						

[a]From Ref. [1].
[b]From Ref. [6].

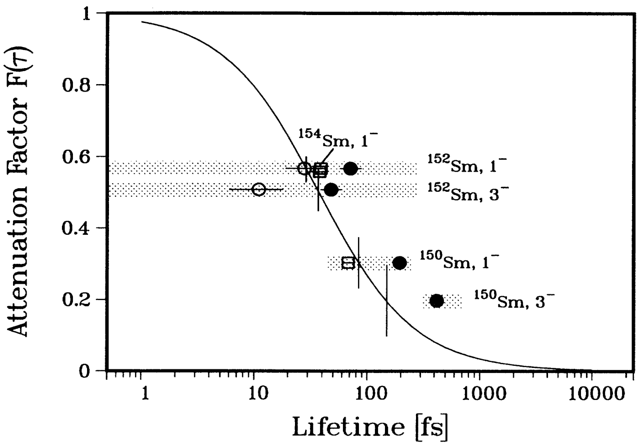

FIG. 3. Theoretical Doppler-shift attenuation for ^{152}Sm (solid curve). The vertical lines on the theoretical curve give the uncertainties of the experimental attenuation factors. Previously measured GRID [1] and NRF [6] lifetimes are shown with the experimental attenuation factors from the present measurement as circles (filled for $\tau_{\rm CTF}$ and open for $\tau_{\rm Bethe}$) and as open squares, respectively. The experimental uncertainties are given as horizontal lines if they are larger than the size of the symbols. The shaded areas correspond to the lifetime windows deduced from the application of the extreme feeding scenarios in GRID.

part of multiplet structures. Even with neutron energies as low as 1.3 MeV, the peak density in the spectra is high because of the presence of many stable Sm isotopes with comparable natural abundances. Figure 1 shows one of the energy regions of interest.

The energies of the γ rays measured at different detector angles Θ have been fitted by the expression [3]

$$E_\gamma(\Theta) = E_0\left(1 + F_{\rm expt}\frac{v}{c}\cos\Theta\right), \quad (2.1)$$

where E_0 is the unshifted energy, c is the speed of light, v is the velocity of the center of mass in the inelastic neutron scattering collision (about $3.5\times10^{-4}c$ or 1 Å/fs), and $F_{\rm expt}$ is the experimental attenuation factor. The $F_{\rm expt}$ values have been determined from the slopes of the straight lines fitted to the experimental energies as a function of cosΘ as shown in Fig. 2. Under the assumption that the slowing down of heavy ions is correctly described by the Lindhard-Scharff-Schiott [4] and the Winterbon [5] treatments, the lifetimes of excited states can then be deduced by comparison of $F_{\rm expt}$ with a theoretically calculated attenuation function $F(\tau)$.

III. RESULTS AND DISCUSSION

The lifetimes determined in this experiment are listed in Table I and are compared with values obtained in the GRID measurement [1] and results from nuclear resonance fluorescence (NRF) experiments [6]. First, the excellent agreement between the lifetimes deduced from the Doppler shifts of two γ rays depopulating the same state should be noted. The values for the 1_1^- state in ^{154}Sm show that, in the lifetime region of tens of femtoseconds and with sufficient statistics (peak areas of >7000 counts), the determination of lifetimes with statistical uncertainties of about 10% is possible despite the small recoil velocities and the correspondingly small Doppler shifts.

The solid curve in Fig. 3 represents the theoretical Doppler shift attenuation for ^{152}Sm. This curve has been used to extract lifetimes in all three Sm isotopes since the deviations in $F(\tau)$ for these different masses are small. It is evident from this figure that the lifetime region of highest sensitivity in our experiment, i.e., the part with the steepest slope of $F(\tau)$, is 20–100 fs. Therefore, ^{152}Sm offers the best opportunity for a comparison between the GRID and DSAM methods (see Table I).

But first, we would like to note the good agreement with the three known lifetimes which were determined in the NRF work of Metzger [6]. They are represented by open squares in Fig. 3. The lifetimes from the DSAM-INS experiment are somewhat shorter than the NRF values in ^{152,154}Sm [6], indicating that feeding was successfully excluded in our experiment through the careful choice of the neutron energy (E_n=1.3 MeV).

The lifetimes $\tau_{\rm CTF}$ and $\tau_{\rm Bethe}$, which were obtained in the GRID analysis [1] under the assumption of completely statistical population of the 1_1^- and 3_1^- states and using either a constant-temperature Fermi-gas (CTF) model [7] or the Bethe formula [7] to calculate the level density, are marked by filled and open circles, respectively, in Fig. 3. The shaded areas correspond to the lifetime windows deduced from the application of extreme feeding scenarios in GRID. As can easily be seen, the DSAM results do not allow a judgement as to which of these approaches, CTF or Bethe, provides the better description. Whereas $\tau_{\rm DSAM}$ is in excellent agreement with $\tau_{\rm Bethe}$ for the 1_1^- state in ^{152}Sm, $\tau_{\rm DSAM}$ overlaps within the errors with $\tau_{\rm CTF}$ in the case of the 3_1^- level. This

TABLE II. Experimental and calculated $E1$ transition rates and $B(E1)$ ratios in selected even-A Sm nuclei.

Nucleus	$B(E1;1^-\to0^+)$ $(10^{-4}\,e^2\,{\rm fm}^2)$ DSAM-INS	Previous	IBM	$B(E1;3^-\to2^+)$ $(10^{-4}\,e^2\,{\rm fm}^2)$ DSAM-INS	Previous	IBM	$\frac{B(E1;1^-\to2^+)}{B(E1;1^-\to0^+)}$ Expt.	Theor.	$\frac{B(E1;3^-\to4^+)}{B(E1;3^-\to2^+)}$ Expt.	Theor.
^{148}Sm	-	11(3)[a]	33	-	35^{+24}_{-11}[b]	78	2.1(10)	3.0	-	-
^{150}Sm	26^{+9}_{-8}	11(1)[b]	15	95^{+89}_{-52}	35(2)[b]	54	2.1(1)	2.0	1.0(1)	0.5
^{152}Sm	108^{+17}_{-13}	44^{+11}_{-9}[b]	98	146^{+32}_{-22}	119^{+27}_{-22}[b]	165	1.8(2)	1.7	1.0(1)	0.8
^{154}Sm	114^{+8}_{-7}	89(13)[a]	103	144^{+20}_{-16}	-	145	1.9(4)	1.9	1.2(1)	1.2

[a]From Ref. [6].

[b]From Ref. [1].

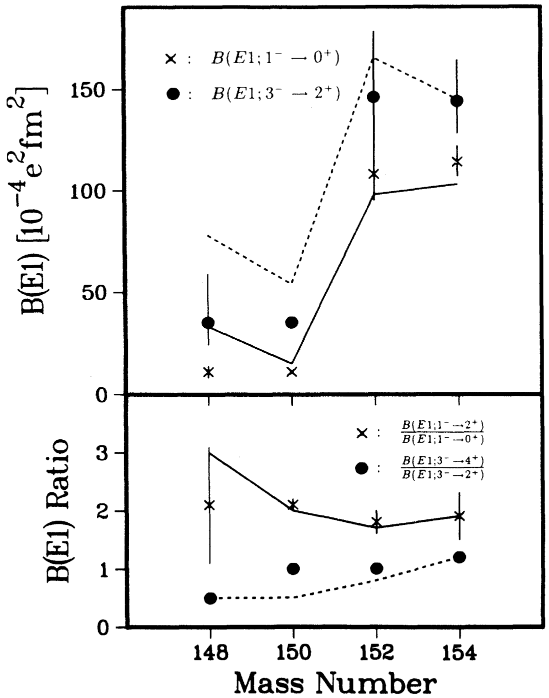

FIG. 4. (a) Reduced $E1$ transition probabilities for the decay of the 1_1^- and 3_1^- states in ^{148,150,152,154}Sm. The experimental values are marked by symbols, while the lines represent the IBM calculations for the $1^- \rightarrow 0^+$ (solid) and $3^- \rightarrow 2^+$ (dashed) transitions. (b) Same as (a) for the $B(E1)$ ratios indicated.

result seems to confirm the suspicion that the statistical description is just not appropriate for the feeding of one specific level at excitation energies as low as 1 MeV. It should be noted that the statistical model was applied in [1] only due to the lack of experimental information about the feeding of the states under investigation. However, except for one case, all lifetimes determined in the DSAM-INS measurement were within the GRID lifetime windows deduced from extreme feeding assumptions. Only our measured lifetime of the 3_1^- state in ^{150}Sm is shorter than the lower limit in GRID, but for $\tau > 150$ fs the accuracy of the DSAM-INS method decreases quite rapidly (see Fig. 3).

The energies and decay properties of the octupole states in the transitional Sm isotopes were successfully described by Scholten, Iachello, and Arima [8] in the framework of the interacting boson model (IBM). In this model the U(5) $\rightarrow$ SU(3) transition is induced by the increasing number of bosons, N_B, in the $(sd)^{N_B-1}f$ space. However, whereas the one-body $E1$ operator in this space is able to describe the experimental trends of the $1^- \rightarrow 0^+$ and $3^- \rightarrow 2^+$ transition rates, it fails to reproduce simultaneously the $1^- \rightarrow 2^+$ and $3^- \rightarrow 4^+$ transition strengths [1]. In order to explain *both* absolute $B(E1;1^- \rightarrow 0^+)$ and $B(E1;3^- \rightarrow 2^+)$ values *and* the branching ratios, it is necessary to consider additional two-body terms. The effective *sdf*-$E1$ operator containing both one- and two-body terms, which was recently proposed in Ref. [9], explains the $B(E1)$ values in $^{148-152}$Sm rather well [1]. In view of the new experimental data we repeated the calculations with this operator and have included ^{154}Sm. The effective $E1$ charge was kept constant (e_1=0.30 e fm) and for the two other parameters the values $\chi_1 = -0.014$ and $\chi_1' = 0.38$, 0.12, and -0.06 for ^{148}Sm, ^{150}Sm, and ^{152}Sm, respectively, were used. For the rotational nucleus ^{154}Sm the values $\chi_1 = -0.030$ and $\chi_1' = -0.06$ were deduced from an Alaga rule constraint [10].

The results of the interacting boson model (IBM) calculations are compared to the experimental data in Table II and illustrated in Fig. 4. In addition to the dramatic increase of the transition rates in going from ^{150}Sm to ^{152}Sm (see discussion in [1]), the saturation of both $B(E1)$ values in ^{152,154}Sm is well reproduced. A slight increase of the effective charge with the neutron number (e_1=0.2–0.3 e fm) could further improve the agreement for the $B(E1)$ values, especially in ^{148}Sm.

IV. CONCLUSION

In conclusion, we have presented the results of a DSAM-INS experiment in the even-mass $^{150-154}$Sm isotopes. The measured lifetimes of the lowest-lying 1^- and 3^- states were compared to the results of a recent investigation using the GRID method, and the decay properties of these octupole states have been successfully described within the IBM using an effective *sdf*-$E1$ operator.

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