Low-lying $E1$ transitions in the stable even Sm isotopes*

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Strong resonant scattering of bremsstrahlung by a level in ^{144}Sm at 3.225-MeV excitation energy has been observed. Angular distribution and linear polarization measurements have led to a 1^- assignment for this level. From a self-absorption study, a value $\Gamma_0 = 220 \pm 30$ meV has been obtained for the partial radiative width of the ground-state transition. For the known 1^- states in ^{150}Sm (1.166 MeV) and ^{154}Sm (0.921 MeV), partial widths $\Gamma_0(1.166) = (5.4 \pm 0.4)$ meV, and $\Gamma_0(0.921) = (7.4 \pm 1.0)$ meV were measured. Combining the results of bremsstrahlung measurements with those of previous resonance fluorescence experiments utilizing high-speed rotation of radioisotopes, a width $\Gamma_0 = (3.1 \pm 0.4)$ meV was arrived at for the ground-state transition from the 1.465-MeV 1^- state in ^{148}Sm. The excitation energies of the 1^- states studied in the even Sm isotopes below $N = 89$ are fairly close to the sums $[E(2_1^+) + E(3_1^-)]$. The $B(E1)$'s initially decrease as one moves away from the deformed region. While this is not unexpected, the reversal of this trend near and at the magic neutron number $N = 82$, as evidenced by the large $B(E1)$ observed in ^{144}Sm and the behavior of the $B(E1)$'s in ^{142,144}Nd, is somewhat surprising.

[NUCLEAR REACTIONS ^{144,148,150,154}Sm(γ,γ); bremsstrahlung E=1.2–3.8 MeV; measured $\sigma(96°)$ and $\sigma(126°)$, LP; deduced J, π, Γ. Enriched ^{144}Sm and ^{150}Sm targets.]

I. INTRODUCTION

The stable even Sm isotopes, ranging in neutron number from $N=82$ to $N=92$, straddle the boundary $N=89$ between spherical and deformed rare-earth nuclei. They are thus well suited for studies of changes in nuclear properties in this transition region. In this paper the concern is with the low-lying 1^- states.

In the deformed nuclei, the low-lying negative-parity states are usually interpreted as one-phonon states, and microscopic calculations,[1] based on the pairing plus octupole-octupole force model and taking into account the strong Coriolis coupling, are able to reproduce the main features of the experimental situation. In the vibrational nuclei, the lowest negative-parity states are thought to be the members of the 1^--5^- quintet attributed to the superposition of quadrupole and octupole one-phonon states. The theoretical analyses[2-4] of the properties of these two-phonon states have provided a qualitative understanding. Further development has been hampered by the paucity of experimental data.

Recently, fairly strong $E1$ excitations have been observed in the $N=82$ nuclei ^{142}Nd,[5] ^{140}Ce,[5] and ^{138}Ba[6] at excitation energies slightly below the sums $E(2_1^+)+E(3_1^-)$. Based on the trend of these excitation energies, the corresponding 1^- state in ^{144}Sm was expected to occur at approximately 3.2 MeV. In (p,p') experiments, a state at 3.227-MeV excitation energy had been tentatively identified as a 1^- state by one group[7] and as a 3^- state by another group.[8] Once an enriched sample of ^{144}Sm became available, a nuclear resonance fluorescence experiment was carried out and showed that a level at 3.225 ± 0.002 MeV represented by far the strongest excitation in ^{144}Sm below 3.5 MeV and was indeed a 1^- state. The fact that the $B(E1)$ for this 1^- level differed by almost an order of magnitude from the $B(E1)$ for the $1^- \to 0^+$ transition in ^{148}Sm made it desirable to study the trend of the $B(E1)$'s in the other Sm isotopes and to recheck the ^{148}Sm value. This paper is a report on measurements in ^{144}Sm as well as in ^{148}Sm, ^{150}Sm, and ^{154}Sm.

II. EXPERIMENTAL PROCEDURES

Bremsstrahlung from a 37-mg/cm^2 gold foil bombarded with electrons from the Bartol Van de Graaff accelerator served as the exciting γ radiation. The arrangement of source, scatterer, detectors, and shielding used for most of the yield measurements is indicated in Fig. 1. For further details on the general procedures, the reader is referred to previous publications.[9-11]

For the ^{144}Sm yield measurements, the scatterer consisted of 23.2 g of enriched Sm_2O_3 (96.47%),[12] contained in a Plexiglas cylinder of 5.72-cm inside diameter and 1.62-cm length. For the ^{148}Sm and ^{154}Sm experiments, a rectangular scatterer of natural Sm metal, measuring $5.72 \times 3.81 \times 0.85$ cm, was used. Finally, the measurements on ^{150}Sm were carried out with 45 g of enriched Sm_2O_3 (95.48%),[12] contained in a Plexiglas cylinder of 5.72-cm inside diameter and 0.95-cm length.

For the linear-polarization experiments, a polarimeter consisting of two Ge(Li) slabs[13] was placed at approximately the position indicated in Fig. 1 for the 55-cm^3 Ge(Li) detector, and the counting rates in the full-energy peaks were measured with the slabs either parallel or perpendicular to the scattering plane.[14]

To render a self-absorption study of the 3.225-MeV transition in ^{144}Sm feasible, the available 23 grams of enriched material were approximately evenly divided between a scatterer (0.67 cm thick) and an absorber (4.6-cm path length). The absorber was placed between the scatterer and the beam dump (see Fig. 1) as close to the beam dump as possible. To separate resonant from nonresonant effects, a series of runs were carried out in which the Sm_2O_3 absorber was replaced by a comparison absorber containing Nd_2O_3. This absorber had been closely matched in nonresonant γ ray attenuation to the Sm_2O_3 absorber using γ lines from radioisotopes.

For the even Sm isotopes, only spin-1 and spin-2 levels are expected to result in observable resonance scattering yields. For these two spin values, the ratios $N(126°)/N(96°)$ of the counting rates in the two detectors differ by more than a factor of 2. Spin determinations are thus feasible for all but the most weakly excited levels.

III. RESULTS

A. ^{144}Sm

Based on the excitation energies of the 1^- states in the other $N = 82$ nuclei,[5,6] the search in ^{144}Sm was carried out with an electron energy $E_e = 3.6$ MeV. A line at 3.225 MeV was found to dominate the spectrum (Fig. 2). Since the flux calibration[10,11] is best known at a bombarding energy E_e exceeding the level energy by 100 keV, subsequent yield measurements were carried out at $E_e = 3.325$ MeV. Under the conditions of these runs, the ratio of the counting rates $N(126°)/N(96°)$ was expected to be 1.20 for a spin-1 state and 0.44 for a spin-2 state. The observed ratio, $N(126°)/N(96°) = 1.15 \pm 0.09$, unambiguously established the spin of the 3.225-MeV level as 1.

The polarimeter experiment was carried out at $E_e = 3.8$ MeV, a compromise between the need for as high a flux as possible and a low background counting rate at the position of the 3.225-MeV line. Denoting the counting rate with the Ge(Li) slabs in the scattering plane by $N_\parallel$, and the counting rate with the slabs perpendicular to the scattering plane by $N_\perp$, the polarimeter experiment with the 3.225-MeV level yielded

$$\frac{N_\parallel - N_\perp}{N_\parallel + N_\perp} = (+3.6 \pm 2.7)\%.$$

Based on our experience with transitions in the 3–4-MeV range, the ratio expected for a 3.2-MeV $E1$ transition is $(+4.5 \pm 1.5)\%$, while the ratio for an $M1$ transition is $(-5.7 \pm 1.1)\%$. The polarimeter experiment thus indicated negative parity for the 3.225-MeV level in ^{144}Sm.

From the yield of scattered 3.225-MeV quanta, a value

$$\Gamma_0^2/\Gamma = 0.22 \pm 0.02 \text{ eV}$$

was calculated for the 3.225-MeV 1^- level. Here Γ_0 represents the partial radiative width of the ground-state transition, while Γ is the total width of the level. The fact that the total width is no longer negligible compared with the thermal Doppler width of $\simeq 2$ eV was taken into account. Furthermore, in correcting for resonant attenuation of the beam within the scatterer, it was assumed

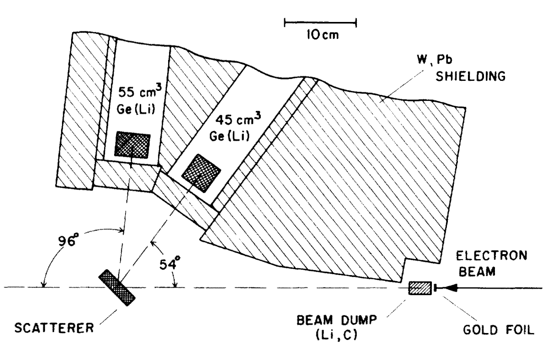

FIG. 1. Geometry used for the scattering-yield measurements. For the self-absorption experiments, the absorbers were placed into the incident bremsstrahlung beam as close to the beam dump as possible.

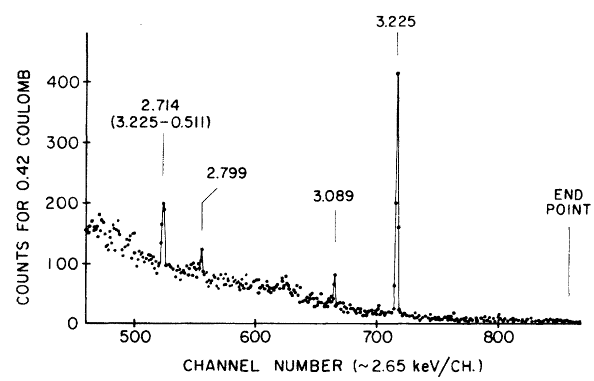

FIG. 2. ^{144}Sm: pulse height distribution measured with a 55-cm^3 Ge(Li) detector at a mean scattering angle of 96°, with 3.2 cm of Pb in front of the detector. The bombarding energy was 3.6 MeV. The scatterer, 5.72 cm in diameter and 1.62 cm thick, consisted of 23.2 g of enriched Sm_2O_3 (96.47% ^{144}Sm). The 3.089-MeV line originated from the ^{13}C in the scatterer container, the 2.799-MeV line from the excitation of a 2^+ level in ^{144}Sm.

that branching from the 3.225-MeV level to other excited states was negligible, i.e., Γ_0/Γ was assumed to be unity. As is so often the case in resonance fluorescence experiments, the spectrum of the scattered radiation was not of much help in providing branching information because the background counting rate increased so rapidly with decreasing energy that even considerable branching would have escaped detection.

To remove the uncertainty in Γ_0 caused by the lack of knowledge of Γ_0/Γ, a self-absorption experiment was carried out. With the small amount of enriched material that was available, some 75 h of running time were needed to achieve $\approx 14\%$ accuracy in the width determination. The absorber with 2.97 g/cm^2 of ^{144}Sm was found to resonantly reduce the yield of scattered 3.225-MeV quanta by $(34.7 \pm 3.1)\%$. From this, a width

$$\Gamma_0 = 220 \pm 30 \text{ meV}$$

was deduced. Comparison of this width with the result of the yield measurements indicates that there is indeed little, if any, branching from the 3.225-MeV level in ^{144}Sm to excited states in that nucleus.

The measured width corresponds to 3.5×10^{-3} single particle units (s.p.u.).[15]

B. ^{148}Sm

A previous study[16] of the 1.465-MeV $E1$ transition in ^{148}Sm had indicated that the strength of this transition was smaller, by almost an order of magnitude, than the strength of the 0.963-MeV transition in ^{152}Sm. The previous measurement[16] on ^{148}Sm had utilized a combination of β recoil and high-speed rotation of a ^{148}Pm source to establish the resonance condition for the 1.465-MeV level. As a consequence, the analysis had involved estimates of the slowing down of Sm recoils with a few eV energy in Pm_2O_3. While there was good agreement between two estimates[16,17] for this slowing down, it was felt that a more direct determination of the width using the bremsstrahlung technique was desirable.

The yield measurement with natural Sm did confirm that the 1.465-MeV transition was weak. Since the signal was small, the presence of the 1.460-MeV background line from ^{40}K affected the measurements and reduced the accuracy of the width determination.

The result of the bremsstrahlung experiment was $\Gamma_0 = 3.8 \pm 1.0$ meV. Combined with the result of the most recent analysis[17] of the high-speed-rotor experiment, this led to a mean width

$$\Gamma_0(1.465) = 3.1 \pm 0.4 \text{ meV},$$

corresponding to 5.2×10^{-4} s.p.u.

C. ^{150}Sm

For most of the yield measurements involving ^{150}Sm, a 30-cm^3 Ge(Li) detector was used in place of the 55-cm^3 detector shown in Fig. 1.

In the past, 2^+ assignments had been made for the 1.166-MeV level on the basis of angular correlation experiments[18] and of the observation, in ^{149}Sm(n,γ) studies,[19,20] of a 392-keV transition which was interpreted as the cascade transition to the 773-keV 4^+ level. However, this 392-keV transition was not observed in a study[21] of the ^{150}Pm decay although the 1.166-MeV level is strongly populated in that decay. The 392-keV transition thus belongs somewhere else in the complicated scheme of levels populated in the (n,γ) reaction. In the presence of strong evidence for a 1^- assignment which had been obtained[22] using Ge(Li) detectors, one must also discount the result of the angular correlation experiment[18] since it had been carried out on the complex spectrum of ^{150}Eu (13 h) using NaI detectors. A 1^- assignment had been suggested on the basis of (d,d') studies.[23]

In the resonant scattering experiment, a ratio $N(126°)/N(96°) = 2.74 \pm 0.24$ was observed. For a spin-1 level, the expected ratio for the combination of 30 and 45-cm^3 detectors is 2.84; for a spin-2 level it is 1.04. The observed ratio is thus only compatible with the assignment of spin 1 to the 1.166-MeV level.

For the measurements of the resonant yields from the 1.166-MeV level, a thin (0.14 cm) cobalt metal disk having the same diameter as the ^{150}Sm scatterer served as a convenient monitor of the γ ray flux since the width of the 1.190-MeV level in ^{59}Co is well known,[24] the yield fairly large, and the angular distribution approximately isotropic.[24] Data were taken with the Co monitor attached to the front of the ^{150}Sm scatterer (i.e., facing the detectors), and with the monitor attached to the back of the scatterer. Using $(g\Gamma_0^2/\Gamma)_{1.190} = 10.25 \pm 0.50$ meV,[24] the yield measurements with the Co-Sm sandwich led to

$$(\Gamma_0^2/\Gamma)_{1.166} = 3.04 \pm 0.23 \text{ meV}.$$

With the exception of the 392-keV branch mentioned earlier, the decay-scheme studies[21,25] agree with the neutron-capture-γ-ray studies[19] with respect to the decay modes of the 1.166-MeV level. The mean branching ratio is $\Gamma_0/\Gamma = 0.56 \pm 0.03$. With this value, the radiative width for the 1.166-MeV ground state transition becomes

$$\Gamma_0(1.166) = (5.4 \pm 0.5) \text{ meV},$$

corresponding to 1.8×10^{-3} s.p.u.

D. ^{154}Sm

The 921-keV 1^- state in ^{154}Sm was studied using a natural Sm metal scatterer. Consequently, the 963-keV level in ^{152}Sm was also excited and provided a convenient flux calibration. Using $\Gamma_0^2/\Gamma(963) = 3.18 \pm 0.28$ meV,[16] the observed yield for the 921-keV level in ^{154}Sm corresponded to

$$\Gamma_0^2/\Gamma = 3.1 \pm 0.4 \text{ meV}.$$

With $\Gamma_0/\Gamma = 0.42 \pm 0.01$,[26] this then led to a partial radiative width

$$\Gamma_0(0.921) = 7.4 \pm 1.0 \text{ meV},$$

corresponding to 4.8×10^{-3} s.p.u.

IV. DISCUSSION

In Table I, the pertinent properties of the low-lying 1^- states in the stable even Sm isotopes are summarized.

It is believed that the states listed in Table I are indeed the lowest 1^- excitations in the respective isotopes. Numerous studies of radioactive decays and of nuclear reactions involving these nuclei failed to produce any evidence for 1^- states at lower excitation energies.

In Fig. 3, the excitation energies of the observed 1^- states are compared with the sums of the excitation energies of the lowest 2_1^+ and 3_1^- states. The similarity of the two curves is striking. However, since the excitation energies of the 2_1^+ states are very small in the deformed region, there is not much difference between $E(2_1^+)+E(3_1^-)$ and $E(3_1^-)$, i.e., the $E(1^-)$'s could as well be said to follow the trend of the $E(3_1^-)$'s. This is no longer true in the region below $N=89$ where the $E(2_1^+)$'s are sufficiently large to leave no doubt that the excitation energies of the 1^- states follow closely the sums of the 2_1^+ and 3_1^- excitation energies. This, of course, was the basis for the theoretical treatments[2-4] of the low-lying 1^- states in the vibrational nuclei as two-phonon excitations. Further support for this interpretation has come from the tentative identification, in ^{144}Sm(p,p') experiments,[7] of the 4^- and 5^- members of the expected $2^+ \otimes 3^-$ quintet, and the observation[7] that the 3.225-MeV 1^- level was located well below the expected 1^- members of neutron particle-hole multiplets.

TABLE I. Properties of the low-lying 1^- levels in the stable even Sm isotopes.

Isotope	$E_{exc}(1^-)$	Γ_0 (meV)	$10^3 \times \frac{B(E1; 1^- \to 0^+)}{B(E1)_{s.p.}}$	N
^{144}Sm	3.225	220±30	3.5±0.5	82
^{148}Sm	1.465	3.1±0.4	0.5±0.1	86
^{150}Sm	1.166	5.4±0.5	1.8±0.2	88
^{152}Sm	0.963	7.3±0.6	4.2±0.4	90
^{154}Sm	0.921	7.4±1.0	4.8±0.7	92

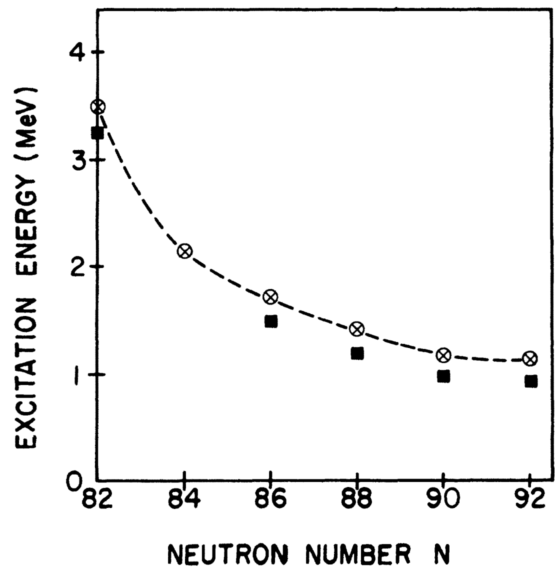

FIG. 3. Comparison of the excitation energies of the known low-lying 1^- levels (■) in the even Sm nuclei with the sums (⊗) of the excitation energies of the 2_1^+ and 3_1^- levels.

The dependence of the observed reduced $E1$ transition probabilities on the neutron number N is shown in Fig. 4. Included in that figure are the results for the 3.426-MeV 1^- level in ^{142}Nd ($N=82$)[5] and the 2.186-MeV 1^- level in ^{144}Nd ($N=84$).[10] They fit quite well into the pattern indicated by the Sm isotopes.

The decrease observed in the $B(E1)$'s as one

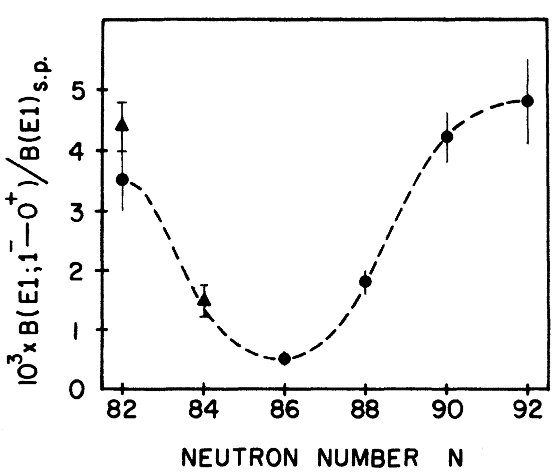

FIG. 4. Trend of the reduced $E1$ transition probabilities for the stable even Sm$(Z=62)$ isotopes (●) and for the Nd$(Z=60)$ isotopes ^{142}Nd and ^{144}Nd (▲).

moves away from the deformed region could be attributed to the levels becoming less collective. However, in this simple picture one would expect the decline to continue right down to $N=82$. We do not have a simple explanation for the rapid increase which takes place as N approaches the magic number 82. It would be of interest to extend the search for 1^- states and the measurement of their $B(E1)$'s to $N<82$.

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