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# Spins of Levels in $^{148}$Sm†

W. Gelletly
*The Physical Laboratories, University of Manchester, Manchester, United Kingdom,*
*and Brookhaven National Laboratory, Upton, New York 11973*

and

W. R. Kane
*Brookhaven National Laboratory, Upton, New York 11973*
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The primary neutron-capture $\gamma$ rays emitted in the decay of the 3.4-eV resonance in $^{147}$Sm have been studied with a Ge(Li) detector and the crystal diffraction neutron monochromator at the Brookhaven high-flux beam reactor. The results obtained complement the average resonance capture studies of Buss and Smither. The spins and parities of levels at 1453.6 and 1663.4 keV are shown to be 2+. The results also indicate previously unreported levels at (1648.6), 1970.9, and 2142.5 keV with spins 2, 3, or 4. The spin of the 3.4-eV resonance is confirmed to be 3−.

## INTRODUCTION

In a recent paper Buss and Smither[1] reported the results of a study of the $^{147}$Sm$(n,\gamma)^{148}$Sm reaction with the average resonance capture technique of Bollinger and Thomas.[2,3] In this technique the capture $\gamma$ rays from an in-pile target surrounded by $^{10}$B are studied. The $^{10}$B filters out neutrons of energy less than 100 eV and the target is thus exposed to epithermal neutrons with energies ranging from 100 eV to 10 keV. This allows the measurement of the average transition probability of the primary capture $\gamma$ rays when neutron capture occurs in a large number of neutron resonances. Simple arguments,[2,3] based on the statistical nature of the neutron-capture process, indicate that under these conditions the measured relative intensities of the primary capture $\gamma$-rays, divided by the fifth power of the $\gamma$-ray energy to remove the energy dependence of the transition strengths, will fall into several clearly defined groups according to the multipolarity of the transition and the spin of the level fed by the transition. Bollinger and Thomas[2,3] have shown that this is indeed so in a number of cases.

In the case of $^{147}$Sm$(n,\gamma)^{148}$Sm, which was studied by Buss and Smither, $s$-wave capture on the $\frac{7}{2}-$ ground state of $^{147}$Sm leads to resonances of spin and parity 3−, and 4−, and we expect to observe, in order of decreasing intensity, two groups of $E1$ transitions feeding states of spin and parity 3, 4+ and 2, 5+, respectively, two groups of $M1$ transitions feeding states of spin and parity 3, 4− and 2, 5−, respectively, and one group of $E2$ transitions feeding 1− and 6− states. The results obtained by Buss and Smither clearly follow the expected pattern. Consequently, they were able to restrict the spins and parities of a large number of low-lying levels in $^{148}$Sm to one of two possible values. Without additional information it is not possible to remove this ambiguity on the basis of the average resonance capture measurements alone. The low-lying levels in $^{148}$Sm have been studied both in radioactive decay[4-13] and in various nuclear reactions.[14-19] The combined results clearly identify which choice of spin is correct in a large number of cases, but many ambiguities remain.

In the case of the observed $E1$ and $M1$ transitions to levels of spins 2 or 5, one way in which the ambiguity may be removed is by studying neutron capture in individual resonances of $^{147}$Sm which have definite spin and parity 3− or 4−. Clearly the observation of a primary dipole transition to one of these levels of spin 2 or 5 from a resonance of spin and parity 3− will rule out the latter possibility. One serious disadvantage attendant on the study of the decay of individual resonances is that no information is obtained if a particular primary transition is not observed, since this may be due to the angular momentum selection rules or the statistical fluctuation[20] in partial $\gamma$-ray widths.

We have recently studied the capture $\gamma$-ray spectrum from the $^{147}$Sm$(n,\gamma)^{148}$Sm reaction, both at thermal energy and at the 3.4-eV resonance with the neutron beam from a crystal diffraction neutron monochromator. In the present paper we report the energies and relative intensities of the primary capture $\gamma$ rays from the 3− resonance at 3.4 eV in the $^{147}$Sm$(n,\gamma)^{148}$Sm reaction. These results allow us to add some further information on the properties of the low-lying levels in $^{148}$Sm to that obtained by Buss and Smither.

## EXPERIMENTAL METHOD AND RESULTS

### A. Target

The target consisted of 3.43 g of $Sm_2O_3$, enriched in $^{147}$Sm, enclosed in an aluminium capsule. The isotopic composition of the Sm in the sample was 0.05% $^{144}$Sm, 98.34% $^{147}$Sm, 0.84% $^{148}$Sm, 0.34% $^{149}$Sm, 0.10% $^{150}$Sm, 0.20% $^{152}$Sm, and 0.12% $^{154}$Sm. In thermal-neutron capture these isotopes are expected to contribute $3.5\times10^{-4}$, 85.87, 0.045, 13.98, $7.4\times10^{-3}$, 0.053, and 0.037%, respectively, to the capture cross section. At a neutron energy of 3.4 eV the $^{147}$Sm in the sample is expected to contribute more than 99% of the total capture cross section from the sample.

### B. Equipment

The properties of the crystal diffraction neutron monochromator have been fully described by Kane *et al.*[21] This instrument was designed specifically for neutron-capture studies. It provides $2\times10^5$ $n$/sec on a 1-in.$^2$ target at an energy of 1 eV. The energy dependence of the beam intensity is $\sim 1/E$. The angular resolution of the monochromator is 12′, giving an energy resolution $\Delta E \sim 0.15$ eV at 3.4 eV. The enriched $Sm_2O_3$ target was irradiated in the monoenergetic neutron beam at a neutron energy of 3.4 eV and the capture $\gamma$-ray spectrum was studied. It was also irradiated in an intense thermal neutron beam[21] at the Brookhaven high-flux beam reactor, which has an intensity of $7\times10^7$ $n$/sec over 1 cm$^2$ with a Cd ratio greater than $2\times10^4$, in order to study the thermal-neutron capture spectrum.

The $\gamma$-ray spectra were studied with a Ge(Li) detector of ~30-cm$^3$ active volume and an energy resolution of ~8 keV at 8.8 MeV. The electronic equipment used in the experiments and the procedures used in the analysis of the data have been described in detail in earlier publications.[22]

### C. $\gamma$-Ray Measurements

The neutron-capture $\gamma$-ray spectra at both thermal and 3.4-eV neutron energies were studied over various energy ranges and under different dispersion.

In all cases both thermal and resonance spectra were recorded under identical experimental conditions. This simplified the careful comparison of the thermal and resonance spectra, which was required in order to assign transitions to the $^{147}$Sm$(n,\gamma)^{148}$Sm reaction.

Figure 1 shows an example of the $^{147}$Sm$(n,\gamma)^{148}$Sm

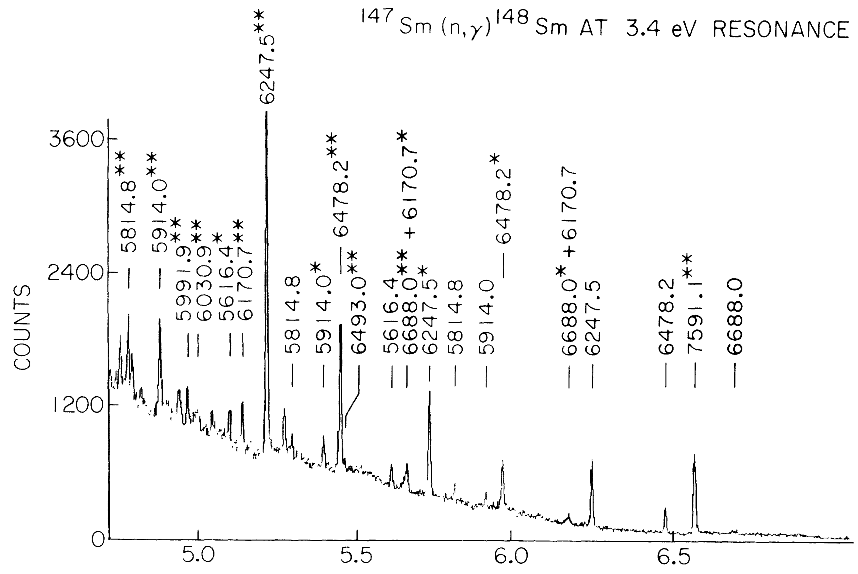

FIG. 1. The $\gamma$-ray spectrum (4.7–7.0 MeV) from the $Sm_2O_3$ target (enriched in $^{147}$Sm) irradiated with a beam of neutrons of 3.4-eV energy from the crystal diffraction neutron monochromator. The spectrum was accumulated in ~16-h running time with a 30-cm$^3$ Ge(Li) detector. The majority of the $^{148}$Sm lines are labeled with energies taken from Ref. 1 (see Table I). Single and double asterisks indicate one- and two-escape peaks, respectively.

spectrum at the 3.4-eV resonance. The energies of the observed peaks assigned to this reaction are indicated on the figure. Single and double asterisks indicate one- and two-escape peaks, respectively. No attempt was made to measure precisely the absolute energies of the observed lines. The differences in energy of the observed transitions were measured by comparison with the well-known[23] difference in energy of the observed total capture and one- and two-escape peaks. With a few exceptions, which are discussed below, these differences in energy are in excellent agreement with the differences in the transition energies reported by Buss and Smither. The majority of the

TABLE I. A comparison of the high-energy γ rays obtained in the $^{147}$Sm$(n, \gamma)^{148}$Sm reaction in average resonance capture and at the 3.4-eV resonance. In column 1 the γ-ray energy is given and in columns 2 and 3 the relative intensity in average resonance capture and the multipolarity assignment are shown. In column 4 the relative intensity at the 3.4-eV resonance (normalized to 1000 for the 6247.5-keV transition) is presented. Column 5 gives the energy of the final state populated and column 6 the spin and parity assignments made possible by combining the two sets of results.

| γ-ray energy[a] (keV) | Average resonance capture | | 3.4-eV resonance | Level energy (keV) | Spin and parity |
|---|---|---|---|---|---|
| | Relative intensity | Multipolarity | Relative intensity | | |
| 7591.1 ± 0.3 | 841 | $E1$ | 363 ± 44 | 550.5 | 2+ |
| 6980.2 ± 0.5 | 108 | $M1$ | ··· | 1162.2 | 3− |
| 6961.5 ± 0.3 | 1072 | $E1$ | ··· | 1180.1 | 4+ |
| 6708.9 ± 1.4 | 25 | $E2$, $M1$ | ··· | (1433.5) | 1−, 6−, (2−, 5−) |
| 6688.0 ± 0.3 | 393 | $E1$ | 78 ± 17 | 1453. | 2+ |
| (6677.3) | <7 | ($E2$) | ··· | (1465.1) | (1−) |
| 6547.4 ± 1.8 | 65 | $M1$ | ··· | 1595.0 | 3−, 4− |
| 6493.0 ± 0.8 | ··· | ··· | 16 ± 7 | 1648.6 | 2, 3, 4 |
| 6478.2 ± 0.6 | 385 | $E1$ | 471 ± 56 | 1663.4 | 2+ |
| 6408.7 ± 0.3 | 737 | $E1$ | ··· | 1732.9 | 4+ |
| 6247.5 ± 0.3 | 630 | $E1$ | 1000 ± 80 | 1894.1 | 4+ |
| 6238.7 ± 0.3 | 652 | $E1$ | ··· | 1902.9 | 3+, 4+ |
| 6170.7 ± 1.0 | ··· | ··· | 145 ± 23 | 1970.9 | 2, 3, 4 |
| 6111.0 ± 1.0 | ≤119 | ($M1$, $E2$) | ··· | (2031.4) | Not 2+, 3+, 4+, 5+ |
| 6061.3 ± 0.4 | 177 | $E1$ | ··· | (2080.3) | 2+, 5+ |
| (6046.3) | <25 | ($M1$, $E2$) | ··· | (2096.1) | Not 2+, 3+, 4+, 5+ |
| 6030.9 ± 0.4 | 616 | $E1$ | 42 ± 19 | 2110.7 | 3+, 4+ |
| 5999.1 ± 1.0 | ··· | ··· | 107 ± 25 | 2142.5 | 2, 3, 4 |
| 5995.2 ± 0.4 | 512 | $E1$ | ··· | 2146.4 | 3+, 4+ |
| 5983.6 ± 0.4 | 155 | $E1$ | ··· | (2158.0) | 2+, 5+ |
| 5968.2 ± 0.9 | 89 | $E1$ | ··· | (2173.4) | 2+, 5+ |
| (5947.8) | <50 | ($M1$, $E2$) | ··· | (2194.6) | Not 2+, 3+, 4+, 5+ |
| 5932.9 ± 0.9[b] | 162 | $E1$ | ··· | 2208.7 | 2+, 5+ |
| 5928.9 ± 1.4[b] | 170 | $E1$ | ··· | 2212.7 | 2+, 5+ |
| 5914.0 ± 0.4 | 436 | $E1$ | 263 ± 37 | 2227.6 | 3+, 4+ |
| 5827.4 ± 0.9 | 224 | $E1$ | ··· | 2314.2 | 2+, 5+ |
| 5814.8 ± 0.8 | ··· | ··· | 145 ± 35 | 2326.8 | (2+, 3+)4+ |
| 5803.8 ± 1.4 | 53 | $M1$ | ··· | 2338.6 | 3−, 4− |
| 5752.4 ± 0.9 | 367 | $E1$ | 114 ± 21 | 2389.2 | 3+, 4+ |
| 5701.7 ± 1.8 | 75 | ($M1$) | ··· | 2440.7 | (3−, 4−) |
| 5652.1 ± 0.7 | 369 | $E1$ | ··· | 2489.5 | 3+, 4+ |
| 5628.2 ± 0.5 | 376 | $E1$ | ··· | (2513.4) | 3+, 4+ |
| 5616.4 ± 0.9 | 400 | $E1$ | 217 ± 33 | 2524.2 | 3+, 4+ |
| 5603.2 ± 0.9 | 169 | $E1$ | ··· | 2538.4 | 2+, 5+ |
| 5572.1 ± 1.8 | 40 | $M1$ | ··· | 2570.3 | 3−, 4− |
| 5502.2 ± 1.8 | 162 | ($E1$) | ··· | 2639.4 | (2+, 5+) |

[a] The majority of the γ-ray energies quoted in this column are taken from Ref. 1. Where no entry appears in Column 2, the energy was measured in the present work.

[b] γ rays of approximately this energy were observed in the 3.4-eV resonance spectrum, but the spectrum in this region is too complicated to allow an accurate measurement of energy and intensity.

$\gamma$-ray peaks in Fig. 1 which are assigned to $^{148}$Sm are labeled with the energies reported in Ref. 1.

The relative intensities of the observed $\gamma$ rays were measured with the aid of a relative efficiency curve for the 30-cm$^3$ Ge(Li) detector obtained in the manner described by Kane and Mariscotti.[24]

The results obtained in the average resonance capture studies and in the present work are summarized in Table I, which lists, in columns 1–3, the energies, relative intensities, and multipolarities of all transitions observed by Buss and Smither in their study of average resonance capture. Column 4 gives the measured relative intensity of the transition if it was observed in the present study of the decay of the 3.4-eV resonance. Where there is no entry in column 2, the transition was only observed in the present work and the energy given in column 1 is that obtained in the present study of the decay of the 3.4-eV resonance. Column 5 gives the energy of the level fed by the primary transition whose energy is given in column 1. Column 6 gives the values deduced from these neutron capture data for the spin and parity of this level.

## DISCUSSION

For the majority of the cases listed in Table I, the primary transition either is not observed in the decay of the 3.4-eV resonance or its observation adds no information to that already known. In these cases the spin and parity assignments given in column 5 are those deduced by Buss and Smither from their average resonance capture results. In a few cases the present work does add to or confirm the results obtained from average resonance capture. These cases are discussed in detail below.

*(a) 7591.1-keV transition.* This $E1$ transition feeds the first excited state in $^{148}$Sm at 550.5 keV. This level has 2+ spin and parity.[4,5] The observation of this transition in the decay of the 3.4-eV resonance confirms the 3– spin and parity of the resonance.

*(b) 6688.0-keV transition.* Buss and Smither reported a 6688.0 ± 0.3-keV $E1$ primary transition to a state at 1453.6 keV. They assign spin and parity 2+ or 5+ to this level on the basis of the measured intensity of the primary transition. The observation of this transition in the decay of the 3.4-eV resonance confirms the existence of this level and firmly establishes its spin and parity as 2+.

As pointed out by Buss and Smither a second 2+ state is expected at approximately this energy on the basis of energy-level systematics in this region. Such a level would be expected to decay to the ground state by an $E2$ transition, and to the first excited 2+ state at 550 keV by a mixed ($E0$)-$M1$-$E2$ transition. In their studies of the decay of $^{148}$Eu Harmatz and Handley[4] observed $K$ conversion lines of the energies appropriate to such transitions, and Cline[5] reported $\gamma$ rays of the corresponding energies. It seems highly probable from the reported conversion-electron and $\gamma$-ray intensities of these transitions that they deexcite the 1453.6-keV level as speculated in Ref. 1.

*(c) 6493.0-keV transition.* A weak, previously unreported, 6493.0 ± 0.8-keV transition was observed in the present work. It appears to belong to the $^{147}$Sm$(n,\gamma)^{148}$Sm reaction. The assignment can only be a tentative one, however, since the three peaks due to this transition lie on the tails of the peaks of the intense 6478.2-keV transition. It is not possible to observe these peaks in the thermal spectrum, because this region of the spectrum is further complicated by the presence of the strong 6483.0-keV transition from $^{150}$Sm. Such a transition would feed a level at 1648.6 keV. The transition is probably of dipole character. Hence the spin of the level is probably 2, 3, or 4.

*(d) 6478.2-keV transition.* The $E1$ primary transition of this energy to a 2+ or 5+ state at 1663.4 keV, which was reported by Buss and Smither, also appears strongly in the 3.4-eV resonance spectrum. This observation confirms the existence of the level and establishes its spin and parity as 2+.

As in (b) earlier observations support and fit in with this assignment. A level at approximately this energy had been excited in the $(d,d')$ and $(p,t)$ reactions.[15,16] The observed angular distributions of the outgoing charged particles in each case were consistent with spin 2. A 2+ state would be expected to deexcite to the 0+ ground state and 2+ first excited state. As in the case of the 1453.6-keV level, Cline[5] and Harmatz and Handley[4] have observed weak $\gamma$ rays and $K$ conversion lines of the energies appropriate to two such transitions deexciting these levels, although the 4-keV difference in energy between the 1664.5-keV $\gamma$ ray of Cline and the 1668.7-keV transition of Harmatz and Handley raises some doubt that they observed the same transition. It seems likely, however, that these authors have observed the transitions deexciting this level.

*(e) 6170.7-keV transition.* The two-escape peak of a moderately strong 6170.7 ± 1.0-keV transition was observed in the present work, and assigned to $^{148}$Sm. The total capture and one-escape peaks of this transition are not fully resolved from the one- and two-escape peaks of the 6688.0-keV transition. This transition would feed a previously unreported level at 1970.9 keV. Since the primary transition is probably a dipole transition, the level spin must be 2, 3, or 4.

*(f) 5999.1-keV transition.* A transition of this energy was observed in the 3.4-eV resonance spectrum. It appears to belong to $^{148}$Sm. The observed difference in energy of 3.9 keV between this transition and the 5995.2-keV $\gamma$ ray reported by Buss and Smither suggests that they are different transitions and feed different levels. Such a transition would feed a previously unreported level at 2142.5 keV. Since the transition is probably of dipole character the spin of the level is 2, 3, or 4.

*(g) 5814.8-keV transition.* A strong 5815-keV $\gamma$ ray was observed by Buss and Smither, but tentatively assigned to the $^{154}$Sm$(n,\gamma)^{155}$Sm reaction in the natural samarium target employed, since it appeared to be too strong to be attributable to $^{147}$Sm$(n,\gamma)^{148}$Sm. The high intensity of this $\gamma$ ray in the present experiment indicates that the transition must indeed be in $^{148}$Sm. Recently, Smither has confirmed the assignment of the 5814.8-keV transition to $^{148}$Sm in new, average resonance capture experiments with isotopically enriched $^{147}$Sm. The $\gamma$-ray intensity obtained indicates that the transition must be a close doublet of two $E1$ transitions.[25] The final state populated has an energy of 2326.8 keV, identical to that of a level reported by Cline[5] for the $^{148}$Eu decay. An energy of 2328.0 keV was reported by Harmatz and Handley[4] for the same level. In both works a 4+ spin and parity assignment was proposed. The $^{148}$Eu decay data appear to favor the 4+ assignment, but 2+ or 3+ spin and parity would also be consistent with both the $(n,\gamma)$ and radioactive-decay results.

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