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E4 MOMENTS in 152Sm AND 15lfSra

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E4 MOMENTS IN ^{152}Sm AND ^{154}Sm*

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The E4 transition moments between the ground state and the 4^+ rotational state in ^{152}Sm and ^{154}Sm have been determined from Coulomb excitation experiments with 10-12 MeV ^{4}He projectiles. The resulting E4 moments are about twice those expected from previously measured β_4 deformations.

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In a previous paper [1] we have reported results on the E4 transition moment of ^{152}Sm determined by comparing the experimental and calculated yields of the 4+ rotational state following Coulomb excitation with ^{4}He projectiles. This moment is of particular interest since it is likely to result from the intrinsic shape of ^{152}Sm; and, if so, can give rather detailed information about that shape. Although data were taken on ^{154}Sm during the original experiments, these could not be interpreted due to the lack of a sufficiently accurate value for B (E2; 4 → 2). This B(E2) value now has been measured with sufficient

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accuracy and, in addition, the best value for the B(E2; 2 → 0) of ^{152}Sm has been reviewed and adjusted slightly from the previously used value. Finally, the quantum-mechanical corrections to the cross sections have recently been calculated by Alder et al. [2] for both ^{152}Sm and ^{154}Sm. Thus, the intent of this note is to present and discuss the current best values for the E4 moments of these two Sm nuclei.

The experiments consisted of an accurate comparison of the cross sections of the 4 → 2 transitions in ^{152}Sm and ^{154}Sm with those of the 2 → 0 transitions in ^{150}Sm and ^{152}Sm from the same (natural samarium) targets following Coulomb excitation with ^{4}He projectiles. The cross sections of the 2 → 0 transitions could be calculated from the known B(E2; 2 → 0) values, and these transitions thus served as two independent internal standards, against which the cross sections for production of the 4+ states in ^{152}Sm and ^{154}Sm could be evaluated. Separate results were obtained from the singles gamma-ray spectra and from those in coincidence with backscattered ^{4}He projectiles. These results depend differently on many of the corrections entering the analysis, so that their consistency as to the extracted E4 moment lends considerable support to our analysis. Isotopically enriched targets of ^{152}Sm and ^{154}Sm were also used, and in the case of ^{152}Sm, its 2 → 0 transition again provided an internal standard. However, the 2 → 0 transition of ^{154}Sm was not a convenient energy to act as such a standard, so that normalization was achieved relative to natural samarium targets by means of the number of alpha particles scattered through 90° from the target into a solid state detector. Additional details of the experiments can be found in Ref. 1. A somewhat different experimental method has been considered in a paper by Winkler [3].

One of the largest corrections applied in the ^{152}Sm case was that for the feeding of the 4+ level from higher "vibrational" states which are populated by direct E2 or E3 excitation. For ^{154}Sm, such corrections are about three times smaller relative to the direct excitation of the 4+ level than for ^{152}Sm. The properties of four vibrational states included in the calculations for ^{154}Sm are listed in table 1. We have taken the uncertainty in each feeding branch to be 50%. Other corrections and uncertainties are similar to those discussed previously [1] for ^{152}Sm.

The ground-band B(E2)-values given in table 2 are the most important quantities for determining the calculated yield of the 4+ states. For B(E2; 2 → 0) we now prefer to use the accurately measured lifetimes of the 2+ states together with the calculated conversion coefficients (table 2). These B(E2) values for ^{152}Sm and ^{154}Sm are significantly lower (≈ 2% and ≈ 10%, respectively) than the direct Coulomb excitation results of Elbek and coworkers[4] but seem to be in better accord with the other B(E2) values in the ground band. For the values of B(E2; 4 → 2) in ^{152}Sm and ^{154}Sm, and the value of B(E2; 2 → 0) in ^{150}Sm, we have used recent recoil-distance measurements [5,6]. The effect of using different B(E2)-values can be estimated easily, since the calculated yields of the 4^+ states are approximately proportional to the product of B(E2; 2 → 0) and B(E2; 4 → 2), and the yields of the 2^+ states used for normalization are about proportional to their B(E2; 2 → 0) values.

A coincidence spectrum from natural samarium which contains both the ^{152}Sm and ^{154}Sm 4 → 2 peaks, together with the reference 2 → 0 peaks, was shown in our earlier paper. The spectra from the enriched targets were much cleaner, giving more accurate peak areas, but they lacked the double internal standards. Each measurement was therefore weighted equally, but more measurements were made

with the natural targets than with the enriched ones. Fig. 1 shows the measured 4^+ total (differential) cross sections for ^{154}Sm, σ ($d\sigma$), divided by those calculated using the semiclassical Coulomb-excitation program with the indicated input data, σ_o ($d\sigma_o$), versus the bombarding energy. The cross sections include the feeding from higher-lying levels. The data do not vary significantly with type of target, type of measurement, or bombarding energy in the range from 10-12.5 MeV. If we ignore the very small variation with bombarding energy which is expected in the ratio $\sigma/\sigma_o(d\sigma/d\sigma_o)$, then we can form average results which are given in table 3. The error limits quoted for these ratios are the rms deviation of the results from the mean value, and therefore do not contain any of the systematic uncertainties.

For the interpretation of these results in terms of an E4 moment, the semi-classical calculated cross sections must be corrected for quantal effects. These have recently been calculated [2], and amount to a reduction of the calculated 4+ cross sections by about 7% in both ^{152}Sm and ^{154}Sm. The quantal corrections to the calculated 2^+ cross sections, which serve as the normalization, are less than 1%. Thus the ratios of the measured cross-sections to the quantal cross-sections are about 6% larger than the values in table 3. The quantum mechanical calculations show that the fractional change of the cross section due to E4 moments is adequately represented by the semiclassical calculation [7]. For the analysis of the present data, the ratios of cross sections given in table 3 were therefore increased by 6% and then evaluated in terms of $\langle 0^+ \| \mathcal{M}(E4) \| 4^+ \rangle$ by the semiclassical calculations as was done previously [1]. The results for ^{152}Sm and ^{154}Sm are given in table 3. The error limits correspond to about 5% uncertainty in the combined ratios σ/σ_o and $d\sigma/d\sigma_o$, which

is our best estimate of the experimental uncertainties and those coming from the parameters entering the analysis. The ^{152}Sm value is about 30% higher than our previous number, due almost entirely to the quantal corrections. A more detailed account of the important sources of uncertainty was given in ref. 1.

If, as previously, the nucleus is assumed to be a rigid, uniformly charged rotor with a sharp surface defined by

$$R + R_o(1 + \beta_2 Y_{20} + \beta_4 Y_{40}) \quad ,$$

then β_2 and β_4 can be evaluated from the measured E2 and E4 transition moments. Using $R_o = 1/2\ A^{1/3}$ F, we find the values for β_2 and β_4 given in table 3. In fig. 2 this shape for ^{154}Sm is shown together with (a) the shape that has $\beta_4 = 0$ and the same E2 moment and (b) the sphere having the same R_o. These β_4 values for the nuclear charge distribution are about twice those obtained for the nuclear field from (α,α') measurements above the Coulomb barrier [8,9,10]. They are also somewhat larger than expected on the basis of present calculations of nuclear shapes [11]. This conclusion differs from that in our previous paper [1] since (1) the value for ^{154}Sm is considerably larger than that for ^{152}Sm and (2) the quantal corrections for ^{152}Sm cause a 50% increase in β_4 for that nucleus. In view of this rather unexpected result, we feel one must consider carefully other possible explanations.

Least interesting of these is the possibility of an error in our analysis of the experimental data (a correction overlooked?) or incorrect input information for the calculated cross sections. Since a difference of only 5-10% in the ratio $\sigma/\sigma_o(d\sigma/d\sigma_o)$ could remove the discrepancy, it is difficult to rule this out entirely. Nevertheless, due to the internal consistency of our results

and of the input B(E2) values with respect to the rotational model, we consider this possibility unlikely. In this regard, some independent experimental results would be valuable, both on the 4^+ cross sections and on the input B(E2) values. A more interesting possibility is that there are effects in the Coulomb excitation process not yet understood nor included in the calculations. An accuracy of better than 5% is required in the calculated double-Coulomb-excitation cross sections, and no experiments of sufficiently high precision have been made to show that this can be achieved. A possible test might be to investigate heavier even-even rare earth nuclei, where the E4 effects should become small.

In spite of these possibilities we feel that our measurements most likely indicate the unexpectedly large β_4 values given in table 3. In comparing the (α,α') results and ours, it should be realized that the analysis of the inelastic alpha scattering data is much more complex than that of our Coulomb excitation data, which we have questioned above. Furthermore the Coulomb excitation results do not distinguish between an E4 matrix element resulting from a stable β_4 deformation and one arising from an rms value of β_4 due to an oscillation. It is not clear to us (i) whether the (α,α') results can distinguish between these two and (ii) to what extent the comparison of β_4 values from the two methods might be sensitive to this. However, the most straightforward explanation is that the different β_4 values represent a slightly different shape for the neutron and proton distributions in these nuclei. Fig. 2 shows the difference between $\beta_4 = 0$ and $\beta_4 = +0.13$; and the difference between β_4 from (α,α') data and ours is only about half this large--variations of about ± 0.2F in the nuclear surface--if R_o and β_2 are similar to those in fig. 2. It does not seem implausible to us that such differences could exist. Thus, the exact meaning of these β_4 values seems to us to be an open and very interesting problem.

In conclusion, our results suggest rather unexpectedly large values of β_4 for the intrinsic charge distributions in ^{152}Sm and ^{154}Sm. Fortunately, there are at least two rather direct approaches open to test our E4 moments. First, according to the trend of the E4 moments indicated by other results [8] and by calculations [11], effects on the cross sections due to these moments should be small in the Yb-W region so that the calculations can be checked without any significant ambiguity due to E4 contributions. The second approach is to use slightly heavier ions in order to excite higher states. The size of the E4 effects relative to the multiple E2 processes goes down with increasing projectile charge, but up strongly with the spin of the excited state. For example, with Li projectiles (if breakup can be avoided) it should be possible to observe the decay of the 6^+ state, where E4 effects of about 50% are expected to occur in these samarium nuclei. Effects of around a factor of two should be observable in the excitation of the 8^+ state with boron projectiles. Although many other effects become important with heavier ions, making the interpretation more difficult, the expected E4 effects are large and this approach seems very promising. It is, therefore, unlikely that the present uncertainties about these E4 moments will persist for long.

We are indebted to Drs. K. Alder and F. Roesel for their calculations of the quantal effects relevant to these experiments. We have also benefitted from many discussions with, and help from, Dr. N. K. Glendenning. One of us (FSS) wishes to acknowledge the hospitality of the Physics Section of the University of Munich during the preparation of this manuscript.

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Table 1

Vibrational states in ^{154}Sm

	beta vib. $\lambda=2$	gamma vib. $\lambda=2$	octupole vibrations $\lambda=3$, K=0	$\lambda=3$, K=1
Excitation energy [MeV]	1.178	1.437	1.011	1.581
Spin and parity, I^{π}	2^+	2^+	3^-	3^-
$B(E\lambda;\ 0 \rightarrow I)$ $[e^2b^{\lambda}]$	0.020	0.069	0.077	0.054
$f(4^+)$ = fraction of decays leading to the 4^+ state.	0.27[a]	0.013	0.3[b]	0.7[b]

[a] Assuming the branching from the 2^+ levels to be given by the vector addition coefficients.

[b] Assumed to be the same as those in ^{152}Sm (given in ref. 1).

Table 2

Table 2. Ground band levels in ^{150}Sm, ^{152}Sm, and ^{154}Sm

	^{150}Sm	^{152}Sm	^{154}Sm
Transition energies			
$2^+ \rightarrow 0^+$ [MeV]	0.3340	0.12178	0.08199
$4^+ \rightarrow 2^+$ [MeV]		0.2446	0.1849
Total conversion coeff.[a]			
$\alpha_T(2^+ \rightarrow 0^+)$	0.042	1.179	5.003
$\alpha_T(4^+ \rightarrow 2^+)$		0.109	0.277
$B(E2; 2^+ \rightarrow 0^+)$ $[eb]^2$	0.272 ± 0.010[c]	0.670 ± 0.015[b]	0.843 ± 0.019[b]
$B(E2; 4^+ \rightarrow 2^+)$ $[eb]^2$		0.989 ± 0.035[c]	1.186 ± 0.039[d]

[a] From calculations of H. Chr. Pauli, private communication, 1970.

[b] Weighted average from F. W. Richter et al. Z. Phys. 212 (1968) 202, and P. J. Wolfe et al. Phys. Rev. 160 (1967) 866.

[c] Ref. 5.

[d] Ref. 6.

Table 3

Averaged results and extracted-values

	^{152}Sm	^{154}Sm
Total cross section ratio for 4^+ state, σ/σ_o	1.11 ± 0.02	1.21 ± 0.03
Diff. cross section ratio for 4^+ state, $d\sigma/d\sigma_o$	1.11 ± 0.04	1.20 ± 0.09
$\langle 0^+ \| \mathcal{M}(E4) \| 4^+ \rangle$ [eb^2]	+0.45 ± 0.09	+0.67 ± 0.08
β_2	+0.248	+0.261
β_4	+0.09 ± 0.03	+0.13 ± 0.03

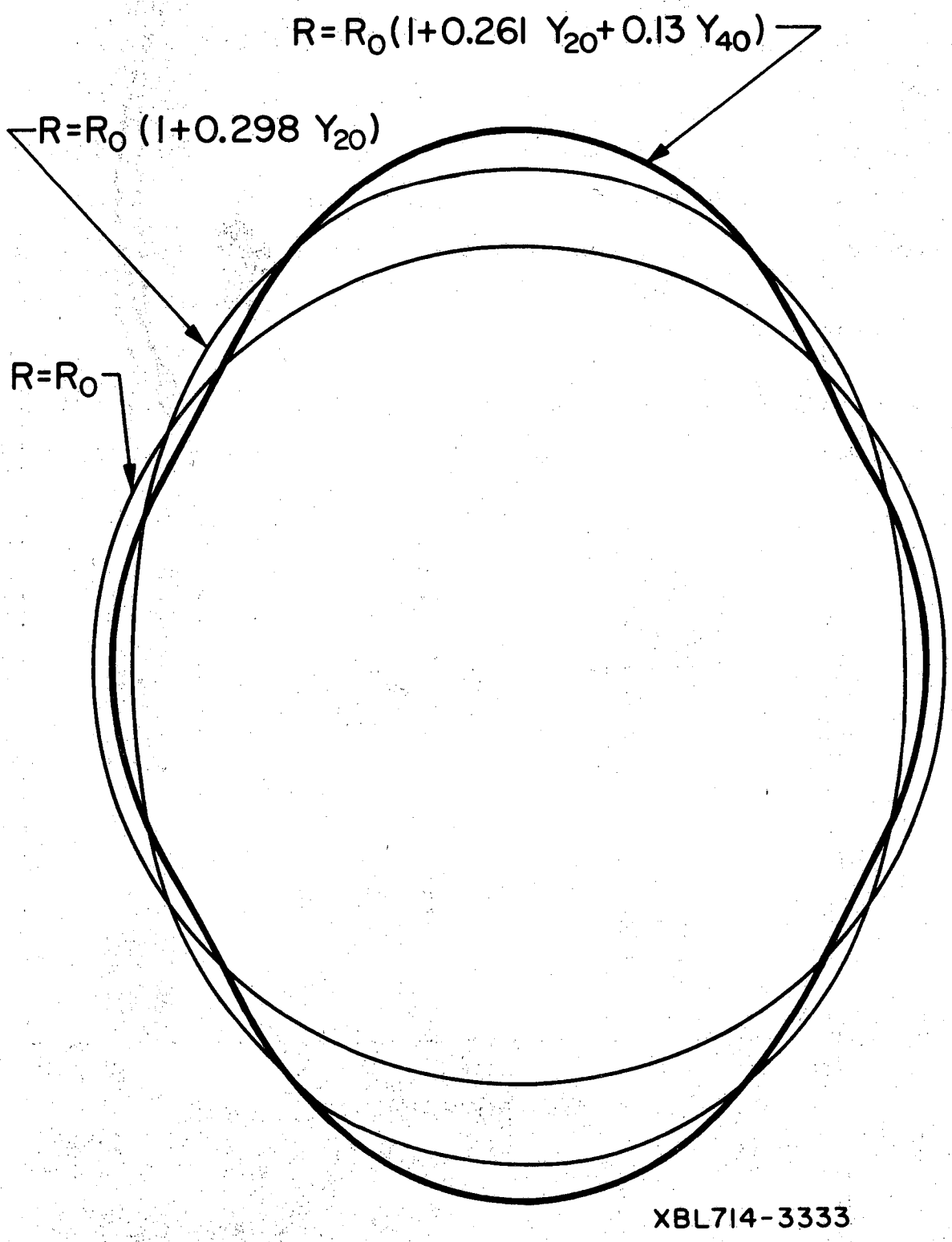

Fig. 2

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