# Excitation of the Ground-State Rotational Band of $^{152}$Sm by 250-MeV Electrons

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Elastic and inelastic angular distributions were measured, including that for the $6^+$ state at 0.712 MeV. Parameters of the charge distribution were determined, and compared with those obtained with low-energy electrons and with mass deformation parameters from $\alpha$ scattering. The data also compared to a Hartree-Fock calculation.

The samarium isotopes have long been a favorite region for studying the deformation properties of nuclei. They span a large range of deformation, from the spherical nucleus $^{144}_{62}Sm_{82}$ to the strongly deformed $^{154}$Sm. The low-lying states in $Sm^{144}$ and $Sm^{148}$ are vibrational, in $Sm^{154}$ they are rotational, while in $Sm^{150}$ and $Sm^{152}$ they exhibit vibrational as well as rotational characteristics. The transition from vibration to rotation is clearest at $Sm^{152}$.

The mass (or optical-potential) distributions of the Sm nuclei have been measured using various strongly interacting particles,[1-3] but we will compare our results mainly with results from the $(\alpha, \alpha')$ experiment at 50 MeV of Hendrie *et al.*[2] This latter experiment determined mass deformation parameters using a deformed Saxon-Woods optical potential in a coupled-channel analysis of the data.

The charge distributions of the Sm nuclei have been studied by electron scattering,[4] Coulomb excitation,[5] and muonic x-ray experiments.[6] The electron scattering from $Sm^{152}$ was measured up to a momentum transfer of $q \approx 1.2$ fm$^{-1}$ using electrons between 50 and 105 MeV. In the latter experiment, angular distributions were obtained for the $0^+$, $2^+$, and $4^+$ states, and charge deformation parameters were obtained by introducing a deformed Fermi charge distribution. By using the same model in the present study, we can conveniently exhibit the agreements and disagreements between the two studies. We will also compare our results with the Coulomb excitation measurements.

We measured the electron scattering from $^{144,148,150,152}$Sm up to large momentum transfers ($q \simeq 2.2$ fm$^{-1}$). In this Letter we present our results for $^{152}$Sm, while the complete results will be published in a subsequent paper. In addition to the higher momentum transfers obtained in the excitation of the same states measured in Ref. 4, we present an angular distribution for the $6^+$ state of the rotational band in $^{152}$Sm.

The $^{152}$Sm targets, enriched to 98.3%, were bombarded with a 251.5-MeV electron beam from the Saclay linear electron accelerator. The scattered electrons entered a magnetic spectrometer and were detected by a multiwire proportional counter placed in the focal plane. A description of the experimental setup can be found in Leconte.[7] The angular range extended from 25° to 104°, corresponding to momentum transfers from 0.6 to 2.2 fm$^{-1}$. The relative efficiencies of different wires in the multiwire proportional counter were obtained by measuring the quasielastic scattering from $^{12}$C, and the absolute efficiency was determined by measuring the elastic scattering from $^{12}$C and using the parameters of Sick and McCarthy[8] for normalization.

The quasielastic region of $^{12}$C was measured repeatedly during the experiment to verify the stability of the detectors. The cross sections were extracted by applying a channel-by-channel procedure for the radiative corrections. We estimate that this data handling introduces a systematic error of approximately 3%. The corrected spectrum was subsequently analyzed with various peak-fitting programs. The peak fitting and the counting statistics introduced additional errors, which are presented, together with the systematic errors.

The results[9] are presented in Fig. 1, where we plot $F^2 = (d\sigma/d\Omega)_{\text{expt}}/(d\sigma/d\Omega)_{\text{Mott}}$ as a function of angle and of the momentum transfer $q$. The $6^+$ state at 0.712 MeV could not be separated from the $0^+$ state at 0.685 MeV. This $0^+$ state is the first member of a $\beta$-vibrational band.[10]

We can estimate the cross section of the $E0$ transition to the $0^+$ $\beta$-vibrational state with the simple one-phonon $\beta$-vibration model. The absolute value of the cross section is normalized with the value of the monopole matrix element estimated by Riedinger, Johnson, and Hamilton.[11] From this calculation we estimate that the amount of $0^+$

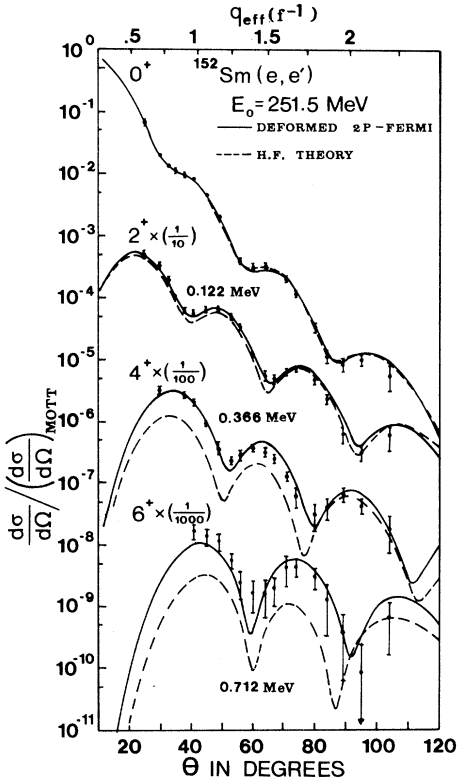


FIG. 1. Experimental values of $\sigma/\sigma_{\text{Mott}}$ for the ground-state rotational band of $^{152}$Sm, as a function of angle and $q_{\text{eff}} = q(1+\frac{4}{3}Z\alpha\langle r^2\rangle^{-1/2}E^{-1})$. The solid lines are phenomenological fits (see text) and the dashed lines are the results of the use of HF wave functions.

contamination in the $6^+$ data can be at most 20%.

We assume a deformed Fermi form for the charge distribution, given by

$$\rho(r,\theta)=\rho_0(1+\exp\{[r-c(\theta)]/t\})^{-1},$$

where

$$c(\theta)=c_0[1+\beta_2 Y_{20}(\theta)+\beta_4 Y_{40}(\theta)+\beta_6 Y_{60}(\theta)].$$

We also assume a pure rotational model in which $Sm^{152}$ is considered to have fixed deformation with axial and reflection symmetries. With these assumptions, the scattering cross section for angular momentum transfer $L$ within the ground-state rotational band is related[4] to the square of the transition charge density $\rho_L^{\text{tr}}(r)=\int\rho(r,\theta)Y_{L0}(\theta)\times d\Omega$. The $\rho_L^{\text{tr}}(r)$ depend on all the deformation parameters $\beta$ in both absolute value and sign. The transition charge densities determine[4] the reduced transition probabilities via the relationship

$$B(EL\uparrow)=|\int_0^\infty \rho_L^{\text{tr}}(r)r^{L+2}dr|^2.$$

The elastic and inelastic cross sections for the ground-state rotational band are then determined by just five variables: $c_0$, $t$, $\beta_2$, $\beta_4$, and $\beta_6$. We performed a least-squares analysis of the four angular distributions, as a function of these five variables. The root-mean-square radius value was constrained to be within 1 standard deviation of the rms value $\langle r^2\rangle^{1/2}=5.085$ fm determined in a recent[6] muonic x-ray experiment. The overall fit was good with $\chi^2=1.9$ per degree of freedom. In analyzing the elastic scattering, a complete phase-shift partial-wave analysis of the Dirac equation is used. For the inelastic cross sections, a distorted-wave Born approximation (DWBA) analysis (computer code HEINEL) is made in which the electron wave function is distorted by the Coulomb monopole field. The best-fit parameters are given in Table I, together with the values of $B(EL)$. We include also the corresponding values of the previous electron scattering, Coulomb excitation, and $(\alpha,\alpha')$ experiments. The best-fit curves are shown in Fig. 1. The agreement of the data with the best-fit curves is good for the entire range of momentum transfer

TABLE I. Charge and mass distribution parameters of $Sm^{152}$.

| Reaction | Reference | $\langle r^2\rangle^{1/2}$ | $c_0$ | $t$ | $\beta_2$ | $\beta_4$ | $\beta_6$ | $B(E2)$ ($e^2\cdot b^2$) | $B(E4)$ ($e^2\cdot b^2$) | $B(E6)$ ($e^2\cdot b^2$) |
|---|---|---|---|---|---|---|---|---|---|---|
| 250 MeV $(e,e')$ | Present work | 5.0246 | 5.778 ± 0.010 | 0.545 ± 0.037 | 0.286 ± 0.002 | 0.092 ± 0.002 | 0.010 ± 0.002 | 3.45 ± 0.06 | 0.210 ± 0.013 | 0.0114 ± 0.0007 |
| Low energy $(e,e')$ | 2,4 | 5.0922 | 5.804 | 0.581 | 0.287 ± 0.003 | 0.070 ± 0.003 | −0.012[a] | 3.38 ± 0.07 | 0.136 ± 0.013 | |
| Coulomb excitation $(\alpha,\alpha')$ | 5 | | | | 0.276 ± 0.012 | 0.065 ± 0.029 | | 3.45 ± 0.07 | 0.137 ± 0.078 | |
| 50 MeV $(\alpha,\alpha')$ | 2,15 | | | | 0.256 | 0.061 | −0.006 | | | |
| HF calculation | 12 | 4.998 | | | | | | 2.99 | 0.089 | 0.0027 |

[a] Fixed.

studied.

For the Sm nuclei, there exist calculations of the ground-state intrinsic wave function using the Hartree-Fock (HF) method.[12] The calculation used a phenomenological two-nucleon interaction that has previously given good agreement with charge distributions measured in other electron scattering experiments. The HF calculation is consistent with the idea[13] that the $Sm^{152}$ nucleus undergoes shape oscillations in its ground and excited states, and cannot simply be explained by a model with fixed deformation. Nonetheless, we approximated the ground-state wave function by taking it to be the HF wave function at a deformation which corresponds to the stable minimum of the potential-energy surface. We calculated the electron scattering cross sections by using this wave function and then assuming a pure rotational model for $Sm^{152}$. The resulting form factors are shown in Fig. 1. The relevant numerical values extracted from the calculation are presented in Table I.

The predictions are good for the elastic-scattering and $2^+$-transition data in both shape and magnitude, and are quite reasonable for the shapes of the $4^+$ and $6^+$ angular distributions for the entire range of momentum transfer studied. The differences between the calculation and the data are largest for the higher spin states. This may reflect the inadequacy of the pure rotational, fixed-deformation assumption, or of the HF force, or of neglecting dispersive effects (which will be discussed further on). It will be of interest to study the electroexcitation of the ground-state band of $Sm^{154}$, and to compare these data also with similar HF calculations. For $Sm^{154}$, the pure rotational model is a better approximation[13] and one can better test the HF wave function.

The ground-state charge density and the $2^+$-state transition density for the HF and best-fit deformed Fermi approaches are similar in the surface region but differ at smaller radii. Yet, they do not yield very different cross sections in the range of momentum transfer studied in the present experiment. To determine more precisely the experimental charge distribution, it will be necessary to carry out a model-independent analysis of the elastic and inelastic data, rather than the specific analysis using the deformed Fermi shape.

The charge deformation parameters determined in the present work are compared with the mass deformation parameters of the $(\alpha, \alpha')$ experiment in Table I. It is well known[14] that the quantities determined by inelastic scattering experiments are not the $\beta$ but rather something like a deformation length $\beta R$. The $(\alpha, \alpha')$ values of Table I are those scaled by Hendrie[15] to a charge radius of $Rc = 1.1A^{1/3}$. Hendrie notes that his scaling formulas are reasonably valid for $\beta_2$ and $\beta_4$, but may have significant errors for $\beta_6$. Our value for the charge $\beta_2$ is about 10% larger than the nuclear $\beta_2$ in agreement with previous observations,[16] while our value for the charge $\beta_4$ is about 30% larger than the nuclear $\beta_4$. These results indicate either the inadequacy of the scaling formulas or the importance of dispersive effects, or that there are real differences between the mass and charge distributions. Real differences in the $\beta$ deformation parameters derived from inelastic scattering of different projectiles are, in fact, expected to be about 15%, on the basis of isospin arguments according to calculations of Madsen, Brown, and Anderson.[17] Our value of $\beta_6$ differs in sign from Hendrie's result, suggesting that the scaling formulas for $\beta_6$ are inadequate, and that the electron-scattering $\beta_6$ value is the more reliable.

The comparison of our results with those of Coulomb excitation is given in Table I. There is agreement within errors for the $\beta_2$ and $\beta_4$ deformation values. The comparison of our results with the previous electron scattering experiment of Bertozzi *et al.*[4] shows that for the region of overlapping momentum transfer there is good agreement with the elastic scattering and $2^+$-state excitation cross sections calculated with their parameters. However, our $4^+$ cross section is larger by approximately 30%. We do not have a definte explanation for this large difference, but it may be due in part to energy-dependent dispersive effects in exciting the $4^+$ state.

In the analysis of electron scattering data, dispersion effects are usually neglected. Mercer and Ravenhall[18] considered some dispersive effects for $Sm^{152}$ at 105 MeV electron energy by carrying out a coupled-channel calculation which included the $0^+$, $2^+$, and $4^+$ states. A preliminary comparison[19] of these calculations to the low-energy electron scattering data[4] shows that only the $\beta_4$ parameter is significantly affected by the dispersion effects: Its value appears to increase by about 7% compared to the simple DWBA value. Calculations[19] for $Sm^{152}$ at 250 MeV, which include the $6^+$ state, are in progress at this time. The eventual comparison[19] of the present data with these calculations will change mainly $\beta_4$ and $\beta_6$, and will determine the definitive values for these parameters. However, the relatively small

change in $\beta_4$ at 105 MeV already suggests that the values presented here will change at most by about 20% when the dispersive effects are included. If the dispersive effects at 250 MeV are different from those at 105 MeV, that could help explain part of the discrepancy for the $\beta_4$ parameter. It would then be of interest to study the $4^+$ cross section as a function of the incident energy to determine better the role played by dispersive effects.

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[1]P. B. Woollam, R. J. Griffiths, F. G. Kingston, C. B. Fulmer, J. C. Hafele, and A. Scott, Nucl. Phys. A179, 657 (1972).

[2]D. L. Hendrie, N. K. Glendenning, B. G. Harvey, O. N. Jarvis, H. H. Duhm, J. Saudinos, and J. Mahoney, Phys. Lett. 26B, 127 (1968).

[3]N. Trautner, G. Lovhoiden, and P. R. Christensen, Phys. Lett. 44B, 41 (1973).

[4]W. Bertozzi, T. Cooper, N. Ensslin, J. Heisenberg, S. Kowalski, M. Mills, W. Turchinetz, C. Williamson, S. P. Fivozinsky, J. W. Lightbody, Jr., and S. Penner, Phys. Rev. Lett. 28, 1711 (1972); T. Cooper, W. Bertozzi, J. Heisenberg, S. Kowalski, W. Turchinetz, C. Williamson, L. Cardman, S. Fivozinsky, J. W. Lightbody, Jr., and S. Penner, Phys. Rev. C 13, 1083 (1976).

[5]T. K. Saylor, J. X. Saladin, I. Y. Lee, and K. A. Erb, Phys. Lett. 42B, 51 (1972); W. Brückner, D. Husar, D. Pelte, K. Traxel, M. Samuel, and U. Smilansky, Nucl. Phys. A321, 159 (1974).

[6]D. Hitlin, S. Bernow, S. Devons, I. Duerdoth, J. W. Kast, E. R. Macagno, J. Rainwater, C. S. Wu, and R. C. Barrett, Phys. Rev. C 1, 1184 (1970); P. Barreau, private communication.

[7]P. Leconte, unpublished.

[8]I. Sick and J. S. McCarthy, Nucl. Phys. A150, 631 (1970).

[9]A table of cross sections can be obtained from the authors.

[10]L. Varnell, J. D. Bowman, and J. Trischuk, Nucl. Phys. A127, 270 (1969).

[11]L. L. Riedinger, N. R. Johnson, and J. H. Hamilton, Phys. Rev. 179, 1214 (1969).

[12]D. Gogny, in *Nuclear Self Consistent Fields*, edited by G. Ripka and M. Porneuf (North-Holland, Amsterdam, 1976); J. Decharge, M. Girod, and D. Gogny, Phys. Lett. 55B, 361 (1975).

[13]P. Debenham and N. M. Hintz, Nucl. Phys. A195, 385 (1972); R. G. Stokstad, J. S. Greenberg, I. A. Fraser, S. H. Sie, and D. A. Bromley, Phys. Rev. Lett. 27, 749 (1971).

[14]J. S. Blair, in *Direct Interactions and Nuclear Reaction Mechanisms*, edited by E. Clementel and C. Villi (Gordon and Breach, New York, 1963), p. 669.

[15]D. L. Hendrie, Phys. Lett. 31, 478 (1973).

[16]R. E. Shamu, C. H. Lagrange, E. M. Bernstein, J. J. Ramirez, T. Tamura, and C. Y. Wong, Phys. Lett. 61B, 20 (1976).

[17]V. A. Madsen, V. R. Brown, and J. D. Anderson, Phys. Rev. Lett. 34, 1339 (1975).

[18]R. L. Mercer and D. G. Ravenhall, Phys. Rev. C 10, 2002 (1974),

[19]L. S. Cardman, D. H. Dowell, R. L. Gulbranson, R. L. Mercer, and D. G. Ravenhall, private communication (to be published).

## Correspondence Between $\alpha$-Transfer and Two-Proton and Two-Neutron Transfer Reactions to the Nickel Isotopes*

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The ($^6$Li,$d$) reaction has been measured at 34-MeV incident energy from targets of $^{54}$Fe, $^{56}$Fe, and $^{58}$Fe using a $Q3D$ spectrograph. A close correspondence is found between the ($^6$Li,$d$) spectra and previous ($t$,$p$) and ($^3$He,$n$) results for the same final nuclei. The $0^+$ proton-pairing vibration states in $^{58}$Ni and $^{60}$Ni are strongly excited, and the pairing vibration is identified for the first time at 3.519 MeV in $^{62}$Ni based on ($^6$Li,$d$). The remainder of the levels in $^{60}$Ni and $^{62}$Ni follow closely the ($t$,$p$) patterns of excitation.

The understanding of multinucleon transfer reactions in general, and $\alpha$ transfer in particular, has long been a goal of nuclear physics, and much work has been devoted to this topic.[1-8] Interpretations of such data have been often confusing and contradictory, but an interesting thread has recently emerged which could provide a possible breakthrough in our understanding of multinucleon transfer and the related problem of clustering in nuclei. Several papers suggest a close correspondence between $\alpha$ transfer and two-nucleon transfer reactions.[4-6] If such relationships