Orbital Magnetic Dipole Strength in ^{148,150,152,154}Sm and Nuclear Deformation

W. Ziegler, C. Rangacharyulu,[a] A. Richter, and C. Spieler
Institut für Kernphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, Germany
(Received 3 July 1990)

Nuclear-resonance-fluorescence spectra have been measured in the chain of ^{148,150,152,154}Sm isotopes. Together with supplementary information from inelastic electron scattering and other reaction studies, orbital $M1$ transition strengths have been deduced from a number of 1^+ states located around an excitation energy of 3 MeV. The systematic study, carried out for the first time, for nuclei within a large range of the deformation parameter δ shows that the orbital $M1$ strength varies quadratically with δ. This result is interpreted in terms of models containing explicitly neutron and proton degrees of freedom.

PACS numbers: 21.10.Re, 23.20.Qz, 25.20.Dc, 27.70.+q

The role of neutron-proton interactions on collective nuclear excitations has been a subject of investigations for over four decades. Soon after the discovery of giant dipole resonances, they were interpreted[1] as isovector volume vibrations with neutrons as a whole oscillating out of phase against protons. More recently, a so-called "scissors mode" of oscillations based on a macroscopic two-rotor model (TRM) was suggested,[2] which predicts that 1^+ levels with strong ground-state $M1$ transitions occur in even-even deformed nuclei. The discovery[3] of $M1$ excitations in heavy deformed nuclei by high-resolution inelastic electron scattering led to a series of detailed investigations on experimental and theoretical fronts.[4] These excitations today still constitute also the best proof for the so-called "mixed-symmetry states" in the neutron-proton interacting-boson model (IBM-2).[5]

Macroscopic calculations predict that the orbital $M1$ strength is to be found in one or a few states, while the experiments indicate that it is generally fragmented into more levels (see, e.g., Refs. 4 and 6). This disparity with macroscopic descriptions is attributed to two-quasiparticle excitations.[7]

Very recently, a systematic study[8] of $M1$ strength in the rare-earth region within the Nilsson model has shown quantitatively a direct correlation between the quadrupole ground-state deformation and the orbital magnetic dipole strength. This finding is also in agreement with predictions[5,9] of the interacting-boson model where in both the SU(3) and the O(6) limits, i.e., the case where nonspherical nuclei rotate and vibrate, respectively, the reduced $M1$ transition strength is proportional to $N_\pi N_\nu/(N_\pi+N_\nu)$, with N_π (N_ν) being the number of valence proton (neutron) bosons, and is thus within a given series of isotopes not only a function of the number of neutrons present but predominantly dependent upon the neutron-proton interaction responsible for the quadrupole deformation of nuclear ground states.[10] Besides these two classes of models, other calculations exist where the deformation parameter δ is explicitly contained in the analytic expressions for the reduced $M1$ transition strength. Some of them are random-phase-approximation predictions;[11-13] others result from the TRM, sum-rule, and so-called giant-angle-dipole approaches.[14-16] These predictions, which are listed in Ref. 17, all point to a linear dependence of the $M1$ transition strength on δ. To our knowledge only one calculation, the neutron-proton-deformation (NPD) model,[18] suggests a quadratic dependence of the orbital $M1$ strength on the deformation parameter.

As nearly all experimental data,[4] to date, were limited to nuclei of about the same deformation ($\delta \approx 0.20$–0.25), the important aspect of orbital $M1$ strength dependence on δ has not yet been examined. The present investigation constitutes a systematic study of orbital $M1$ strength in even-mass samarium isotopes for which the deformation parameter varies by a factor of ~ 3.5. Earlier, Metzger[19] measured nuclear-resonance-fluorescence (NRF) spectra on ^{144}Sm ($\delta=0.078$). In this Letter, we report the results of our measurements on ^{148}Sm ($\delta=0.122$), ^{150}Sm ($\delta=0.164$), ^{152}Sm ($\delta=0.249$), and ^{154}Sm ($\delta=0.274$). Present-day model arguments and experimental results[4,8] concur that the orbital $M1$ strength in heavy deformed nuclei lies below 4-MeV excitation energy and that spin strength appears at higher energies. Here we restrict ourselves solely to a discussion of orbital $M1$ strength.

Nuclear-resonance-fluorescence spectra for the four samarium isotopes have been measured with the recently developed facility for NRF experiments at the new Superconducting Darmstadt Linear Accelerator[20] (S-DALINAC). Enriched isotopic targets were exposed to cw bremsstrahlung radiation with photon beams at end-point energies between 3 and 5 MeV to selectively explore different regions of excitation. Figure 1 displays the spectra for all the isotopes, taken at 4.6-MeV end-point energy. As can be seen, ^{148}Sm, the nucleus of the smallest deformation, shows very few transitions. The number of transitions increases with deformation and ^{154}Sm, with the largest deformation, exhibits the highest density of transitions. It is also worth noting that the $M1$ transitions cluster around 3-MeV excitation energy.

Multipolarities of individual transitions are ascertained by simultaneous two-point angular distribution measurements taken at 90° and 127°. Those data

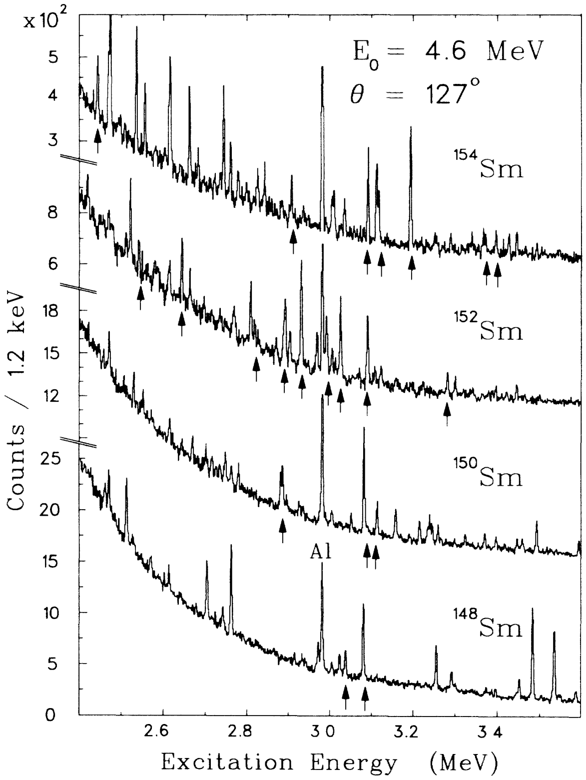

FIG. 1. Nuclear-resonance-fluorescence spectra for the samarium isotopes. A cw bremsstrahlung beam at an endpoint energy of 4.6 MeV was incident on the targets. Note the increase in the number of transitions with increasing mass number (deformation). $M1$ transitions are marked by arrows. The line marked "Al" is the aluminum calibration γ ray.

sufficed to clearly distinguish between quadrupole and dipole transitions. In the case of ^{152,154}Sm, we were able to determine the parity of the transitions ($M1$, $E1$) by supplementing the present (γ,γ') data with (e,e') data taken earlier at the DALINAC.[21] For ^{148,150}Sm, we have assigned the parities of the $J=1$ states by comparing our results with the data from single-nucleon-transfer reactions, β^- decay, and (n,γ) processes.[22] Transition strengths were determined from (γ,γ') data with the help of calibration standards in ^{27}Al measured simultaneously. From our measurements we could determine all transitions with $B(M1)\uparrow \geq 0.07\mu_N^2$ for the 2–4-MeV excitation region.

In all nuclei, we observe one or two strong $M1$ transitions $[B(M1)\uparrow \sim (0.3\text{–}0.8)\mu_N^2]$ near 3-MeV excitation energy and a few more levels with smaller transition strengths. As our main emphasis is in the variation of orbital $M1$ strength with δ, it is instructive, for a comparison with models, to use summed $B(M1)$ strengths $[\sum_i B_i(M1)]$ and mean excitation energies

$$\bar{E} = \sum_i E_i B_i(M1) \Big/ \sum_i B_i(M1)\,,$$

where $B_i(M1)$ is the transition strength for the level at E_i. Table I lists these quantities for all the four isotopes, measured by us. In the case of ^{144}Sm we adopt the 3.966-MeV level to be the only 1^+ state below 4-MeV excitation, as deduced from the linear polarization of the scattered γ rays.[19] We include this transition in the table.

First, we compare our results with IBM-2 calculations. Figure 2 shows the plot of $\sum_i B_i(M1)$ versus mass number. The results of Scholten *et al.*,[9] fixing the "scissors level" at 3-MeV excitation, are shown as a dash-dotted line. It is clear that this calculation, with boson g factors $g_\pi = 1$, $g_\nu = 0$, already underestimates the transition strengths. In the SU(3) limit, one obtains[23] in that case

$$B(M1)\uparrow = \frac{3}{4\pi}\frac{8N_\pi N_\nu}{[2(N_\pi+N_\nu)-1]}\mu_N^2\,. \tag{1}$$

The result for valence bosons beyond $Z=50$, $N=82$ major shell closures is shown as a solid line in Fig. 2. The agreement between experiment and the simple prediction is quite impressive for the ^{152,154}Sm isotopes. For the ^{148,150}Sm isotopes predictions with $Z=64$ subshell closure are shown as a dashed line on the same figure. The experimental results are in very good agreement with the model. It seems to support the observation of Casten, Brenner, and Haustein[10] that the $Z=64$ subshell closure, while appearing for $N \leq 90$, disappears for heavier isotopes. In either case, the IBM predicts zero transition

TABLE I. Deformation parameter δ, mean 1^+ excitation energy $\bar{E}_x$, and orbital $M1$ strength $\sum_i B_i(M1)$ are shown along with the stiffness and inertia parameters for the orbital mode (C_1, B_1) and ground-state bands (C_γ, B_γ) in the samarium isotopes.

Nucleus	δ	$\bar{E}_x$ (MeV)	$\sum_i B_i(M1)$[a] (μ_N^2)	C_1 (MeV)	C_γ (MeV)	B_1 ($\hbar^2$/MeV)	B_γ ($\hbar^2$/MeV)
^{154}Sm	0.27	3.09	2.65	98	874	10.3	446
^{152}Sm	0.25	2.98	2.35	104	443	11.8	401
^{150}Sm	0.16	3.18	0.97	114	809	11.6	614
^{148}Sm	0.12	3.07	0.51	105	790	11.9	490
^{144}Sm[b]	0.08	3.97	0.28	186	···	13.7	···

[a]Uncertainty ± 10%.
[b]From Ref. 19.

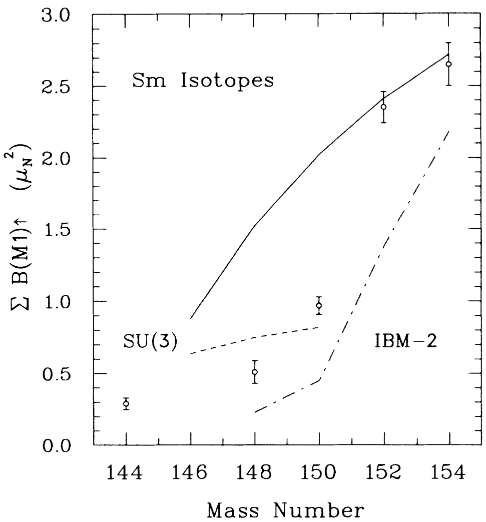

FIG. 2. The orbital $M1$ strength vs mass number. The full IBM calculations of Ref. 9 (dash-dotted line) are shown together with results in the SU(3) limit using a $Z=50$ shell closure (solid line), and $Z=64$ subshell closure (dashed line).

strength for the semimagic nucleus ^{144}Sm. However, a fraction of valence bosons ($N_v < 0.5$) is enough to reconcile the prediction with experimental data. It implies a small breaking (at percent level) of the major shell closure, which is not surprising at all.

Second, we examine the explicit dependence of the $M1$ transition strength on deformation. As is seen in Fig. 3, where $\sum_i B_i(M1)$ is plotted against δ^2, the linear relation between the two variables is striking. Since—as noted above—there is only one model that predicts $B(M1) \propto \delta^2$, the so-called neutron-proton deformation model of Rohozinski and Greiner,[18] we take our summed $B(M1)$ and $\bar{E}_x$ values and interpret them in terms of this model. The NPD model, dealing with separate neutron and proton deformations like the IBM-2, is in a way the geometrical counterpart of the latter.

The NPD model (for details, see Ref. 18) gives the following expressions for the excitation energy and the strength of the collective 1^+ state:

$$E_1^+ = \hbar\sqrt{C_1/B_1} + \hbar^2/2J\,, \tag{2}$$

$$B(M1) \approx (9/4\pi)\beta^2(B_1C_1/\hbar^2)^{1/2} g_{\rm rel}^2 \mu_N^2\,, \tag{3}$$

where C_1 and B_1 are the stiffness and mass parameters, respectively. The quantity J is the moment of inertia and $g_{\rm rel}$ is the difference of the gyromagnetic factors of proton and neutron taken here to be unity.

From the experimentally determined $\bar{E}_x$ and $\sum_i B_i(M1)$, we deduce C_1 and B_1, for each nucleus. They are listed in Table I. With the exception of ^{144}Sm, C_1 and B_1 remain fairly constant (within 10%). The C_1 parameter for ^{144}Sm ($N=82$) is nearly twice as large as for the other isotopes. As C_1 is a measure of stiffness, the enhancement is easily understood as due to shell closure. For the heavier isotopes, we have also deduced C_γ and B_γ, the corresponding parameters for the γ bands in these nuclei (Table I). In agreement with Ref. 18, we find that the stiffness and mass parameters for the dipole mode are considerably smaller than those for the γ bands. We thus conclude that the NPD model, which explains the orbital $M1$ excitations of 1^+ states around $E_x \approx 3$ MeV as one-phonon neutron skin vibrations in a deformed nucleus, gives very meaningful physical parameter sets over the wide range of δ values studied experimentally.

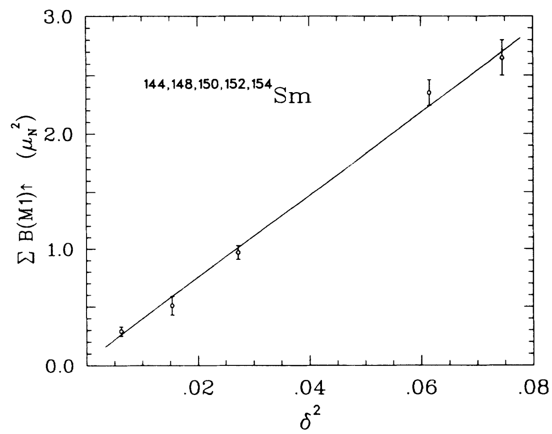

FIG. 3. The orbital $M1$ strength vs the square of the nuclear deformation parameter δ. The straight line results from a least-squares fit.

Finally, we remark that for the $M1$ mode, Nojarov, Bochnacki, and Faessler[24] deduced these parameters in a semimicroscopic calculation also. For ^{154}Sm, they are nearly 3 times as large as our numbers in the macroscopic picture. It should be noted, however, that in Ref. 24 the $B(M1)$ strength is overestimated by about a factor of 2. The reason might be the following: In a classical picture,[25] we can roughly estimate the number of nucleons participating in a given mode (λ) of vibration as $B_\lambda \propto A^{5/3}/\lambda$. Thus, for the dipole mode

$$A_1^{\rm eff} = A_2(B_1/2B_\gamma)^{0.6}\,, \tag{4}$$

where $A_1^{\rm eff}$ is the effective number of nucleons contributing to the dipole mode and A_2 is the same for the γ mode. Assuming that the entire nucleus participates in γ vibrations, we obtain $A_1^{\rm eff} \approx 10$ nucleons for the dipole mode in the samarium isotopes. The $A_1^{\rm eff}$ is smaller by nearly a factor of 7 compared to that of Ref. 24.

In conclusion, we reported a systematic study of orbital $M1$ strengths for even samarium isotopes by the NRF technique with cw bremsstrahlung beams from the S-DALINAC. For the first time, we were able to determine the $M1$ strengths over a large range of nuclear deformation δ and found a striking linear dependence of the strength on δ^2. IBM-2 sum-rule predictions with free-boson g factors, in the SU(3) limit, are exhausted in the heavier isotopes. The macroscopic neutron-proton deformation model offers the simplest explanation of the $M1$ strength dependence on nuclear deformation. From this model and the experimental data, we conclude that orbital $M1$ strengths in these nuclei are weakly collective as only a small fraction ($<10\%$) of the total number of nucleons participate in these excitations.[26] This observation is in qualitative agreement with the predictions of the IBM and other models.

It is a great pleasure to thank Dr. H. D. Gräf, Dr. K. Alrutz-Ziemssen, Dr. D. Flasche, and Dr. H. Weise for the excellent beams from S-DALINAC. We acknowledge several helpful discussions with Dr. R. D. Heil and Dr. H. H. Pitz, regarding the experimental aspects. We have benefited from several interesting and informative discussions with Professor K. Keyde and H. J. Wörtche. This work was supported by Deutsche Forschungsgesellschaft and by Bundesministerium für Forschung und Technologie under Contracts No. SP-162-11-4 and No. 06 DA 184I, respectively. One of us (C.R.) held a grant from the Heraeus-Stiftung and Natural Sciences and Engineering Research Council, Canada.

[a]On sabbatical leave from the Department of Physics, University of Saskatchewan, Saskatoon, Canada S7N 0W0.

[1]M. Goldhaber and E. Teller, Phys. Rev. **74**, 1046 (1948).

[2]N. Lo Iudice and F. Palumbo, Phys. Rev. Lett. **41**, 1532 (1978).

[3]D. Bohle, A. Richter, W. Steffen, A. E. L. Dieperink, N. Lo Iudice, F. Palumbo, and O. Scholten, Phys. Lett. **137B**, 27 (1984).

[4]For a summary, see A. Richter, Nucl. Phys. **A507**, 99c (1990).

[5]F. Iachello, Phys. Rev. Lett. **53**, 1427 (1984).

[6]B. Kasten, R. D. Heil, P. v. Brentano, P. A. Butler, S. D. Hoblitt, U. Kneissl, S. Lindenstruth, G. Müller, H. H. Pitz, K. W. Rose, W. Scharfe, M. Schumacher, U. Seemann, Th. Weber, C. Wesselborg, and A. Zilges, Phys. Rev. Lett. **63**, 609 (1989).

[7]D. Zawischa, M. Macfarlane, and J. Speth, Phys. Rev. C **42**, 1461 (1990).

[8]C. De Coster and K. Heyde, Phys. Rev. Lett. **63**, 2797 (1989).

[9]O. Scholten, K. Heyde, P. Van Isacker, J. Jolie, J. Moreau, M. Waroquier, and J. Sau, Nucl. Phys. **A438**, 41 (1985).

[10]R. F. Casten, D. S. Brenner, and P. E. Haustein, Phys. Rev. Lett. **58**, 658 (1987).

[11]D. R. Bes and R. H. Broglia, Phys. Lett. **137B**, 141 (1984).

[12]I. Hamamoto and S. Åberg, Phys. Lett. **145B**, 163 (1984).

[13]H. Kurasawa and T. Suzuki, Phys. Lett. **144B**, 151 (1984).

[14]G. De Franceschi, F. Palumbo, and N. Lo Iudice, Phys. Rev. C **29**, 1496 (1984).

[15]E. Lipparini and S. Stringari, Phys. Lett. **130B**, 139 (1983).

[16]R. R. Hilton, J. Phys. (Paris), Colloq. **45**, C6-255 (1984).

[17]D. Bohle, G. Küchler, A. Richter, and W. Steffen, Phys. Lett. **148B**, 260 (1984).

[18]S. G. Rohozinski and W. Greiner, Z. Phys. A **322**, 271 (1985).

[19]F. Metzger, Phys. Rev. C **17**, 939 (1978).

[20]H.-D. Gräf and A. Richter, Continuous Electron Beam Accelerator Facility Report No. CEBAF-Report-89-001, 1989 (to be published), p. 231.

[21]H. Diesener, R. A. Meyer, A. Nitsch, A. Richter, and H. Wörtche (to be published).

[22]E. der Mateosian, Nucl. Data Sheets **48**, 345 (1986); L. K. Peker, *ibid.* **59**, 393 (1990), and references therein.

[23]B. R. Barrett and P. Halse, Phys. Lett. **155B**, 133 (1985).

[24]R. Nojarov, Z. Bochnacki, and A. Faessler, Z. Phys. A **324**, 289 (1986).

[25]D. J. Rowe, *Nuclear Collective Motion* (Methuen, London, 1970).

[26]N. Lo Iudice and A. Richter, Phys. Lett. B **228**, 291 (1989).