PHYSICAL REVIEW C VOLUME 44, NUMBER 2 AUGUST 1991

Shape coexistence in ^{140}Sm and the onset of deformation below $N=82$ from lifetime measurements

M. A. Cardona*
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Legnaro, Padova, Italy

S. Lunardi and D. Bazzacco
Dipartimento di Fisica dell'Università di Padova and Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Padova, Italy

G. de Angelis and V. Roca
Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Napoli, Italy

(Received 17 April 1991)

Different deformations for the two bands built above the $(\pi h_{11/2})^2$ 10^+ and the $(\nu h_{11/2})^{-2}$ 10^+ states in ^{140}Sm have been determined from lifetime measurements using the reaction ^{106}Pd(^{37}Cl,$p2n$)^{140}Sm at 143 MeV. The β values derived for the $N=78$ and $N=80$ core nuclei, coexisting in ^{140}Sm, complete the systematics of nuclear deformation from $N=72$ to 80.

The nuclei of Sm and Gd with neutron number $N=78$ have ground-state bands with a collective behavior which are interrupted at $I=10^+$ by two isomeric states of single-particle character [1]. These two states have been interpreted as an $h_{11/2}$ two-proton particle excitation and as an $h_{11/2}$ two-neutron hole excitation, respectively. The g factors of the 10^+ states have been measured confirming these assignments [2,3].

Two independent level sequences of stretched $E2$ transitions have been established above the two 10^+ single-particle excitations in the Nd, Sm, and Gd $N=78$ isotones [1,4,5]. These two bands have qualitatively different $\Delta I=2$ level spacings and resemble the ground-state bands of the respective core nuclei, which are the $N=78$ core for the levels above the $(\pi h_{11/2})^2$ 10^+ and the $N=80$ core for the levels above the $(\nu h_{11/2})^{-2}$ 10^+ state. An interpretation in terms of coexistence, at about the same excitation energy, of the two cores, which are supposed to have different quadrupole deformations, has been suggested [1,5].

Lifetime measurements in the collective sequences found above the two isomers can give a more definite answer to the question of the coexistence of different nuclear deformations. The present Brief Report reports the results of such a measurement in the $N=78$ nucleus ^{140}Sm.

Another problem that has been widely investigated both theoretically and experimentally [6–13] in this region is the transition from spherical to deformed shapes in nuclei with neutron number below $N=82$. Lister *et al.* [11] derived the deformation from the energy of the first 2^+ state in the even-even nuclei and discussed its behavior as a function of the neutron number. The $B(E2)$ values of the $2^+ \rightarrow 0^+$ transition and the deformation parameters β in even-even Sm isotopes for $N=72$, 74, and 76 obtained from lifetime measurement of the 2^+ excited state have been reported by Kern *et al.* [7], Soramel *et al.* [12], and Wadsworth *et al.* [13].

Similar measurements are not possible for $N=78$ and 80 nuclei where the presence of high-lying isomeric states in the nanosecond range prevents the determination of the true lifetime of the first 2^+ state with the plunger method. It is, however, a matter of fact that the collective bands built above the 10^+ isomers of ^{140}Sm are well described as the decoupling of two $h_{11/2}$ proton particles and two $h_{11/2}$ neutron holes to the $N=78$ and 80 core nuclei, respectively. Therefore, picosecond lifetime measurements performed for the states of these bands allow one to extract $B(E2)$ values and deformation parameters which can be assigned within this frame to the $N=78$ and 80 core nuclei.

For the present work lifetime measurements have been performed by means of the recoil-distance Doppler-shift technique, using a precision plunger apparatus. Excited levels in ^{140}Sm were populated through the ^{106}Pd(^{37}Cl,$p2n$)^{140}Sm reaction at a bombarding energy of 143 MeV. The beam was provided by the Tandem XTU accelerator of the Laboratori Nazionali di Legnaro. The target consisted of a stretched self-supporting ^{106}Pd foil with a thickness of 830 μg/cm^2. The evaporation residues were stopped in a stretched gold foil. The separation between the foils was adjusted with a micrometer screw, and the target to stopper capacity was continuously monitored during the experiment. At foil separations smaller than 300 μm the distance was also measured using an electromagnetic gauge head. Data were recorded at 20 distances ranging from electrical contact to 3 mm. The average recoil velocity $v=5.85(6)$ μm/ps was determined experimentally from the energy difference between the shifted and unshifted components of the strongest peaks. Gamma rays were detected using three Compton-suppressed germanium detectors positioned at 15°, 30°, and 90° with respect to the beam direction. In order to reduce low-multiplicity events originated mainly by Coulomb excitation and β-decay processes, a multiplicity filter composed of 17 BaF$_2$ crystals was used. Germanium events in coincidence with at least one element of the filter were recorded in list mode. At each distance the intensity of the lines was normalized with respect to the $2^+ \to 0^+$ transition of ^{140}Sm measured in the γ-ray spectrum of the detector placed at 90°. With a normalization performed using γ rays following Coulomb excitation of the Au stopper, one obtains the same results.

The recoil-distance data were analyzed starting at the highest observed state in each cascade. When appropriate, known discrete feeder states together with their measured effective lifetimes and feeding intensities have been taken into account. Gamma-ray intensities were obtained from the detector at 30° and corrected for angular distribution effects. While fitting the data, the side feeding was considered in two ways. In the first we assumed for it a negligible lifetime value, and in the second we used the lifetime of the feeding cascade. The error in the final lifetime includes the uncertainty in the side-feeding time.

An effective lifetime of 2.9(7) ps was estimated for the 16^+ state of the band built on the $(\pi h_{11/2})^2$ 10^+ isomer, fitting the decay curve of the 994-keV transition with a single exponential. From the decay curves of the 751- and 442-keV transitions, the lifetime values of the 14^+ and 12^+ states were obtained. In the case of the band built on the $(\nu h_{11/2})^{-2}$ 10^+ state, an effective value of 6(2) ps was obtained for the lifetime of the 14^+ state, and then from the decay curve of the 619-keV γ ray the lifetime of the 12^+ state was extracted. In Fig. 1 the recoil-distance data for the 442- and 619-keV transitions, and the best fit through the experimental points are shown. The obtained lifetimes together with the extracted $B(E2)$ values are summarized in Table I. The quadrupole deformation β for the two bands was obtained from the $B(E2)$ values, using the formula of an axially symmetric rotor:

$$B(E2,I+2\to I)=\frac{5}{16\pi}Q_0^2\langle I+2,K,2,0|I,K\rangle^2 ,$$

$$Q_0=\frac{3}{\sqrt{5\pi}}Zer_0^2A^{2/3}\beta , \quad r_0=1.2 \text{ fm} .$$

Since both bands built on the 10^+ isomers have a rotationally aligned structure, small K effective values are expected. The value $K=2$ was assumed, as it was previously used in the case of ^{136}Nd [14]. In the case of the band of proton character, this assumption is consistent with a prolate shape where both protons occupy orbitals at the bottom of the $h_{11/2}$ shell. Conversely, low K values for neutrons which are at the top of the $h_{11/2}$ shell require an oblate nuclear shape.

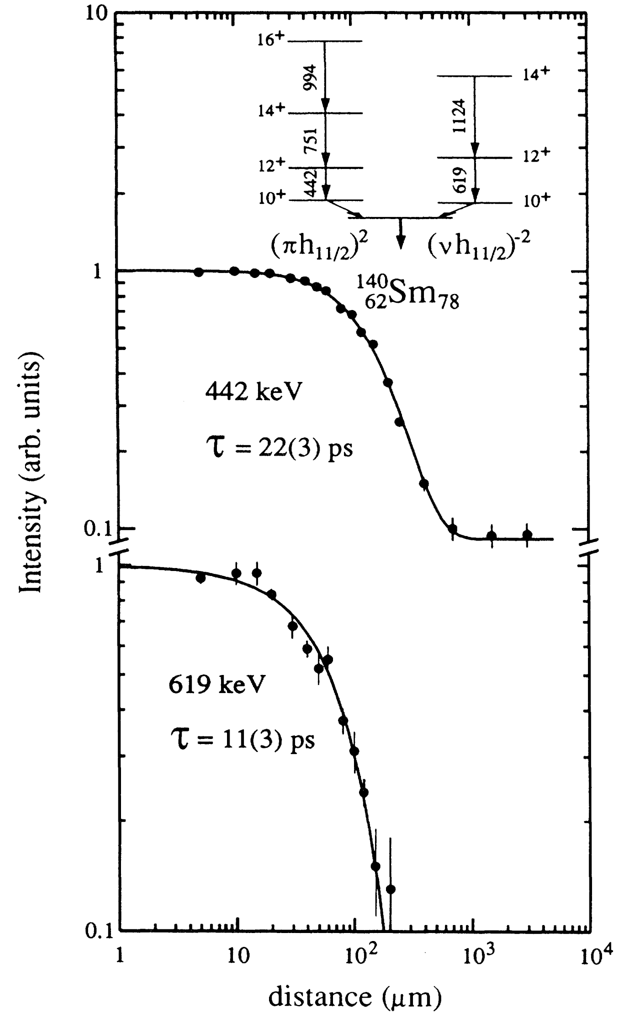

FIG. 1. Intensity of the stop peak of the 442- and 619-keV transitions in ^{140}Sm. A partial level scheme of ^{140}Sm with the first members of the $(\pi h_{11/2})^2$ and the $(\nu h_{11/2})^{-2}$ bands is shown in the inset.

The deformation parameters β obtained in this way are also shown in Table I. A change of two units of the K value produces a β variation less than 11%. It has also to be noted that the inclusion of the γ parameter following the assumption of a triaxial rotor model produces a maximum change in the β value of 10% when varying γ between 0° and 30°.

The different β values obtained for the two excited

TABLE I. Lifetimes, electromagnetic transition rates, and deformation parameters deduced from the present work.

Nucleus	$J_i \to J_f$	E_γ (keV)	τ (ps)	$B(E2)$ (e^2fm^4)	(W.u.)	$\lvert\beta\rvert$
^{140}Sm	$12^+ \to 10^+$	442	22(3)	2160(290)	50(7)	0.142(10)
	$14^+ \to 12^+$	751	1.7(7)	2010(830)	47(19)	0.135(28)
	$12^+ \to 10^+$	619	11(3)	820(220)	19(5)	0.088(12)
^{141}Eu	$\frac{15}{2}^- \to \frac{11}{2}^-$	526	13(3)	1540(360)	36(8)	0.123(14)

bands above the $(\pi h_{11/2})^2$ and $(\nu h_{11/2})^{-2}$ 10^+ states ($\beta = 0.142$ and 0.088, respectively) definitely confirm the description of ^{140}Sm at excitation energies above 3 MeV in terms of the coexistence of two shapes.

As a by-product of the present work, we got also the lifetime of the $\frac{15}{2}^-$ state in the $N=78$ ^{141}Eu nucleus and the $B(E2)$ corresponding to the $\frac{15}{2}^- \rightarrow \frac{11}{2}^-$ transition. The obtained values are also shown in Table I. For the band based on the $\frac{11}{2}^-$ state in ^{141}Eu [15], we assume an effective K value of $\frac{3}{2}$ as was already done for analogously decoupled $\pi h_{11/2}$ bands in the odd Pm and Eu nuclei of this region [13,16,17]. With this assumption a deformation parameter $\beta = 0.123(14)$ was extracted, which may represent the deformation at $N=78$.

As already mentioned in the Introduction, the β values of the two excited bands in ^{140}Sm can be associated with the quadrupole deformation of the $N=78$ and 80 core nuclei, which in our case are ^{138}Nd and ^{142}Sm, respectively. Several theoretical calculations [6–10] predict the nuclear quadrupole deformation in the Nd-Sm region below $N=82$. However, a comparison with $B(E2)$ values or with quadrupole deformation parameters derived from lifetime measurements was possible only for $N \leq 76$ in Sm and for $N \leq 74$ in Nd. Adding our two new values of β we have now, for the samarium isotopes, data from $N=72$ to 80, which can be used to map the trend of the nuclear deformation in this region. We should keep in mind that, with the assumptions made before, the value of β for $N=78$ is related to Nd and not to Sm and this must be remembered when comparing with theoretical calculations for samarium isotopes. A value of β about 20% higher in Sm than in Nd at $N=78$ is indeed foreseen in both the calculations which we adopt in the following [6,7]. In Fig. 2 the deformation parameters obtained from the present lifetime measurement, together with the ones deduced from previous experiments [12,13,18,19], are plotted as a function of the neutron number for the samarium isotopes with $N<82$. The results of two available potential-energy calculations are also plotted in the same figure. One calculation is based on a Woods-Saxon (WS) model with pairing [7] and the other one on a folded Yukawa (FY) model [6].

As it is evident from Fig. 2 some discrepancies between the experimental data exist, especially at $N=74$, where the results of the two theoretical calculations are most at variance. The set of data obtained at Padova [12,18] is in agreement with the WS calculations, whereas the sharp increase of deformation predicted in the FY model at $N=72$–74 is in accordance with the Daresbury data [13]. Anyway, the two new points from the present experiment nicely follow the expected trend of deformation towards $N=82$. At $N=80$ the experimental value is somewhat larger than expected from theory, but not in disagreement with the calculations since (see, e.g., Fig. 5 of Ref. [7]) there is a rather flat minimum at $N=80$ in the calculated potential-energy surfaces.

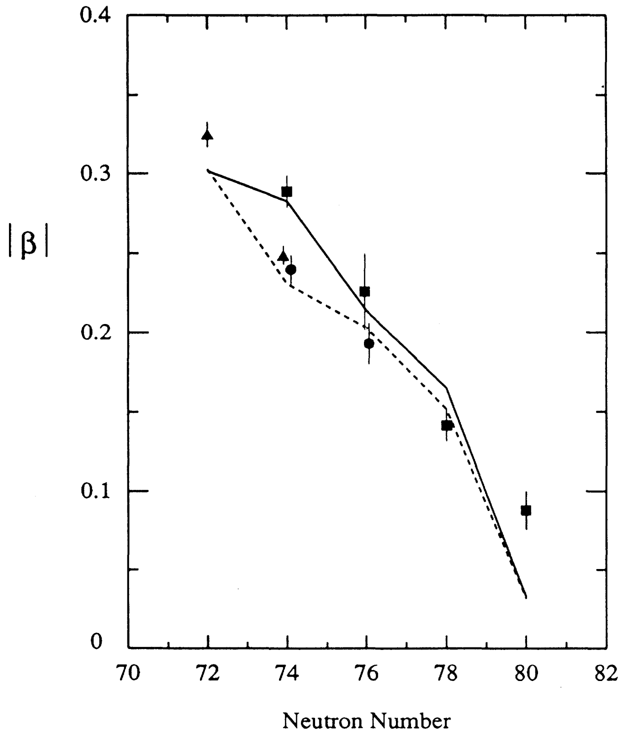

FIG. 2. Experimentally deduced quadrupole deformation parameter β as a function of neutron number in Sm isotopes. The squares represent the data points of the Padova group (Refs. [12] and [18] and this work), the circles those of Makishima *et al.* [19], and the triangles those of Wadsworth *et al.* [13]. In cases where the lifetime of the 4^+ state was also available, the weighted average of β derived from the $B(E2)$ of the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions is plotted. The dashed line represents the predictions of the FY model [6], while the solid one corresponds to the WS calculations [7].

In conclusion, from the present lifetime measurement it was possible to complete the systematics of the onset of deformation below $N=82$ and to confirm the shape coexistence description of ^{140}Sm above 3 MeV.

---

*Permanent address: Departamento de Física CNEA, 1429 Buenos Aires, Argentina.

[1] W. Starzecki, G. de Angelis, B. Rubio, J. Styczen, K. Zuber, H. Güven, W. Urban, W. Gast, P. Kleinheinz, S. Lunardi, F. Soramel, A. Facco, C. Signorini, M. Morando, W. Meczynski, A. M. Stefanini, and G. Fortuna, Phys. Lett. B **200**, 419 (1988).
[2] D. Bazzacco, F. Brandolini, K. Löwenich, S. Lunardi, P. Pavan, C. Rossi Alvarez, F. Soramel, M. De Poli, A. M. I. Haque, and G. de Angelis, Phys. Lett. B **206**, 404 (1988).
[3] D. Bazzacco, F. Brandolini, K. Löwenich, P. Pavan, C. Rossi Alvarez, M. De Poli, and A. M. I. Haque, Report No. LNL-INFN (REP)-014/88, 1988, p. 7.
[4] S. Lunardi, D. Bazzacco, G. Nardelli, F. Soramel, J. Rico, E. Maglione, M. de Poli, and G. de Angelis, Phys. Rev. C **42**, 174 (1990).

[5] G. de Angelis, F. Terrasi, D. Bazzacco, S. Lunardi, and M. De Poli, in Abstracts of the 3rd International Spring Seminar on Nuclear Physics, Ischia, 1990 (Universitá di Napoli, Napoli, 1990), p. 6.

[6] G. A. Leander and P. Möller, Phys. Lett. **110B**, 17 (1982); P. Möller and J. R. Nix, At. Data Nucl. Data Tables **26**, 165 (1981).

[7] B. D. Kern, R. L. Mlekodaj, G. A. Leander, M. O. Kortelahti, E. F. Zganjar, R. A. Braga, R. W. Fink, C. P. Perez, W. Nazarewicz, and P. B. Semmes, Phys. Rev. C **36**, 1514 (1987).

[8] N. Redon, J. Meyer, M. Meyer, P. Quentin, M. S. Weiss, P. Bonche, H. Flocard, and P. H. Heenen, Phys. Lett. B **181**, 223 (1986).

[9] L. Goettig and W. Nazarewicz, J. Phys. G **16**, L51 (1990).

[10] M. O. Kortelahti, B. D. Kern, R. A. Braga, R. W. Fink, I. C. Girit, and R. L. Mlekodaj, Phys. Rev. C **42**, 1267 (1990).

[11] C. J. Lister, B. J. Varley, R. Moscrop, W. Gelletly, P. J. Nolan, D. J. G. Love, P. J. Bishop, A. Kirwan, D. J. Thornley, L. Ying, R. Wadsworth, J. M. O'Donnell, H. G. Price, and A. H. Nelson, Phys. Rev. Lett. **55**, 810 (1985).

[12] F. Soramel, S. Lunardi, S. Beghini, M. Morando, C. Signorini, W. Meczynski, G. Fortuna, G. Montagnoli, and A. M. Stefanini, Phys. Rev. C **38**, 537 (1988).

[13] R. Wadsworth, J. M. O'Donnell, D. L. Watson, P. J. Nolan, P. J. Bishop, D. J. Thornley, A. Kirwan, and D. J. G. Love, J. Phys. G **13** 205 (1987).

[14] J. Billowes, K. P. Lieb, J. W. Noé, W. F. Piel, Jr., S. L. Rolston, G. D. Sprouse, O. C. Kistner, and F. Christancho, Phys. Rev. C **36**, 974 (1987).

[15] H. Güven, R. Julin, M. Lach, J. Styczen, M. Müller-Veggian, A. Krämer-Flecken, and P. Kleinheinz, Z. Phys. A **330**, 437 (1988).

[16] S. M. Mullins, M. D. Cohler, A. Ghazarian, J. R. Hughes, R. Wadsworth, D. L. Watson, P. J. Bishop, A. J. Kirwan, P. J. Nolan, R. J. Poynter, D. J. G. Love, and J. Heese, J. Phys. G **14**, 1373 (1988).

[17] P. J. Bishop, M. J. Godfrey, A. J. Kirwan, P. J. Nolan, D. J. Thornley, J. M. O'Donnell, R. Wadsworth, D. J. G. Love, and L. Goettig, J. Phys. G **14**, 995 (1988).

[18] S. Lunardi, F. Scarlassara, F. Soramel, S. Beghini, M. Morando, C. Signorini, W. Meczynski, W. Starzecki, G. Fortuna, and A. M. Stefanini, Z. Phys. A **321**, 177 (1985).

[19] A. Makishima, M. Adachi, H. Taketani, and M. Ishii, Phys. Rev. C **34**, 576 (1986).