Extreme Prolate Deformation in Light Strontium Isotopes

C. J. Lister
Department of Physics, Schuster Laboratory, University of Manchester, Manchester M13 9PL, England, and Brookhaven National Laboratory, Upton, New York 11973

and

B. J. Varley
Department of Physics, Schuster Laboratory, University of Manchester, Manchester M13 9PL, England

and

H. G. Price
Daresbury Laboratory, Warrington WA4 4AD, England

and

J. W. Olness
Brookhaven National Laboratory, Upton, New York 11973
(Received 28 May 1982)

Multiple-particle, γ-ray coincidence techniques have been used to study neutron-deficient isotopes near $N = Z = 40$. Results are presented for $^{77-80}Sr$. Levels in ^{78}Sr were seen to $J = 10$ with $E(2^+) = 278$ keV and $T_{1/2} = 155 \pm 19$ ps. The results suggest that this region contains some of the most deformed nuclei known, with quadrupole deformations $\epsilon_2 \approx 0.4$. These data resolve conflicting theoretical predictions of nuclear shapes and emphasize the important contribution of hexadecapole deformation in determining the most stable shape.

PACS numbers: 21.20.Ft, 21.10.Ky, 23.20.-g, 27.50.+e

Major advances are being made in calculating the binding energy of the nuclear potential energy surface under conditions of varying shape and spin.[1-4] These ambitious calculations attempt to predict the most stable shapes and binding energies for thousands of isotopes in a self-consistent manner. The models all treat the total binding energy as the sum of two parts; a macroscopic "liquid drop" contribution and a microscopic "shell correction" term, which are combined using the Strutinsky formalism.[5] The exact parametrization of both parts of the calculation vary; for instance, Ref. 1 uses a formalism based on a modified oscillator potential and parametrizes deformation in terms of quadrupole and triaxial degrees of freedom (ϵ_2, γ), while Ref. 2 uses Yukawa potentials and considers only axial deformation with quadrupole and hexadecapole (ϵ_2, ϵ_4) variables. Both parts of the calculations have many parameters which are determined from the wealth of data available on stable and near-stable nuclei. Because of this, the models generally agree on their predictions of shape and binding for the more stable isotopes, but discrepancies appear among the predictions of the properties of isotopes further from stability. Consequently, experimental measurements of the shapes and binding energies of isotopes very far from stability provide the most stringent tests of these models.

This Letter reports on a series of γ-ray measurements in the mass region with N and Z both near 40. The calculations all predict that isotopes in this region will exhibit considerable collectivity, and this is supported by experimental evidence from both γ-ray spectroscopy of light Kr isotopes[6] and hyperfine atomic structure studies of Rb isotopes.[7] However, there is considerable variance among calculations as to which isotopes are predicted to be most deformed, the size of that deformation, and which shapes are most stable.

Gamma-ray spectroscopy can answer these questions of shape through the extraction of the sign and size of the electromagnetic multipole moments of excited states. However, observation of γ-emitting states in these neutron-deficient isotopes is extremely difficult. Cross sections are small and are masked by copious production of isotopes nearer stability. This necessitates the use of multiple-particle, γ-ray coincidence methods.

The experiments reported in this work were all carried out at the Brookhaven National Laboratory Van de Graaff accelerator facility. 1.0-mg/cm^2 ^{58}Ni targets (^{208}Pb backed) were bombarded with ^{24}Mg and ^{28,29}Si beams, and 0.5-mg/cm^2 ^{40}Ca targets with ^{39}K and ^{40}Ca beams, at energies from 0.9 to 1.5 times the Coulomb barrier. A light-charged-particle, neutron, γ-ray triple coincidence apparatus permitted the identification of the isotopic origin of γ rays produced in compound nuclear reactions. The evaporated light charged particles were detected in a silicon surface barrier E-ΔE telescope mounted at 0° and subtending a solid angle of 0.85 sr. Neutrons were detected in an array of five NE213 liquid scintillator detectors also mounted at 0° and subtending 3.9 sr. Gamma rays were detected in Ge and Ge(Li) detectors of 18%–22% efficiency and < 2.1 keV resolution placed at ± 125° to the beam direction.

Gamma-ray singles spectra, together with one- and two-neutron–gated coincidence spectra, were collected for each γ-ray detector. In the E vs ΔE telescope map protons, deuterons, and α particles were clearly resolved, as were peaks arising from combinations of charged particles entering the telescope ($2p$, $3p$, αp, etc.). "On-line" windows were set on all these features, and for each a series of γ-ray spectra corresponding to γnn, γn, and γ coincidences were accumulated. Also four-parameter data were collected on tape for later analysis. Twenty-six different identification γ-ray spectra were thus accumulated for each beam and target combination. Excited states in many previously unstudied nuclei were seen, including ^{75}Kr, ^{76,77}Rb, ^{77,78,79}Sr, ^{80,81,82,83}Y, ^{82,83}Zr, and ^{84}Nb. In this paper we concentrate on the properties of the light Sr isotopes as a test of recent calculations.

The decay schemes deduced for $^{77-80}$Sr are shown in Fig. 1. ^{77}Sr was optimally produced in the reaction ^{40}Ca(^{40}Ca,$2pn$)^{77}Sr at 117 MeV. A parallel study[10] of the radioactive decay of ^{77}Sr to ^{77}Rb strongly favors a ground-state spin and parity of $J^\pi = \frac{5}{2}^+$. The nucleus ^{78}Sr was populated in the reaction ^{58}Ni(^{24}Mg,$2p2n$)^{78}Sr at 100 MeV. Level lifetimes were extracted in a neutron-gated recoil-distance-method study. For this

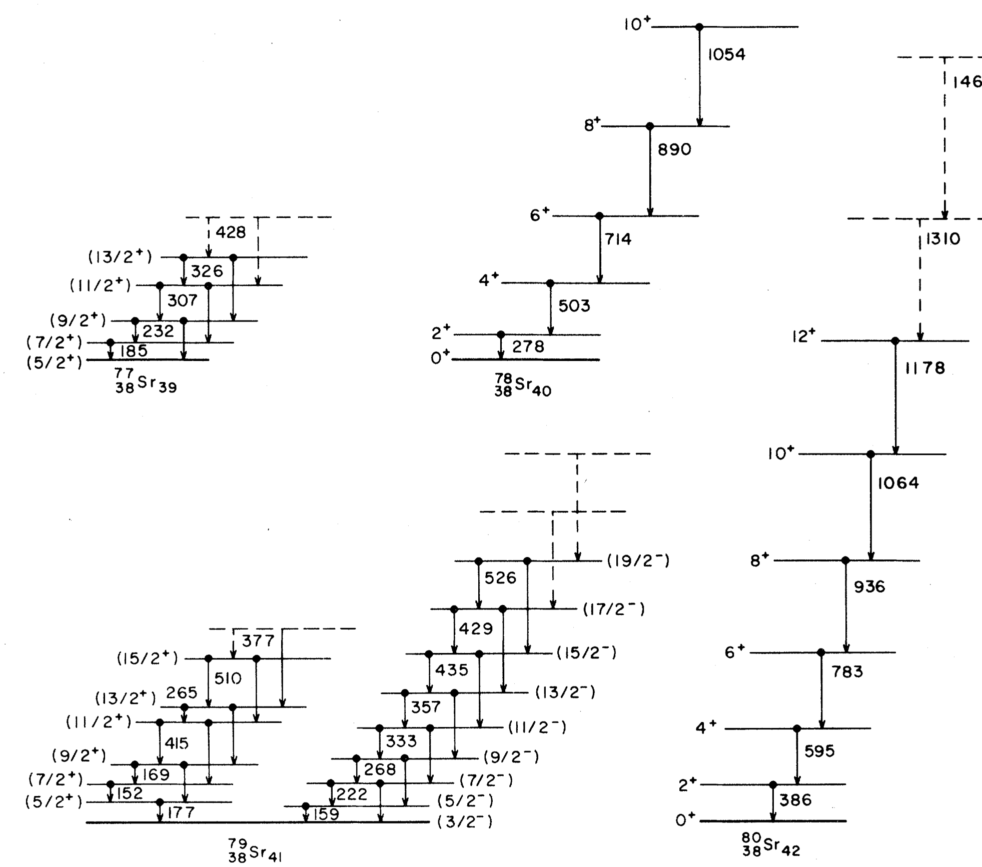

FIG. 1. Band structure observed in $^{77-80}$Sr. Lower states in ^{80}Sr have been reported in Refs. 8 and 9.

TABLE I. Quadrupole moments extracted from level lifetimes (even A) and deduced from angular distributions (odd A). The ^{79}Sr results use a gyromagnetic ratio $g_K - g_R = -1.30$ calculated as discussed in the text. The 386-keV level in ^{80}Sr has been previously measured (Ref. 9) to have $T_{1/2} = 44 \pm 6$ ps.

Nucleus	E_γ (keV)	$J_i^\pi \rightarrow J_f^\pi$	$T_{1/2}$ (ps)	$\delta(E2/M1)$	Q_0 (b)
^{78}Sr	278	$2^+ \rightarrow 0^+$	155 ± 19	···	$\lvert 3.29 \pm 0.19 \rvert$
	503	$4^+ \rightarrow 2^+$	5.1 ± 0.5	···	$\lvert 3.47 \pm 0.17 \rvert$
^{80}Sr	386	$2^+ \rightarrow 0^+$	37 ± 3	···	$\lvert 2.98 \pm 0.12 \rvert$
	595	$4^+ \rightarrow 2^+$	3.3 ± 0.5	···	$\lvert 2.85 \pm 0.23 \rvert$
^{79}Sr	159	$(5/2^- \rightarrow 3/2^-)$		-0.09 ± 0.06	$+1.8 \pm 1.2$
	222	$(7/2^- \rightarrow 5/2^-)$		-0.17 ± 0.07	$+3.6 \pm 1.5$
	268	$(9/2^- \rightarrow 7/2^-)$		-0.13 ± 0.06	$+3.0 \pm 1.3$
	333	$(11/2^- \rightarrow 9/2^-)$		-0.24 ± 0.06	$+5.4 \pm 1.4$
	357	$(13/2^- \rightarrow 11/2^-)$		-0.07 ± 0.07	$+1.8 \pm 0.8$
	435	$(15/2^- \rightarrow 13/2^-)$		-0.15 ± 0.05	$+3.6 \pm 1.2$

experiment, the neutron array was placed at 0° and both stopped and Doppler-shifted γ rays were detected at 153° to the beam direction. ^{79,80}Sr were observed in the reactions ^{58}Ni(^{24}Mg, $2pn$)^{79}Sr and ^{58}Ni(^{24}Mg, $2p$)^{80}Sr, respectively. Spectroscopic studies were made at 75 MeV where the prompt γ-ray spectra were sufficiently simple to allow measurements to be made without particle-γ coincidence requirements. ^{79}Sr was found to have two distinct bands; a band based on the ground state ($J = \frac{3}{2}$),[11] and a much more staggered band based on an isomeric (2 ns $< T_{1/2} <$ 10 ns) state at 177 keV. The $L = 1$ angular distribution of the 177-keV state indicates that it has spin $J = \frac{5}{2}$. Thus, $^{79}_{38}$Sr$_{41}$ was observed to have a band structure similar to that of its isotone $^{77}_{36}$Kr$_{41}$, where $K = \frac{5}{2}^+$ and $(\frac{3}{2}^-)$ bands are known.[12]

Lifetimes were extracted for the 2^+ and 4^+ members of the ground-state band in ^{78,80}Sr (Table I). The $E2$ transition strengths are very enhanced, especially in ^{78}Sr, with $B(E2; 2 \rightarrow 0) = 106 \pm 13$ Weisskopf units (W.u.) and $B(E2; 4 \rightarrow 2) = 169 \pm 17$ W.u. Such collectivity, together with the energy level spacing, indicates rotational behavior, as does the $B(E2; 2 \rightarrow 0)/B(E2; 4 \rightarrow 2)$ ratio. However, the E_J/E_{2^+} ratios do not exactly satisfy the relationship expected for a rigid rotor and the moment of inertia increases with spin as is shown in Fig. 2. Only at $J > 10$ do the odd and even isotopes appear to approach a common, rigid shape. Even so, the quadrupole moments extracted from $B(E2)$ values for the $J = 2^+$ and 4^+ states in ^{78,80}Sr provide a discriminating test of the shapes predicted from the calculations discussed in the introduction. In the estimates of Åberg[1] and Bucurescu,[4] ^{78,80}Sr are predicted to be nearly spherical in their ground state ($Q_0 \approx 0$), and to evolve to a soft, mildly oblate ($Q_0 = -1.4$ b) shape at spin 10. This is at variance with the calculation of Möller and Nix,[2] who predict large prolate ground states with a quadrupole moment of $Q_0 = +3.2$ b. The data clearly favor the latter model; $|Q_0^{2^+}| = 3.29 \pm 0.19$ b in ^{78}Sr and 2.98 ± 0.12 in ^{80}Sr.

Additional, indirect evidence supporting a prolate-deformed shape is found from the structure of the odd-A isotopes. The sign and the magnitude of the quadrupole moment were extracted from the in-band multipole mixing ratios, δ, when the gyromagnetic factor $g_K - g_R$ was calculated by using the Nilsson model in a potential with deformation predicted for ^{79}Sr by Möller and Nix.[2] The levels $\frac{5}{2}^+|422\rangle$ and $\frac{3}{2}^-|301\rangle$ are located near the Fermi surface for $N = 39, 41$ and explain the bandheads observed in ^{77,79}Sr. For

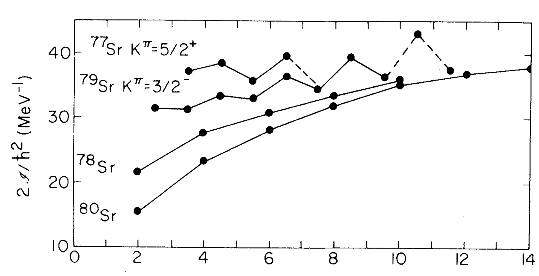

FIG. 2. The evolution of moment of inertia with spin for light Sr isotopes seen in this work. $2\mathcal{J}/\hbar^2 = (4I - 2)/E$ for even-A and $2I/E$ for odd-A bands.

the $K=\frac{3}{2}^-$ band, the calculations give $g_K - g_R = -1.30$, with use of $g_s = 0.7 g_{\text{free}}$ and $g_R = Z/A$. The resulting quadrupole moments extracted from the ^{79}Sr $K=\frac{3}{2}$ band are given in Table I, and may be seen to be consistent both in size and in sign (prolate) with the results of Möller and Nix[2] and the values obtained from our lifetime studies. This is in marked contrast to a similar calculation performed with the oblate potential predicted by Åberg.[1] Here, the Nilsson model predicts $K=\frac{9}{2}$ and $\frac{1}{2}$ bandheads, and for $K=\frac{3}{2}$ levels nearest the Fermi surface, $g_K - g_R$ was again found to be negative which implies the contradictory result of a positive quadrupole moment for an oblate nuclear shape.

The differing predictions of calculations in this region may be traced to the treatment of hexadecapole (ϵ_4) deformation. When ϵ_4 deformation is either ignored,[4] or included only in the macroscopic part of the calculation,[1] or included in both microscopic and macroscopic parts[2] but held fixed at $\epsilon_4 = 0$, the models all agree and predict an ϵ_2-soft oblate ($\epsilon_2 \sim -0.2$) shape. However, minimizing ϵ_4 widens the $N=38$ prolate ($\epsilon_2 \sim +0.4$) shell gap and gives ~2 MeV extra binding energy for $\epsilon_4 \sim +0.06$. This contribution moves the minimum of the potential energy surface from a slightly oblate to a very prolate deformation.

In conclusion, a sensitive and versatile method has been developed for γ-ray spectroscopic studies of very neutron-deficient nuclei. $^{77-80}$Sr have been observed to have bands of states which have the electromagnetic properties of nuclei with extremely large ($\epsilon_2 \approx 0.4$) prolate deformation which is close to that of an ellipsoid with an axis ratio of 3:2. These observations are consistent with one recent theoretical calculation, but in disagreement with several others. The results emphasize the important role played by hexadecapole deformation in establishing which nuclear shapes are the most stable.

The authors would like to acknowledge the assistance of Dr. A. D. Irving and Dr. E. K. Warburton in this project. This work was supported by the U. S. Department of Energy under Contract No. DE-AC02-76CH00016 and by grants from the United Kingdom Science and Engineering Research Council administered by the University of Liverpool.

[1] S. Åberg, Phys. Scr. 25, 23 (1982).
[2] P. Möller and J. R. Nix, At. Data Nucl. Data Tables 26, 165 (1981).
[3] I. Ragnarsson, S. G. Nilsson, and R. K. Sheline, Phys. Rep. 45, 1 (1978).
[4] D. Bucurescu *et al.*, Rev. Roum. Phys. 24, 971 (1979).
[5] V. M. Strutinsky, Nucl. Phys. A122, 1 (1968).
[6] J. H. Hamilton *et al.*, in Proceedings of the Fourth Conference on Nuclei far from Stability, Helsingor, Denmark, 1981 (to be published); H. P. Hellmeister *et al.*, Phys. Lett. 85B, 34 (1979).
[7] C. Thibault *et al.*, Phys. Rev. C 23, 2720 (1981).
[8] E. Nolte *et al.*, Z. Phys. A 268, 267 (1974).
[9] L. V. Theisen *et al.*, Phys. Rev. C 25, 1325 (1982).
[10] D. Alburger *et al.*, to be published.
[11] C. J. Lister *et al.*, Phys. Rev. C 24, 260 (1981).
[12] E. Nolte and P. Vogt, Z. Phys. A 275, 33 (1975).