Shape coexistence in $^{96,98}$Sr studied by low-energy Coulomb excitation

E. Clément$^1$, M. Zielińska$^2$, A. Görgen$^3$, W. Korten$^2$, S. Péru$^4$, J. Libert$^4$, H. Goutte$^2$, S. Hilaire$^4$, D.T. Doherty$^{2,5}$

$^1$ GANIL, Caen, France; $^2$ CEA Saclay, France; $^3$ University of Oslo, Norway; $^4$ CEA/DAM, Bruyères-le-Châtel, France $^5$ University of York, UK;

and the IS451 collaboration:


$^6$ TU Darmstadt, Germany; $^7$ IKP Cologne, Germany; $^8$ KU Leuven, Belgium; $^9$ University of Liverpool, UK; $^{10}$ CERN, Switzerland; $^{11}$ University of Lund, Sweden; $^{12}$ University of Manchester, UK; $^{13}$ CSNSM, Orsay, France; $^{14}$ LMU Munich, Germany; $^{15}$ Heavy Ion Laboratory, Warsaw, Poland; $^{16}$ University of Jyväskylä, Finland;
Shape transition at N=60 and shape coexistence around $^{100}$Zr

- dramatic change of the ground state structure observed at N = 58, 60 for Rb, Sr, Y, Zr
- onset of deformation at N=60 confirmed by $2^+$ energies and transition probabilities in even-even Zr, Sr
- low-lying $0^+$ states observed in N=58,60 Zr, Sr

P. Campbell et al., Prog. Part. Nucl. Phys. 86 (2016) 127
Shape coexistence and type-II shell evolution in Zr isotopes

- p-n tensor interaction reduces the Z=40 gap when $\nu g7/2$ is being filled
- $0_2^+$ states created by 2p-2h (+ 4p-4h...) excitation across Z=40
- very different configurations and small mixing of $0_1^+$ and $0_2^+$
Coulomb excitation

- population of excited states via purely electromagnetic interaction between the collision partners

- \( B(E2) \) transition probabilities – measure of collectivity
- direct measurement of quadrupole moments including sign – ideal tool to study shape coexistence
- easy way to access non-yrast states and study their properties
- renaissance of the technique as ideally suited for state-of-the-art RIB facilities:
  - beam energies available perfect for Coulomb excitation (2-5 MeV/A)
  - high cross sections (excitation of \( 2^+ \): barns)
  - practical at the neutron-rich side
Coulomb excitation of $^{96,98}$Sr at ISOLDE

gamma-ray detection array:
MINIBALL
8 triple clusters, 8% efficiency

particle detection setup:
annular DSSD detector at forward angles
detection of scattered Sr and recoiling target nuclei

- deexcitation $\gamma$ rays measured in coincidence with particles (Sr and target recoils)
- targets: $^{109}$Ag, $^{120}$Sn ($^{96}$Sr), $^{60}$Ni, $^{208}$Pb ($^{98}$Sr)
- beam intensities: $7 \cdot 10^3$ pps for $^{96}$Sr (REX-TRAP problem), $6 \cdot 10^4$ pps for $^{98}$Sr
Deformation of $^{96}$Sr


$\beta$ (from $Q_s$) = $0.11^{+0.15}_{-0.14}$

B(E2) in agreement with lifetime but more precise

low deformation of gsb confirmed
$^{98}$Sr: quadrupole moments and transition probabilities

- well deformed prolate band ($\beta \geq 0.3$)
- low deformation of the excited band ($\beta < 0.1$)
- similar deformation of $0_1^+$ in $^{96}$Sr and $0_2^+$ in $^{98}$Sr

Shape coexistence: two-state mixing


Mixing of the g.s. (from distortion of rotational bands)

Mixing amplitudes for $^{98}$Sr (from ME): $\cos^2 \theta_0 = 0.87(1)$, $\cos^2 \theta_2 = 0.99(1)$
Theoretical predictions for Sr isotopes

- beyond mean field calculations: GCM (GOA) D1S, (S. Péru, H. Goutte, J. Libert et al)
- first detailed calculation of transition probabilities on both sides of the N=60 shape transition
- shape change at N=60 and shape coexistence reproduced
Theoretical predictions for Sr isotopes

- collectivity in ground-state bands overestimated as well as mixing of the structures
Theoretical predictions for Sr isotopes

- collectivity in ground-state bands overestimated as well as mixing of the structures
- calculated K=2 band in $^{98}$Sr has no experimental counterpart
Triaxiality in $^{98}$Sr

- gamma $\approx 25^\circ$ would explain the reduction of $Q_s(2^+_1)$ in $^{98}$Sr

- but where is the gamma band?

J. Xiang et al., PRC 93, 054324 (2016), 5DCH with PC-PK1 interaction
Summary and outlook

- shape coexistence in $^{98}\text{Sr}$ and similarity of $0_1^+$ in $^{96}\text{Sr}$ and $0_2^+$ in $^{98}\text{Sr}$ confirmed by measured quadrupole moments and quadrupole invariants

- low mixing of coexistent structures in contrast to Hg and Kr nuclei

- general features well reproduced by beyond-mean-field calculations

- $^{96}\text{Sr}$ to be revisited (development of deformation in the ground-state band, structures built on $0_{2,3}^+$ states)

- the role of triaxiality in $^{96,98}\text{Sr}$ remains an open question
Quadrupole sum rules

K. Kumar, PRL 28 (1972) 249

- electromagnetic multipole operators are spherical tensors – products of such operators coupled to angular momentum 0 are rotationally invariant

- in the intrinsic frame of the nucleus, the E2 operator may be expressed by 2 parameters related to charge distribution:

\[
E(2, 0) = Q \cos \delta
\]

\[
E(2, 2) = E(2, -2) = \frac{Q}{\sqrt{2}} \sin \delta
\]

\[
E(2, 1) = E(2, -1) = 0
\]

\[
\langle Q^2 \rangle = \langle i | [E2 \times E2]^0 | i \rangle = \frac{1}{\sqrt{(2I_i + 1)}} \sum_t \langle i|E2||t \rangle \langle t||E2||i \rangle \left\{ \begin{array}{ccc}
2 & 2 & 0 \\
2I_i & I_i & I_t \\
\end{array} \right\}
\]

\[
\langle Q^2 \rangle: \text{overall deformation parameter}
\]
Quadrupole sum rules: triaxiality

K. Kumar, PRL 28 (1972)

\[
\sqrt{\frac{2}{35}} \langle Q^3 \cos 3\delta \rangle = \langle i|\{[E2 \times E2]^2 \times E2\}_0^0|i\rangle \\
= \frac{1}{(2I_i + 1)} \sum_{i, u} \langle i||E2||u\rangle \langle u||E2||t\rangle \langle t||E2||i\rangle \begin{pmatrix} 2 & 2 & 2 \\ I_i & I_t & I_u \end{pmatrix}
\]

\[\langle \cos 3\delta \rangle: \text{ triaxiality parameter}\]
Theoretical predictions for Sr isotopes

GCM(GOA) D1S vs experiment
Coulomb excitation of $^{98}$Sr

- 2 targets differing in Z: $^{60}$Ni and $^{208}$Pb
- gsb populated up to $8^+$
- good statistics: 4 subdivisions of CM angles for $^{208}$Pb, 3 for $^{60}$Ni