Shape Coexistence

- Neutron-deficient Kr and Se isotopes
- Coulomb excitation (RIB) and lifetimes
- “Beyond mean field” calculations

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Shape coexistence

Configuration mixing:

\[ |0_1^+\rangle = + \cos \eta |0_{pro}^+\rangle + \sin \eta |0_{obl}^+\rangle \]

\[ |0_2^+\rangle = - \sin \eta |0_{pro}^+\rangle + \cos \eta |0_{obl}^+\rangle \]

electric monopole (E0) transition

\[ \langle 0_2^+ | M(E0) | 0_1^+ \rangle \propto \sin \eta \cos \eta (\beta_{pro}^2 - \beta_{obl}^2) \]
Systematics of the light krypton isotopes

- energy of excited $0^+$
- $E0$ strengths $\rho^2(E0)$
- configuration mixing
- Inversion of ground state shape for $^{72}$Kr
- Coulomb excitation to determine the nuclear shapes directly

Mixing of the ground state
(two-level mixing extrapolated from distortion of rotational bands)

Radioactive beam production: SPIRAL

ECRIS

Target

SPIRAL

CIME

CSS1

CSS2

SPIRAL: Système de Production d’Ions Radioactifs en Ligne

\[ \text{74}^{\text{Kr}} \]
\[ 4.7 \text{ MeV/u} \]
\[ 10^4 \text{ pps} \]

\[ \text{78}^{\text{Kr}} \]
\[ 68.5 \text{ MeV/u} \]
\[ 10^{12} \text{ pps} \]
Coulomb excitation of $^{74}$Kr and $^{76}$Kr

**SPIRAL beams**
- $^{76}$Kr $5 \times 10^5$ pps
- $^{74}$Kr $10^4$ pps

- 4.7 MeV/u

**Coulomb excitation at sub-barrier energies:**
- purely electromagnetic (‘safe’)
- multi-step excitation possible
- differential measurement $d\sigma/d\theta$

**Graphs**

- [Counts vs. $E_y$ for $^{74}$Kr]
Fit matrix elements (transitional and diagonal) to reproduce experimental γ-ray yields (as function of θ):

- 14 B(E2) values
- 5 quadrupole moments

E. Clément et al., PRC 75, 054313 (2007)
Comparison with ‘beyond-mean-field’ calculations

GCM calculation
axial deformation
Skyrme SLy6
M. Bender et al.
PRC 74, 024312 (2006)

experimental B(E2;↓) [e²fm⁴]
E. Clément et al.,
PRC 75, 054313 (2007)

GCM (GOA) calculation
q₀, q₂: triaxial deformation
Gogny D1S
M. Girod et al.

\begin{itemize}
  \item pms\quad oms
  \item Q_s<0\quad Q_s>0
  \item prolate\quad oblate\quad prolate\quad oblate
  \item K=2\quad \gamma\quad vibration
\end{itemize}
Configuration mixing calculations (Generator coordinate method)

Difference #1: effective interaction

Skyrme SLy6 ⇔ Gogny D1S
Bender et al. Girod et al.

very similar single-particle energies
⇒ no big differences on the mean-field level

Difference #2: generator coordinates

axial quadrupole deformation \( q_0 \) ⇔
triaxial quadrupole deformation \( q_0, q_2 \)
(exact GCM formalism)

Euler angles \( \Omega=(\theta_1, \theta_2, \theta_3) \)
⇒ 5-dimensional collective Hamiltonian
(Gaussian overlap approximation)

- good agreement for in-band B(E2)
- wrong ordering of states: oblate
- ground-state shape for \(^{72}\text{Kr} \rightarrow ^{78}\text{Kr}\)
- K=2 outside model space

⇒ triaxiality seems to be the key to describe
prolate-obl ate shape coexistence in this region
Shape transition in the light krypton isotopes

- **Experimental (direct and indirect evidence)**

- **Theory: HFB-based configuration mixing treating all quadrupole deformations**

  - Probability density $\rho_I(\beta, \gamma)$

  - Also mixing of $K=0$ and $K=2$ states

  $\Rightarrow$ inversion of ground-state shape for $^{72}$Kr
Shape coexistence in light Selenium isotopes

similar $J^{(1)}$ in $^{68}\text{Se}$ and $^{70}\text{Se}$:

- $^{70}\text{Se}$ oblate near ground state
- prolate at higher spin


Coulomb excitation of $^{70}\text{Se}$ at CERN / ISOLDE

- $^{70}\text{Se}$ on $^{104}\text{Pd}$ at 2.94 MeV/u
- integral measurement
- excitation probability via normalization to known $^{104}\text{Pd}$

$P_{2^+}$ is function of
- transitional matrix element $B(\text{E2})$
- diagonal matrix element $Q_0$

- one measurement, but two unknowns!

A.M. Hurst et al., PRL 98, 072501 (2007)
Matrix elements for 2+ in $^{70}\text{Se}$

> only prolate shape consistent with both Coulex and lifetime measurement contradicting previous assumptions

$\tau = 1.5(3) \text{ ps}$
J. Heese et al., Z. Phys. A 325, 45 (1986)

Coulomb excitation probability (1σ)

A.M. Hurst et al., PRL 98, 072501 (2007)

upper limit for $^{68}\text{Se}$ from GANIL intermediate-energy Coulex
E. Clément et al., NIM A in press
Lifetimes in $^{70}\text{Se}$ and $^{72}\text{Se}$ revisited

GASP and Köln Plunger at Legnaro Recoil-distance Doppler shift

$^{40}\text{Ca}(^{36}\text{Ar},\alpha 2\text{p})^{70}\text{Se}$

$^{40}\text{Ca}(^{36}\text{Ar},4\text{p})^{72}\text{Se}$

12 distances between 8 and 400 µm

<table>
<thead>
<tr>
<th></th>
<th>old [1] $\tau$ (ps)</th>
<th>new[2] $\tau$ (ps)</th>
<th>B(E2;↓) ($e^2f m^4$)</th>
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<tbody>
<tr>
<td>$^{70}\text{Se}$</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$2^+$</td>
<td>1.5(3)</td>
<td>3.2(2)</td>
<td>342(19)</td>
</tr>
<tr>
<td>$4^+$</td>
<td>1.4(3)</td>
<td>1.4(1)</td>
<td>370(24)</td>
</tr>
<tr>
<td>$6^+$</td>
<td>3.9(9)</td>
<td>1.9(3)</td>
<td>530(96)</td>
</tr>
<tr>
<td>$^{72}\text{Se}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2^+$</td>
<td>4.3(5)</td>
<td>4.2(3)</td>
<td>405(25)</td>
</tr>
<tr>
<td>$4^+$</td>
<td>2.7(4)</td>
<td>3.3(2)</td>
<td>882(50)</td>
</tr>
<tr>
<td>$6^+$</td>
<td>2.3(2)</td>
<td>1.7(1)</td>
<td>1220(76)</td>
</tr>
</tbody>
</table>

Consequences

- Prolate shape can be excluded for $2^+$ in $^{70}\text{Se}$
- Higher precision coulex measurement needed

Heese et al.


J. Ljungvall et al.

Smooth systematic behavior with neutron number
Shape evolution in the light Selenium isotopes

- oblate rotation prevails only in $^{68}$Se
  - best example for shape coexistence in $A=70$ region
- experimental matrix elements and quadrupole moments needed for $^{68}$Se

$Q_S$ from Gogny configuration mixing calculation

![Diagram of energy levels and $B(E2)$ values for $^{68}$Se, $^{70}$Se, and $^{72}$Se]
Summary and Conclusions

- direct evidence for shape coexistence in light Kr isotopes
- quadrupole moments from Coulomb excitation experiments with RIB
- inversion from prolate ground state in $^{78}$Kr to oblate in $^{72}$Kr
- excellent agreement with GCM for $E_x$, $B$(E2), and $Q_s$
- importance of triaxiality to describe prolate-oblate shape coexistence
- inconsistencies resolved for $^{70}$Se
- coherent picture of shape coexistence in the light Se isotopes
- complementarity of Coulomb excitation and lifetime measurements
Collaboration

CEA Saclay – DSM / IRFU / SPhN:
- **E. Clément (Kr Coulex)**
- **J. Ljungvall (Se Lifetimes)**
W. Korten, A. Obertelli, Ch. Theisen, M. Zielińska
A. Chatillon, E. Bouchez, A. Hürstel, Y. Le Coz

CEA Bruyères-le-Châtel – DIF / DPTA / SPN:
- **M. Girod, J.-P. Delaroche (Theory)**

GANIL experiments:
Warsaw, Liverpool, GSI, GANIL, Surrey, NBI

Legnaro experiments:
Köln, Padova, Legnaro, Oslo, Warsaw

ISOLDE experiments:
Liverpool, York, CERN, Leuven, Köln, München,
Lund, Warsaw, Edinburgh, Legnaro, Oslo,
Padova, Darmstadt, Heidelberg, Manchester

**Gratulerer med dagen, Geirr !**
**Skål !**
(Jeg håper at fysikk har vært bedre enn denne vinen...)