Oblate nuclear shapes and shape coexistence in neutron-deficient rare earth isotopes

Andreas Görgen
Service de Physique Nucléaire
CEA Saclay

Sunniva Siem
Department of Physics
University of Oslo
ultimate goal:
comprehensive microscopic description of all nuclei and low-energy reactions from the basic interactions between the constituent nucleons

specific goal:
provide experimental data on nuclear shapes and collectivity in a sensitive region of shape transition and shape coexistence for benchmarking
Mean field and beyond: an example

Self-consistent HFB constrained to collective coordinate, e.g. \((q_{20}, q_{22})\)

- set of basis states \(\ket{\Phi_q}\)
- potential energy surface

Correlations beyond mean field

- configuration mixing \(\ket{\Psi_i} = \int f_i(q) \ket{\Phi_q} dq\)
- properties of excited states: \(E_x, Q_s, B(E2), \ldots\)

Approaches / choices

- collective coordinates: e.g. axial, triaxial, octupole, …
- relativistic or non-relativistic
- effective interaction: Skyrme, Gogny

**Experiment**: \(E_x, Q_s, B(E2)\) from low-energy Coulomb excitation

![Diagram](https://example.com/diagram.png)
Multi-step Coulomb excitation

- safe energy ⇒ purely electromagnetic excitation
- transitional matrix element ⇒ $B(E2)$
- diagonal matrix element ⇒ $Q_s$
- reorientation effect ⇒ sensitive to nuclear shape
- multi-step excitation
- de-excitation $\gamma$-ray yields ⇒ $d\sigma/d\theta$
- $\chi^2$ minimization of matrix elements to reproduce experimental $\gamma$-ray yields
Nuclear shapes

Gogny HFB

M. Girod, CEA Bruyères-le-Châtel


oblate shapes in medium / heavy nuclei just beneath shell closure ➢ holes in $\Omega=1/2$ orbitals

region of ➢ oblate shapes ➢ rapid shape transition ➢ shape coexistence ?

Andreas Görgen

INTC 16.2.2009
Previous experiments

- No lifetimes known at low spin
- Only few non-yrast states from β decay studies
- No experimental information on the shape at low spin

Extensive studies at high spin e.g. magnetic dipole bands

E.O. Lieder et al.
Predictions for $^{142}$Gd

experiment

configuration mixing calculation GCM(GOA)
5-dimensional ($q_{20}, q_{22}, \alpha, \beta, \gamma$)
Gogny D1S interaction parameter free

analytic solution of Bohr Hamiltonian with square-well potential
E(5) symmetry
normalized to experimental $E_x(2^+)$ and $B(E2, 2^+ \rightarrow 0^+)$ from GCM(GOA)

need $B(E2)$ values and quadrupole moments to test predictions

oblate shape near ground state
transition to prolate at higher spin
$\gamma$ vibration built on oblate states
Shape transitions

M. Girod et al.
CEA Bruyères-le-Châtel

Andreas Görgen
INTC
16.2.2009
Shape coexistence?

**shape transitions**
- neutron number: spherical (N=82) $\Rightarrow$ oblate (N=78) $\Rightarrow$ prolate (N<78)
- proton number: prolate (Nd, Sm) $\Rightarrow$ oblate (Gd, Dy)
- spin: oblate near ground state (Gd) $\Rightarrow$ prolate above 4$^+$ (Gd)

**is there also shape coexistence?**
indication: low-lying 0$^+$ states
(tentative) 0$^+$ state in $^{140}$Sm at 990 keV
Simulation

\[ ^{142}\text{Gd} \]

experimental level scheme theoretical B(E2) and \( Q_s \)

- \( 6^+ \)
- \( 4^+ \)
- \( 2^+ \)
- \( 0^+ \)

\[ ^{142}\text{Gd} + ^{208}\text{Pb} \]

2.9 MeV / u

- 2 \times 10^4 \text{ pps}
- 1 \text{ mg/cm}^2 \]

15 shifts
Differential cross section

\[ ^{142}\text{Gd} + ^{208}\text{Pb} \]

2.9 MeV / u

Experimental level scheme

Theoretical B(E2) and Q_s

\[ \text{prolate} \]

\[ \text{oblate} \]

\[ ^{138}\text{Nd}, ^{140}\text{Sm}, ^{142}\text{Gd}, ^{144}\text{Dy} \]
Sensitivity to quadrupole moments

$^{142}$Gd

experimental level scheme
theoretical $B(E2)$ and $Q_s$

$\sigma / \Omega$ (mb/sr) vs $\theta_{CM}$ (deg)

$138$Nd $140$Sm $142$Gd $144$Dy

$6^+$ $5135$ $2^+$ $3647$ $2^+$ $2376$ $0^+$

$4^+$ $3775$ $2^+$ $119$ $1623$ $(0^+)$

$2^+$ $8$ $2^+$ $1$
Proposed experiment

- REX beams at maximum energy of 2.95 MeV/u
- Measured yields realistic beam intensities
  - $^{138}$Nd: ? (large) $\sim 10^6$
  - $^{140}$Sm: $2 \times 10^8$
  - $^{142}$Gd: $1.2 \times 10^6$
  - $^{144}$Dy: ?
- RILIS to suppress isobaric contaminants crucial
- Ionization schemes exist, Sm and Gd not yet tested at ISOLDE
- Coulomb excitation target: $^{206}$Pb or $^{208}$Pb
  (normalization point vs. spectrum simplicity)
- Double-sided annular silicon detector and MINIBALL

shape transition and coexistence predicted for N=78 isotones

- Measure quadrupole moments for $2_1^+$ ($2_2^+$, $4_1^+$) in $^{140}$Sm and $^{142}$Gd
- Measure transition rates between all low-lying states
- Identify low-lying $0^+$ states
- Extend study to $^{144}$Dy and N=76 if feasible

beam time request

- $^{140}$Sm: 6+3 shifts
- $^{142}$Gd: 15+3 shifts

Testing required to determine / improve intensity and purity
Collaboration

**CEA Saclay, IRFU/SPhN**  A. Görgen, W. Korten, A. Obertelli, B. Sulignano, Ch. Theisen


**CEA DIF, Bruyères-le-Châtel**  J.-P. Delaroche, M. Girod

**CERN-ISOLDE**  J. Cederkäll, J. Van de Walle

**GANIL**  E. Clément, G. de France, J. Ljungvall

**University of Liverpool**  P.A. Butler, M. Scheck

**University of York**  D.G. Jenkins

**University of Manchester**  S. Freeman

**Universität Köln**  P. Reiter, M. Seidlitz, A. Wendt