Nuclear shapes and collectivity studied using low-energy Coulomb excitation

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Measurements of transition probabilities and spectroscopic quadrupole moments:
- Coulomb excitation
- direct lifetime (plunger, fast-timing) measurements

Oblate shapes, shape coexistence:
- 74,76Kr (GANIL, Legnaro)
- 70,72Se (Legnaro, HIE-ISOLDE)
- 74Se (Orsay)

Octupole deformation
- 222-228Ra, 220-226Rn (HIE-ISOLDE)
- 148Sm, 146Nd (Orsay)

Shape evolution and coexistence beyond N=58
- Coulex of 96-98Sr, 97-99Rb (ISOLDE)
- Coulex of 100Zr (ANL-CARIBU)
- Lifetimes in A~100 fission fragments (GANIL, ILL)

Triaxial shapes
- Coulex of 110Ru (ANL-CARIBU), Coulex of 78-82Ge (SPES?)
- Lifetimes in A~100 fission fragments (GANIL?, ILL)

Evolution of collectivity around 68Ni and 48Ca
- 70-80Zn (Legnaro, Warsaw, HIE-ISOLDE)
- 44Ar, 43-45Ar(?) (GANIL)
Why do we like Coulomb excitation?

• 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 $2_1^+$: barns)
  ◦ practical at the neutron-rich side

• direct measurement of quadrupole moment including sign – ideal tool to study shape coexistence

• $B(E2)$ as a measure of collectivity – studies around magic numbers

• easy way to access non-yrast states and study their properties
What we can get from a Coulex experiment?

- observation of new excited levels, selective population of collective states
  - first excited state in $^{80}$Zn (J. Van de Walle et al, PRL 99 (2007) 142501)
  - rotational bands in $^{97,99}$Rb

- $B(E2)$ and $B(M1)$ values between low-lying states, as well as $B(E1)$’s, $B(E3)$’s
  - decay of opposite parity states proceeds via E1 and E2, but excitation cross sections are related to $B(E3)$

- signs and magnitudes of static E2 moments of excited states

- relative signs of matrix elements

- out of a complete set of matrix elements: quadrupole shape parameters using the sum rules formalism
Determination of matrix elements

- extraction of individual electromagnetic matrix elements from measured gamma-ray intensities following Coulomb excitation
  - simple cases (rare): first/second order perturbation theory
  - typical cases: set of coupled equations for excitation amplitudes – solved numerically: dedicated analysis codes

Coulomb excitation of $^{74,76}$Kr

- experiments using SPIRAL1 beams
- EXOGAM Ge array in coincidence with annular Si detector

- results inconsistent with previously published lifetimes
- new RDM lifetime measurement: Köln Plunger & GASP
  $^{40}$Ca ($^{40}$Ca,$\alpha$2p) $^{74}$Kr
  $^{40}$Ca ($^{40}$Ca,4p) $^{76}$Kr
### Lifetime measurement

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Old State</th>
<th>Old Lifetime</th>
<th>New State</th>
<th>New Lifetime</th>
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</thead>
<tbody>
<tr>
<td>$^{76}$Kr</td>
<td>$2^+$</td>
<td>35.3(10) ps</td>
<td></td>
<td>41.5(8) ps</td>
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<tr>
<td>$4^+$</td>
<td>4.8(5) ps</td>
<td></td>
<td>3.87(9) ps</td>
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<tr>
<td>$^{74}$Kr</td>
<td>$2^+$</td>
<td>28.8(57) ps</td>
<td></td>
<td>33.8(6) ps</td>
</tr>
<tr>
<td>$4^+$</td>
<td>13.2(7) ps</td>
<td></td>
<td>5.2(2) ps</td>
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</table>

$^{74}$Kr, forward detectors (36°) gated from above

- New lifetimes in agreement with Couleex
- Enhanced sensitivity for diagonal and intra-band transitional matrix elements
Results: shape coexistence in light Kr isotopes

$^{76}$Kr: 18 transitional + 5 diagonal ME

$^{74}$Kr: 14 transitional + 5 diagonal ME

$\langle 2_1^+ \parallel E2 \parallel 2_1^+ \rangle = -0.70^{-0.33}_{-0.30}$

$\langle 4_1^+ \parallel E2 \parallel 4_1^+ \rangle = -1.02^{+0.59}_{-0.21}$

$\langle 2_2^+ \parallel E2 \parallel 2_2^+ \rangle = +0.33^{+0.28}_{-0.23}$

First measurement of diagonal E2 matrix elements using Coulex of a radioactive beam

Shape coexistence and evolution in light Se isotopes

- oblate shapes predicted for ground states in $^{68,70,\ldots}$Se
- calculations indicate shape coexistence and considerable gamma softness in $^{68-74}$Se
- no direct measurement of $Q_s$: low intensities of exotic Se beams
- Coulex of $^{72}$Se accepted at HIE-ISOLDE
- Coulex of $^{74}$Se measured a week ago at IPN Orsay
Shape transition at N=60

- dramatic change of the ground state structure observed at N = 58, 60 for Rb, Sr, Y, Zr isotopes
- considerable theoretical and experimental effort in this mass region
- southern border of the phenomenon less known experimentally
- onset of deformation at N=60 confirmed by $2^+$ energies and transition probabilities in even-even nuclei (Sr, Zr, Mo...)

Shape transition and coexistence in $^{96,98}\text{Sr}$

- low-lying $0^+$ states observed in $N=58,60\ Zr,\ Sr$ isotopes
- enhanced $E0$ transition of $\rho^2(E0)=0.053$ in $^{98}\text{Sr}$
- regular rotational band in $^{96}\text{Sr}$ (W. Urban et al., Nucl. Phys. A 689 (2001))

- shape coexistence?
- configuration inversion at $N=60$?
Shape transition and coexistence in $^{96,98}$Sr

E. Clément, M. Zielińska et al, to be published

$\beta$ (from $Q_s$) = 0.11$^{+5}_{-4}$

B(E2) in agreement with lifetime but more precise low deformation of gsb confirmed
Shape transition and coexistence in $^{96,98}$Sr: quadrupole moments

E. Clément, M. Zielińska et al, to be published

- well deformed prolate band ($\beta \geq 0.3$)
- low deformation of the excited band ($\beta < 0.1$)
Coulomb excitation of $^{97-99}$Rb

- identification of rotational bands in $^{97-99}$Rb (first observation of collective states in these nuclei!)
- statistics sufficient for gamma-gamma coincidences – level schemes established

C. Sotty, M. Zielińska et al, to be published

- extracted B(E2) values confirm strong constant deformation in gsb in $^{97,99}$Rb
• Q₀ values in $^{97}$Rb consistent with those in N=60 Zr and Sr nuclei
• visible reduction of Q₀ for N=60 $^{96}$Kr – similar to what is observed at N=58
Future plans

- extraction of E2 transition probabilities in $^{97,99}$Sr and $^{98}$Rb (no or little transition probabilities known)
- Coulomb excitation measurements with refractory neutron-rich beams (Mo, Zr) at CARIBU (our first experiment on $^{100}$Zr to be reproposed)
- possible lifetime measurement in $^{97}$Rb – verification of the model assumptions used in Coulex analysis
- further lifetime measurements following fusion-fission to be proposed for AGATA + FATIMA campaign at GANIL
Octupole deformation: E3 moments measured in Coulomb excitation

Regions of enhanced octupole collectivity

"Magic" numbers: 34, 56, 88, 134

L. M. Robledo, G. F. Bertsch: GCM (GOA)

Very high $B(E3)$ in $^{152}$Gd: 52(17) W.u. measured in (d,d’)

- How reliable is this value?
- Is there a peaking in octupole strength in this mass region similar to what is observed for Ra-Rn isotopes?
- Is it octupole vibration or static deformation?
Vicinity of $^{68}$Ni: transition probabilities in heavy Zn isotopes

- $2^+$ lifetimes measured with AGATA at LNL (C. Louchart, PRC 87 (2013) 054302) in agreement with previous $B(E2; 2^+ \to 0^+)$ values

- discrepancy of the new lifetimes for $4^+$ states with low-energy Coulex results (especially for $^{74}$Zn)

- Coulomb excitation of $^{70}$Zn: November 2012, HIL Warsaw, Poland: preliminary confirmation of the high $B(E2; 4^+ \to 2^+)$ value

- Coulomb excitation of $^{74-80}$Zn at HIE-ISOLDE: proposal accepted
  - collectivity of higher-lying states
  - quadrupole moments in exotic Zn isotopes?
Structure of low-lying states in $^{43,45}$Ar studied using Coulomb excitation of SPIRAL beams

M. Zielińska et al, LoI endorsed

- erosion of the N=28 shell closure south of $^{48}$Ca: properties of excited states in odd Ar isotopes sensitive to the interaction

Where is the first excited state in $^{43}$Ar?

What is the structure of $3/2^-$ states in $^{45}$Ar?

How the deformation of exotic Ar nuclei changes when approaching N=28?
Triaxiality in neutron-rich Ru and Mo nuclei

- low-lying $2^+_2$ states in $^{110-114}$Ru
- $E(3^+) \approx E(2^+_1) + E(2^+_2)$ suggests breaking of axial symmetry
- Coulex experiment at CARIBU (October 2014) in order to measure quadrupole moments and $B(E2)$ values between the $\gamma$ and ground state band
- data under analysis at SPhN, continuation towards heavier isotopes and Mo nuclei under consideration
- complementary data from fast-timing campaign at ILL/RDDS measurements at GANIL
Exploring the Z=32 triaxiality corridor towards N=50 via safe Coulomb excitation at SPES

D. Verney, M. Zielińska et al, LoI endorsed

- Local minimum of the effective N=50 gap at Z=32: maximum of collectivity
- Triaxiality confirmed for stable Ge isotopes but transition probabilities and quadrupole moments in neutron-rich Ge isotopes crucial to understand its role towards N=50
- Expected high intensities of Ge beams from SPES make a low-energy Coulex experiment feasible in a short measuring time:
  - Quadrupole moments of $2^+_1$ states in $^{78-82}$Ge: precise measurement (20-30% uncertainty) in one day of beamtime at $10^6$ pps
  - Longer measurements: detailed information on transition probabilities and static moments for $^{78,80,82}$Ge, possibility to extract triaxiality parameters for $^{78,80}$Ge via quadrupole sum rules approach
Summary

• strong physics programme complementary to lifetime measurements
• expertise in Coulomb excitation analysis
• several publications expected in 2015 (Rb, Sr, $^{70}$Zn)

• relatively simple apparatus existing in many laboratories: investment costs $\sim$ 2-3 kEUR/year (targets, cables, minor mechanical adaptations)
• travel costs $\sim$ 2-3 kEUR/year
Plunger lifetime measurements in fission fragments

L. Grente et al, E604 experiment

238U on 9Be (2.3 mg/cm²), 6 MeV/A
degradation: 24Mg, 5 mg/cm²
7 plunger distances (35-1550 µm, τ ~ 1-100 ps)
Lifetime measurements in $A \sim 100$ fission fragments

L. Grente et al, E604 experiment
Lifetime measurements in $A \sim 100$ fission fragments

- Identification of over 100 nuclei: from Se ($Z=34$) to Xe ($Z=54$)
- Exotic nuclei produced: up to 10 neutrons from stability
- 20 lifetimes of $4^+$ and $6^+$ states extracted (10 measured for the first time)

L. Grente et al, E604 experiment
Lifetime measurements in $^{70-74}\text{Zn}$

Deep inelastic reaction: $^{76}\text{Ge}$ (577 MeV) + $^{238}\text{U}$

PRISMA spectrometer at grazing angle (55°)

Cologne plunger

Target: 1.4 mg/cm$^2$
Degrader: Nb – 4.2 mg/cm$^2$
5 plunger distances:
100, 200, 500, 1000, 1900 µm
(20 hours each)
Quadrupole sum rules

- number of matrix elements obtained from a Coulomb excitation analysis can reach 20-50 (+ for some of them signs are determined)

- quadrupole collectivity produces strong correlations of E2 matrix elements: number of significant collective variables is much lower than the number of matrix elements

- direct comparison of each ME’s from experiment and theory is not always conclusive.

- quadrupole invariants provide a syntetic information that can be compared with model predictions.

- electromagnetic multipole operators are spherical tensors $\rightarrow$ 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:

  $E(2, 0) = Q \cos \delta$

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

  $E(2, 1) = E(2, -1) = 0$
Quadrupole sum rules

K. Kumar, PRL 28 (1972) 249

- operator products may be expressed by matrix elements using the intermediate state expansion formula

\[
\frac{\langle Q^2 \rangle}{\sqrt{5}} = \langle i | [E2 \times E2]^0 | i \rangle = \frac{1}{\sqrt{(2I_i + 1)}} \sum_t \langle i | E2 || t \rangle \langle t | E2 | i \rangle \left\{ \begin{array}{ccc} 2 & 2 & 0 \\ I_i & I_i & I_t \end{array} \right\}
\]

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

K. Kumar, PRL 28 (1972)

\[ \sqrt{\frac{2}{35}} \langle Q^3 \cos 3\delta \rangle = \langle i | \{ [E2 \times E2]^2 \times E2 \}^0 | i \rangle \]

\[ = \frac{1}{(2I_i + 1)} \sum_{i, u} \langle i | E2 | u \rangle \langle u | E2 | t \rangle \langle t | E2 | i \rangle \left\{ \begin{array}{ccc} 2 & 2 & 2 \\ I_i & I_t & I_u \end{array} \right\} \]


\[ \langle \cos 3\delta \rangle : \text{triaxiality parameter} \]
Theoretical predictions for $^{97}$Rb

R. Rodriguez-Guzman et al., PRC 82 (2010) 061302
Theoretical predictions for Sr isotopes

H. Goutte et al., priv. comm, GCM(GOA) D1S
Comparison with model predictions

- calculations for $^{42}$Ar in worse agreement than for more exotic isotopes
- $B(E2; 2^+_1 \rightarrow 0^+)$ for $^{42}$Ar known with lower precision than those of more exotic isotopes
- conflicting predictions for the shape of $^{42}$Ar
- axial beyond mean-field calculations seem to be biased towards oblate shapes – similar to light Kr isotopes (?)