Recent achievements and future developments in low-energy Coulomb excitation studies

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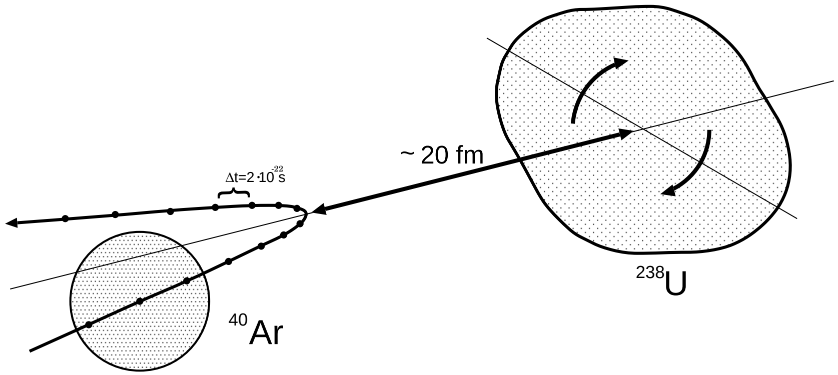
- How does it work?
- What kind of physics can we study?
  - shape coexistence (^{96,98}Sr)
  - development of deformation (^{97,99}Rb)
  - octupole collectivity (^{220}Rn, ^{224}Ra)
  - superdeformation and triaxiality (^{42}Ca)
- Future developments
  - possibilities with HIE-ISOLDE
  - new detectors: SPIDER and SPEDE

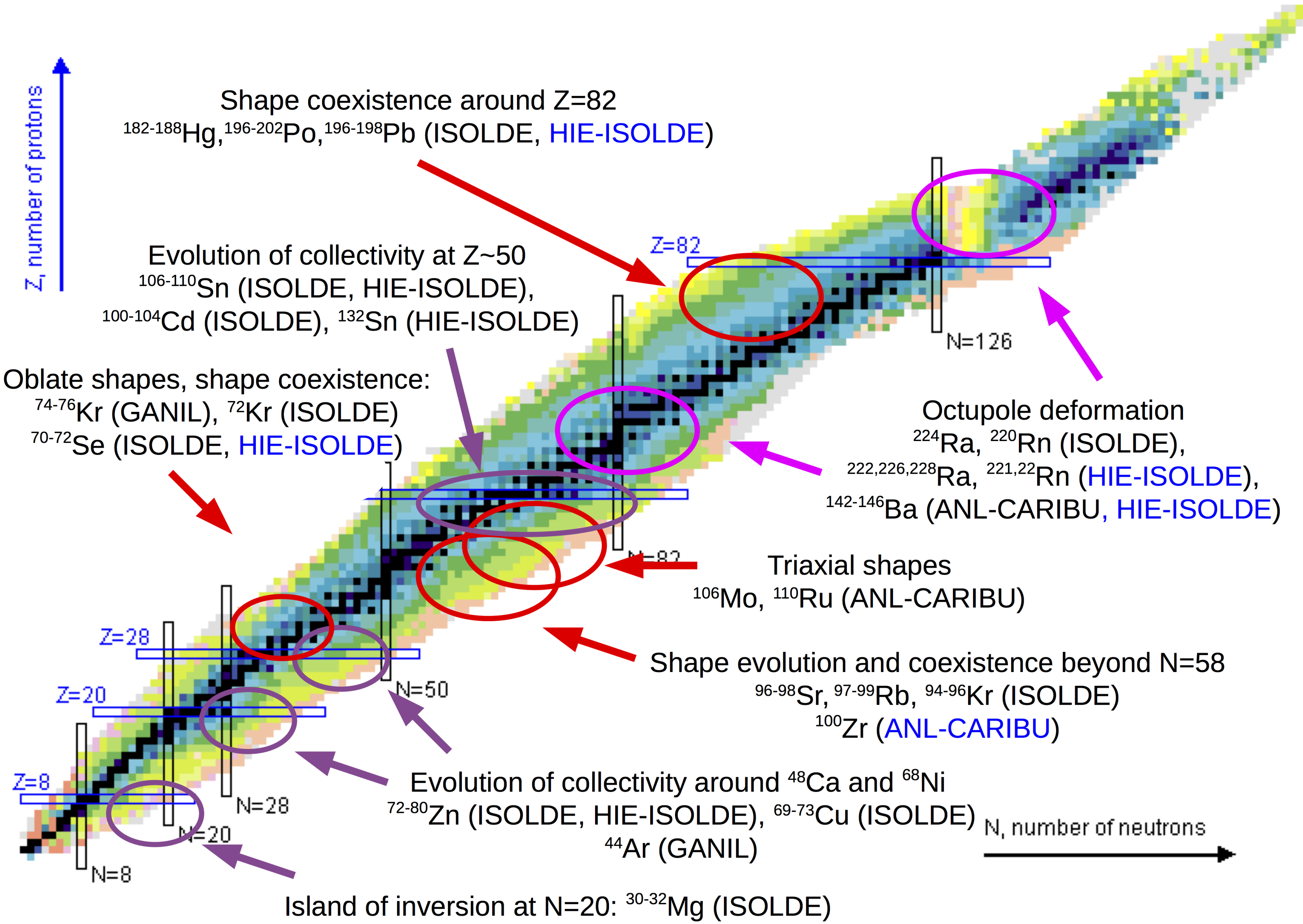
Coulomb excitation

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

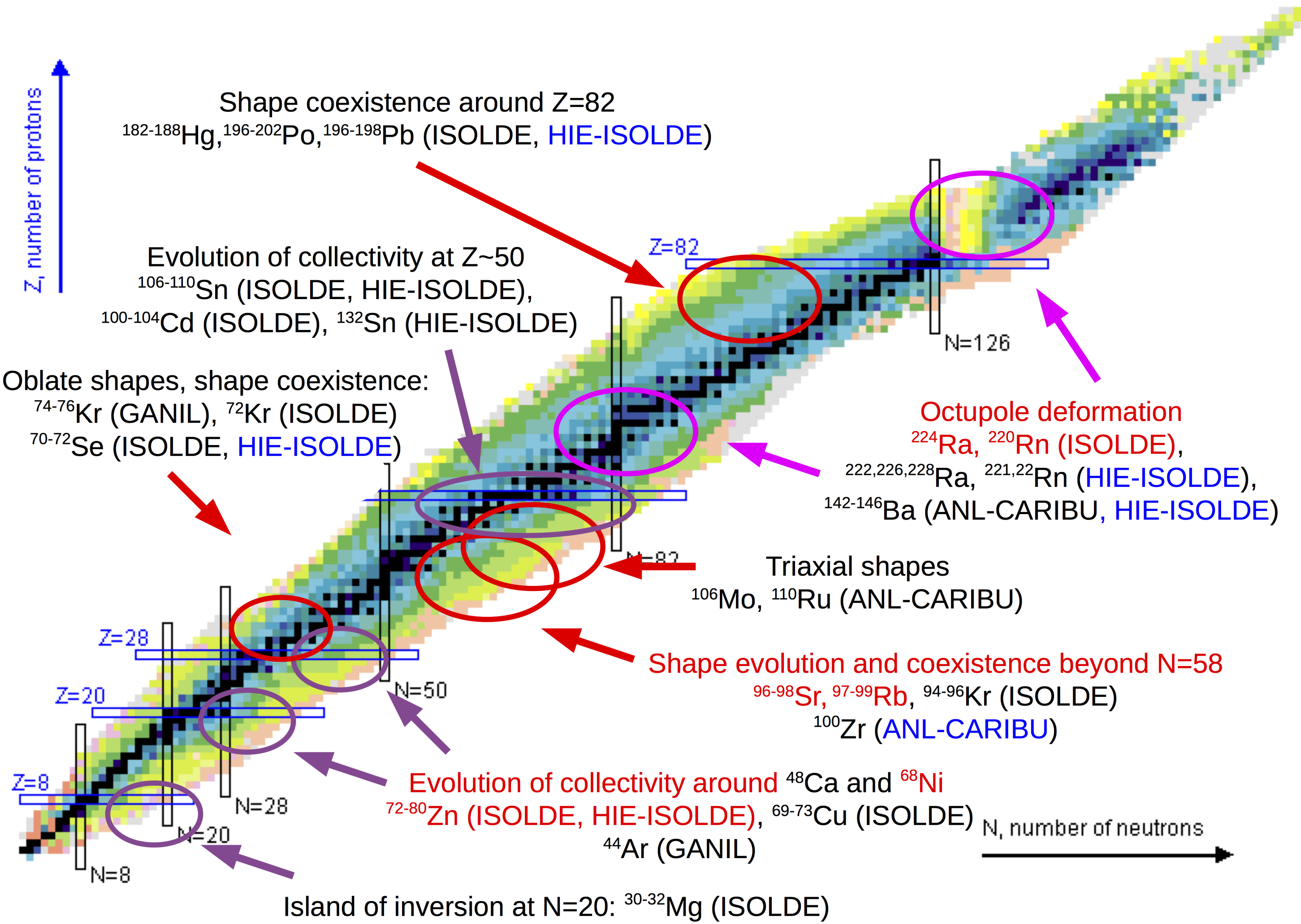


- B(E2) transition probabilities – measure of collectivity
- direct measurement of quadrupole moments including sign – ideal tool to study shape coexistence
- easy way to access non-yrast states and study their properties
- renaissance of the technique as ideally suited for state-of-the-art RIB facilities:
  - beam energies available perfect for Coulomb excitation (2-5 MeV/A)
  - high cross sections (excitation of 2_1^+: barns)
  - practical at the neutron-rich side

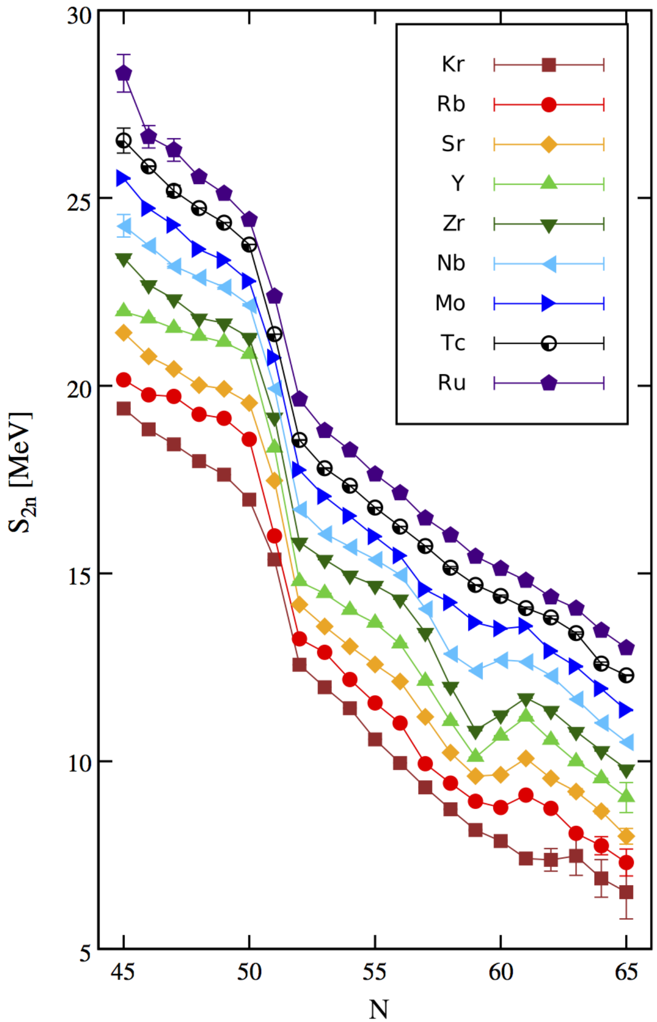
Examples of recent Coulex studies with RIB's



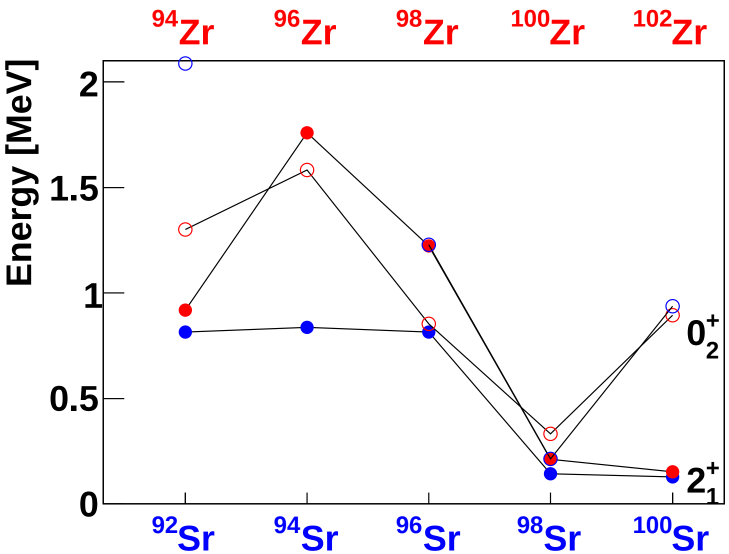
Examples of recent Coulex studies with RIB's



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

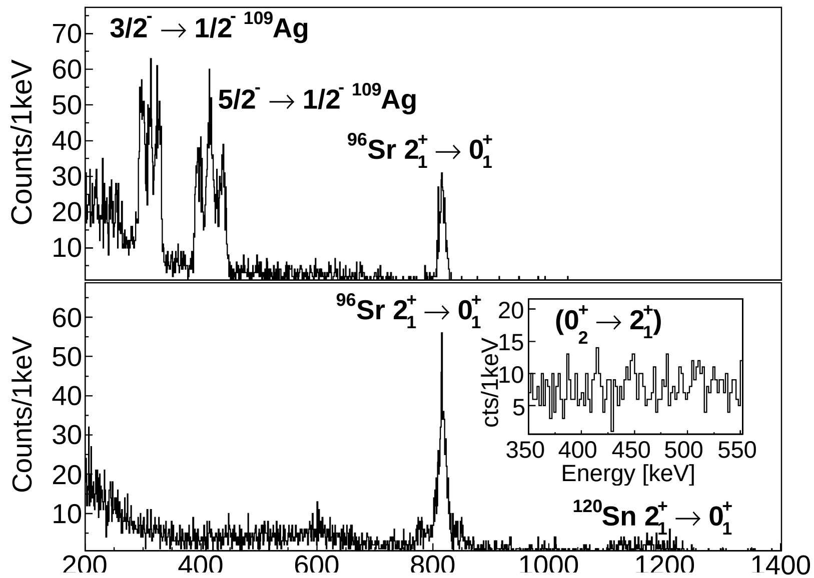


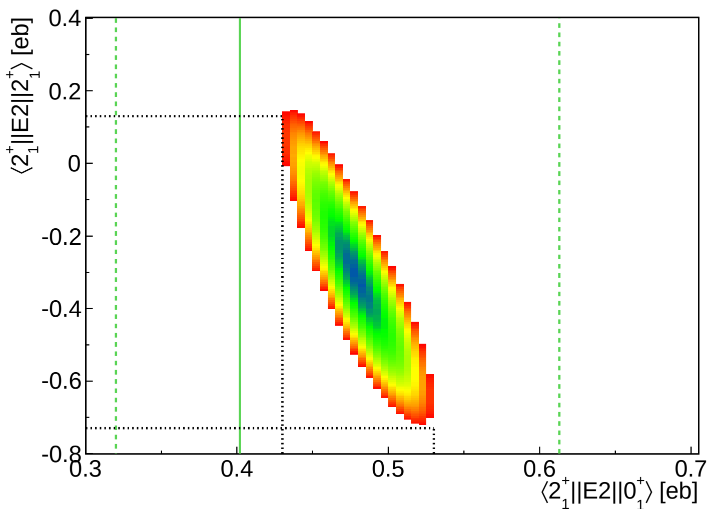
P. Campbell *et al.*, Prog. Part. Nucl. Phys. 86 (2016) 127

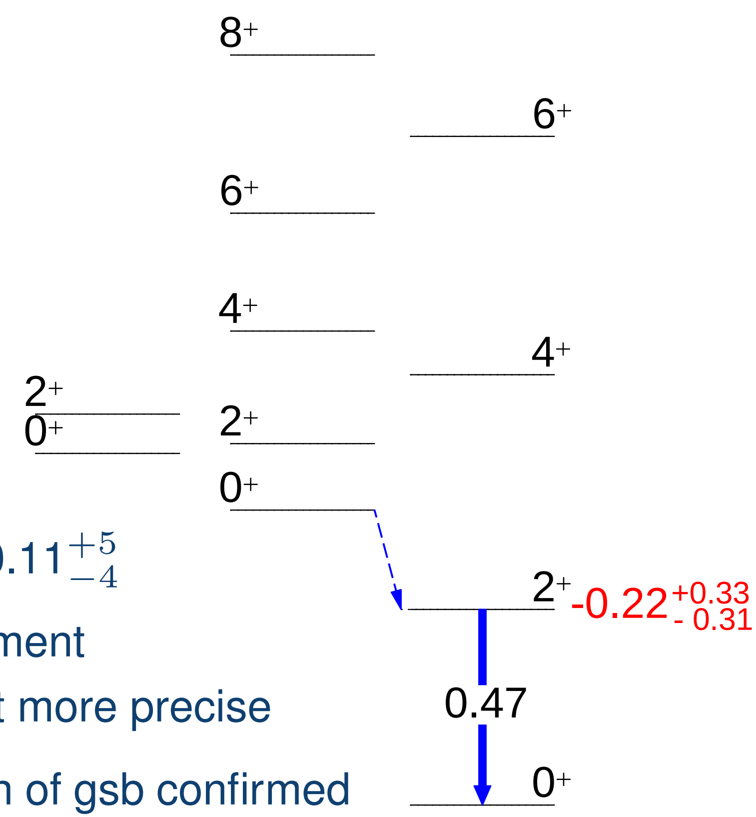
Deformation of ^{96}Sr

E. Clément *et al.* PRL 116, 022701 (2016)

Coulomb excitation at REX-ISOLDE: ^{96}Sr on ^{109}Ag, ^{120}Sn, ^{98}Sr on ^{60}Ni, ^{208}Pb







β (from Q_s) = 0.11^{+5}_{-4}

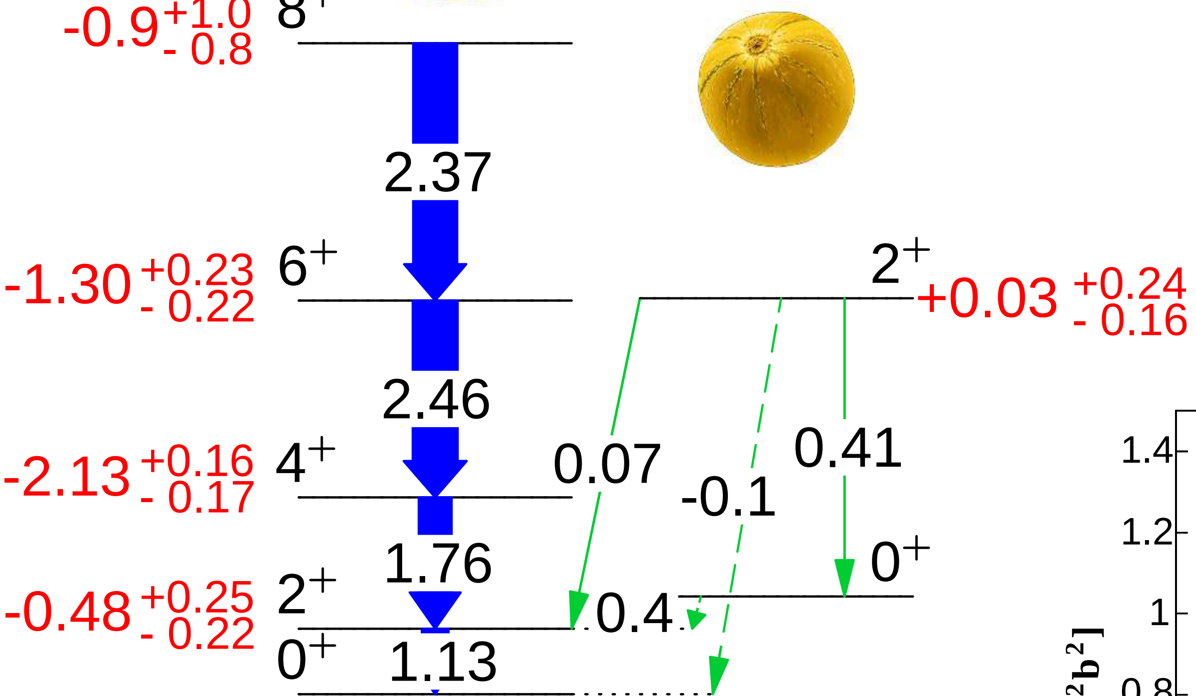
B(E2) in agreement

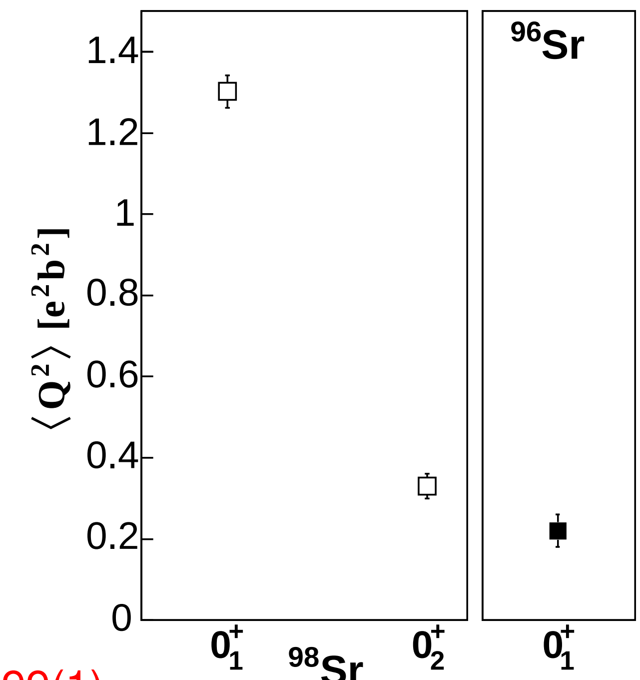
with lifetime but more precise

low deformation of gsb confirmed

^{98}Sr: quadrupole moments and transition probabilities

E. Clément *et al.* Phys. Rev. Lett. 116, 022701 (2016)

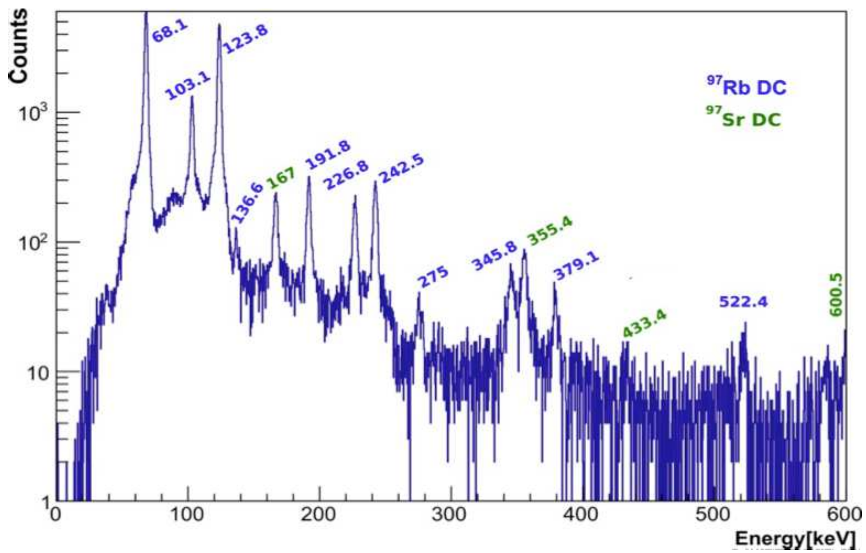


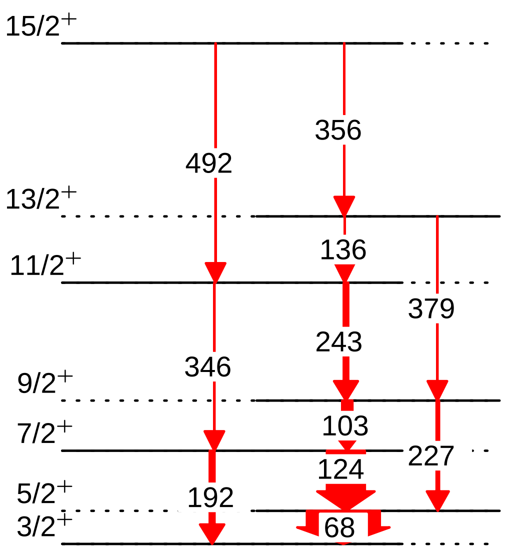


- well deformed prolate band ($\beta \geq 0.3$)
- low deformation of the excited band ($\beta < 0.1$)
- similar deformation of 0_1^+ in ^{96}Sr and 0_2^+ in ^{98}Sr
- mixing amplitudes for ^{98}Sr: $\cos^2\theta_0$=0.87(1), $\cos^2\theta_2$=0.99(1)

Deformation of N=60,62 ^{97,99}Rb studied by Coulex at REX-ISOLDE

- 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

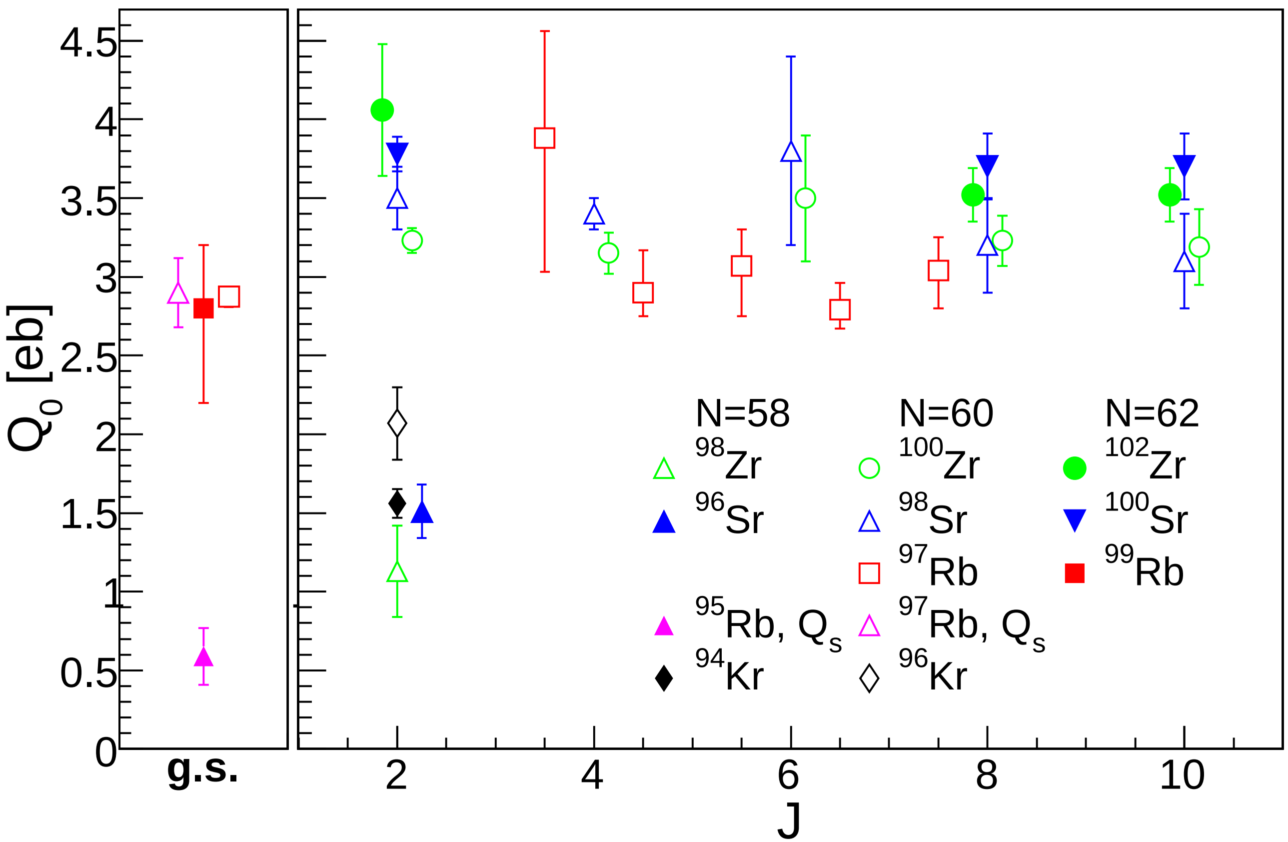




C. Sotty *et al.*, PRL 115 (2015) 172501

- extracted B(E2) values confirm strong constant deformation in gsb in ^{97,99}Rb
- B(M1)/B(E2) ratios in ^{97}Rb favour $3/2^+$[431] configuration of the ground state

Results: deformation of ^{97,99}Rb and neighbouring N=58,60,62 nuclei

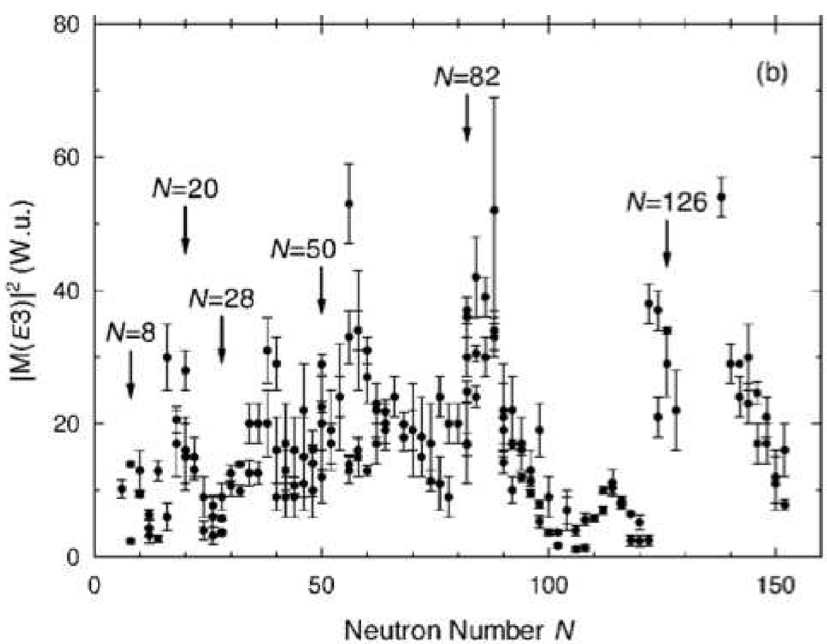


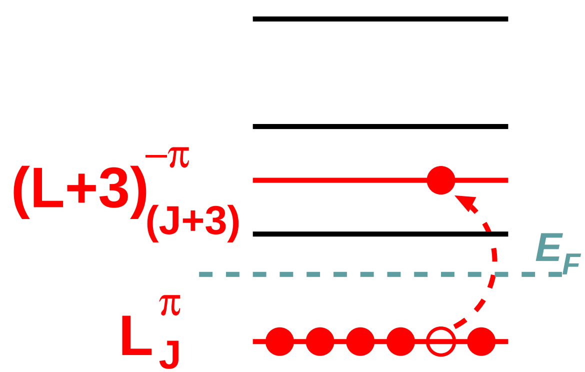
- visible reduction of Q_0 for N=60 ^{96}Kr – similar to what is observed for N=58 nuclei
- large deformation appears in ^{97}Rb and remains constant with increasing Z and N: Q_0 in ^{97,99}Rb similar to that of N=60,62 Zr and Sr nuclei
- Q_{sp} values from laser spectroscopy confirm a dramatic shape change at N=60 in Rb isotopes, deformation for ^{97}Rb consistent with Coulex results

Coulex studies of octupole strength

- Q_3 moments are a sensitive probe of octupole collectivity
- decay of negative-parity states proceeds predominantly via E1 and E2 transitions; E3 branches are usually below observation limits
- ...but population of these states in Coulomb excitation proceeds via E3 transitions;

→ Coulex excitation cross-sections can be related to E3 matrix elements

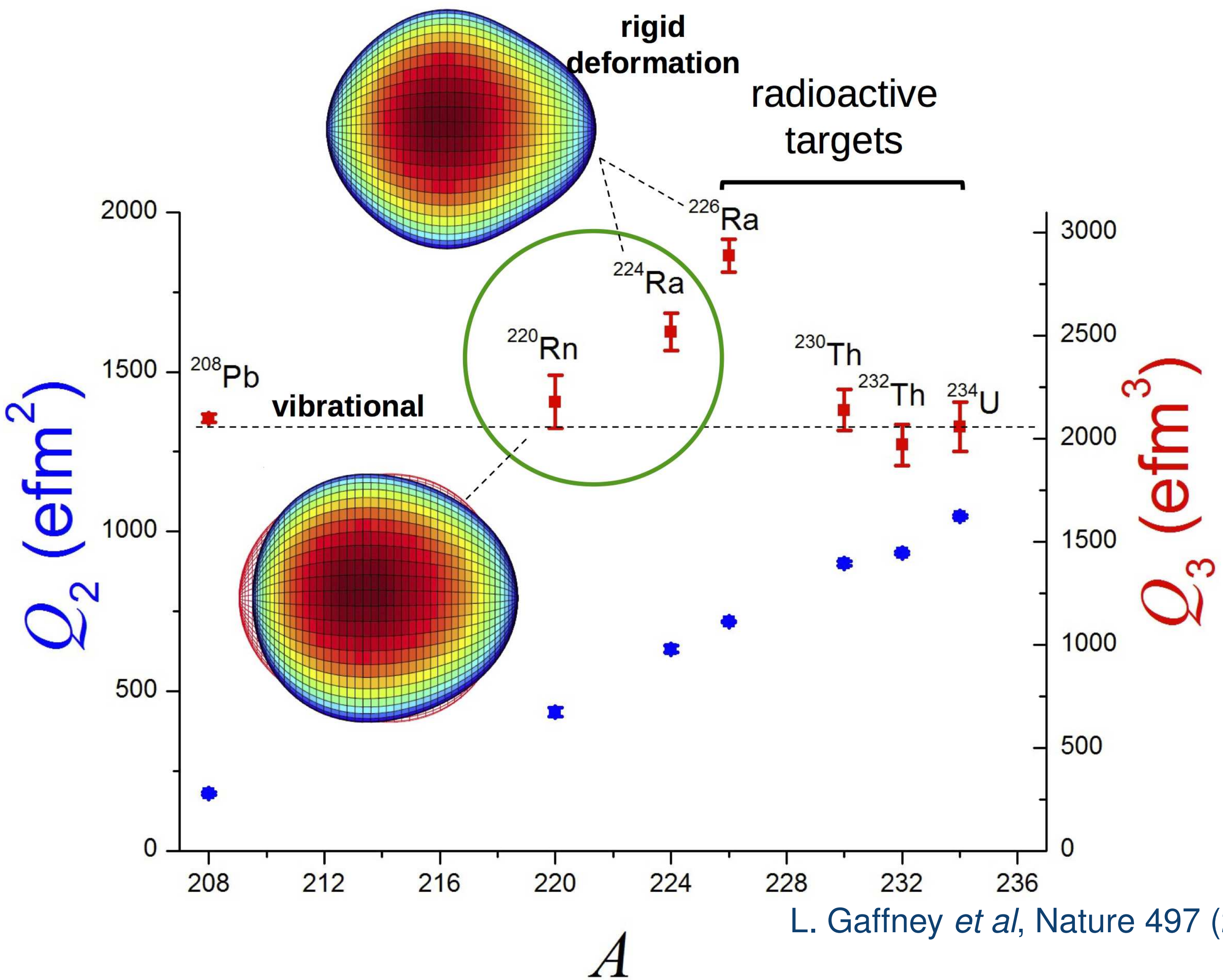




compilation: T. Kibedi, At. Data Nucl. Data Tables 80 (2002) 35

”Magic” numbers: 34, 56, 88, 134: opposite-parity orbitals with $\Delta L = 3\hbar$

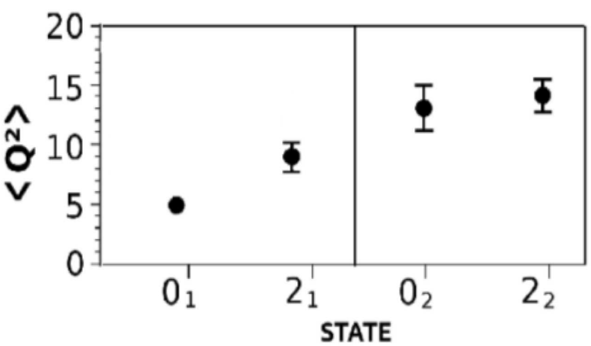
Octupole deformation: E3 moments measured in Coulomb excitation

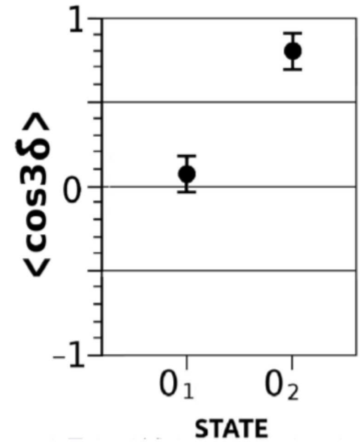


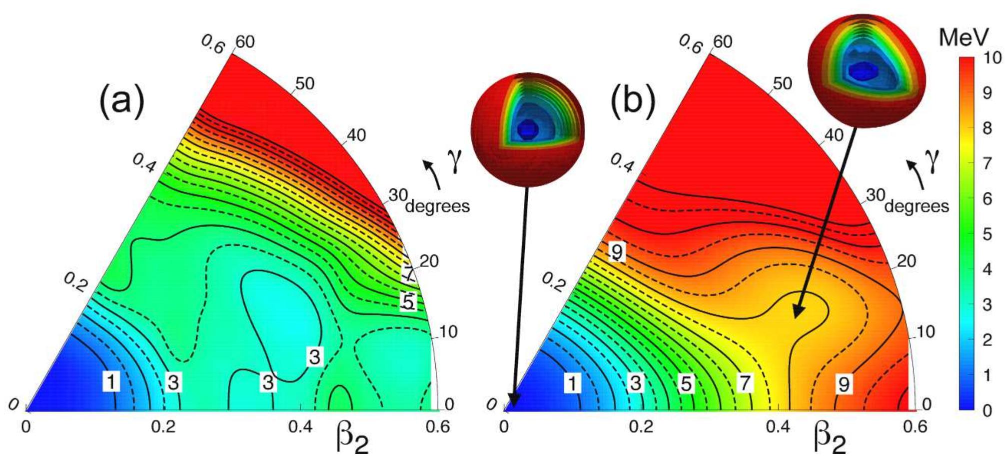
L. Gaffney *et al*, Nature 497 (2013) 199

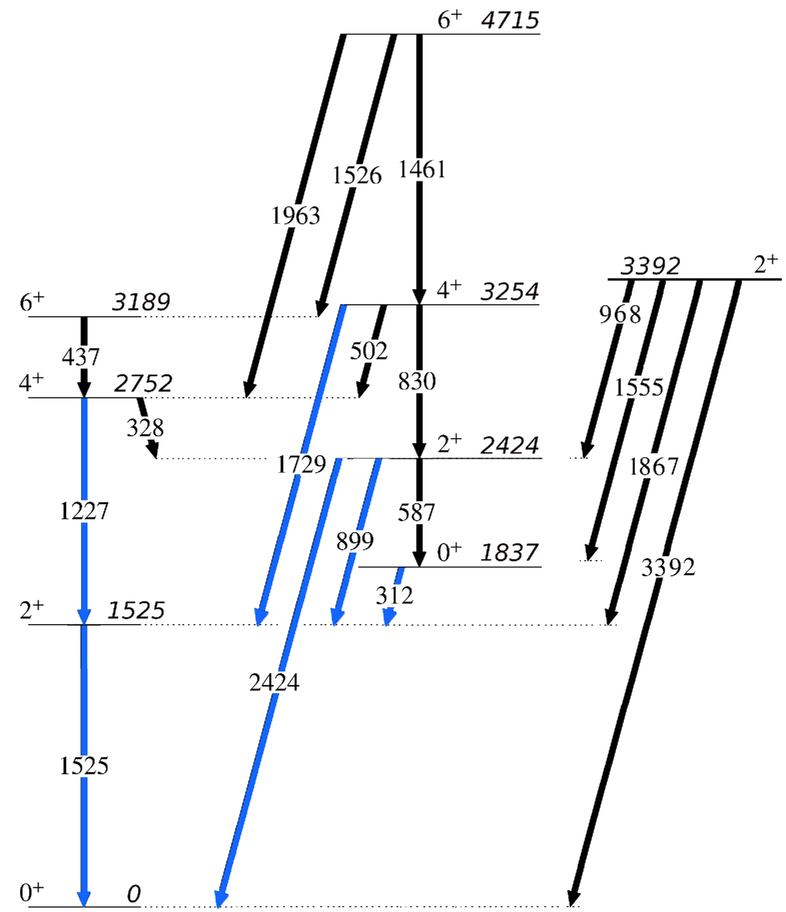
^{42}Ca: first population of a very highly-deformed band in Coulex

- Coulomb excitation of ^{42}Ca on ^{208}Pb studied with AGATA at LNL Legnaro
- shape parameters of $0^+_{1,2}$ and $2^+_{1,2}$ states determined using quadrupole sum rules
- deformation in the side band: β=0.43(2), γ=13(6)°



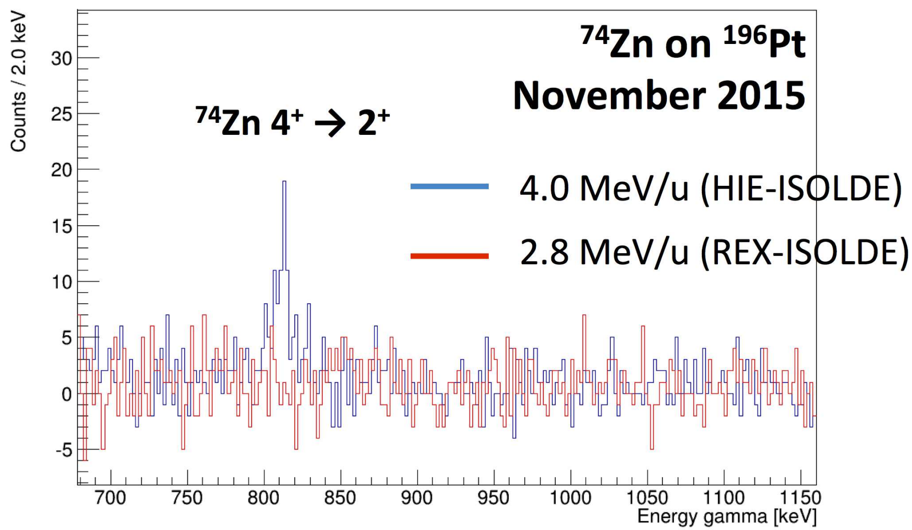




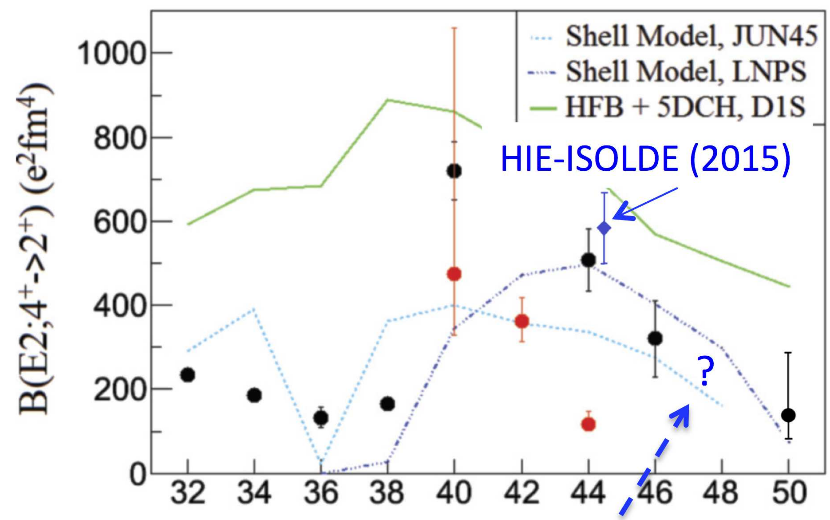


K. Hadyńska-Klęk, PRL 117 (2016) 062501

The first HIE-ISOLDE experiment: Coulex of $^{74-78}$Zn



Analysis: A. Illana Sison (KU Leuven)

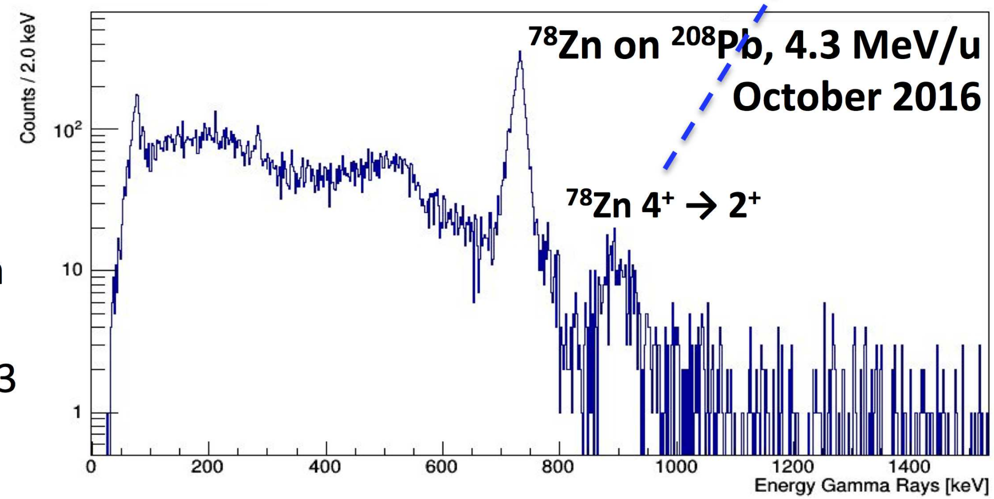


Louchart PRC 2013, Van de Walle PRL 2007

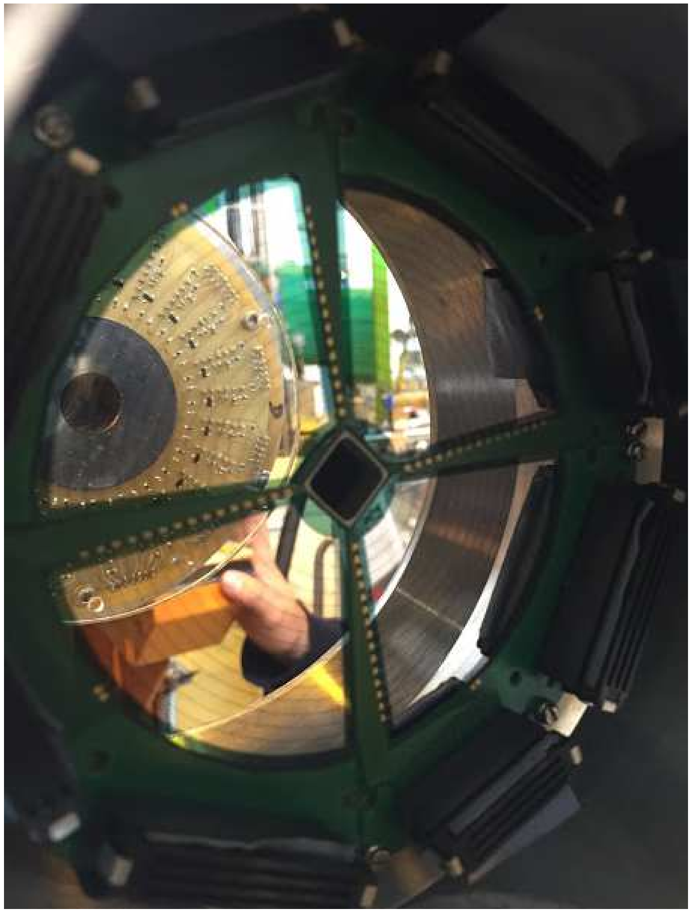
Cross section for multi-step Coulex strongly increased for HIE-ISOLDE beam energies
–> population of higher-lying states

Verification of conflicting results for ^{74}Zn

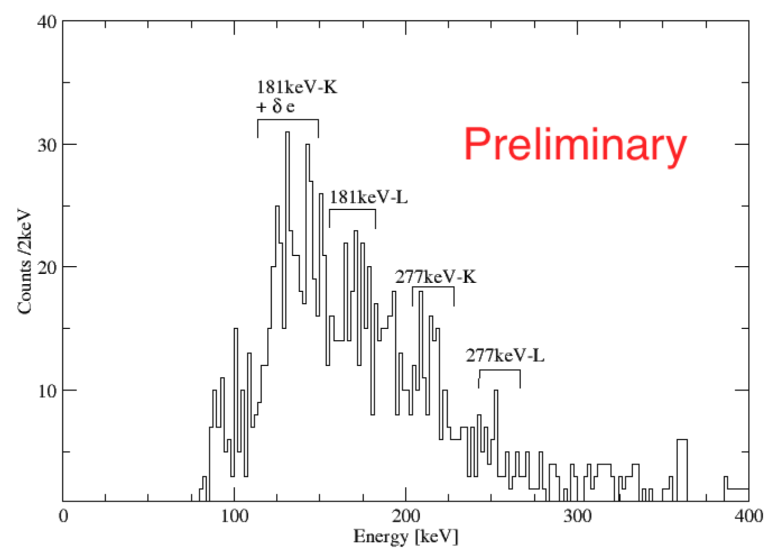
Statistics for ^{78}Zn 20x higher than in 2003 REX-ISOLDE run, observation of 4^+ state

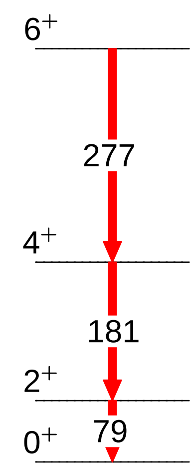


SPEDE: new conversion electron detector for in-beam measurements



- E0 transitions: measure of mixing of coexisting states and difference of their deformation
- internal conversion important for E2 and M1 transitions in heavy nuclei
- commissioning in November 2016
- collaboration of Uni. Jyväskylä, Uni. Liverpool, KU Leuven

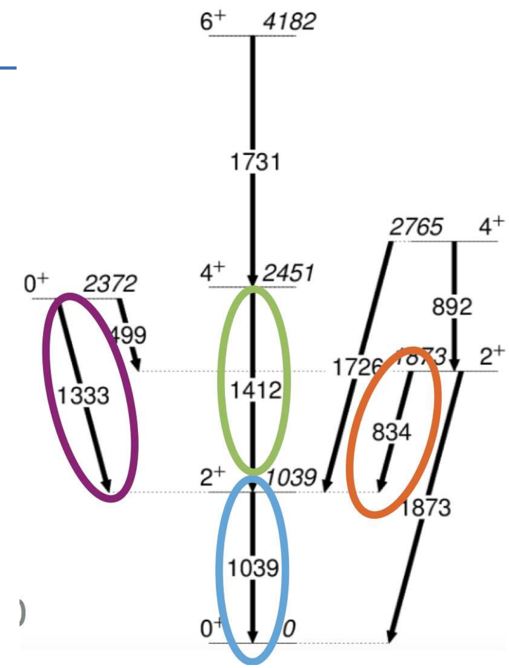


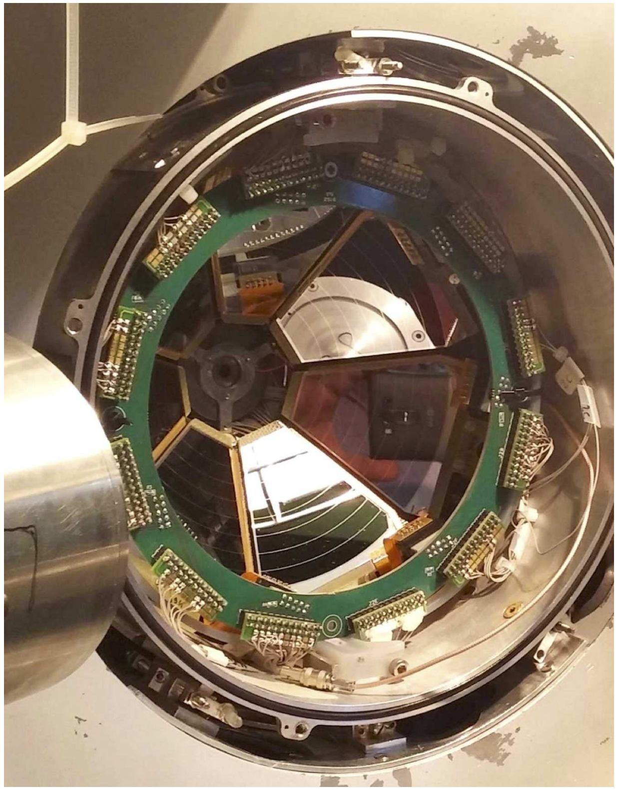


Courtesy of D. Cox

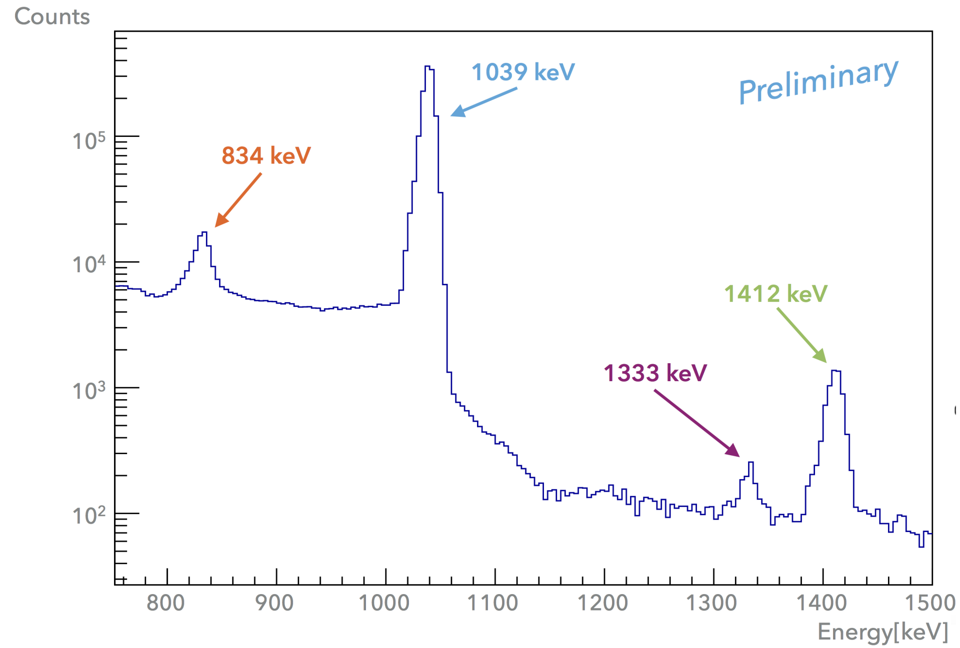
SPIDER: segmented Si detector for Coulex at SPES

- two geometries possible: CD-like (8 sectors) or conical (7 sectors); mounted at backward angles for stable beams, forward for RIB's
- developed at INFN Firenze, commissioned in July 2016





Courtesy of M. Rocchini



Conclusions

- low-energy Coulomb excitation has a long tradition and a great future
- great opportunities thanks to higher beam energies at HIE-ISOLDE, new beams at GANIL-SPIRAL1, development of SPES...
- new ancillary detectors are being developed to make efficient use of radioactive beams