Onset of deformation in neutron-rich Rb isotopes from Coulomb excitation studies

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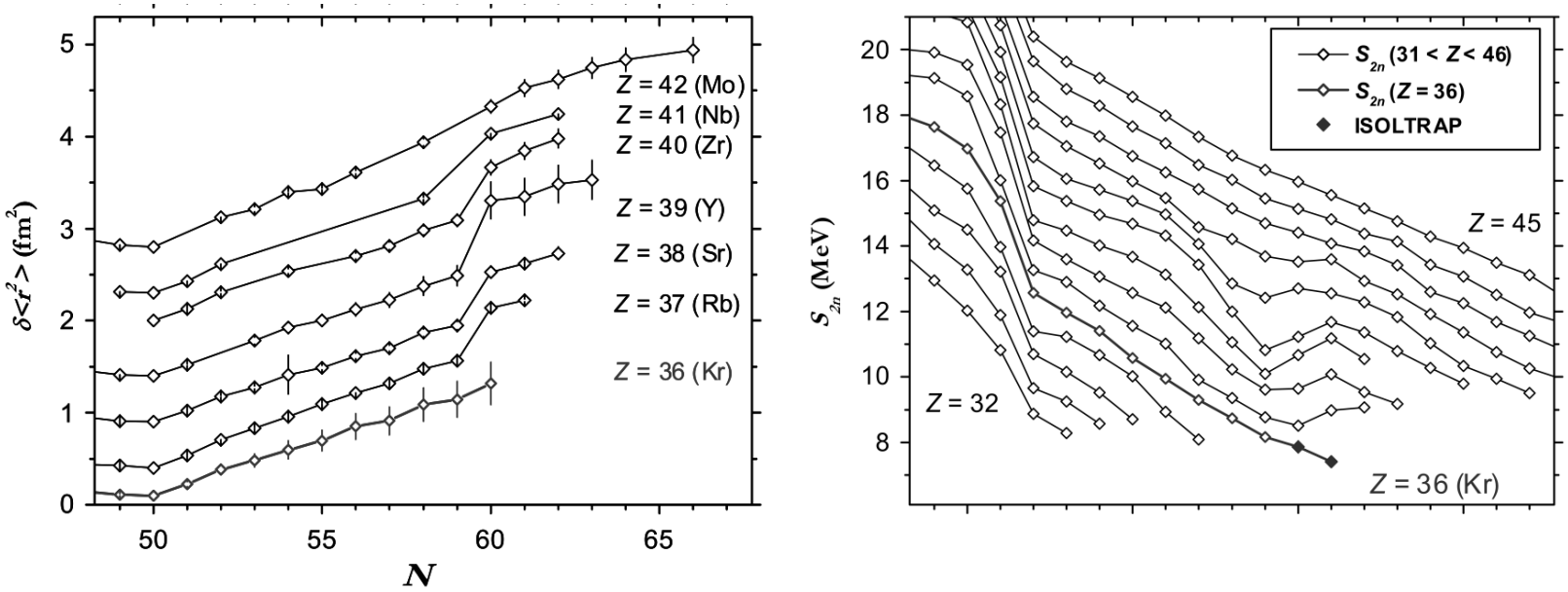
- Motivation
- Experiments on ^{97,99}Rb
  - Methods and assumptions used in Coulex analysis
  - Results
- Outlook
  - Shape coexistence in neutron-rich Kr isotopes

Motivation: shape transition at N=60

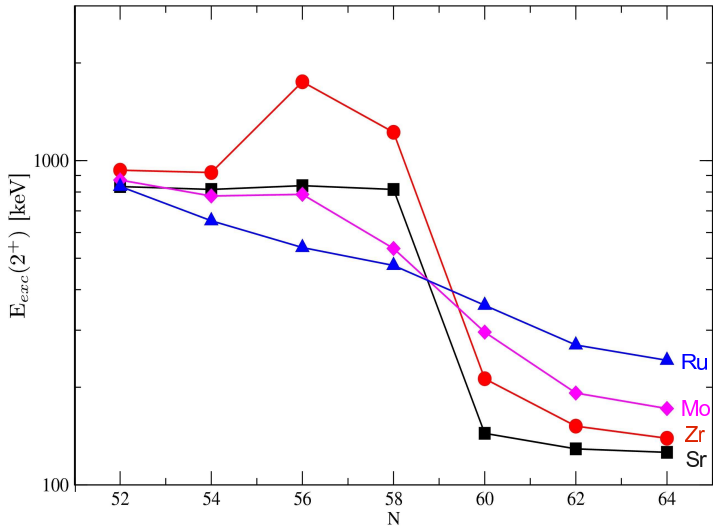
- dramatic change of the ground state structure observed at N = 58, 60 for Rb, Sr, Y, Zr isotopes
- considerable theoretical and experimental effort in this mass region
- onset of deformation at N=60 confirmed by 2^+ energies and transition probabilities in even-even nuclei (Sr, Zr, Mo...)

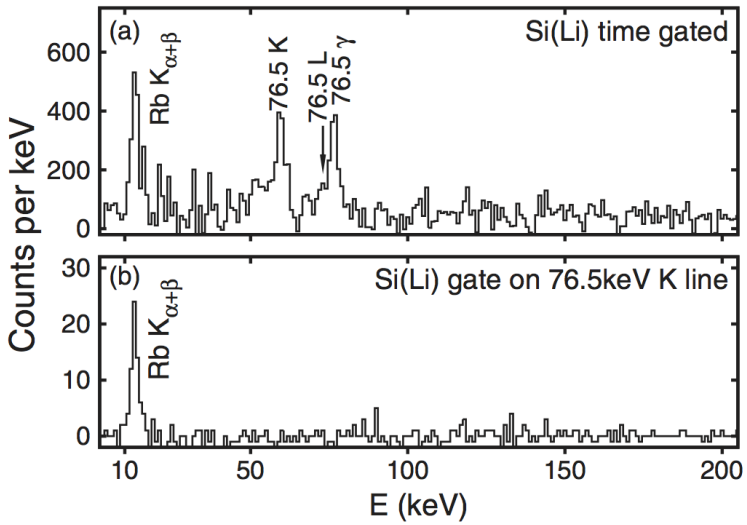


Kr mass measurement: S. Naimi et al., Phys. Rev. Lett. 105 (2010) 032502

Rubidium isotopes beyond N=58

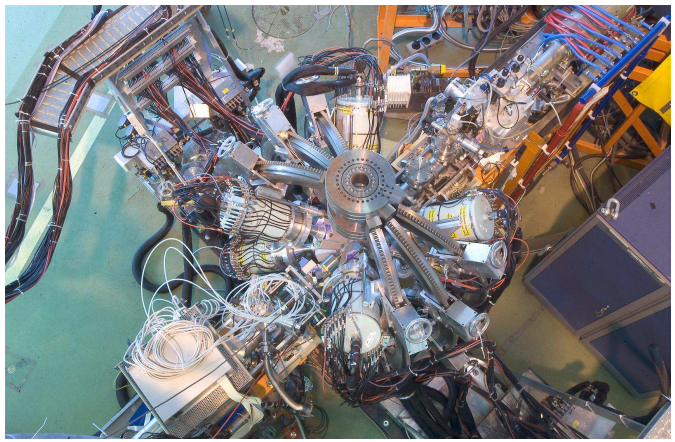
- onset of deformation at N=60 confirmed by 2^+ energies and transition probabilities in even-even nuclei (Sr, Zr, Mo...)
- less data for odd nuclei and along southern border of the region – low fission yields make such studies more difficult

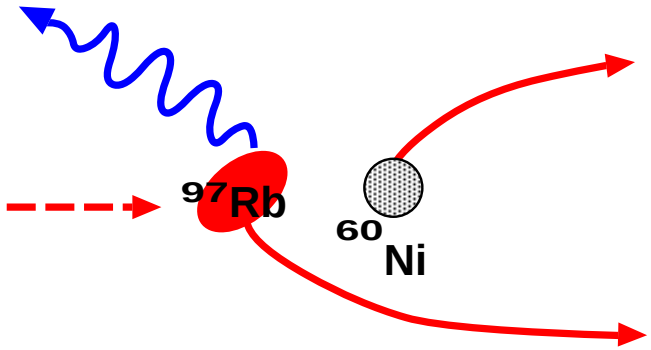




- no excited states known in $^{97-99}$Rb except for 76keV 5μs isomer in ^{97}Rb (M. Rudigier et al, PRC 87 (2013) 064317)
- ground state spins and quadrupole moments measured in laser spectroscopy (C. Thibault et al, PRC23 (1981) 2720) consistent with a structure change at N=60

Coulomb excitation of $^{93-99}$Rb at ISOLDE





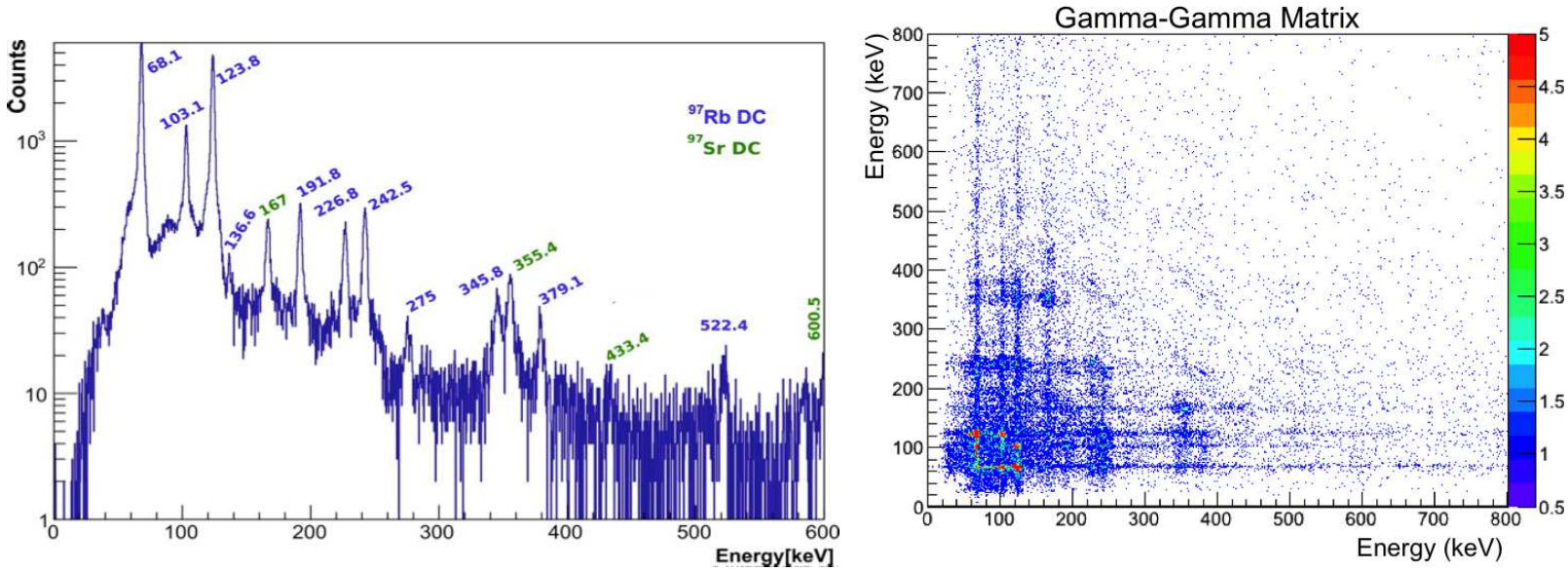
gamma-ray detection array:
MINIBALL
8 triple clusters, 8% efficiency

particle detection setup:
annular DSSD detector at forward angles
detection of scattered Rb
and recoiling Ni nuclei

- deexcitation γ rays mesured in coincidence with scattered particles (Rb and Ni)
- 10^5-10^6pps beams (10^3 for ^{99}Rb)
- short measurement time sufficient: about 20 hours of data taking for ^{97}Rb!

Results: first observation of collective states in $^{97-99}$Rb

- statistics sufficient for gamma-gamma coincidences – level schemes established
- identification of regular rotational bands



C. Sotty, PhD thesis, Université Paris-Sud (2013)

- Second step: extraction of E2 and M1 matrix elements using GOSIA code

C. Sotty *et al.* Phys. Rev. Lett. 115, 172501 (2015)

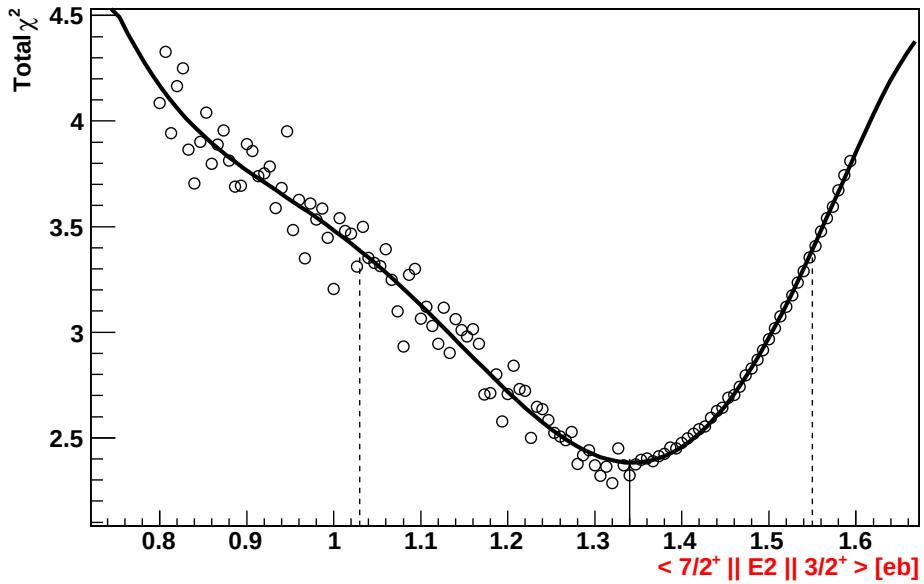
Coulex analysis: ^{97}Rb

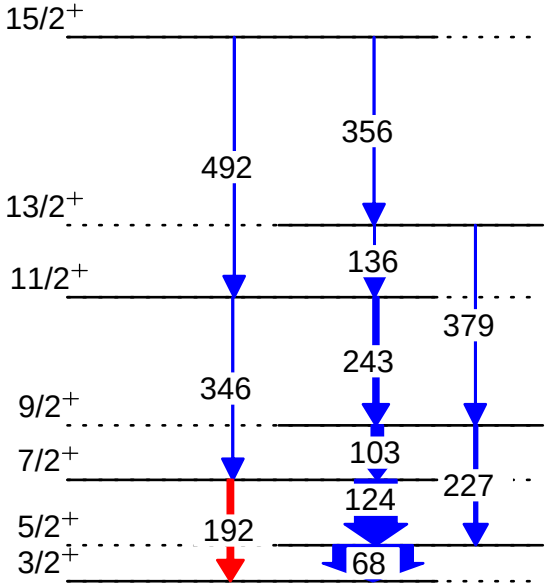
- underdetermined problem: 20 gamma rays, 24 matrix elements (E2 and M1), strong correlations between matrix elements $\rightarrow$ model assumptions necessary

  Alaga rules: $\langle KI_f||E2||KI_i\rangle = \sqrt{(2I_i+1)}(I_i,K,2,0|I_f,K)\sqrt{\frac{5}{16\pi}}eQ_0$

$\Rightarrow$ within rotational model E2 branching ratio depends on spins only (Q_0 cancel out)

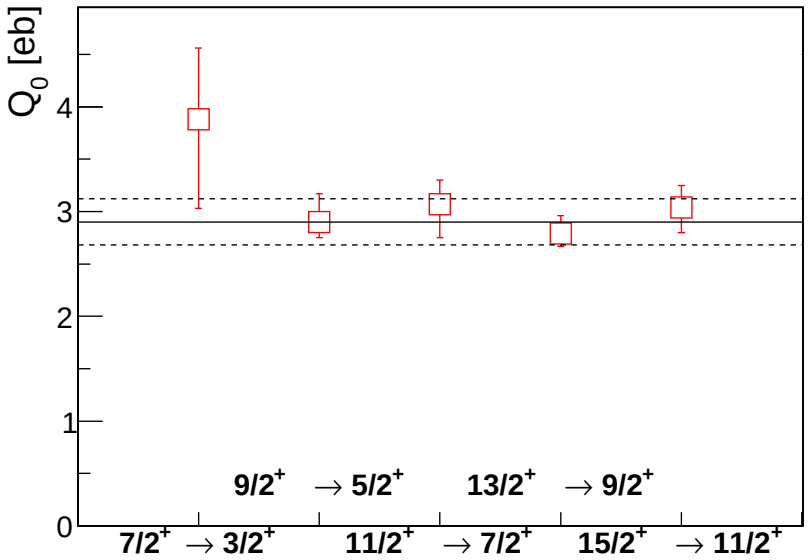
- Step 1: for each value of $\langle 7/2^+||E2||3/2^+\rangle$ all remaining matrix elements in Rb and Ni are fitted to observed gamma-ray intensities and known spectroscopic data

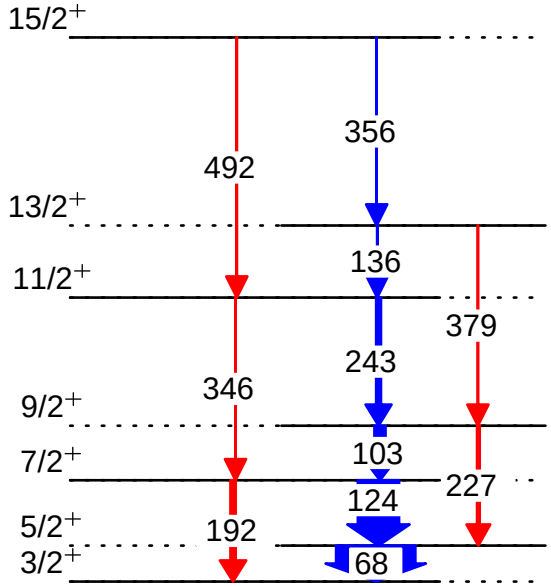




- Step 2: for all other transitions a standard GOSIA analysis assuming this value of $\langle 7/2^+||E2||3/2^+\rangle$

Results: deformation of ^{97}Rb



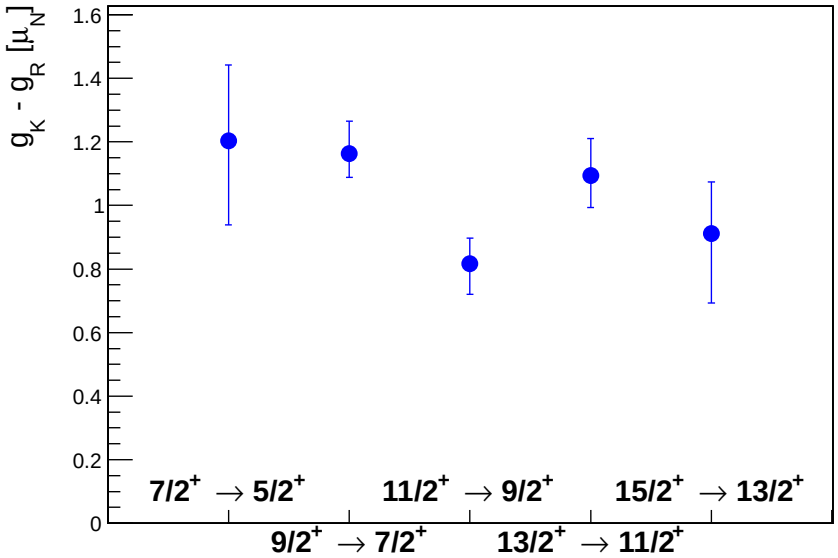


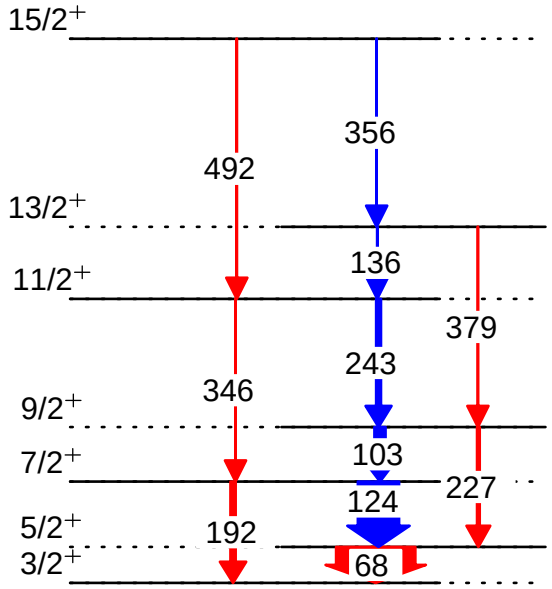
- Alaga rules assumed for each pair of I $\rightarrow$ I-2 / I $\rightarrow$ I-1 transitions:

E2 part of a mixed E2/M1 transition determined from the I $\rightarrow$ I-2 intensity, the remaining part of I $\rightarrow$ I-1 attributed to M1 decay

- constant Q_0 within the band
- results consistent with Q_{sp} of the ground state measured in laser spectroscopy
- transition strengths of 60-110 W.u., β deformation $\approx$ 0.31

Results: M1 matrix elements in ^{97}Rb





$3/2^-[301]$

K=3/2, Q_0=2.90, g_R=0.30

$|g_K - g_R| = 1.610$

$3/2^+[431]$

K=3/2, Q_0=2.90, g_R=0.30

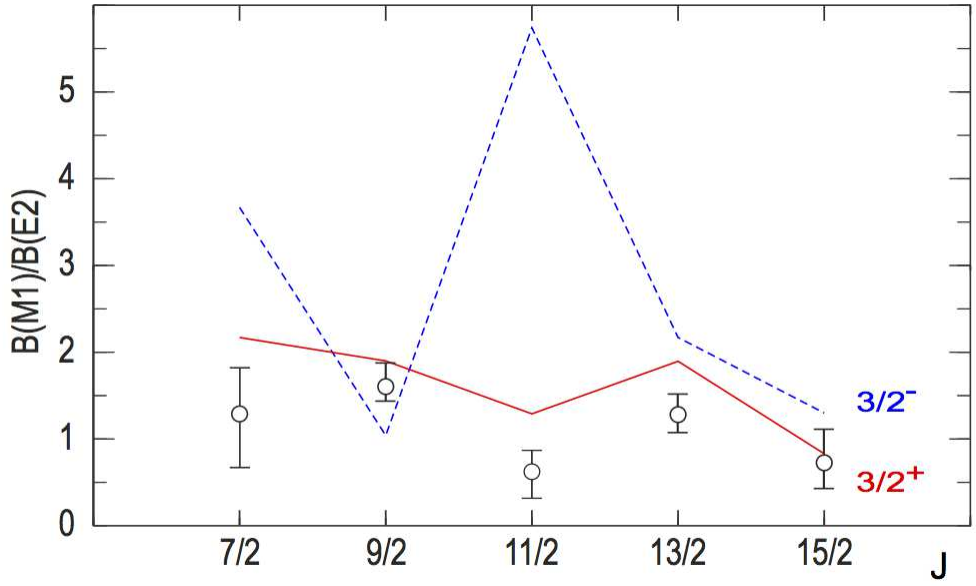
$|g_K - g_R| = 1.410$

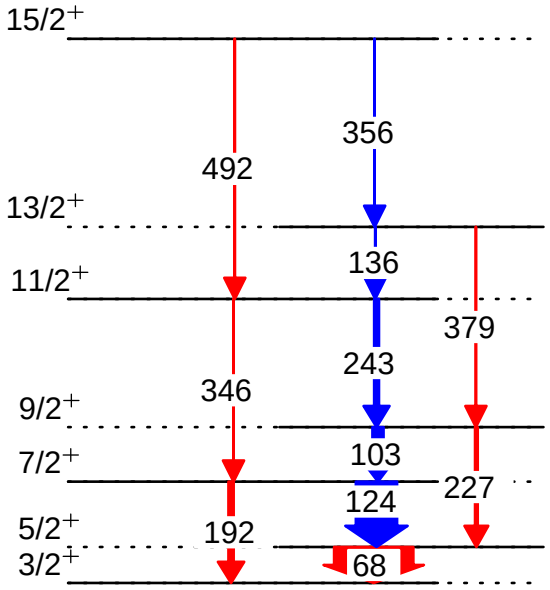
$3/2^+[431]$ configuration more probable for the ground state in ^{97}Rb

Woods-Saxon potential with universal parametrisation from P. Moller, ADNDT 59 (1995) 185;

F. Kondev priv. comm.

Results: M1 matrix elements in ^{97}Rb





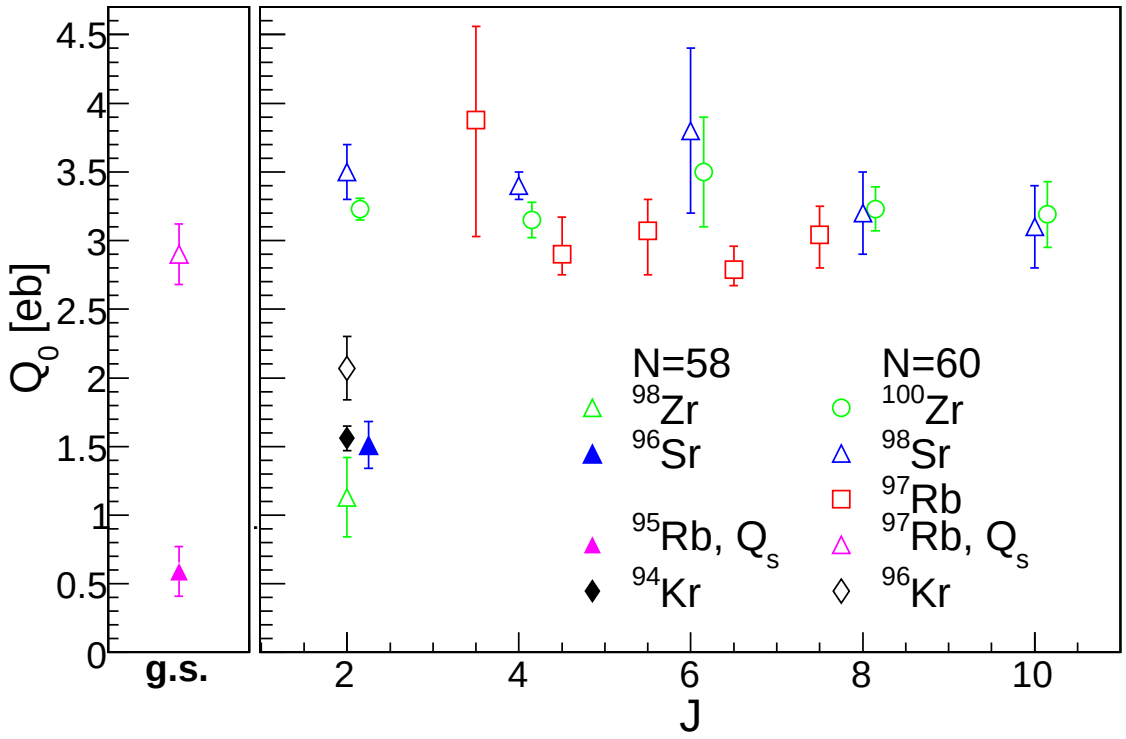
particle + rotor calculation: A. Stuchbery

B(E2)/B(M1) ratios in ^{97}Rb consistent with positive parity

further support for the $3/2^+[431]$ configuration of the ground state

C. Sotty *et al.* Phys. Rev. Lett. 115, 172501 (2015)

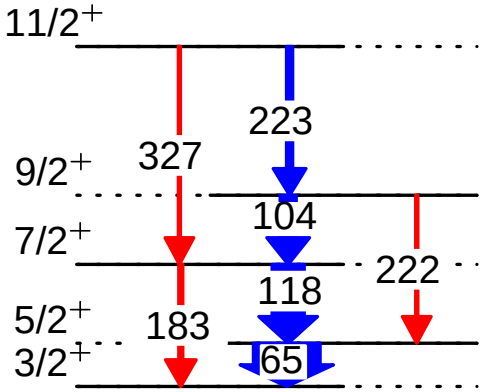
Comparison with neighbouring N=58,60 nuclei

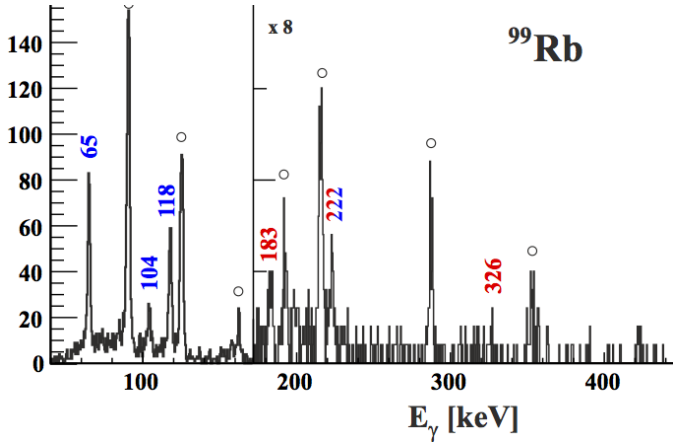


- Q_0 values in ^{97}Rb consistent with those in N=60 Zr and Sr nuclei
- visible reduction of Q_0 for N=60 ^{96}Kr – similar to what is observed for N=58 nuclei
- Q_{sp} values from laser spectroscopy confirm a dramatic shape change at N=60 in Rb isotopes, deformation for ^{97}Rb consistent with Coulex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

Next step: ^{99}Rb

- strong correlations of all matrix elements like in the ^{97}Rb case and...
  - very low statistics (few hundred counts in the strongest line)
  - target excitation not observed
  - unresolved doublet at 222 keV
  - extremely underdetermined problem: 6 gamma rays, 15 matrix elements

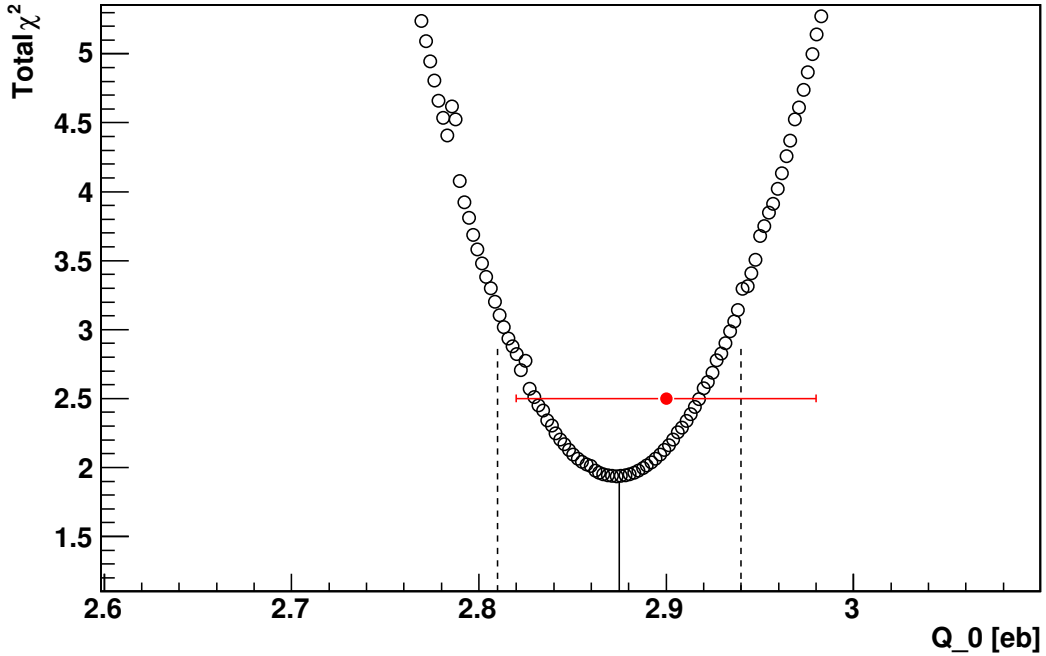


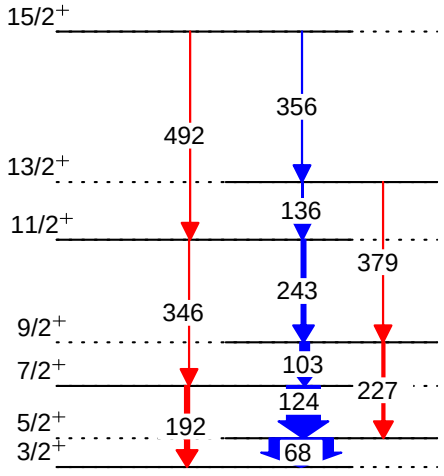


... but matrix elements in the upper part of a strongly deformed rotational band are related to observed intensity ratios in the nucleus under study (no external normalisation required)

^{99}Rb: proposed solution and test on ^{97}Rb data

- all E2 matrix elements (including Q_s) coupled using rotational model
- then we fit only M1 matrix elements and one Q_0 to measured gamma-ray intensities

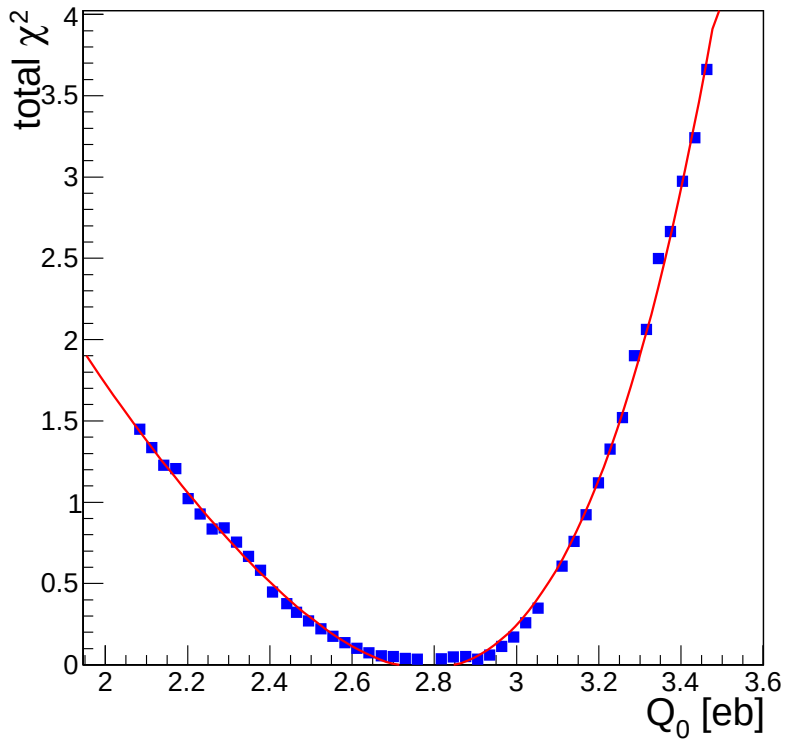


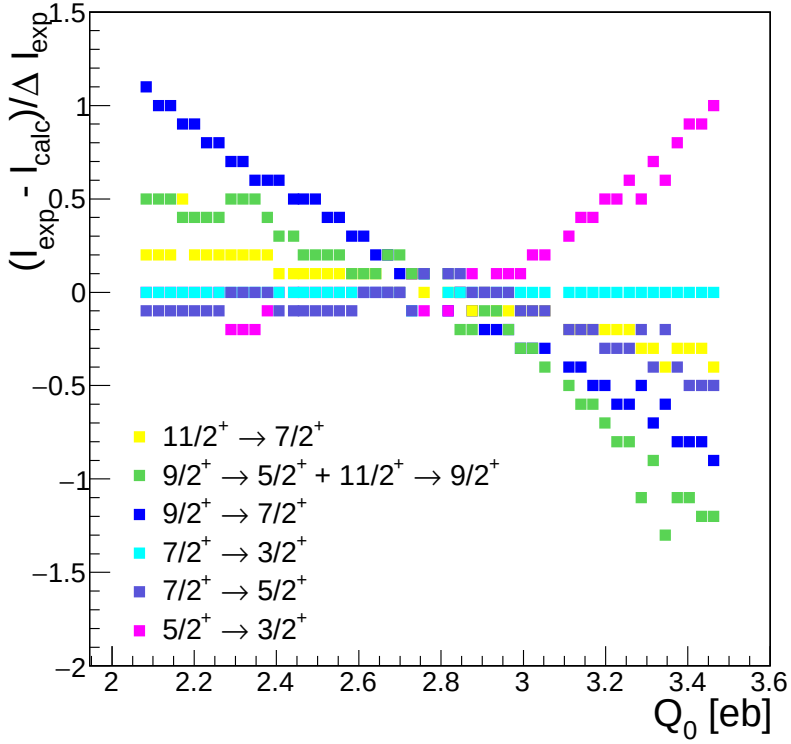


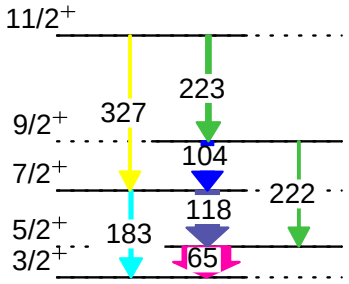
- tested on ^{97}Rb data, result consistent with weighted average of Q_0 values obtained in standard analysis

^{99}Rb: results

- 4 M1 matrix elements and one Q_0 fitted to measured gamma-ray intensities in ^{99}Rb

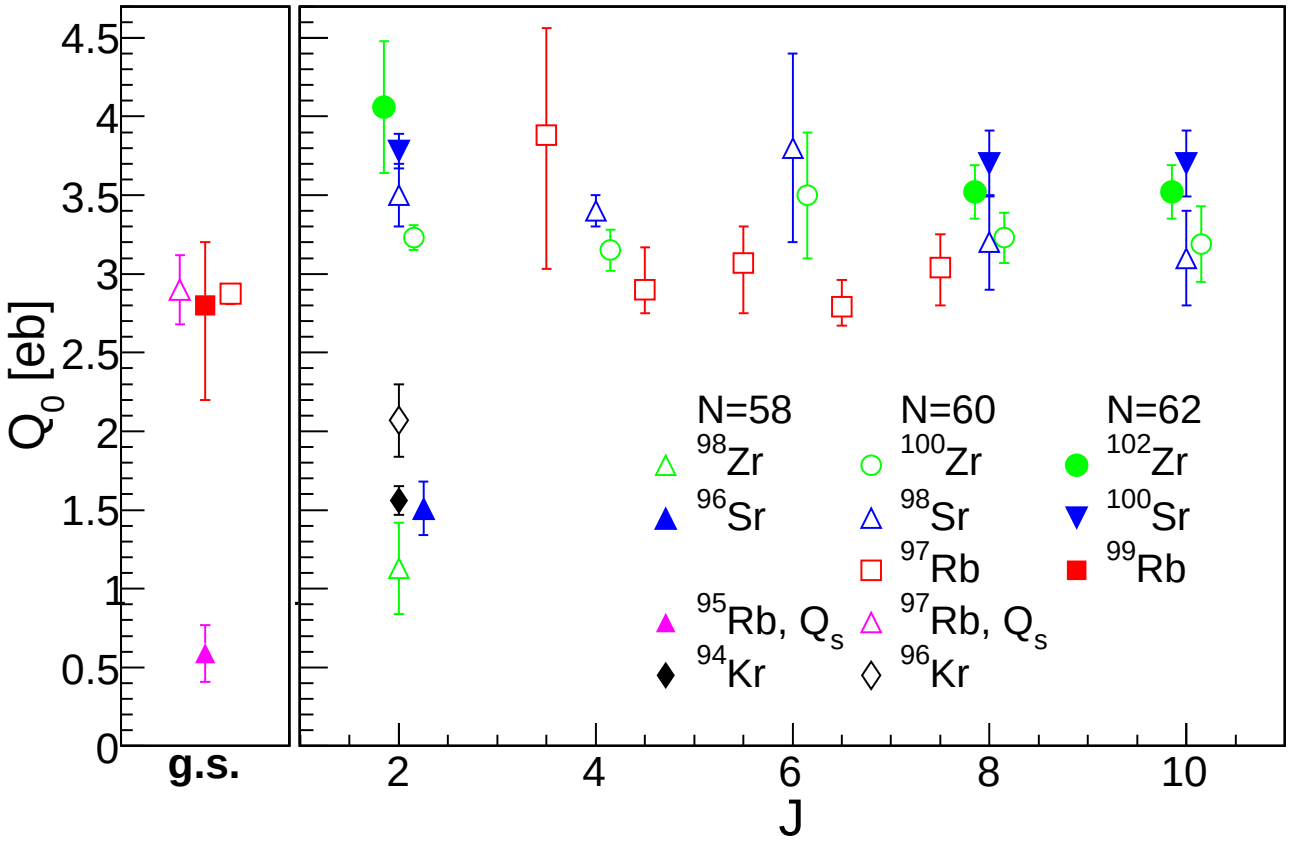






- one clear χ^2 minimum for all observed transitions
- precision rather low due to limited statistics

Comparison with neigbouring N=58,60,62 nuclei



- Q_0 in N=62 ^{99}Rb similar to that of ^{97}Rb and N=60,62 Zr and Sr nuclei
- large deformation appears in ^{97}Rb and remains constant (in terms of Q_0) with increasing Z and N

Summary and outlook

- large quadrupole deformation of ^{97,99}Rb confirmed by results of ISOLDE Coulex experiment:
  - first observation of the rotational ground state bands
  - measurement of transition probabilities

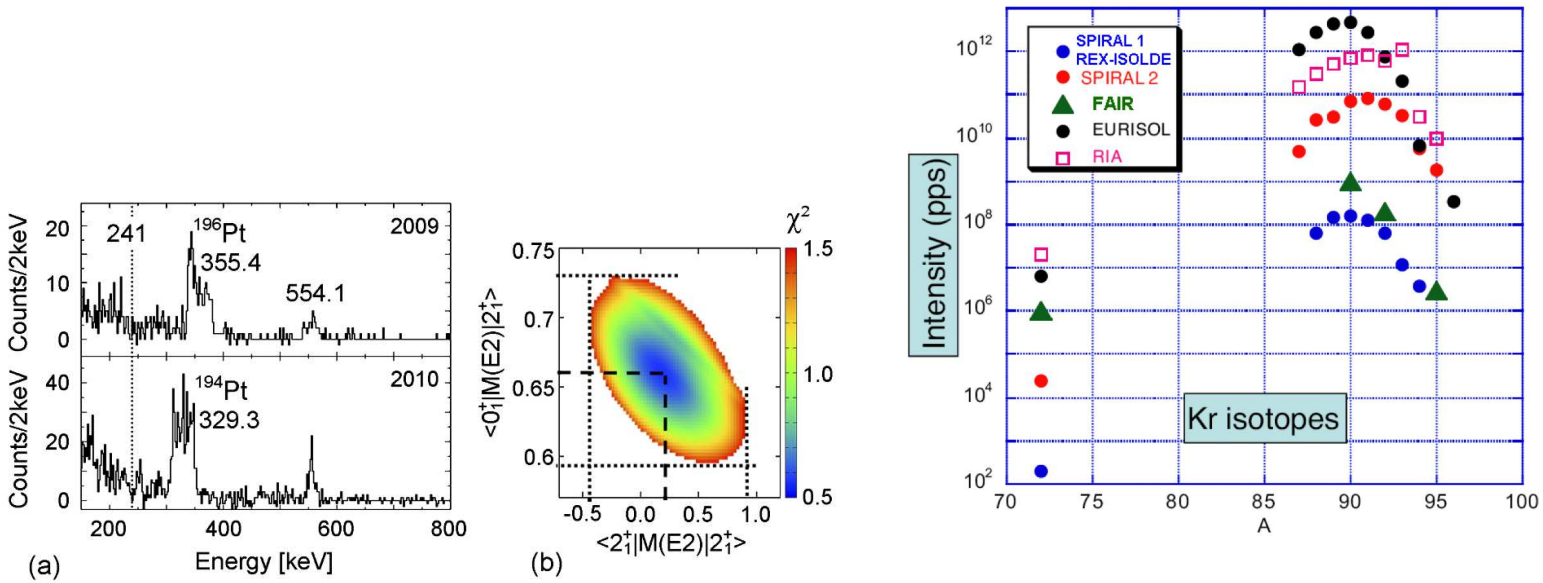
Short-term perspectives:

- extraction of E2 transition probabilities in ^{93,95}Rb and ^{97,99}Sr (no or few transition probabilities known)
- possible lifetime measurement in ^{97}Rb – verification of the model assumptions used in Coulex analysis:
  - change of $\langle\, 9/2^+ \| \text{ M1 } \| \, 7/2^+ \rangle$ from 0.5 to 2 μ_N changes $9/2^+$ lifetime by one order of magnitude (1 ns vs 100ps)

Long-term perspectives:

- Coulex of $^{94-98}$Kr?

Kr isotopes around N=60: where we are?

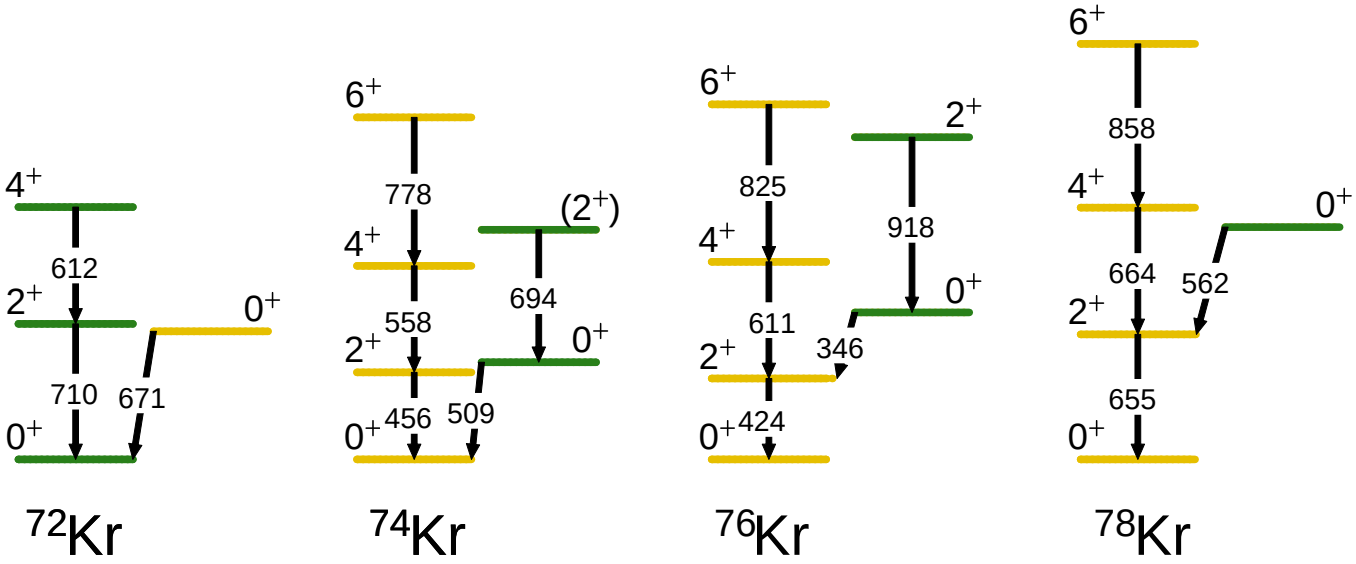


M. Albers *et al.* Phys. Rev. Lett. 108, 062701 (2012)

- Coulex of ^{96}Kr at REX-ISOLDE (2010): $7 \cdot 10^3$ pps
  - statistics not really sufficient to determine $Q_s(2_1^+)$
- at 10^5 pps observation of non-yrast states likely
- intensity expected at new generation ISOL facilities
  - LoI for SPES: V. Modamio et al

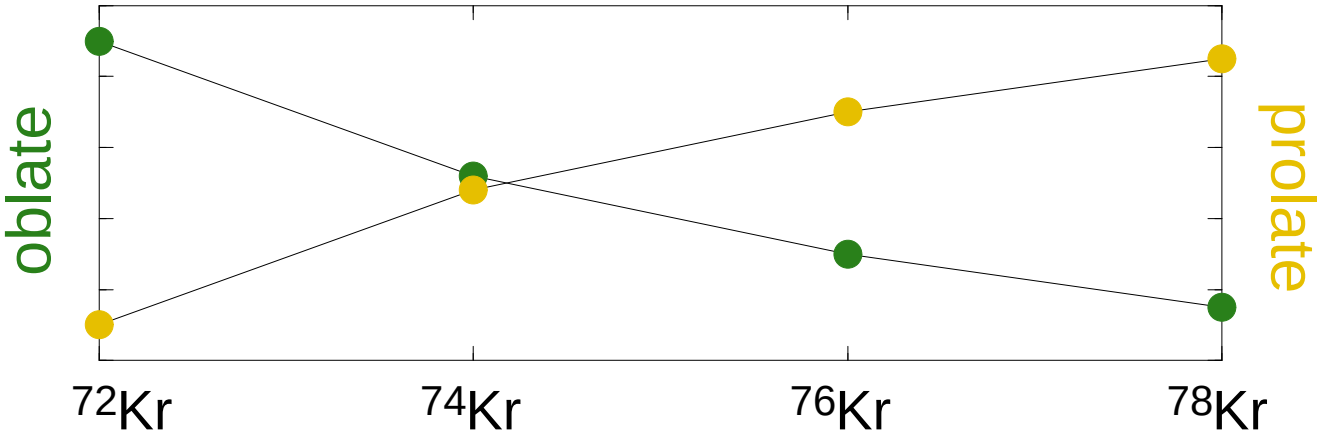
Shape coexistence: two-state mixing

Kr: E. Bouchez *et al.* Phys. Rev. Lett. 90, 082502 (2003)



prolate

oblate



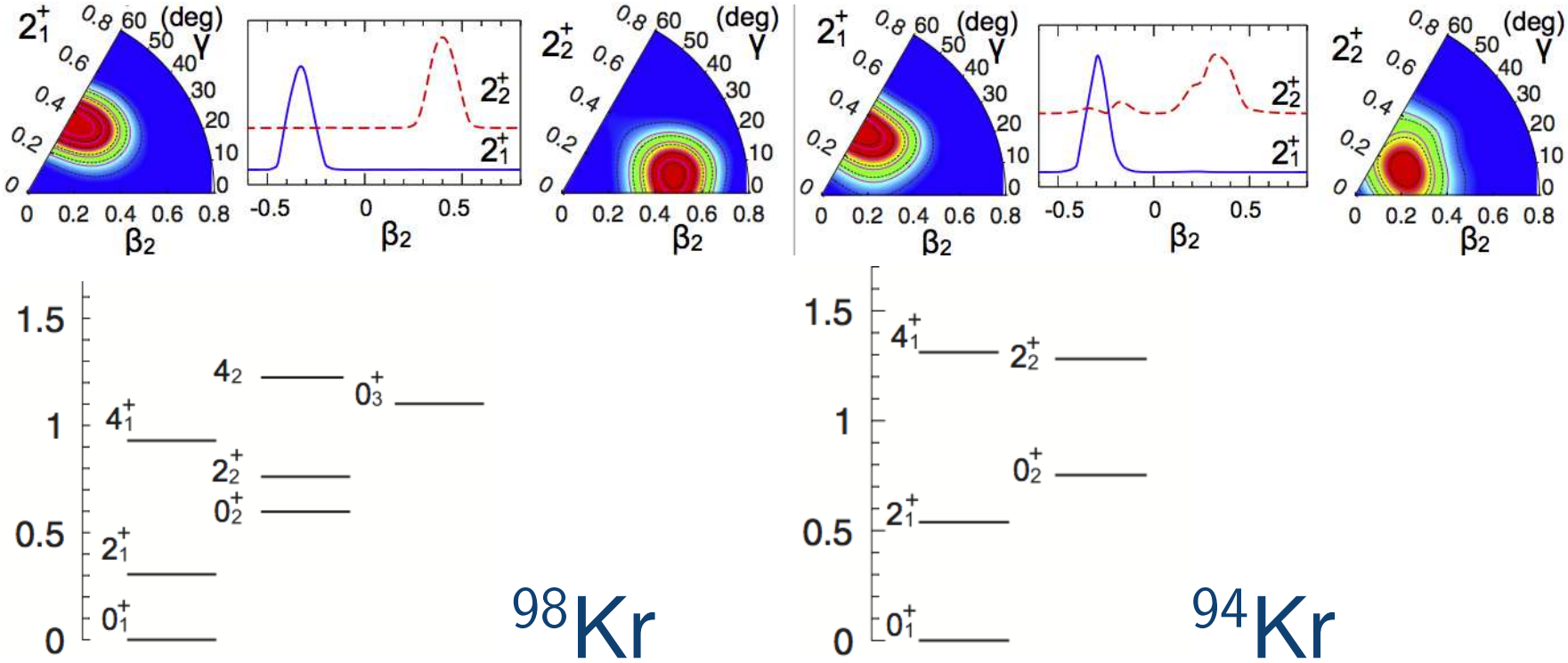
mixing of the g.s. (from distortion of rotational bands)

mixing amplitudes for ^{98}Sr (from ME): cos $^2\theta_0$=0.82, cos $^2\theta_2$=0.99

E. Clément *et al.* Phys. Rev. Lett. 108, 022701 (2016)

Shape coexistence in ^{94,98}Kr: theoretical predictions

T. R. Rodriguez *et al.* Phys. Rev. C 90, 034306 (2014)



- coexistence of prolate-oblate (^{98}Kr) or oblate-triaxial shapes (^{94}Kr)
- 0_2^+ states predicted below 1 MeV – accessible in Coulex
- smooth evolution of measured 2_1^+ energies suggests mixing of $2_{1,2}^+$ states
- measurement of 0_2^+ decay will already give an idea about mixing