# Coulex of odd and odd-odd Rb isotopes: problems and solutions

$^{98}$Rb: E. Clément[1,2], M. Zielińska[3], A. Görgen[4], W. Korten[3], H. Goutte[3], J. Libert[5], S. Péru[5], S. Hilaire[5], B. Bastin[1], C. Bauer[6], A. Blazhev[7], N. Bree[8], B. Bruyneel[7], P. Butler[9], J. Butterworth[10], P. Delahaye[1,2], A. Dijon[1], D. Doherty[3], A. Ekström[11], C. Fitzpatrick[12], C. Fransen[7], G. Georgiev[13], R.Gernhäuser[14], H. Hess[7], J. Iwanicki[15], D.Jenkins[10], A. C. Larsen[4], J.Ljungvall[3,13], R. Lutter[14], P. Marley[10], K. Moschner[7], P. Napiorkowski[15], J. Pakarinen[2,16], A. Petts[9], P. Reiter[7], T. Renstrom[4], M. Seidlitz[7], B. Siebeck[7], S. Siem[4], C. Sotty[8,13], J. Srebrny[15], I. Stefanescu[8], G.M. Tveten[4], J. Van de Walle[2], M. Vermeulen[10], D. Voulot[2], N. Warr[7], F. Wenander[2], A. Wiens[7], H. De Witte[8], K. Wrzosek-Lipska[8,15]

$^{97,99}$Rb: C. Sotty[8,13], M. Zielińska[3,15], G. Georgiev[1], D. Balabanski[17], A. Stuchbery[18], A. Blazhev[7], N. Bree[8], R. Chevrier[5], S. Das Gupta[19], J.M. Daugas[5], T. Davinson[20], H. De Witte[8], J. Diriken[8], L. Gaffney[8,9], K. Geibel[7], K. Hadyńska-Klęk[15], F. Kondev[21], J. Konki[2,16], T. Kröll[6], P. Morel[5], P. Napiorkowski[15], J. Pakarinen[2,16], P. Reiter[7], M. Scheck[6], M. Seidlitz[7], B. Siebeck[7],G. Simpson[22], N. Warr[7], F. Wenander[2]

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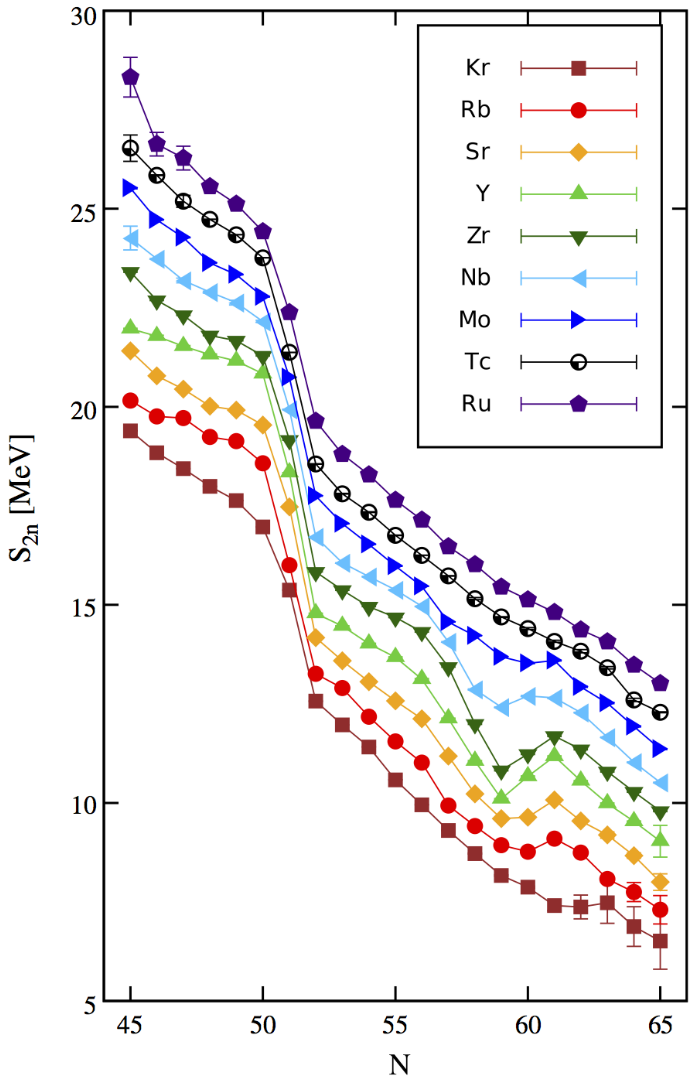
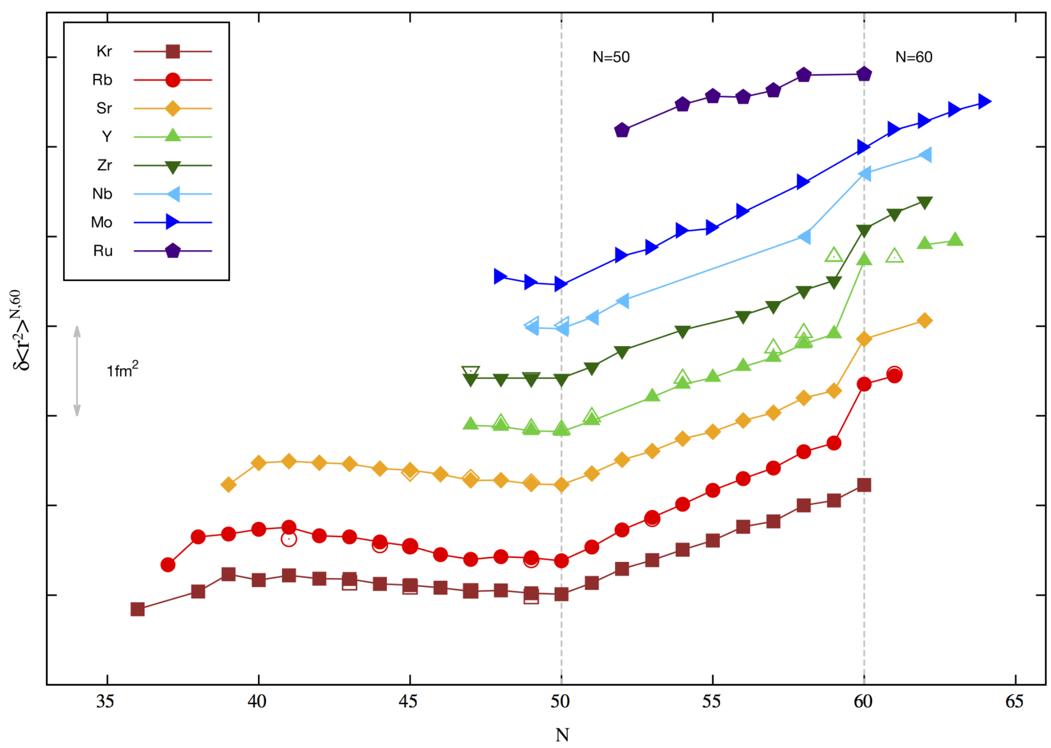
# Shape transition at N=60



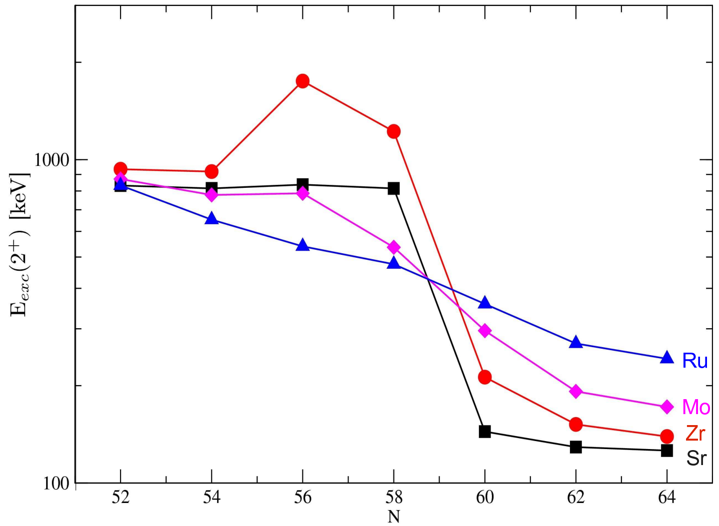

- dramatic change of the ground state structure observed at N = 58, 60 for Rb, Sr, Y, Zr
- considerable theoretical and experimental effort in this mass region

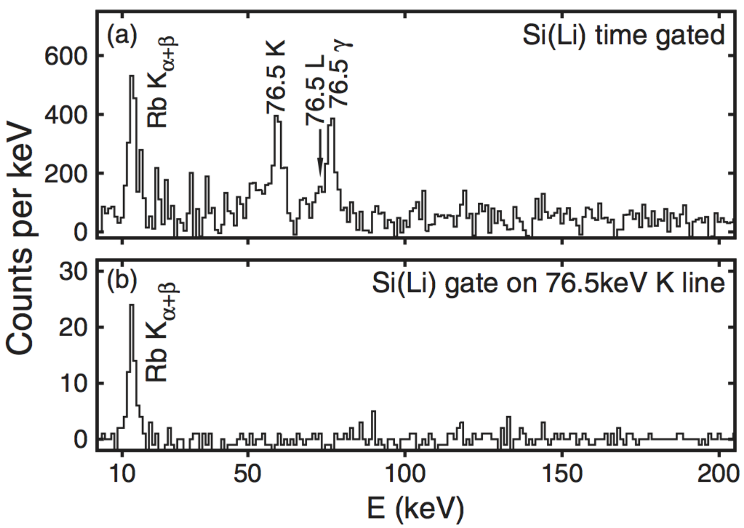



P. Campbell *et al.*, Prog. Part. Nucl. Phys. 86 (2016) 127

# Rubidium isotopes beyond N=58

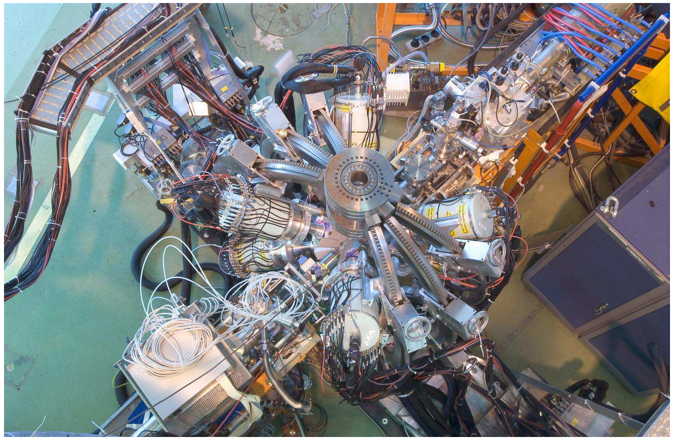
- onset of deformation at N=60 confirmed by $2^+$ energies and transition probabilities in even-even nuclei (Sr, Zr, Mo...)
- less data for odd nuclei and along southern border of the region – low fission yields make such studies more difficult

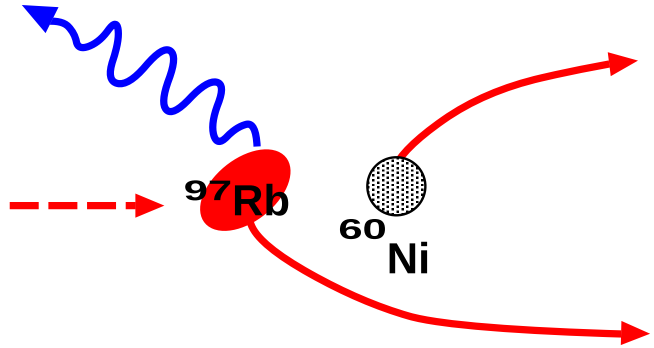



- no excited states known in $^{97-99}$Rb except for 76keV 5$\mu$s isomer in $^{97}$Rb (M. Rudigier et al, PRC 87 (2013) 064317)
- ground state spins and quadrupole moments measured in laser spectroscopy (C. Thibault et al, PRC23 (1981) 2720) consistent with a structure change at N=60

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





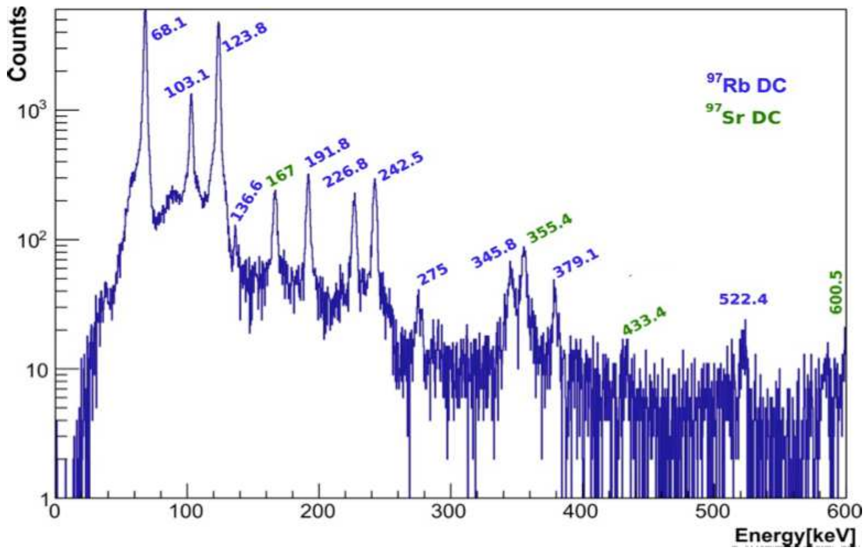

gamma-ray detection array:
MINIBALL
8 triple clusters, 8% efficiency

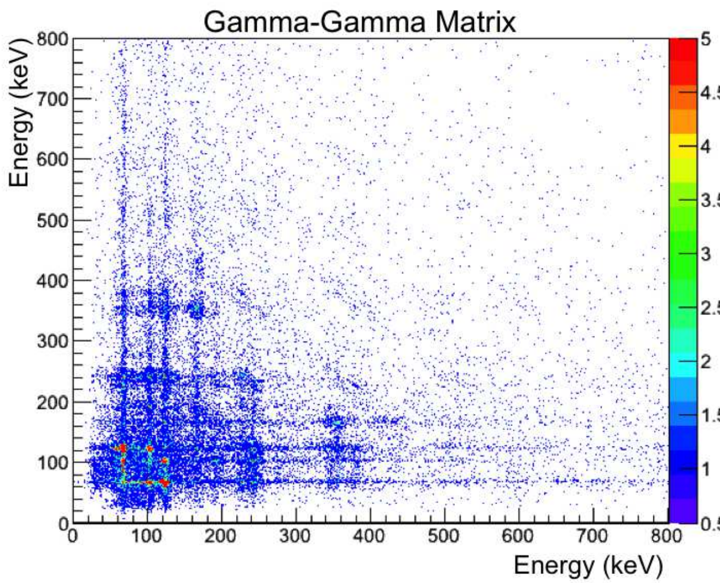
particle detection setup:
annular DSSD detector at forward angles
detection of scattered Rb
and recoiling Ni nuclei

- deexcitation $\gamma$ rays mesured in coincidence with scattered particles (Rb and Ni)
- $10^5$-$10^6$pps 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



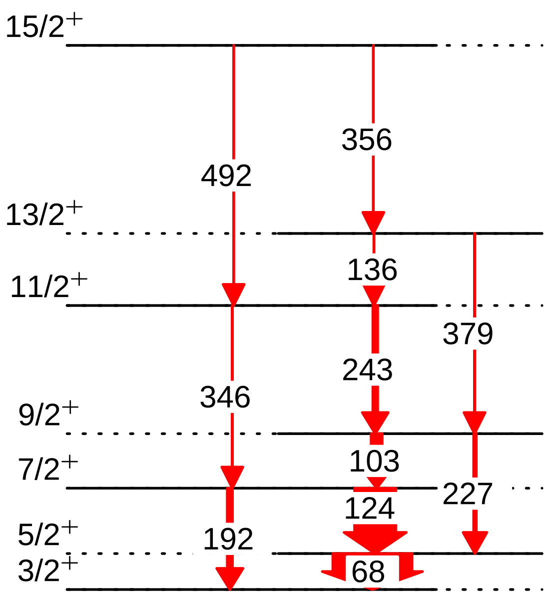

C. Sotty, PhD thesis, Université Paris-Sud (2013)

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

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

# Problems in $^{97}$Rb Coulex data analysis

- Cline's safe Coulex criterion not fulfilled for high CM angles
- efficiency for the 68 keV line uncertain
- 355 keV transition obscured by a line in $^{97}$Sr
- underdetermined problem: 20 gamma rays, 24 matrix elements (E2 and M1)
- very strong correlations between matrix elements



# Problems in $^{97}$Rb Coulex data analysis and solutions

- Cline's safe Coulex criterion not fulfilled for high CM angles

→ 15 % of statistics excluded from the analysis

- efficiency for the 68 keV line uncertain

→ would be a natural choice for normalisation but had to be excluded from the analysis

- 355 keV transition obscured by a line in $^{97}$Sr

→ intensity obtained from gamma-gamma coincidences

- underdetermined problem: 20 gamma rays, 24 matrix elements (E2 and M1)

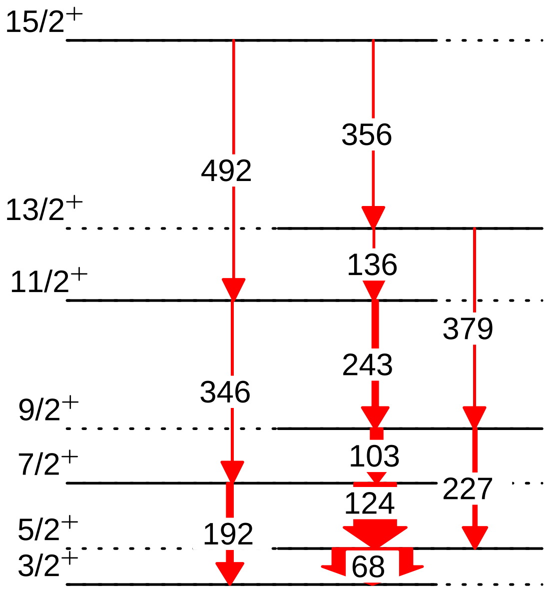
→ model assumptions necessary: Alaga rules

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

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

- very strong correlations between matrix elements

→ large uncertainties for low-lying transitions; need for model assumptions

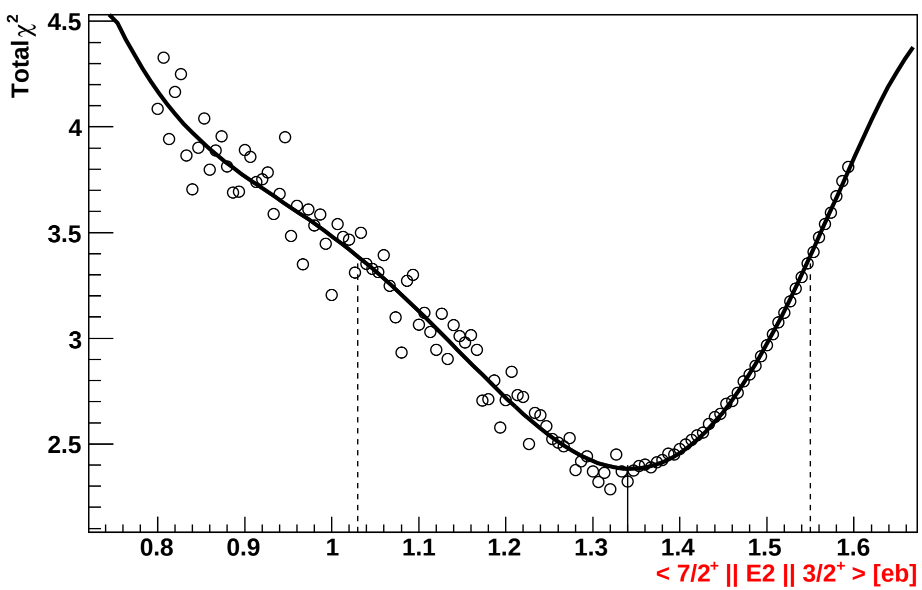


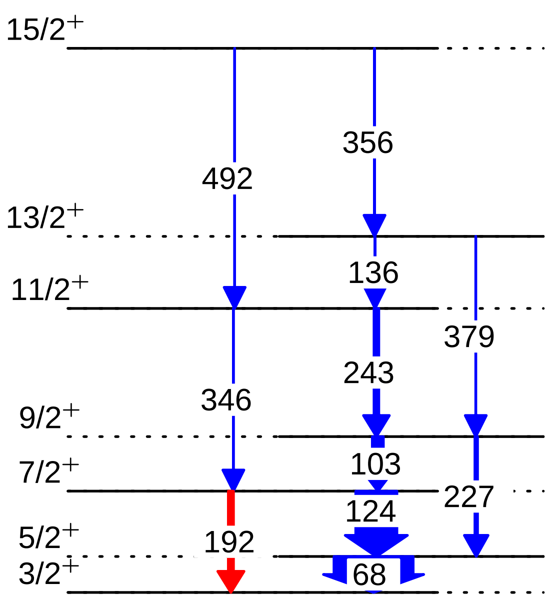
## Normalisation to target excitation

MZ *et al.* EPJA 52, 99 (2016)

- 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

- Alaga rules assumed for each pair of I $\rightarrow$ I-1 and I $\rightarrow$ I-2 E2 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

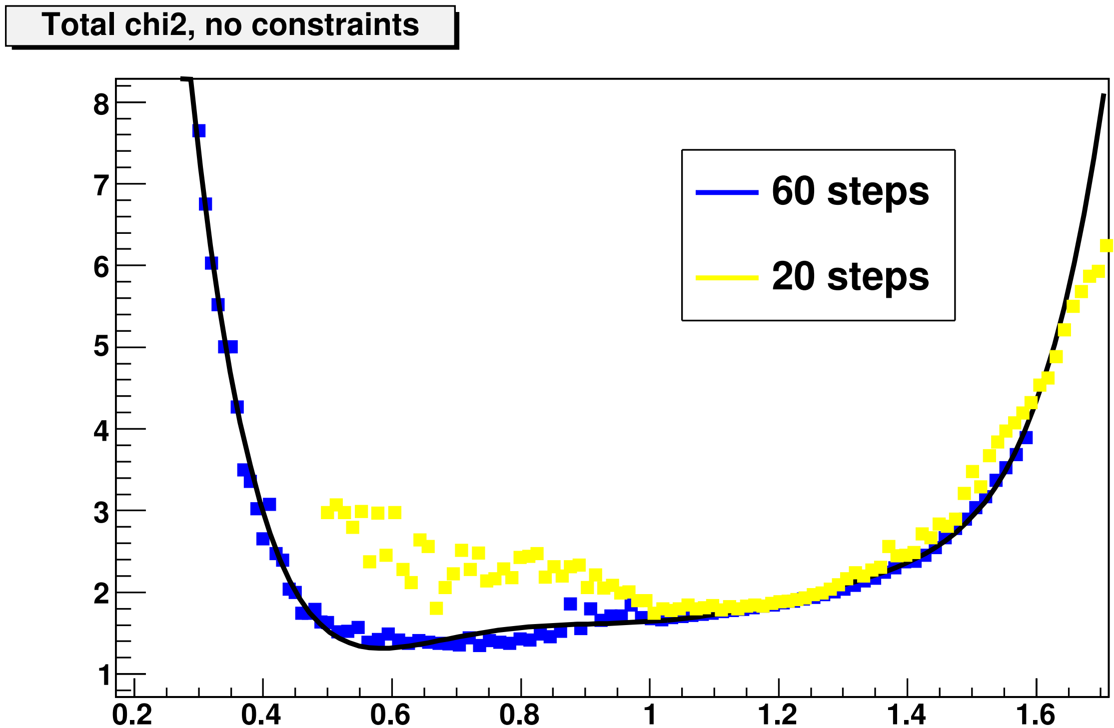



- Step 2: for all other transitions a standard GOSIA1 analysis assuming this value of $\langle 7/2^+ \| E2 \| 3/2^+ \rangle$

## Normalisation to target excitation

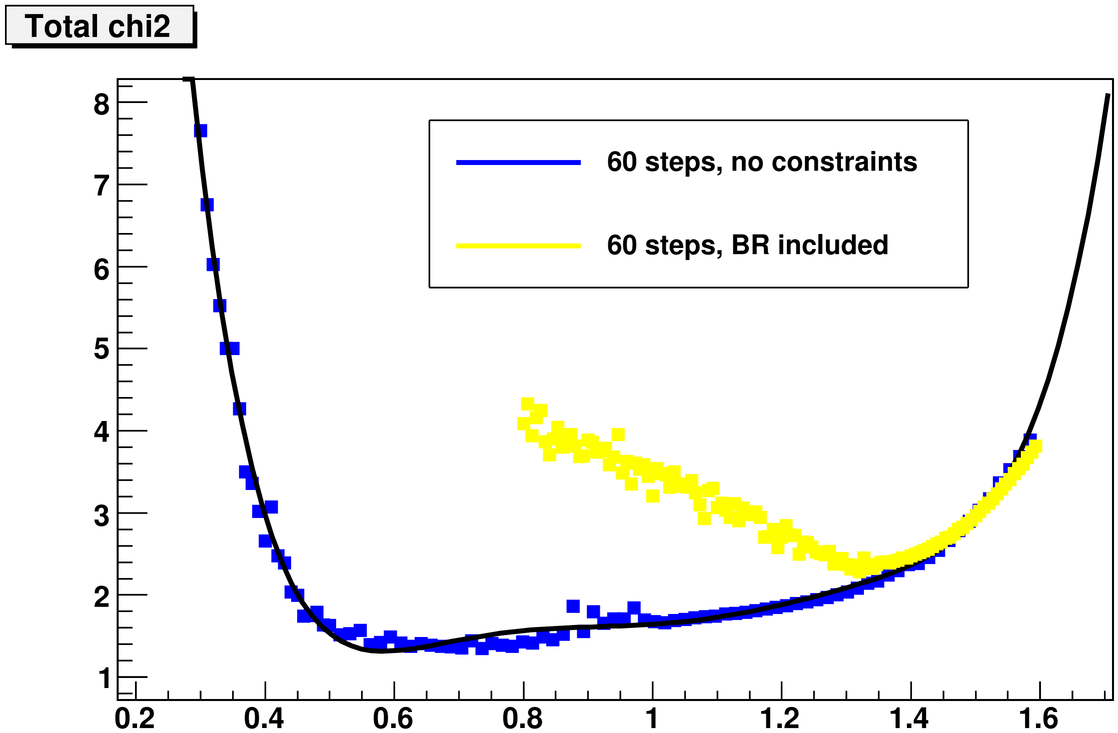
- full minimisation for each value of $\langle 7/2^+ \| E2 \| 3/2^+ \rangle$



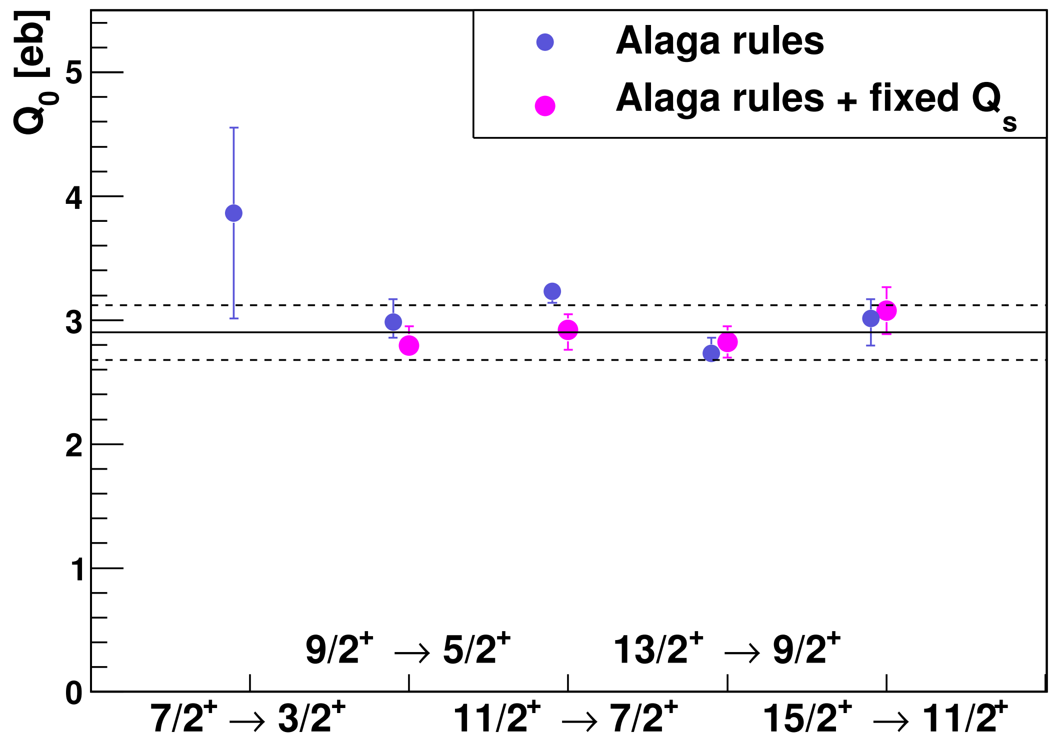

- fluctuations due to local minima, more steps (”mawr” variable in GOSIA2) give a more smooth dependence (and a new global minimum)
- smooth parts of the $\chi^2$ curve do not change much
- additional test: GOSIA procedure of error estimation (total integrated probability distribution = 68.3%) and $\chi^2$ +1 approach give very similar results

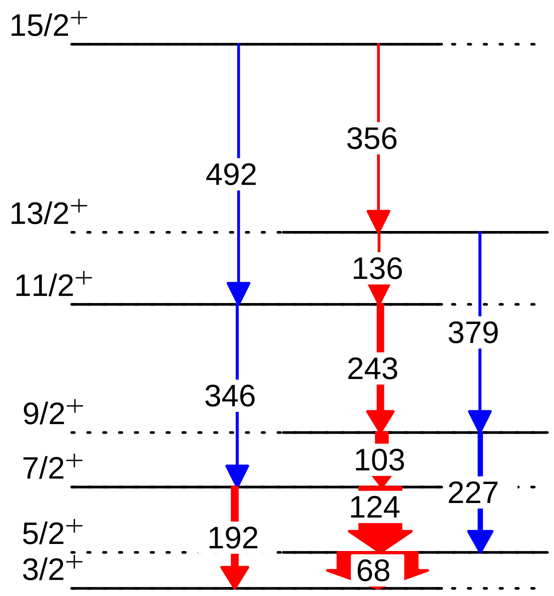
# Normalisation to target excitation

- different minimum if Alaga rules imposed



# Results: deformation of $^{97}$Rb

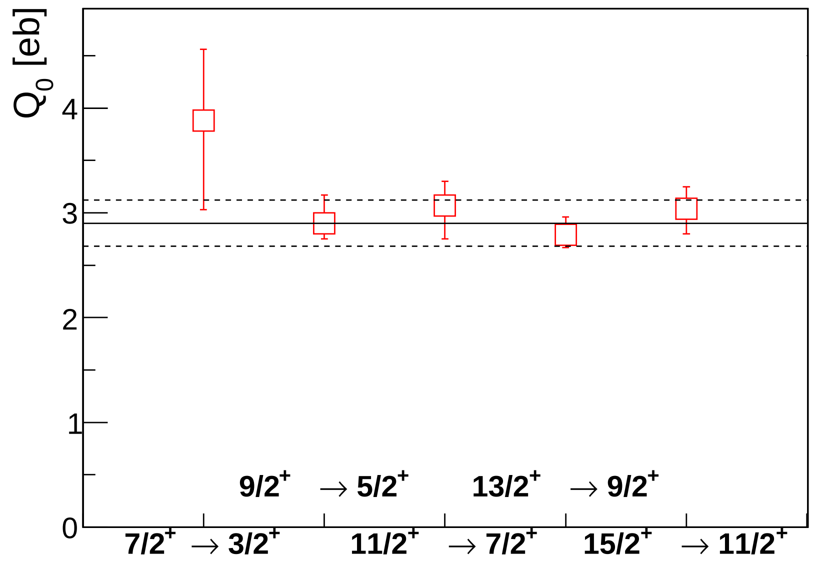


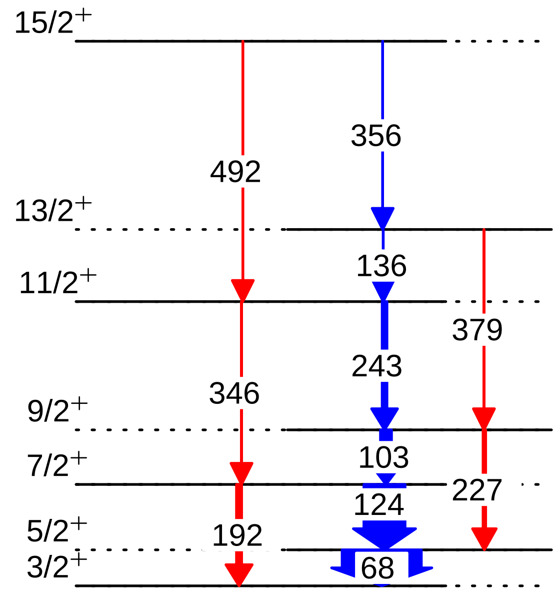




- two different assumptions give consistent results for 4 matrix elements
- these 4 transitions are populated in multi-step excitation → matrix elements related to observed intensity ratios in $^{97}$Rb (no need for other normalisation)

## Results: deformation of $^{97}$Rb

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

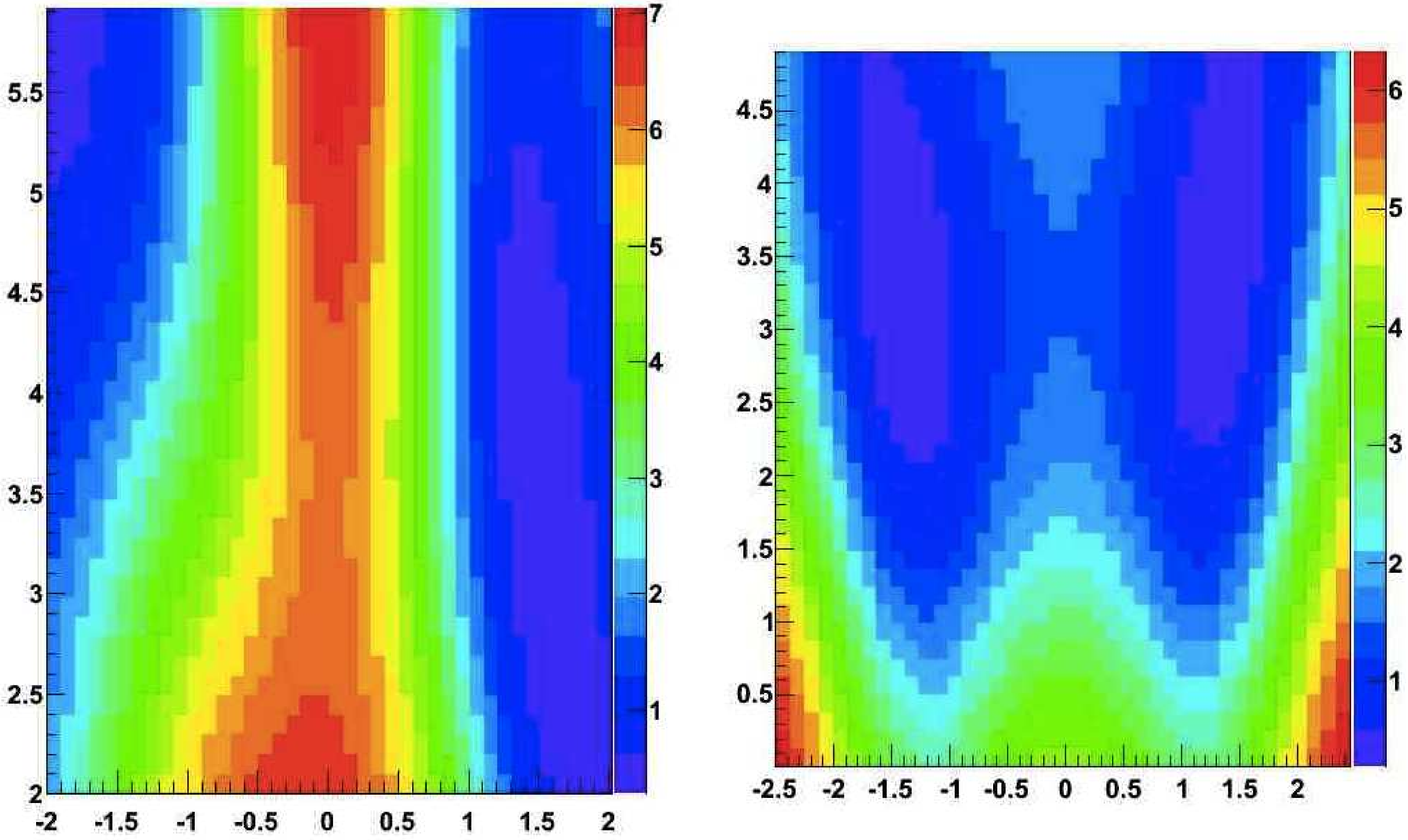


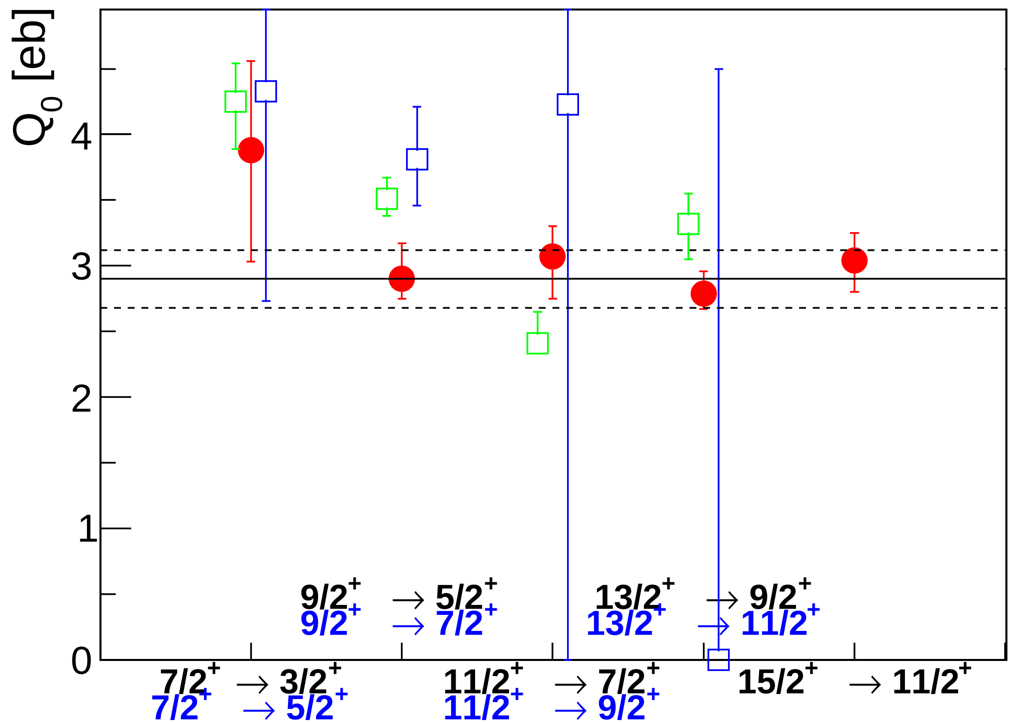

- final values of ME: weighted average of values obtained using both assumptions, errors cover the full uncertainty range
- constant $Q_0$ within the band
- results consistent with $Q_{sp}$ of the ground state measured in laser spectroscopy
- transition strengths of 60-110 W.u., $\beta$ deformation $\approx$ 0.31

## Relative signs of E2 matrix elements

- GOSIA analysis (not GOSIA2)
- Left: $\langle 13/2^+ \| E2 \| 9/2^+ \rangle$ vs $\langle 13/2^+ \| E2 \| 11/2^+ \rangle$ – the same signs preferred
- Right: $\langle 15/2^+ \| E2 \| 11/2^+ \rangle$ vs $\langle 13/2^+ \| E2 \| 11/2^+ \rangle$ – no sensitivity to relative signs



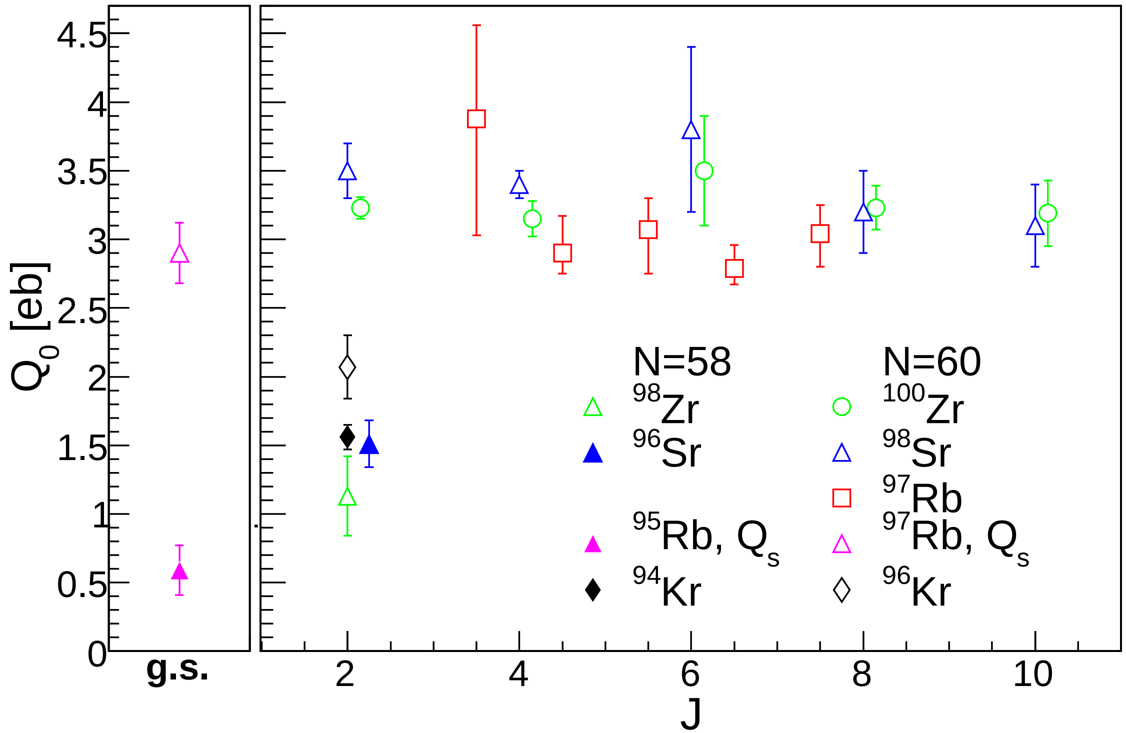
## Effect of correlations




- initial analysis (blue and green):
  - non-safe Coulex included – ME for lower states overestimated
  - uncertainty on $\langle 9/2^+ \| M1 \| 7/2^+ \rangle$ and $\langle 9/2^+ \| E2 \| 7/2^+ \rangle$ underestimated – narrow local minimum
  - scattering of $Q_0$ values around the average due to correlations

## Comparison with neighbouring N=58,60 nuclei

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

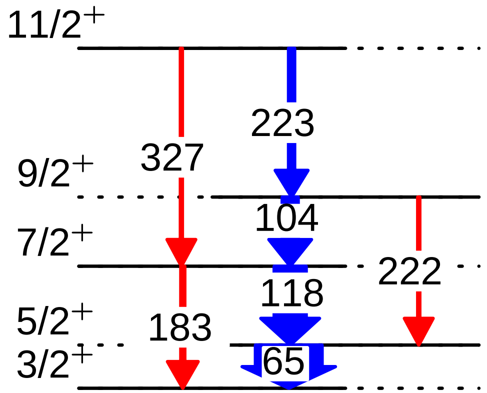


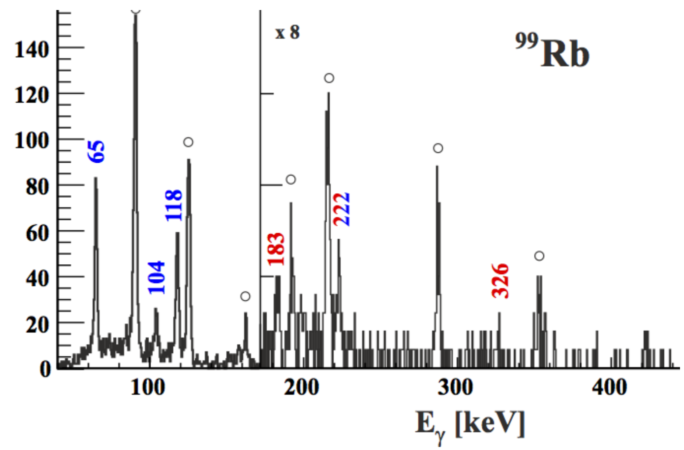

- $Q_0$ values in $^{97}$Rb consistent with those in N=60 Zr and Sr nuclei
- visible reduction of $Q_0$ for N=60 $^{96}$Kr – similar to what is observed for N=58 nuclei
- $Q_{sp}$ values from laser spectroscopy confirm a dramatic shape change at N=60 in Rb isotopes, deformation for $^{97}$Rb consistent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

## Next step: $^{99}$Rb

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

- 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



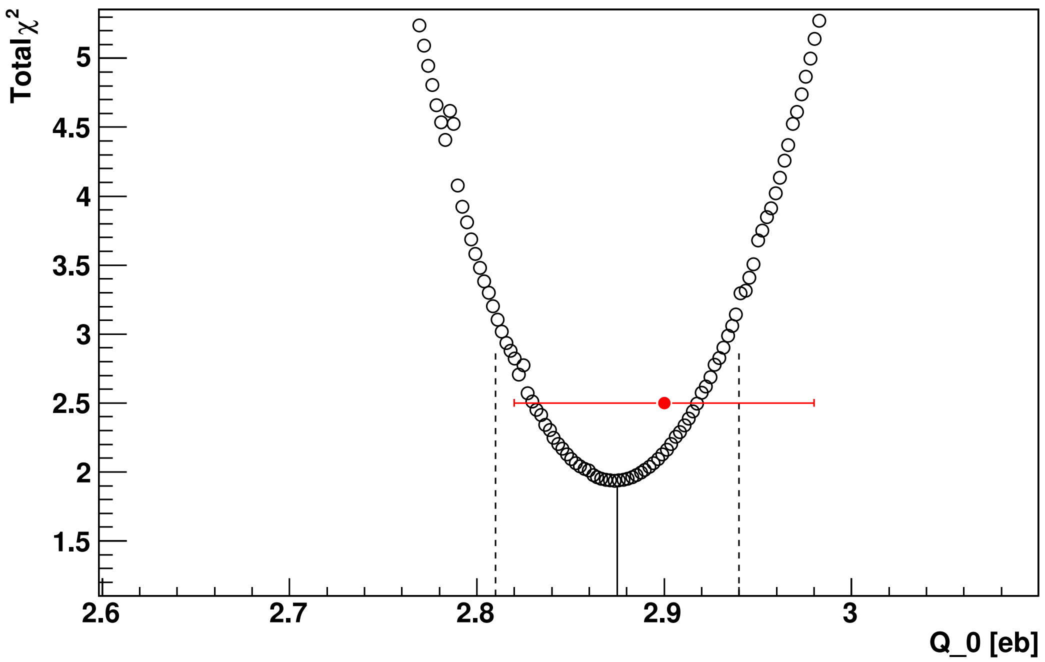



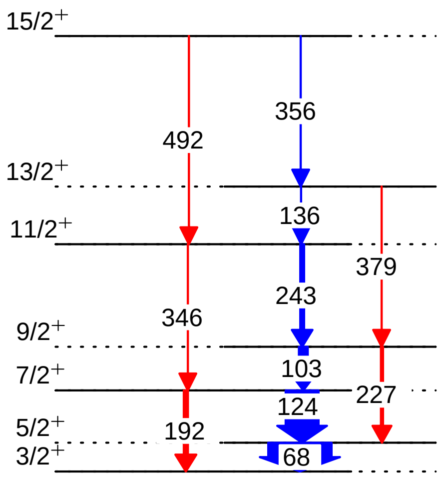

... but matrix elements in the upper part of a strongly deformed rotational band are related to observed intensity ratios in the nucleus under study (no external normalisation required)

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

MZ *et al.* EPJA 52, 99 (2016)

- 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

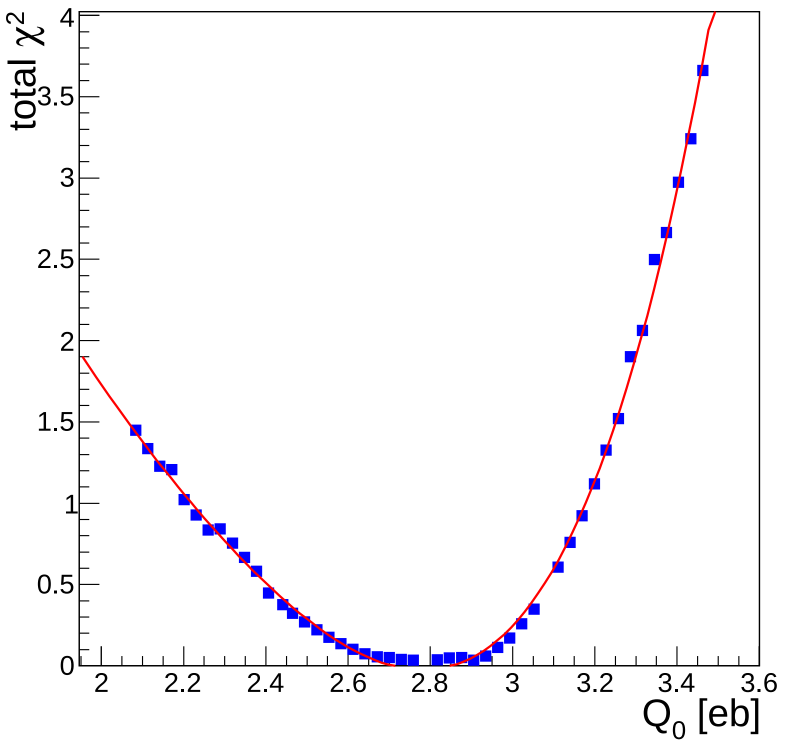


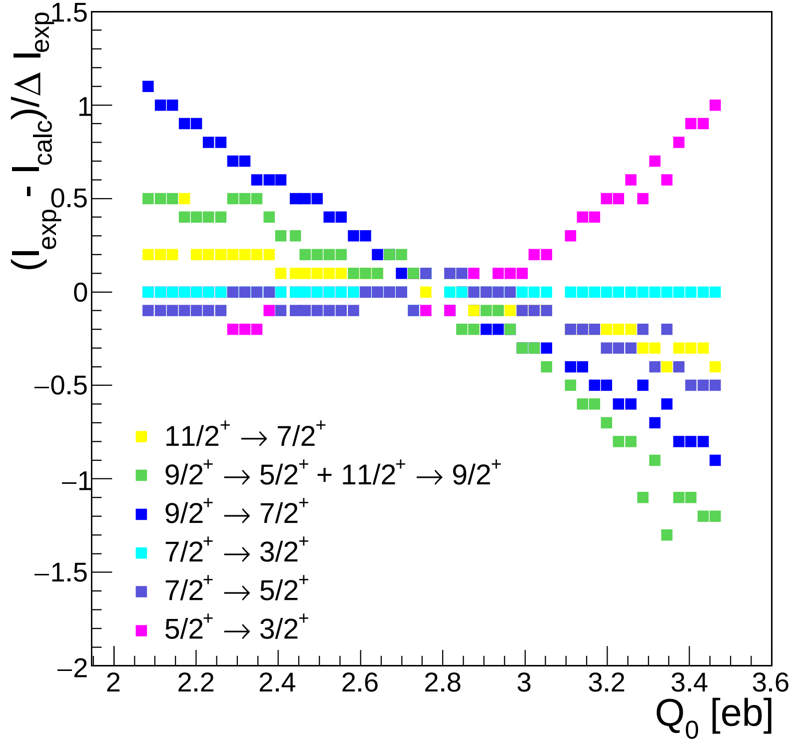



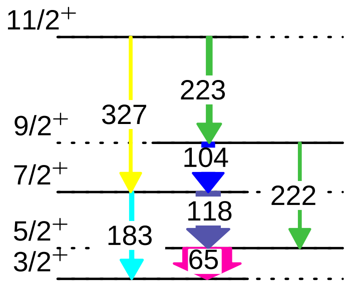

- tested on $^{97}$Rb data, result consistent with weighted average of $Q_0$ values obtained in standard analysis

# $^{99}$Rb: results

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



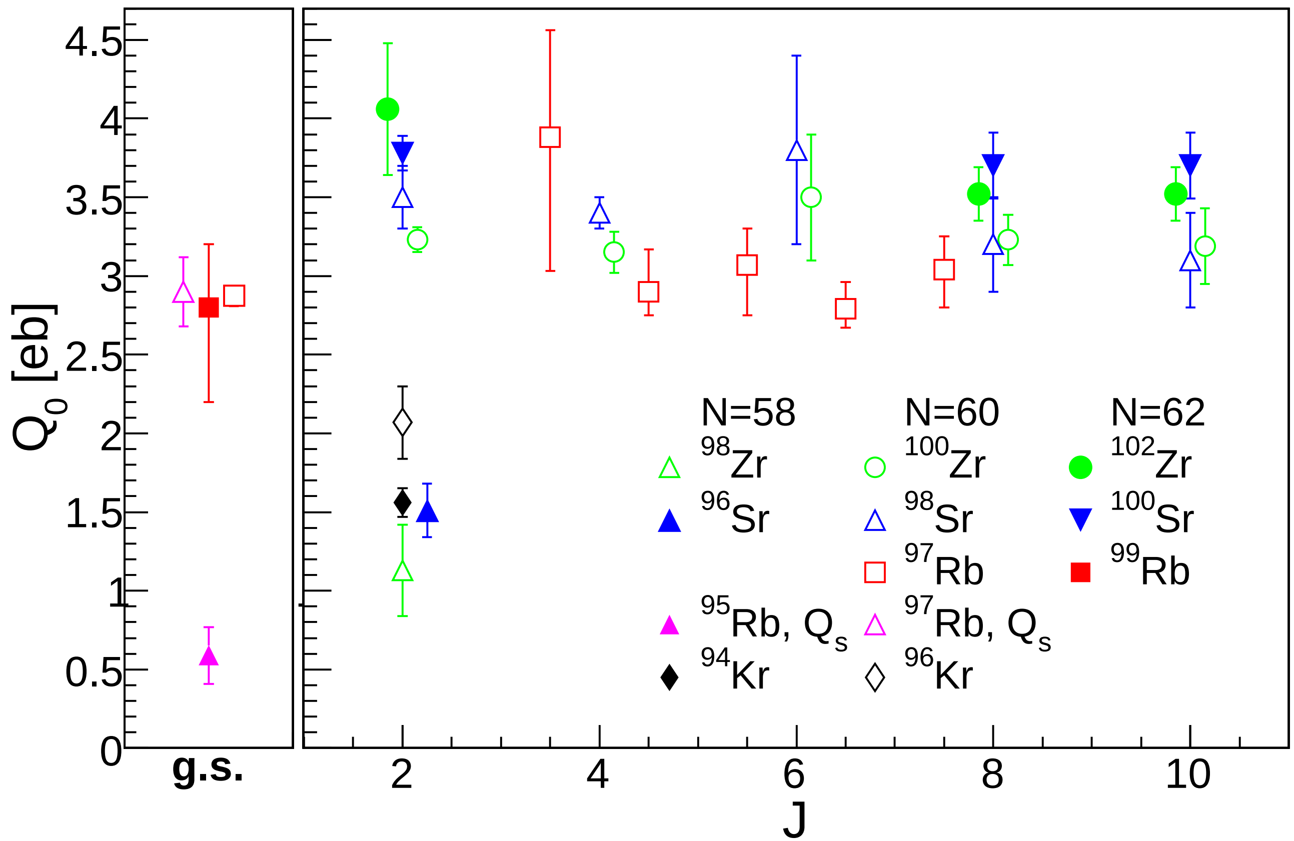




- one clear $\chi^2$ minimum for all observed transitions
- precision rather low due to limited statistics

# Comparison with neighbouring N=58,60,62 nuclei

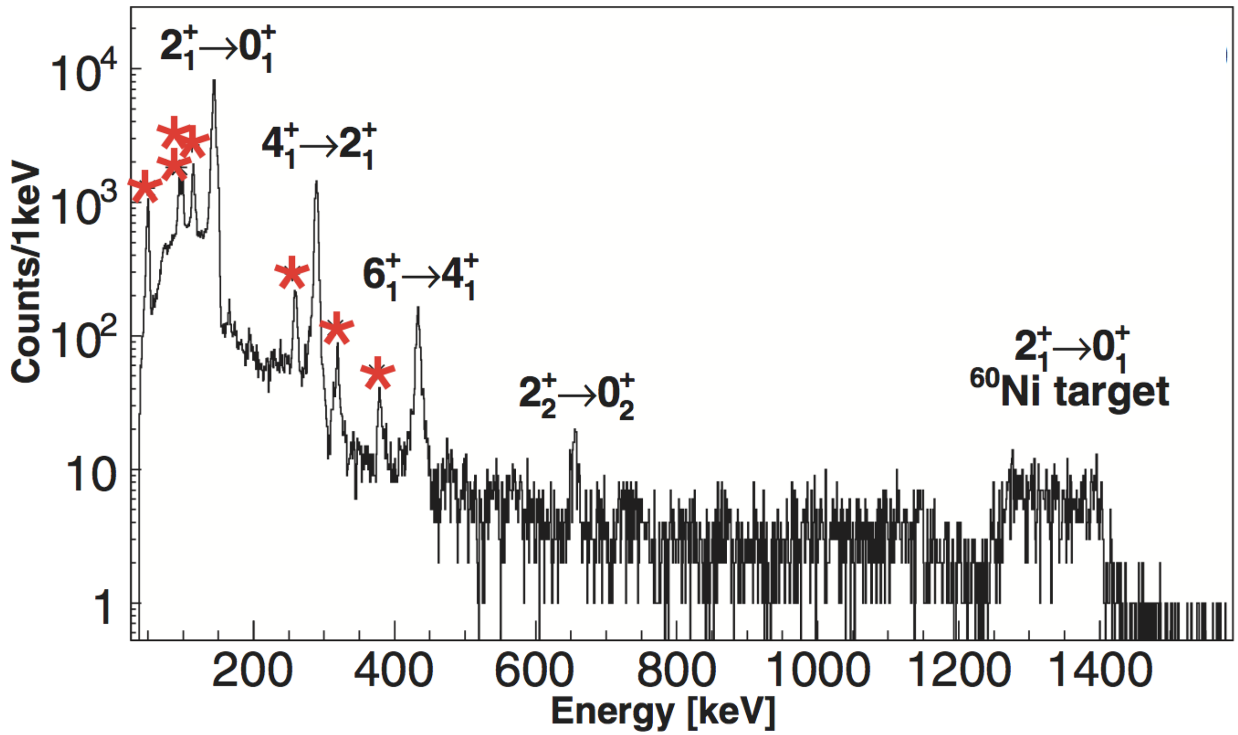
C. Sotty, MZ *et al.* PRL 115, 172501 (2015)




- $Q_0$ 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

# Identification of transitions in $^{98}$Rb

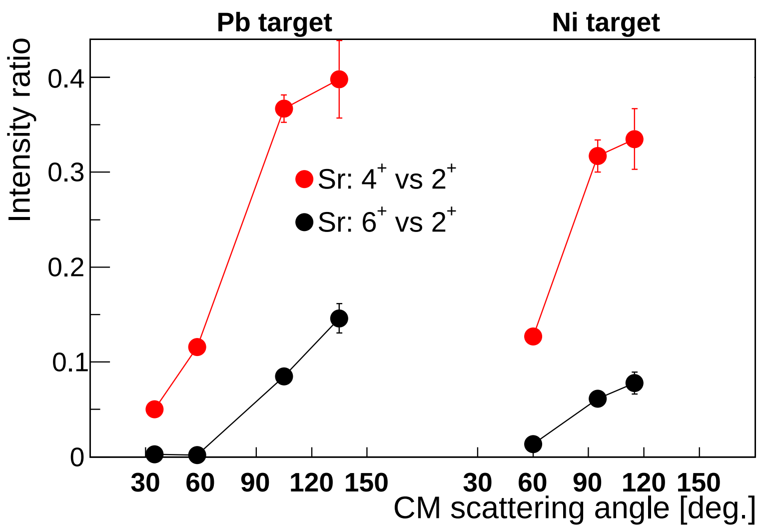
E. Clément, MZ *et al.*
Phys. Rev. C 94, 054326 (2016)

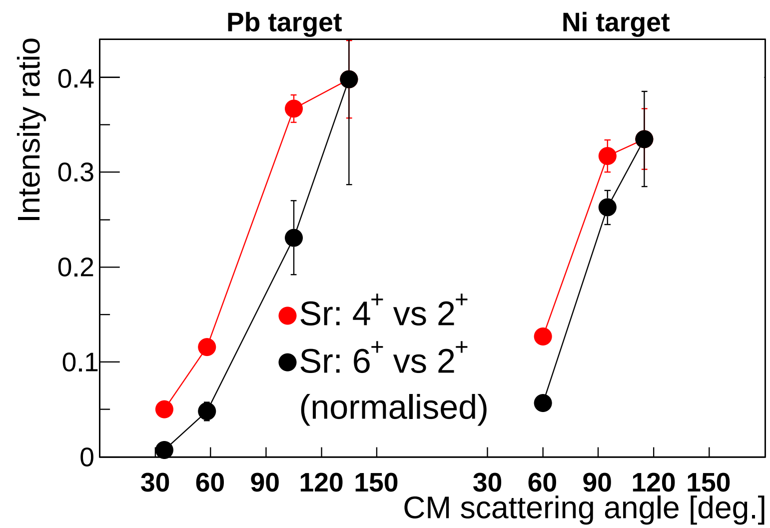



- 7 low-energy transitions observed, not in coincidence with any transition in $^{98}$Sr
- mutual coincidences of 50 keV, 94 keV and 99 keV; 114 keV and 318 keV; 258 and 378 keV
- transitions at 51 keV, 95 keV and 115 keV observed in $^{98}$Rb + $^{12}$C at 2.7 MeV/A (S. Bottoni, Phys. Rev. C 92 (2015) 024322): one-step or two-step excitation

## Differential cross sections in $^{98}$Sr

E. Clément, MZ *et al.*
Phys. Rev. C 94, 054326 (2016)

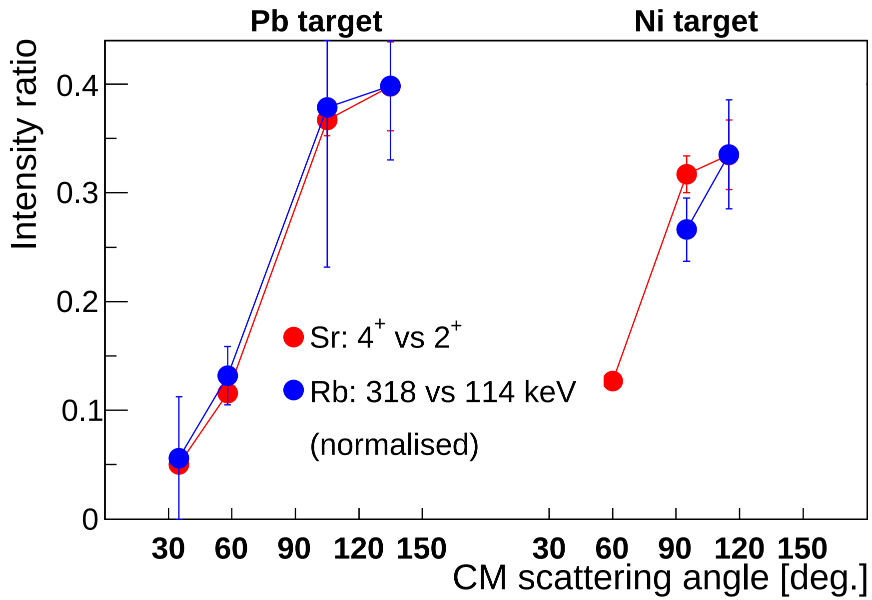


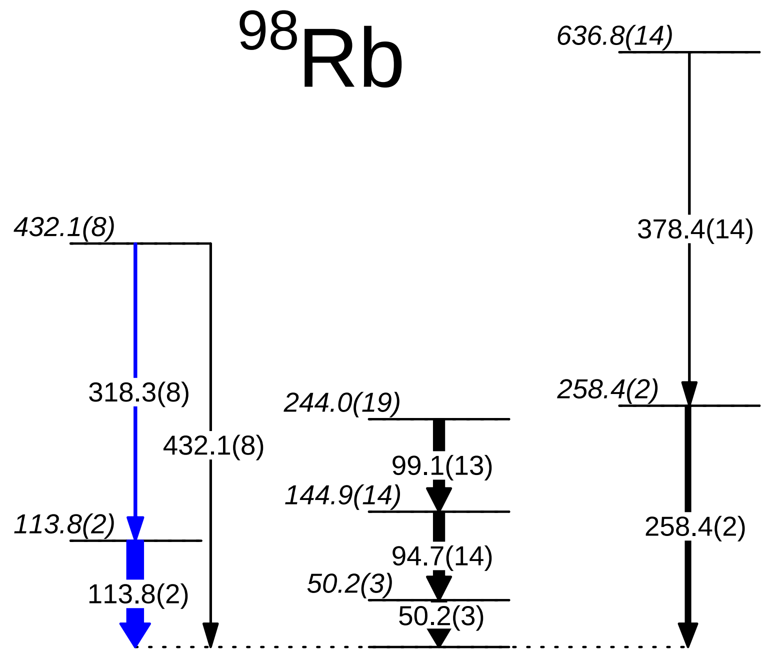




- transition intensity normalised to that of the $2_1^+$ state
- very different behaviour with scattering angle for two-step and three-step excitation

# Construction of $^{98}$Rb level scheme

E. Clément, MZ *et al.*
Phys. Rev. C 94, 054326 (2016)




- pattern consistent with two-step excitation

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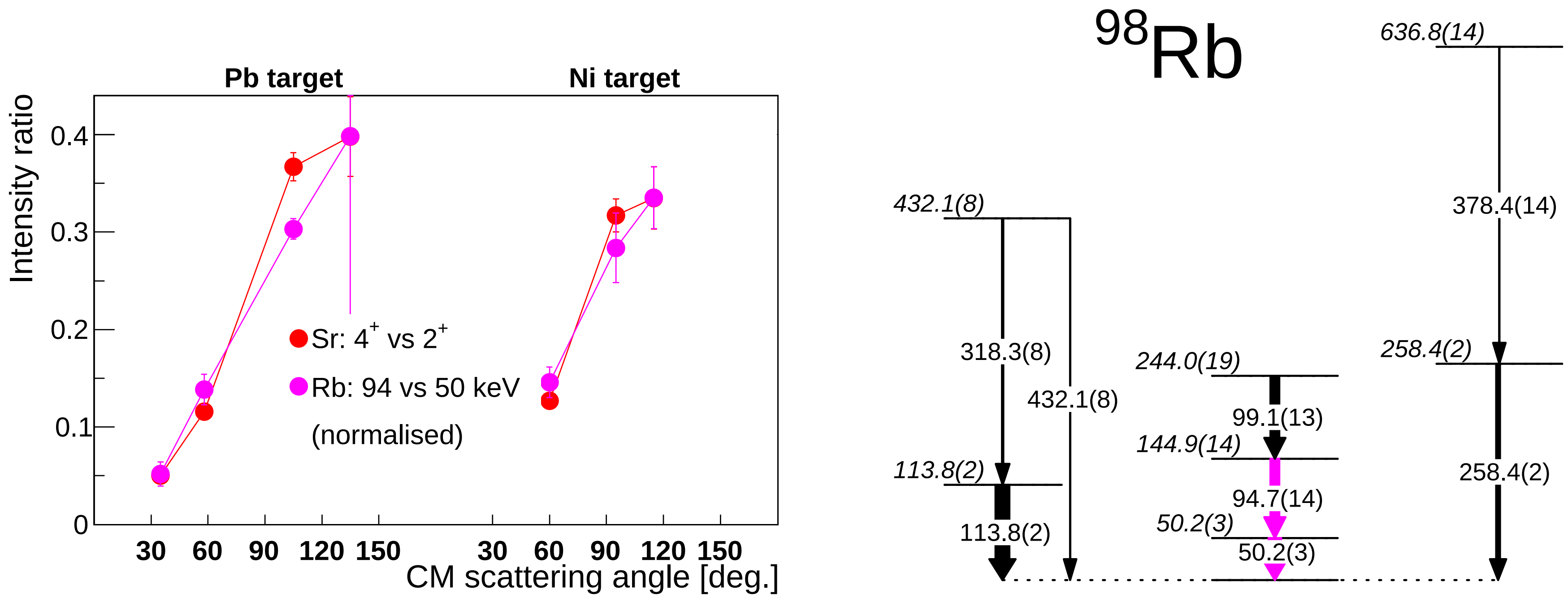
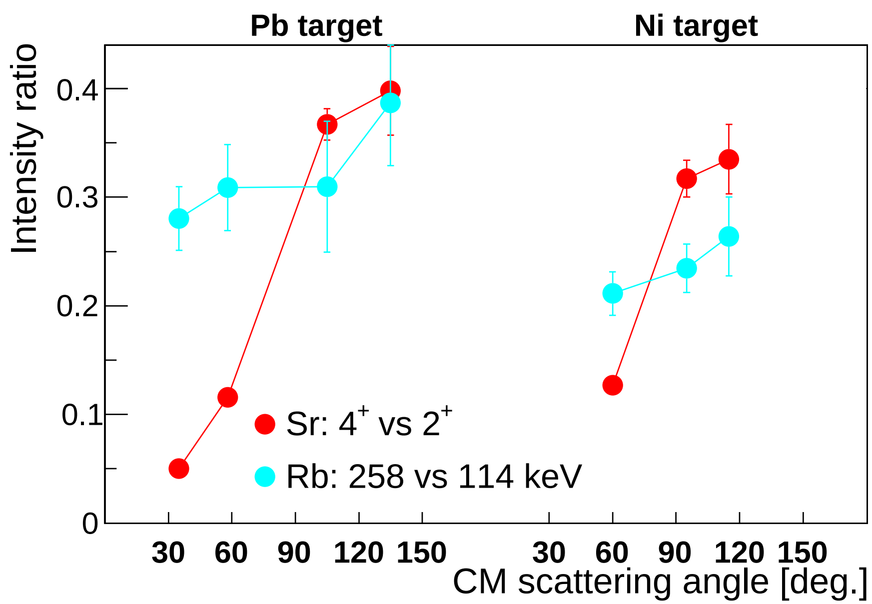
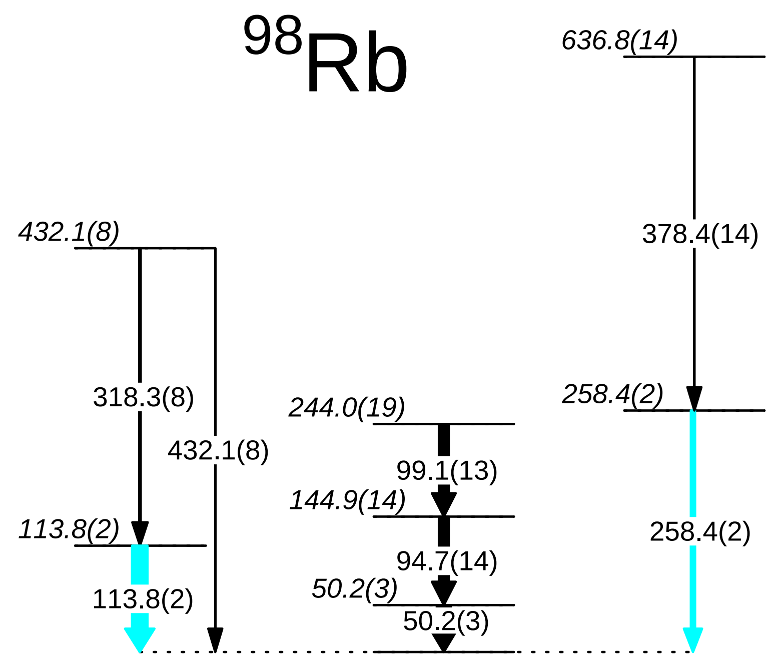



- pattern consistent with two-step excitation (the same observed for the 99-keV line, which we relate to very low energy differences between the three states)
- less consistent than for 318 keV vs 114 keV, so one-step excitation of the 145 keV level may play a role (the transition would overlap with $2^+ \rightarrow 0^+$ in $^{98}$Sr)

# Construction of $^{98}$Rb level scheme

E. Clément, MZ *et al.*
Phys. Rev. C 94, 054326 (2016)




- clearly one-step excitation: increase of the intensity ratio with scattering angle is related to higher level energy (258 keV vs 114 keV)