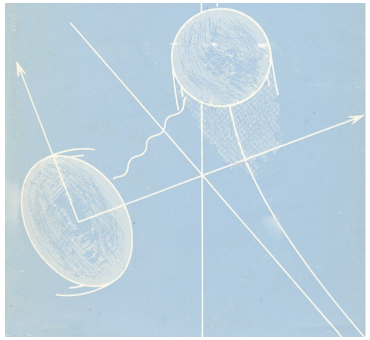
Coulomb excitation with radioactive ion beams



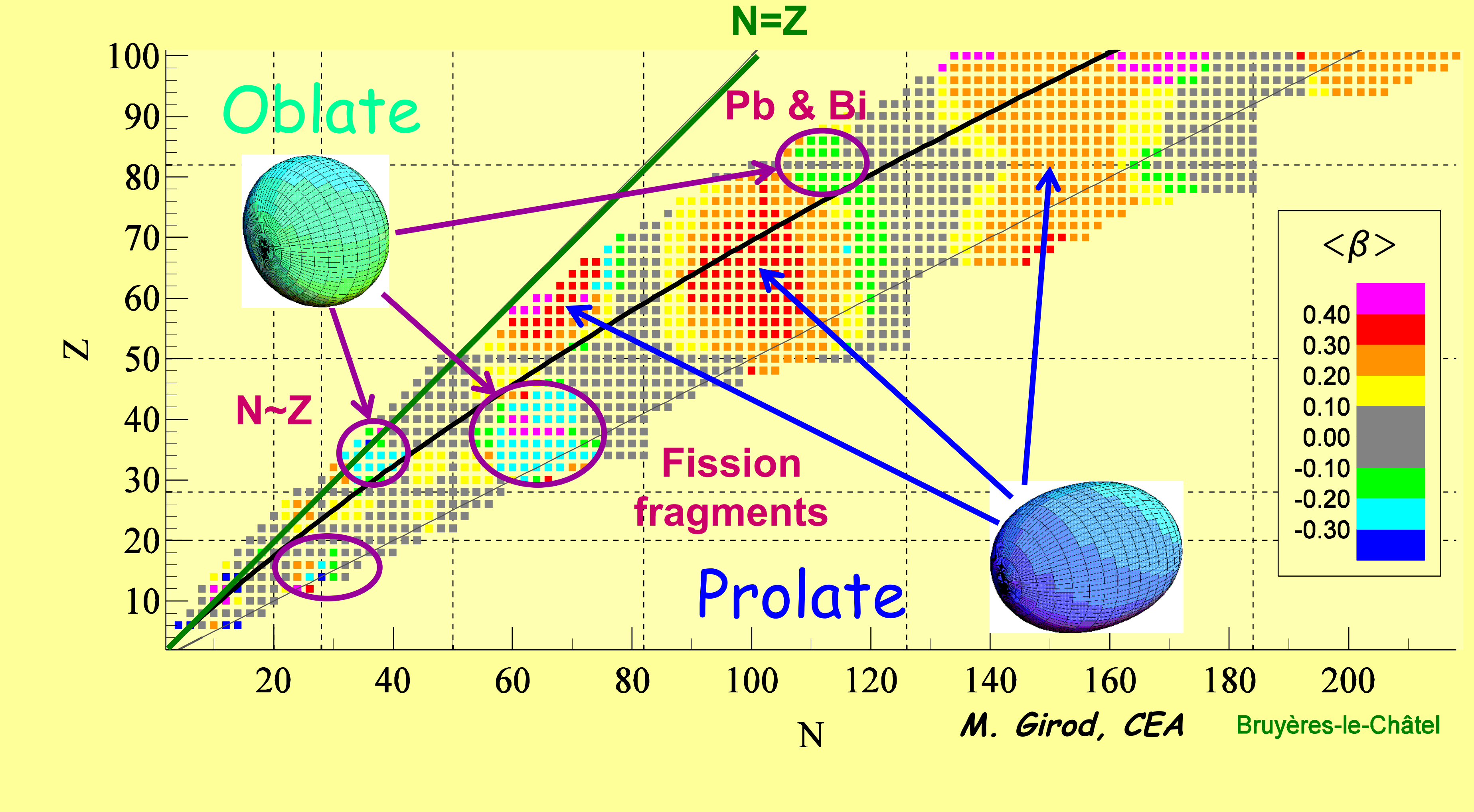
a tool to study nuclear collectivity and more

- Motivation and introduction
- Theoretical aspects of Coulomb excitation
- Experimental considerations, set-ups and analysis techniques
- Recent experiments and future perspectives

Lecture given at the
International School of Physics "Enrico Fermi”
Varenna, July 2017

Wolfram KORTEN - CEA Paris-Saclay

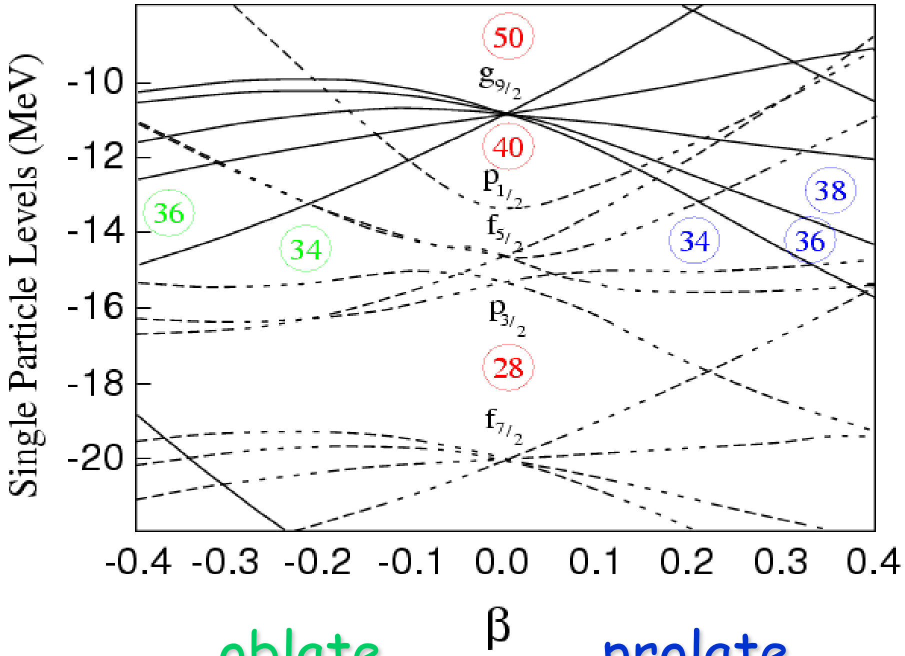
Quadrupole deformation of nuclei

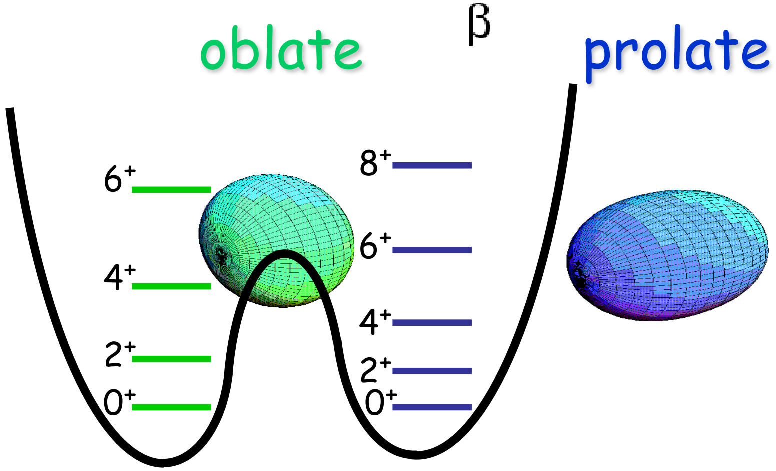


Oblate deformed nuclei are far less abundant than prolate nuclei

Shape coexistence possible for certain regions of N & Z

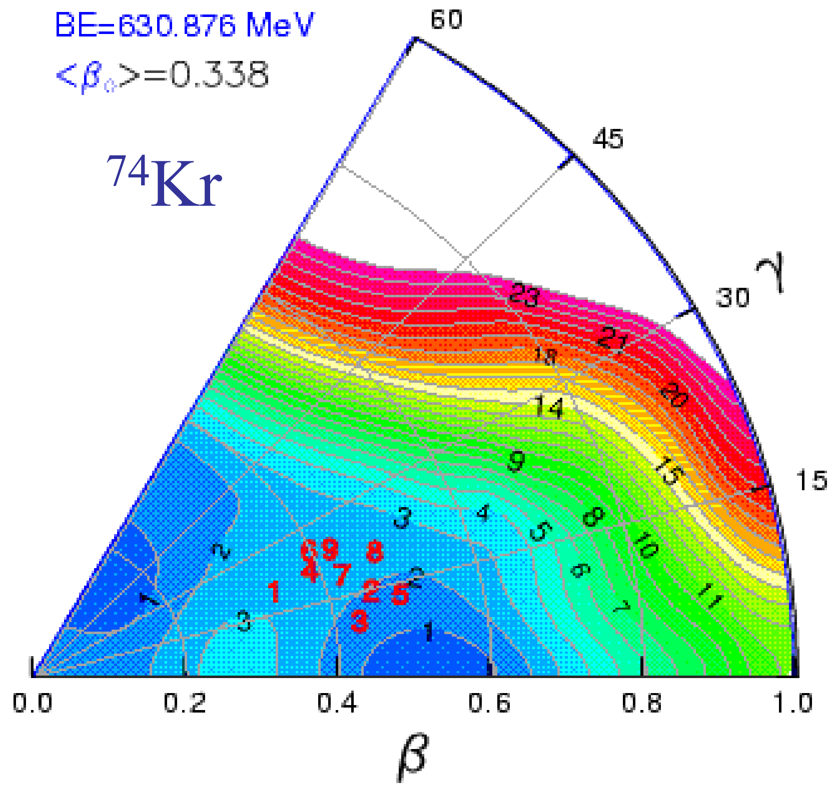
Shape coexistence around A=70





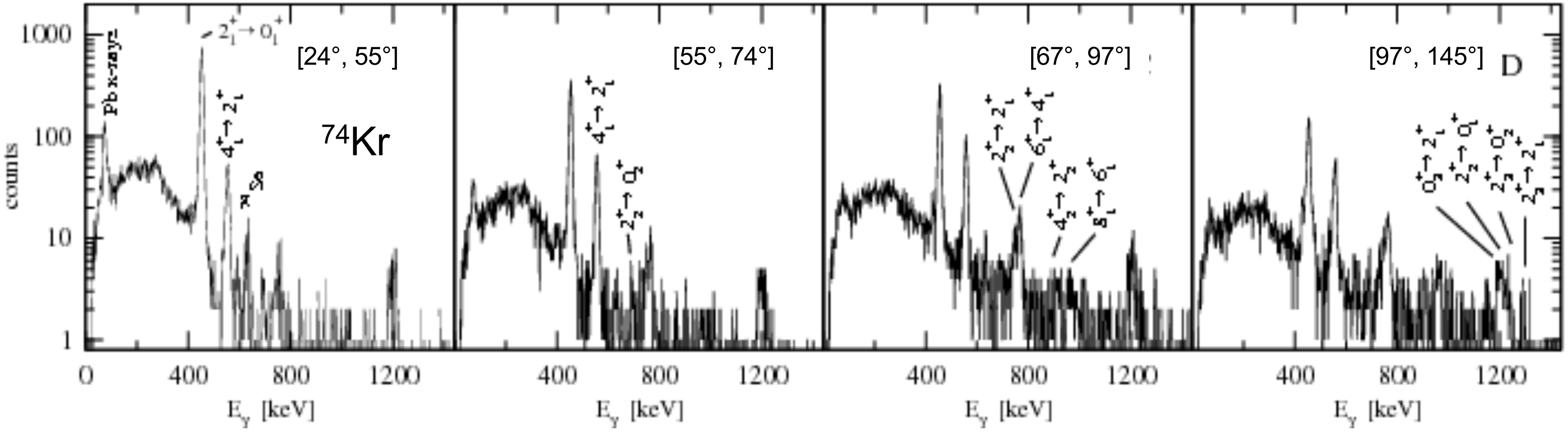
expected e.g. in:

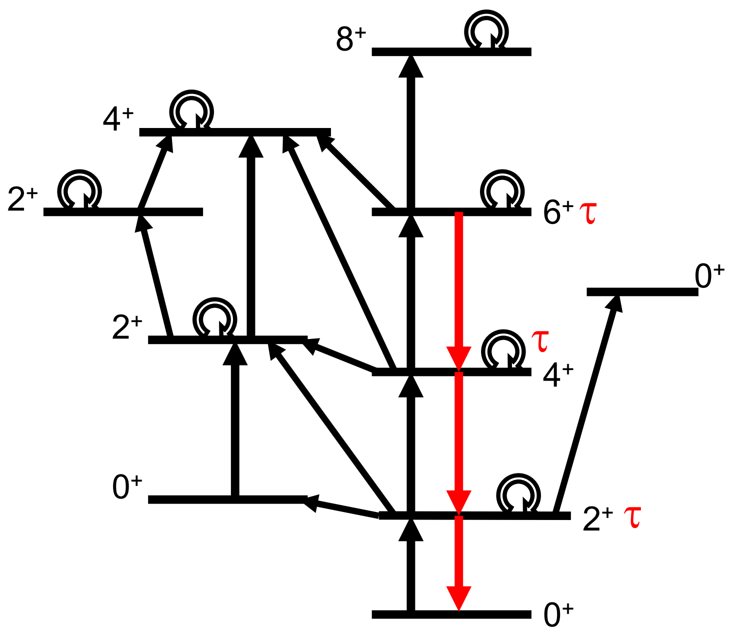
$^{72}_{36}Kr_{36}$ $^{74}_{36}Kr_{38}$ $^{68}_{34}Se_{34}$ $^{70}_{34}Se_{36}$



- Observation of 0^+ shape isomers
- Coulomb excitation to determine shape parameters and configuration mixing

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

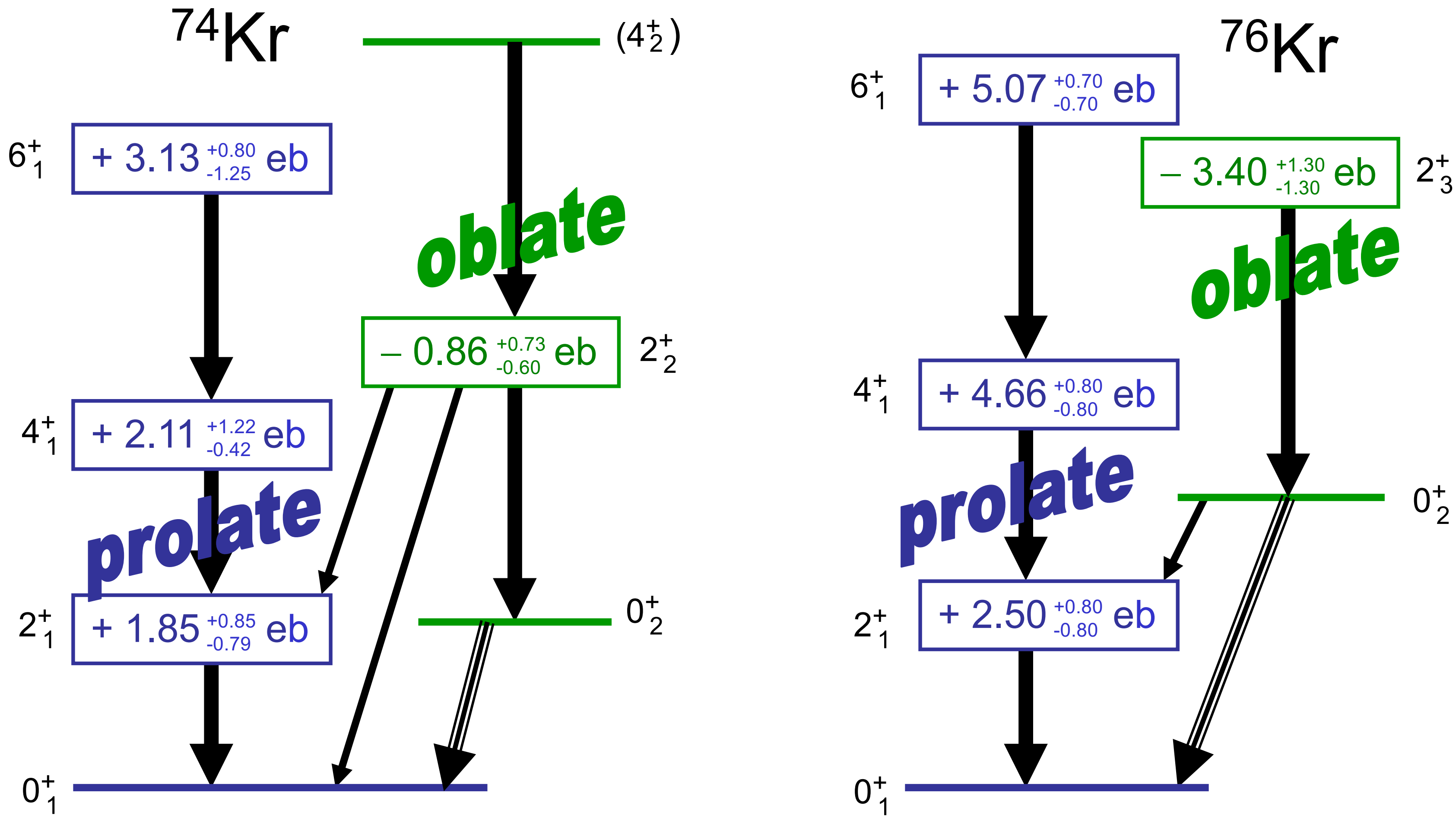




- ^{74}Kr + ^{208}Pb at 4.7 MeV/u (SPIRAL)
  ➔ multi-step Coulomb excitation
- γ-ray yields as function of scattering angle (differential excitation cross section)
- experimental spectroscopic data (lifetimes, branching ratios)
- least squares fit of ~ 30 matrix elements (transitional and diagonal)

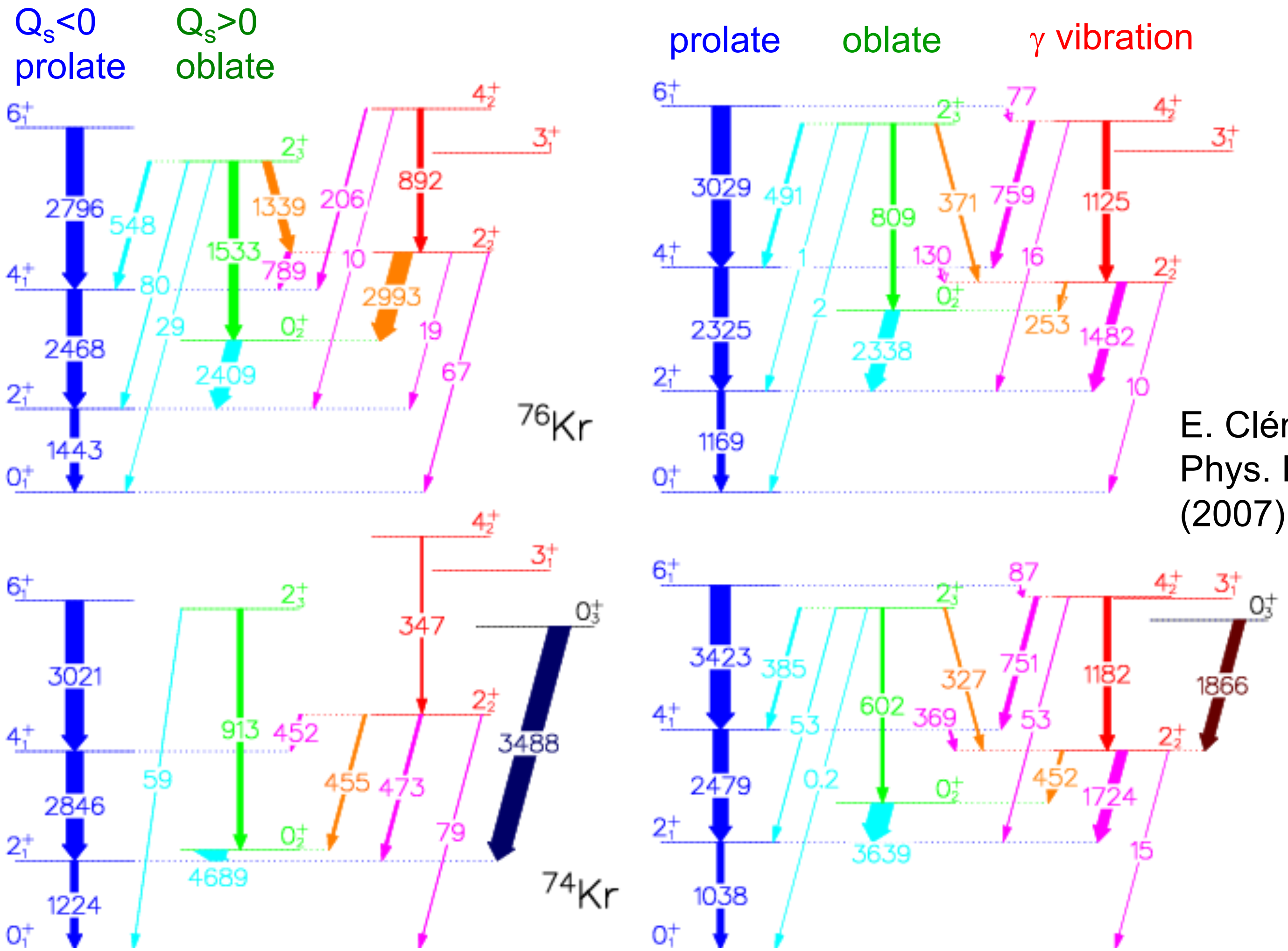
E. Clément et al., Phys. Rev. C 75, 054313 (2007)

Quadrupole moments (Q_0) in ^{74}Kr and ^{76}Kr



- direct confirmation of the prolate – oblate shape coexistence
- first reorientation measurement with radioactive beam

Experimental results and comparison with theory



E. Clément et al., Phys. Rev. C 75, 054313 (2007)

experimental B(E2;↓) [e^2fm^4]

Calculation HFB-Gogny 5-dim GCM

- complete set of e.m. matrix elements, incl. static moments
- quantitative understanding of shape coexistence and configuration mixing
- triaxiality is the key to reproduce experimental data and shape evolution

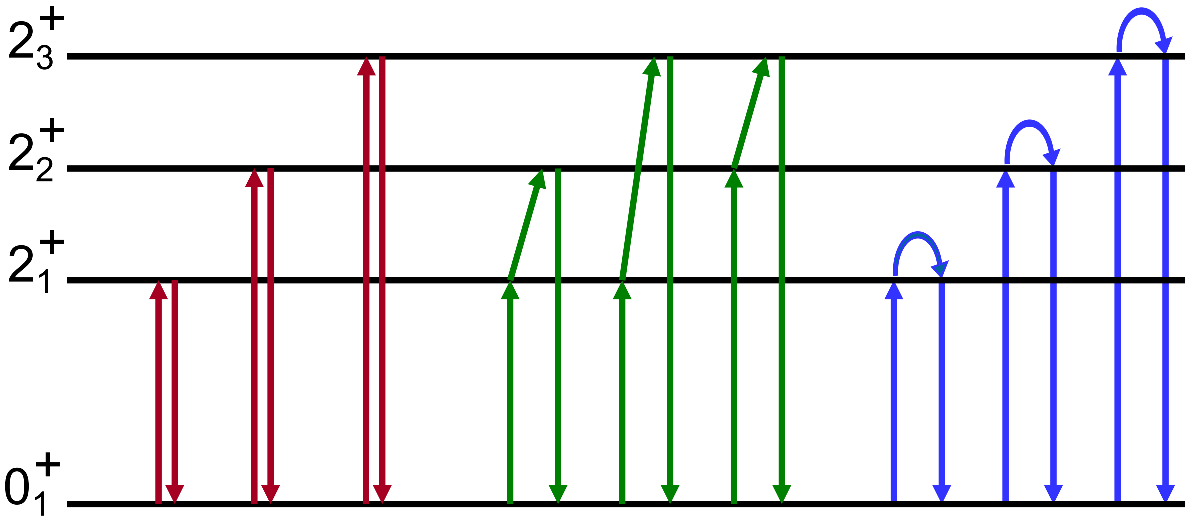
Quadrupole deformation from sum rules

Model-independent method to determine charge distribution parameters (Q,δ) from a (full) set of E2 matrix elements

$$\mathcal{M}(E2, \mu = 0) = Q\cos\delta$$
$$\mathcal{M}(E2, \mu = \pm 1) = 0$$
$$\mathcal{M}(E2, \mu = \pm 2) = \tfrac{1}{\sqrt{2}} Q\sin\delta$$

$$\langle s|[E2\times E2]_0|s\rangle = \frac{1}{\sqrt{5}}Q^2 = \frac{(-1)^{2s}}{\sqrt{2s+1}}\sum_t \langle s||E2||t\rangle\langle t||E2||s\rangle \begin{Bmatrix} 2 & 2 & 0 \\ s & s & t \end{Bmatrix}$$

$$\langle s|[[E2\times E2]_2\times E2]_0|s\rangle = -\sqrt{\frac{2}{35}}Q^3\cos(3\delta) = \frac{1}{2s+1}\sum_{tu} \langle s||E2||t\rangle\langle t||E2||u\rangle\langle u||E2||s\rangle \begin{Bmatrix} 2 & 2 & 2 \\ s & t & u \end{Bmatrix}$$

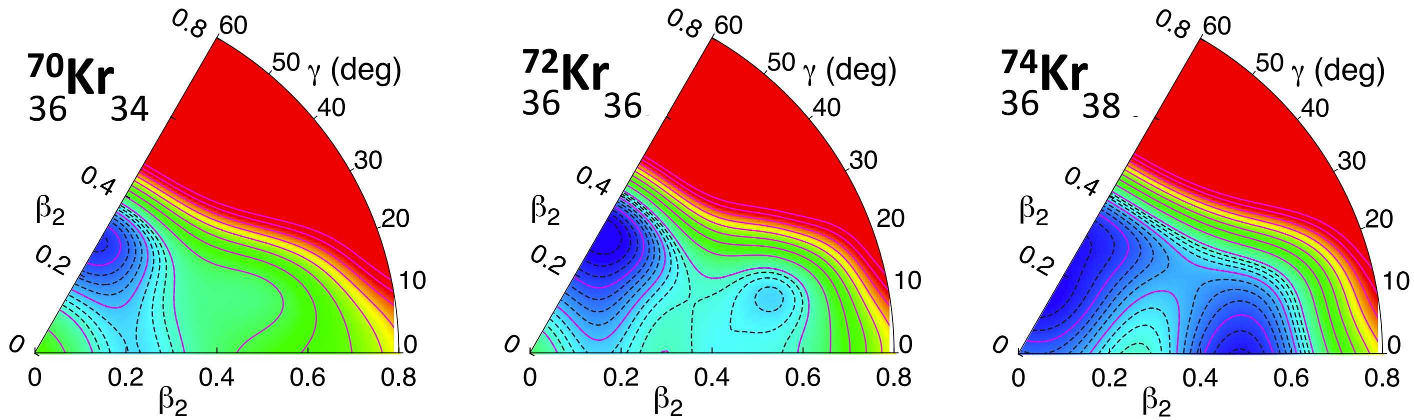


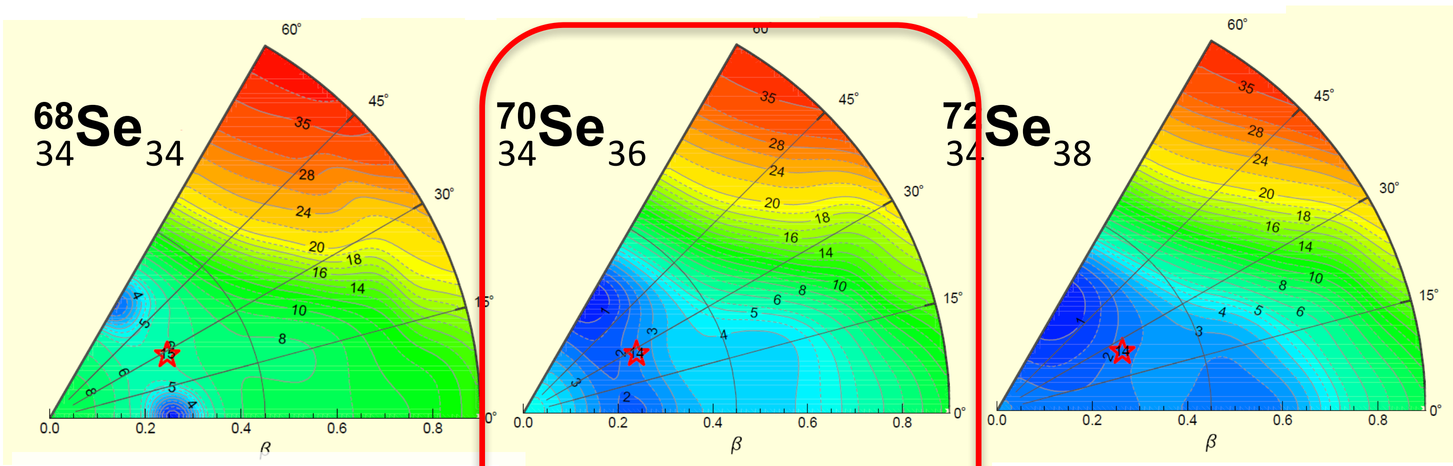
~ Q^2 ~ $Q^3\cos 3\delta$

"intrinsic ground state shape can be determined by a full set of E2 matrix elements linking the ground state to all (collective) 2^+ states

What do we know in the N~Z nuclei around A=70

SPIRAL LE CoulEx:
$Q(2_1^+, 4^+, 2_2^+, \ldots\ )$
PRC 054313 (2007)





NSCL HE Coulex
$B(E2; 0^+ \rightarrow 2^+)$
PRC 80 (2009) 031304

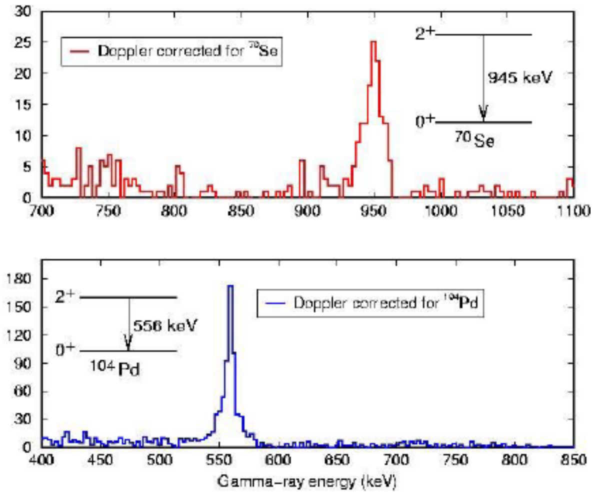
REX-Isolde LE CoulEx
$\sigma_{tot}(0^+ \rightarrow 2^+)$ only
PRL 98, 072501 (2007)

HIE-Isolde LE CoulEx:
$Q(2_1^+, 4^+, 2_2^+, \ldots\ )$
planned 2017

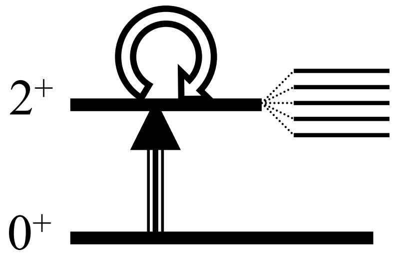
Coulomb excitation of ^{70}Se at CERN / ISOLDE

- ^{70}**Se** on ^{104}**Pd** at 2.94 MeV/u
- integral measurement
- excitation probability P(2⁺) via normalization to known ^{104}Pd

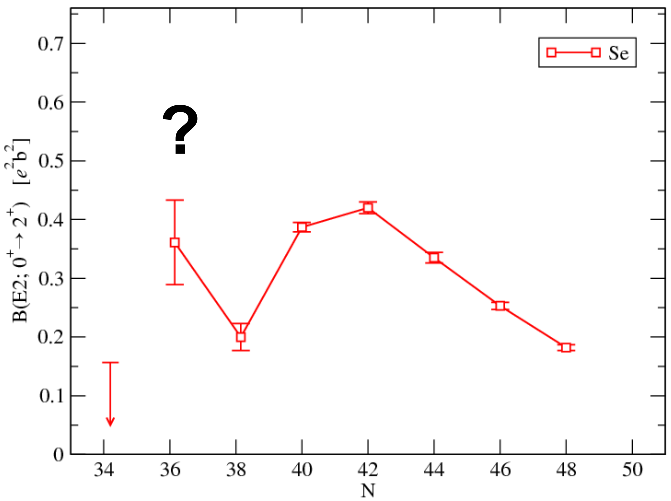
P_{2+} depends on
- transitional matrix element B(E2)
- diagonal matrix element Q_0



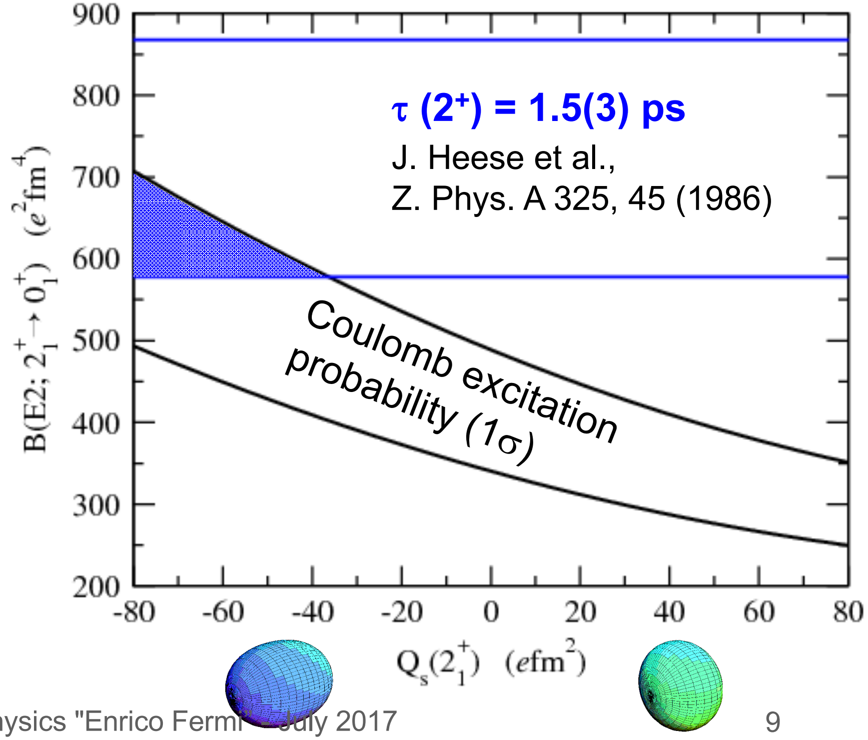
A.M. Hurst et al., PRL 98, 072501 (2007)
(Univ. Liverpool)



- one measurement, but two unknowns !



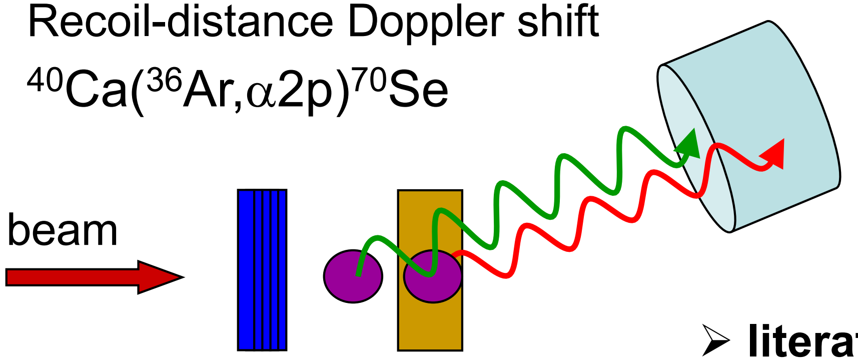
^{68}Se intermediate-energy Coulex GANIL
E. Clément et al., NIM A 587, 292 (2008)

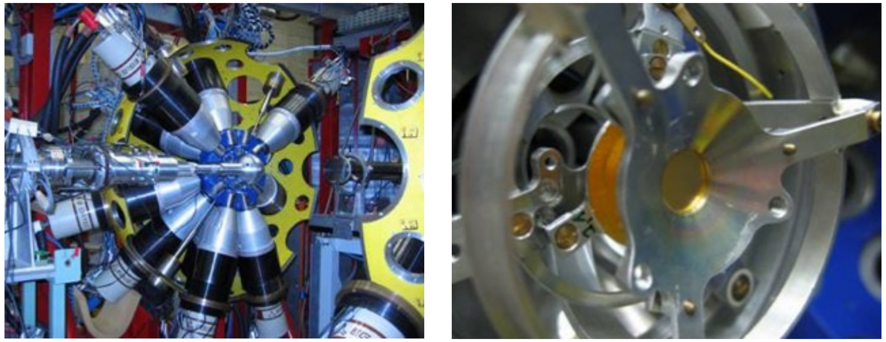


Lifetimes in ^{70}Se revisited

Recoil-distance Doppler shift

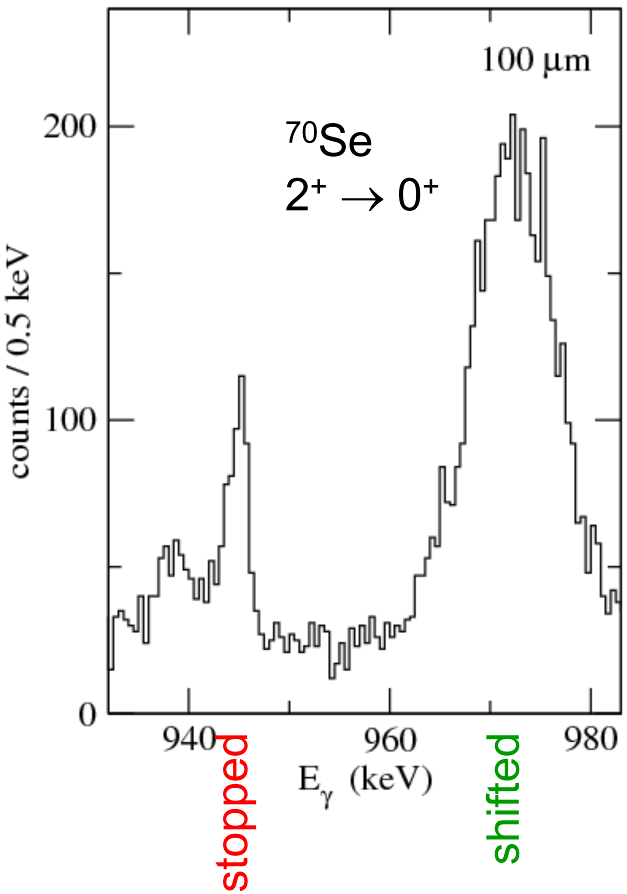
$^{40}Ca(^{36}Ar,\alpha 2p)^{70}Se$

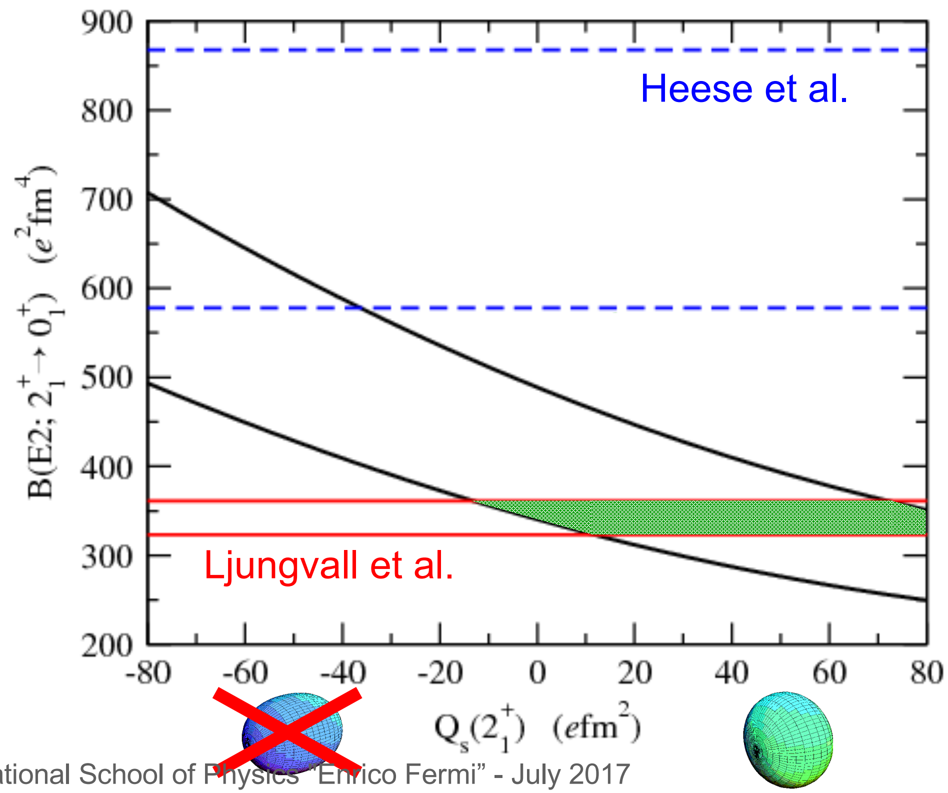




GASP and Köln Plunger at Legnaro

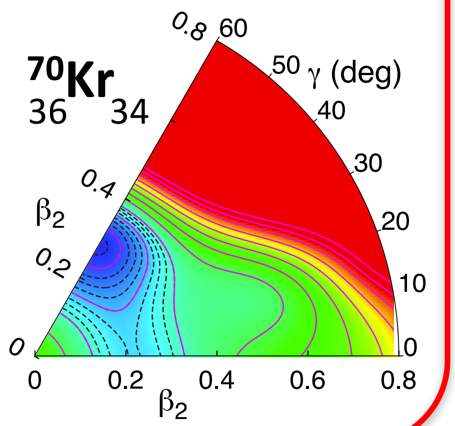
- **literature value: τ = 1.5(3) ps**
  J. Heese et al., Z. Phys. A 325, 45 (1986)
- **new lifetime for 2$^+$ in ^{70}Se: τ = 3.2(2) ps**
  J. Ljungvall et al., Phys. Rev. Lett. 100, 102502 (2008)



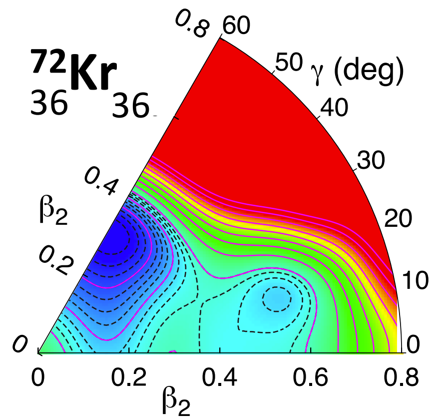


What do we know in the N~Z nuclei around A=70

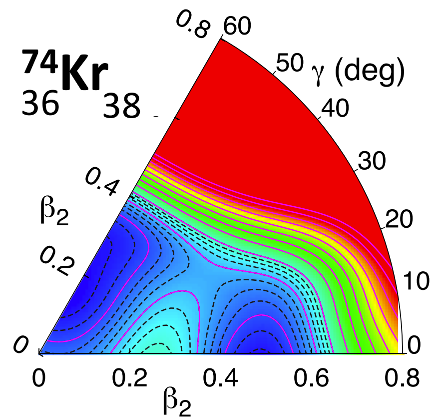
RIKEN HE CoulEx & "knock-out"
RIBF94 May 2015

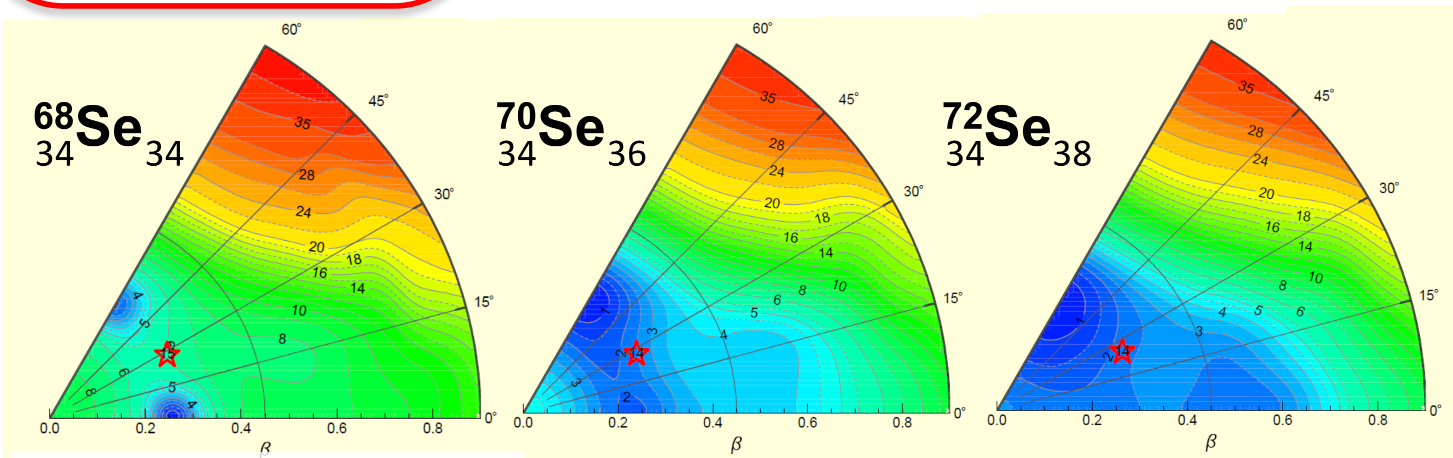


NSCL RDDS & HE CoulEx
$T_{1/2}$ (2^+,4^+); B(E2; $0^+ \rightarrow 2^+$)
PRL 112, 142502 (2014)



SPIRAL LE CoulEx:
Q(2_1^+,4^+,2_2^+,…)
PRC 054313 (2007)





NSCL HE Coulex
B(E2; $0^+ \rightarrow 2^+$)
PRC 80 (2009) 031304

REX-Isolde LE CoulEx
σ_{tot}($0^+ \rightarrow 2^+$) only
PRL 98, 072501 (2007)

HIE-Isolde LE CoulEx:
Q(2_1^+,4^+,2_2^+,…)
planned 2017

Coulomb excitation – the different energy regimes

	Low-energy regime (< 5 MeV/u)		High-energy regime (>>5 MeV/u)	
Energy cut-off	$\Delta E_{max} = \frac{\hbar v_\infty}{a\,\varepsilon} \approx 2\,\text{MeV}$		$\Delta E_{max} = \hbar c \frac{\beta\gamma}{a\,\varepsilon} \approx 10\,\text{MeV}(\beta = 0.4)$	
Spin cut-off:	L_{max}:	up to 30ħ	mainly single-step excitations	
Cross section:	$d\sigma/d\theta \sim \langle I_i \| M(\sigma\lambda) \| I_f \rangle$ differential		$\sigma_\lambda \sim (Z_p e^2/\hbar c)^2\, B(\sigma\lambda, 0\rightarrow\lambda)$ integral	
Luminosity:	low	mg/cm^2 targets	high	g/cm^2 targets
Beam intensity:	high	>10^3 pps	low	a few pps

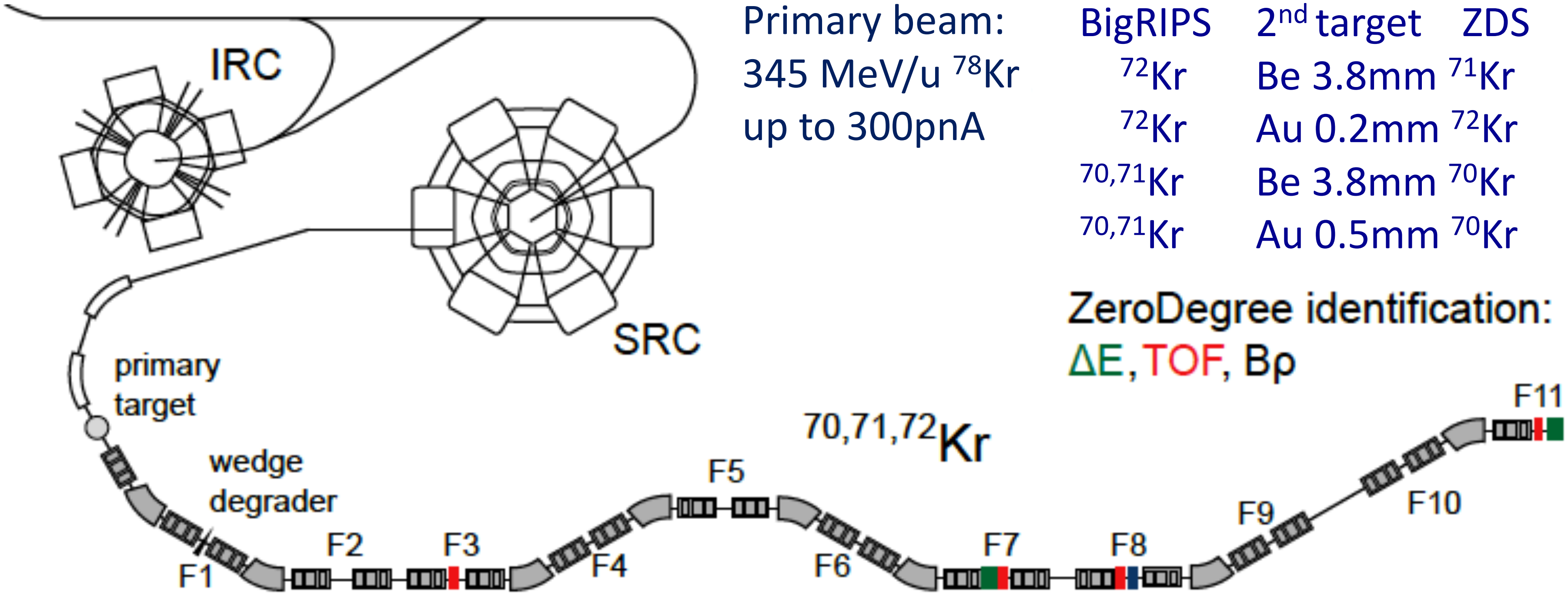
Comprehensive study of low-lying exitations

First exploration of excited states in very "exotic" nuclei

High energy Coulex of ^{70,72}Kr at RIBF

Primary beam:
345 MeV/u ^{78}Kr
up to 300pnA

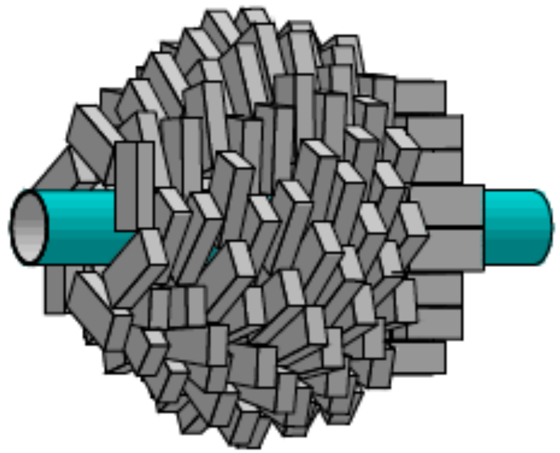
BigRIPS	2nd target	ZDS
^{72}Kr	Be 3.8mm	^{71}Kr
^{72}Kr	Au 0.2mm	^{72}Kr
^{70,71}Kr	Be 3.8mm	^{70}Kr
^{70,71}Kr	Au 0.5mm	^{70}Kr



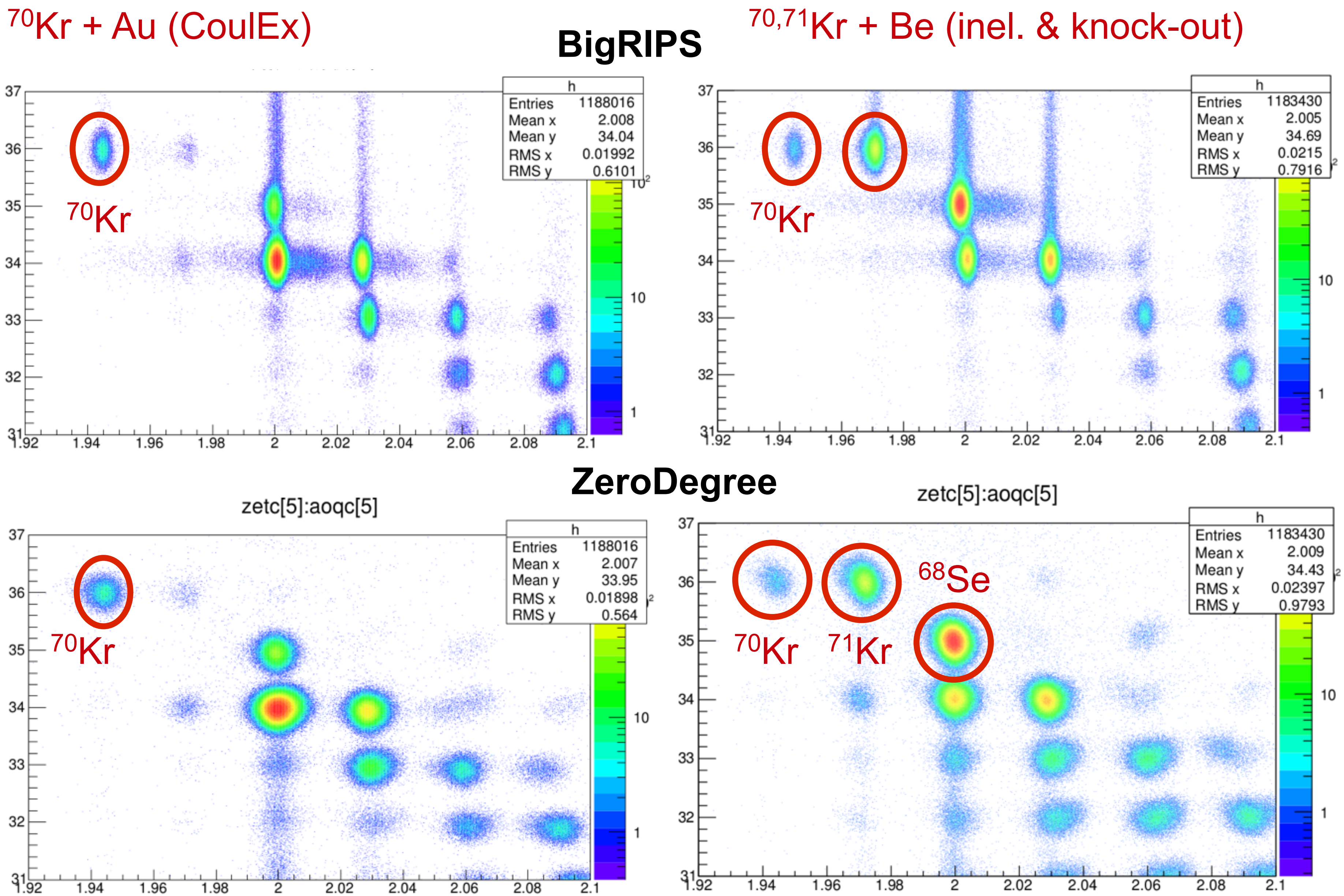
BigRIPS identification by:
ΔE, TOF, Bρ

secondary target:
Be, Au

- performed at RIBF, RIKEN Nishina Center
- two beam settings, centered on ^{72}Kr and ^{70,71}Kr
- DALI2 Na(I) array for γ-ray detection
- PPACs for scattering angle reconstruction

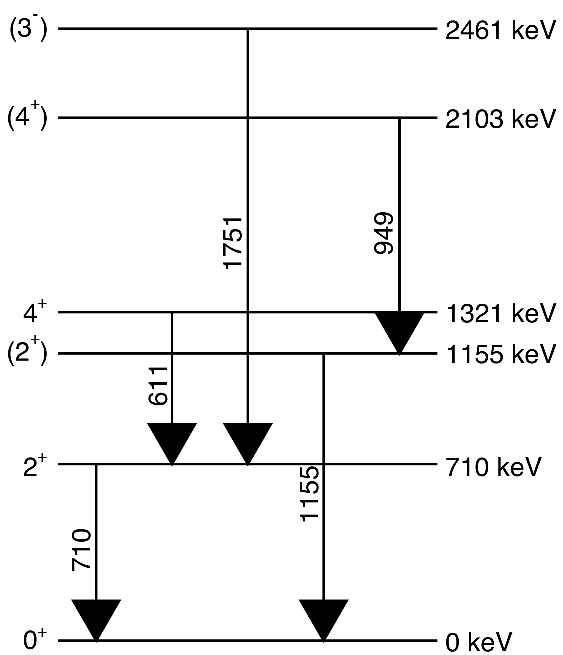


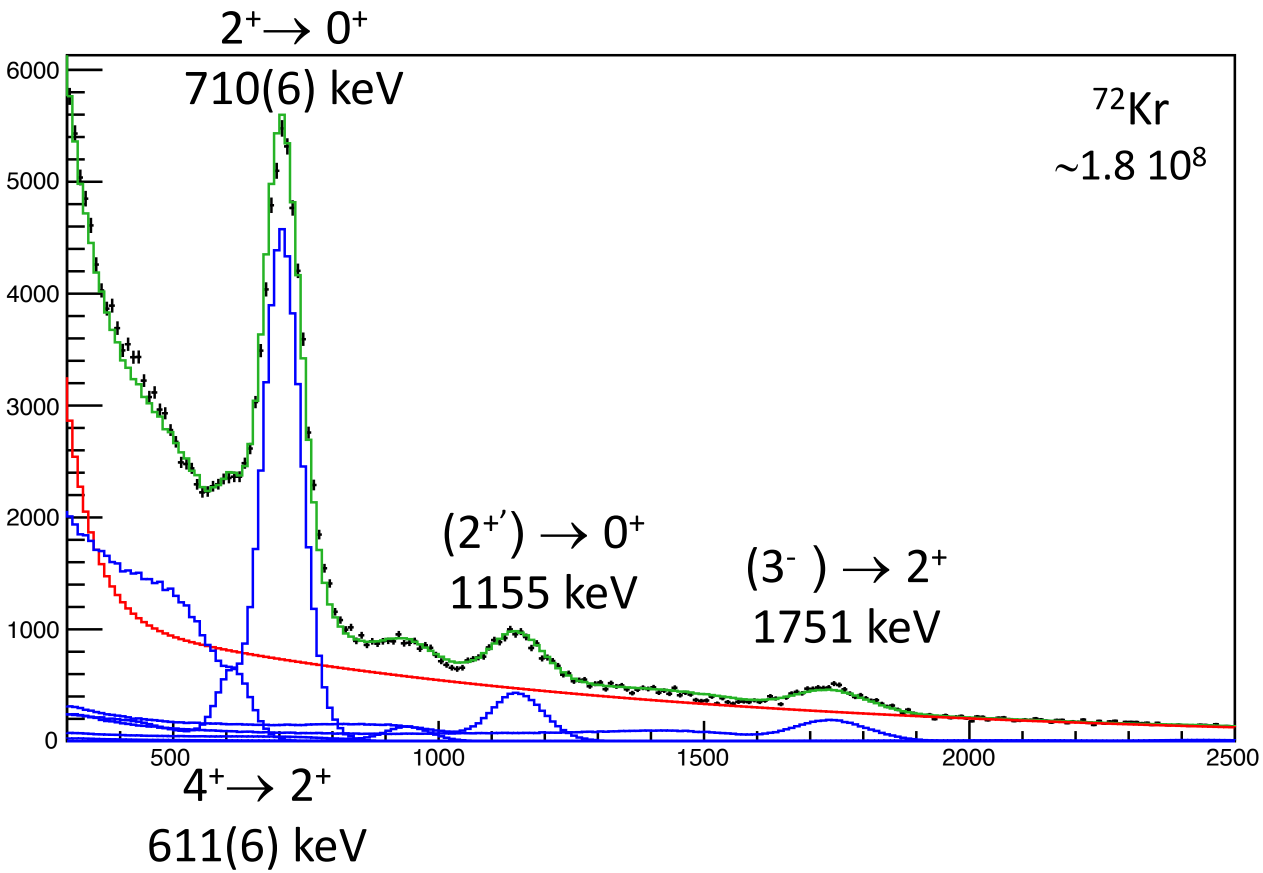
Identification with BigRIPS and ZeroDegree



Inelastic excitation of ^{72}Kr on Be target

^{72}Kr
(preliminary)

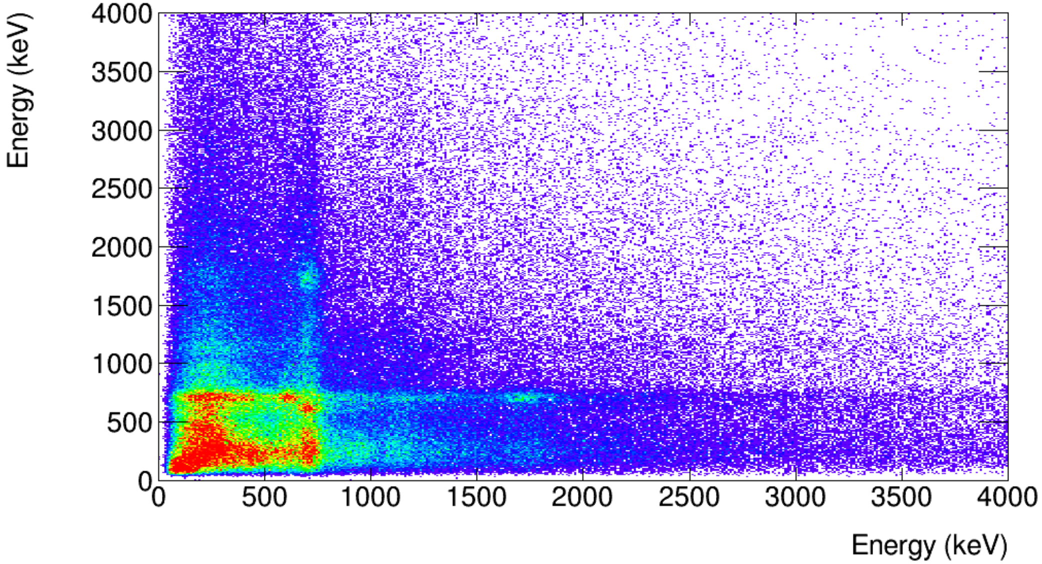


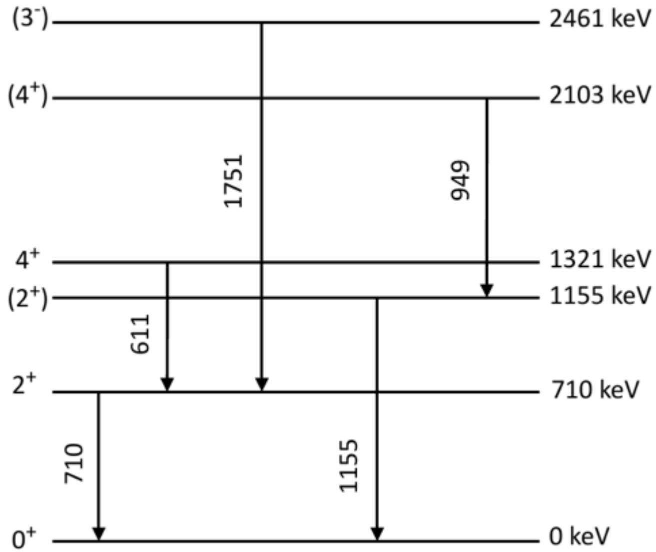


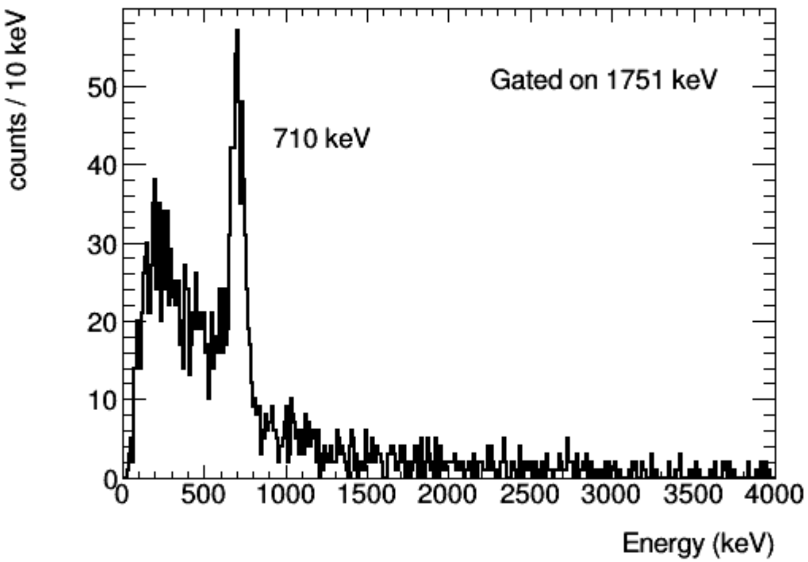
- **First observation of new excited states (second 2^+ and low-lying state 3^- ?)**

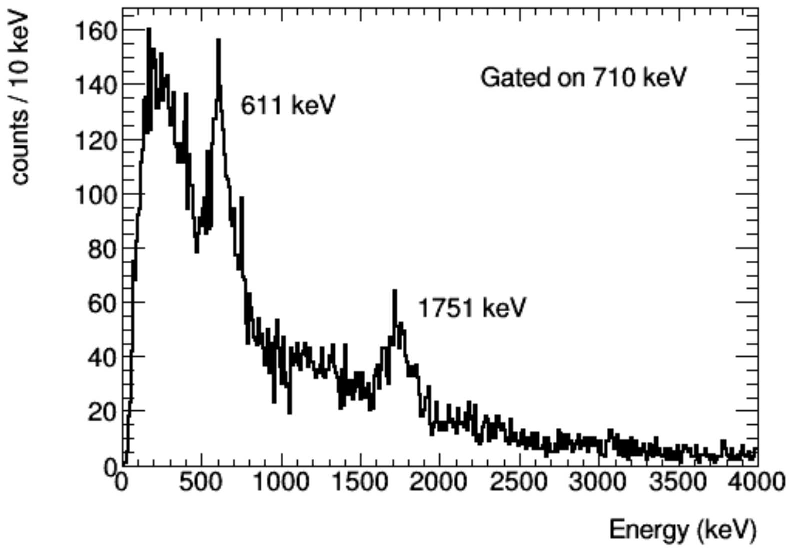
Irfu
cea
saclay

^{72}Kr γ–γ coincidence analysis

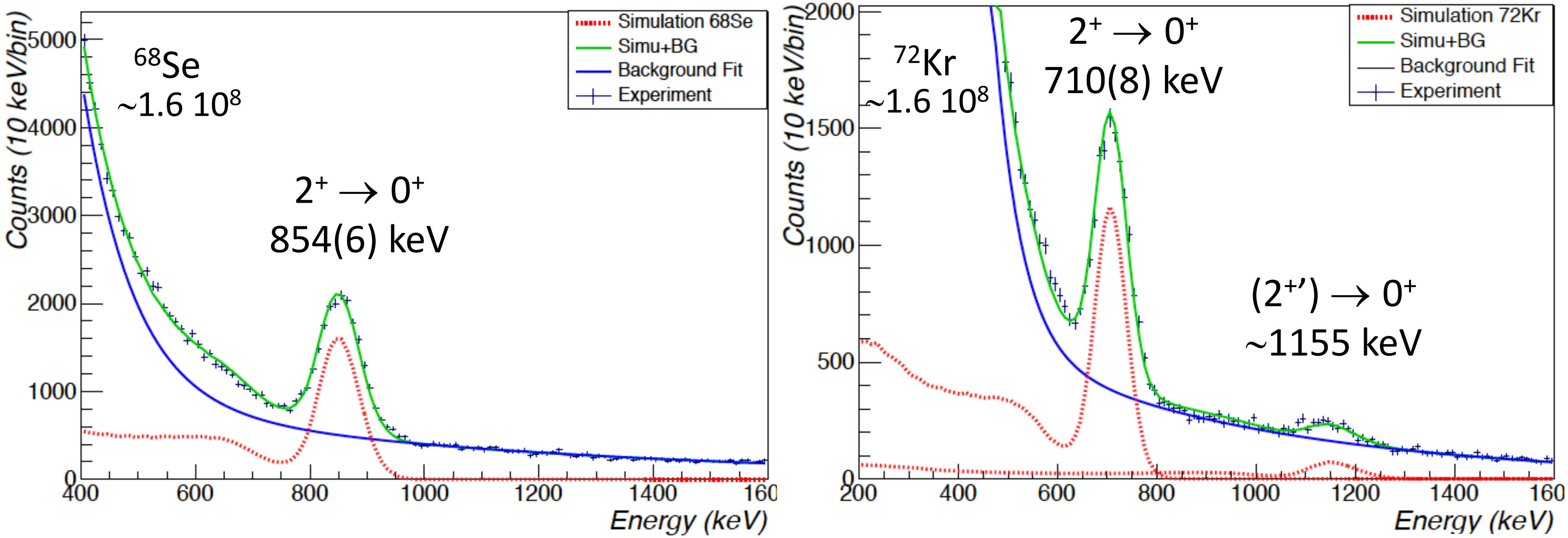








Electromagnetic excitation of ^{68}Se,^{72}Kr on Au target



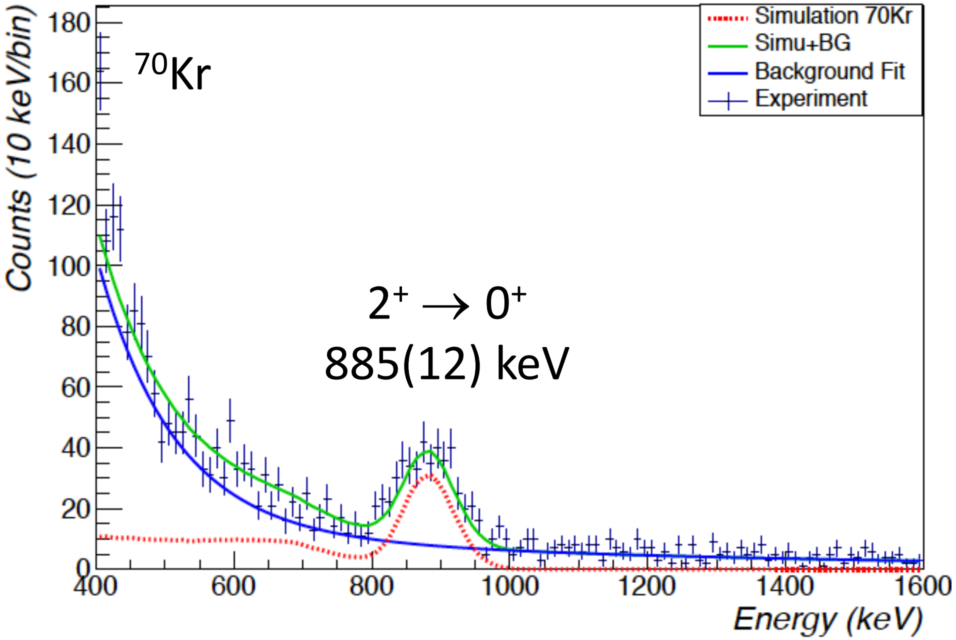
nucleus	$B(E2\uparrow)$ (e^2fm^4) prev.	$B(E2\uparrow)$ (e^2fm^4) this
^{68}Se	CoulEx 2158(290)	2550 (400)
	lifetime 1960(350)	
^{72}Kr	CoulEx 4997(647)	4910 (700)
	lifetime 4050(750)	

- **B(E2) values in ^{72}Kr (and ^{68}Se) similar to previous CoulEx experiment**

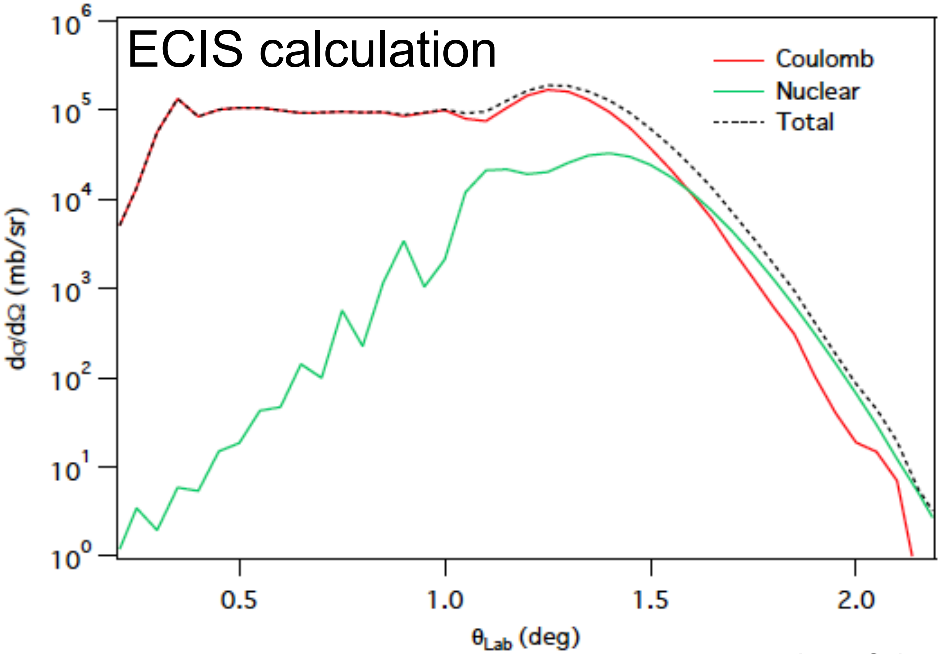
  corrections for nuclear excitation and feeding (still under investigation)

^{68}Se: A. Obertelli et al., Phys. Rev. C 80 (2009) 031304, A. J. Nichols et al., Phys. Lett. B 733 (2014) 52
^{72}Kr : A. Gade et al., Phys. Rev. Lett 95 (2005) 022502, H. Iwasaki et al., Phys. Rev. Lett 112 (2014) 142502

Electromagnetic excitation of ^{70}Kr on Au target

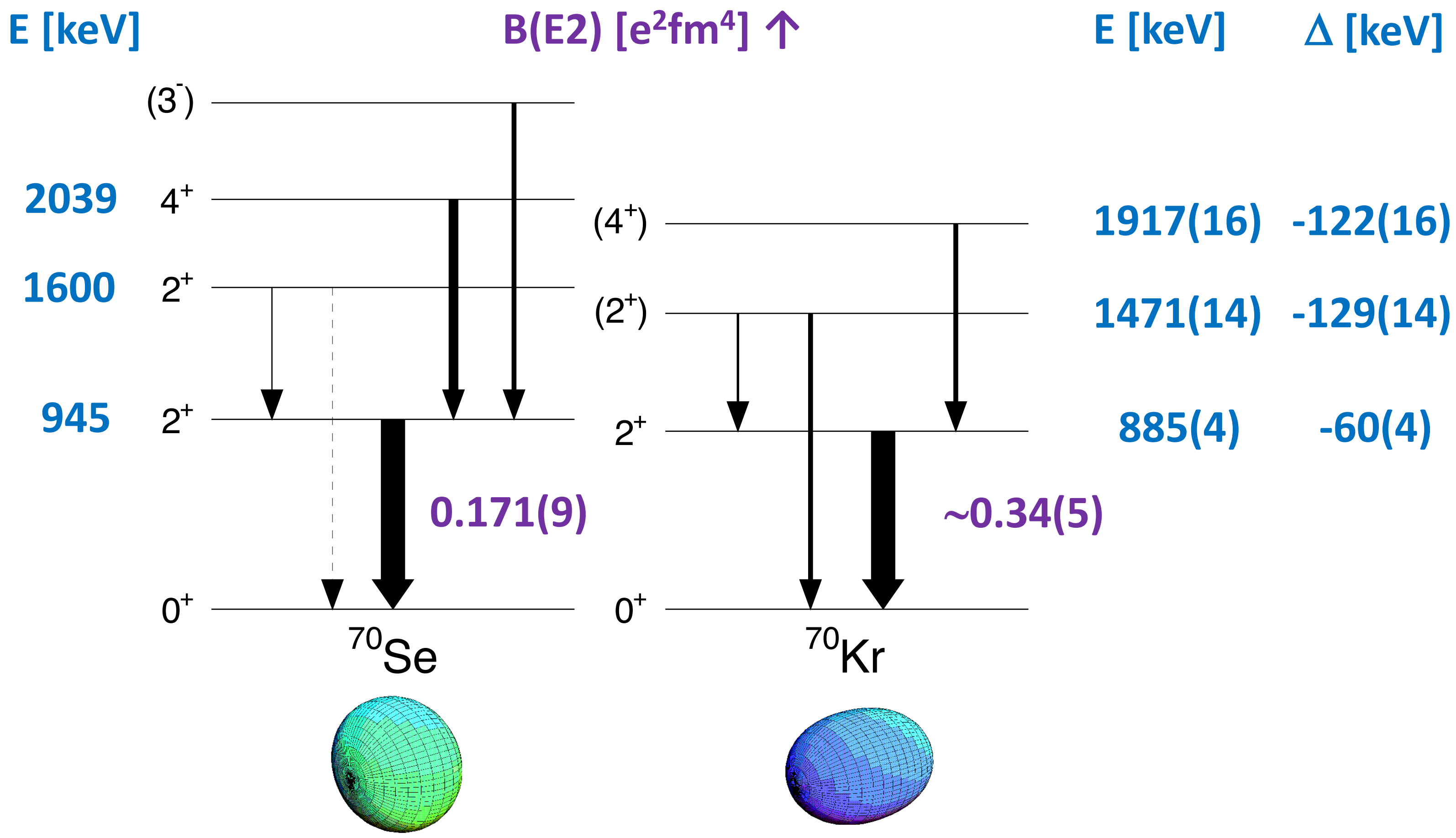


	^{70}Kr	^{68}Se	^{70}Br	^{72}Kr
Au target				
$\sigma_{2_1^+}$ [mb]	281(28)	231(3)	157(9)	339(5)
$\sigma_{2_2^+}$ [mb]		20(2)		41(3)
Be target				
$\sigma_{2_1^+}$ [mb]	18(3)	22(1)	17(1)	26.0(10)
$\sigma_{2_2^+}$ [mb]		4.4(4)		4.5(3)



- measurement of **absolute, integrated cross section** Au(^{70}Kr,^{70}Kr*)Au
- nuclear contributions taken from inelastic scattering on Be target
- preliminary result: **B(E2; $0^+ \rightarrow 2^+$) = 3400(500) e^2fm^4**
- feeding corrections from (observed) higher-lying states included
- final uncertainty, statistic and systematic, expected to be ~20 %

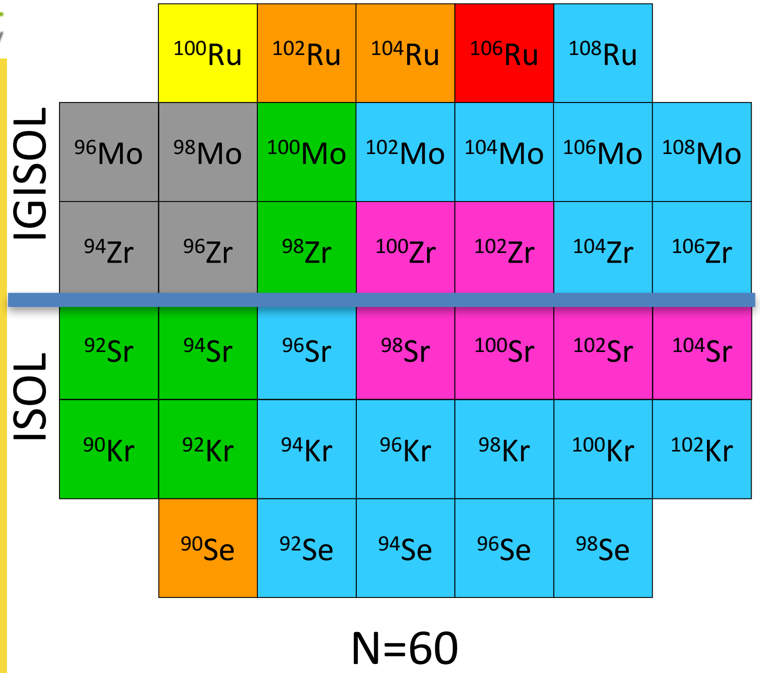
Collectivity of A=70 T=1 mirror nuclei

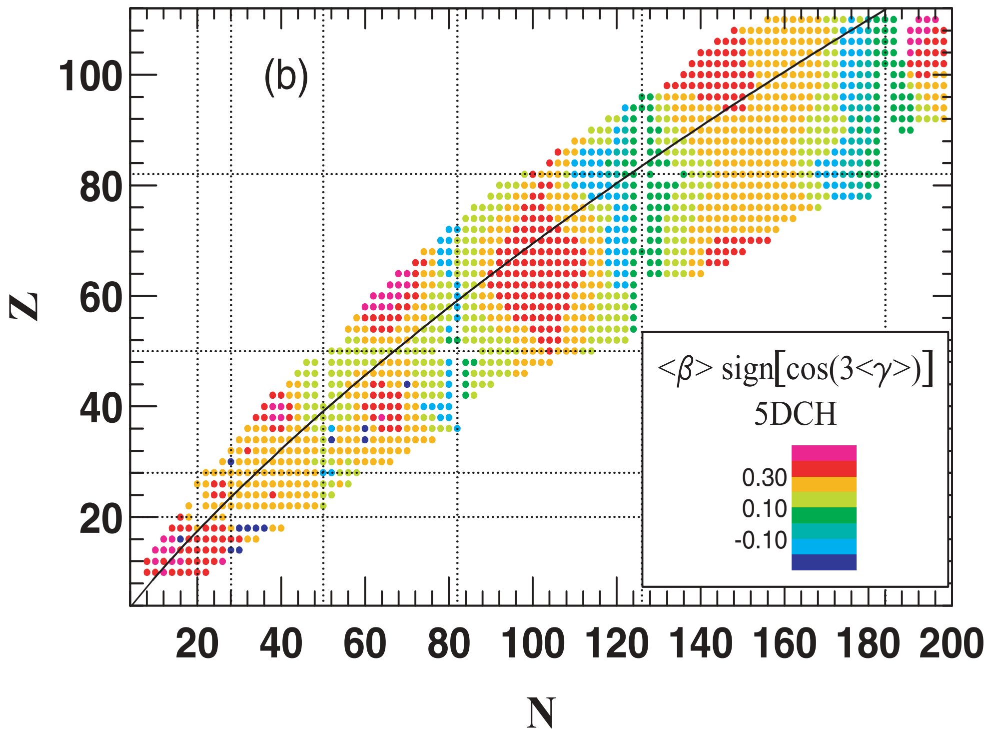


Lower E(2⁺,4⁺) and **higher B(E2)** in **^{70}Kr** than in mirror ^{70}Se

➔ may indicate shape change between A=70 T=1 mirror nuclei ?

Coulomb excitation of neutron-rich nuclei at A~100





HFB Gogny-D1S
M.Girod et al.,

Z<40 (Se, Kr, Sr) available at standard ISOL facilities:
Isolde/CERN, **ISAC2/Triumf**, SPIRAL2, SPES, …
Coulex of ^{96,98}Sr, ^{97,99}Rb, ^{96}Kr, …

40≦Z≦46 (Zr, Mo, Ru, Pd) are **refractory elements**
only available at IGISOL facilities: JYFL, **Caribu/ANL**
Coulex of ^{100}Zr, ^{106}Mo & ^{110}Ru

Coulomb excitation of neutron-rich nuclei at A~100

		^{100}Ru	^{102}Ru	^{104}Ru	^{106}Ru	^{108}Ru	
IGISOL	^{96}Mo	^{98}Mo	^{100}Mo	^{102}Mo	^{104}Mo	^{106}Mo	^{108}Mo
IGISOL	^{94}Zr	^{96}Zr	^{98}Zr	^{100}Zr	^{102}Zr	^{104}Zr	^{106}Zr
ISOL	^{92}Sr	^{94}Sr	^{96}Sr	^{98}Sr	^{100}Sr	^{102}Sr	^{104}Sr
ISOL	^{90}Kr	^{92}Kr	^{94}Kr	^{96}Kr	^{98}Kr	^{100}Kr	^{102}Kr
		^{90}Se	^{92}Se	^{94}Se	^{96}Se	^{98}Se	

N=60

Z<40 (Se, Kr, Sr) available at standard ISOL facilities:
Isolde/CERN, **ISAC2/Triumf**, SPIRAL2, SPES, …
Coulex of ^{96,98}Sr, ^{97,99}Rb, ^{96}Kr, …

40≦Z≦46 (Zr, Mo, Ru, Pd) are **refractory elements**
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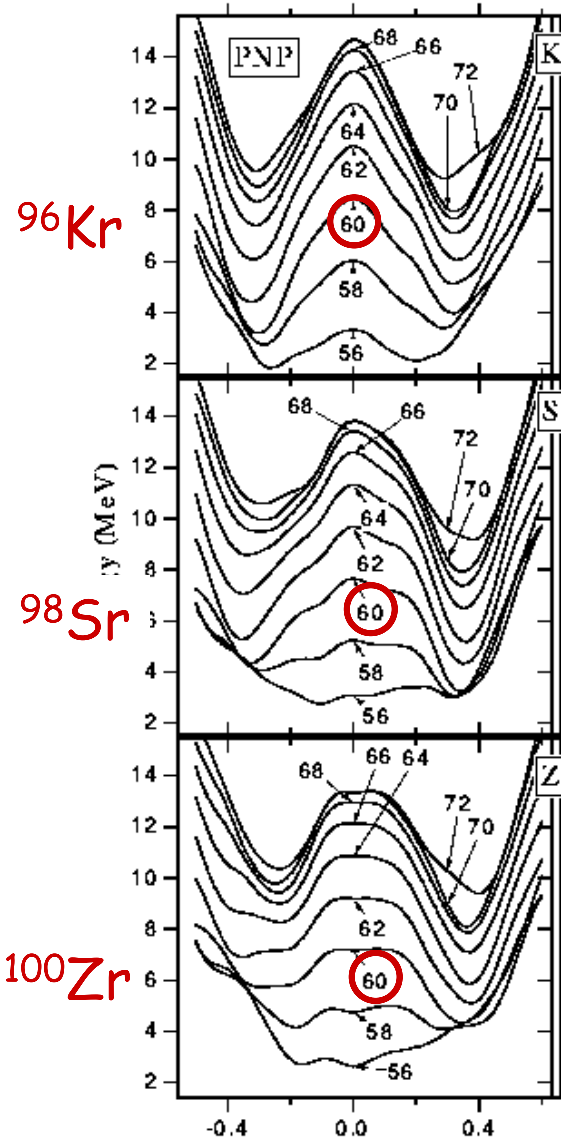
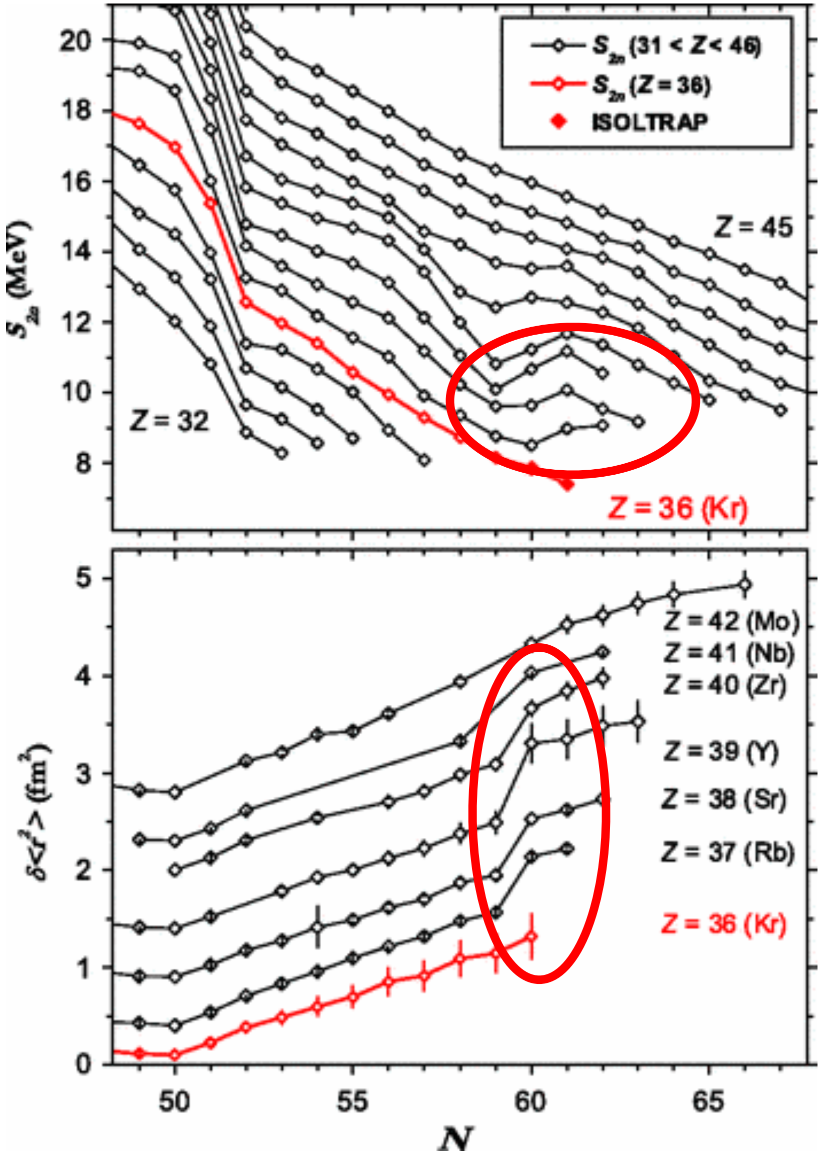


J. Skalski et al.,
NPA 617, 282 (1997)

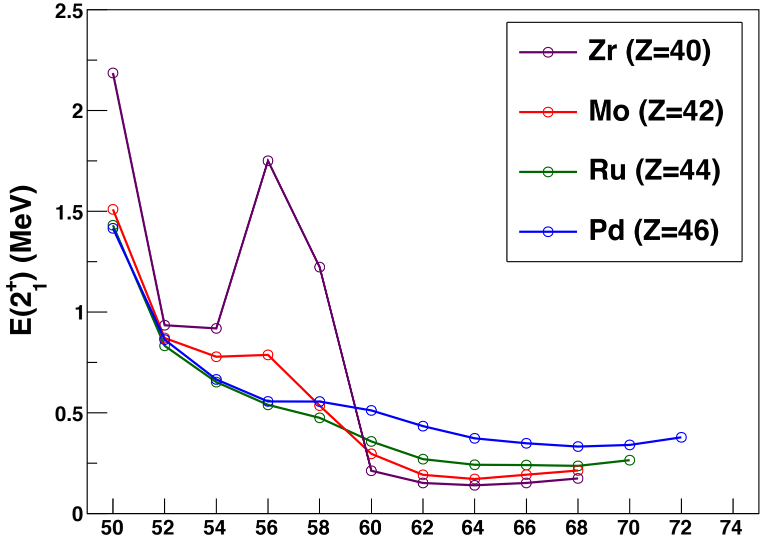
Evidence for sudden shape changes at N=60

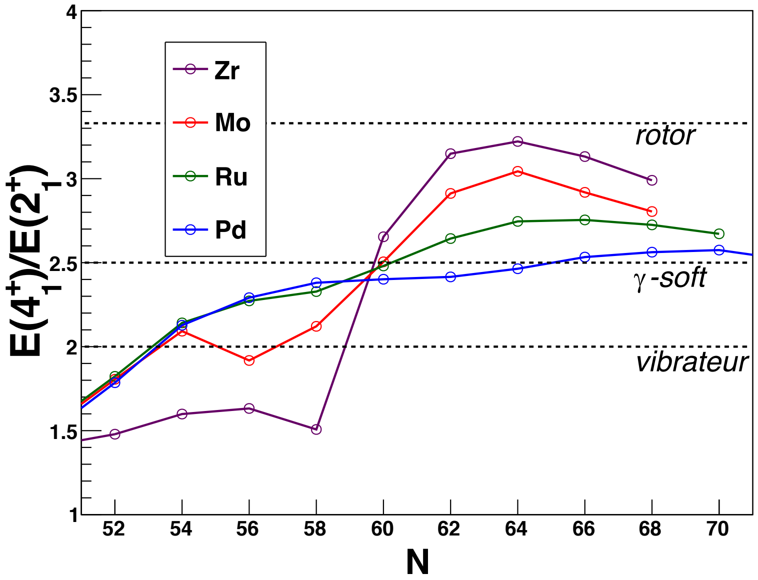
Two-neutron separation energies and mean square radii



S. Naimi et al., PRL 105 (2010) 032502

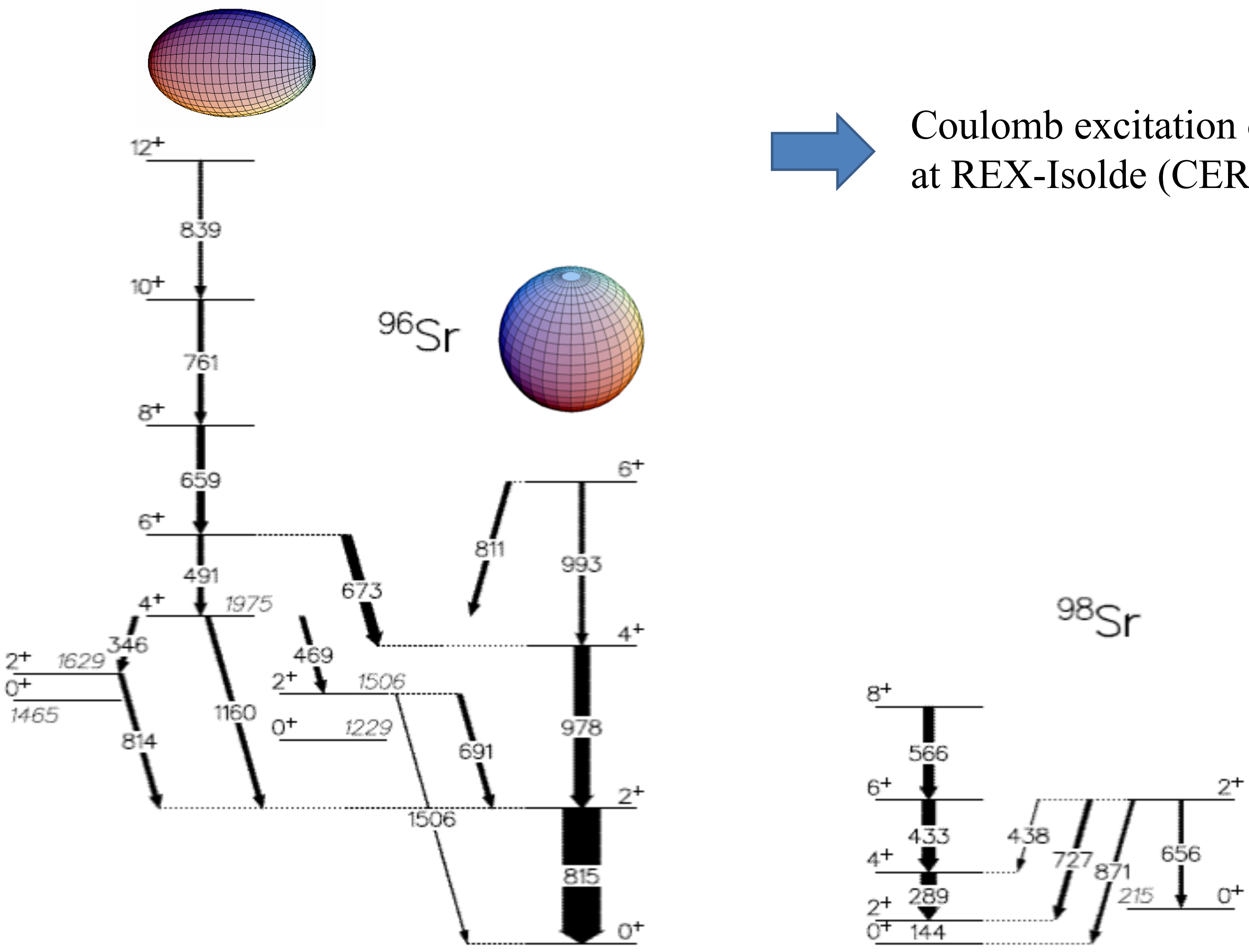
Excitation energies of first 2^+ and 4^+ states





Shape evolution in $_{38}$Sr isotopes at N=60

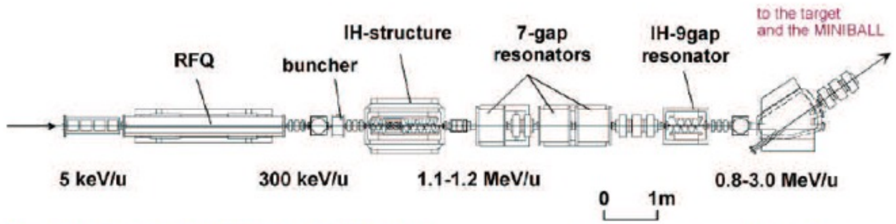
Shape transition at N=60 well established from prompt spectroscopy using fission fragments
Investigation of the nuclear shapes through **electromagnetic probes** :
B(E2) values to probe the **collectivity** and the **mixing** of different configurations
Q_0 to determine the **quadrupole deformation**

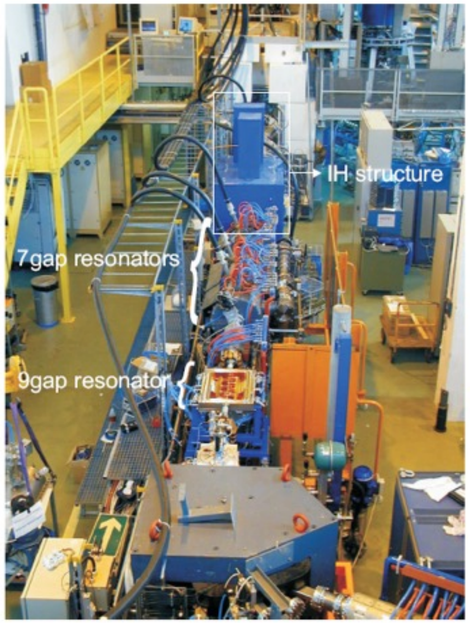


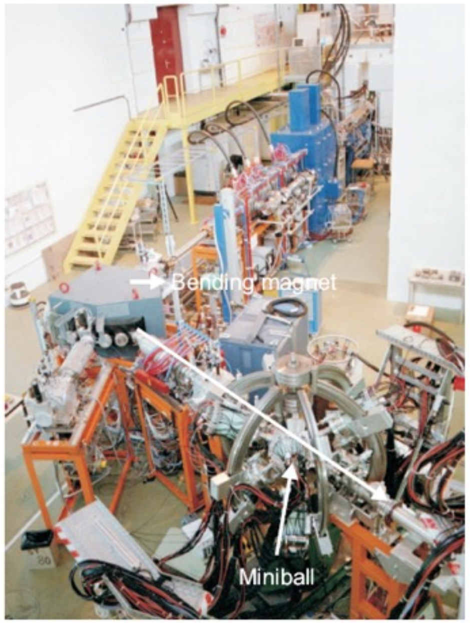
N=58 N=60

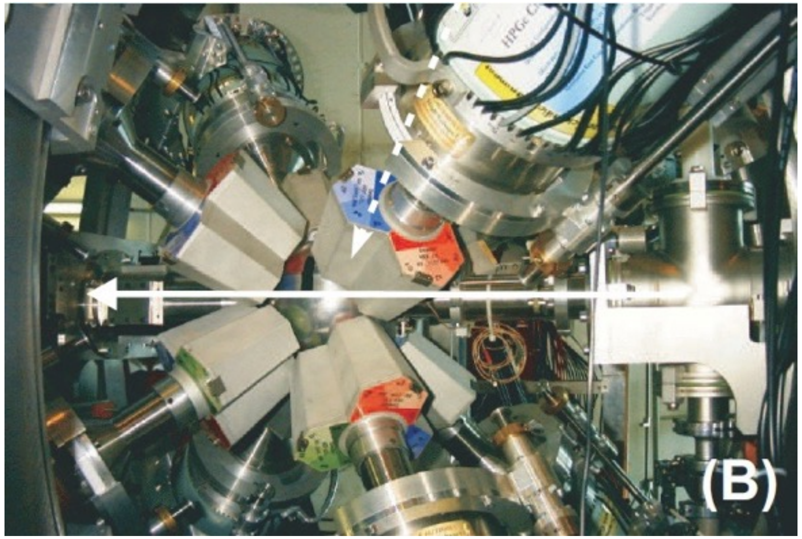
Coulomb excitation of ^{96,98}Sr at REX-Isolde (CERN)

Coulomb excitation set-up at REX-ISOLDE





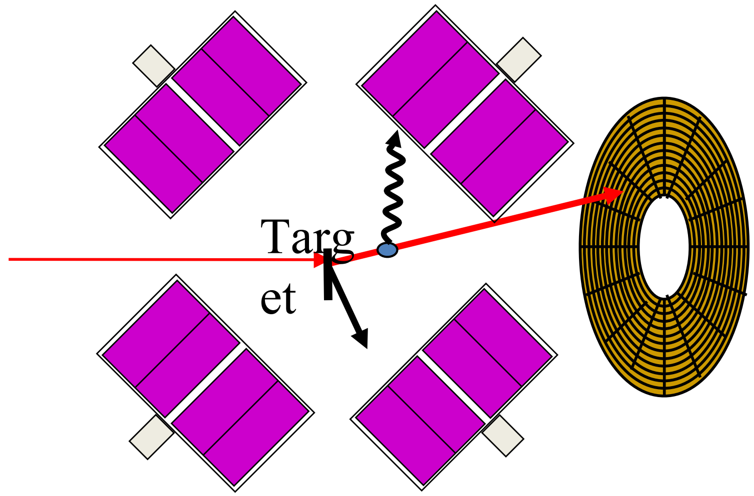




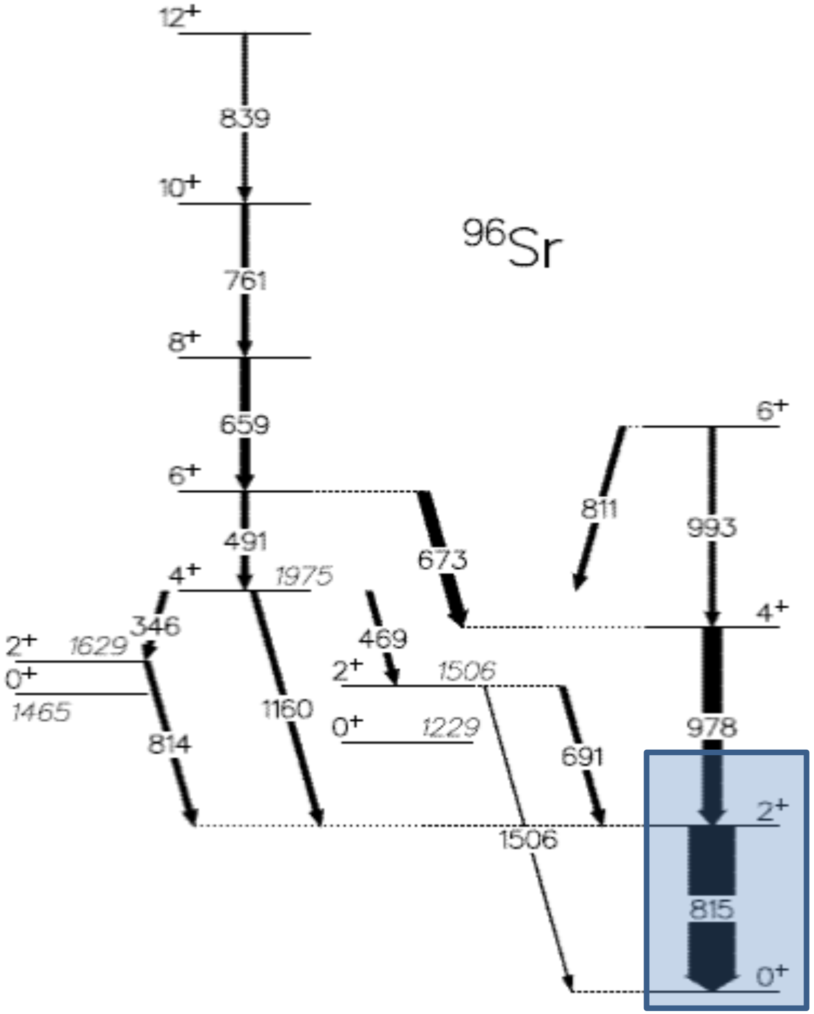
8 MINIBALL Ge cluster detectors (~7% efficiency)

DSSSD for particle detection (proj. & recoil)

Doppler correction and differential cross section



Coulomb excitation on “spherical” ^{96}Sr

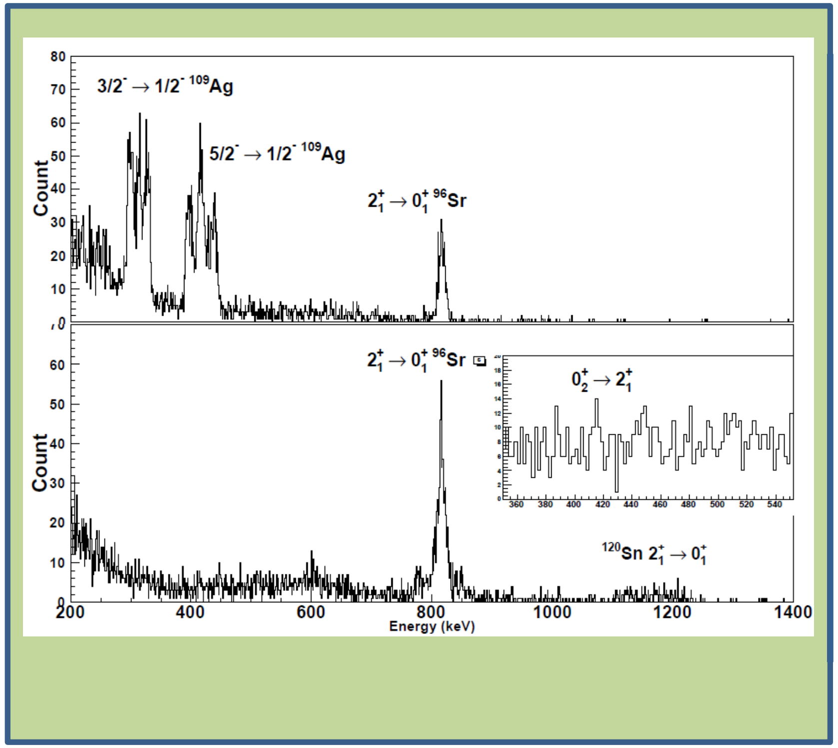


Coulomb excitation of ^{96}Sr at Rex-Isolde

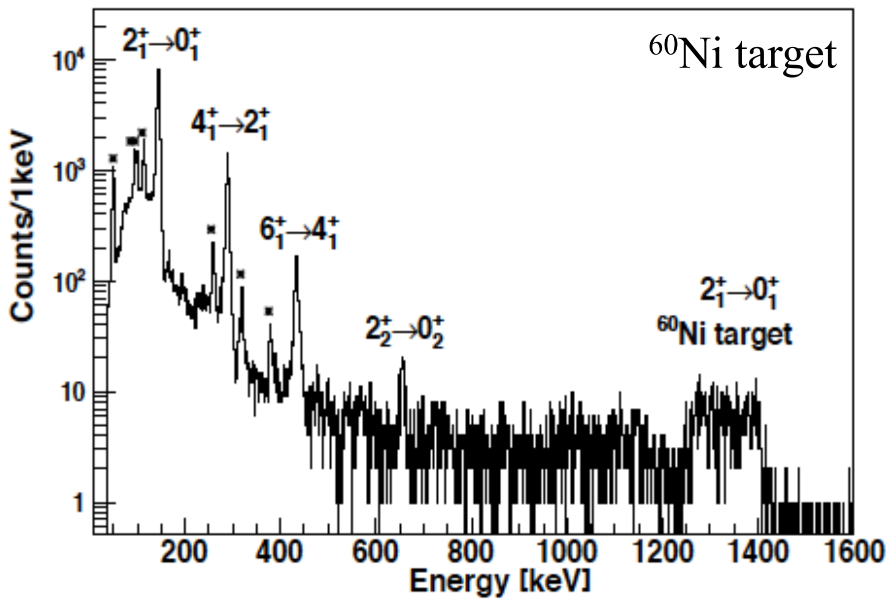
≈**10^4 pps**, (**>80%** after awaiting Rb decay)

2.82 MeV/u on ^{109}Ag and ^{120}Sn targets

→ mainly 1st excited 2^+ state populated



Coulomb excitation on "deformed" ^{98}Sr

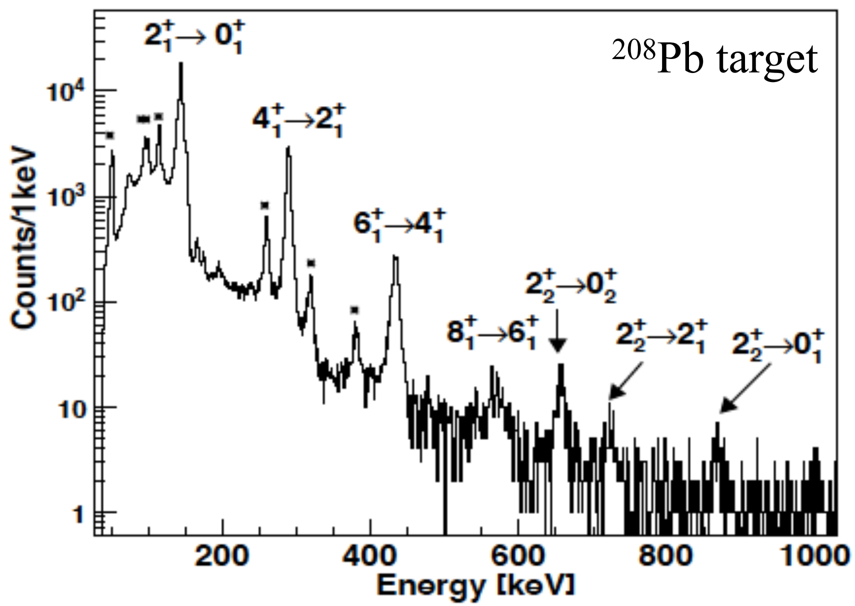


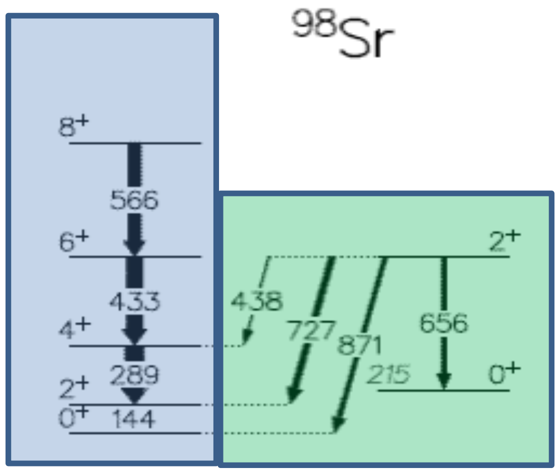
Coulomb excitation of ^{98}Sr at Rex-Isolde

6.10^4 pps, (**>80%** awaiting Rb decay in REX-trap)

2.82 MeV/u on ^{208}Pb and ^{60}Ni targets

→ gs band (8^+) and **second 2^+ state** populated



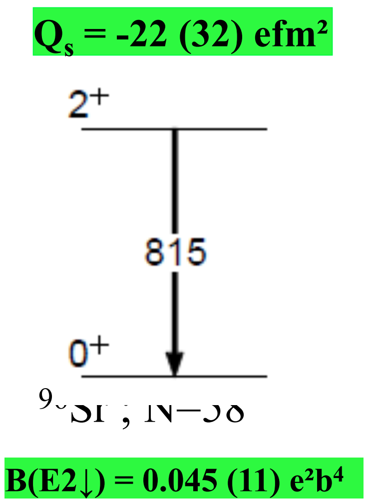


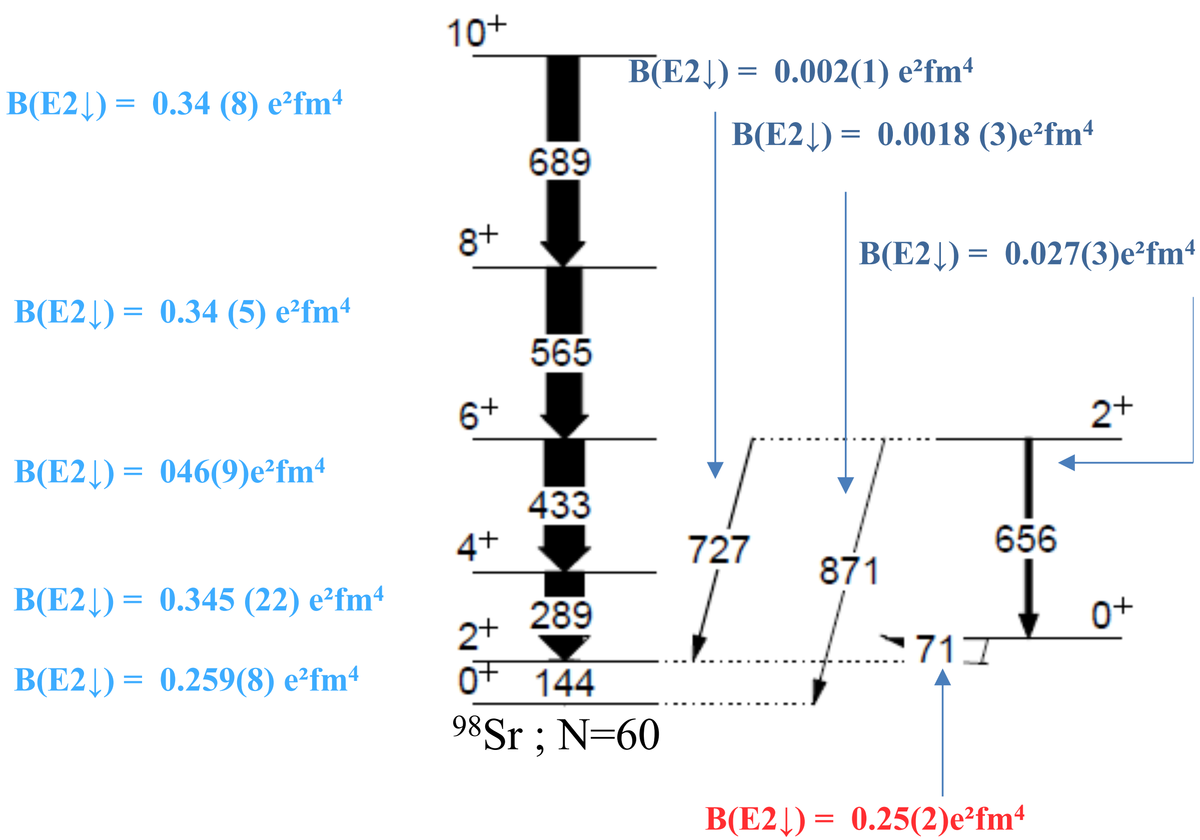
E. Clement, M. Zielinska et al,
Phys. Rev. Lett. 116, 022701 (2016)

Coulomb excitation results on Sr isotopes at N=60

^{96}Sr
Spectroscopic quadr. moment $Q_0 \sim 0$
despite a quite sizeable B(E2) value
→ No static quadrupole deformation
→ Purely vibrational character

^{98}Sr
→ The ground state band behaves like a perfect rotor
→ The excited configuration is similar to ^{96}Sr
→ **The B(E2; 0_2 → 2_1) indicates strong mixing**

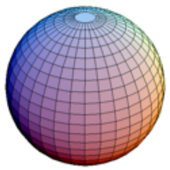




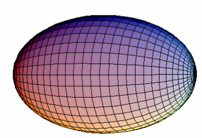
Coulomb excitation results on Sr isotopes at N=60

^{96}Sr
Spectroscopic quadr. moment $Q_0 \sim 0$
albeit the B(E2) is quite sizeable
- → Purely vibrational character (dynamic E2)
- → No static quadrupole deformation

^{98}Sr
- → The ground state band behaves like a perfect rotor
- → The excited configuration is similar to ^{96}Sr
- → The B(E2; $0_2 \rightarrow 2_1$) indicates strong mixing
- → **The quadrupole moments confirm shape coexistence**



$|\beta| < 0.1$

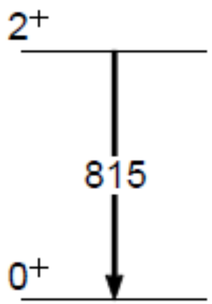


$\beta \sim 0.4$

$|\beta| < 0.1$

$|Q_s| < 15$ efm²

Q_s = -22 (32) efm²



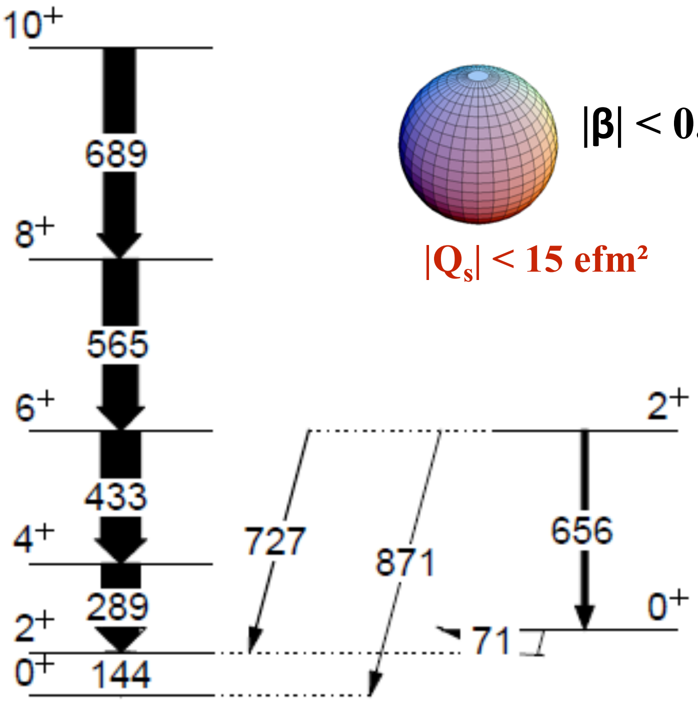
^{96}Sr ; N=58

B(E2↓) = 0.045 (11) e²b⁴

Q_s = -121(39) efm²

Q_s = -187 (25) efm²

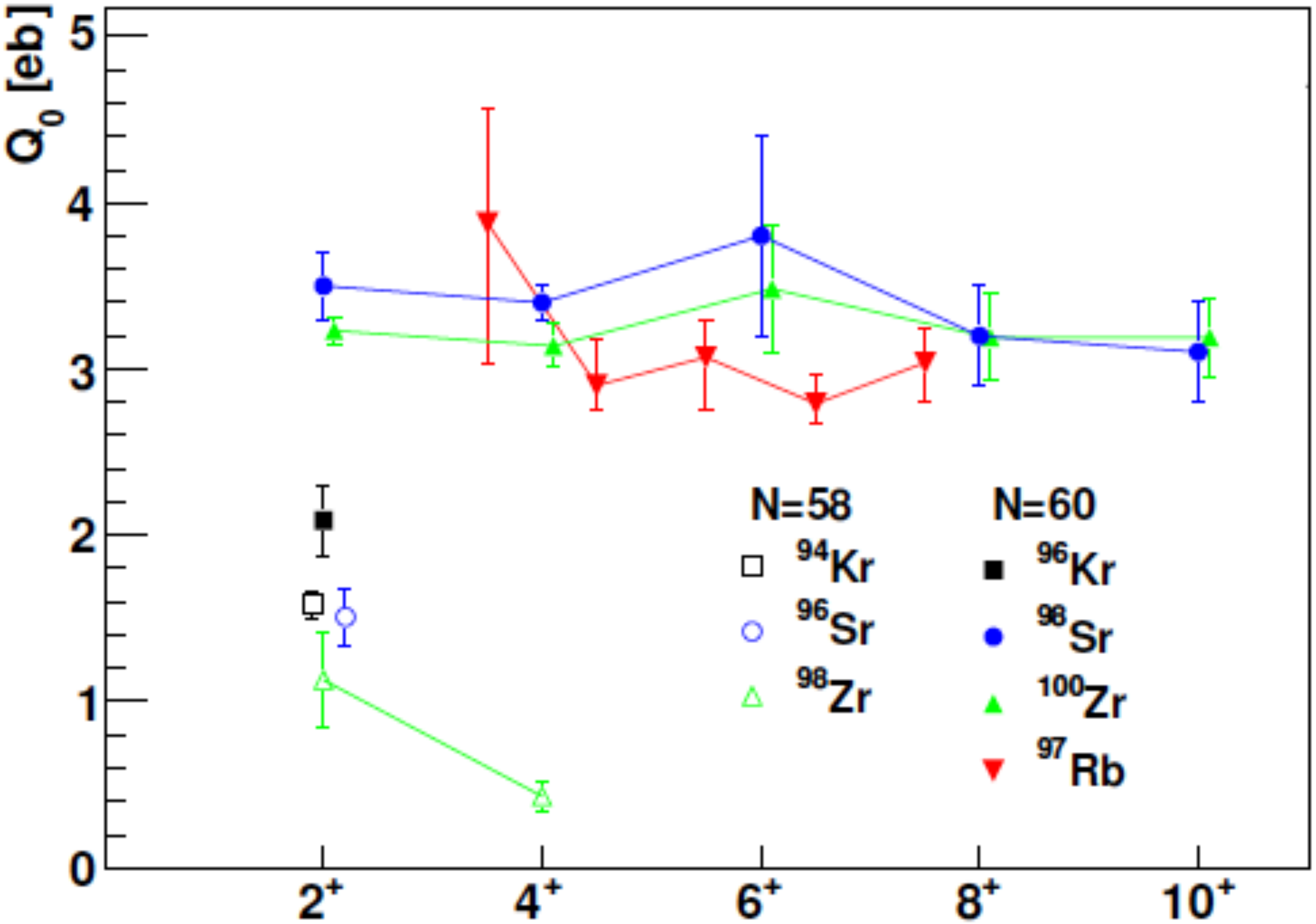
Q_s = -52 (24) efm²



^{98}Sr ; N=60

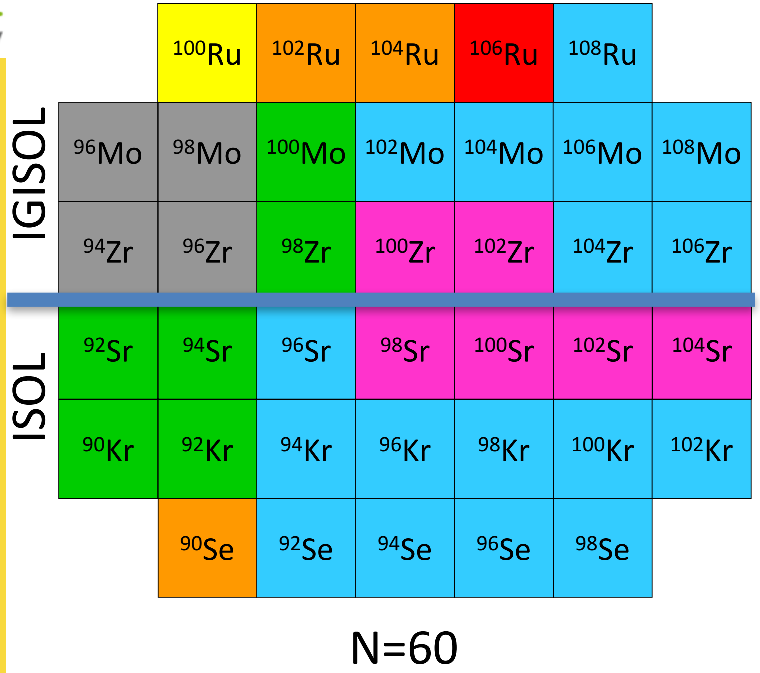
E. Clement, M. Zielinska et al,
Phys. Rev. Lett 116, 022701 (2016)

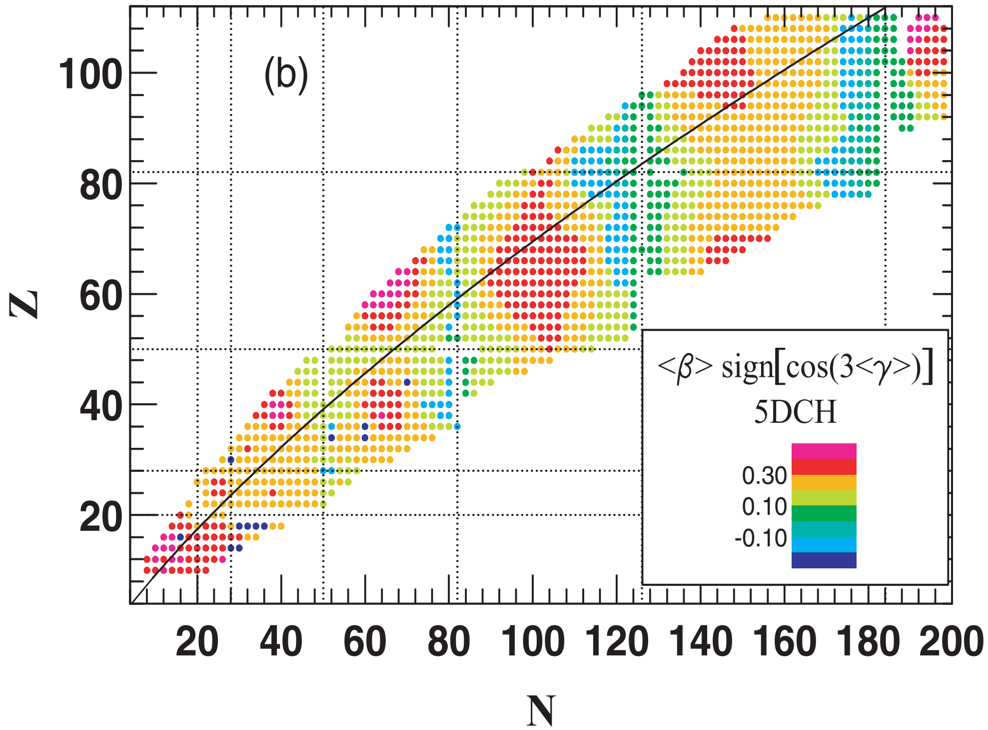
Quadrupole moments from Coulomb excitation



adapted from E. Clement et al. Phys. Rev. C **94**, 054326

Coulomb excitation of neutron-rich nuclei at A~100





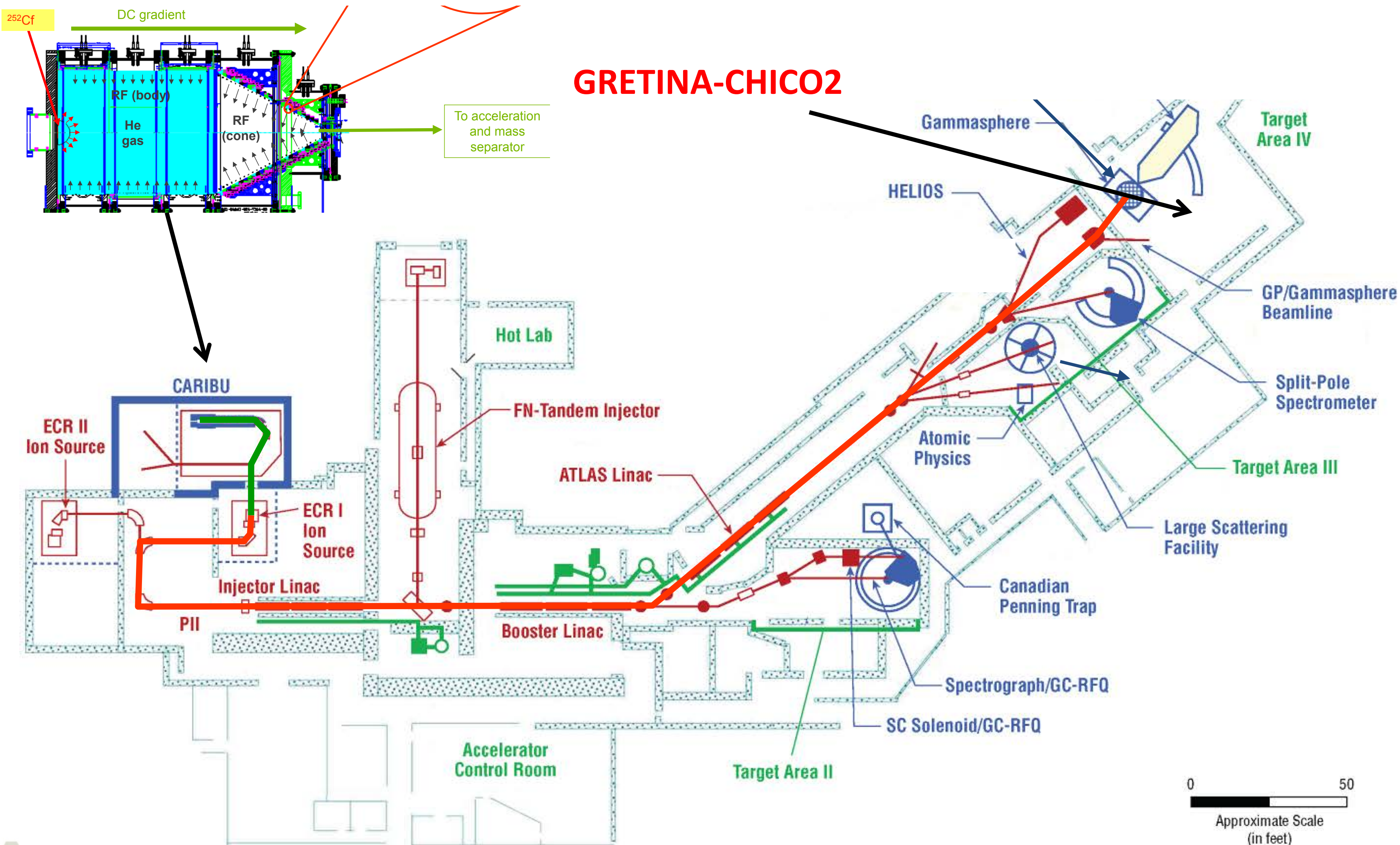
Z<40 (Se, Kr, Sr) available at standard ISOL facilities:
Isolde/CERN, **ISAC2/Triumf**, SPIRAL2, SPES, …
Coulex of ^{96,98}Sr, ^{97,99}Rb, ^{96}Kr, …

HFB Gogny-D1S
M.Girod et al.,

40≦Z≦46 (Zr, Mo, Ru, Pd) are **refractory elements**
only available at IGISOL facilities: JYFL, **Caribu/ANL**
Coulex of ^{100}Zr, ^{106}Mo & ^{110}Ru

ATLAS/CARIBU facility at ANL

CAlifornium **R**are **I**sotope **B**reeder **U**pgrade



^{100}Zr at **3.84 MeV/u (10/2014), ^{110}Ru** at **3.91 MeV/u (11/2014), ^{106}Mo** at **3.91 MeV/u (04/2015)**

Coulomb excitation set-up at CARIBU

γ-ray spectroscopy

GRETINA

Particle detection
- **angles**
- **ToF**

CHICO2

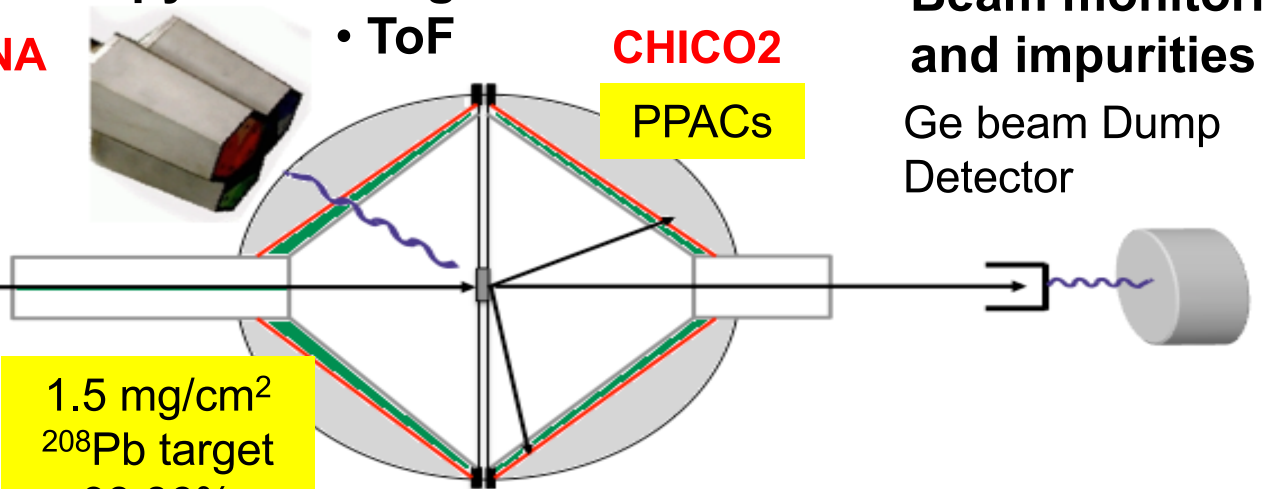
PPACs

Beam monitoring and impurities

Ge beam Dump Detector

CARIBU beams from ATLAS

1.5 mg/cm^2 ^{208}Pb target 98.86% purity



Coulomb excitation of ^{110}Ru

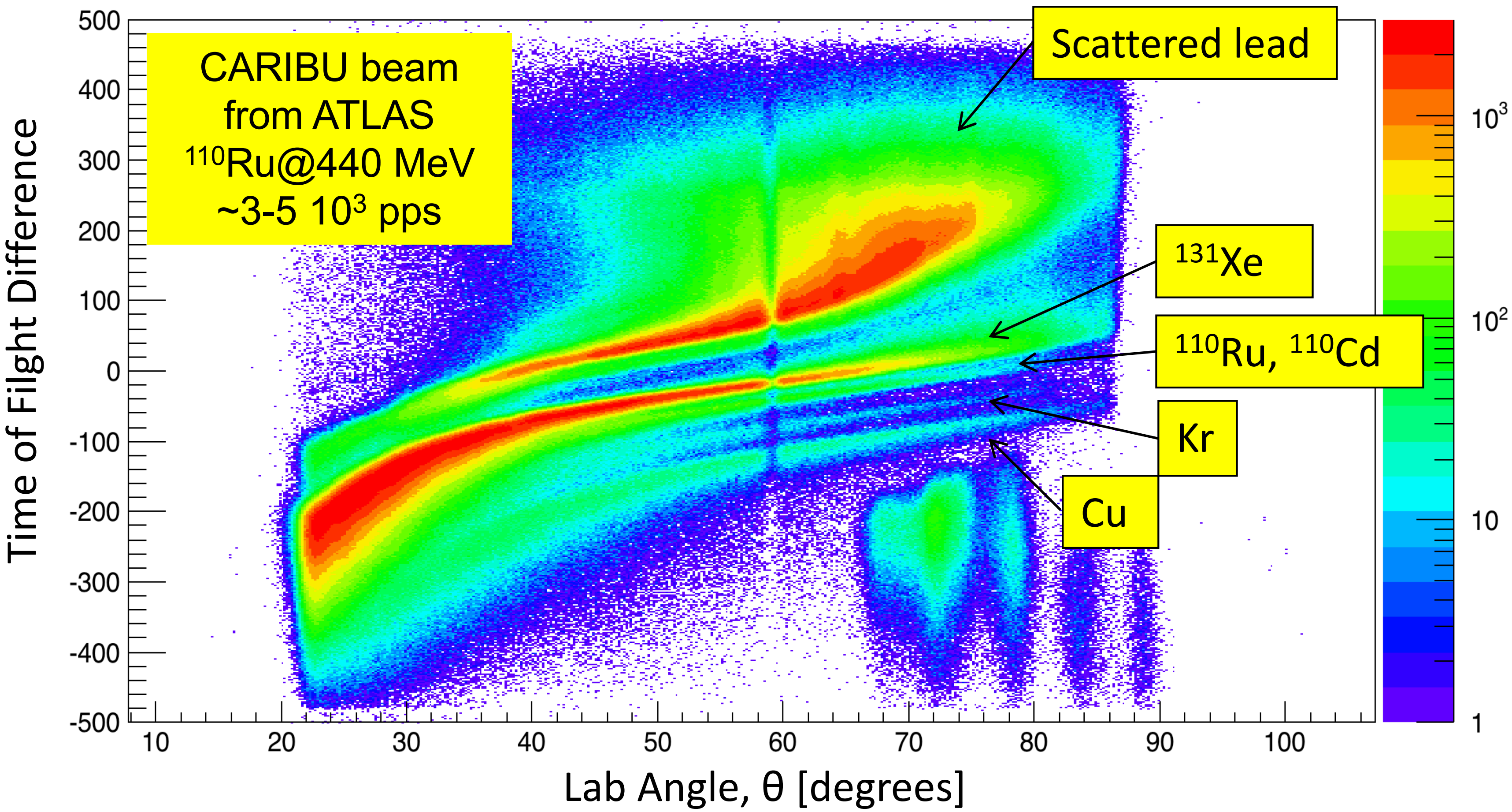
Particle detection with Chico2

- **Scattering angle**

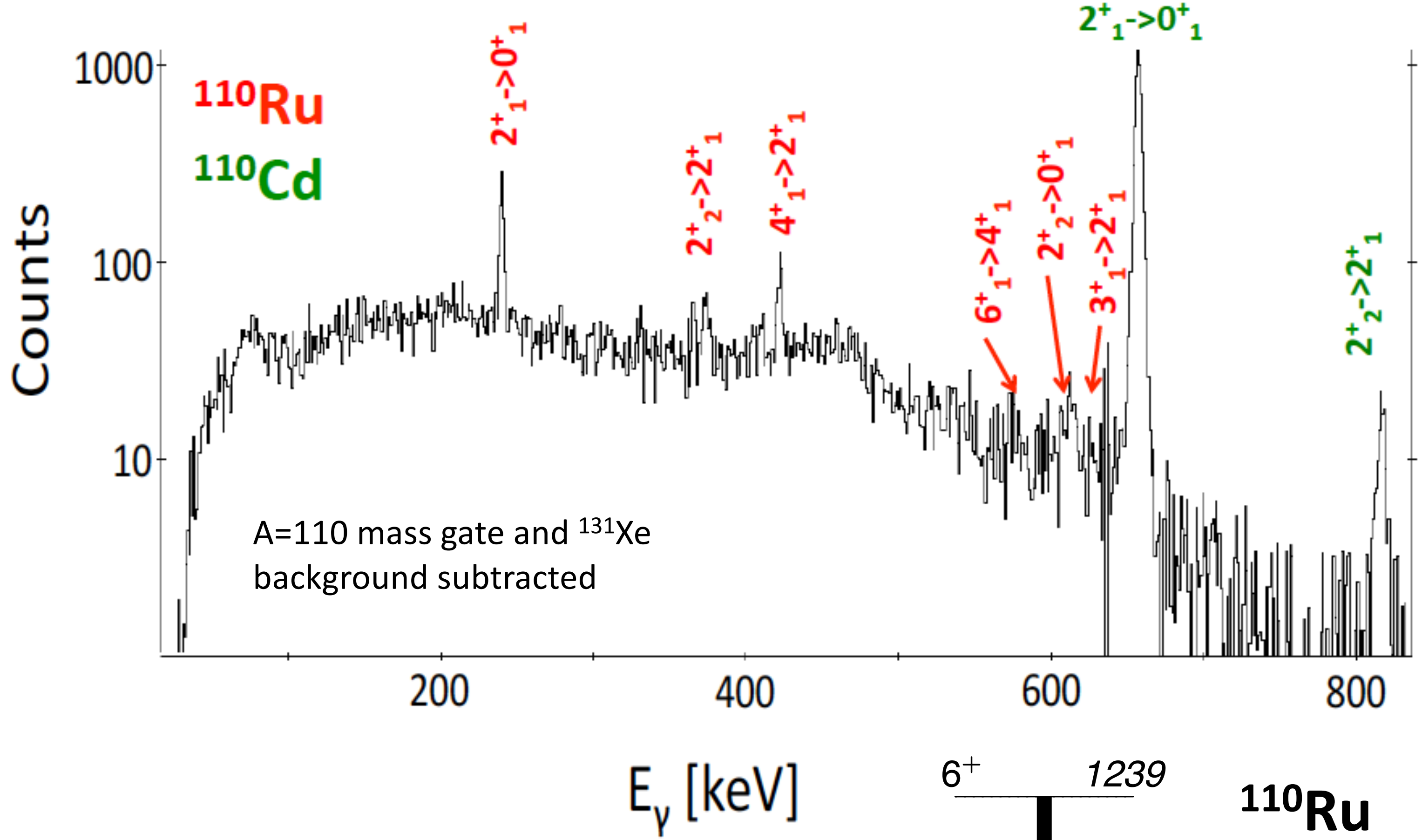
→ **important for Doppler correction (together with GRETINA position determ.)**

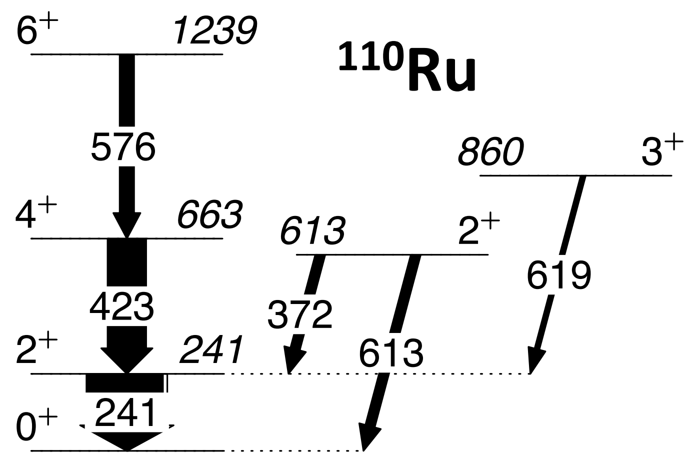
- **Time of Flight (for kinematical coincidences)**

→ **extremely important for mass identification (ΔA/A~10%)**



Coulomb excitation of 110Ru at CARIBU

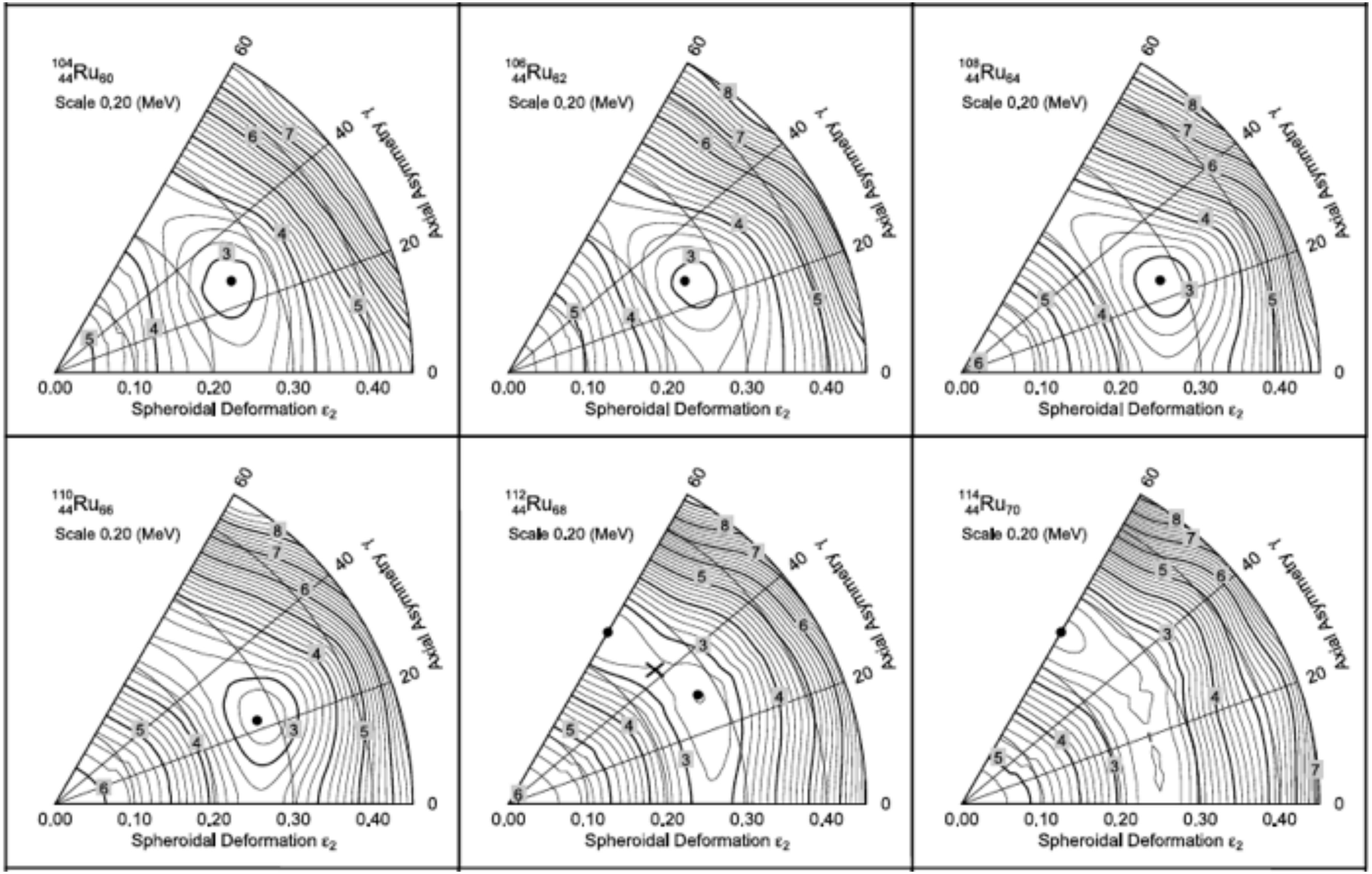




Partial 110Ru level scheme, showing only transitions as observed in the present work
D. Doherty et al., Phys. Lett. B 766, 334 (2017)

Shape evolution in neutron-rich Ru isotopes

Potential energy surfaces for $_{44}$Ru isotopes from FRLDM model

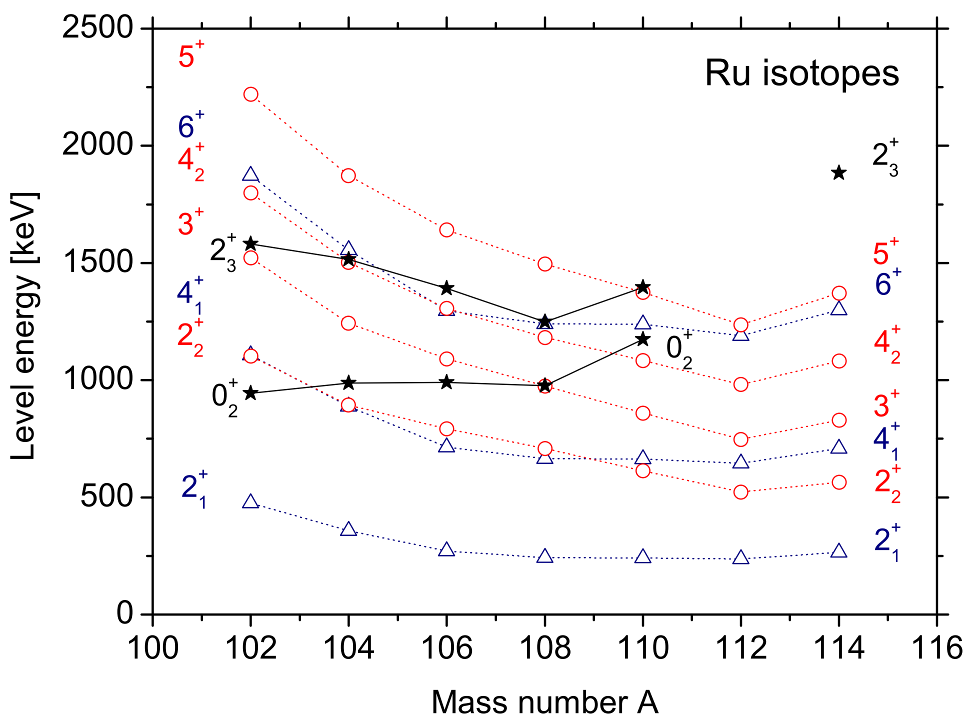


P. Moeller et al., At. Data Nucl. Data Tabl. 94 (2008)

Evidence for Triaxiality in ^{110}Ru

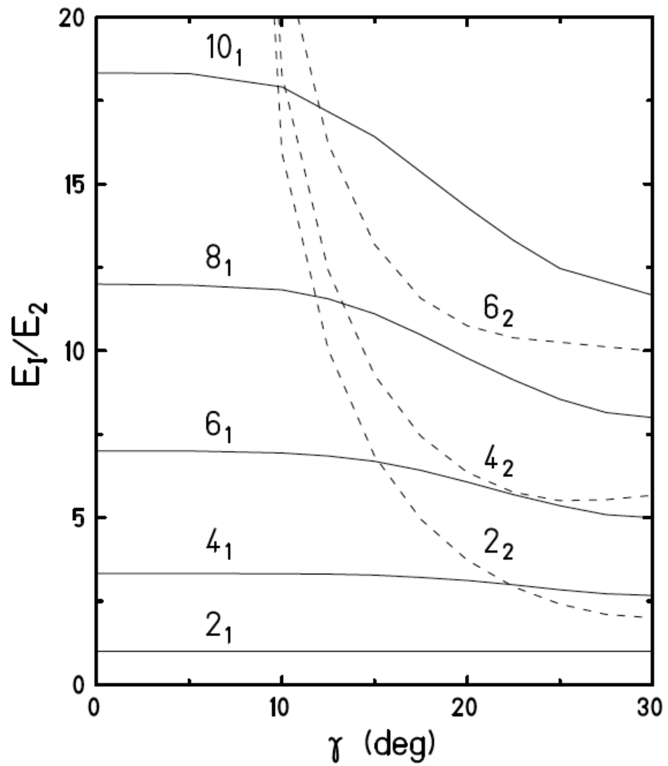
Empirical conditions for triaxiality on **excitation energies** satisfied in neutron-rich Ru isotopes

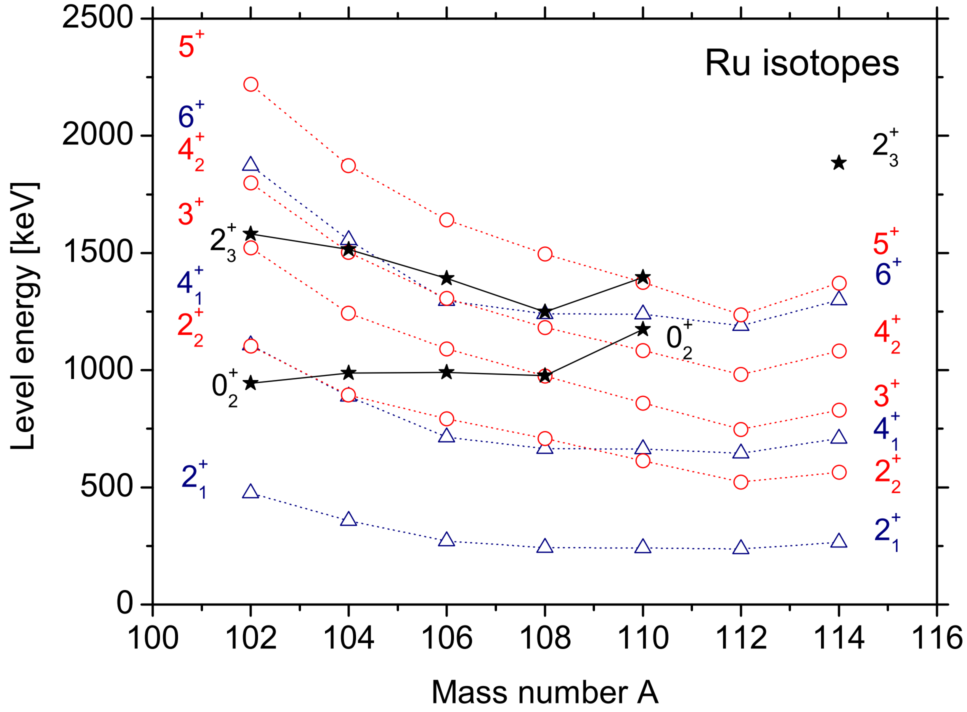
- Systematics of 2^+_1 energies: **$E(2^+)$** approximately constant between ^{108}Ru and ^{114}Ru (around mid shell)
- Energy ratio, **R_{42}** never reaches rigid rotational limit, in contrast to Sr and Zr isotopes.
- Energy of **$E(2^+_2)$** falls below **$E(4^+_1)$** strong indication for triaxiality according to **Triaxial Rotor Model**



Evidence for Triaxiality in ^{110}Ru ?

Empirical conditions for triaxiality on **excitation energies** satisfied in neutron-rich Ru isotopes





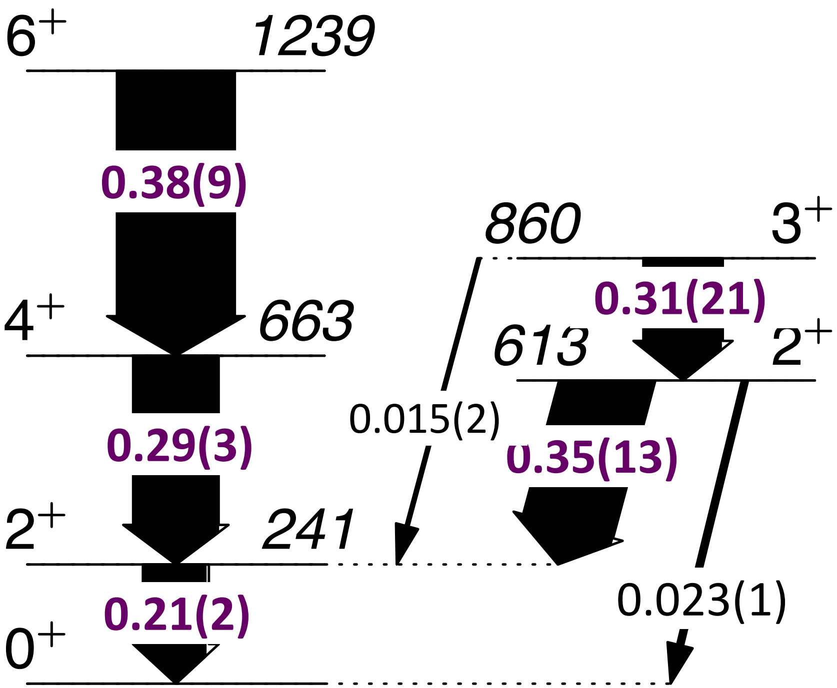
From ^{110}Ru energies γ ~ 20

- **What about B(E2) values and quadrupole moments ?**

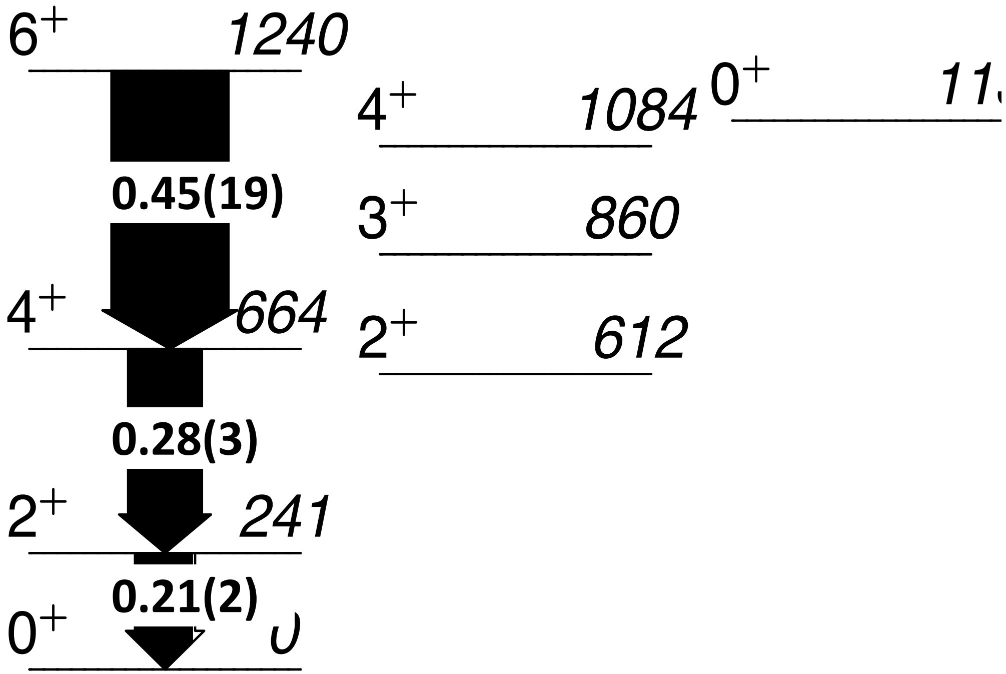
Coulomb excitation results on ^{110}Ru

Coulomb excitation

All B(E2) values in e^2b^2



Energies & lifetimes from NNDC



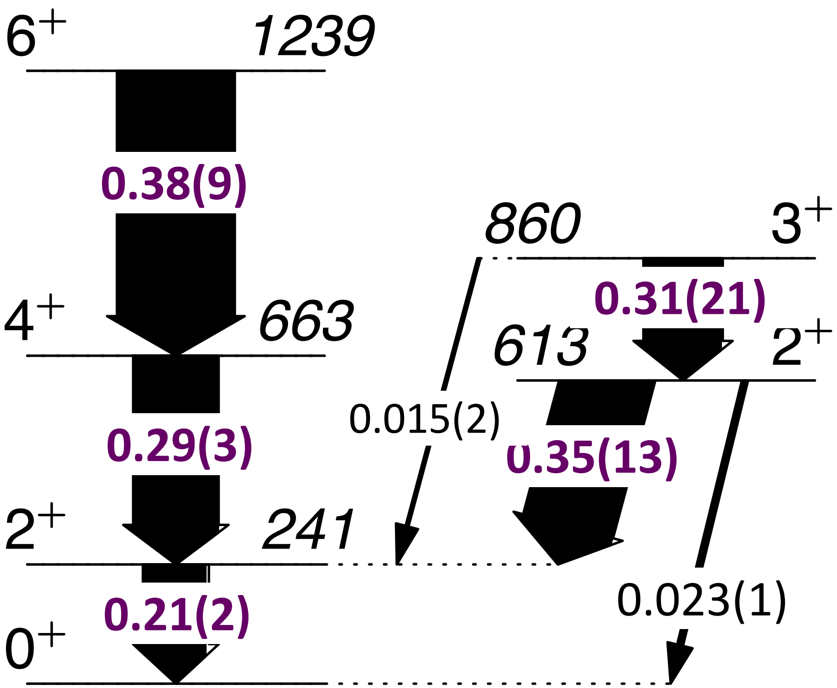
Lifetimes and branching rations used as constraints for GOSIA calc. Normalisation to known data from ^{110}Cd

All excitation energies given in keV
All B(E2) values in e^2b^2

Coulomb excitation results on ^{110}Ru

Coulomb excitation

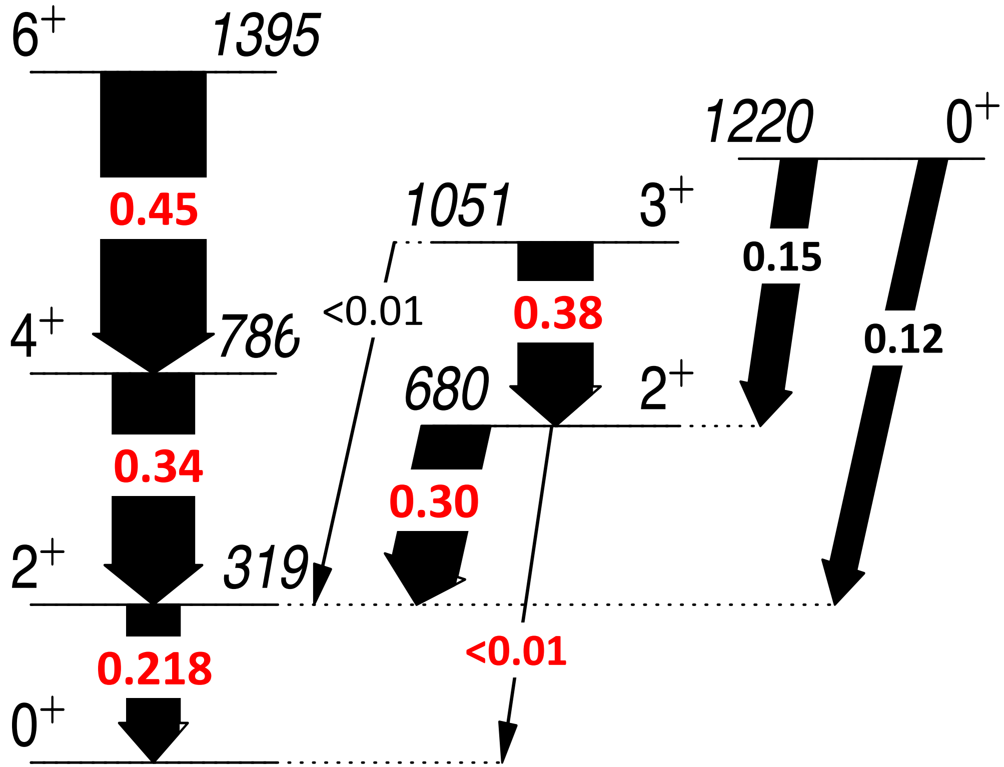
All B(E2) values in e^2b^2



$Q(2^+)=-83\pm39$ e fm^2

Lifetimes and branching rations used as constraints for GOSIA calc. Normalisation to known data from ^{110}Cd

HFB-GCM(GOA) theory with Gogny D1S Force



$Q(2^+)=-35$ efm^2

All excitation energies given in keV

All B(E2) values in e^2b^2

Evidence for Triaxiality in ^{110}Ru

γ	$b(E2;2_1 \to 0_1)$	$b(E2;2_2 \to 0_1)$	$b(E2;2_2 \to 2_1)$	$\frac{b(E2;2_2 \to 2_1)}{b(E2;2_2 \to 0_1)}$
0^0	1.000	0.	0.	1.43
5^0	0.993	0.0074	0.011	1.49
10^0	0.972	0.028	0.051	1.70
15^0	0.947	0.053	0.143	2.70
20^0	0.933	0.067	0.357	5.35
25^0	0.955	0.0425	0.865	20.6
30^0	1.000	0.	1.43	∞

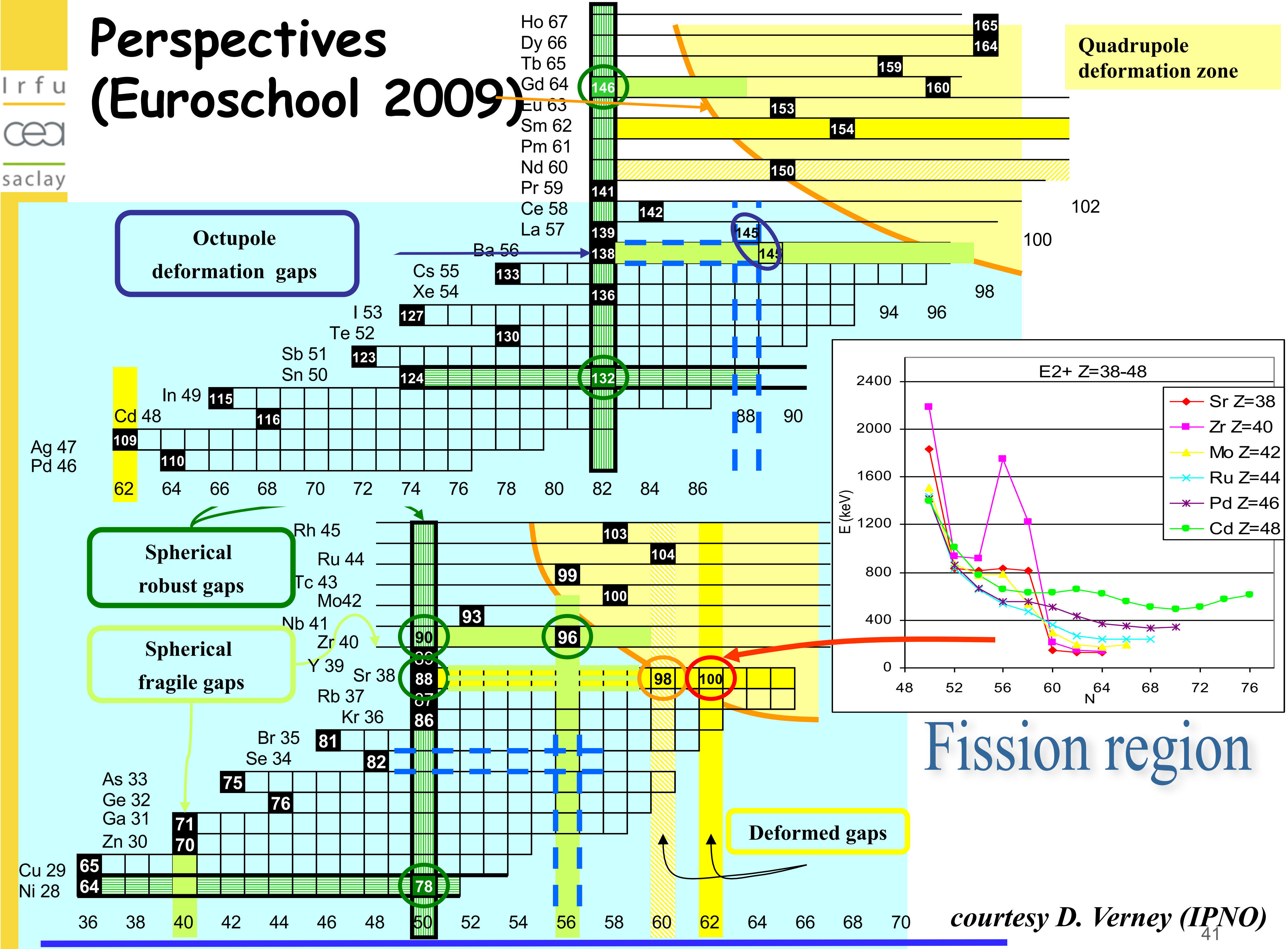
Table 2: Reduced transition probabilities for several values of γ.

Lifetimes from fast timing: $\tau(2_1^+) = 0.32(2)\ ns$ Coulex: $\tau(2_2^+) = 16(7)\ ps$

$$\frac{B(E2;2_2^+ \to 2_1^+)}{B(E2;2_2^+ \to 0^+)} = 15.5 \quad \frac{B(E2;2_2^+ \to 0^+)}{B(E2;2_1^+ \to 0^+)} \approx 0.07(2) \quad \frac{B(E2;2_2^+ \to 2_1^+)}{B(E2;2_1^+ \to 0^+)} \approx 1.55(58)$$

→ All B(E2) values in accordance with $\gamma \sim 25^\circ$

Perspectives (Euroschool 2009)

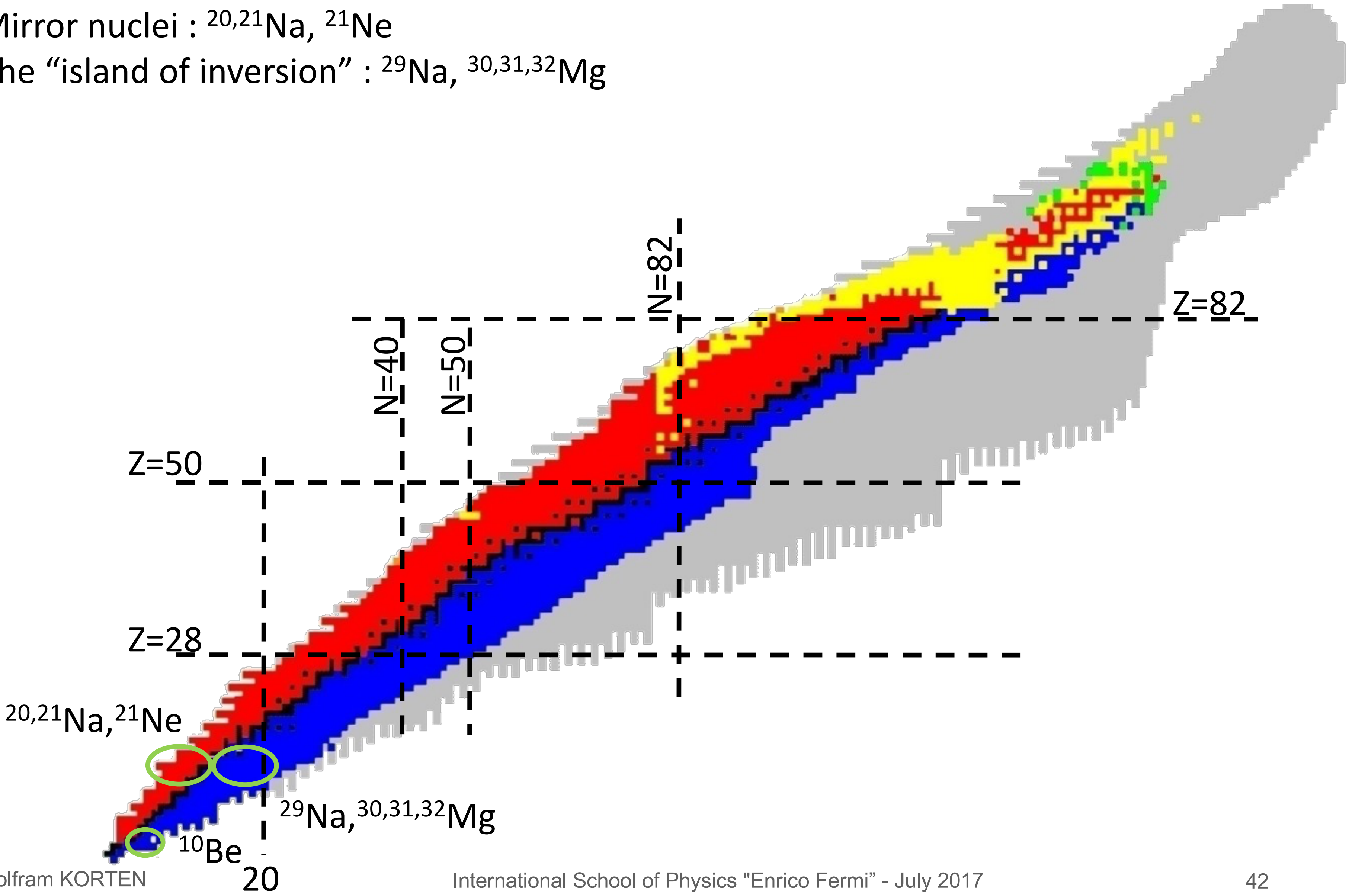


courtesy D. Verney (IPNO)

Coulomb excitation studies with low-energy RIBs

Drip lines and shell Structure in light nuclei

- ✓ Drip-line nuclei: ^{10}Be
- ✓ Mirror nuclei : ^{20,21}Na, ^{21}Ne
- ✓ The "island of inversion" : ^{29}Na, ^{30,31,32}Mg

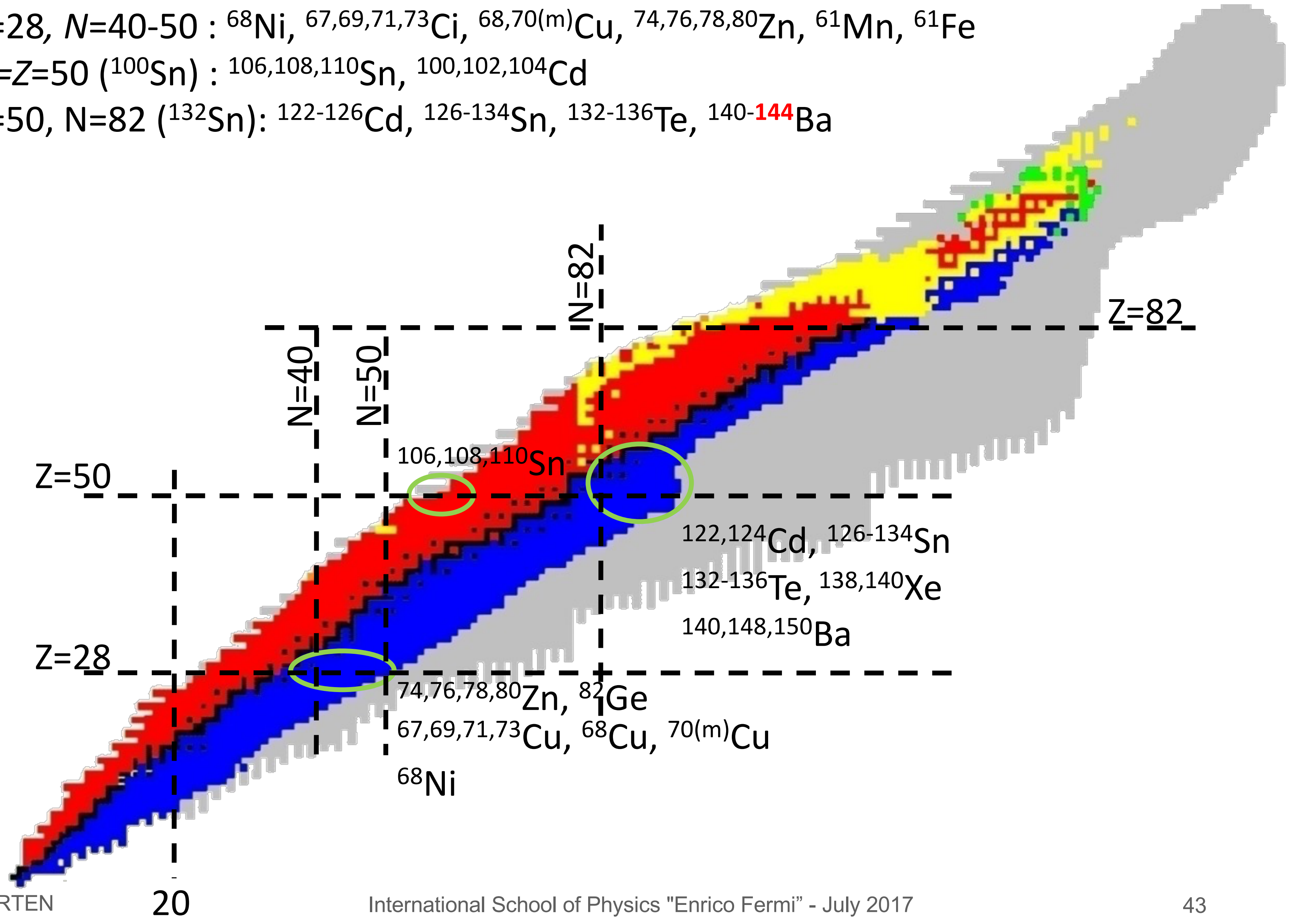


Coulomb excitation studies with low-energy RIBs

Irfu cea saclay

Evolution of Shell Structure far from stability

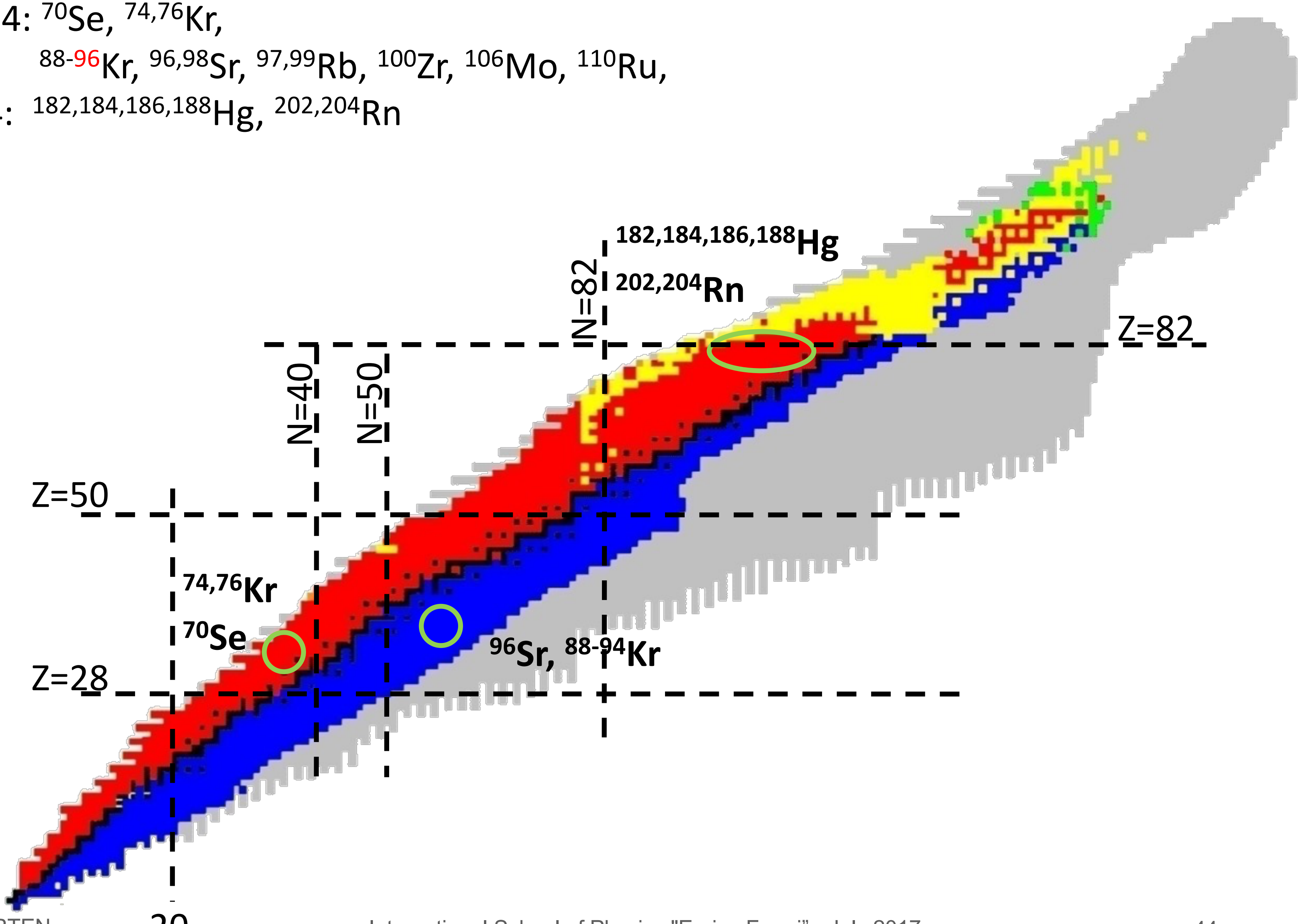
- ✓ N=28: ^{44}Ar
- ✓ *Z*=28, *N*=40-50 : ^{68}Ni, ^{67,69,71,73}Ci, $^{68,70(m)}$Cu, ^{74,76,78,80}Zn, ^{61}Mn, ^{61}Fe
- ✓ *N*=*Z*=50 (^{100}Sn) : ^{106,108,110}Sn, ^{100,102,104}Cd
- ✓ Z=50, N=82 (^{132}Sn): $^{122-126}$Cd, $^{126-134}$Sn, $^{132-136}$Te, $^{140-144}$Ba



Coulomb excitation studies with low-energy RIBs

Evolution of nuclear shapes and shape coexistence

- ✓ N=Z ≈ 34: ^{70}Se, ^{74,76}Kr,
- ✓ N ≈ 60: $^{88\text{-}96}$Kr, ^{96,98}Sr, ^{97,99}Rb, ^{100}Zr, ^{106}Mo, ^{110}Ru,
- ✓ N ≈ 104: ^{182,184,186,188}Hg, ^{202,204}Rn



End of Lecture 3