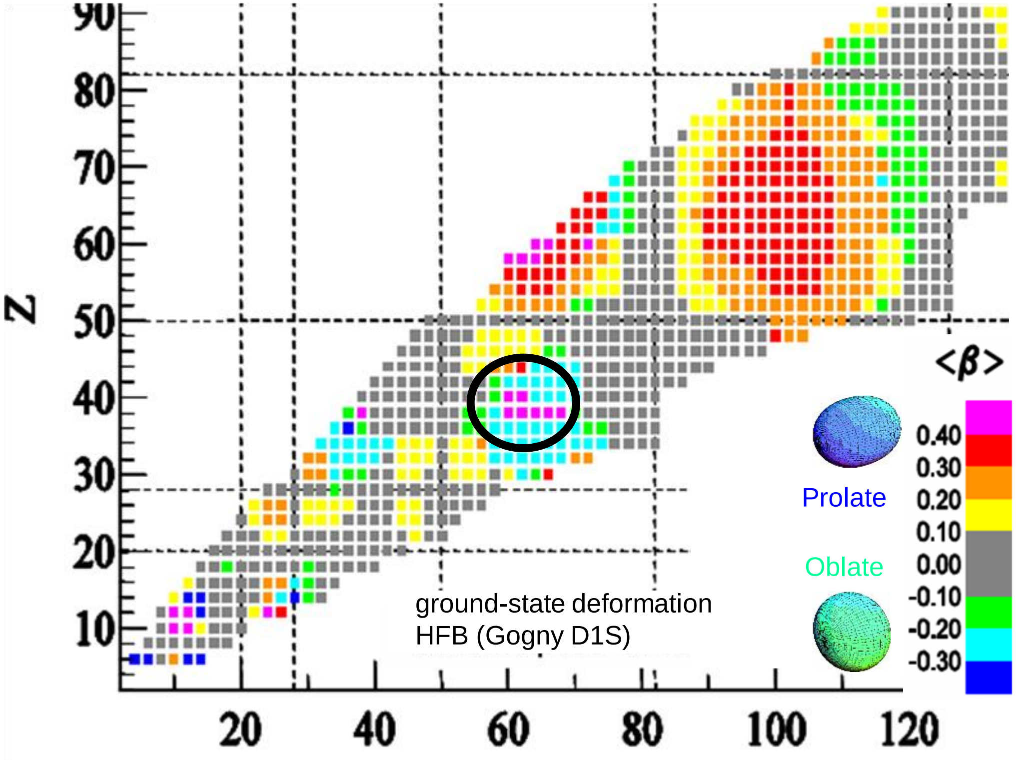
Nuclear Shapes

Lecture III

Andreas Görgen
Department of Physics
University of Oslo, Norway
andreas.gorgen@fys.uio.no

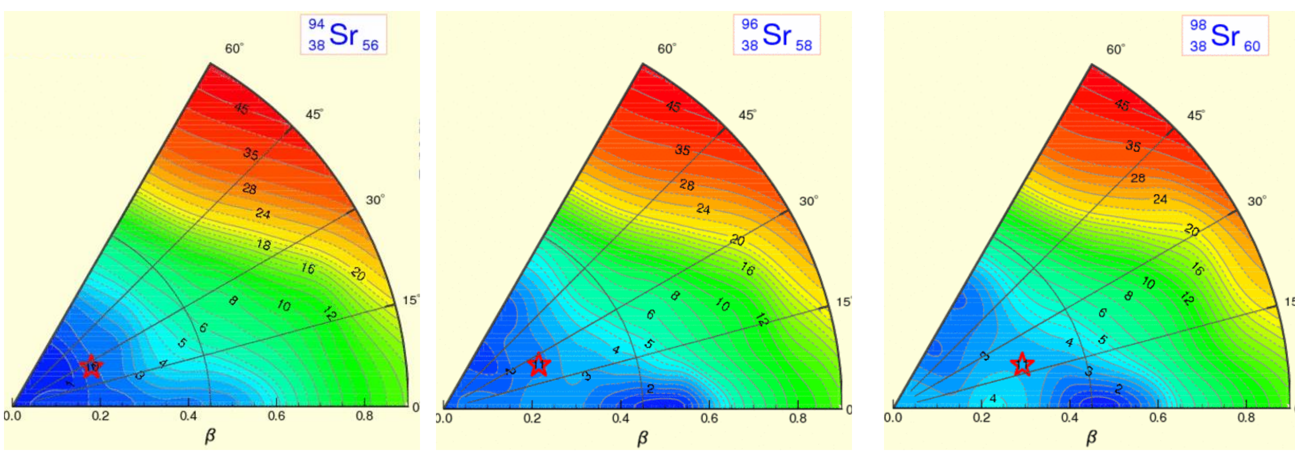
Selected Topics in Nuclear and Atomic Physics
Fiera di Primiero
2.-6. October 2017

Shapes and shape transitions in the nuclear chart

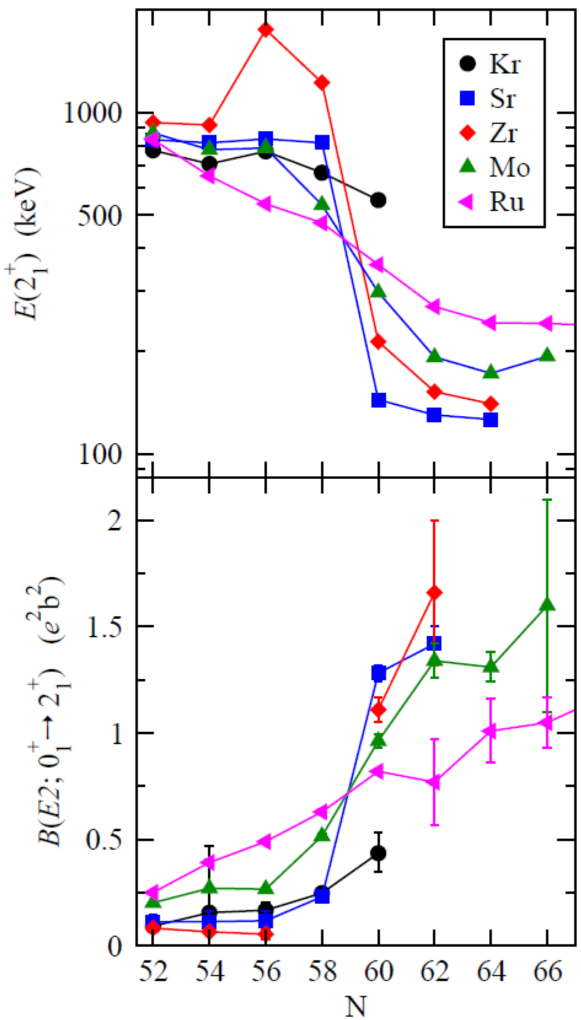


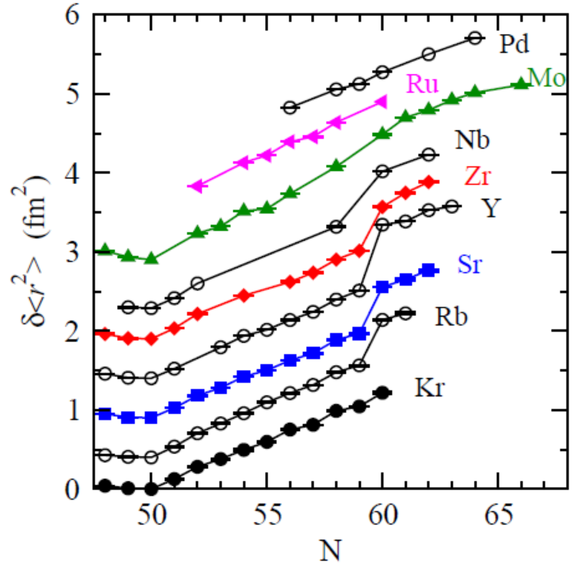
- rapid changes in the ground-state deformation for $Z \approx 40$ and $N \approx 60$
- shape coexistence in the regions of shape transition
- observables related to nuclear shape: quadrupole moments, B(E2) values
- benchmarks for theory

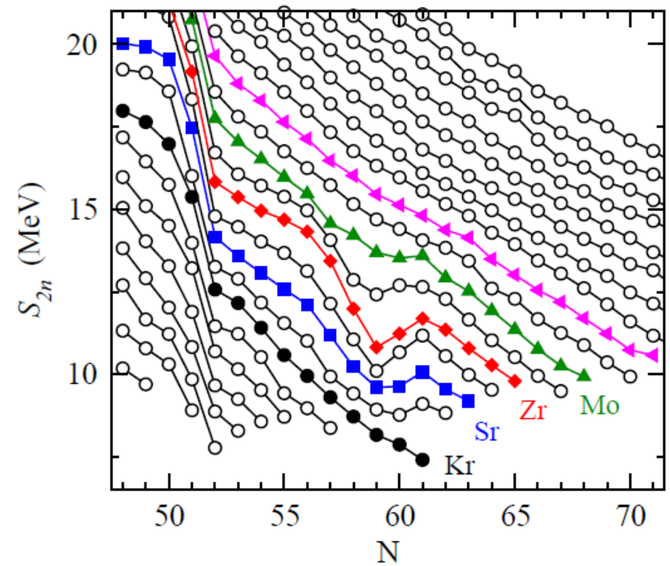
http://www-phynu.cea.fr/
S.Hilaire, M.Girod, Eur. Phys. J. A 33, 237 (2007)



Shape transition at $N = 60$





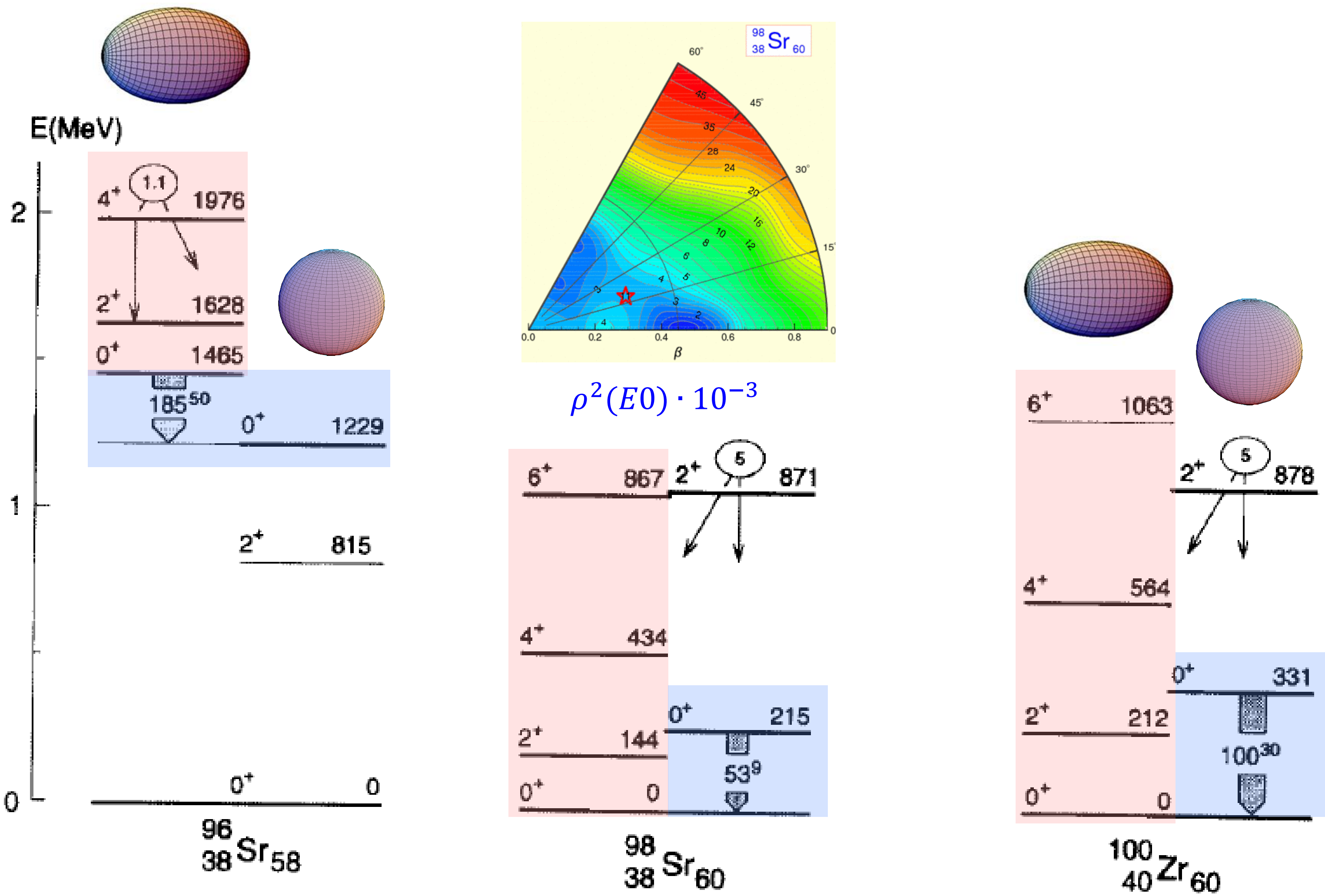


At $N = 60$:

- ➢ drop in energy of first 2^+ state
- ➢ steep increase of $B(E2;\ 0^+ \rightarrow 2^+)$
- ➢ discontinuity in charge radii
- ➢ irregularity in two-neutron binding energy

A.Görgen and W.Korten,
J.Phys.G 43, 024002 (2016)

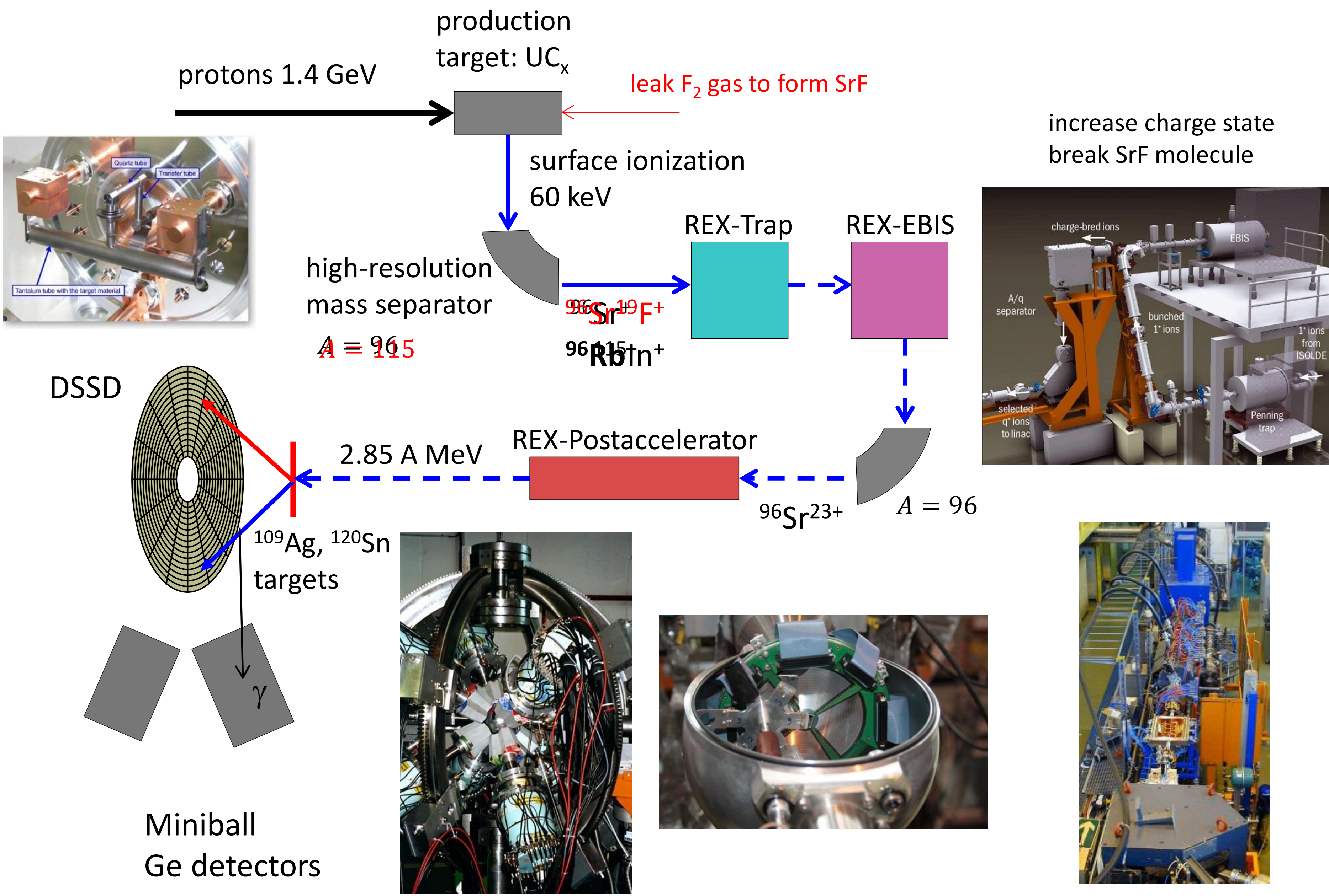
E0 transitions in Sr and Zr isotopes at $N \approx 60$



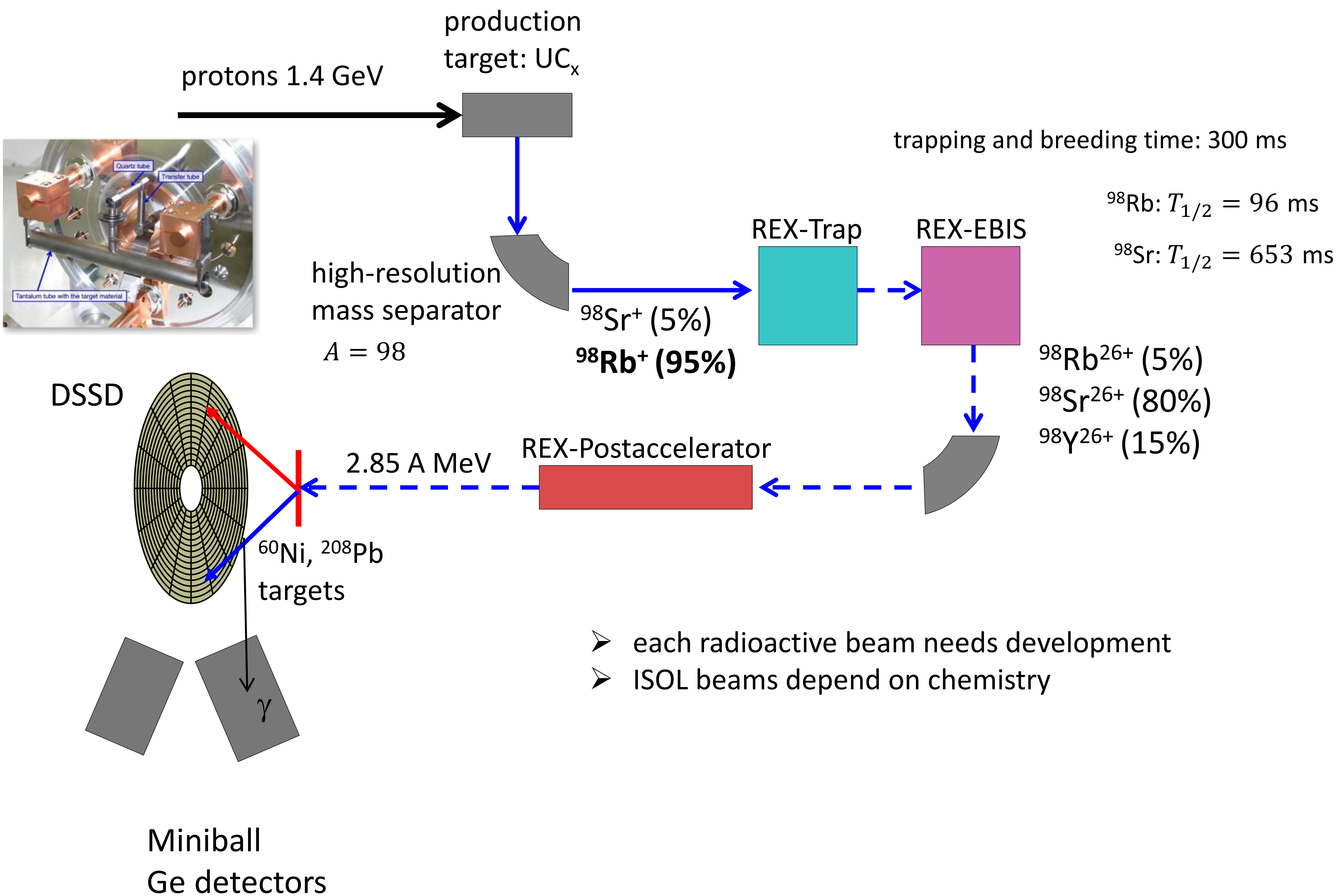
- rotational band
- low-lying 0_2^+ state with large $\rho^2(E0)$

J.L. Wood et al.,
Nucl. Phys. A 651, 323 (1999)

Isotope separation on-line and postacceleration at CERN-ISOLDE

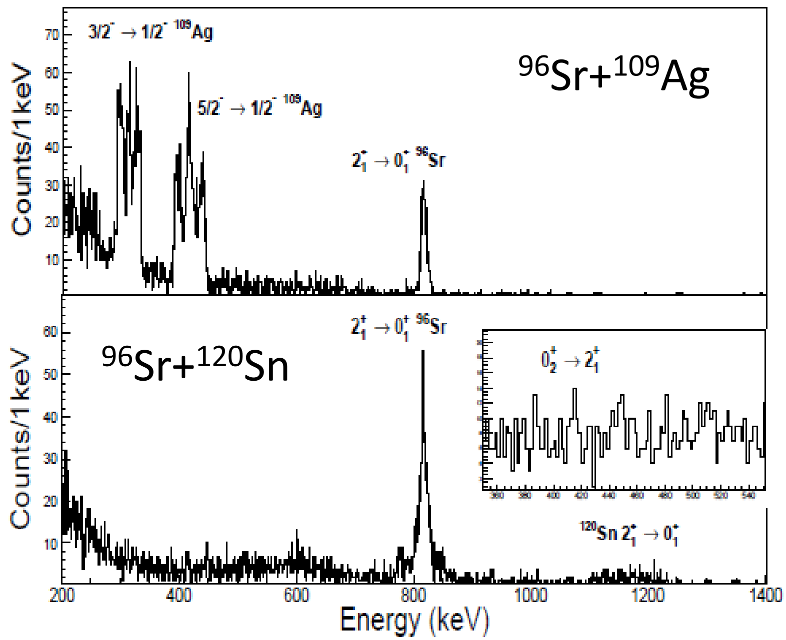


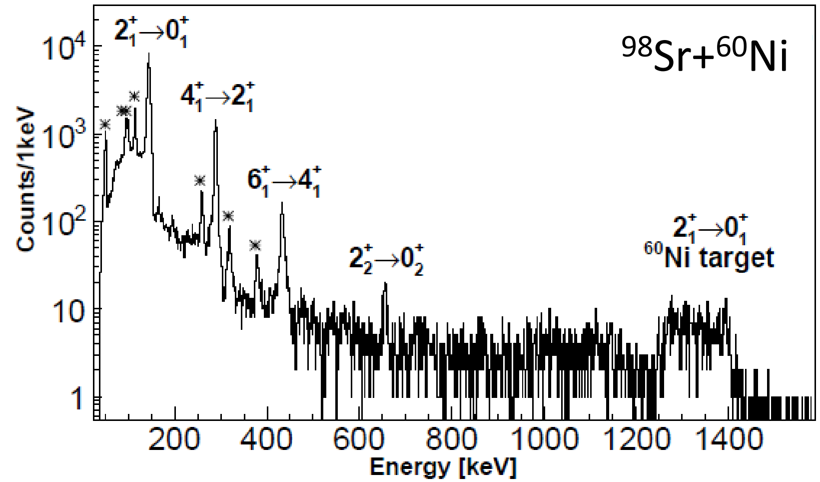
Isotope separation on-line and postacceleration at CERN-ISOLDE

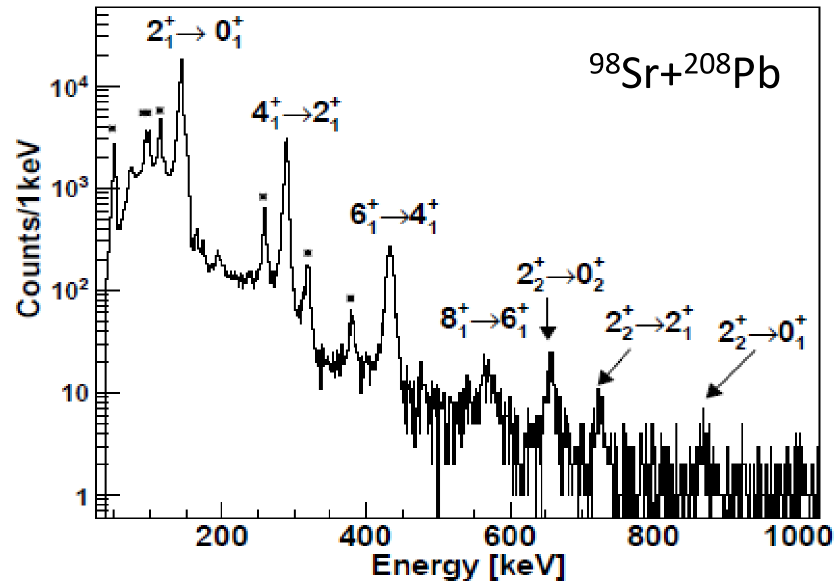


- each radioactive beam needs development
- ISOL beams depend on chemistry

Coulomb excitation of ^{96,98}Sr at CERN – ISOLDE







Doppler correction for projectiles

normaliztion to known $B(E2)$ values in target

Coulomb excitation probabilities:
(as function of θ and Z)
$\Rightarrow$ B(E2) values
$\Rightarrow$ spectroscopic quadrupole moments Q_s
(reorientation effect)

E. Clément et al.
Phys.Rev.Lett. 116, 022701 (2016)
Phys.Rev. C 94, 054326 (2016)

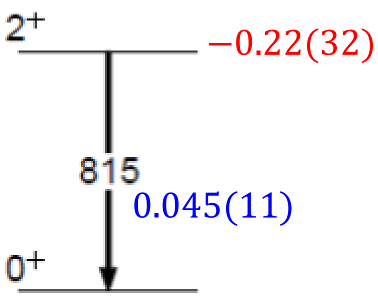
Coulomb excitation of ^{98}Sr at CERN – ISOLDE

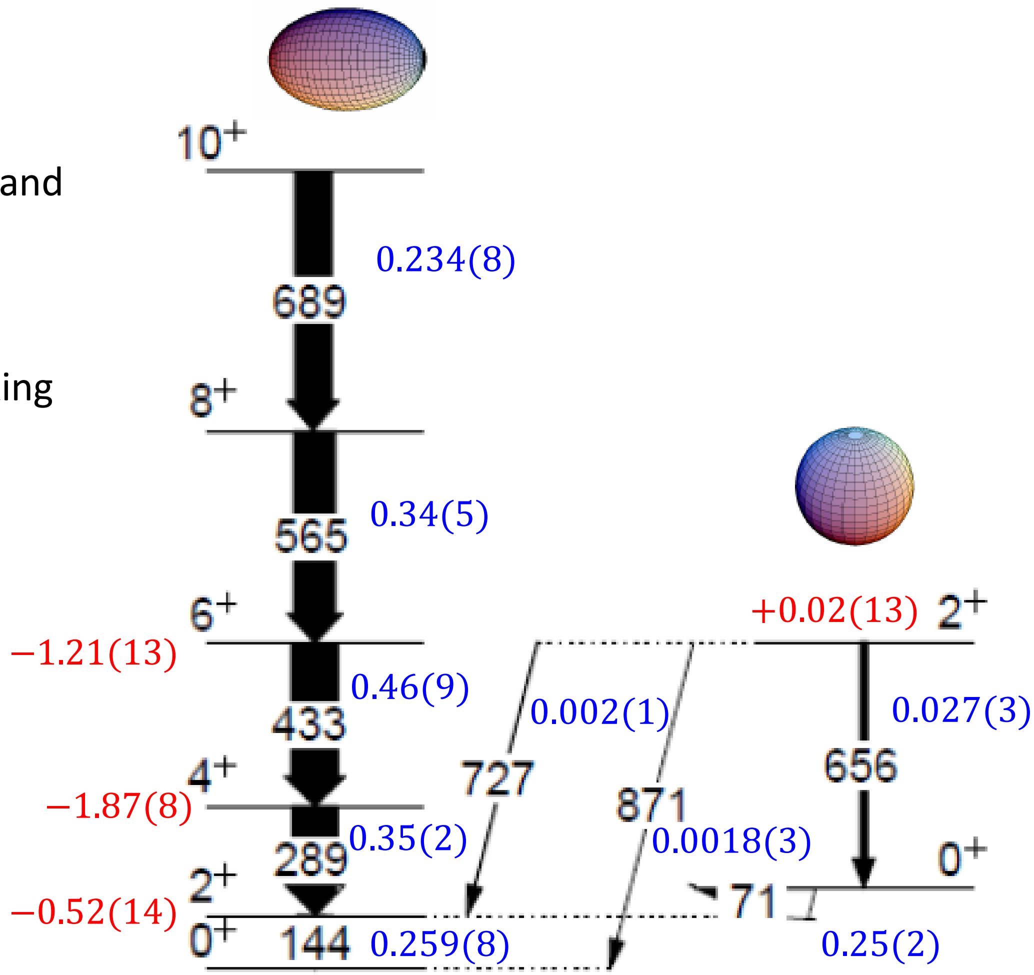
^{98}Sr

- rotational behavior of ground-state band
- excited configuration similar to ^{96}Sr
- quadrupole moments confirm shape coexistence
- $B(E2; 2_2^+ \rightarrow 0_1^+)$ indicates strong mixing

$B(E2;\downarrow)$ $[e^2\text{b}^2]$

Q_s $[e\text{b}]$



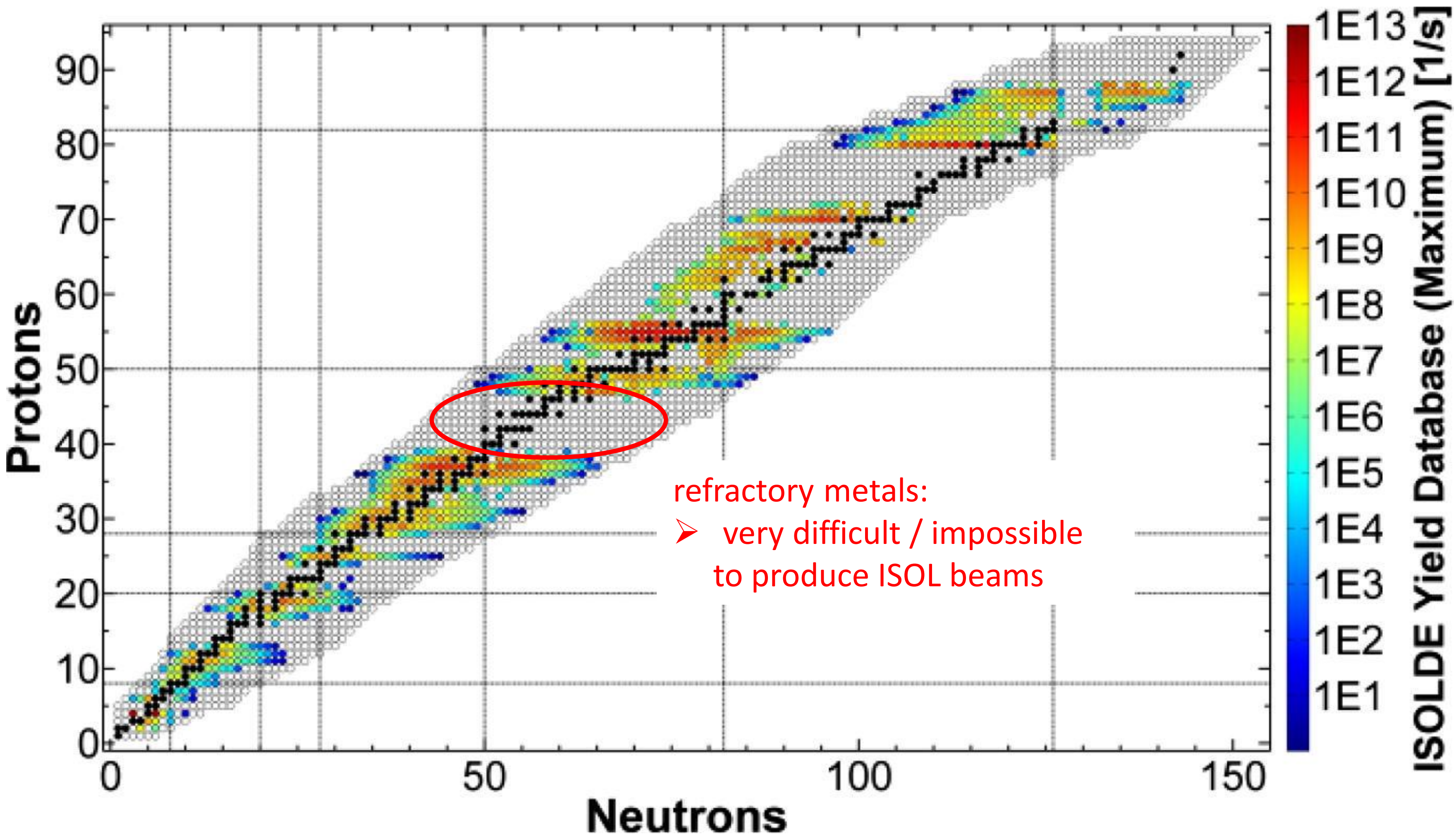


^{96}Sr

- $Q_s(2_1^+) \approx 0$
  $\Rightarrow$ no static quadrupole deformation
- sizeable $B(E2)$
  $\Rightarrow$ vibrational character of 2_1^+

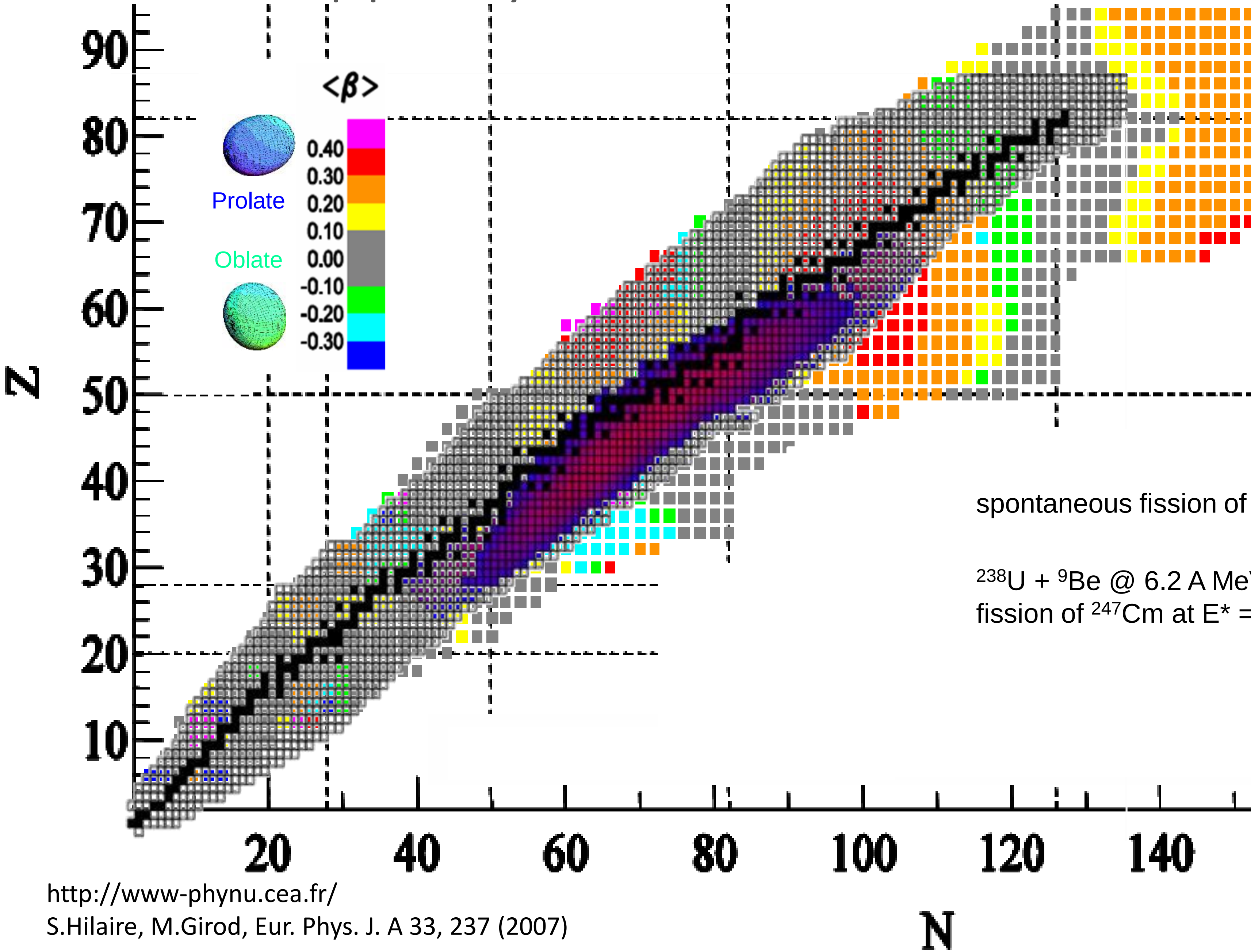
E. Clément et al.
Phys.Rev.Lett. 116, 022701 (2016)
Phys.Rev. C 94, 054326 (2016)

ISOL beams produced at CERN-ISOLDE



this is a region of dramatic shape transitions
and shape coexistence !

Neutron-rich nuclei populated by fission

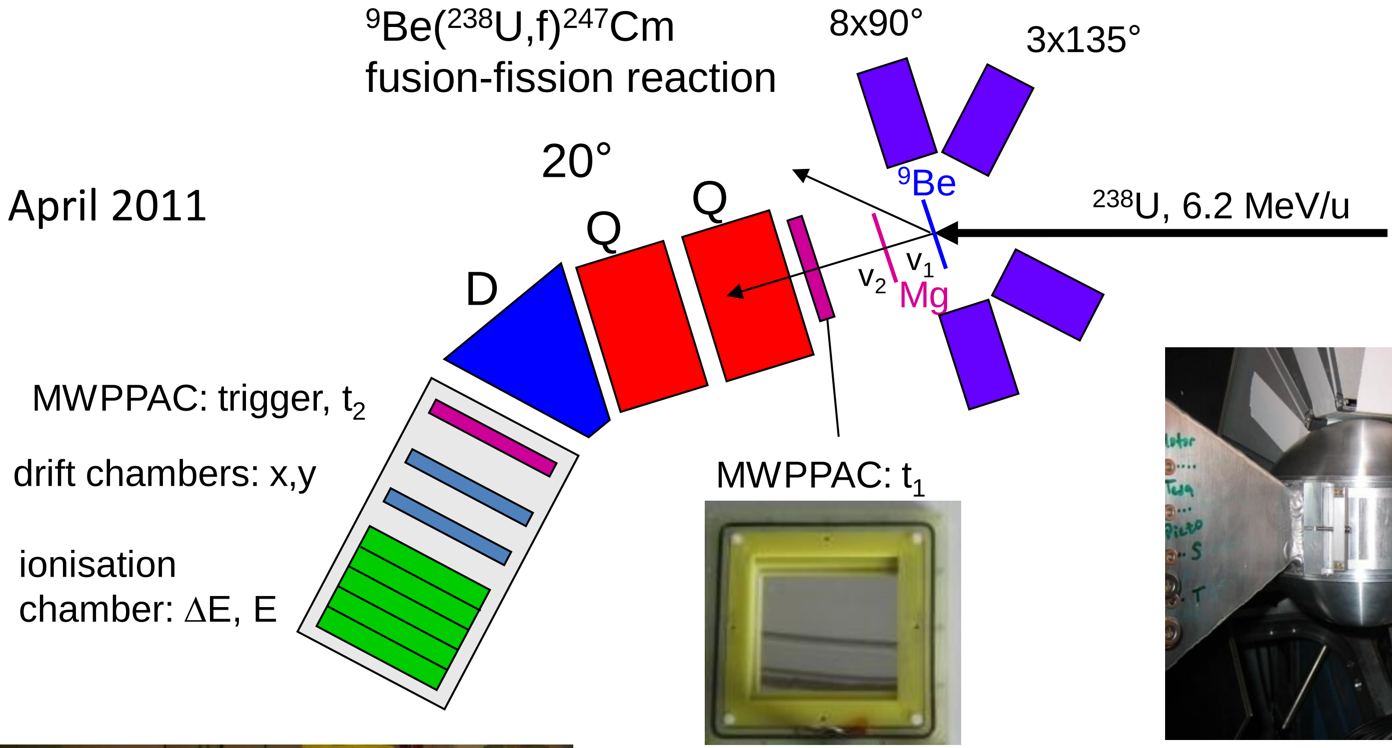


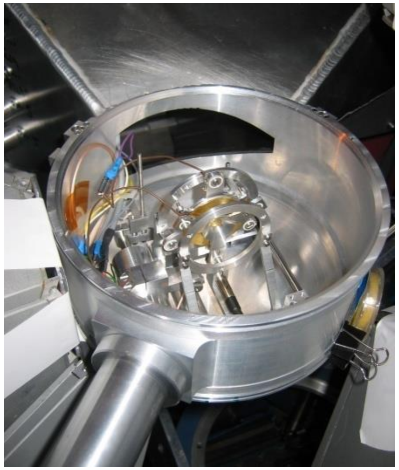
spontaneous fission of ^{250}Cf

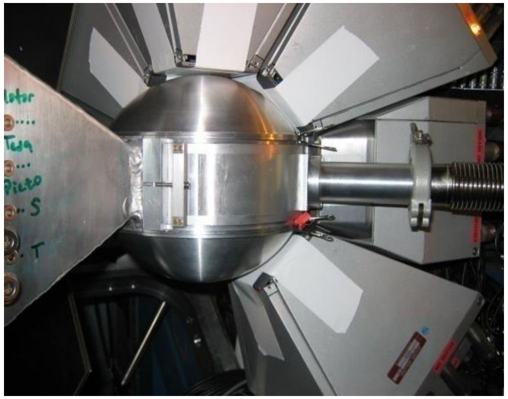
$^{238}U + ^{9}Be$ @ 6.2 A MeV
fission of ^{247}Cm at E* = 45 MeV

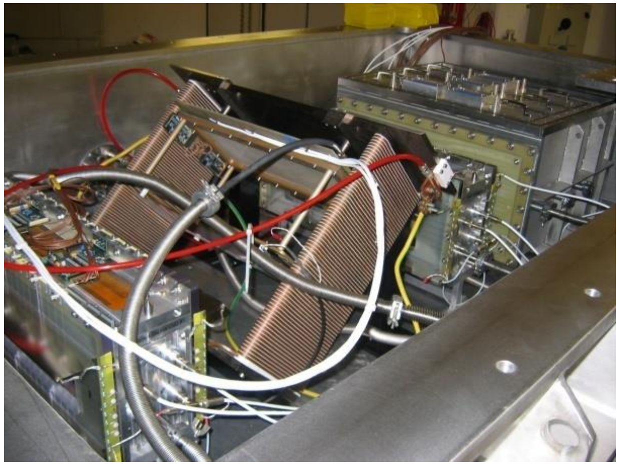
http://www-phynu.cea.fr/
S.Hilaire, M.Girod, Eur. Phys. J. A 33, 237 (2007)

Heavy-ion induced fission experiments with VAMOS





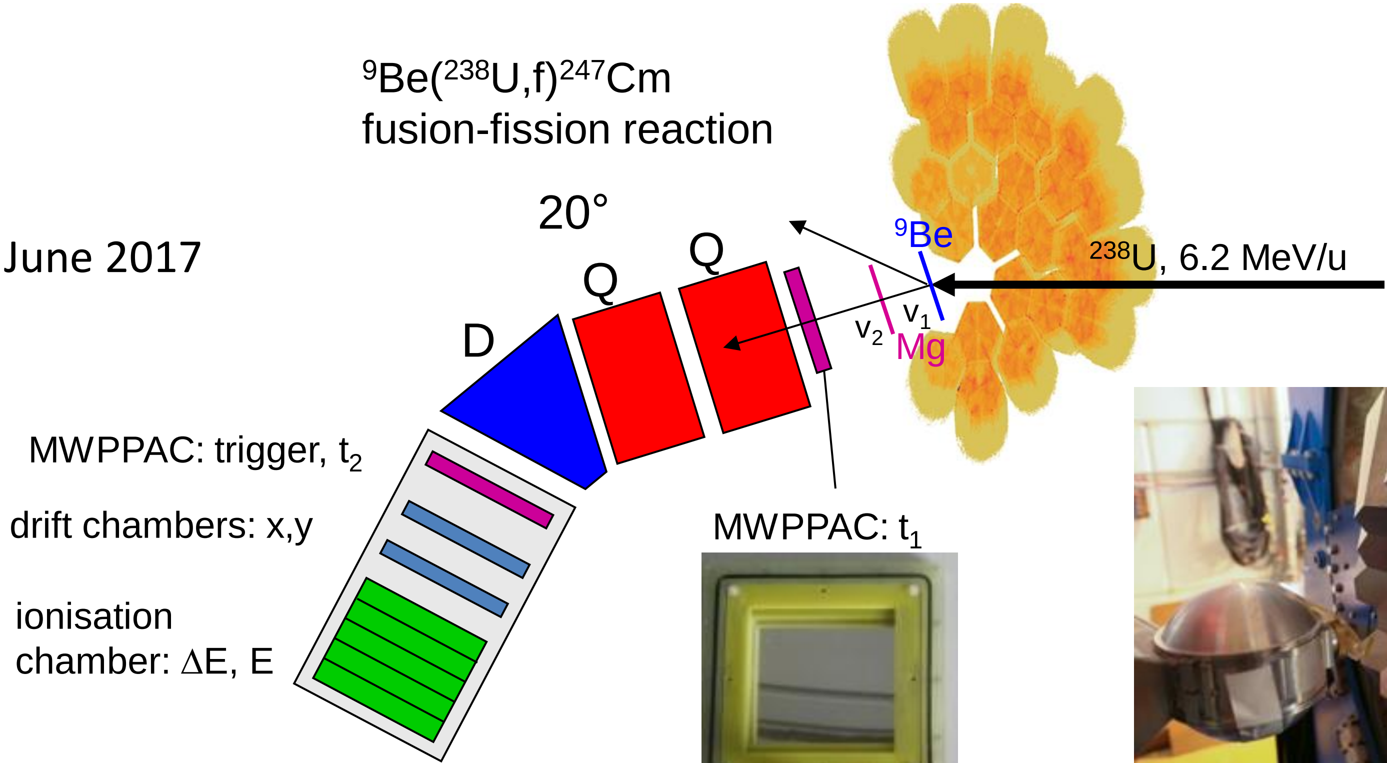


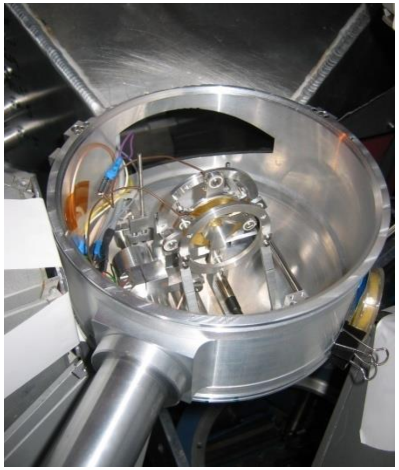


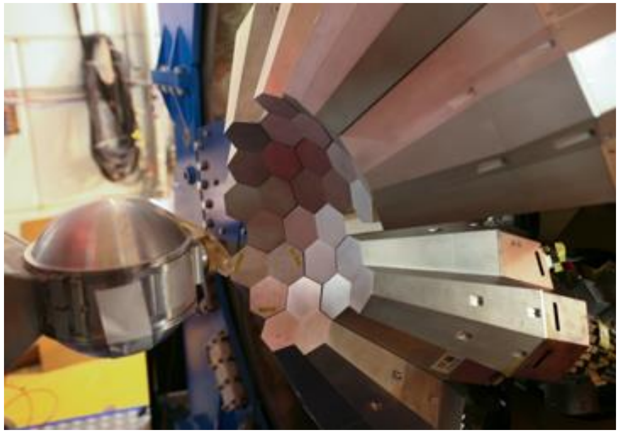
Heavy-ion induced fission experiments with VAMOS

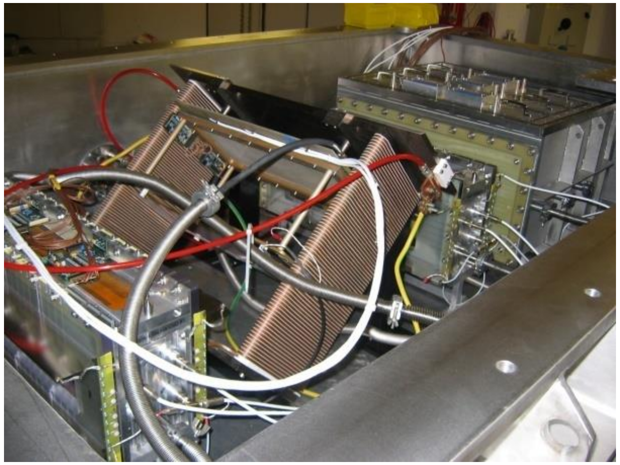
$^{9}Be(^{238}U,f)^{247}Cm$
fusion-fission reaction

June 2017



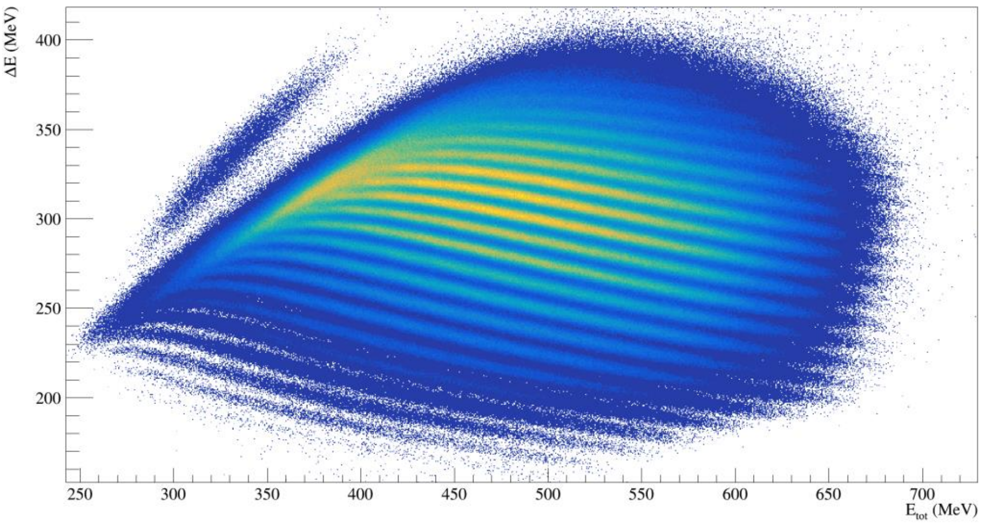




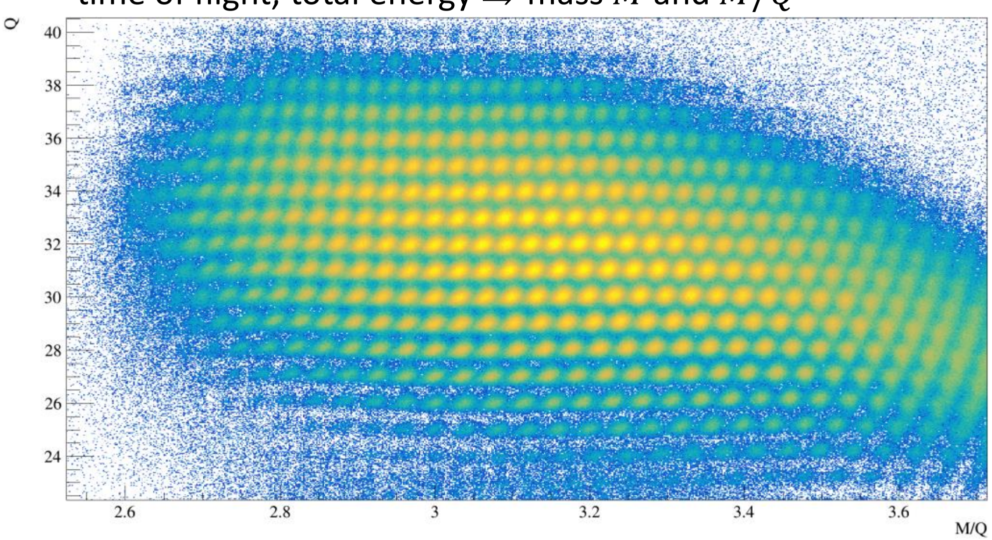


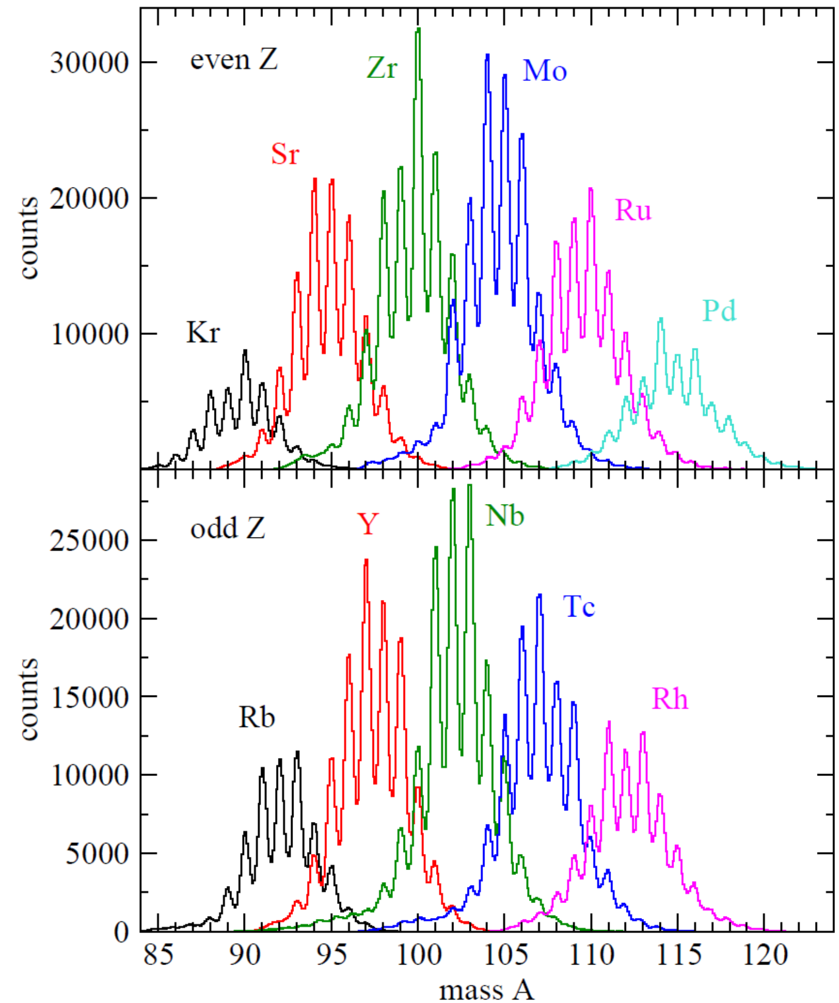
Identification of fission fragments in VAMOS

energy loss and total energy in ionization chamber $\Rightarrow Z$



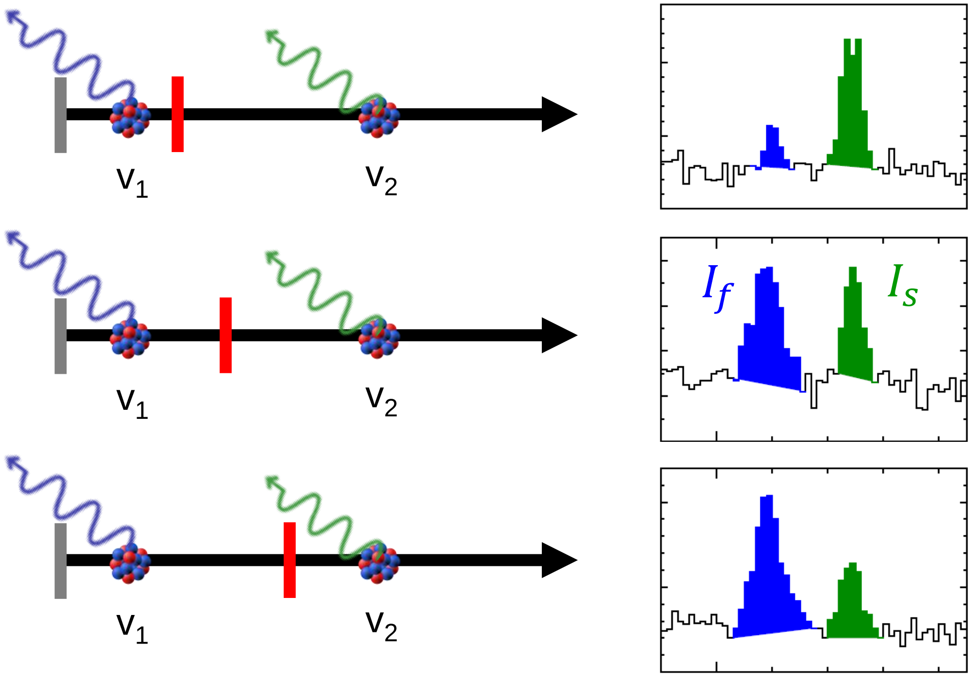
reconstructed trajectory, magnetic rigidity
time of flight, total energy $\Rightarrow$ mass M and M/Q

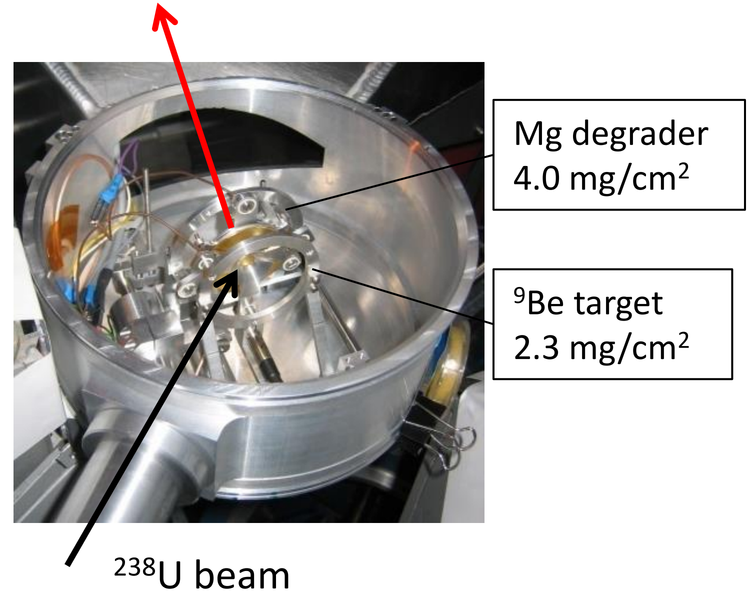




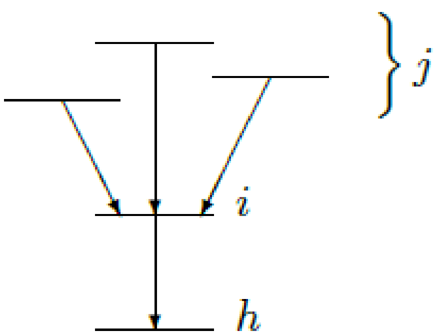
event-by-event identification
in Z and A of more than 200
fission fragments

Recoil distance Doppler shift (RDDS) method





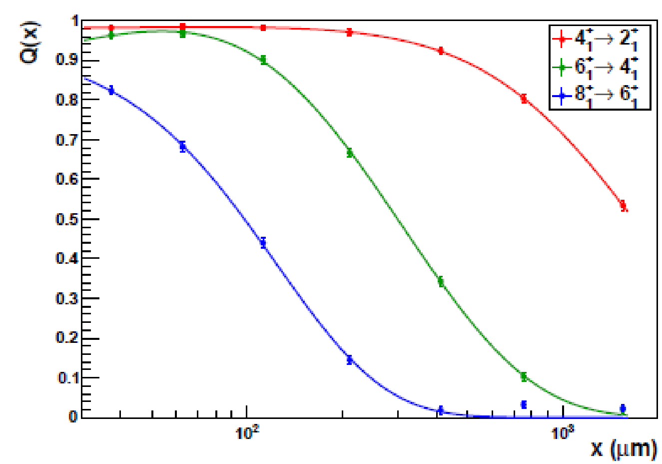
10 distances: 30 – 2650 μm
18 h per distance



decay curve:

$$Q_i(x) = \frac{I_{i,s}(x)}{I_{i,s}(x) + I_{i,f}(x)}$$

$$\tau_i(x) = -\frac{Q_i(x) - \sum_j \alpha_{ij}\, Q_j(x)}{v_1 \frac{dQ_i}{dx}(x)}$$



A. Dewald et al., Z. Phys. A. 334, 163 (1989)

Lifetime results in even-even nuclei

Lifetimes in ps
- adopted values
- this work

^{112}Pd
2^+ 84 (14)
4^+ **5.4 (1.7)**

^{114}Pd
2^+ 82 (14)
4^+ **5.7 (9)**

^{116}Pd
2^+ 110 (30)
4^+ **8.7 (12)**
6^+ **2.6 (9)**

^{108}Ru
2^+ 360 (30)
4^+ 13.4 (10)
13.6 (9)
6^+ **2.9 (3)**

^{110}Ru
2^+ 320 (20)
4^+ 15.4 (17)
15.1 (9)
6^+ 2.4 (10)
3.2 (5)

^{112}Ru
2^+ 320 (30)
4^+ **14.6 (21)**

^{102}Mo
2^+ 125 (4)
4^+ 12.5 (25)
9.4 (10)
6^+ **3.4 (6)**

^{104}Mo
2^+ 970 (80)
4^+ 26.1 (3)
18.6 (9)
6^+ 4.73 (15)
2.8 (2)

^{106}Mo
2^+ 1250 (30)
4^+ 25.4 (51)
28.0 (13)
6^+ 4.2 (18)
3.1 (3)

^{108}Mo
2^+ 500 (300)
4^+ **23.3 (51)**

L. Grente, PhD Univ. Paris Sud, 2014
and to be published

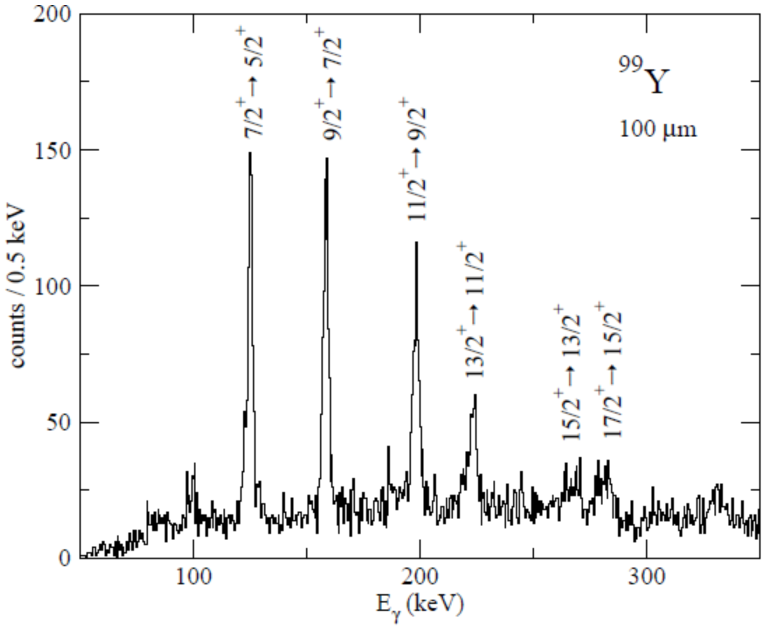
^{98}Zr
2^+ <11ps
4.9 (26)
4^+ 28 (3)

^{100}Zr
2^+ 590 (30)
4^+ 37 (3)
18.1 (14)
6^+ 4.9 (11)
3.1 (3)

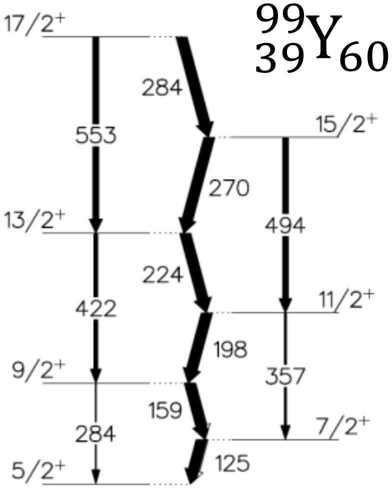
^{102}Zr
2^+ 1800 (400)
4^+ **32.1 (34)**
6^+ **4.7 (5)**

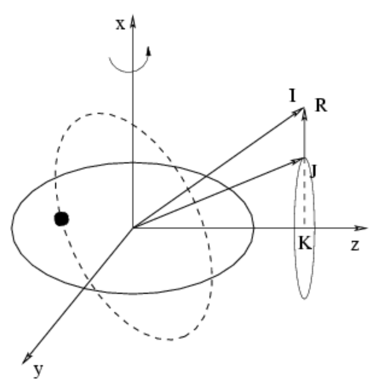
⇒ comparison of B(E2) values
with beyond-mean field calculations

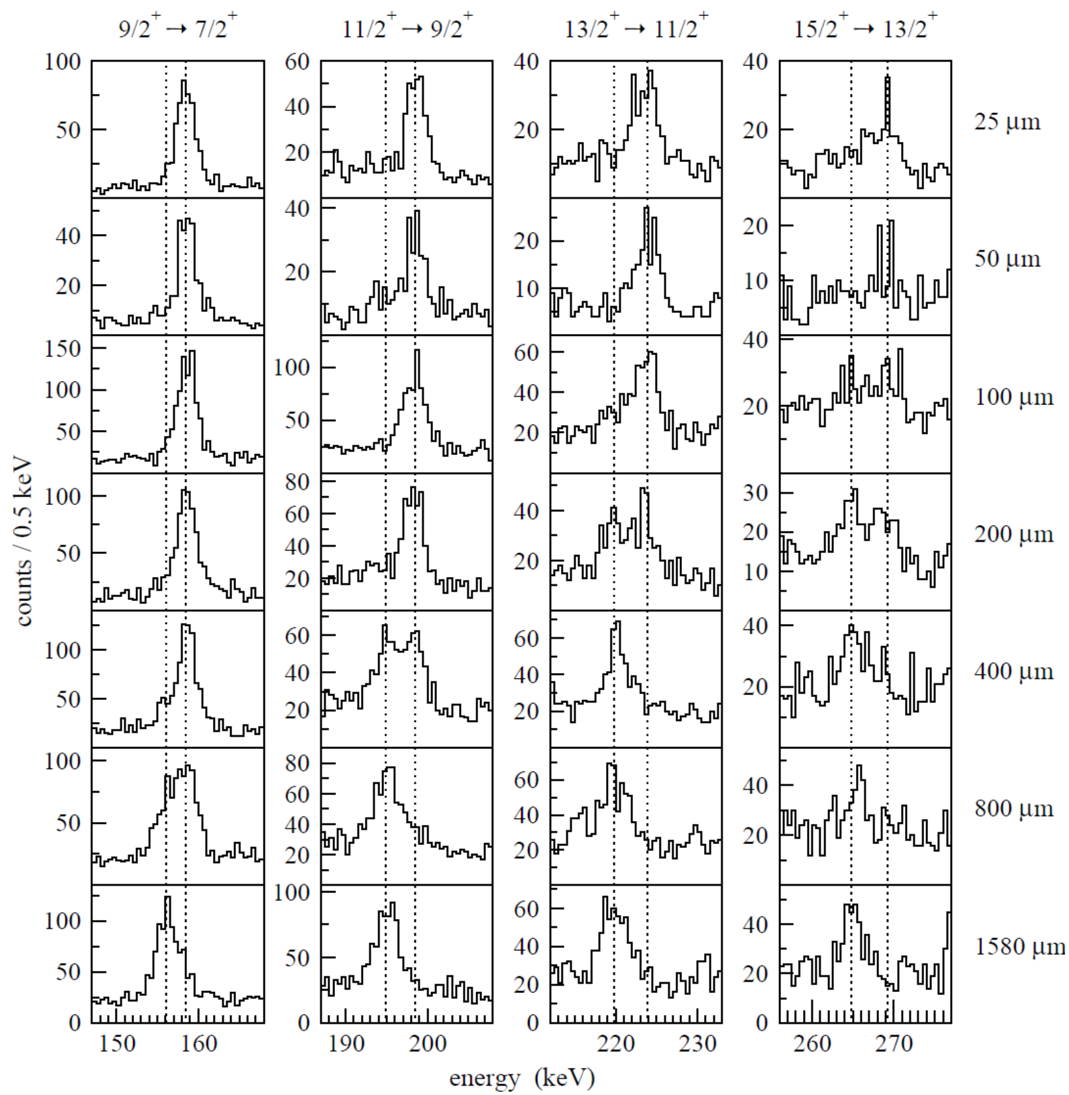
Lifetime measurement for odd-mass Y isotopes with EXOGAM



$^{99}_{39}Y_{60}$



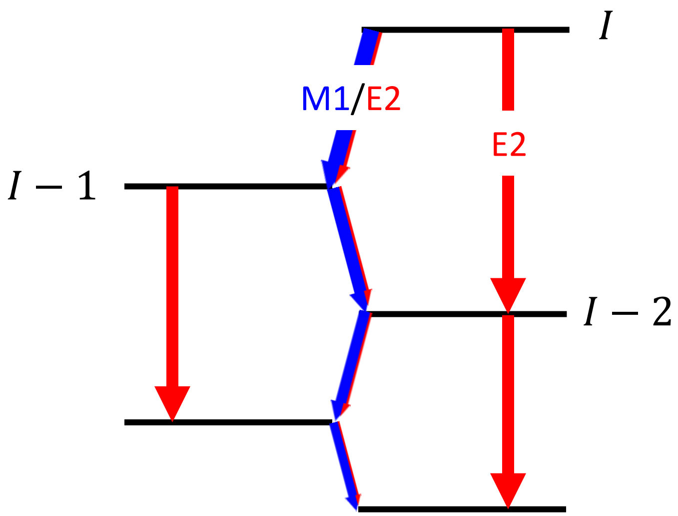




deformed ^{98}Sr plus extra proton
⇒ strongly coupled band

T.W.Hagen et al.,
PRC 95, 034302 (2017)

Rotational bands in the particle – rotor model



branching ratio: $\dfrac{I_\gamma(\Delta I = 1)}{I_\gamma(\Delta I = 2)} \Rightarrow \dfrac{B(M1)}{B(E2)}$

lifetime: $\dfrac{1}{\tau} = \lambda_{tot} = \lambda_{M1} + \lambda_{E2,\Delta I=1} + \lambda_{E2,\Delta I=2}$

$\Rightarrow$ absolute $B(M1)$ and $B(E2)$ values

$\Rightarrow$ comparison with theoretical calculations

Particle – rotor model:

$$B(M1; I_i K \to I_f K) = \frac{3}{4\pi} e^2 (g_K - g_R)^2 K^2 \left| \langle I_i 1 K 0 | I_f K \rangle \right|^2$$

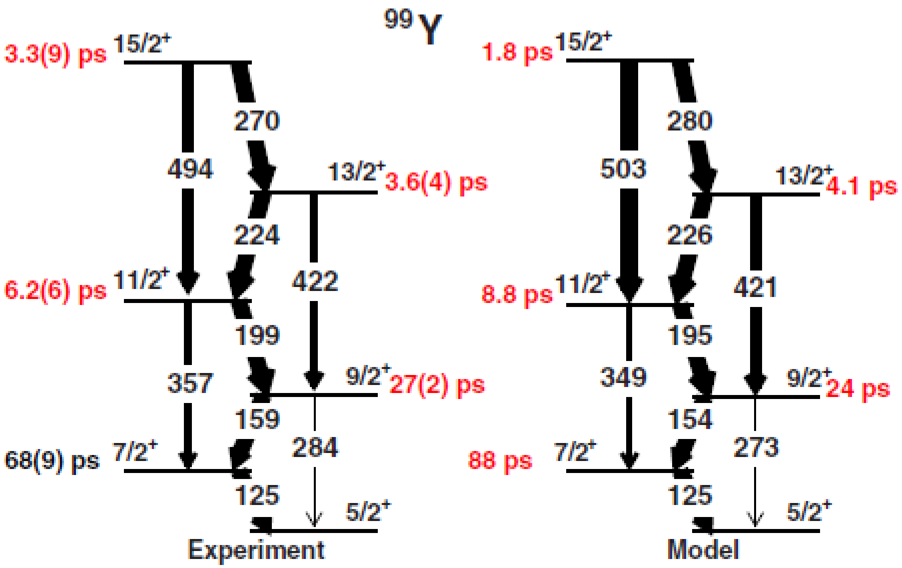
$$B(E2; I_i K \to I_f K) = \frac{5}{16\pi} e^2 Q_0^2 \left| \langle I_i 2 K 0 | I_f K \rangle \right|^2$$

branching ratio: $\dfrac{B(M1)}{B(E2)} \Rightarrow \dfrac{(g_K - g_R)}{Q_0}$

lifetime:

- $(g_K - g_R) \Rightarrow$ configuration of the odd particle
- $Q_0 \Rightarrow$ deformation of the core

Results for ^{99}Y



microscopic article-rotor calculations
with $\varepsilon_2 = 0.41$ and $\gamma = 0°$

T.W.Hagen et al.,
PRC 95, 034302 (2017)

I_i	$b_{E2/M1}$	τ [ps]	$g_K - g_R$	Q_0 [eb]
9/2	0.18	27	0.97	5.0
11/2	0.35	6.2	1.25	5.9
13/2	0.45	3.6	1.27	5.0
15/2	0.64	3.3	0.92	3.7

Laser spectroscopy of **$5/2^+$ ground state**

B. Cheal et al., Phys. Lett. B 645, 133 (2007)

- $\mu = 3.18(2)\ \mu_N$

  with $g_R = Z/A \Rightarrow (g_K - g_R) = 1.23$

  consistent with [422]5/2$^+$ configuration

- $Q_s = +1.55(17)\ eb$

  rotational model: $Q_s = \frac{3K^2 - I(I+1)}{(I+1)(2I+3)} Q_0$

  $\Rightarrow Q_0 = 4.34(48)\ eb$

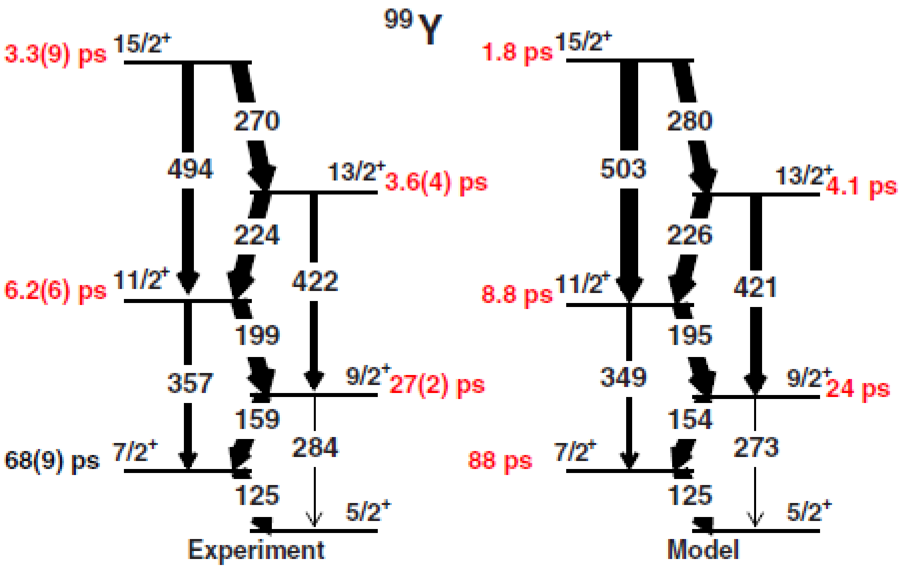
Coulomb excitation of ^{98}**Sr**:

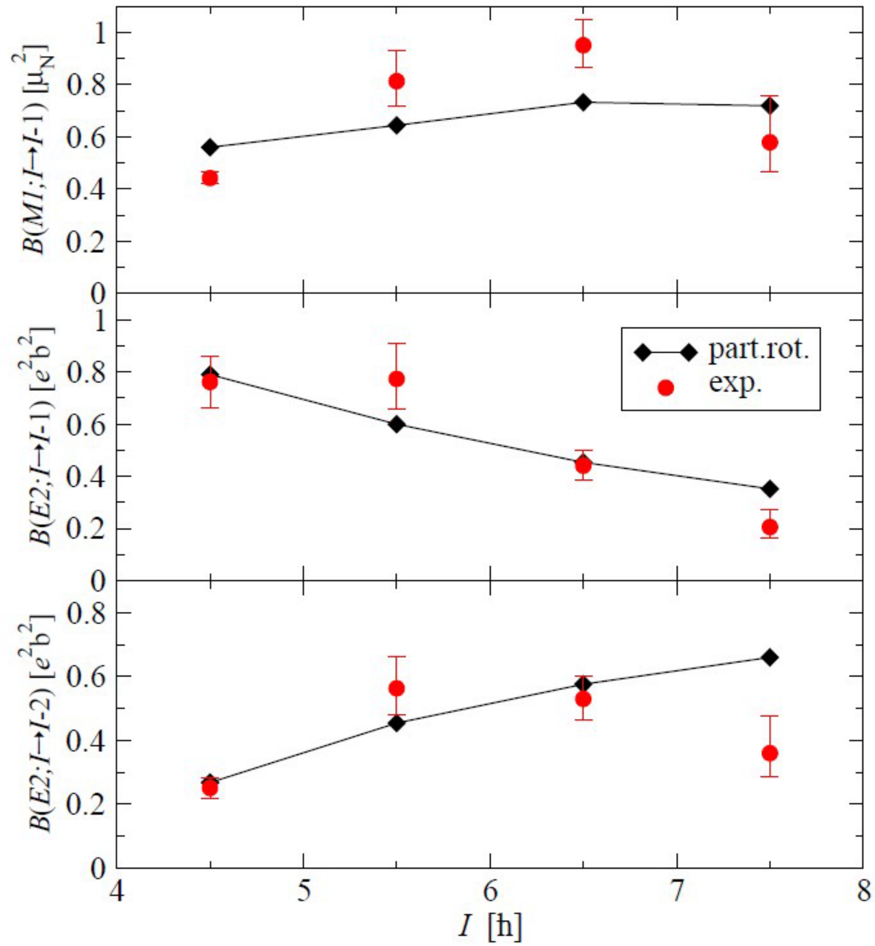
E. Clément et al., PRL 116, 022701 (2016)

- $Q_s(4^+) = -1.87^{+14}_{-25}\ eb$

  $\Rightarrow Q_0 = 5.14^{+0.39}_{-0.69}\ eb$

Results for ^{99}Y

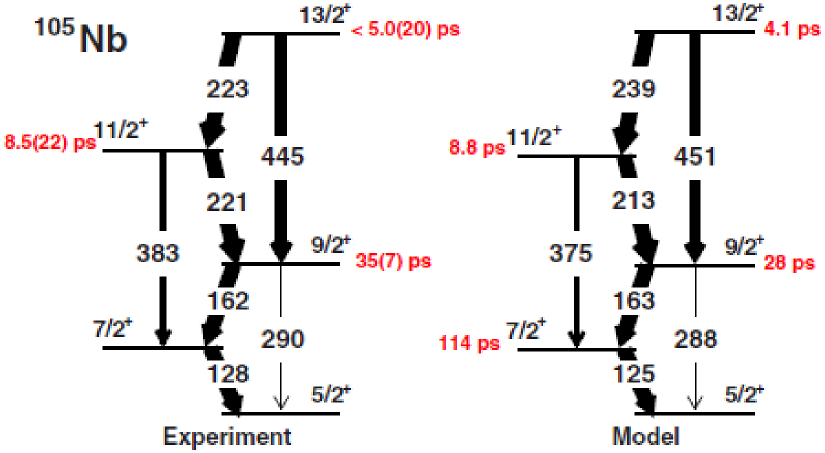




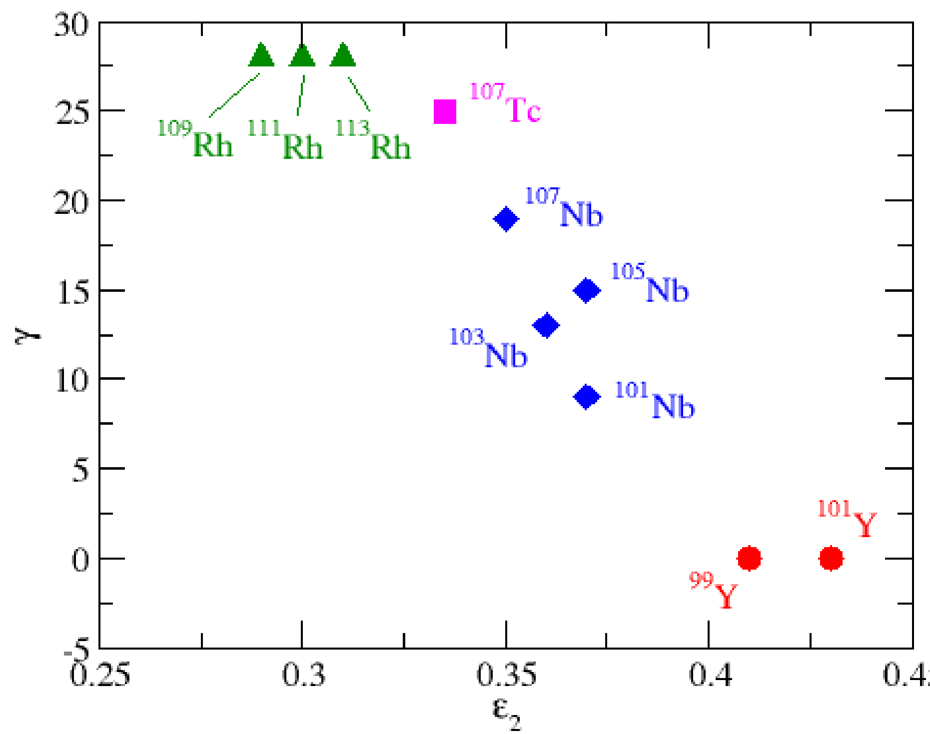
microscopic article-rotor calculations with $\varepsilon_2 = 0.41$ and $\gamma = 0°$

T.W.Hagen et al.,
PRC 95, 034302 (2017)

Many more results from the same experiment

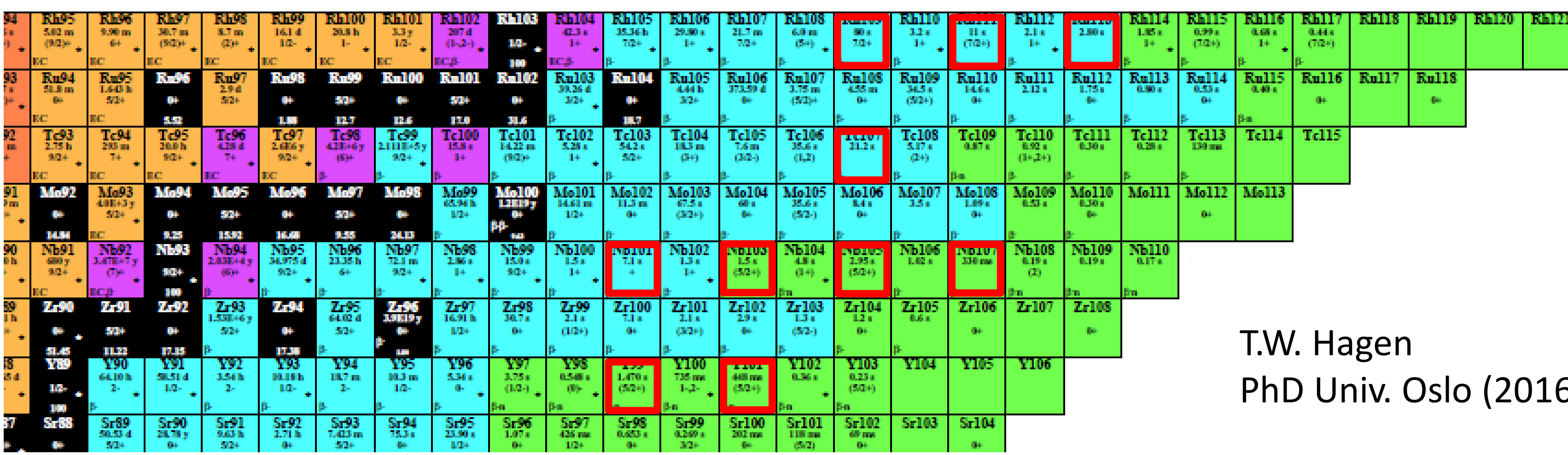


$\varepsilon_2 = 0.36, \gamma = 13°$



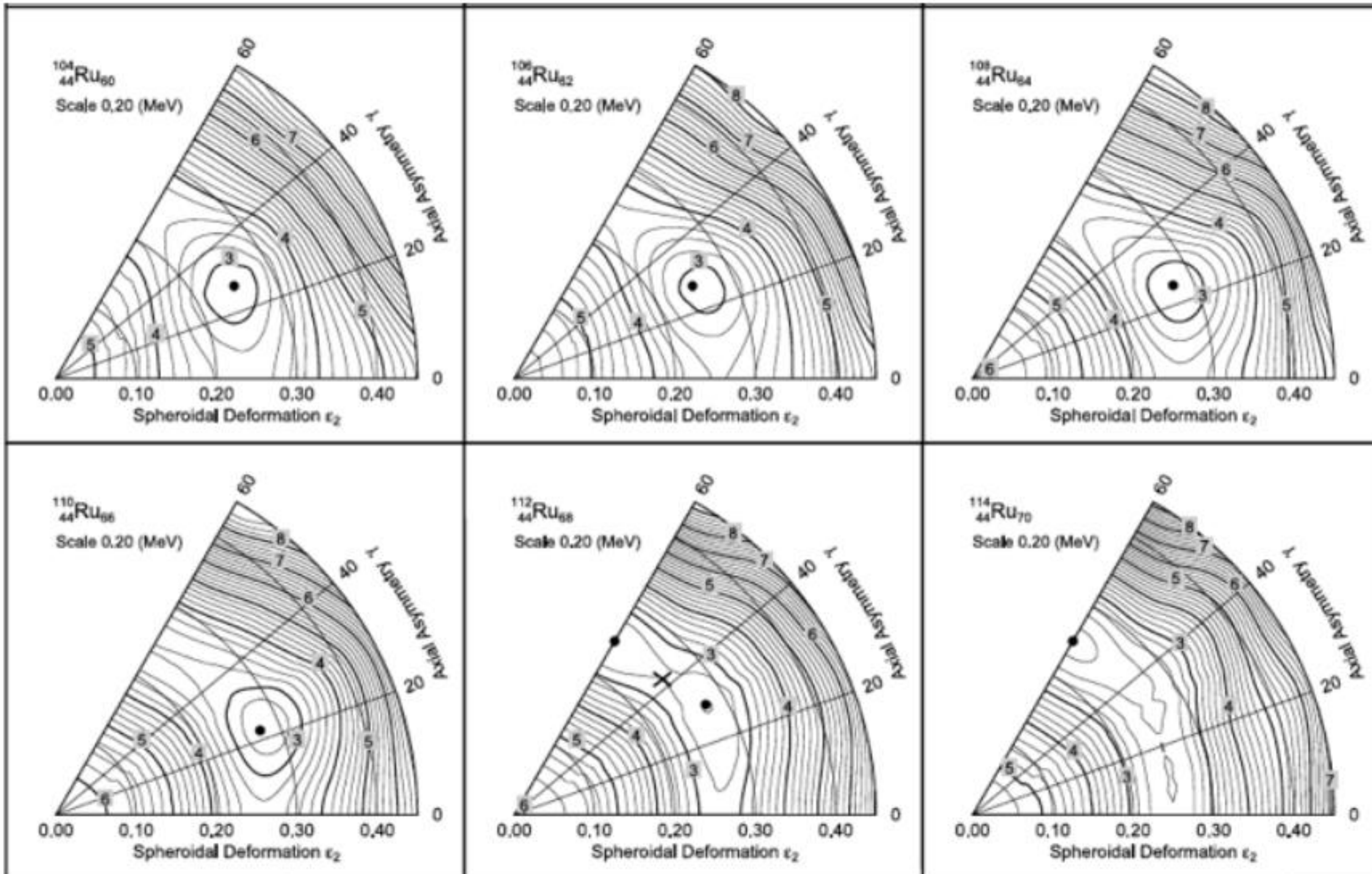
Results for $_{39}$Y, $_{41}$Nb, $_{43}$Tc, $_{45}$Rh:
with increasing Z:

- ➢ increase of triaxiality γ
- ➢ decrease of deformation ε_2



T.W. Hagen
PhD Univ. Oslo (2016)

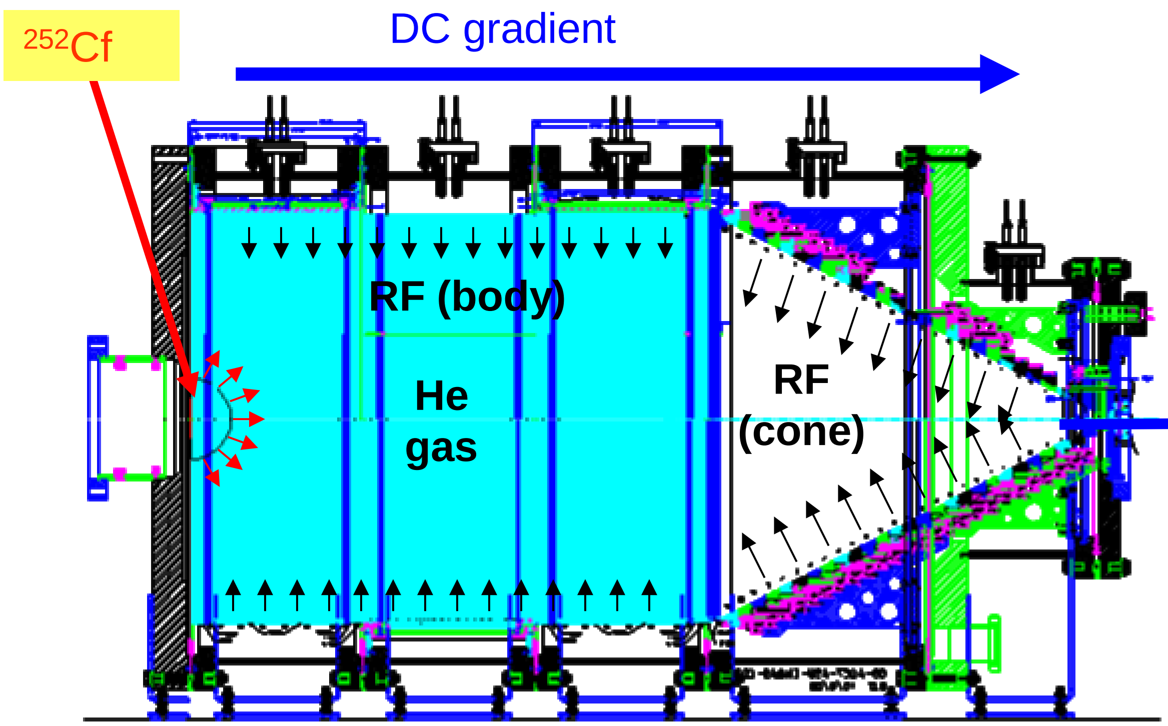
Triaxilaity predicted for $Z \approx 44$ and $N \approx 64$

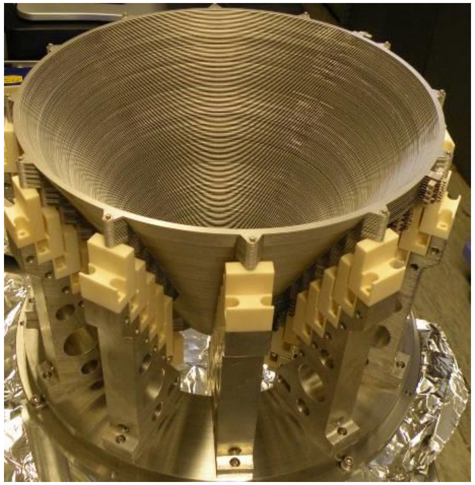


P. Möller et al., At. Data Nucl. Data Table 94 (2008)

CARIBU (CAlifornium Rare Isotope Breeder Upgrade) at Argonne

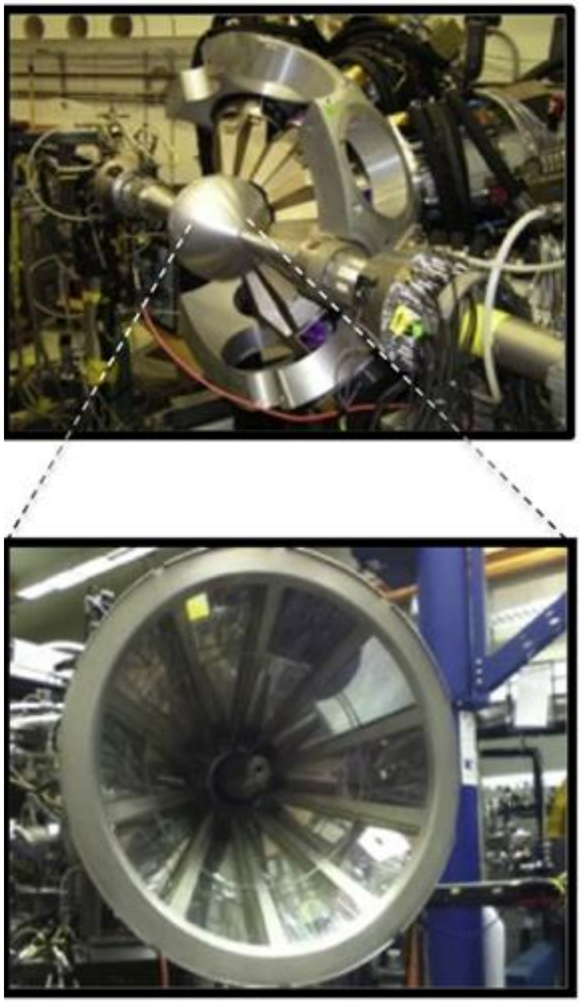
- 1.7 Ci ^{252}Cf source
- recoiling fission fragments stopped in Helium gas
- ion transport by RF field + DC field + gas flow
- Fast and independent of chemistry
- Extraction in 2 RFQ sections

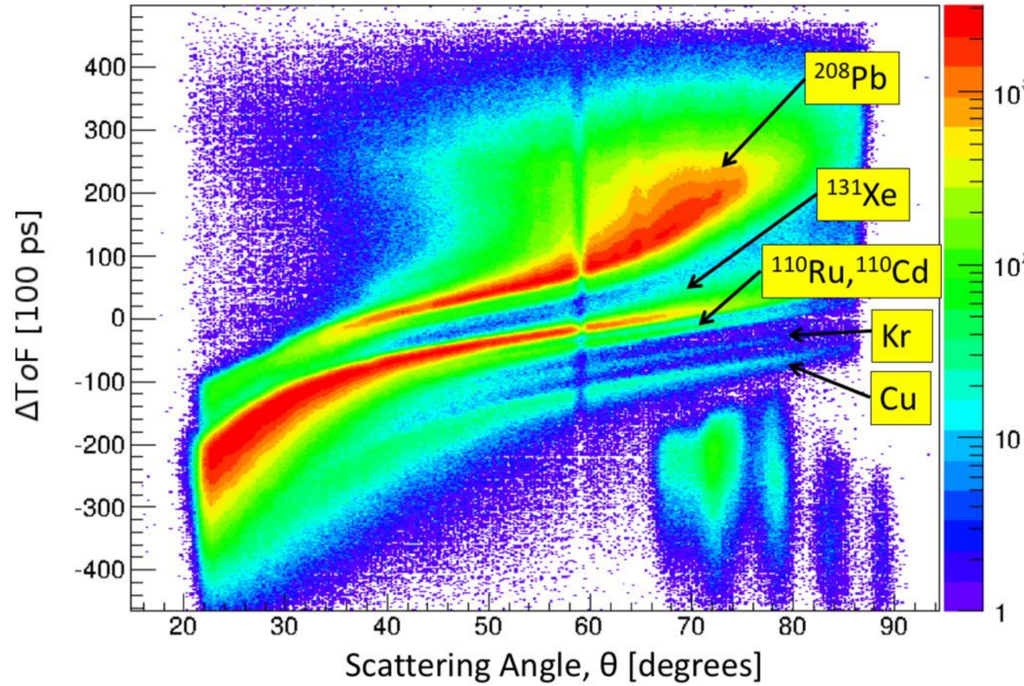




G.Savard et al., Nucl. Instr. Meth. B 266, 4086 (2008)

Coulomb excitation of ^{110}Ru with GRETINA and CHICO2

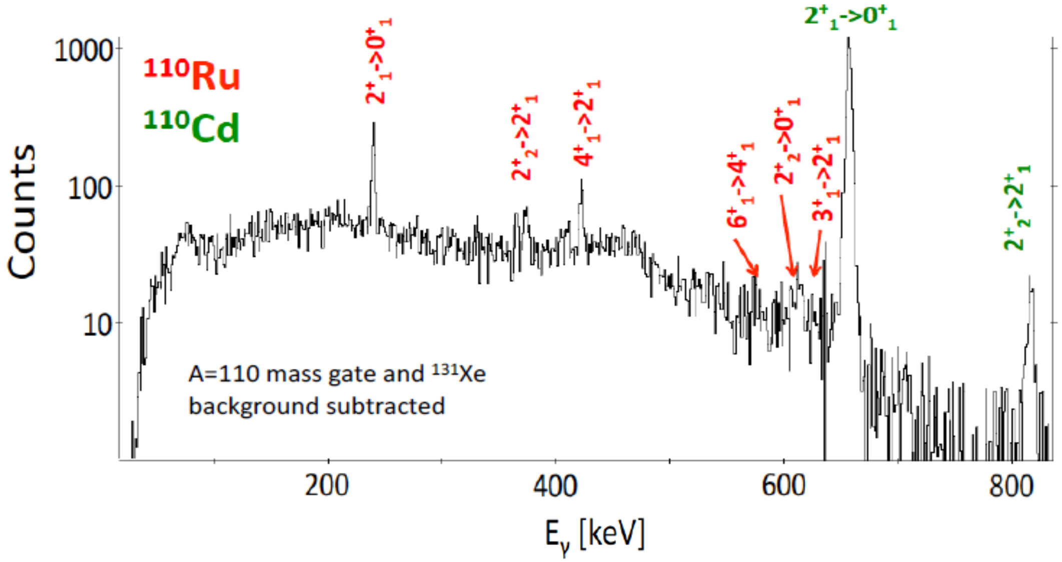




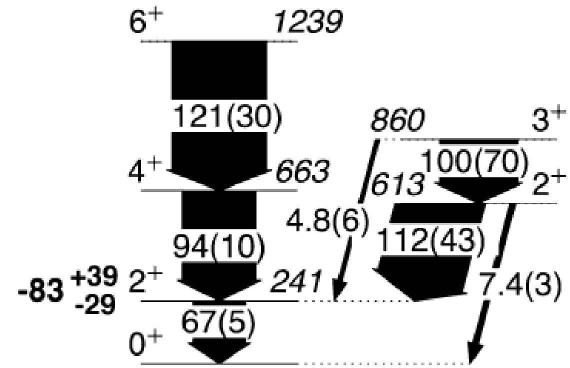
- ToF in CHICO2:
  $\Rightarrow$ some mass identification: $\frac{\Delta A}{A} \approx 10\%$
- position resolution in GRETINA and CHICO2:
  $\Rightarrow$ Doppler correction
- isobaric contaminants problematic

D.Doherty et al., Phys.Lett.B 766, 334 (2017)

Coulomb excitation of ^{110}Ru with GRETINA and CHICO2



$B(E2)$ in W.u.



D.Doherty et al., Phys.Lett.B 766, 334 (2017)

γ	$\varepsilon_1(2)/\varepsilon_1(2)$	$b(E2;\ 22 \to 0)$	$b(E2;\ 22 \to 21)$	$b(E2;\ 22 \to 21)/b(E2;\ 22 \to 0)$
0	∞	0	0	1.43
5	64.2	0.0074	0.011	1.49
10	15.9	0.028	0.051	1.70
15	6.85	0.053	0.143	2.70
20	3.73	0.067	0.357	5.35
22.5	2.93	0.0625	0.563	19.02
24	2.59	0.052	0.782	15.1
25	2.41	0.0425	0.865	20.6
26	2.26	0.0324	1.01	31.2
28	2.07	0.010	1.28	126
29	2.01	0.004	1.41	363
30	2.00	0	1.43	∞

A.S.Davydov and G.F.Filippov, Nucl. Phys. 8, 237 (1958)

$$\frac{E(2_2^+)}{E(2_1^+)} = 2.54$$

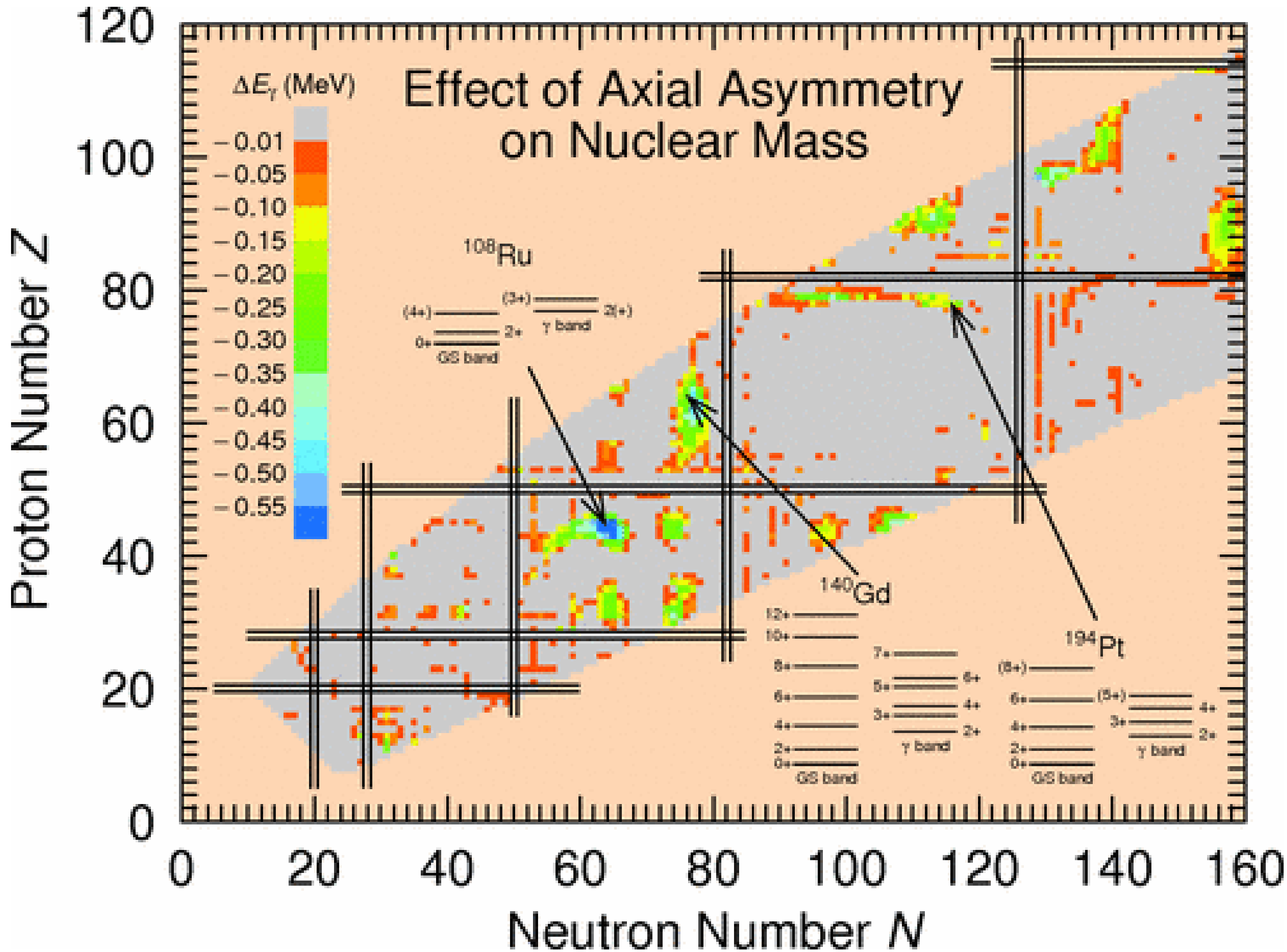
$$\frac{B(E2;2_2^+ \to 0_1^+)}{B(E2;2_1^+ \to 0_1^+)} = 0.11(1)$$

$$\frac{B(E2;2_2^+ \to 2_1^+)}{B(E2;2_1^+ \to 0_1^+)} = 1.67(65)$$

$$\frac{B(E2;2_2^+ \to 2_1^+)}{B(E2;2_2^+ \to 0_1^+)} = 15(6)$$

$B(E2)$ values compatible with $\gamma \approx 25°$

Regions of triaxilaity near the ground state

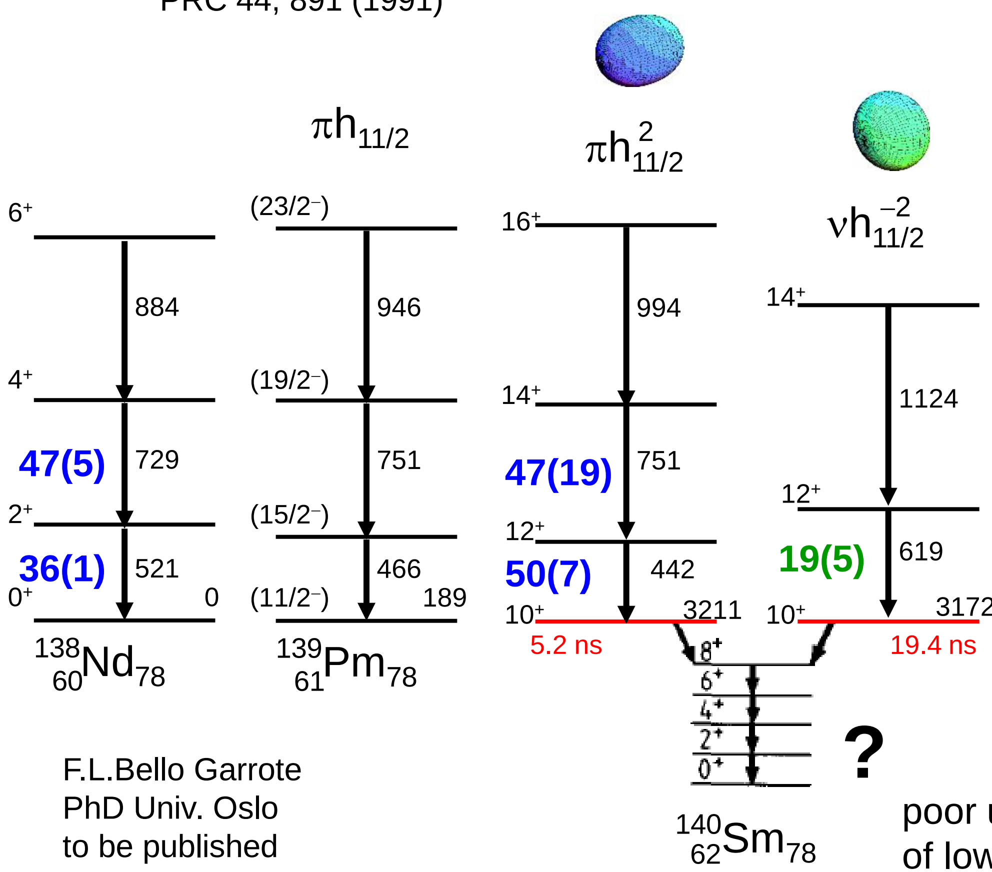


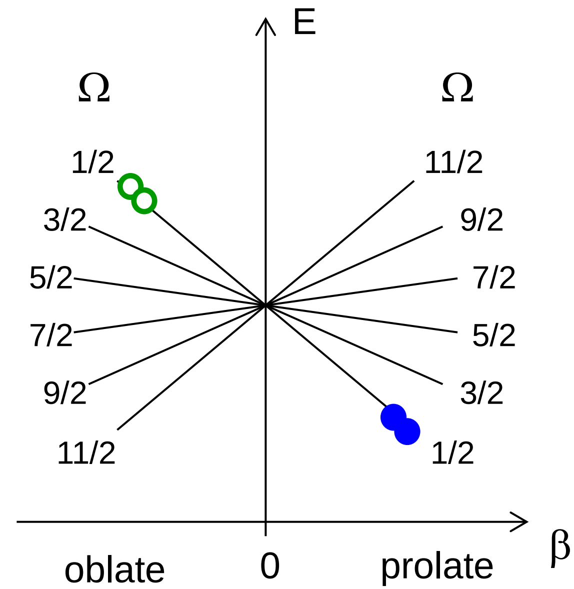
P. Möller et al., Phys. Rev. Lett. 97, 162502 (2006)

Shape coexistence in ^{140}Sm

B(E2) [W.u.]

M.A. Cardona et al.
PRC 44, 891 (1991)





rotationally aligned 2qp bands built on $\pi(h_{11/2})^2$ and $\nu(h_{11/2})^{-2}$

indirect evidence for shape coexistence at intermediate spins

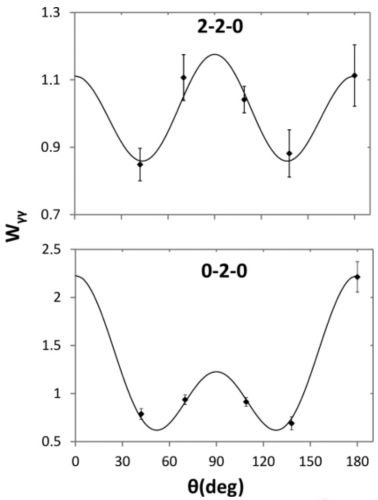
poor understanding of low-spin structure

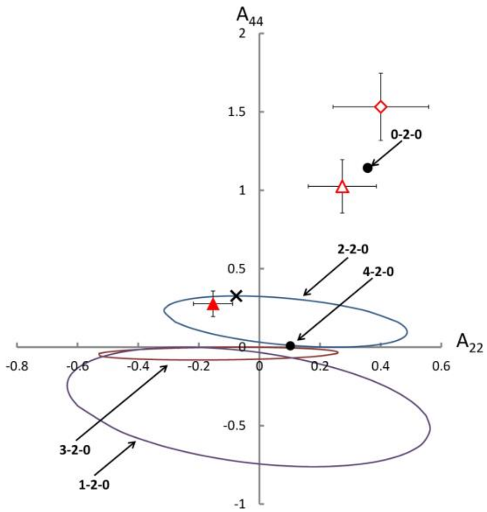
need B(E2) and Q_s

⇒ Coulomb excitation

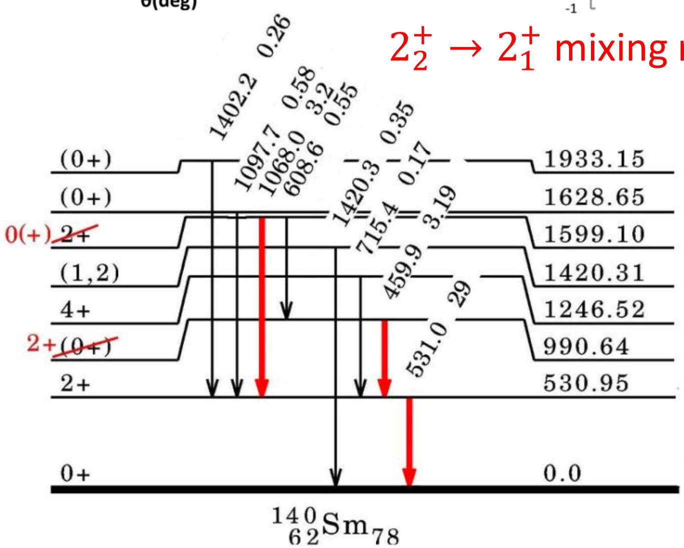
Shape coexistence also at low spin?

angular correlation measurement
$^{112}Cd(^{32}S,p3n)^{140}Eu \rightarrow {}^{140}Sm$



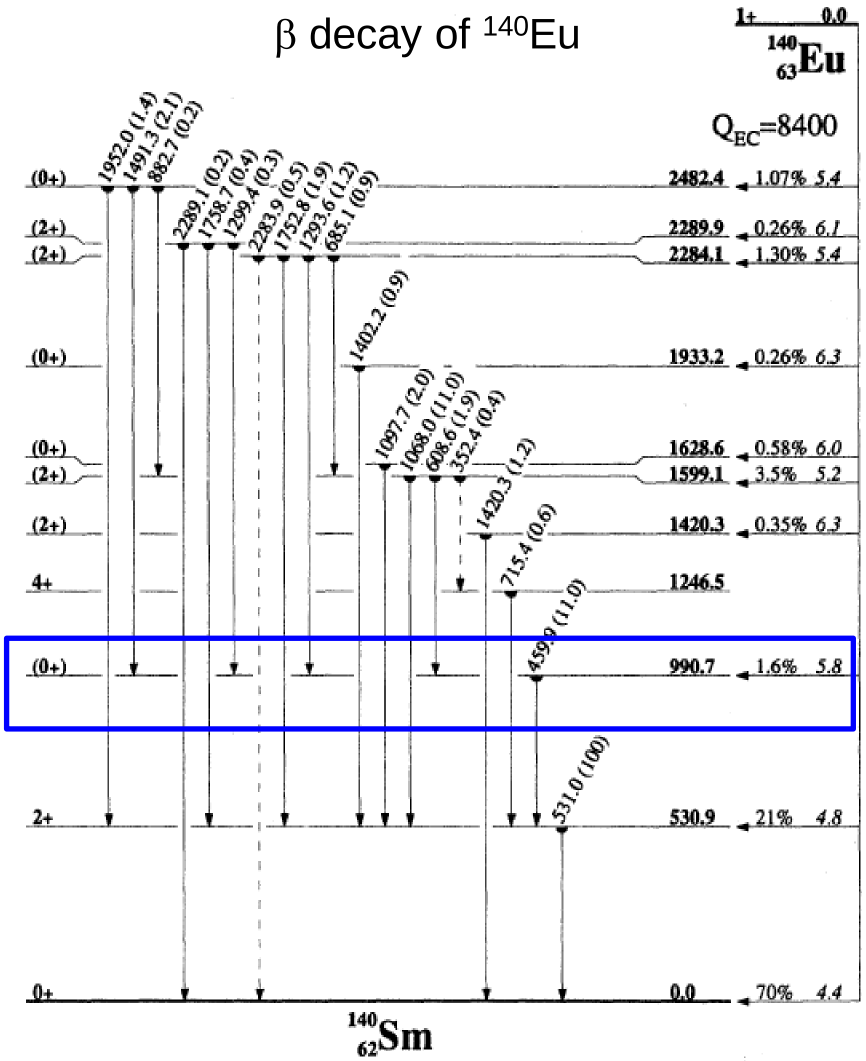


$2_2^+ \rightarrow 2_1^+$ mixing ratio: 98% E2



J.Samorajczyk et al., PRC 92, 044322 (2015)

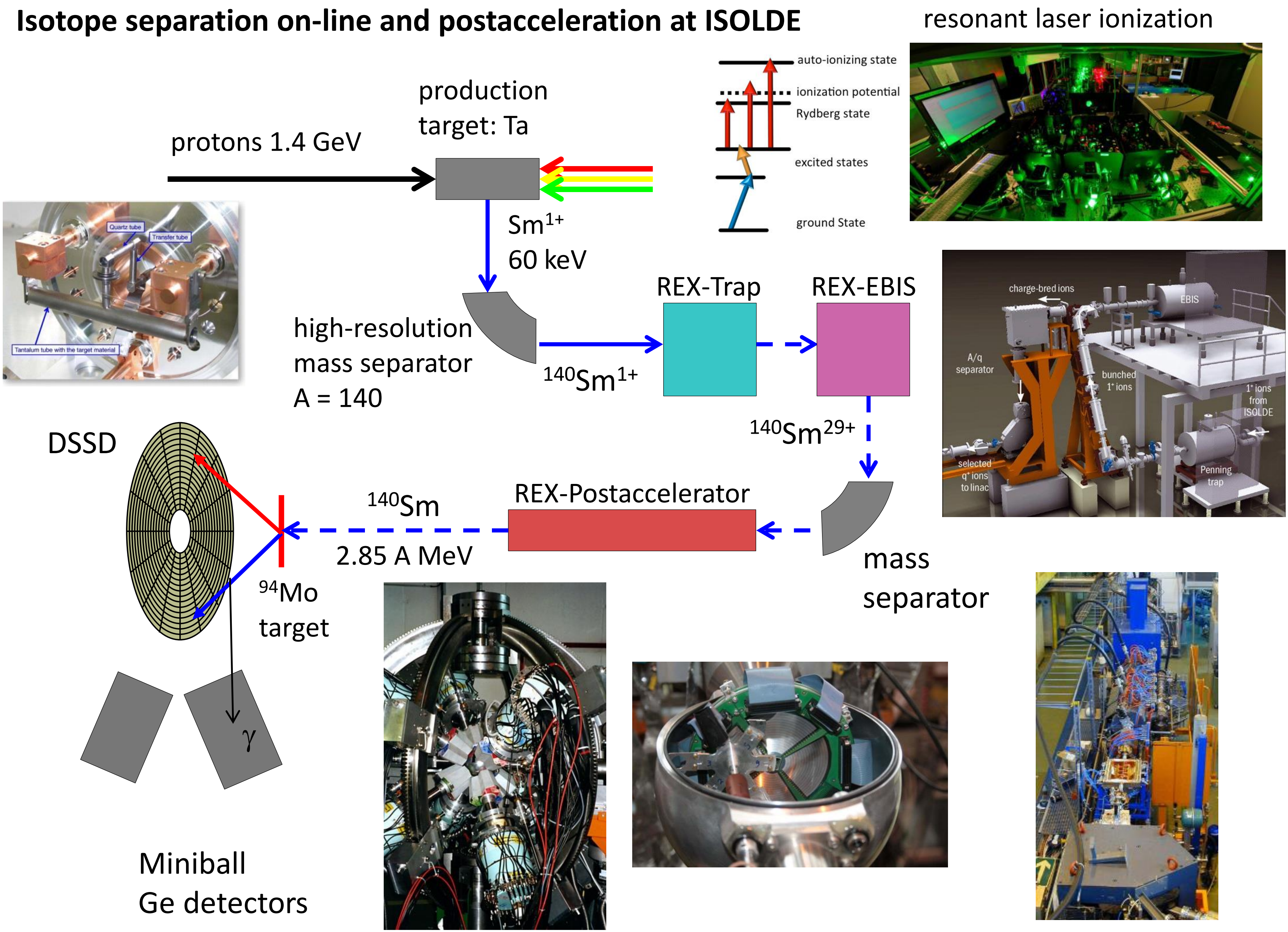
β decay of ^{140}Eu



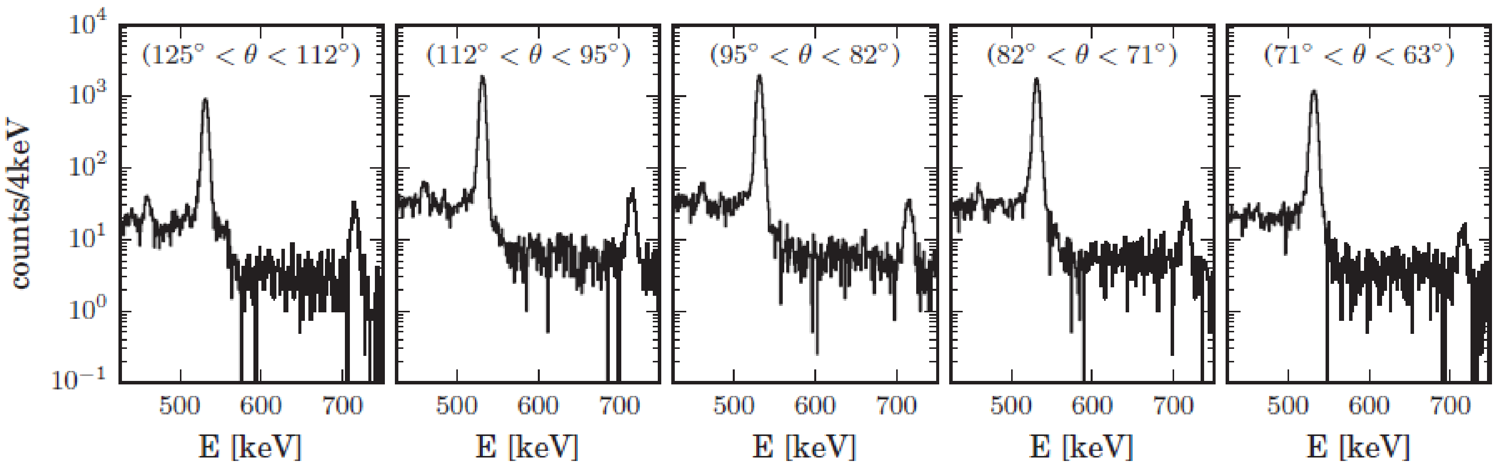
R.B. Firestone et. al.
PRC 43, 1066 (1991)

low-lying (0^+) state ?

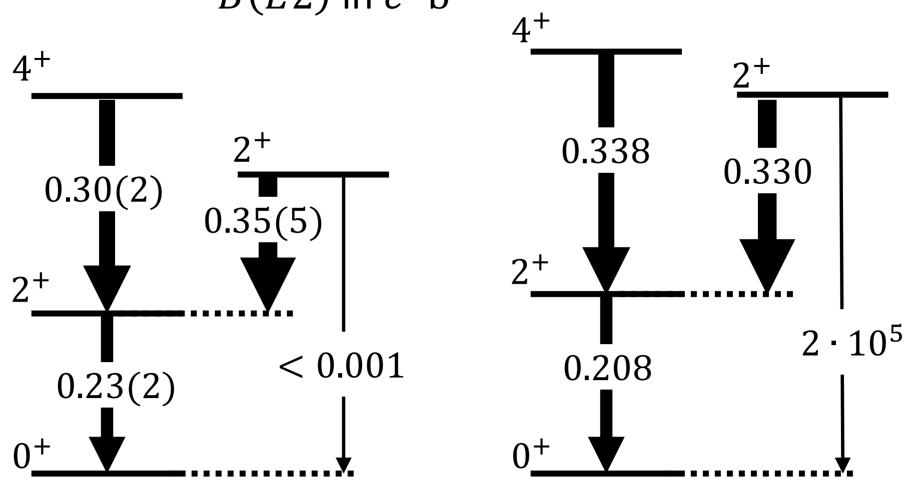
Isotope separation on-line and postacceleration at ISOLDE



Coulomb excitation of ^{140}Sm

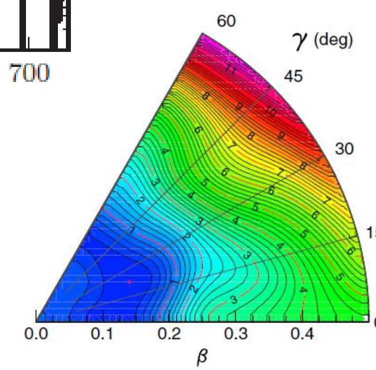


$B(E2)$ in e^2b^2



experiment

Gogny 5DCH



$Q_s(2_2^+) = +0.11\ eb$

$Q_s(2_1^+) = -0.12\ eb$

$Q_s(2_1^+) = -0.06^{+0.41}_{-0.15}\ eb$

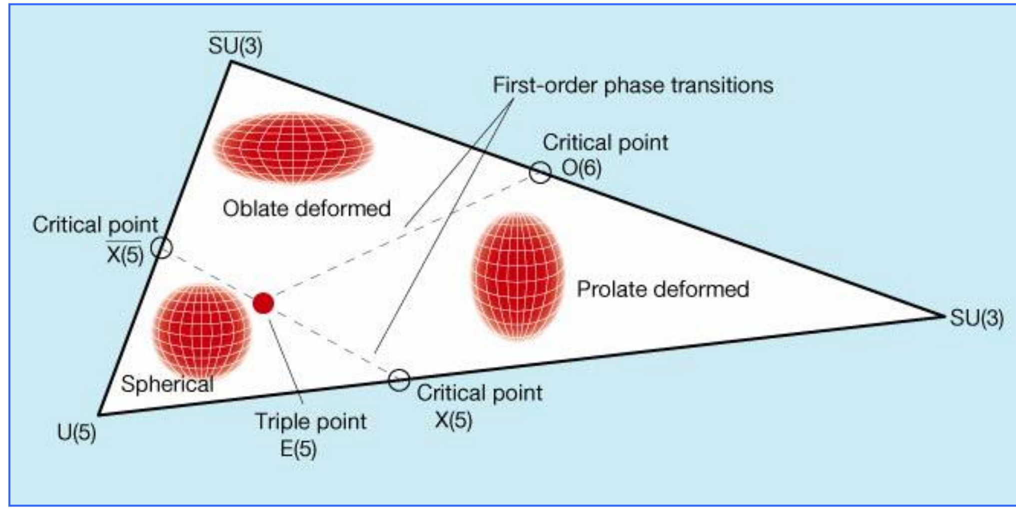
γ rigid?
γ soft?

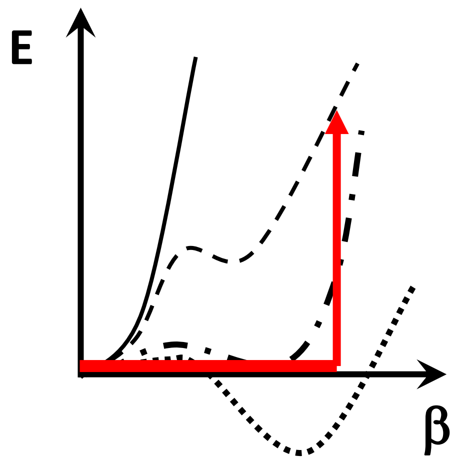
M. Klintefjord et al. Phys. Rev. C 93, 054303 (2016)

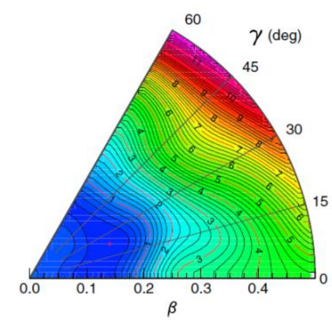
Phase diagram of nuclear shapes

Quantum phase transitions in equilibrium shapes of nuclei

control parameters: *N*, *Z*







approximation: infinite square-well potential

- analytically solvable
- certain characteristics of 1. order phase transition
- X(5) critical point symmetry

F. Iachello, Phys. Rev. Lett. 87, 052502 (2001)

square well that is also independent of γ

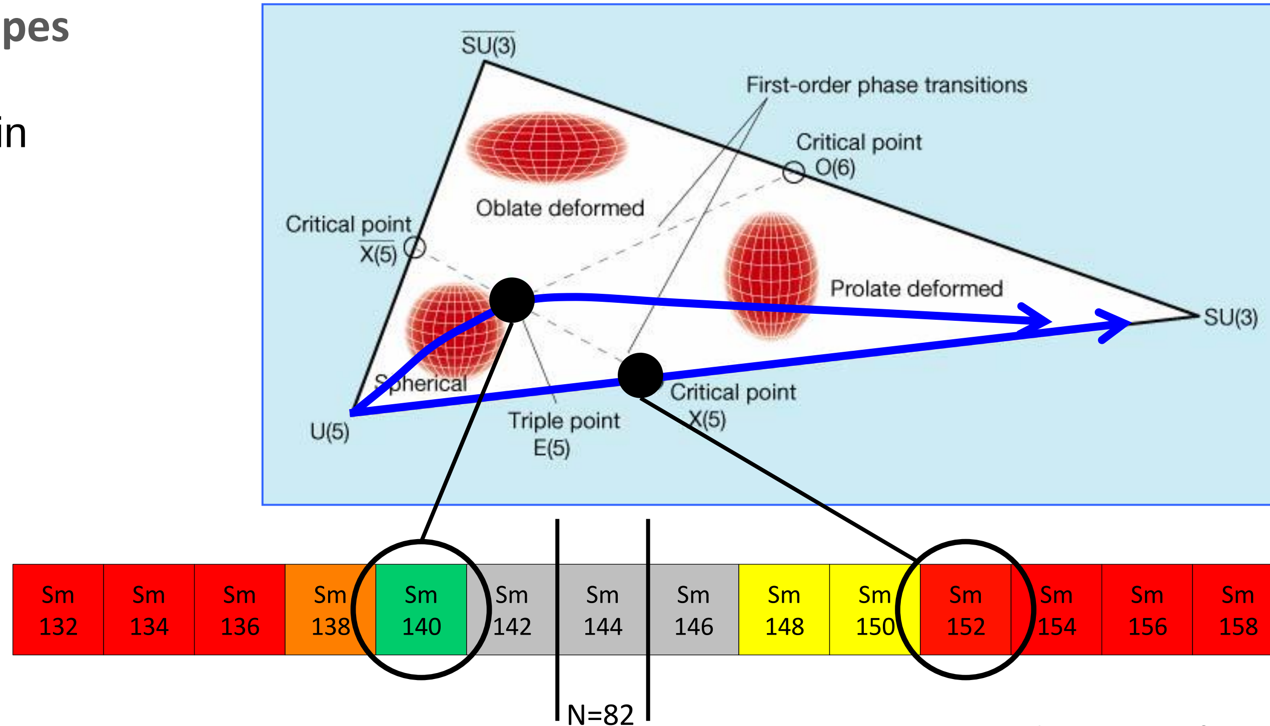
- also analytically solvable
- characteristics of 2. order phase transition
- E(5) critical point symmetry

F. Iachello, Phys. Rev. Lett. 85, 3580 (2000)

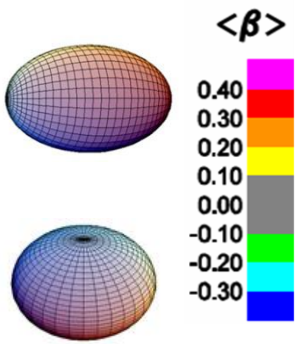
Phase diagram of nuclear shapes

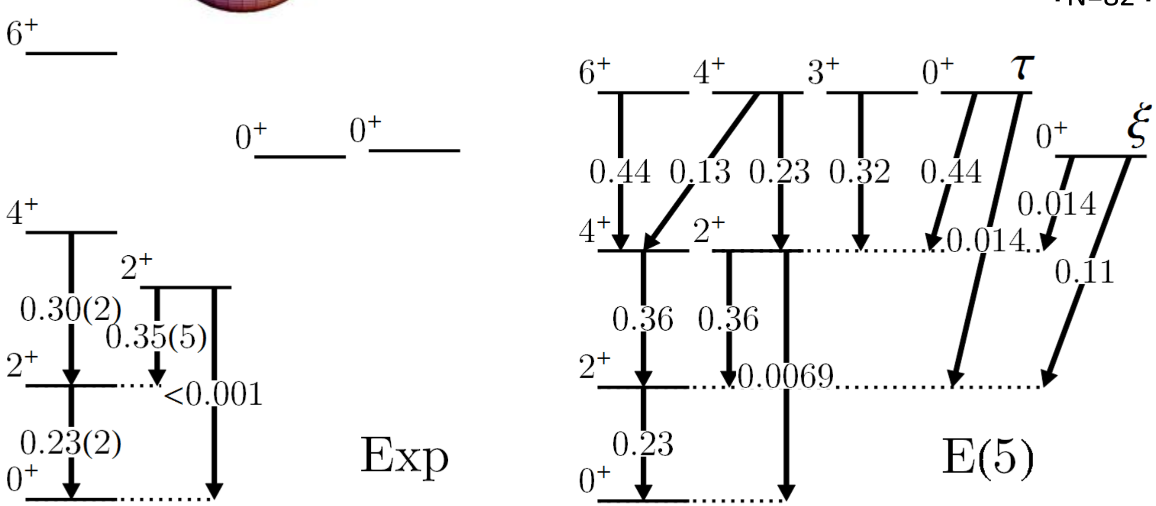
Quantum phase transitions in equilibrium shapes of nuclei

control parameters: *N*, *Z*



R. F. Casten and N. V. Zamfir
PRL 87, 052503 (2001)





new HIE-ISOLDE experiment
August 2017

M. Klintefjord, PhD Univ. Oslo 2016
M. Klintefjord et al. Phys. Rev. C 93, 054303 (2016)