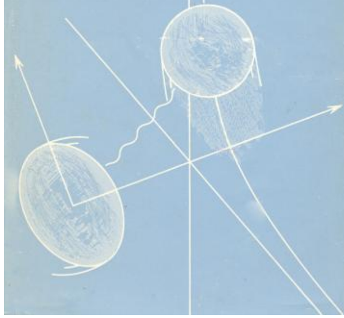
Coulomb excitation - a tool for nuclear shapes and more



- Introduction
- Theoretical aspects of Coulomb excitation
- Experimental considerations, set-ups and analysis techniques
- Recent highlights and future perspectives

Lecture given at the
Ecole Joliot Curie 2012
Wolfram KORTEN
CEA Saclay

Coulomb excitation – the different energy regimes

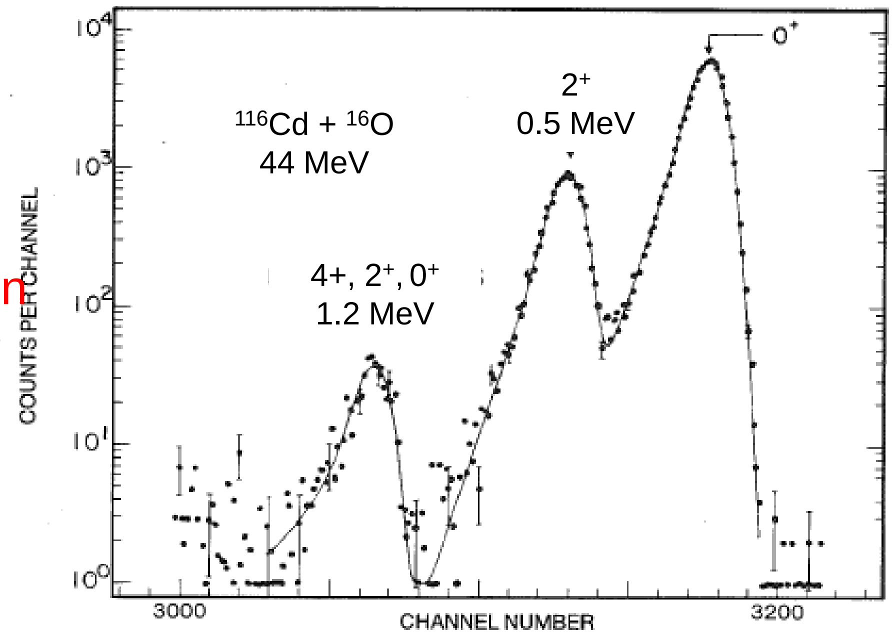
	Low-energy regime (< 5 MeV/u)		**High-energy regime (>>5 MeV/u)**	
Energy cut-off	$\Delta E_{max} = \frac{\hbar v_\infty}{a\,\varepsilon} \approx 2\,\mathrm{MeV}$		$\Delta E_{max} = \hbar c \frac{\beta\gamma}{a\,\varepsilon} \approx 10\mathrm{MeV}(\beta = 0.4)$	
Spin cut-off:	L_{max}:	up to 30ħ	mainly 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

Coulomb excitation with stable beams

Early experimental approach, until ~1970: light ion beams (p,α,^{12}C,^{16}O, …)
Particle spectroscopy using spectrometers or Si detectors



Advantages:
Direct measurement of $P=\sigma/\sigma_{ruth}$

Disadvantages :
Si detectors have limited energy resolution (>100 keV), despite thin targets etc.

High-resolution spectrometers have very limited angular coverage ➔angular scan

➔ limitation to first excited state(s) and nuclei with low level density

Method limited to light beams (α, ^{12}C, ^{16}O, ^{20}Ne)
since energy resolution scales with mass (E/A~const.)

Coulomb excitation with stable beams

1970/80: Particle-gamma coincidence spectroscopy using NaI and/or Ge detector arrays in conjunction with charged particle detectors

Advantages:
high resolution (few keV with Ge detectors) combined with
high efficiency (close to 100% with NaI arrays)

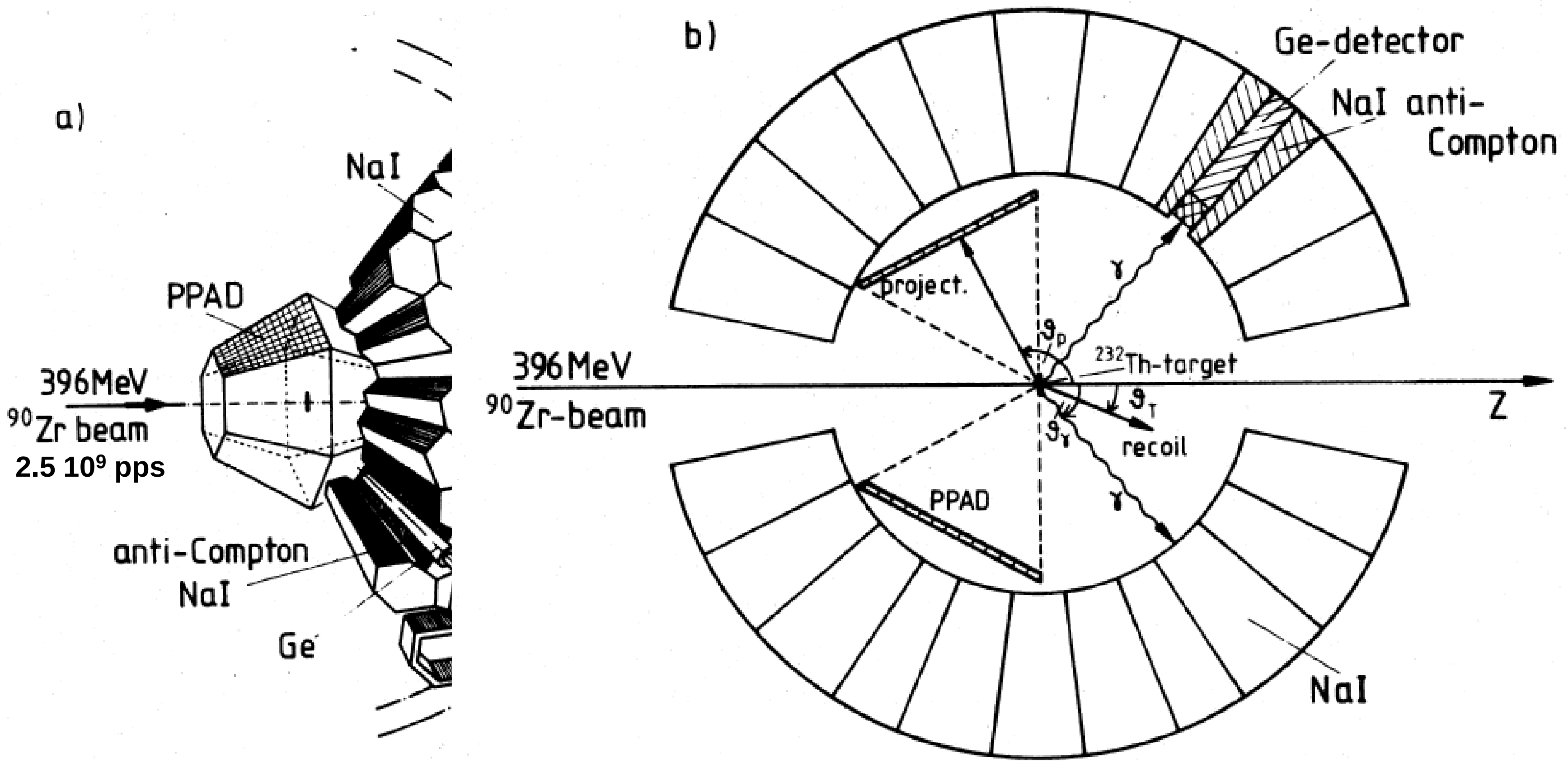
Disadvantages :

Energy resolution limited by Doppler effect
➔ high granularity for detection of both particle and gamma rays

Need to detect particle-gamma coincidences
➔ 4π arrays or reduced (coincidence) efficiency

Indirect measurement $Y_\gamma (I_i \rightarrow I_f) \rightarrow \sigma(I_i,\theta_{cm})$
➔ need to take into account branching ratios, particle–γ angular distribution,
➔ corrections needed for efficiencies, etc.

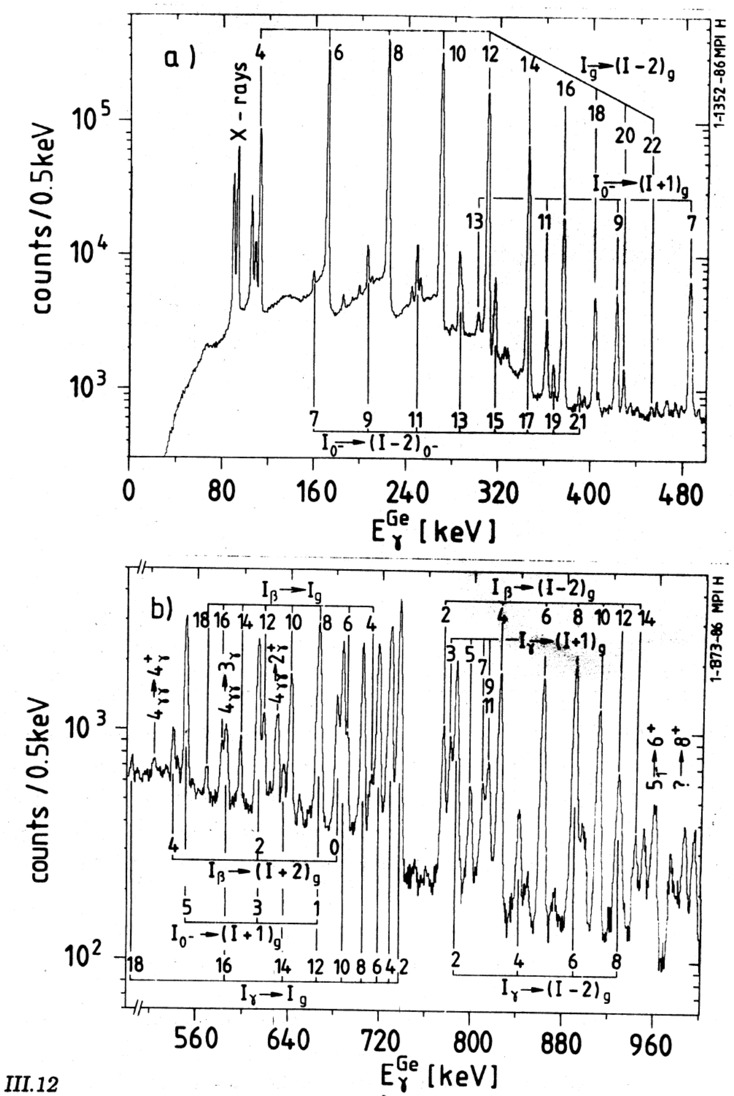
Experimental setup for multi-step Coulomb excitation experiments with stable beams



Advantage: 4π array for both particles and γ rays ; good spatial resolution (few °)
Identification of reaction partners through Time-of-Flight

Limitation: low resolution for NaI scintillators,
low efficiency for Ge detectors (~0.5%) due to large distance (~25cm)

Example for a multi-step Coulomb excitation experiment with a stable heavy ion beam



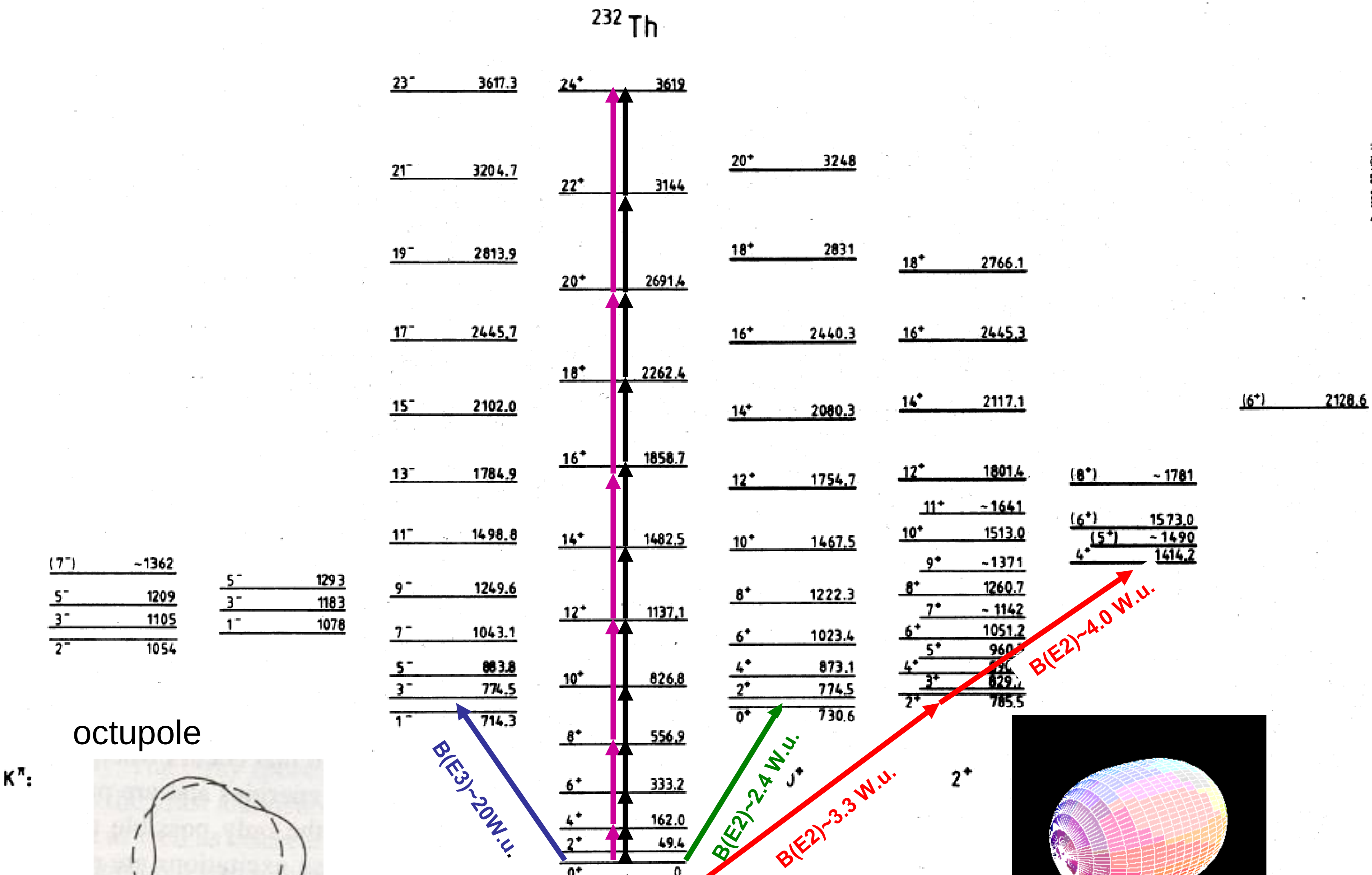
III.12

ex.: ^{90}Zr + ^{232}Th @ 396 MeV (4.44 MeV/u)
backward angle scattering (θ > 100°)
➔ favours multi-step excitation (I~20ħ)
and higher lying states (β, γ, oct. vibration)

Excellent energy resolution (4keV@1MeV)
but low Ge-Ge coincidence efficiency

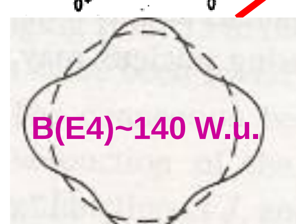
NaI-Ge concidences and γ-ray multiplicity
still allow to disentangle the level scheme

Multiple rotational band structure in ^{232}Th

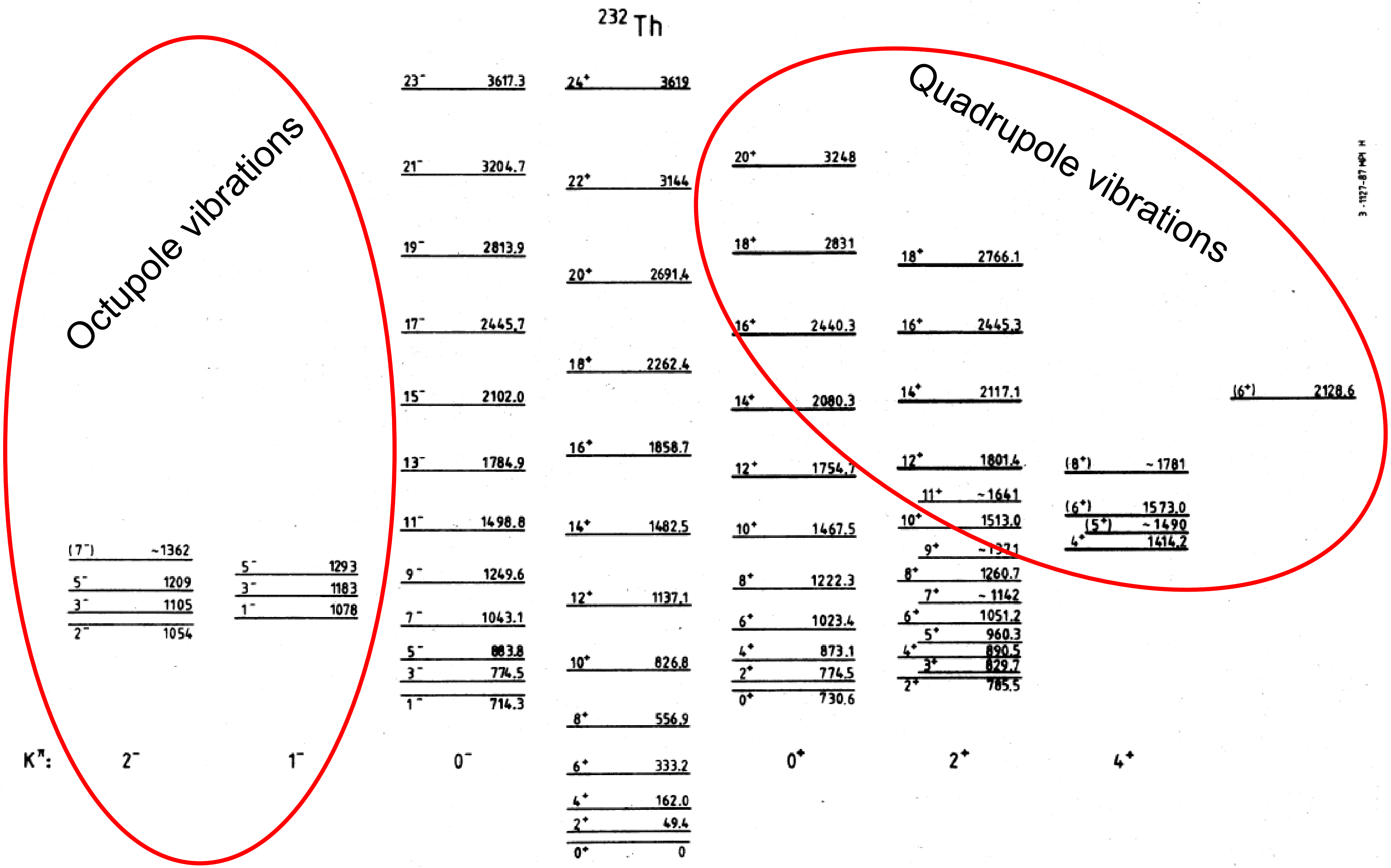


octupole

quadrupole + hexadecapole



Multiple rotational band structure in ^{232}Th



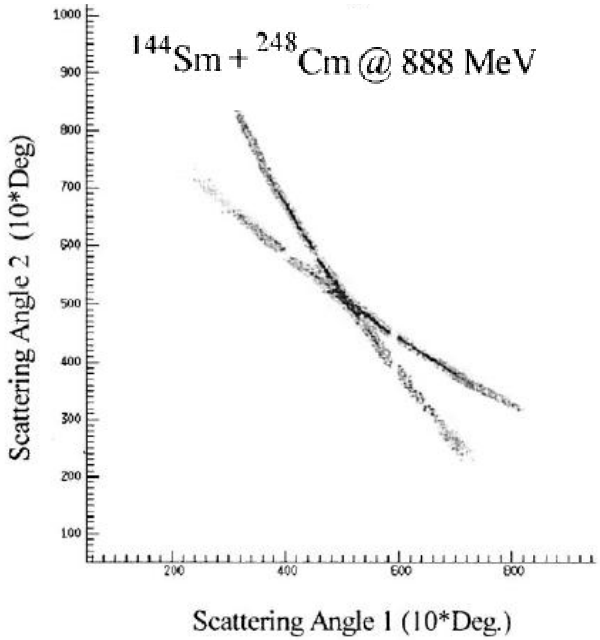
Multiple "vibrational" bands incl. inter-band B(σλ) and intra-band B(E2) values (rotational model assumptions within the bands)

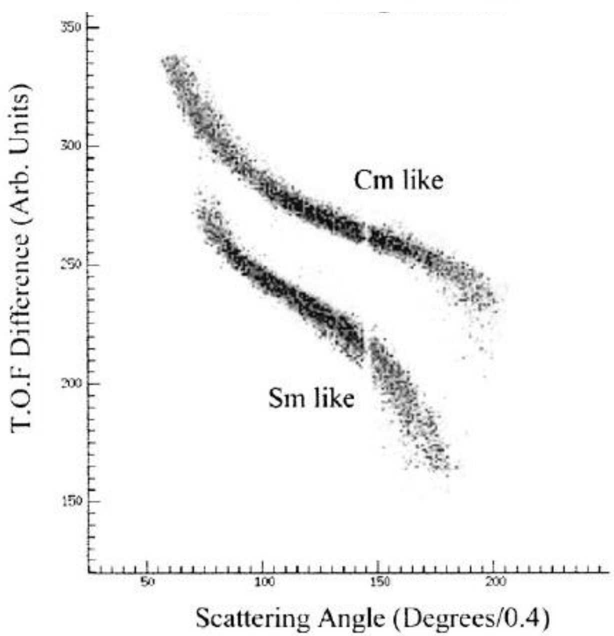
4π HPGe arrays with charged particle detectors

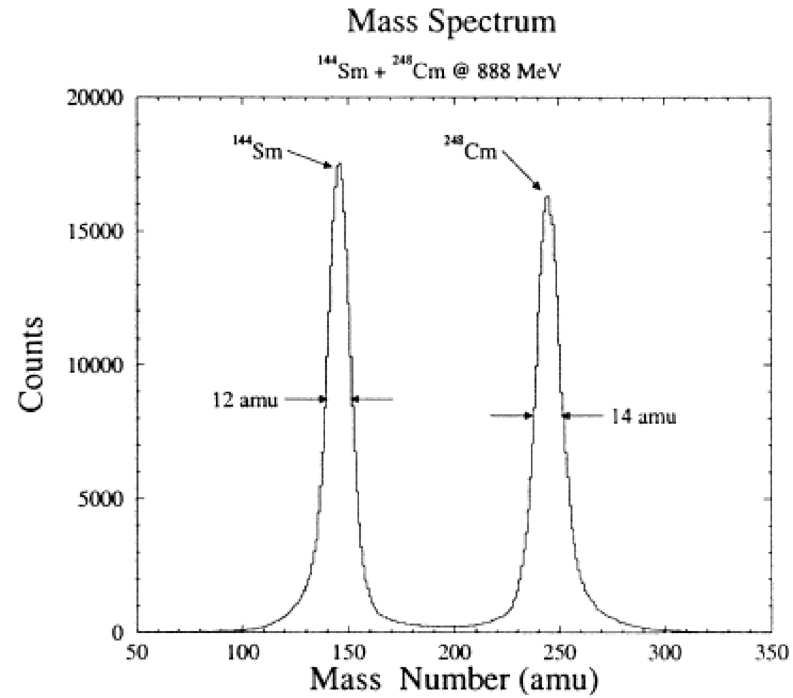
From ~1995: Ex. Chico 4π PPAC array (Univ. Rochester) and Gammasphere

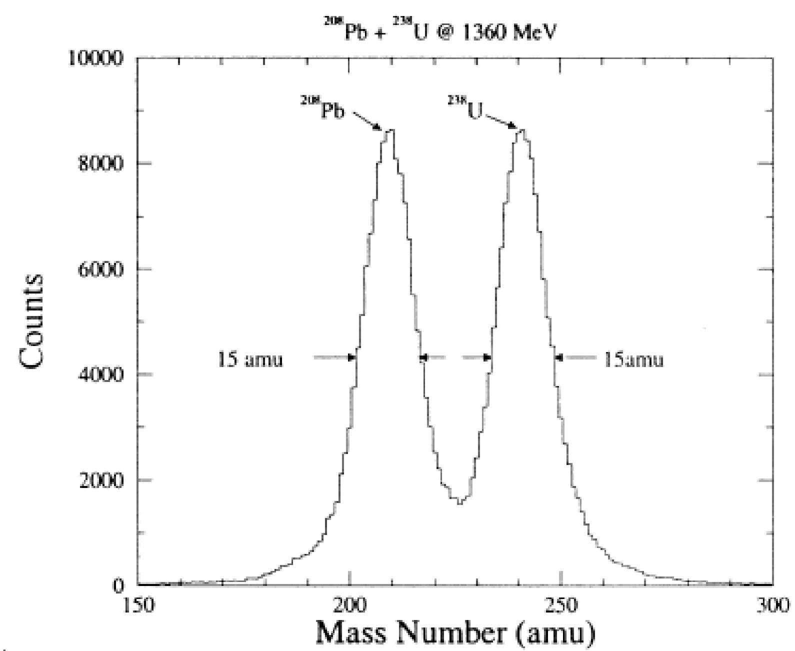
M.W.Simon, D. Cline, C.Y. Wu et al., Nucl. Inst. Meth. A452 (2000) 205

Performance of Chico PPAC

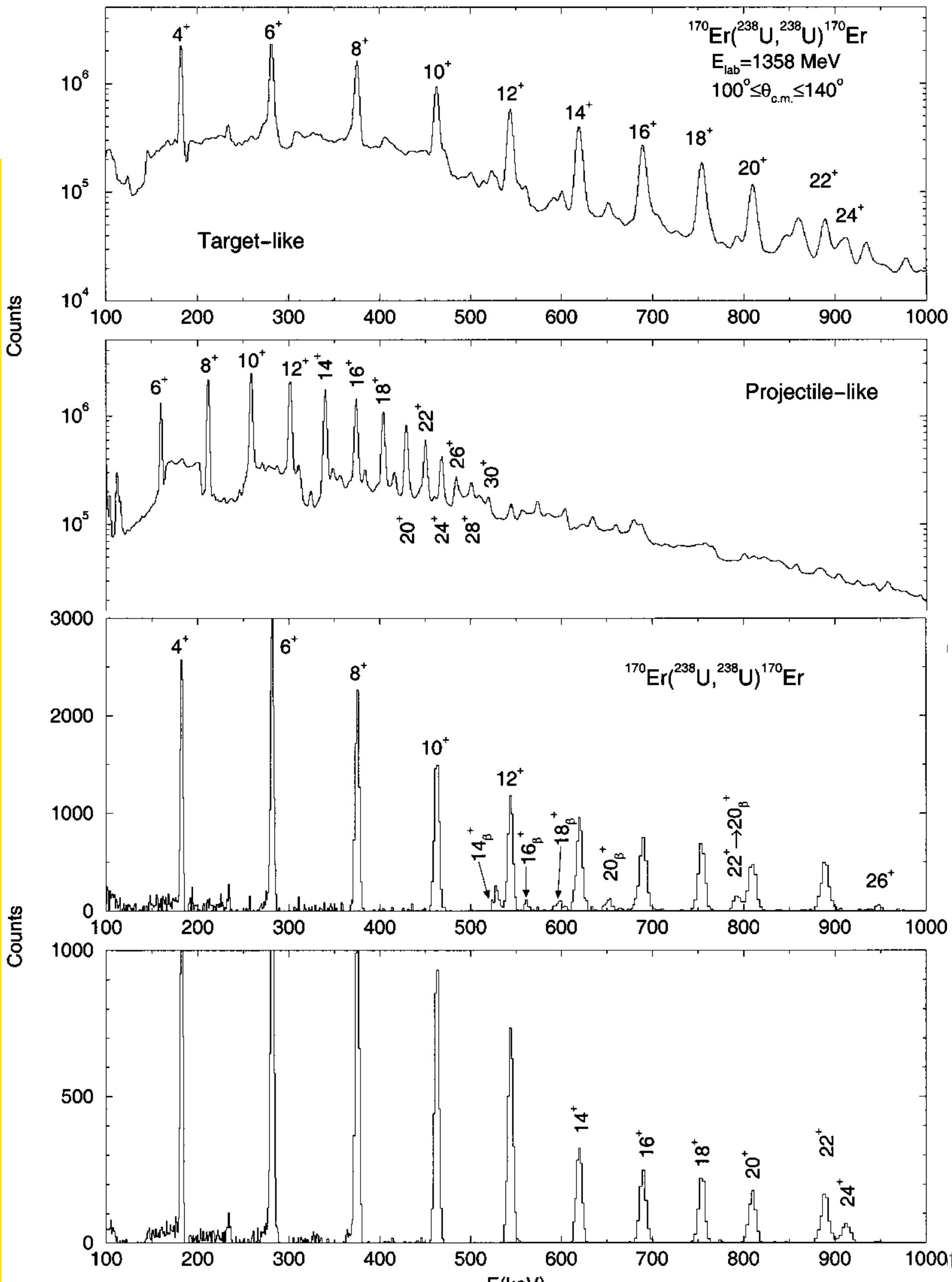


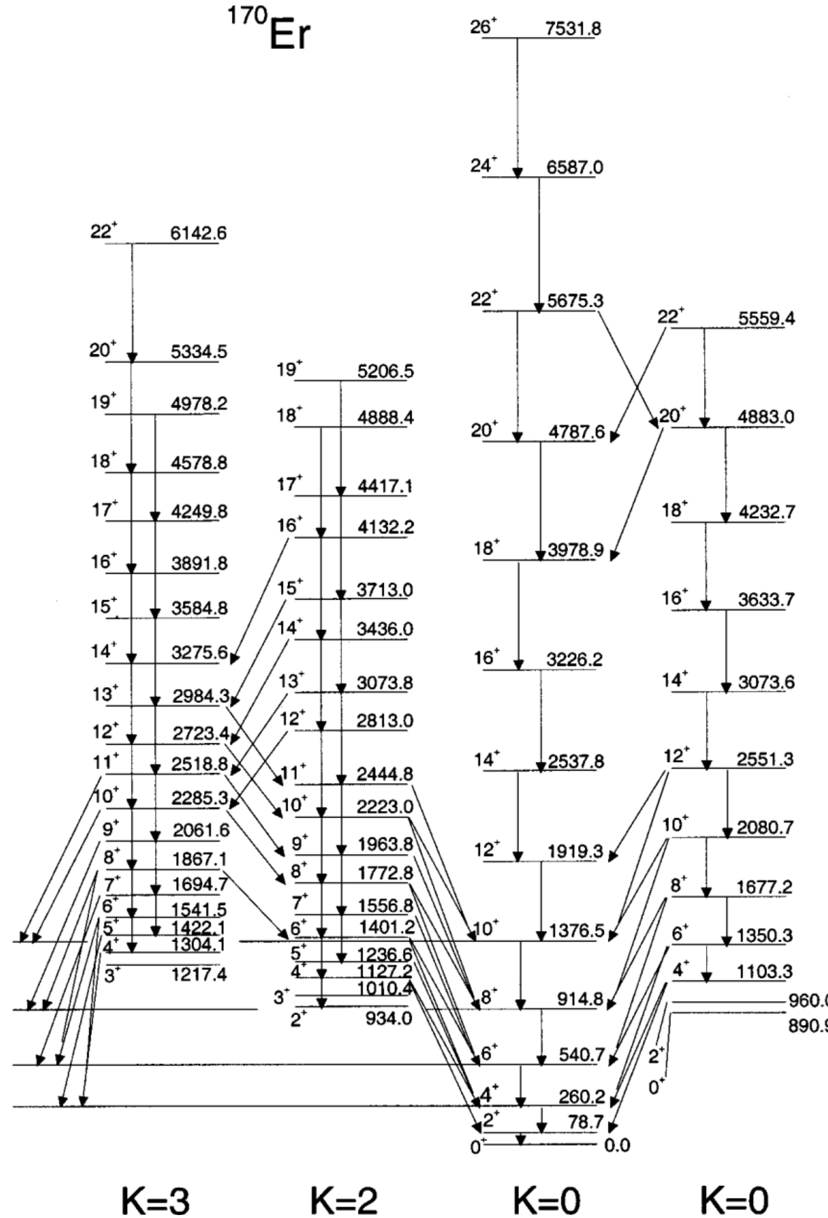






Some results from Chico and Gammasphere





Experimental results from Coulomb excitation

Need to deduce:

- **Velocity vectors of recoiling ions (eventually also masses and reaction Q-value)**
- **Correct for Doppler shift of de-excitation γ-rays on an event-by-event basis**
- **Identify γ-rays which were emitted by each recoiling ion on an event-by-event basis**
- **Normalize projectile yields using an accurately known B(E2): target or low-lying state**
- **Determine Coulomb excitation cross sections to excited states as function of impact parameter.**
- **Use computer codes to extract individual electromagnetic matrix elements from measured yields for both target and projectile excitation.**

Expected results

- **Observation of (new) excited states, in particular (higher lying) collective states (2_1^+ 4_1^+ 2_2^+, …)**
- **B(E2) and B(M1) values between (all) low-lying states, eventually also higher B(Eλ) values**
- **Sign and magnitude of static E2 moments of excited states**
- **Signs and magnitudes of observable products of Eλ matrix elements**
- **M1 moments of excited states may be obtained from the measured attenuation of the γ-ray angular correlations for ions recoiling in vacuum**

Rochester - Warsaw GOSIA computer code

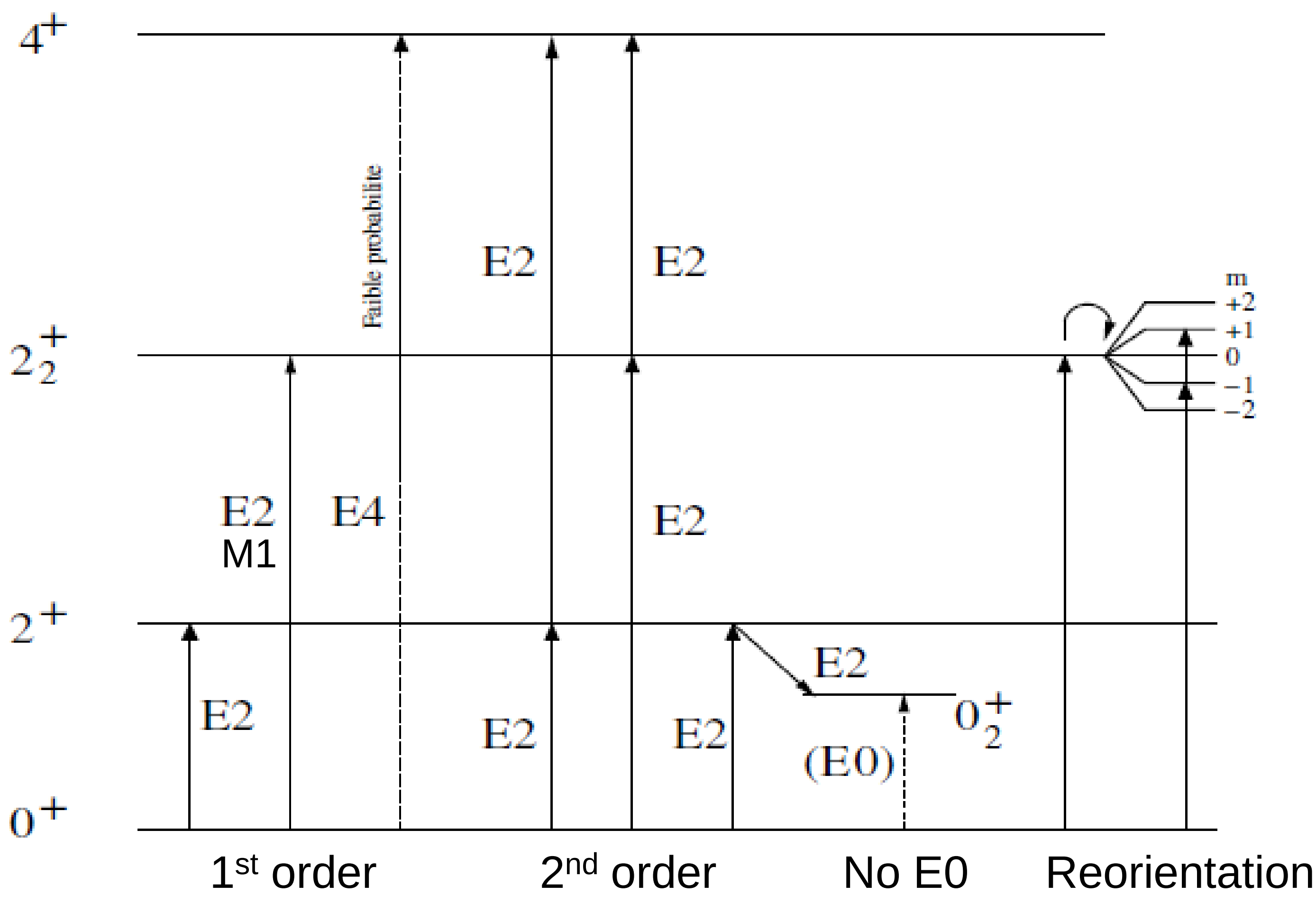
Irfu cea saclay

I) Excitation stage:

1) Semi-classical approximation and pure electromagnetic interaction
   - max. 5% deviation from full quantal calculation at η~30
2) Classical hyperbolic trajectories
   - symmetrised in energy : $v_\infty \rightarrow ½(v_i+v_f)$
   - atomic screening, vacuum polarization, relativistic effects ignored
     ➔ change in distance of closest approach <0.2%
3) Virtual excitation of unobserved states
   - Include higher lying (unobserved) states
   - Include Giant E1 Resonance through dipole polarisation term (12%)
4) Mutual excitation of colliding nuclei
   - Monopole-multipole interaction of either the target or projectile
     ➔ multipole-multipole correction very small (0.05% in mass-70)
   - Mutual excitation explicitly treated in new code (Gosia2)
5) Particle solid angle and target thickness
   - Numerical integration over solid angle of particle detectors and energy loss in the target

➔ excitation probability and statistical tensor for ALL excited states

Model for GOSIA excitation stage



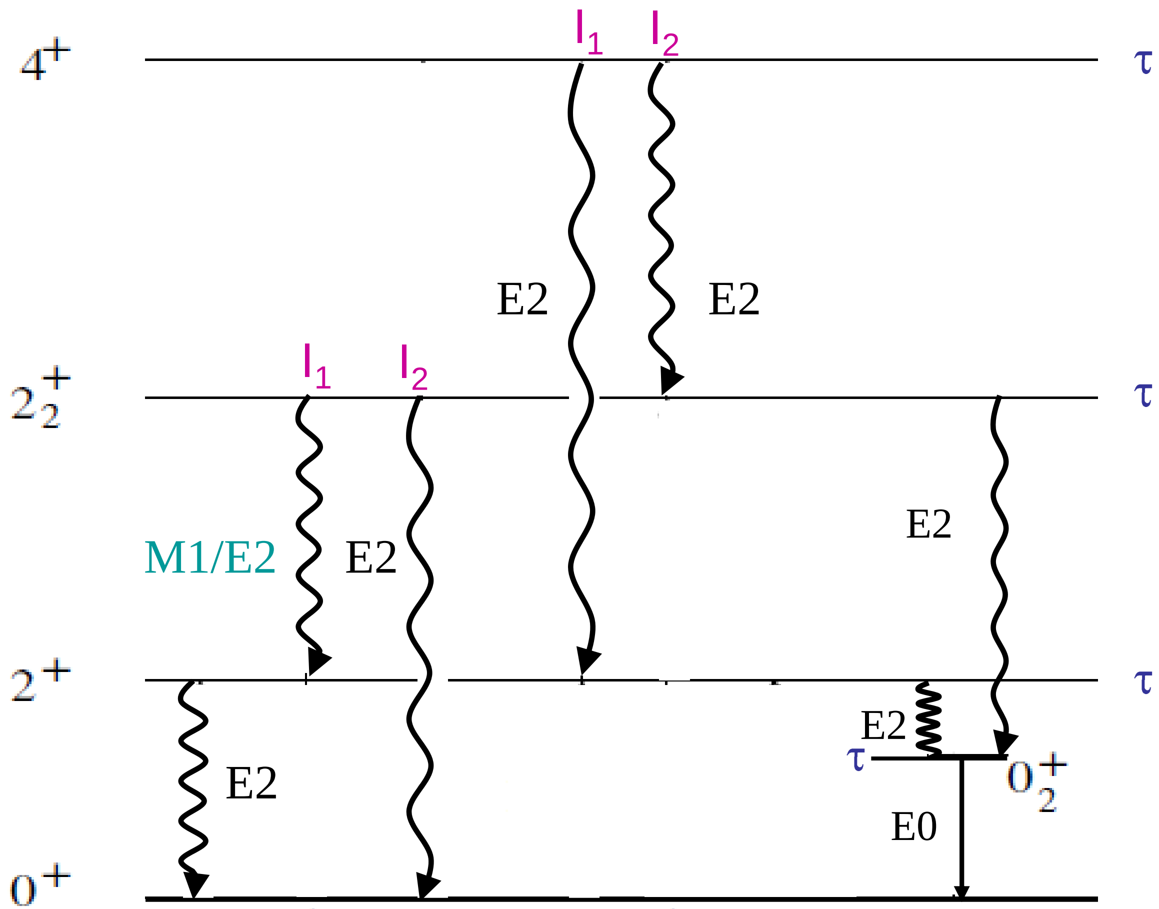
Rochester - Warsaw GOSIA computer code

II) Decay stage:

1) Use statistical tensors calculated in the excitation stage
   - ➢ Information on excitation probability and initial sub-state population
2) Include cascade feeding from higher-lying states
3) Include deorientation of the angular distribution (due to recoil in vacuum)
   - ➢ two-state model by Brenn and Spehl to model hyperfine interactions
4) Include Relativistic transformation of solid angles
5) Include solid angle of gamma-ray detectors
   - ➢ Simplified (cylindrical) detector geometry with attenuation factors
6) Possibility to include in-flight decays for long-lived states

➔ calculate gamma ray yields for all possible transitions

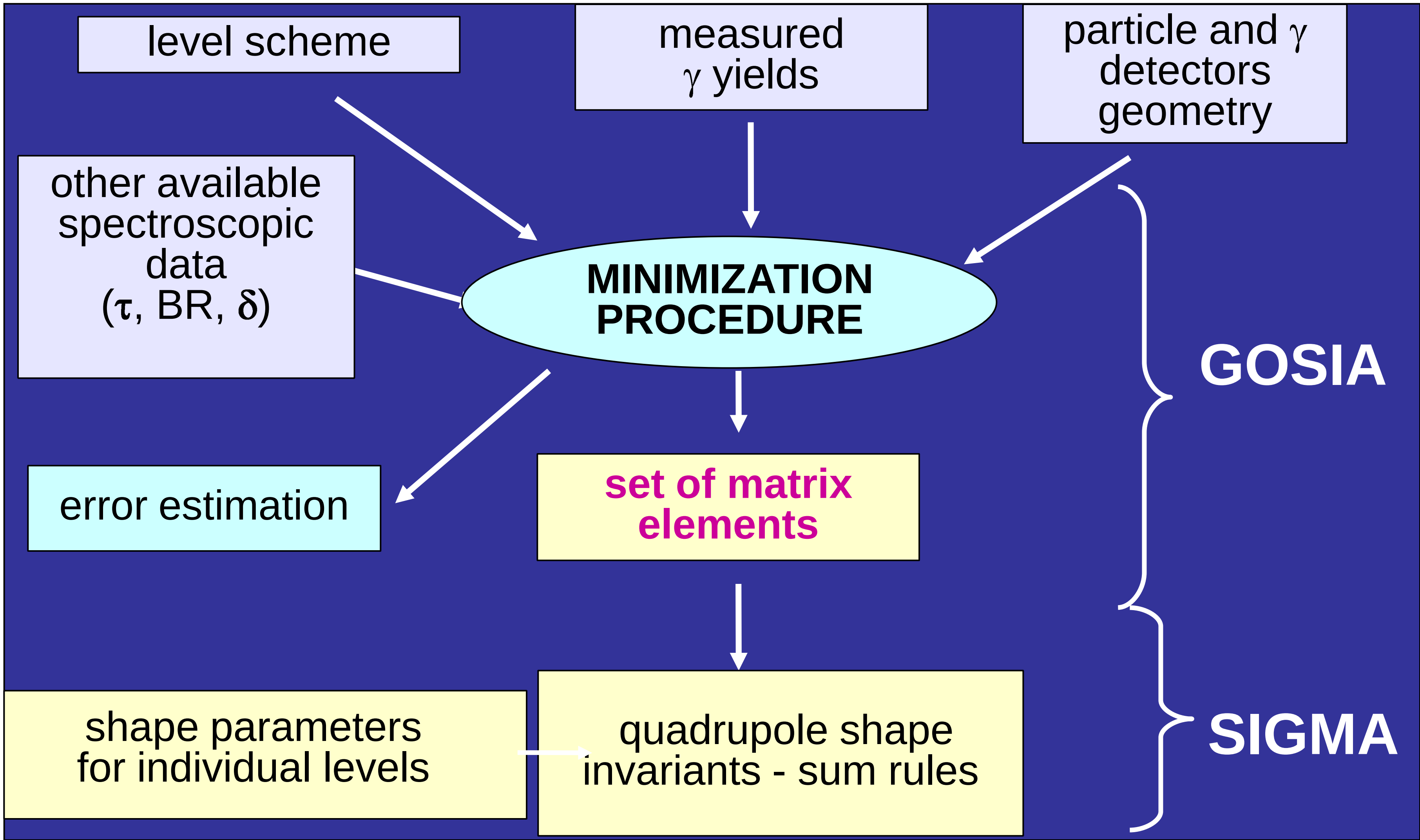
Model for GOSIA decay stage



Lifetimes, branching and mixing ratios from independent sources can be added as additional constraints

Rochester - Warsaw GOSIA computer code

GOSIA is a semi-classical coupled-channel Coulomb excitation code using a two-stage approach and a least-squares search to reproduce experimentally observed gamma-ray intensities



Coulomb excitation studies using radioactive beams

Production and reacceleration schemes for ISOL beams at different facilities

GANIL/SPIRAL: Heavy Ion beam (50-100 MeV/u) & Cyclotron (3-20 MeV/u)

ISOLDE/REX: Proton beam (1.4 GeV, $3 \cdot 10^{13}$/pulse) & HI Linac (3 MeV/u)

TRIUMF/ISAC: Proton beam (500 MeV, 0.1 mA) & HI Linac (2/5 MeV/u)

ORNL/HRIBF: Low-energy proton induced fission & Tandem (2-5 MeV/u)

Principal differences in

- production ➔ fragmentation, spallation, fission
- preparation ➔ extraction, selection, ionisation
- availability ➔ elements & mass range, purity
- acceleration ➔ beam energy & possible reactions

"Ideal" ISOL facilitiy does not yet exist, soon SPIRAL2, HIE-ISOLDE, ISAC2
Highest yields over largest part of the nuclear chart (not only fission fragm.)
Largest variety and best purity of beams with well-defined beam energy

Experimental considerations for RIB experiments

Principle

- Scattering of a (radioactive) ion beam on a (high-Z) target at "safe" energy
- Choice of target depends (mainly) on available beam energy and state(s) of interest

Experimental Method:

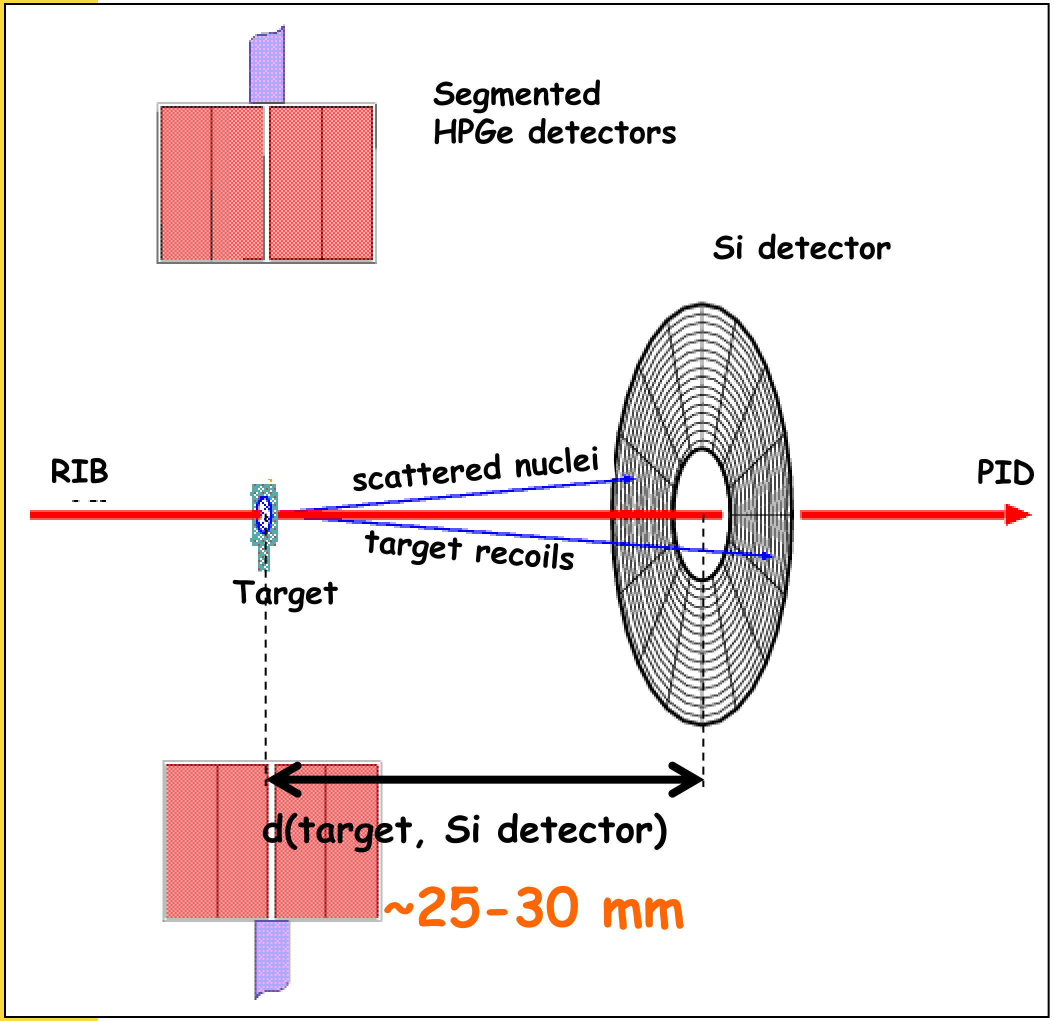
- Use thin targets so that excited nuclei (and the unscattered beam) recoil in vacuum
- Measure scattering angles and velocities of recoiling ions over a wide range of scattering angles
- Detect deexcitation γ-rays in coincidence with the scattered ions

Principal difficulties

- Background from radioactive decay of beam particles (Rutherford)
- Beam contaminants (isobars)
- Low beam intensity and limited statistics (in particular of higher lying states)

Coulomb excitation set up with radioactive ions

- **Identification of reaction partners**
  - Energy deposition in Si detector



- **Differential cross section**
  - annular rings
  - projectile and recoil detection

  → 30°< θ_{CM} < 130°

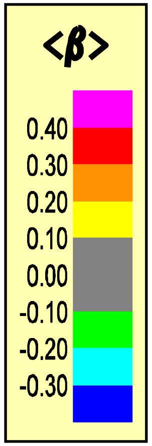
- **Identification of excited states**
  - Large volume Ge detectors
  - → high resolution gamma-ray spectroscopy (few keV)

- **Doppler correction (v/c ~ 10%)**
  - highly segmented Si detector
  - highly segmented Ge detectors

- **Trigger condition**
  - Ge-Si coincidences: differential cross section, gamma background reduction
  - Si singles data: normalisation

Shape coexistence in N=28 isotones

Z \ N	20	22	24	26	28	30
20	Ca 40 96.94	Ca 42 0.65	Ca 44 2.08	Ca 46 0.003	Ca 48 0.19	Ca 50 13.9 s
18	Ar 38 0.07	Ar 40 99.59	Ar 42 32.9 y	Ar 44 11.9 m	Ar 46 8.4 s	Ar 48 0.48 s
16	S 36 0.015	S 38 170 m	S 40 8.8 s	S 42 1.01 s	S 44 123 ms	S 46 50 ms
14	Si 34 2.77 s	Si 36 0.45 s	Si 38 >1 µs	Si 40 33 ms	Si 42 13 ms	Si 44 10 ms
12	Mg 32 86 ms	Mg 34 20 ms	Mg 36 3.9 ms	Mg 38 >260 ns	Mg 40 1 ms	



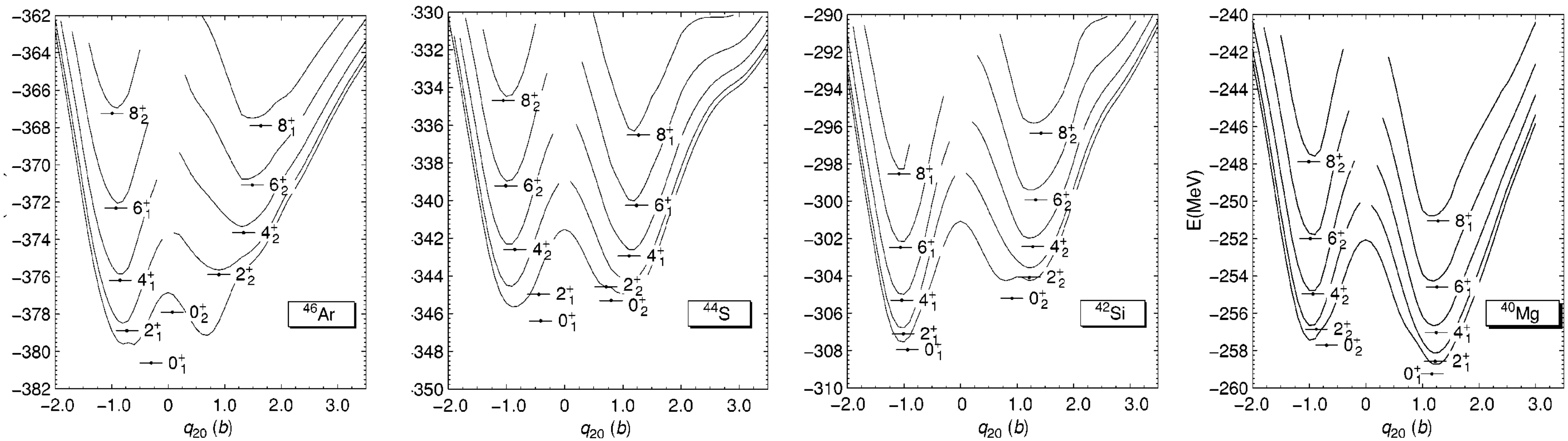
M. Girod
Bruyères-le-Châtel

Rapid onset of deformation in N~28 nuclei below Ca ?

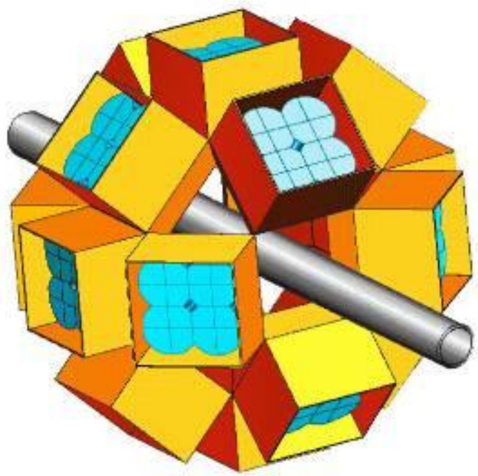
All N=28 isotones predicted to show shape coexistence

Precision measurement of e.m. matrix elements in ^{44}Ar

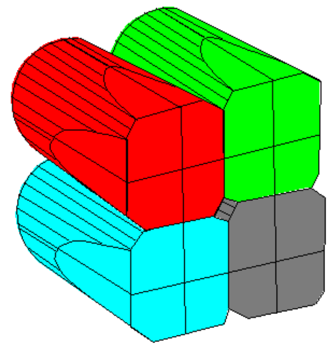
R. Rodríguez-Guzmán, PRC 65, 024304

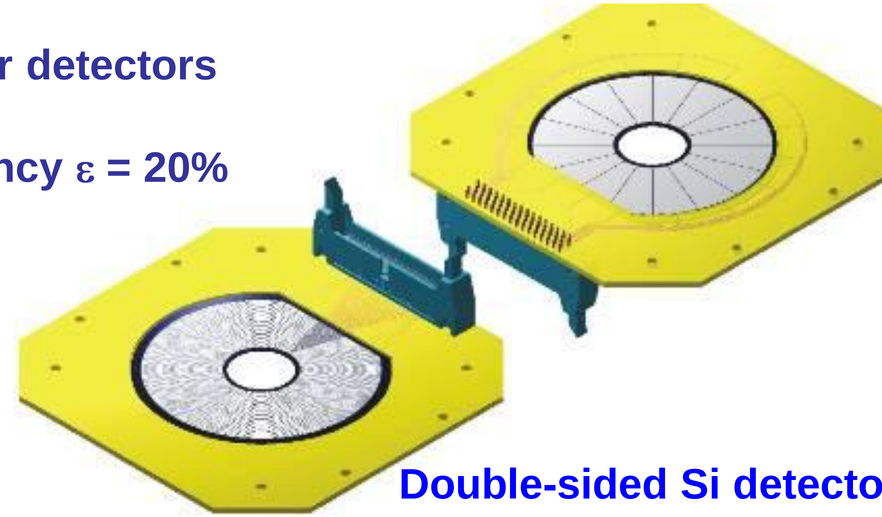


Coulomb excitation set-up for RIBs (ex. SPIRAL)

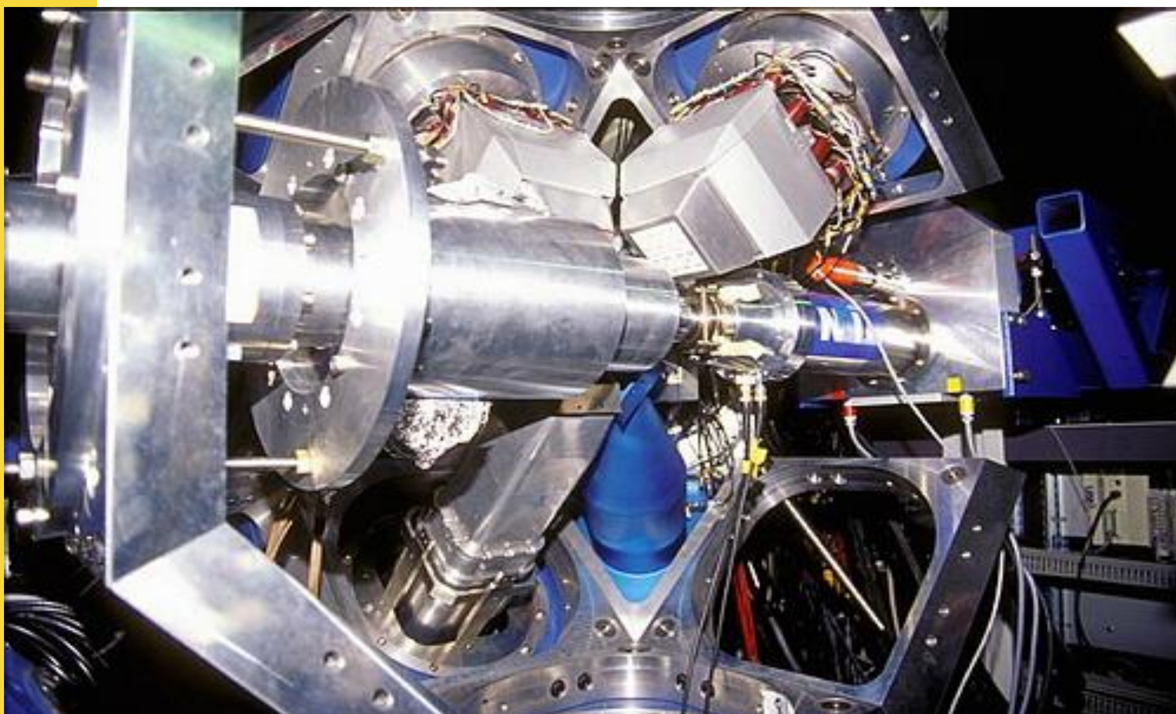


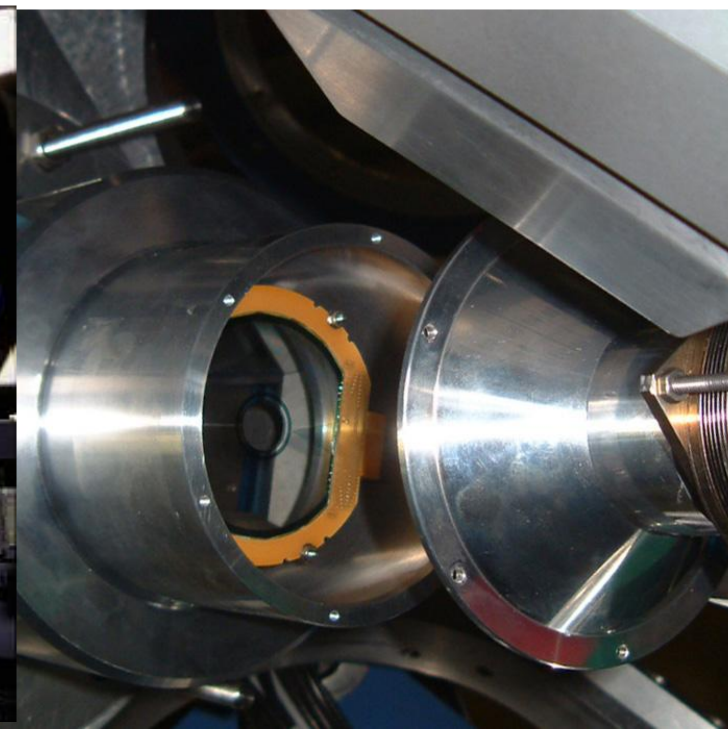
16 large Ge Clover detectors
4 × 4 segmented
photopeak efficiency ε = 20%





Double-sided Si detector
48 rings × 16 sectors





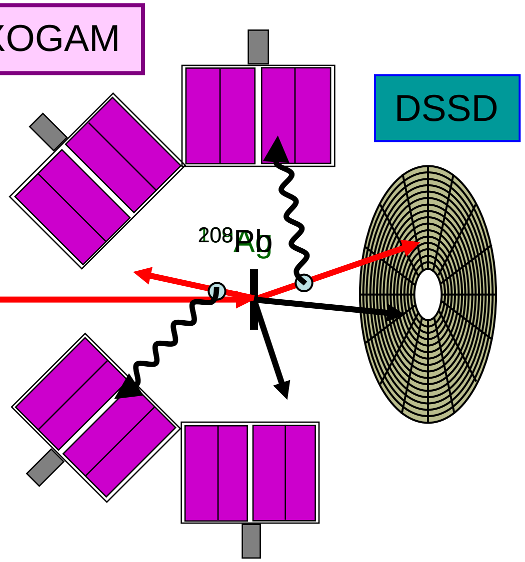
Coulomb excitation of ^{44}Ar at SPIRAL / GANIL

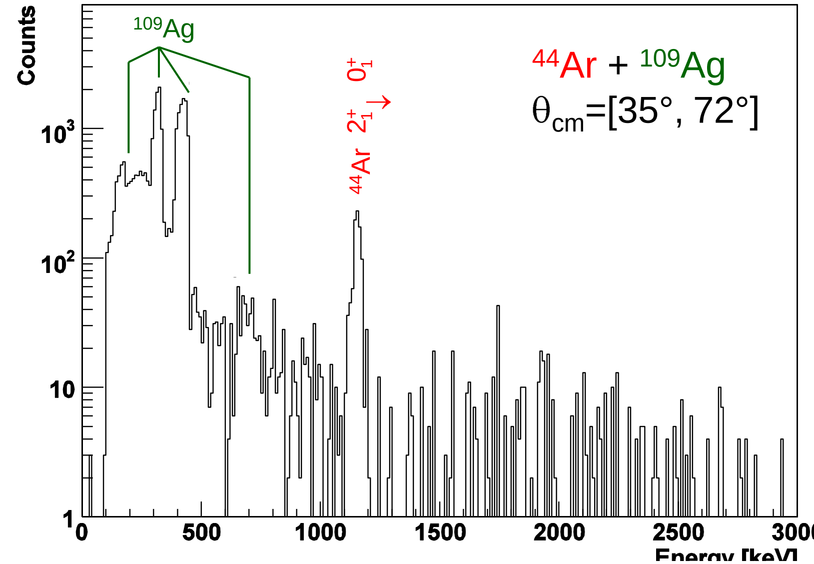
SPIRAL beam

^{44}Ar $3 \cdot 10^5$ pps

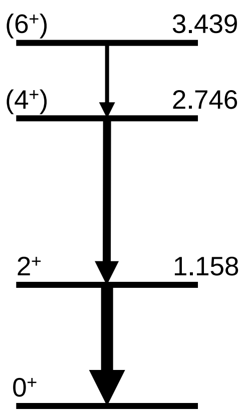
2.8·A MeV (Ag)

3.8·A MeV (Pb)

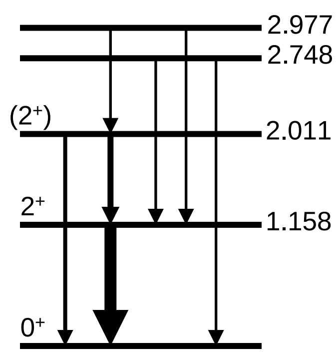




deep inelastic

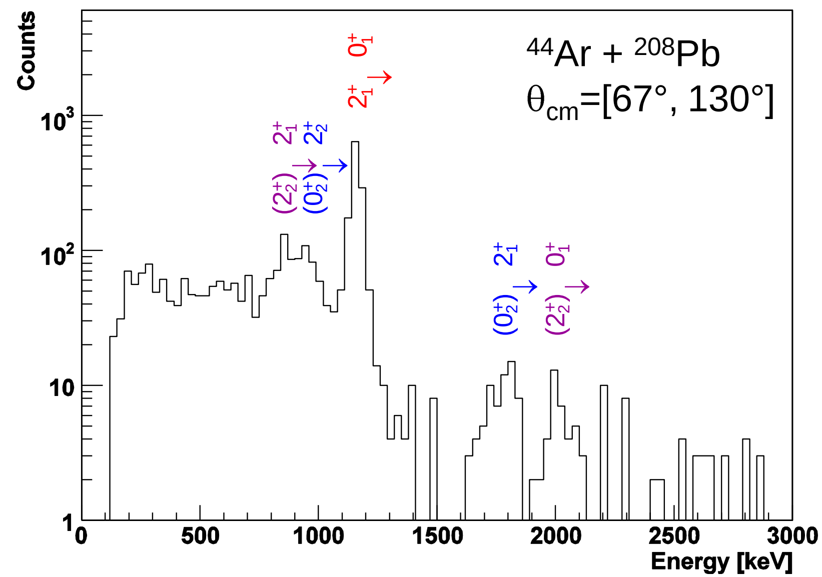


beta decay

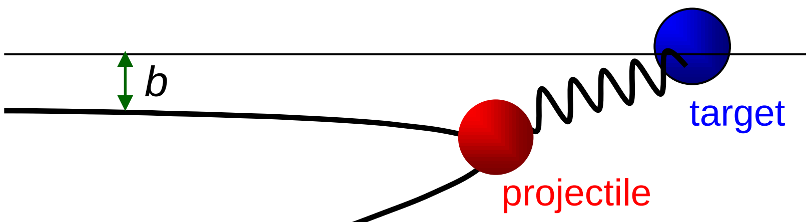


B. Fornal et al.,
EPJA 7, 147 (2000)

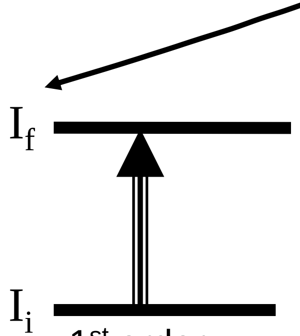
J. Mrazek et al.,
Nucl. Phys. A 734, E65 (2004)

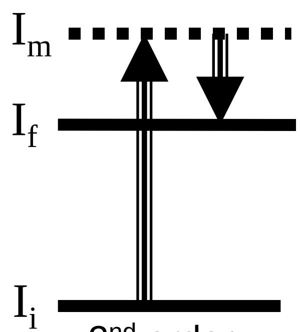


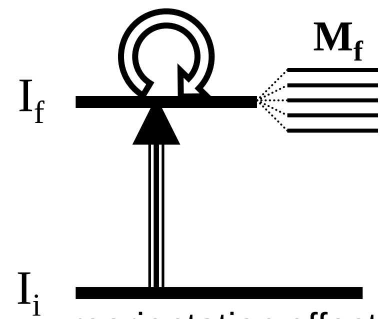
Determination of quadrupole moments



The excitation cross section is a direct measure of the $E\lambda$ matrix elements.







1st order:

$$a^{(1)}_{i\to f} \propto \langle I_f \| \mathbf{M}(E2) \| I_i \rangle$$

2nd order:

$$a^{(2)}_{i\to f} \propto \langle I_f \| \mathbf{M}(E2) \| I_m \rangle \langle I_m \| \mathbf{M}(E2) \| I_i \rangle$$

reorientation effect:

$$a^{(2)}_{i\to f} \propto \langle I_f \| \mathbf{M}(E2) \| I_f \rangle \langle I_f \| \mathbf{M}(E2) \| I_i \rangle$$

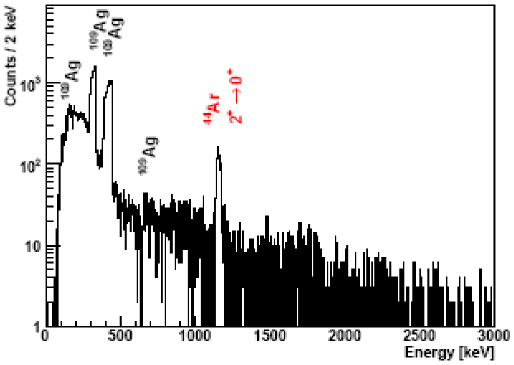
$$P^{(2)}_{0\to 2}(\vartheta,\xi) = P^{(11)}_{0\to 2}(\vartheta,\xi)\,\left[1 + q\cdot K(\vartheta,\xi)\right]$$

$$q = \frac{A_{T/P}\,\Delta E_{MeV}}{Z_{P/T}(1 + A_P/A_T)}\sqrt{\frac{7}{2\pi}}\,\frac{5}{4}\,Q_2$$

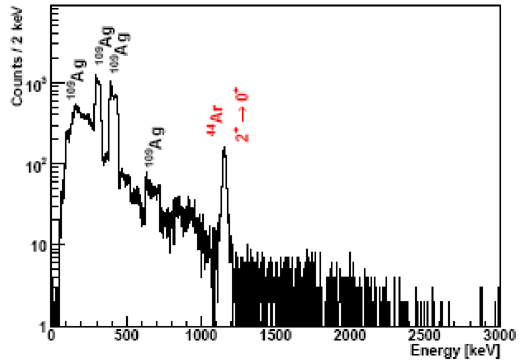
Sensitivity to Q_2 by varying Z, θ, $\xi(a,v_\infty)$

Coulomb excitation of ^{44}Ar at SPIRAL / GANIL

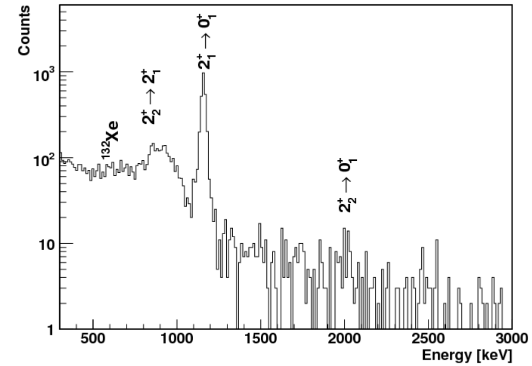
Ag target, 35°<θ_{cm}<70°

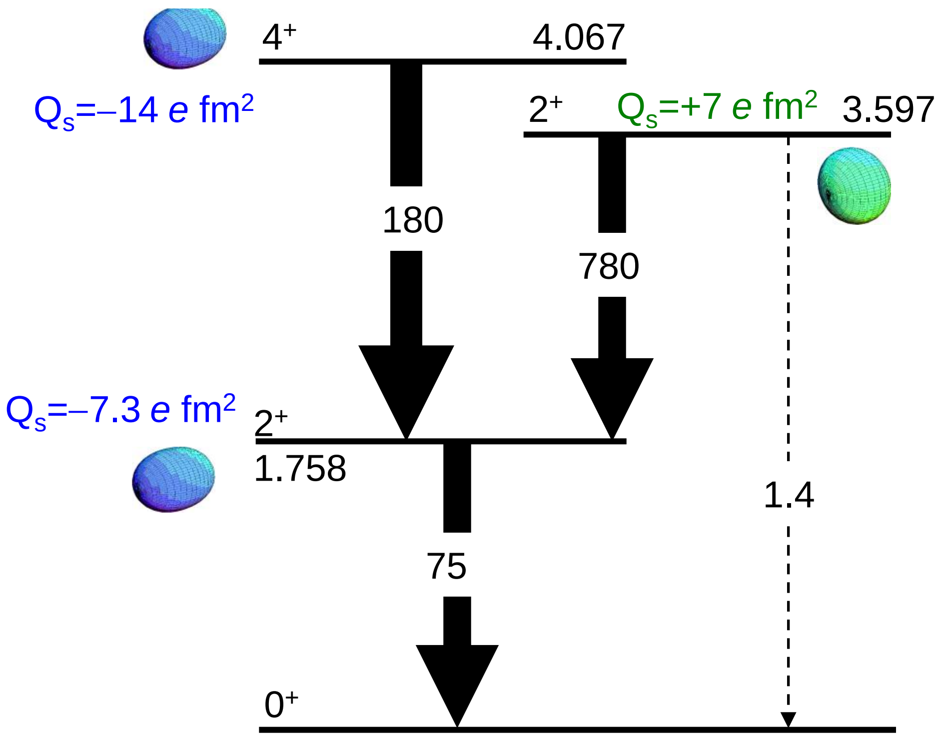


Ag target, 70°<θ_{cm}<130°



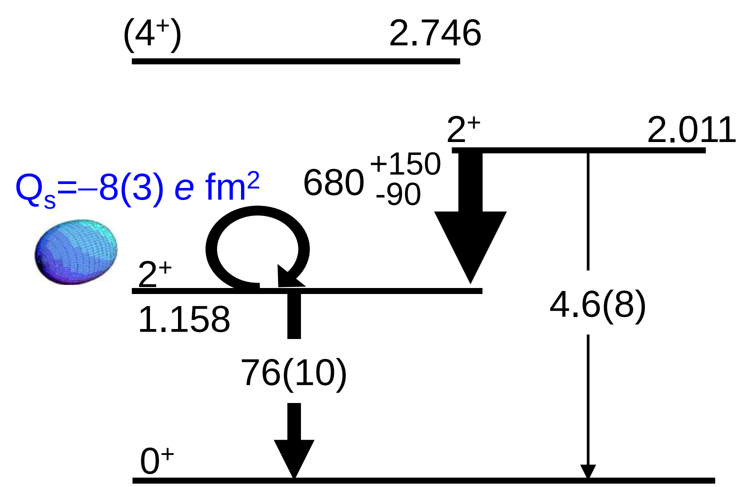
Pb target, 30°<θ_{cm}<130°





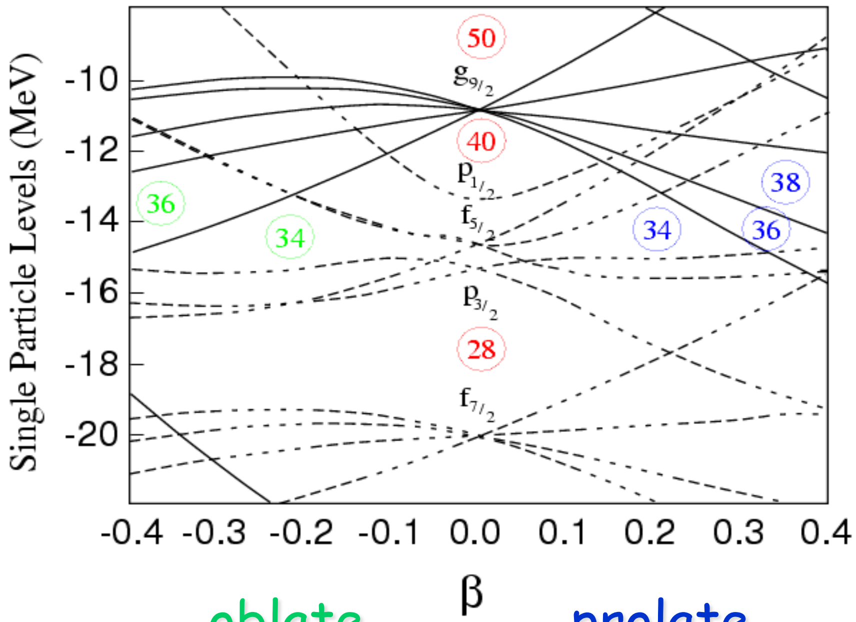
theory HFB+GCM(GOA)

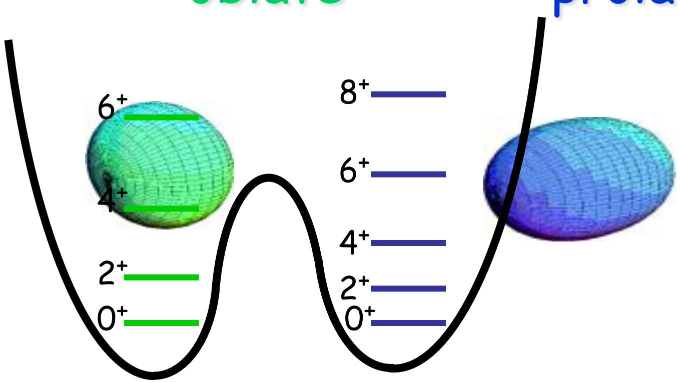
- ➢ **good agreement for B(E2) and Q**
- ➢ **energy spectrum too spread out**



experiment B(E2;↓) in e^2fm^4

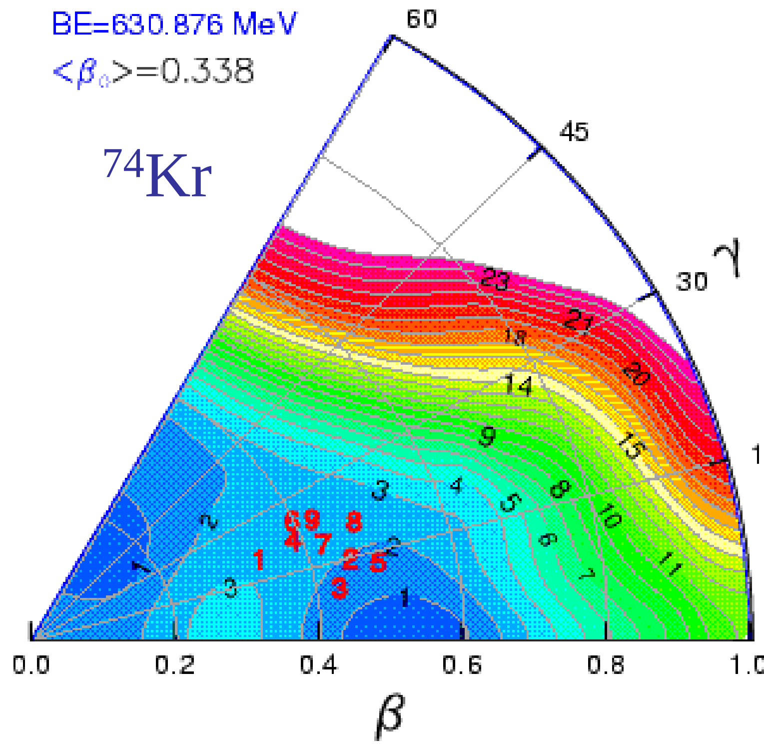
Shape coexistence around A=70





expected e.g. in:

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

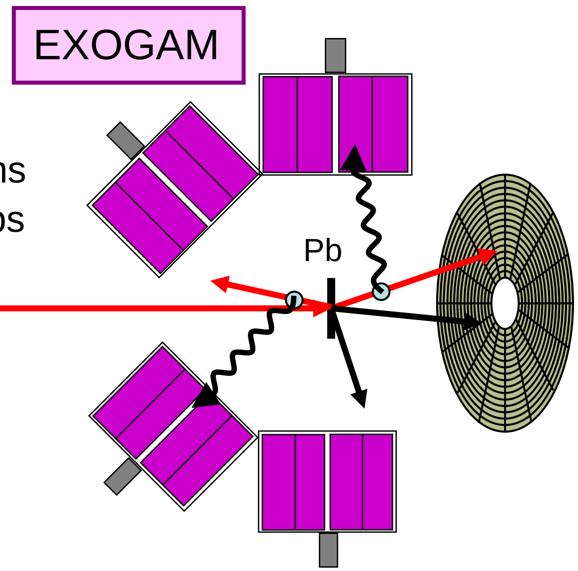


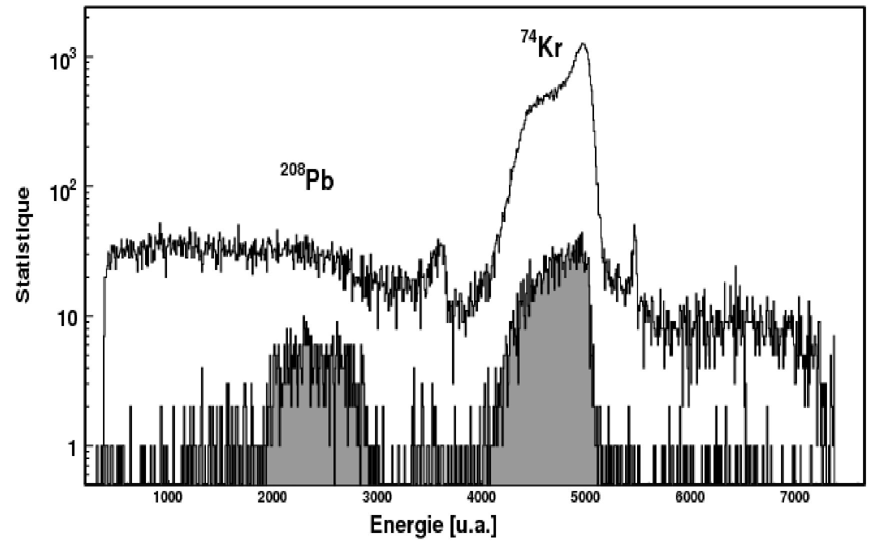
Possible 0^+ shape isomers
and configuration mixing

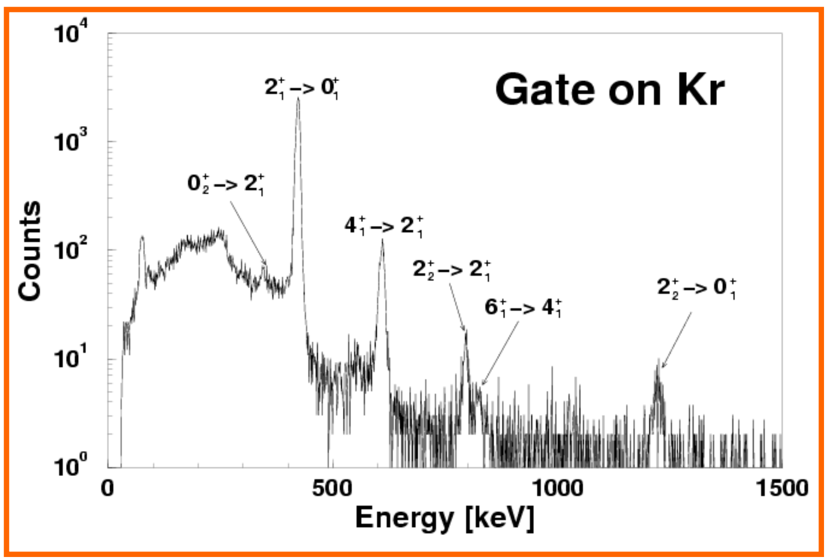
Coulomb excitation of ^{74,76}Kr at SPIRAL

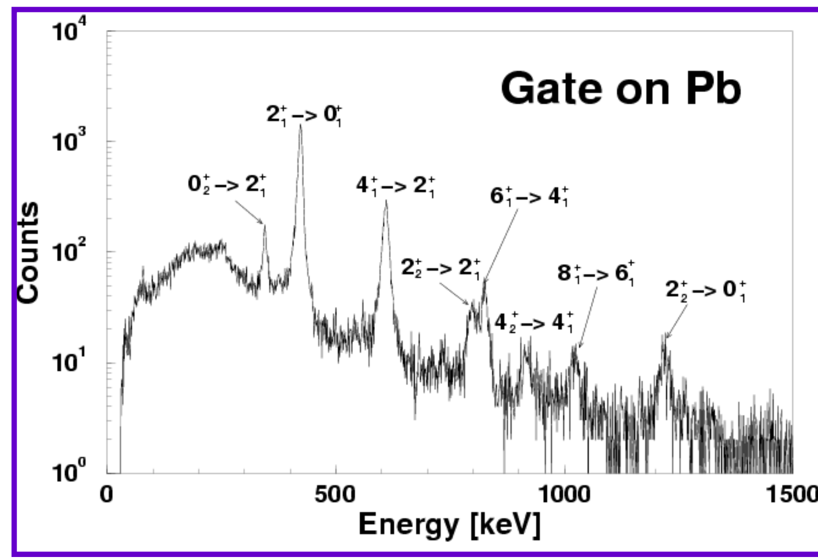
SPIRAL beams
^{76}Kr $5{\times}10^5$ pps
^{74}Kr 10^4 pps

4.5 MeV/u



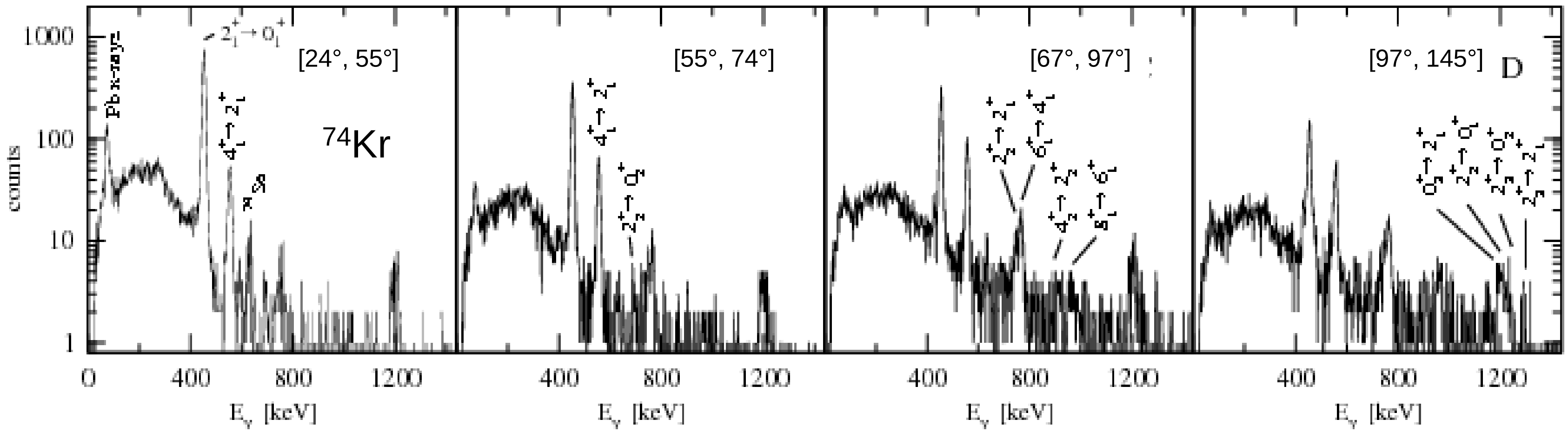


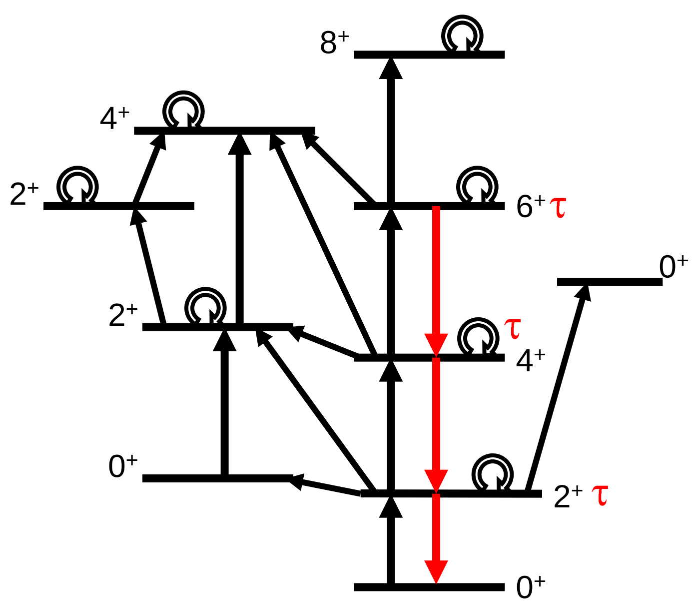




Acta Phys. Pol. B 36, 1281 (2005)

Shape coexistence in ^{74}Kr

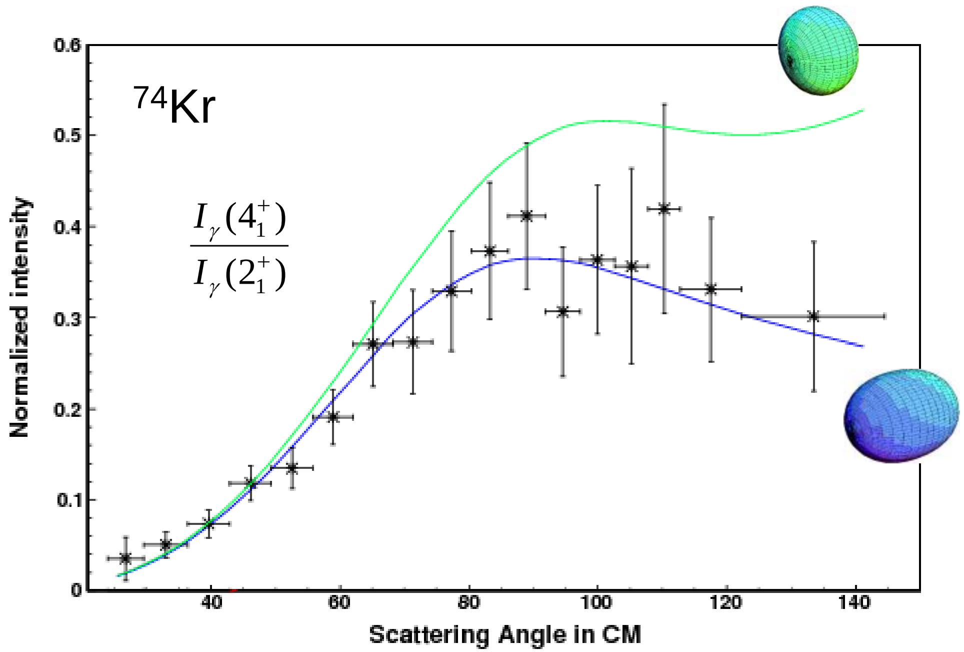




- ^{74}Kr + ^{208}Pb at 4.7 MeV/u (SPIRAL)
  ➔ multi-step Coulomb excitation
- γ-ray yields as function of scattering angle (differential excitation cross section)
- experimental spectroscopic data (lifetimes, branching ratios)
- least squares fit of ~ 30 matrix elements (transitional and diagonal)

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

Sensitivity to quadrupole moments



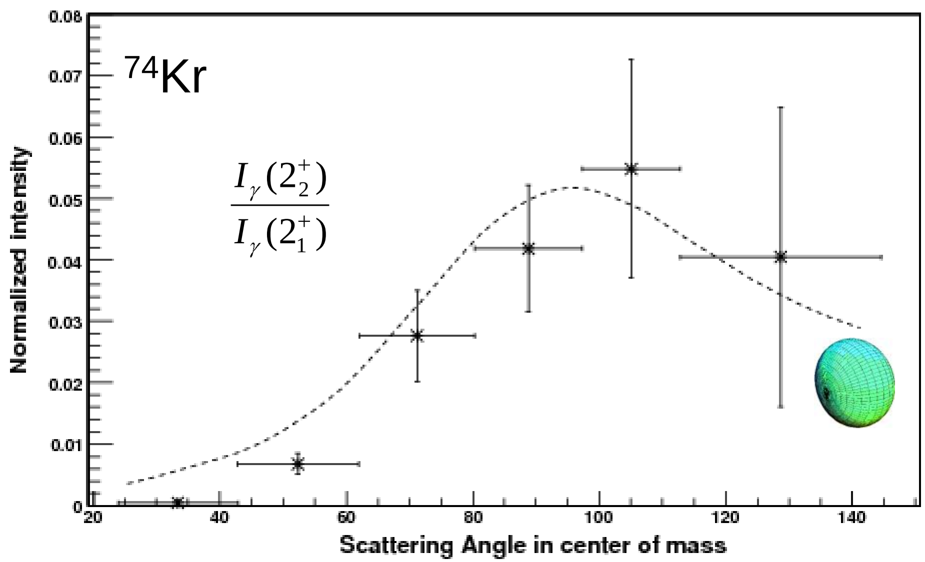
full χ^2 minimization:

$$\langle 2_1^+ \| \mathrm{M}(E2) \| 2_1^+ \rangle = -0.70^{+0.33}_{-0.30}$$

$$\langle 4_1^+ \| \mathrm{M}(E2) \| 4_1^+ \rangle = -1.02^{+0.59}_{-0.21}$$

negative matrix element
(positive quadrupole moment Q_0)

$\Rightarrow$ prolate shape

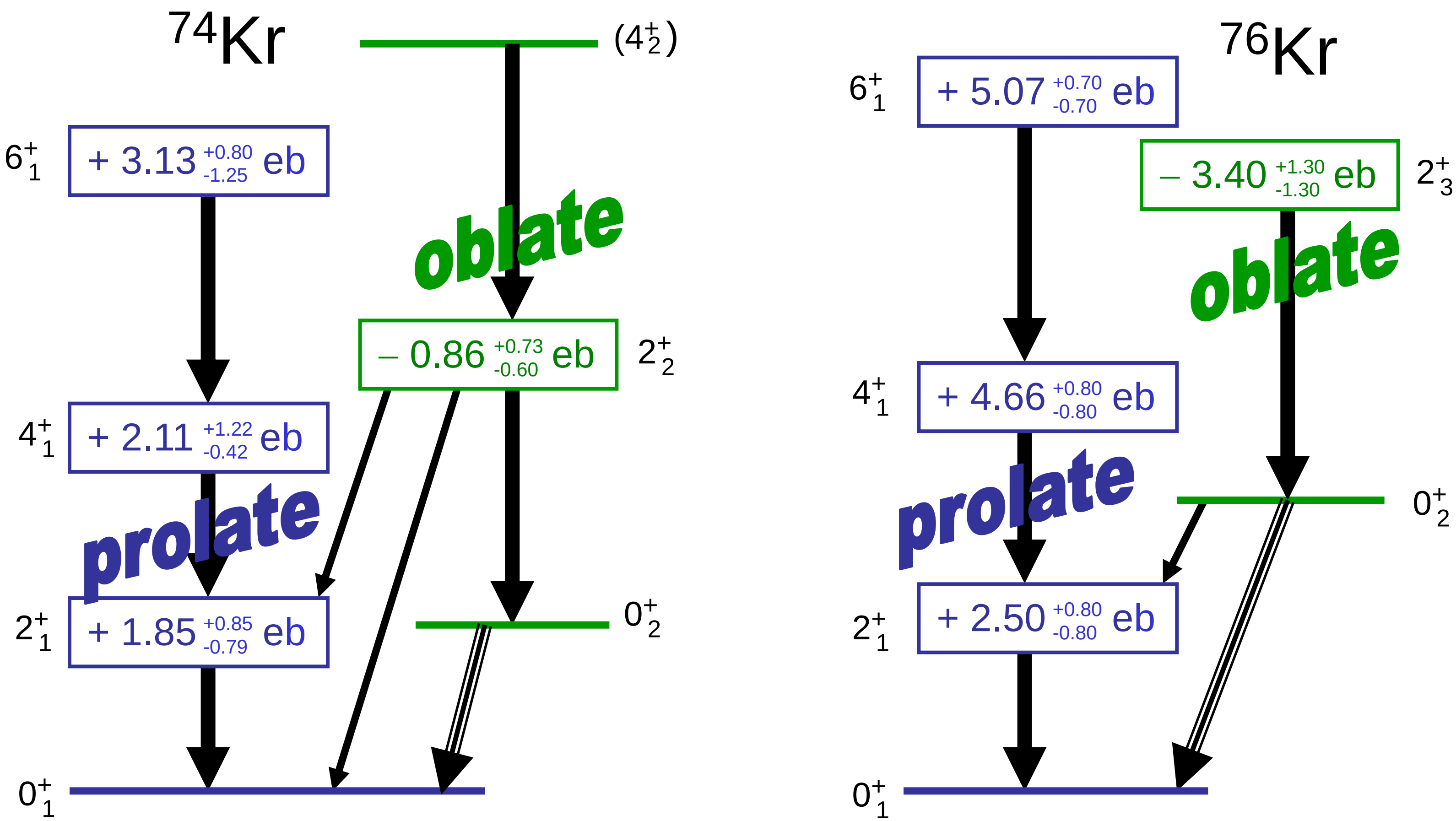


$$\langle 2_2^+ \| \mathrm{M}(E2) \| 2_2^+ \rangle = +0.33^{+0.28}_{-0.23}$$

positive matrix element
(negative quadrupole moment Q_0)

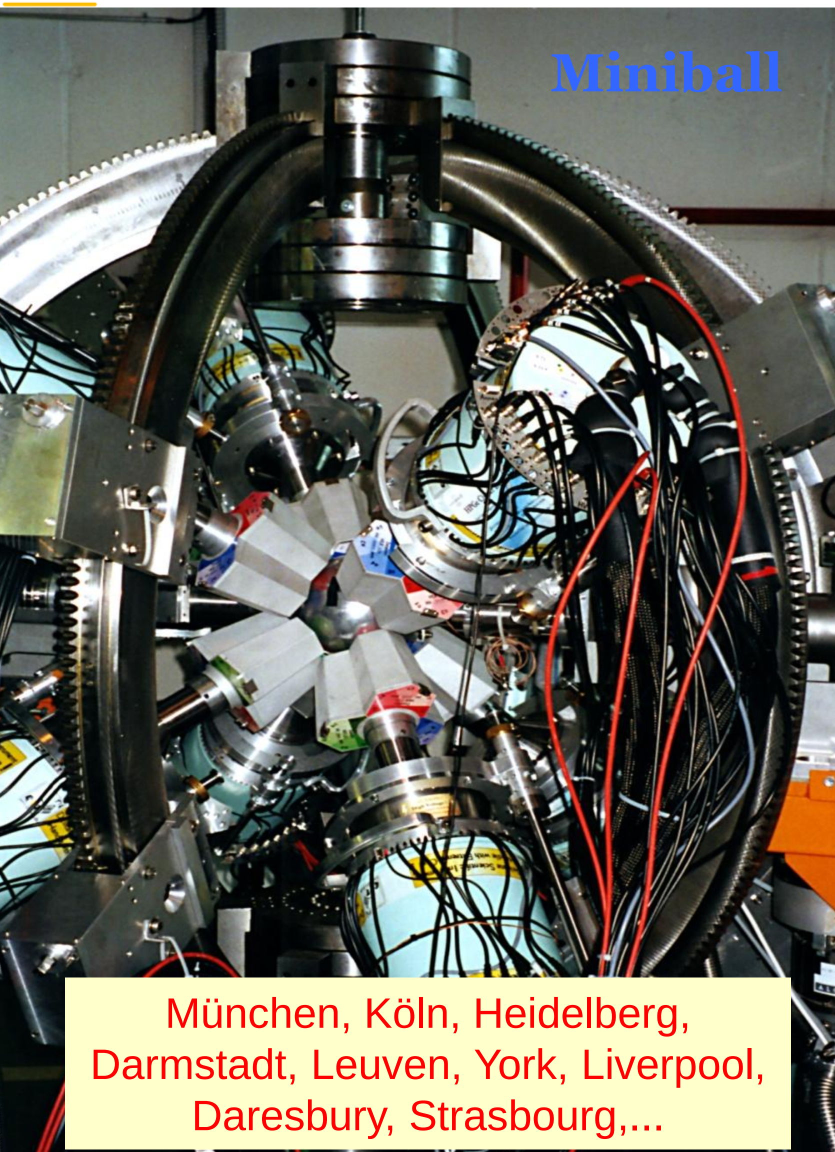
$\Rightarrow$ oblate shape

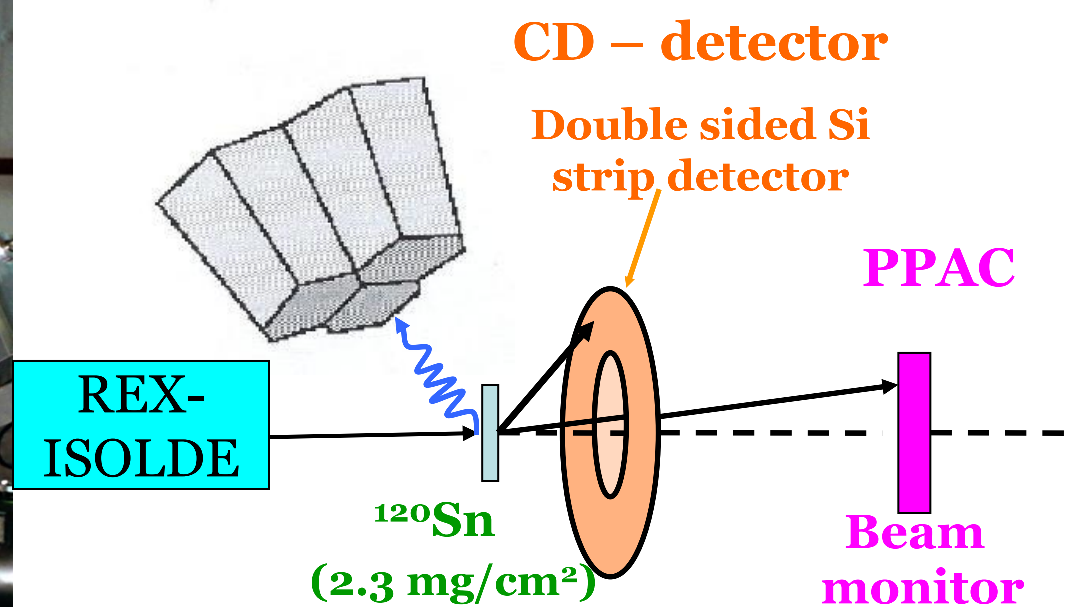
Quadrupole moments (Q_0) in ^{74}Kr and ^{76}Kr

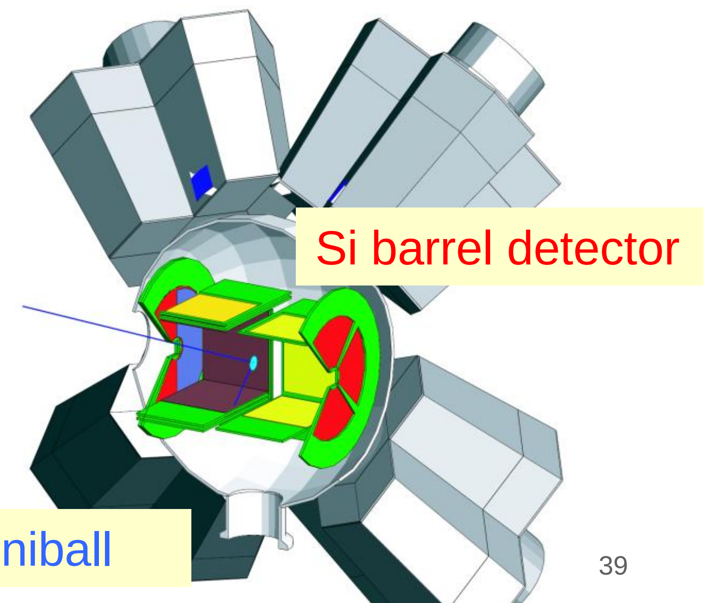


- direct confirmation of the prolate – oblate shape coexistence
- first reorientation measurement with radioactive beam

Coulomb excitation at Rex-Isolde (CERN)







J. Eberth *et al., Prog. Part. Nucl. Phys. 46, 389 (2001)*

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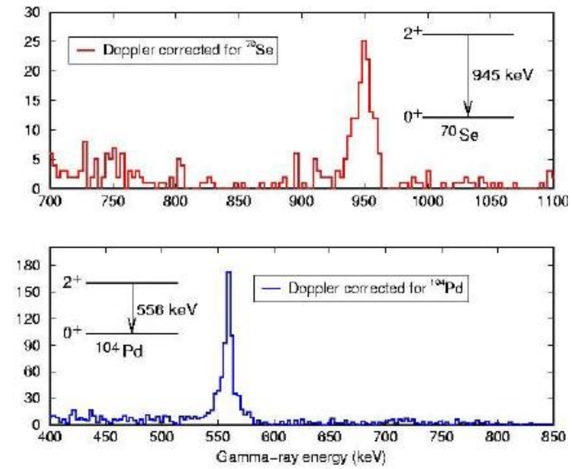
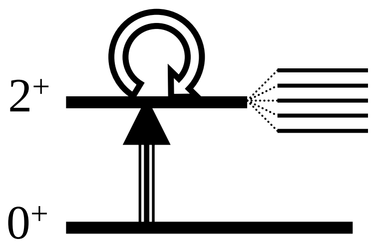
Coulomb excitation of ^{70}Se at Rex-ISOLDE

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

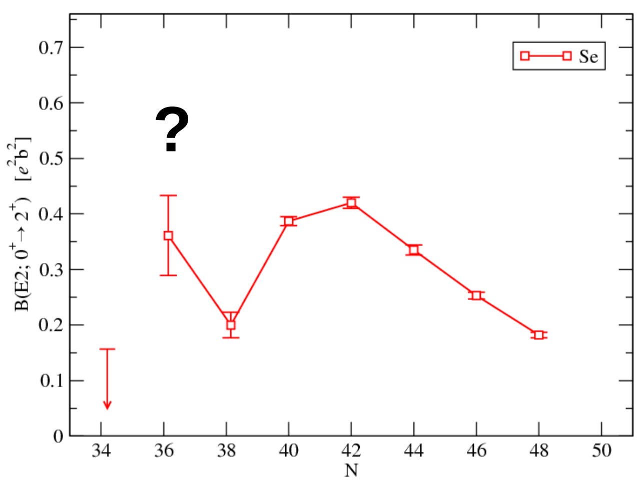
P_{2+} depends on
- transitional matrix element B(E2)
- diagonal matrix element Q_0



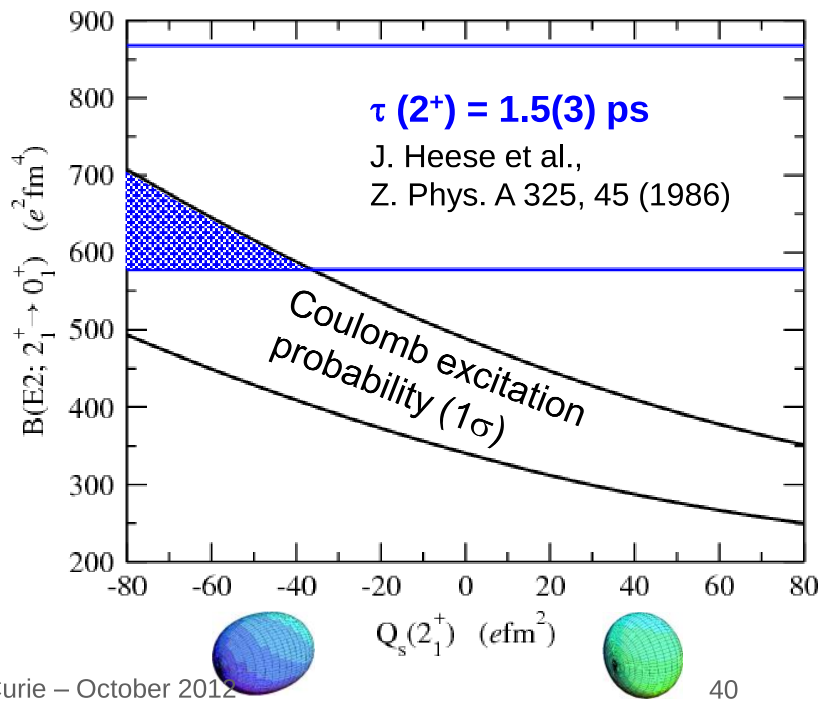
A.M. Hurst et al., PRL 98, 072501 (2007) (Univ. Liverpool)



- one measurement, but two unknowns !



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

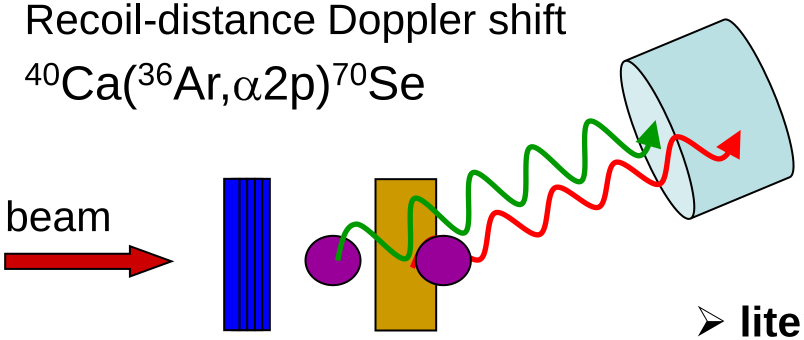


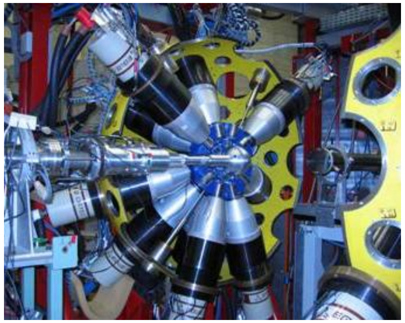
Lifetimes in ^{70}Se revisited

GASP and Köln Plunger at Legnaro

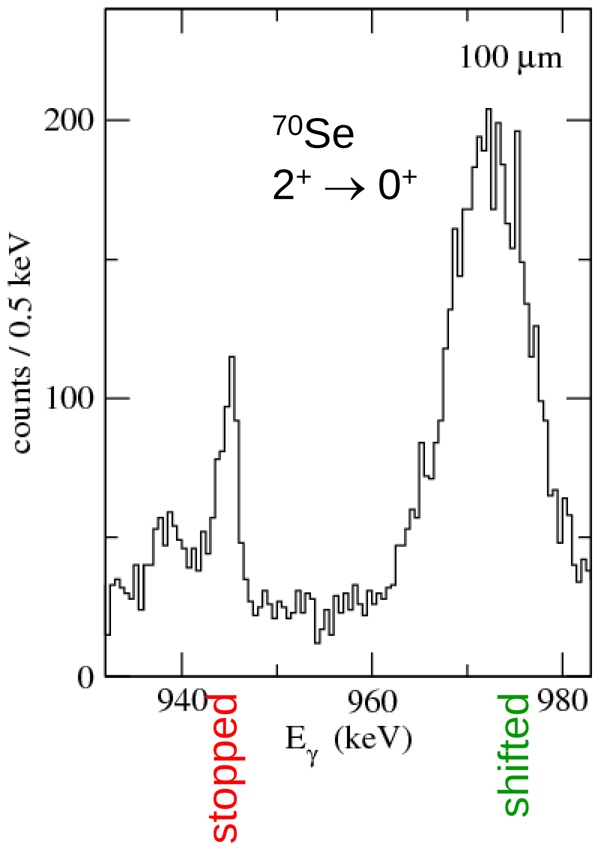
Recoil-distance Doppler shift

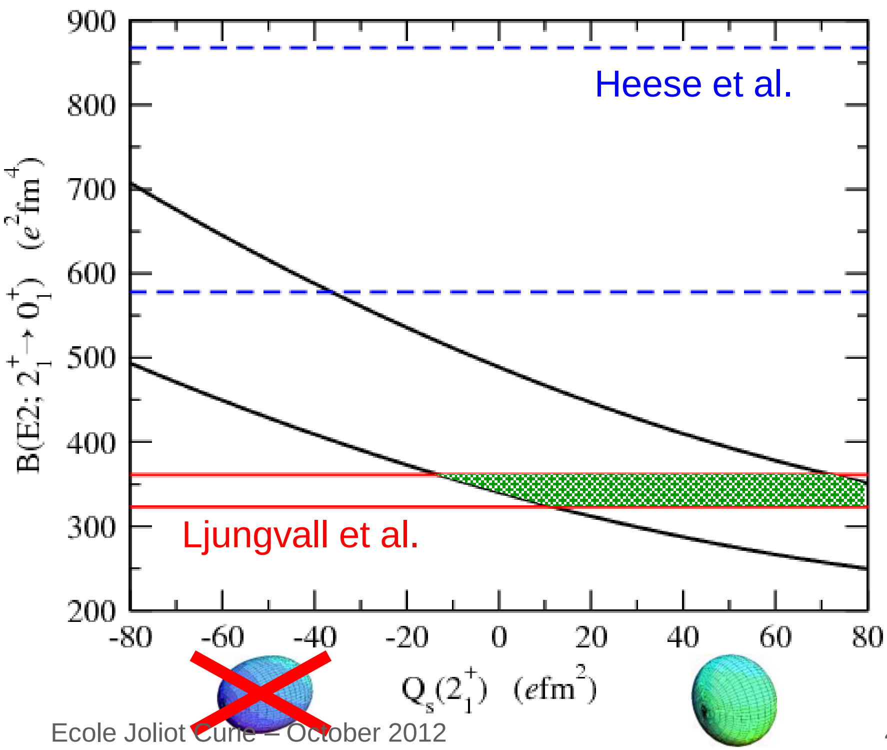
^{40}Ca(^{36}Ar,α2p)^{70}Se





- **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)





Coulomb excitation of $^{74-80}Zn$ at Rex-Isolde

A	$T_{1/2}$ (s)	f_{Ga}/f_{Zn} (%)	Zinc beam intensity (ions/s) (1)	(2)
74	95.6(12)	0.1	4.0E7	3.0E5
76	5.7(3)	1.5(1)	1.0E7	1.1E5
78	1.47(15)	5.8(6)	7.8E5	4.3E3
80	0.54(2)	16.2(6)	6.8E4	3.0E3

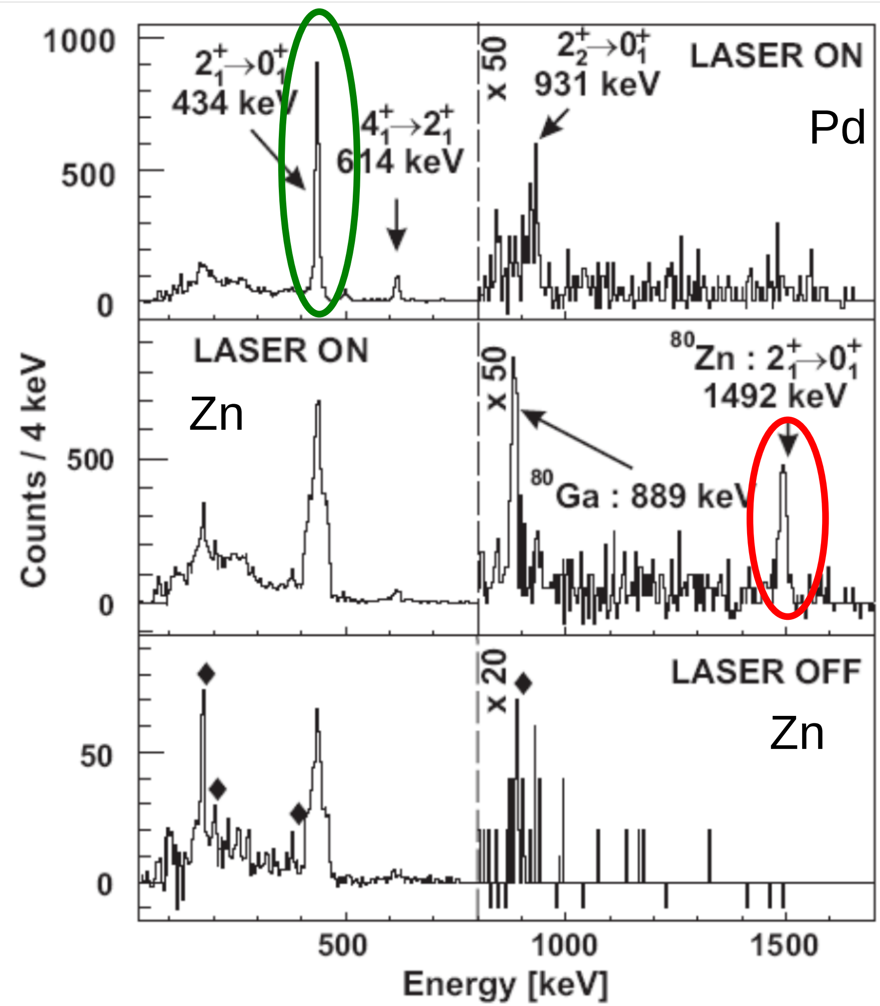
$$\frac{\sigma(Zn)}{\sigma(Pd)} = \frac{\varepsilon_\gamma(Pd)}{\varepsilon_\gamma(Zn)} \frac{W_\gamma(Pd)}{W_\gamma(Zn)} \frac{N_\gamma(Zn)}{N_\gamma(Pd)}$$

Beam contaminants

- increase for more exotic beams
- must be taken into account when calculating the target excitation

$$\frac{N_\gamma^{Zn}(Pd)}{N_\gamma^{Tot}(Pd)} = \left[1 + \left(\frac{f_{Ga}}{f_{Zn}} - \frac{I_{Ga}^S}{f_{Zn} I^L}\right) \frac{\sigma^{Ga}(Pd)}{\sigma^{Zn}(Pd)}\right]^{-1}$$

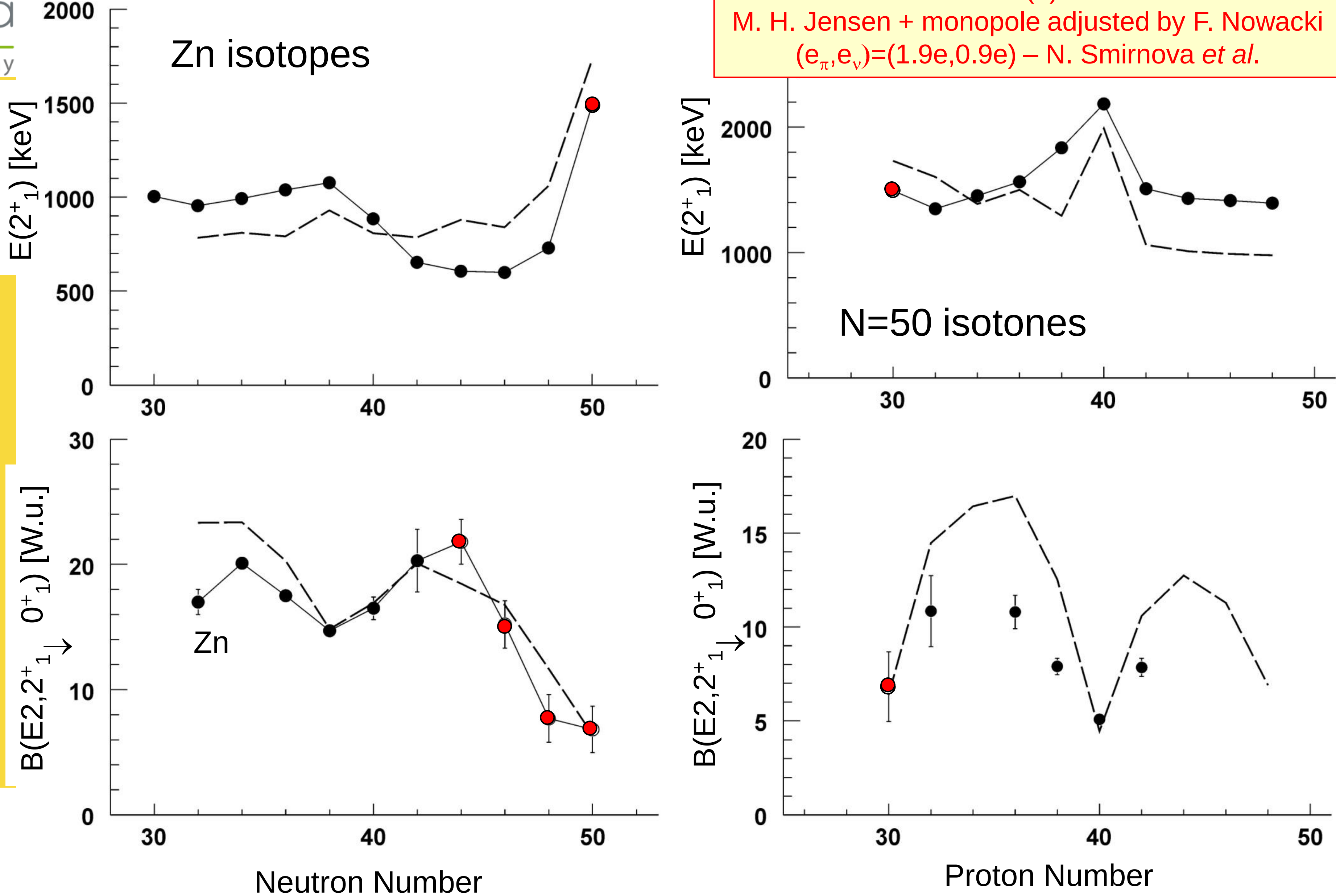
^{80}Zn on ^{108}Pd (2.87 MeV/u, 2.0 mg/cm^2, 3000 pps)



J. Van de Walle et al., PRL 99, 142501 (2007) and PRC 79, 014309 (2009)

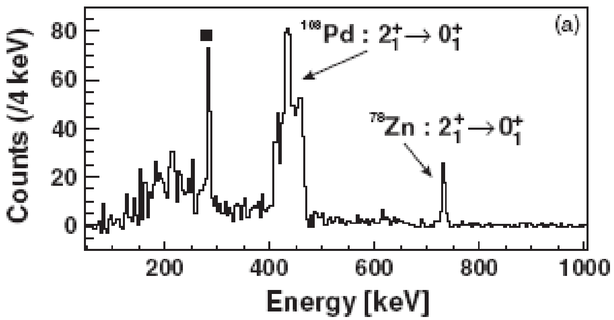
Quadrupole collectivity of the Zn isotopes

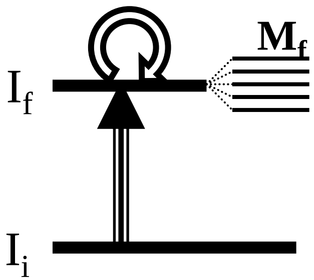
Shell Model (1) ^{56}Ni core
M. H. Jensen + monopole adjusted by F. Nowacki
(e_π,e_ν)=(1.9e,0.9e) – N. Smirnova *et al.*



Coulomb excitation of ^{74}Zn at Rex-Isolde

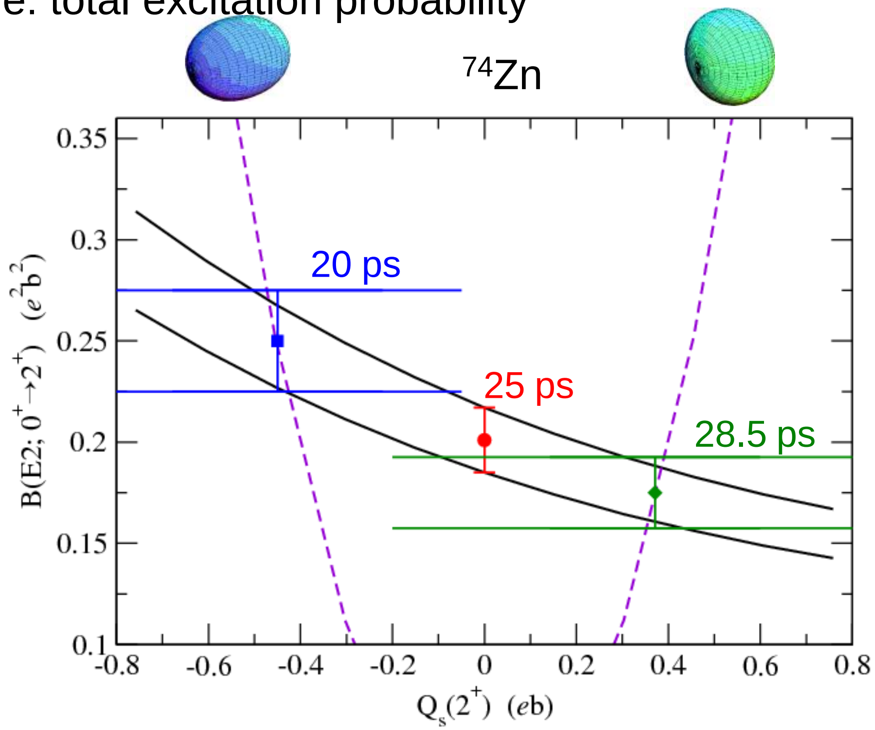
Integral measurement ➔ one observable: total excitation probability





two unknowns:

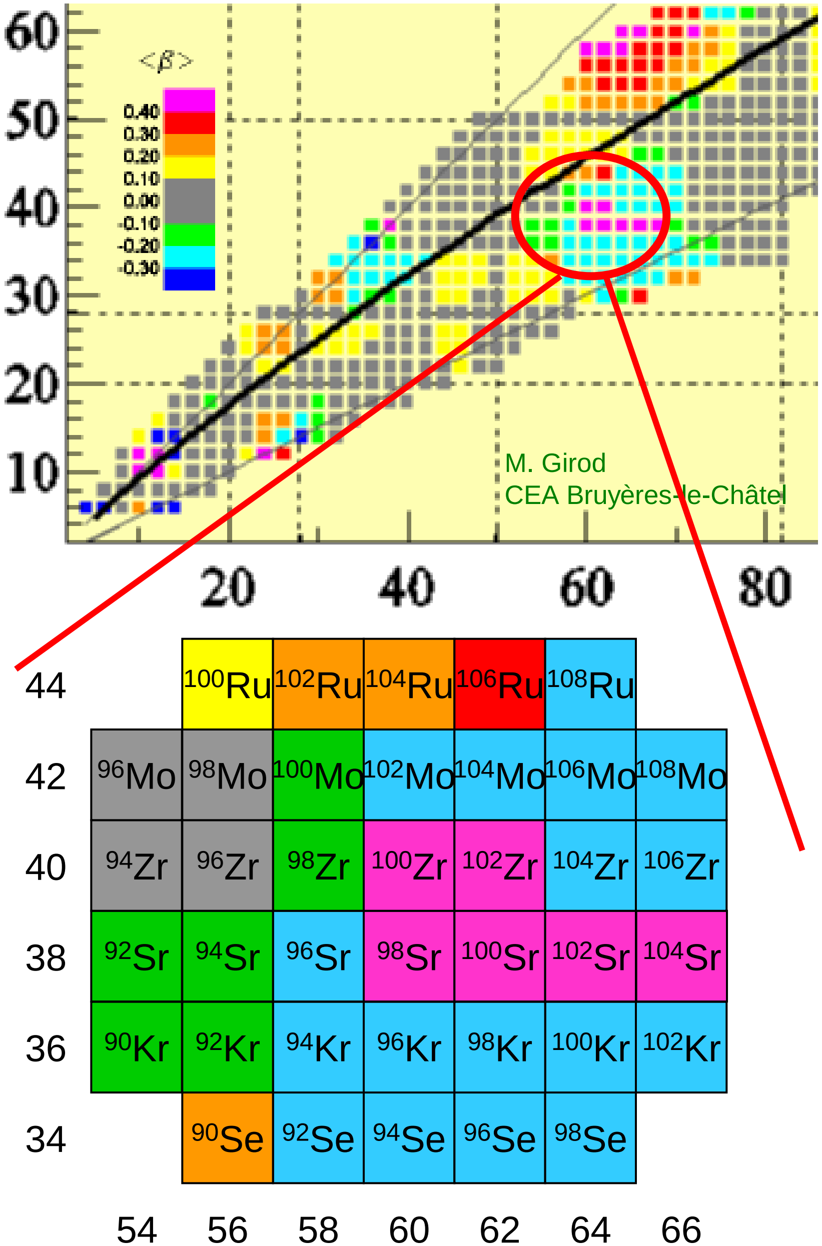
- B(E2)
- Q_s

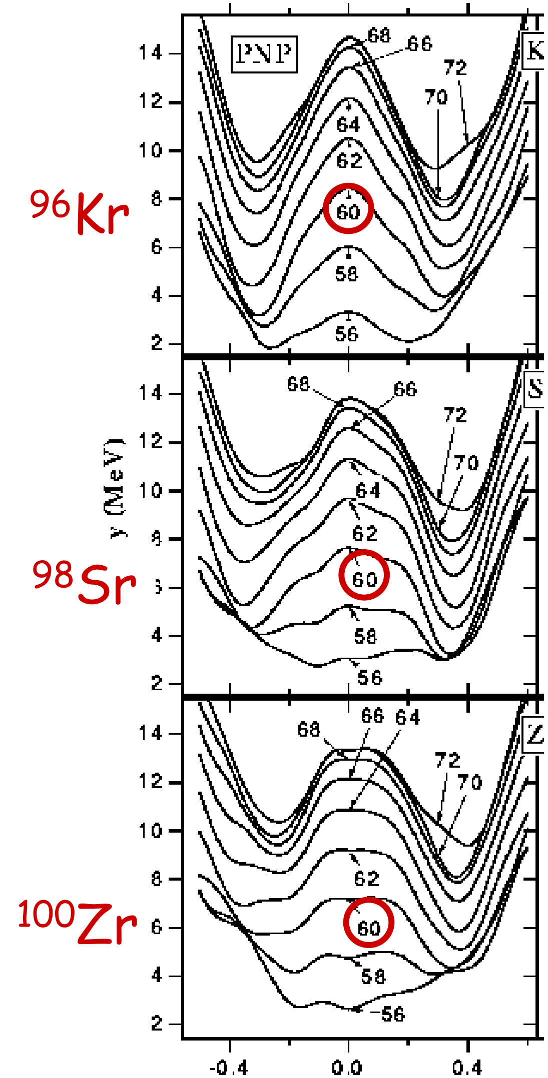


Life time measurements possible after multi-nucleon transfer reactions by using RDDS technique : reduce B(E2) error and determine Q_0

$\tau(2^+) \sim 28.5 \pm 3.6$ ps ➔ slight preference for oblate shape

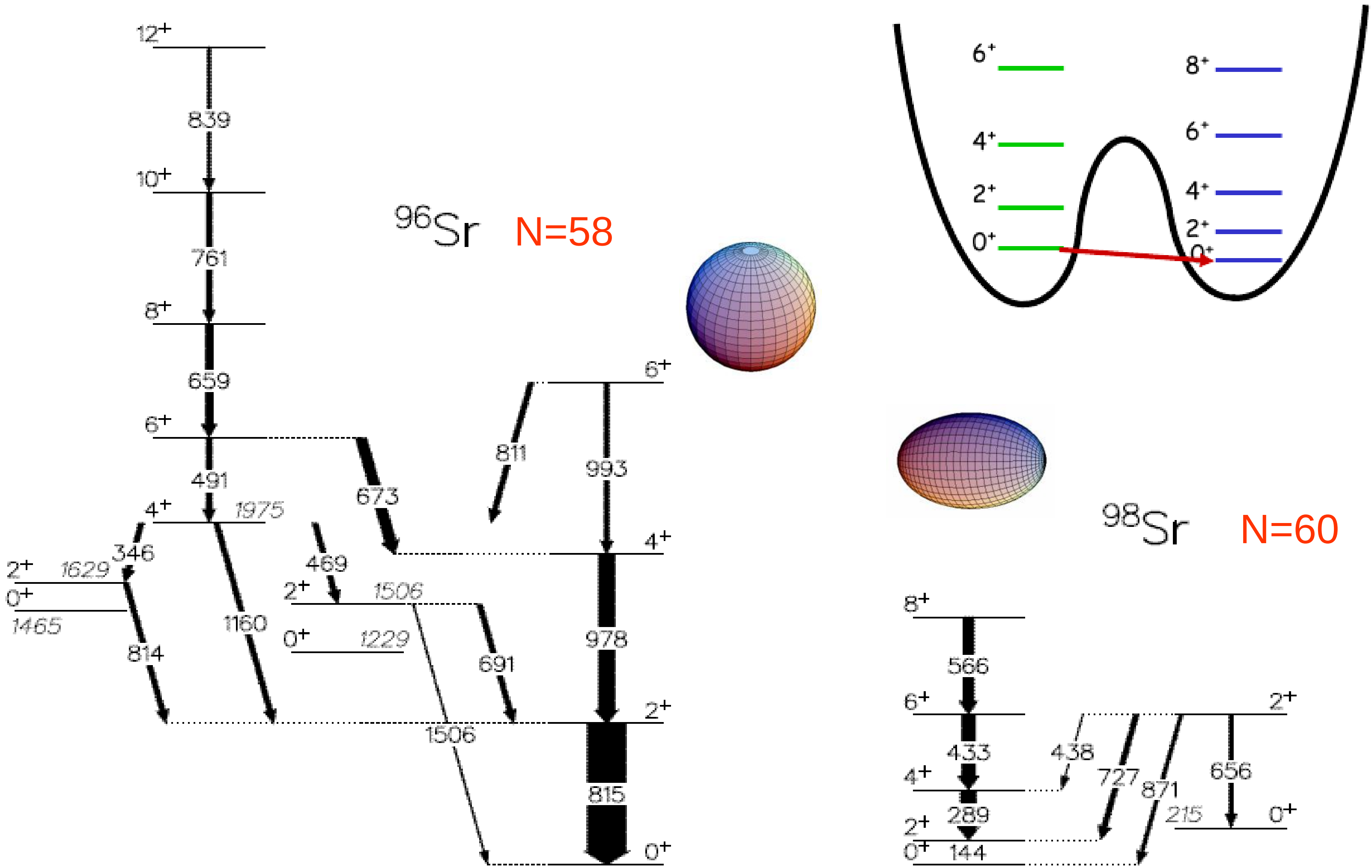
Shapes in neutron-rich A=100 nuclei





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

Shape transition in Sr isotopes



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

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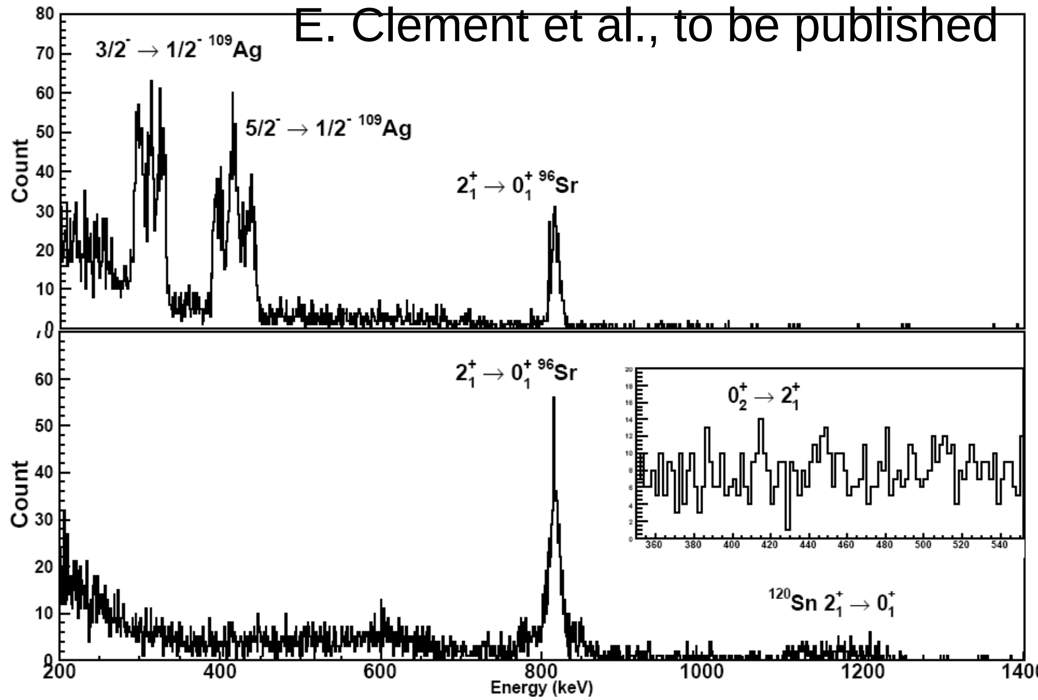
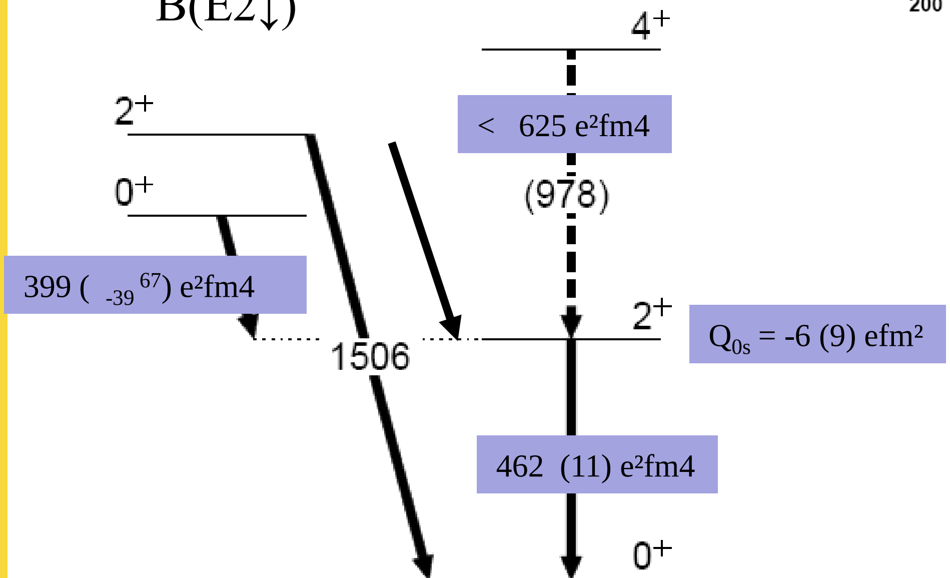
Coulomb excitation on ^{120}Sn and ^{109}Ag

- Coulex normalisation through the target gamma line
- Differential and integrated cross section
  → GOSIA analysis

E. Clement et al., to be published



B(E2↓)

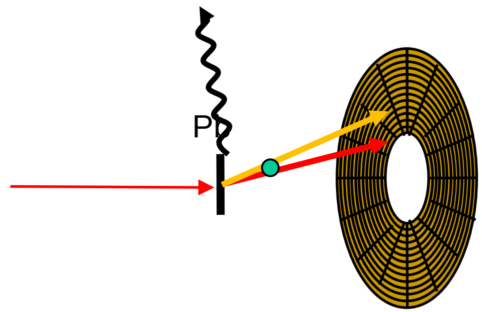


❑ The Electric spectroscopic Q_0 is null as its B(E2) is rather large

→ Quasi vibrator character
→ No quadrupole deformation
→ Weak mixing

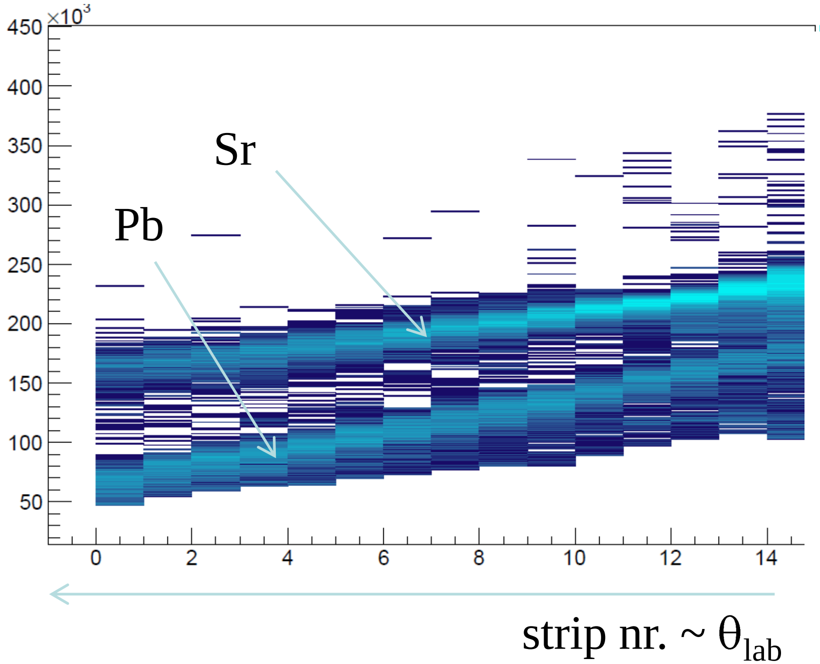
Coulomb excitation results on ^{98}Sr

E. Clement et al., to be published

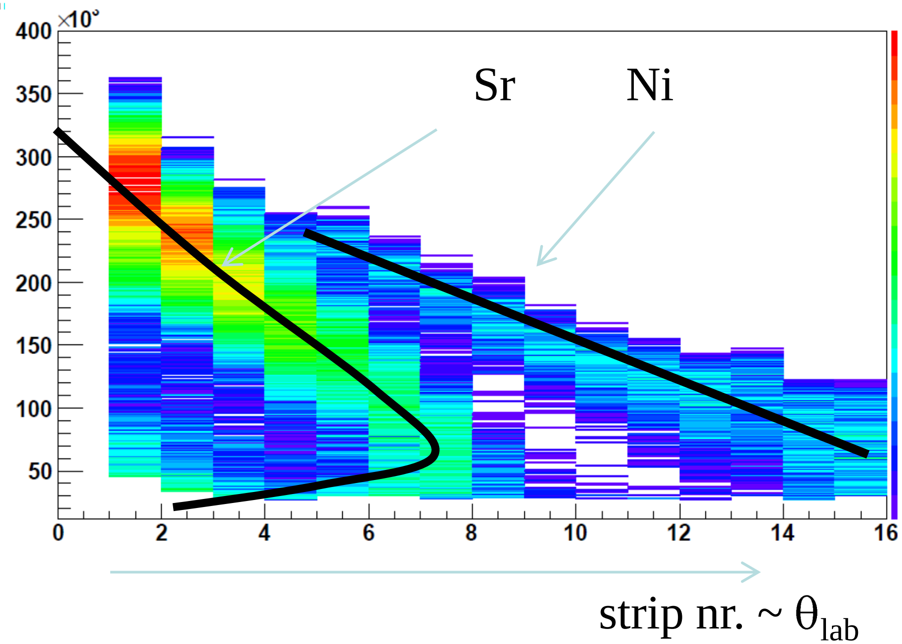


- 2 targets : ^{208}Pb & ^{60}Ni
- clean kinematic separation

^{208}Pb target : direct kinematics

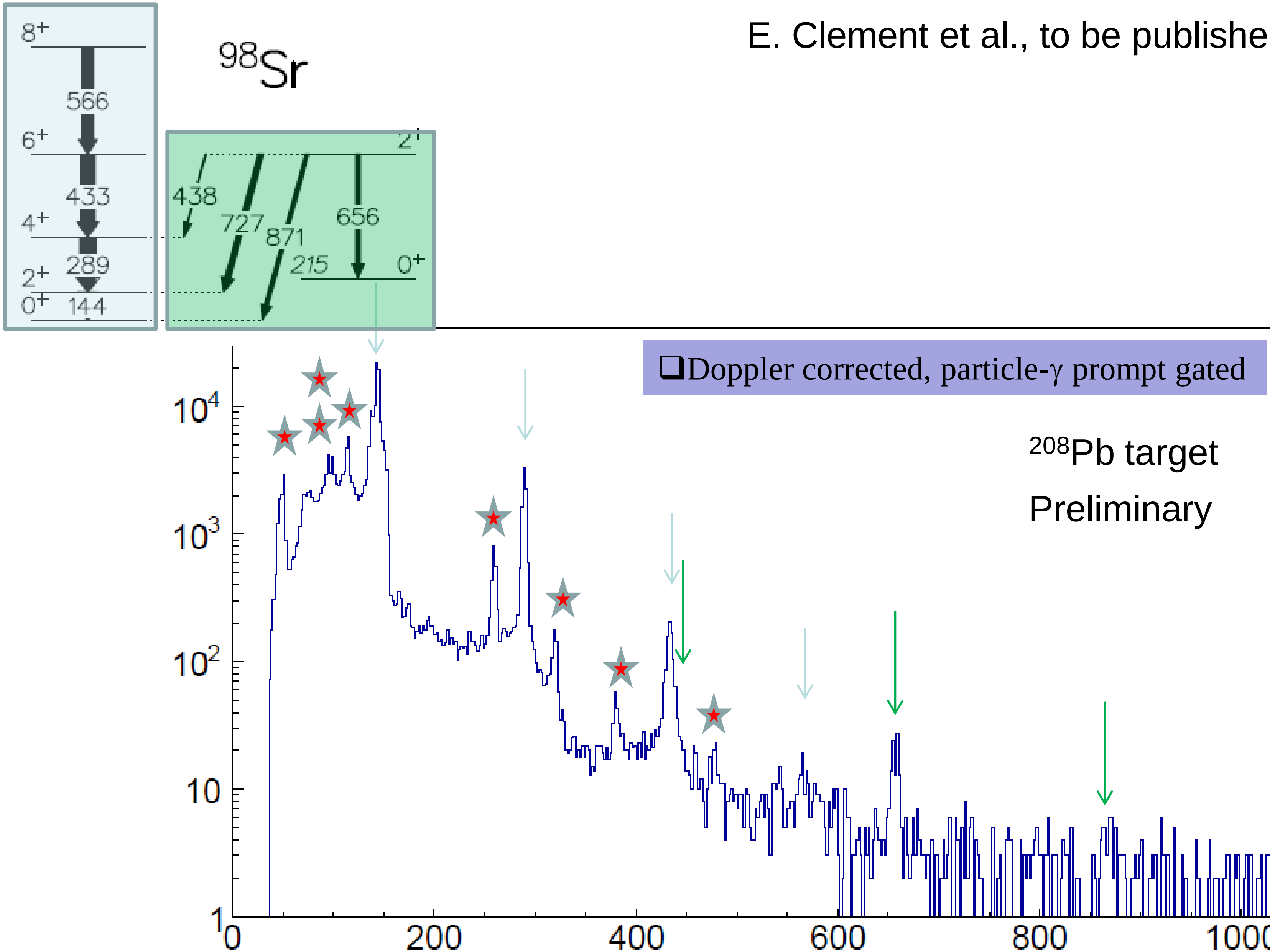


^{60}Ni target: inverse kinematics



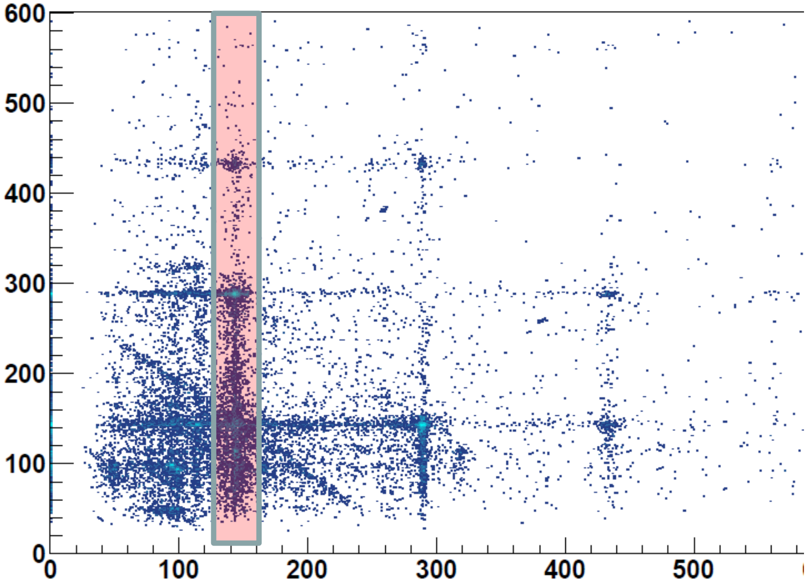
Coulomb excitation results on ^{98}Sr

E. Clement et al., to be published



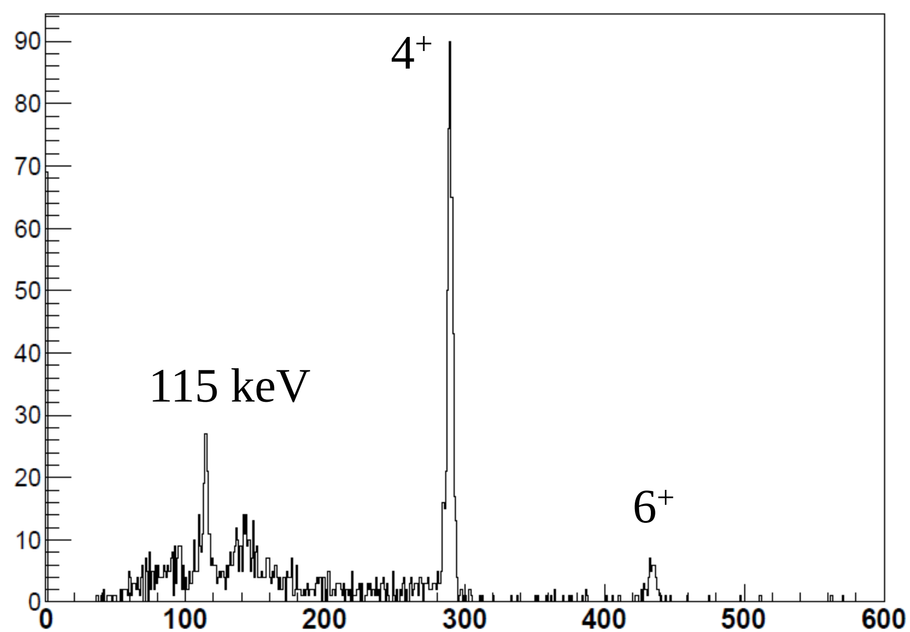
Coulomb excitation on ^{98}Sr (γ–γ analysis)

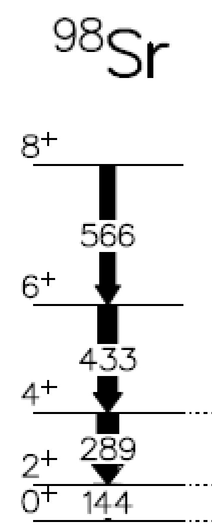
E. Clement et al., to be published



- γ–γ matrix (using RIB ….)
- Many transitions are in coincidence

Gated on the 2$^+$ decay

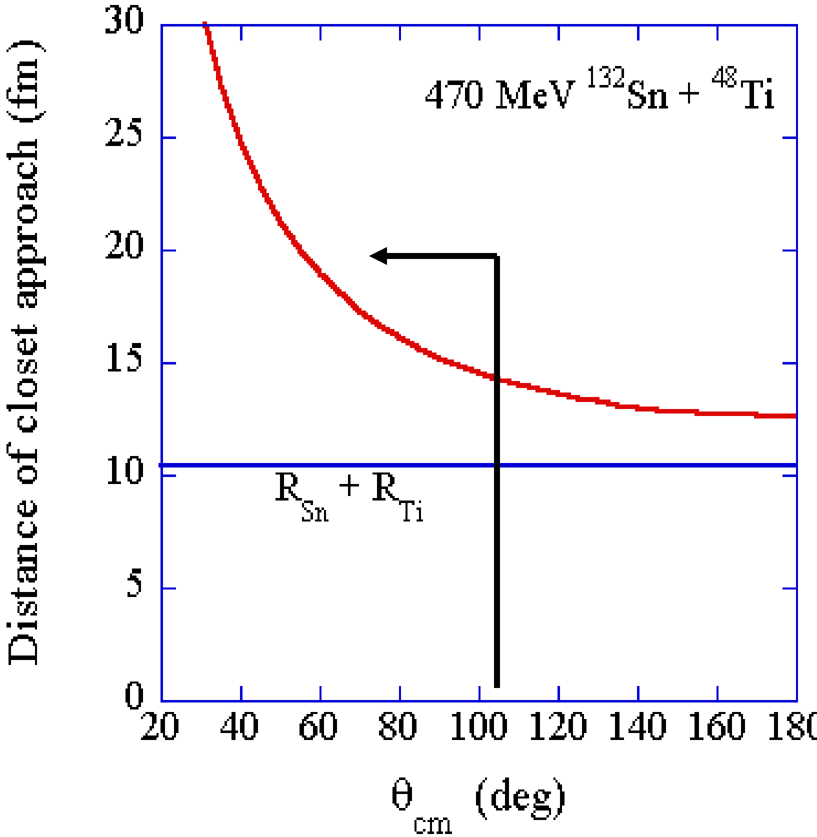




Coulomb Excitation of ^{132}Sn at HRIBF

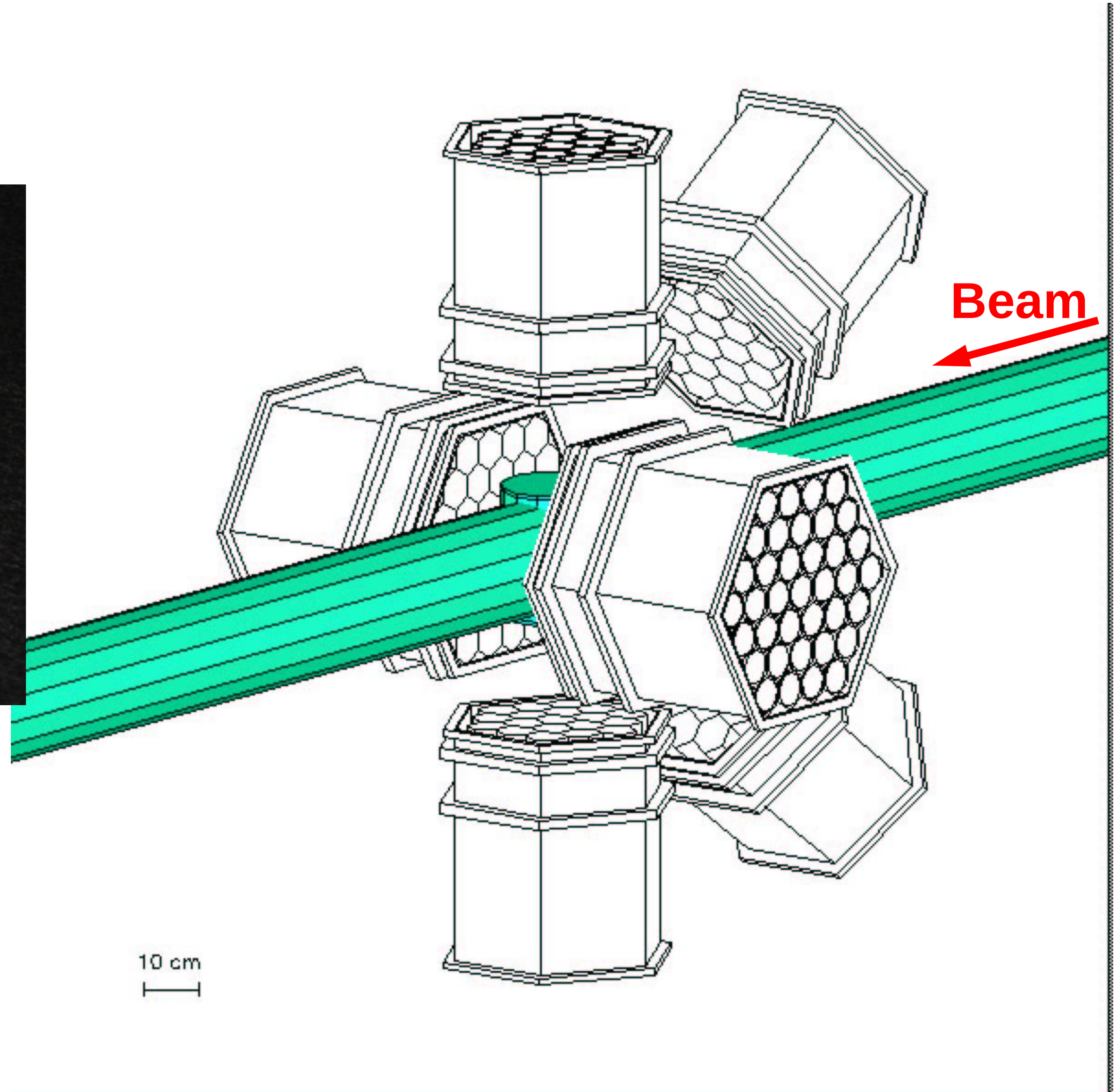
- Opportunity to study a new doubly magic nucleus
- Study collectivity of N=82, Z=50 core excitation
- High E(2^+) ~ 4MeV + small B(E2) + weak beam (10^4 pps)
  ➔ very low event rate

- Employ high efficiency BaF_2 γ-array
  - ~ 40% full-energy at 4 MeV
- Use high-Z target (^{48}Ti)
- Run at higher ("unsafe") energies (495 MeV and 470 MeV)
- Limit distance of closest approach by looking only at forward angles in center of mass



Setup for ^{132,134}Sn Coulomb Excitation

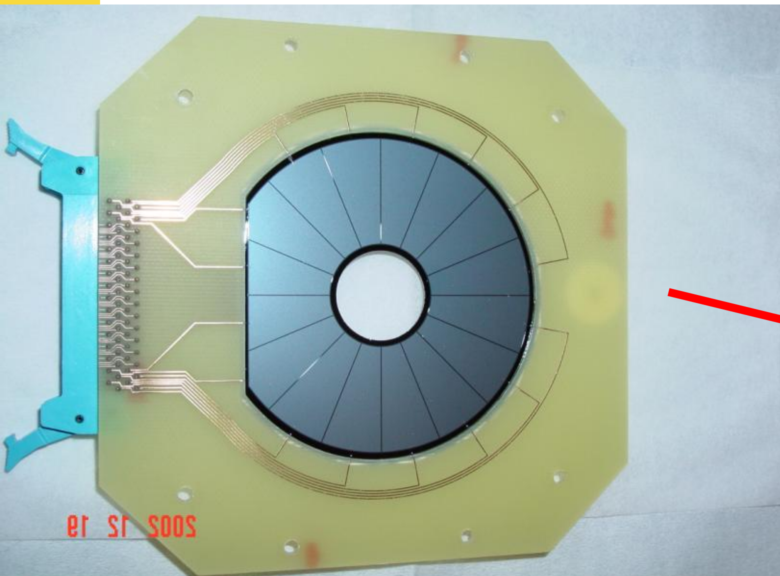
BaF_2 array (150 crystals) for gamma-rays

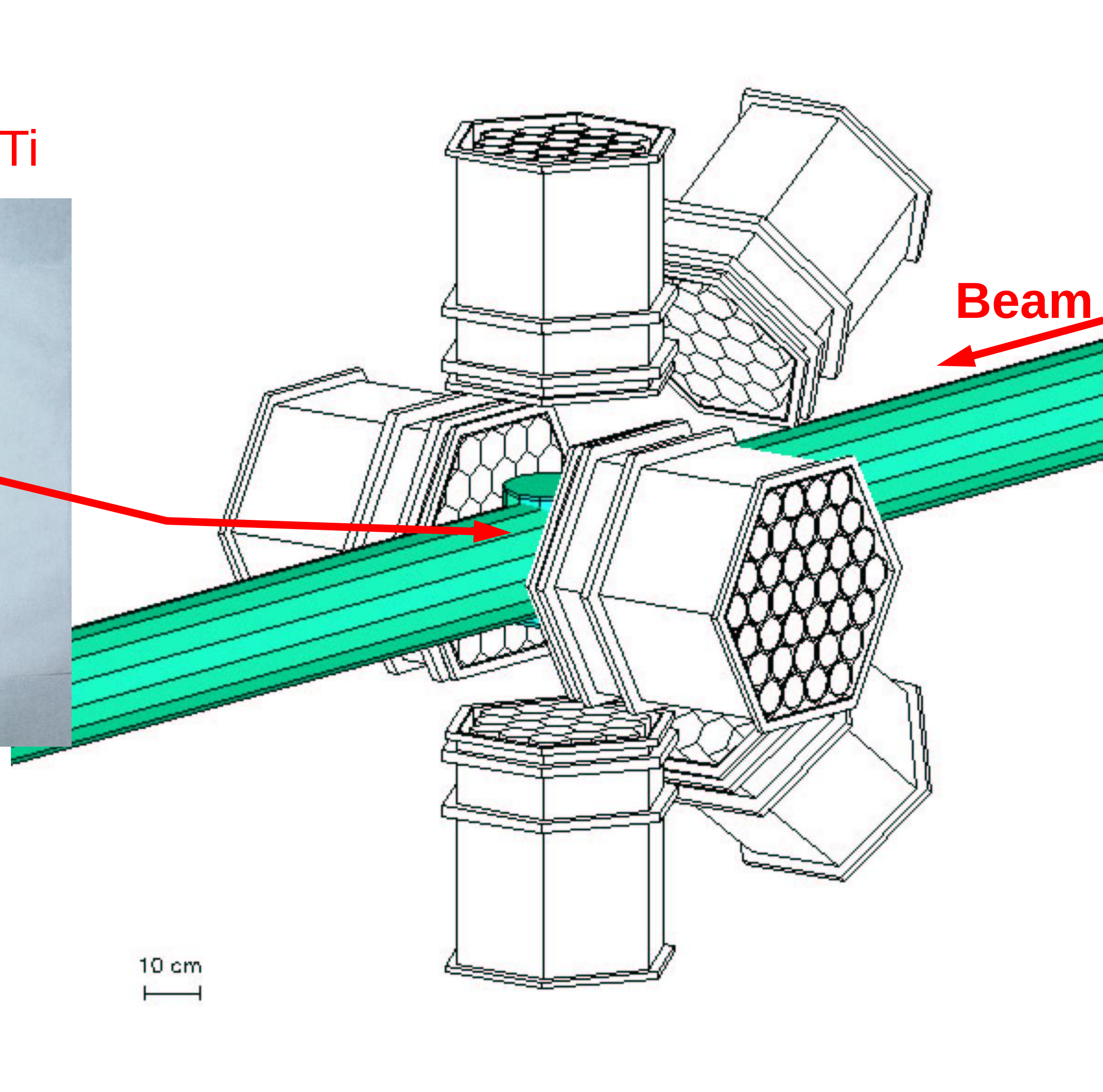


courtesy of D. Radford

Setup for ^{132,134}Sn Coulomb Excitation

"CD"-type Si detector for
scattered Sn and Ti





- 7 cm diameter
- 48 radial strips
- 16 sectors

θ_{LAB} ~ 7° – 25°

θ_{CM} ~ 30° - 160°

courtesy of D. Radford

First results on ^{132}Sn

- ^{132}Sn beam, doubly stripped
    - 96% pure
    - 1.3×10^5 ions/s
    - 3.75 & 3.56 MeV/u
- ^{48}Ti target
- High γ efficiency (~ 40%)
- Two-week experiment
- Fast γ–ion coincidences
  to suppress background

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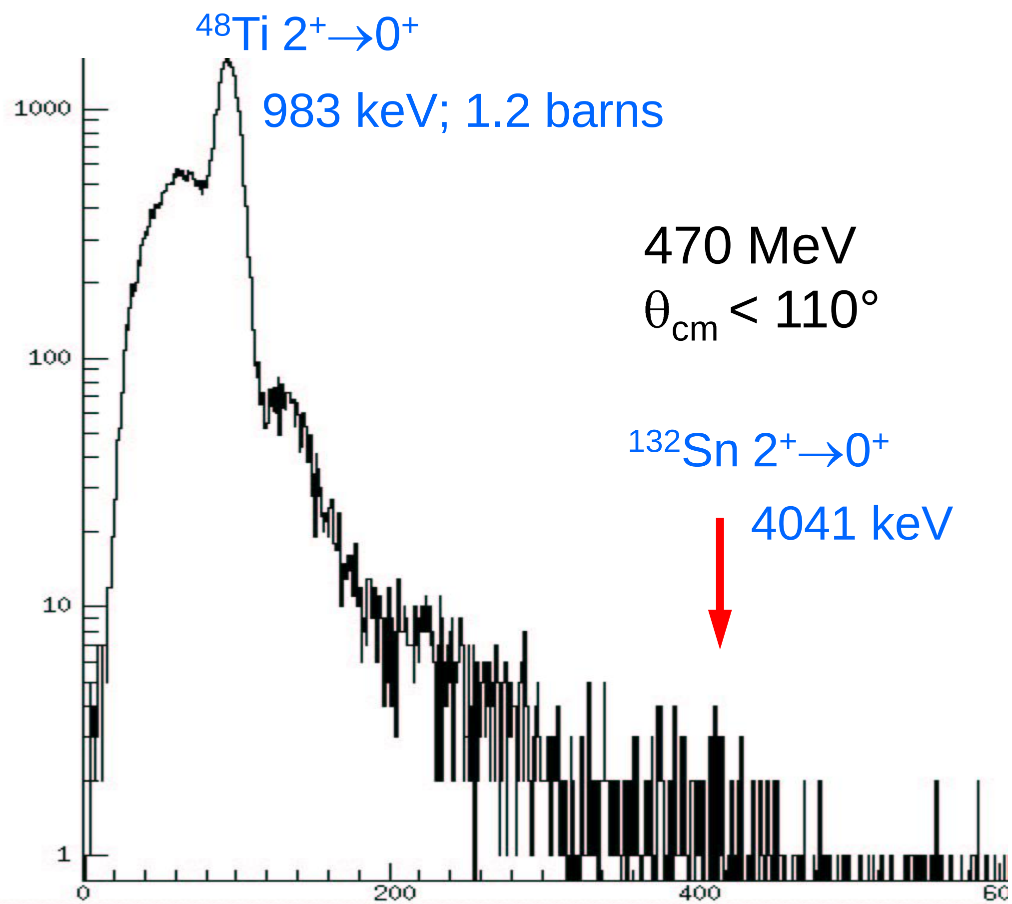
Sample gamma-ray spectrum:

- *~30% of data*
- *Crystal gain matching & background suppression not yet optimum*



First results on ^{132}Sn

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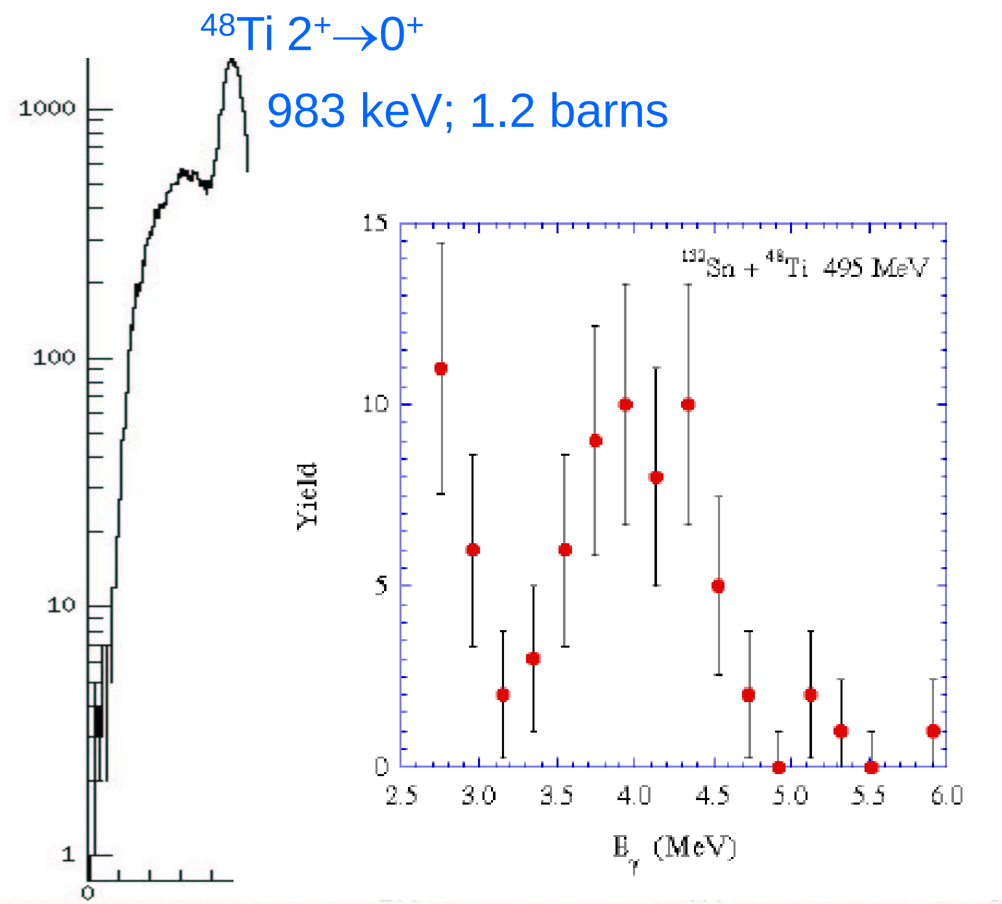
  - 96% pure
  - 1.3 x 10^5 ions/s
  - 3.75 & 3.56 MeV/u
- ^{48}Ti target
- High γ efficiency (~ 40%)
- Two-week experiment
- Fast γ–ion coincidences to suppress background

B(E2; $0^+ \rightarrow 2^+$) ~ 0.11(3) e^2b^2

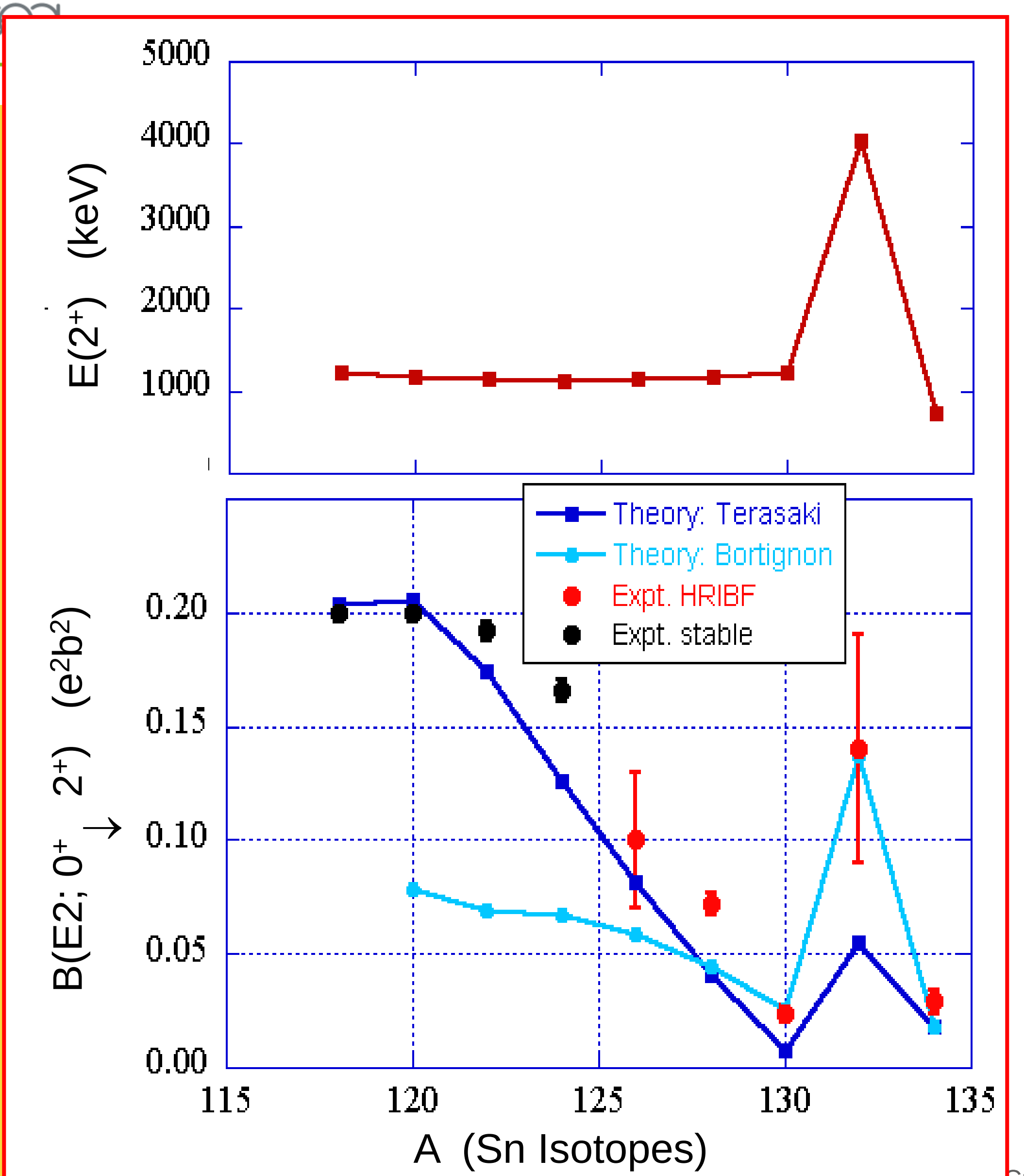
R. Varner *et al.*,
EPJ. A 25, s01, 391 (2005)

Sample gamma-ray spectrum:

- *~30% of data*
- *Crystal gain matching & background suppression not yet optimum*



Coulomb Excitation Results for Sn isotopes

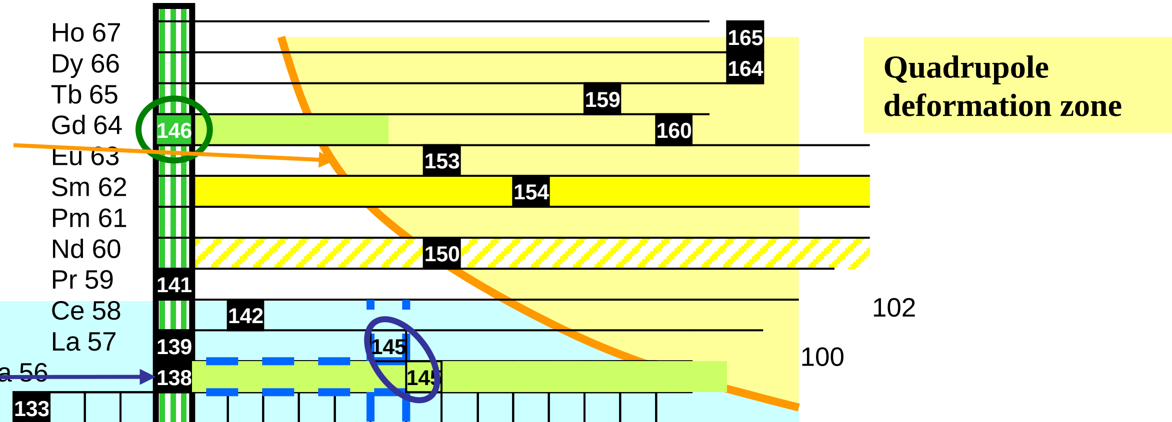


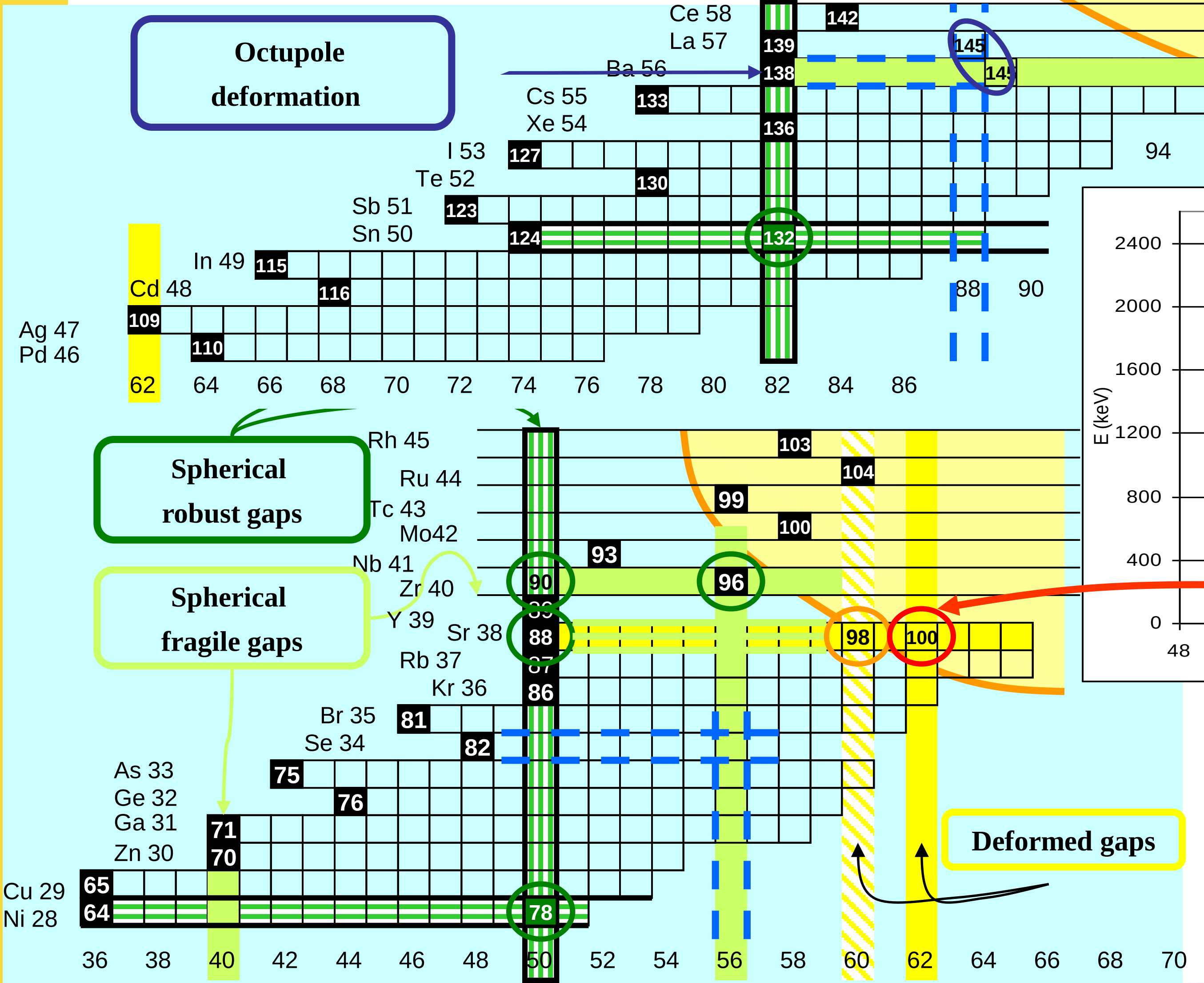
- ^{132}Sn: **B(E2) ~ 0.11(3) e^{2}b^2**
  - 14% Isoscalar E2 EWSR
- ^{134}Sn: **B(E2) = 0.029(5) e^{2}b^2**

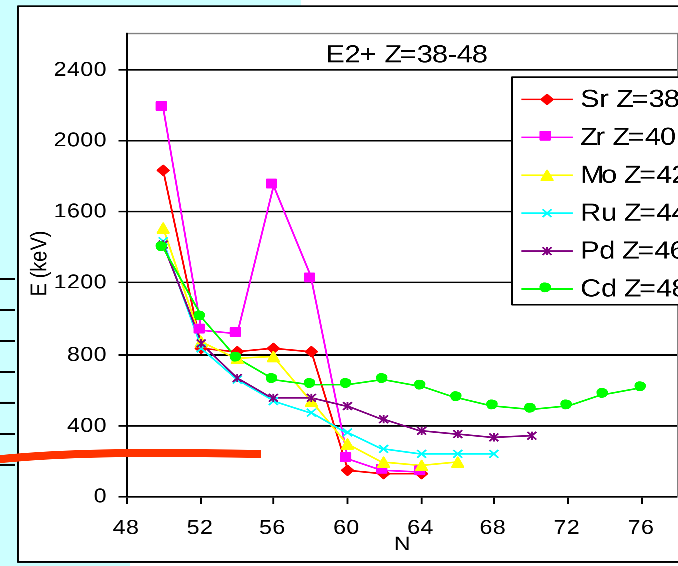
New facilities needed in order to fully explore this mass region

Perspectives

SPIRAL2, HIE-ISOLDE, TRIUMF, …







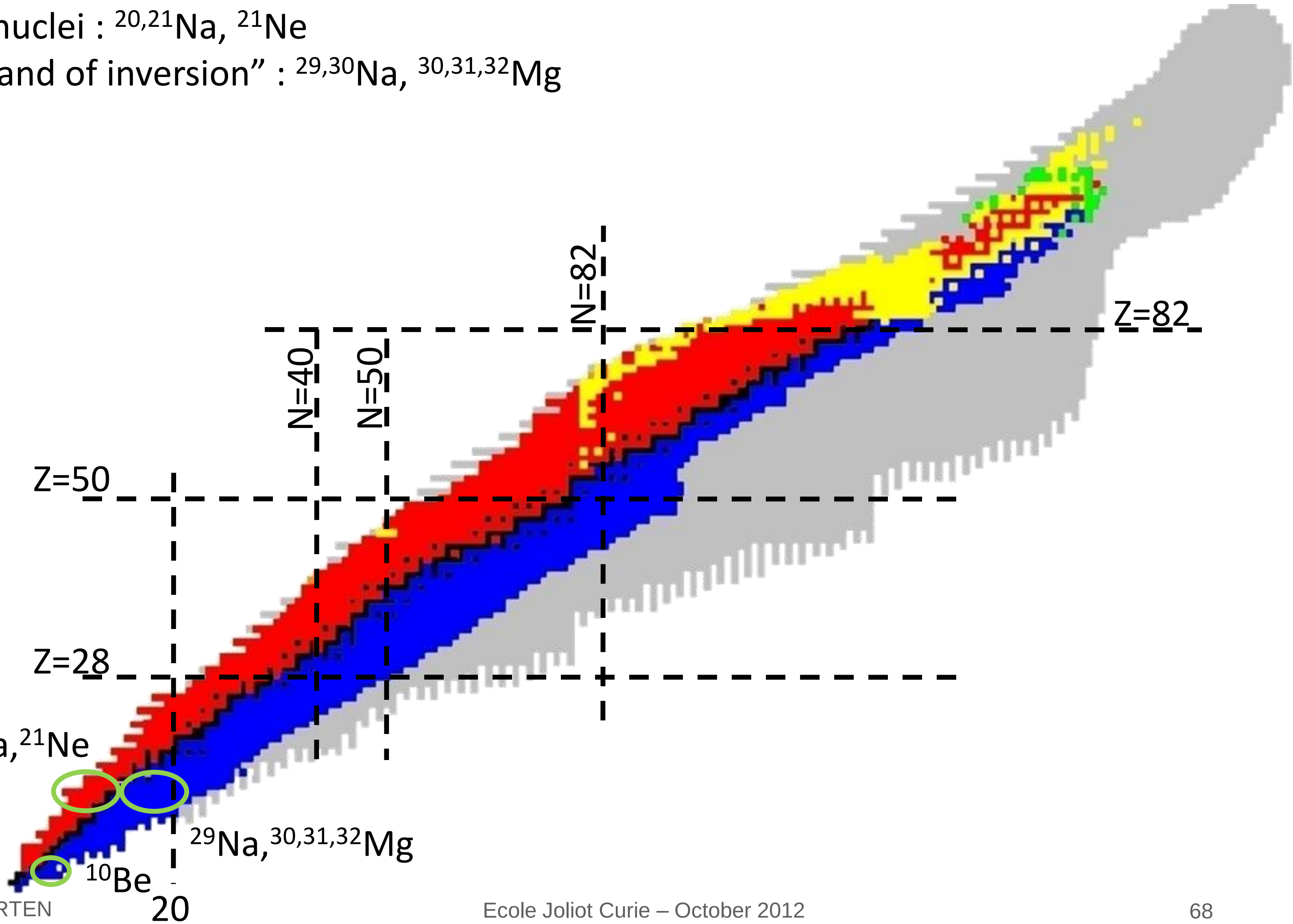
Fission region

courtesy D. Verney (IPNO)

Coulomb excitation studies with low-energy RIBs

Drip lines and shell structure in light nuclei

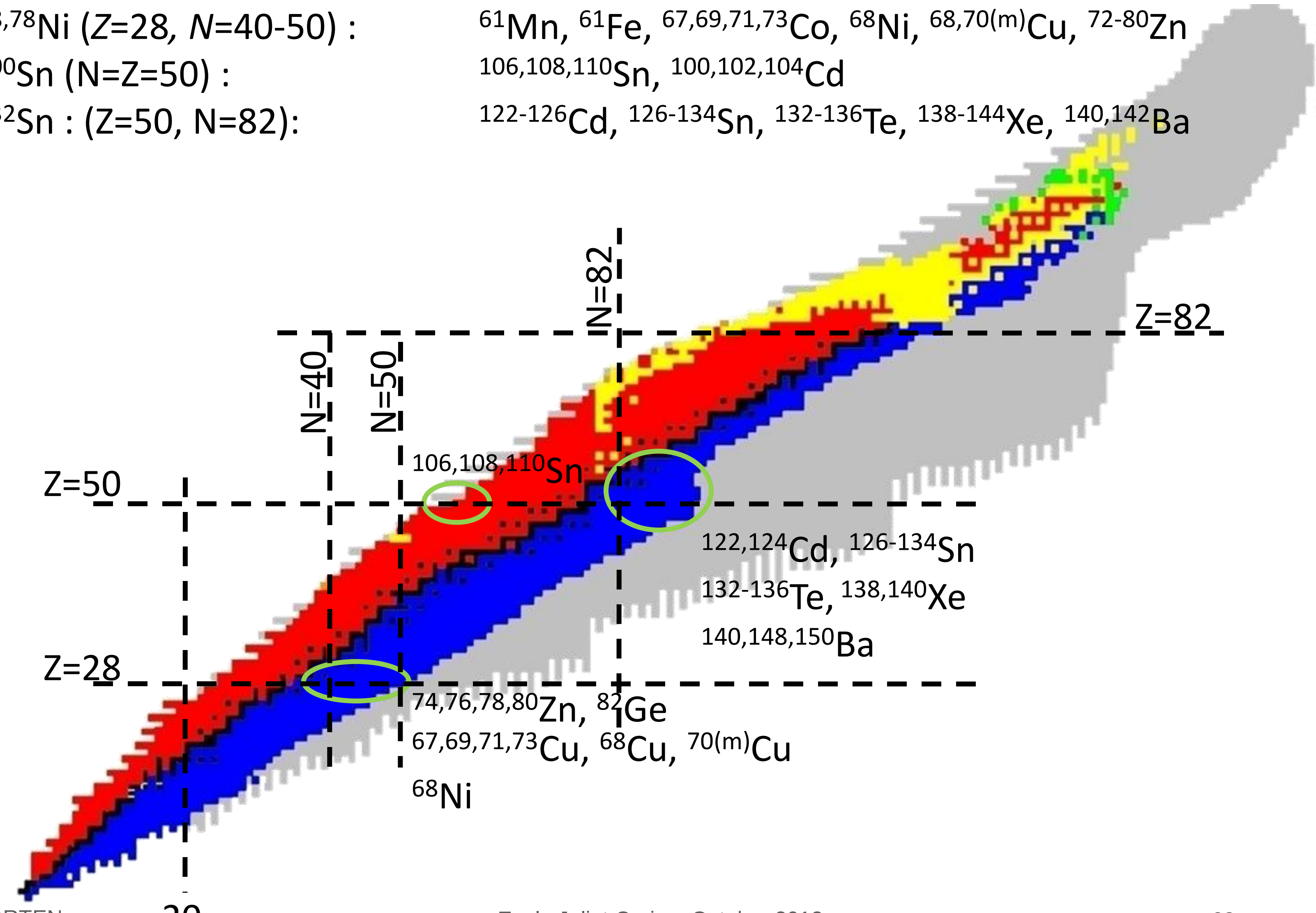
- ✓ Drip-line nuclei: ^{10,11}Be, …
- ✓ Mirror nuclei : ^{20,21}Na, ^{21}Ne
- ✓ The "island of inversion" : ^{29,30}Na, ^{30,31,32}Mg



Coulomb excitation studies with low-energy RIBs

Evolution of Shell Structure far from stability

- ✓ ^{44}Ar (N=28)
- ✓ $^{68,78}Ni$ (*Z*=28, *N*=40-50) : ^{61}Mn, ^{61}Fe, $^{67,69,71,73}Co$, ^{68}Ni, $^{68,70(m)}Cu$, $^{72-80}Zn$
- ✓ ^{100}Sn (N=Z=50) : $^{106,108,110}Sn$, $^{100,102,104}Cd$
- ✓ ^{132}Sn : (Z=50, N=82): $^{122-126}Cd$, $^{126-134}Sn$, $^{132-136}Te$, $^{138-144}Xe$, $^{140,142}Ba$



Coulomb excitation studies with low-energy RIBs

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saclay

Evolution of nuclear shapes and shape coexistence

- ✓ N=Z ≈ 34: ^{70}Se, ^{72,74,76}Kr,
- ✓ N ≈ 60: $^{88\text{-}96}$Kr, ^{96,98}Sr, $^{93\text{-}99}$Rb, …
- ✓ N ≈ 82: ^{140}Nd, ^{140,142}Sm
- ✓ Z ≈ 82: $^{182\text{-}188}$Hg, ^{186,188,200}Pb, $^{196\text{-}202}$Po, ^{202,204}Rn, …