Senter for Akseleratorbasert
Forskning og Energifysikk

Low-energy Coulomb excitation with RIB

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Coulomb excitation (1)

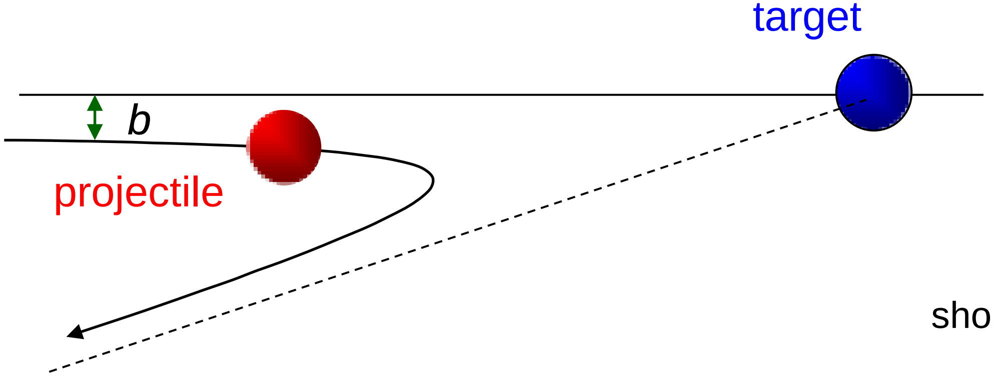
nuclear excitation by electromagnetic field acting between passing nuclei

well-understood process ⇒ quantitative nuclear structure information
without uncertainties due to incomplete knowledge of nuclear interaction

direct measure of electromagnetic matrix elements
⇒ sensitive test of nuclear structure theories

technique well suited for use with radioactive beams:
- fundamental quantities in the most exotic nuclides: $E(2^+)$, $B(E2;0^+ \rightarrow 2^+)$
- in-depth studies with more intense beams:
  - rotational, vibrational, octupole bands
  - spectroscopic quadrupole moments, shape coexistence
  - …

Coulomb excitation (2)



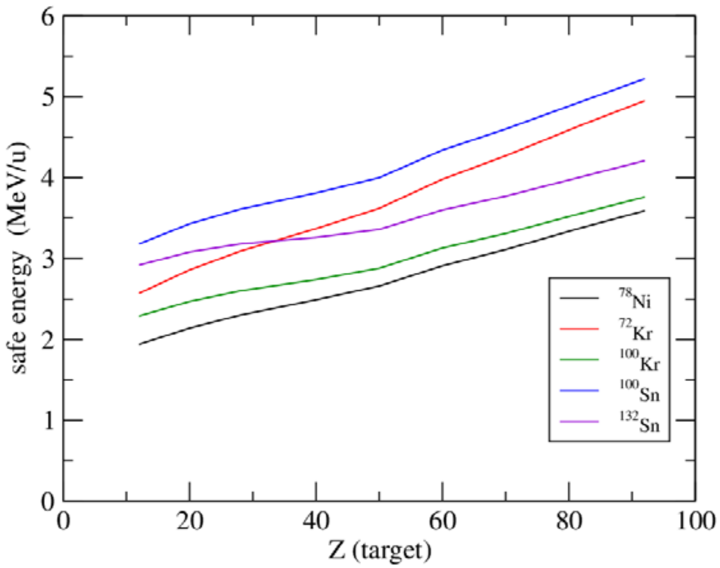
monopole – monopole ⇒ Rutherford scattering
nuclear excitation by electromagnetic interaction:
monopole – multipole ⇒ target excitation
multipole – monopole ⇒ projectile excitation
(multipole – multipole ⇒ simultaneous excitation)

short-lived radioactive isotopes ⇒ projectile excitation

"safe" Coulomb excitation: purely electromagnetic process
distance of closest approach: $2a_0 \geq [1.25\,(A_1^{1/3} + A_2^{1/3}) + 5]$ fm

limit projectile energy to fulfill safe condition (for all angles)
⇒ typical safe energies 3 – 5 MeV/u

choose small scattering angles ⇒ large impact parameters
⇒ intermediate-energy Coulomb excitation



Sommerfeld parameter: $\eta = \frac{a_0}{\lambda\!\!\!^{-}} >> 1$

fulfilled for heavy ions
⇒ classical treatment of relative motion

adiabaticity parameter: $\xi = \frac{\tau_{collision}}{\tau_{nucl}} = \frac{\Delta E}{\hbar}\frac{a_0}{v} < 1$

⇒ limits (single-step) excitations to ΔE = 1 – 2 MeV

⇒ multi-step excitation possible

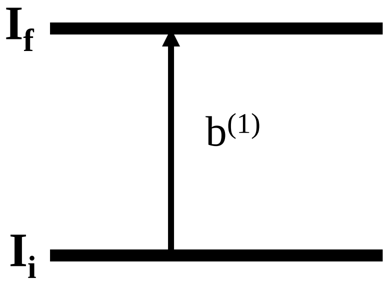
Coulomb excitation (3)

$$\left(\frac{d\sigma}{d\Omega}\right)_{if} = \left(\frac{d\sigma}{d\Omega}\right)_{Ruth} P_{if}(\vartheta,\xi)$$

first-order perturbation:

$$\mathrm{P}_{\mathrm{if}}(\vartheta,\xi) = (2\mathrm{I}_{\mathrm{i}}+1)^{-1}\sum_{\sigma=E,M}\sum_{\lambda=1}^{\infty}\sum_{\mathrm{m_i m_f}}|\,\mathrm{b}_{\mathrm{if}}^{(1)}(\sigma\lambda)\,|^2$$

$$\mathrm{P}_{\mathrm{if}}(\vartheta,\xi) \propto B(\sigma\lambda; I_i \to I_f)$$

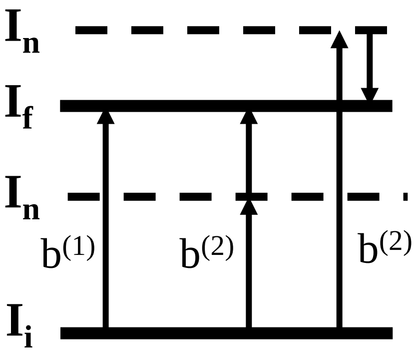


$$\mathrm{b}_{\mathrm{if}}^{(1)}(\sigma\lambda) \propto \left\langle \mathrm{I_f} \left\| \mathrm{M}(\sigma\lambda) \right\| \mathrm{I_i} \right\rangle$$

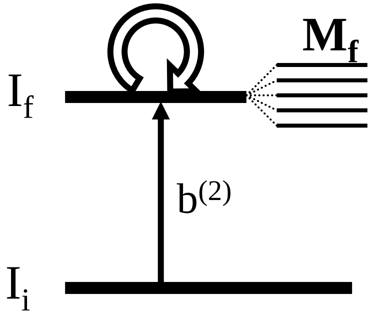
Eλ >> Mλ

second-order perturbation:

$$\mathrm{b}_{\mathrm{if}}^{(2)} = b_{if}^{(1)} + \sum_n b_{\mathrm{inf}}^{(2)}$$



$$\mathrm{b}_{\mathrm{inf}}^{(2)} \propto \sum_{\mathrm{n}} \left\langle \mathrm{I_f} \left\| \mathrm{M}(\sigma\lambda) \right\| \mathrm{I_n} \right\rangle \left\langle \mathrm{I_n} \left\| \mathrm{M}(\sigma\lambda) \right\| \mathrm{I_i} \right\rangle$$



$$b_{iff}^{(2)} \propto \left\langle I_f \left\| \mathbf{M}(\sigma\lambda) \right\| I_f \right\rangle \left\langle I_f \left\| \mathbf{M}(\sigma\lambda) \right\| I_i \right\rangle$$

reorientation effect

excitation probability depends on transitional and diagonal matrix elements
⇒ transition probabilities and static moments

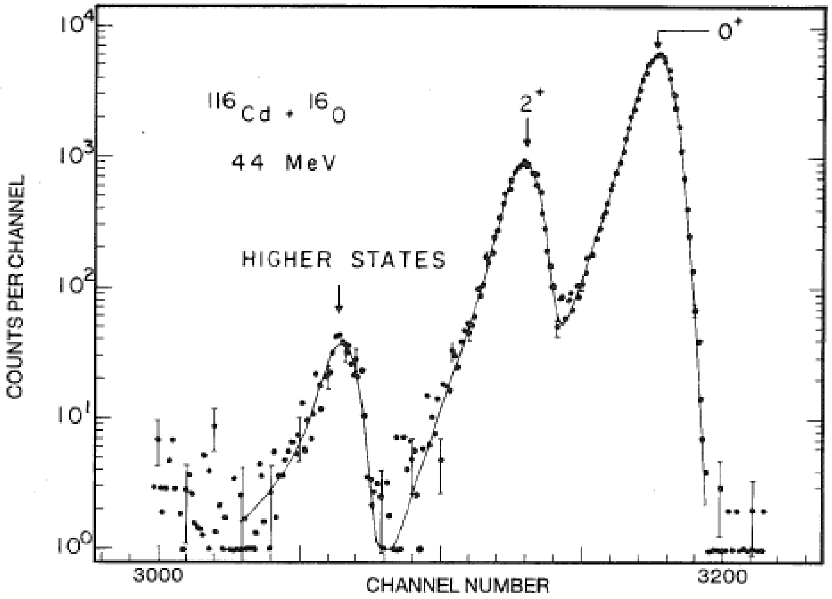
Early experiments: direct measurements using particle spectroscopy

direct measurement of P=σ/σ_{ruth}

high-resolution spectrometers
$\Rightarrow$ limited angular coverage

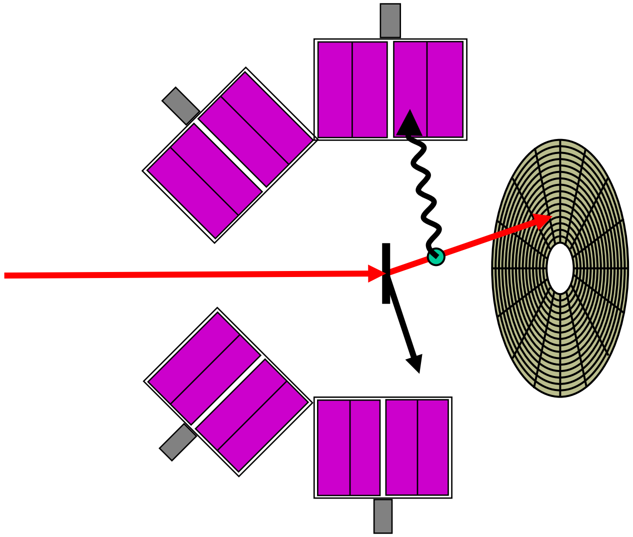
silicon detectors
$\Rightarrow$ limited energy resolution

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

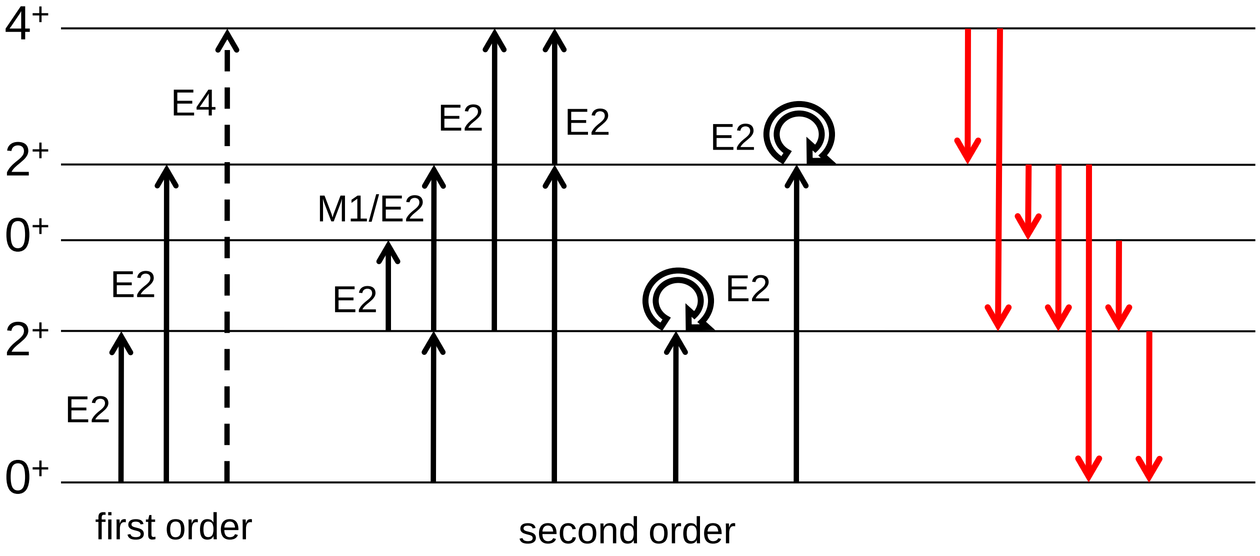


$\Rightarrow$ particle – gamma coincidences
with high-resolution Ge detectors

- ➢ measure scattered particles
    - ➢ with high angular resolution, but
    - ➢ with low energy resolution
- ➢ extract matrix elements from γ-ray yields



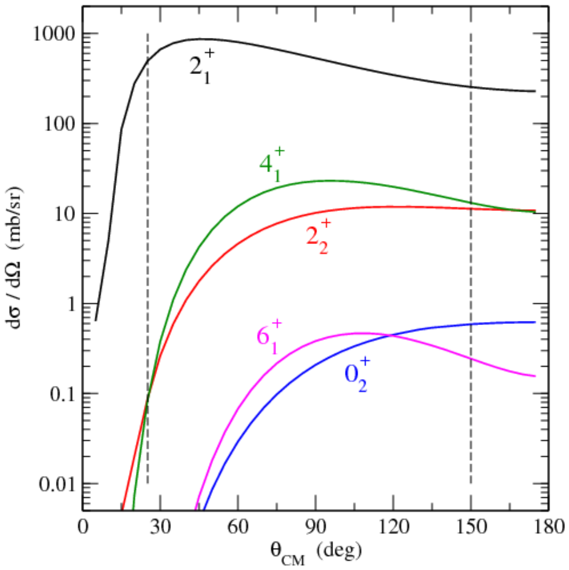
Extracting matrix elements from γ-ray yields



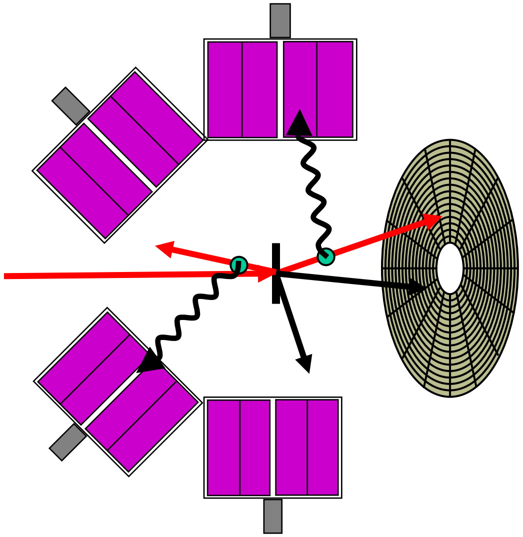
- need detector efficiencies
- angular distribution
  - de-orientation (hyperfine interaction with atomic electrons)
- no one-to-one correspondence between excitation and decay
  - e.g. E2 excitation and M1 decay
  - influence of diagonal matrix elements
- usually more matrix elements than γ-ray yields

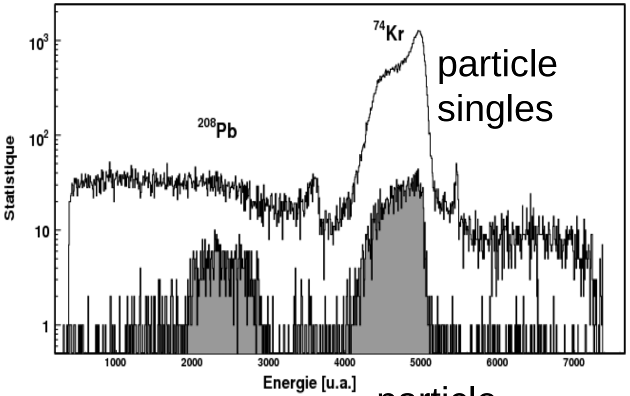
- needs differential measurements
  - yields as a function of scattering angle
  - yields as a function of Z
- least-squares fit ⇒ GOSIA

- use independent measurements as constraints
  - branching ratios
  - lifetimes



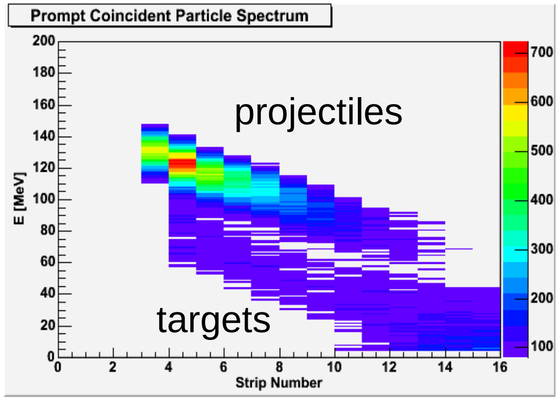
Experimental setup





particle singles

particle - γ coincidences



projectiles

targets

single ”CD-type” Si detector, ca. 25 mm from target

$\Rightarrow$ large range of θ_{CM}

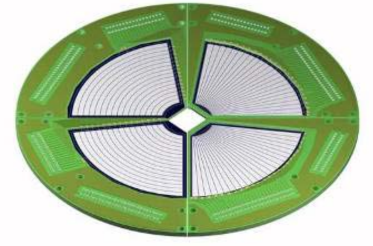
e.g. A_p=100, A_t=208: 15 <θ_{lab}<50 $\Rightarrow$ 22 <θ_{CM}<150

$\Rightarrow$ differential measurement

Micron S2

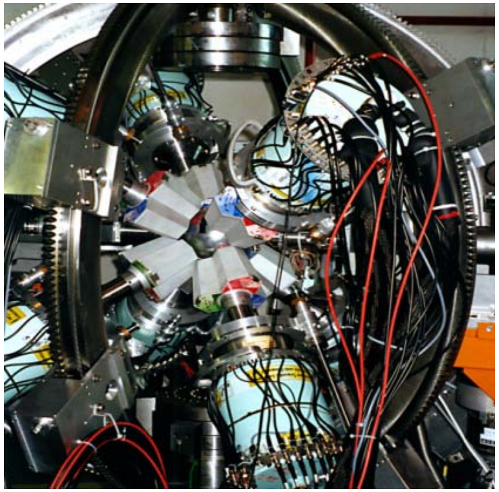
48 annular strips
16 azimuthal strips

Micron QQQ2

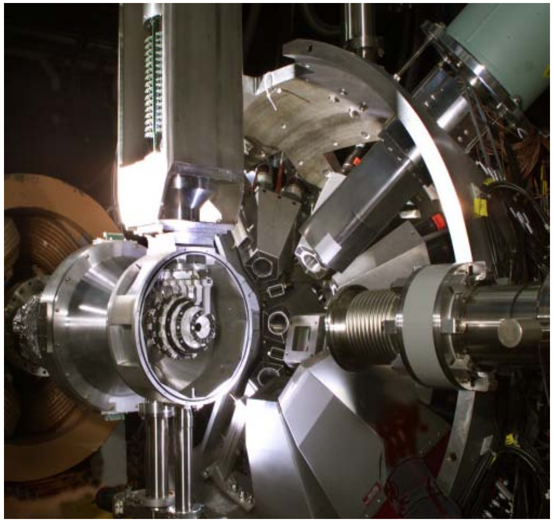


16 annular strips
24 azimuthal strips
per quadrant

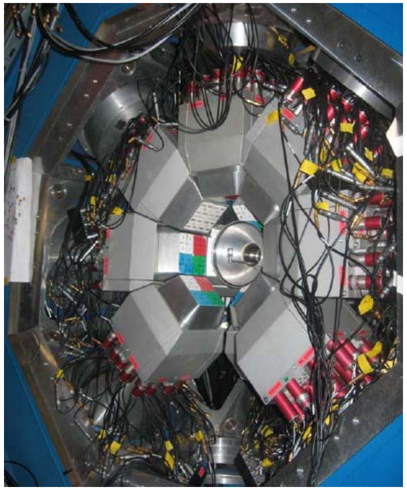
Experimental setups used with RIB



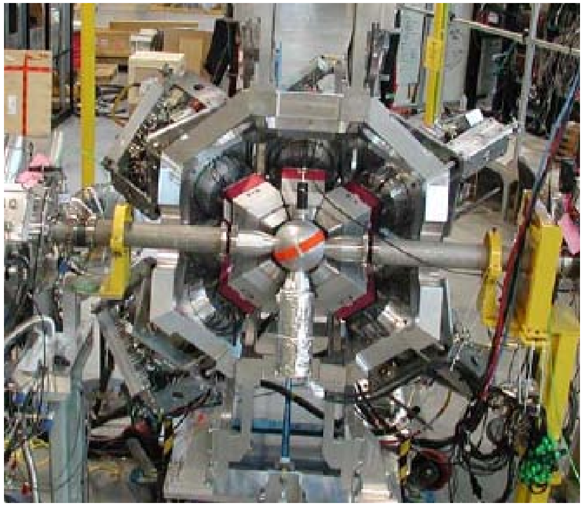
Miniball + QQQ2, ISOLDE, CERN



Clarion + Hyball, HRIBF, ORNL

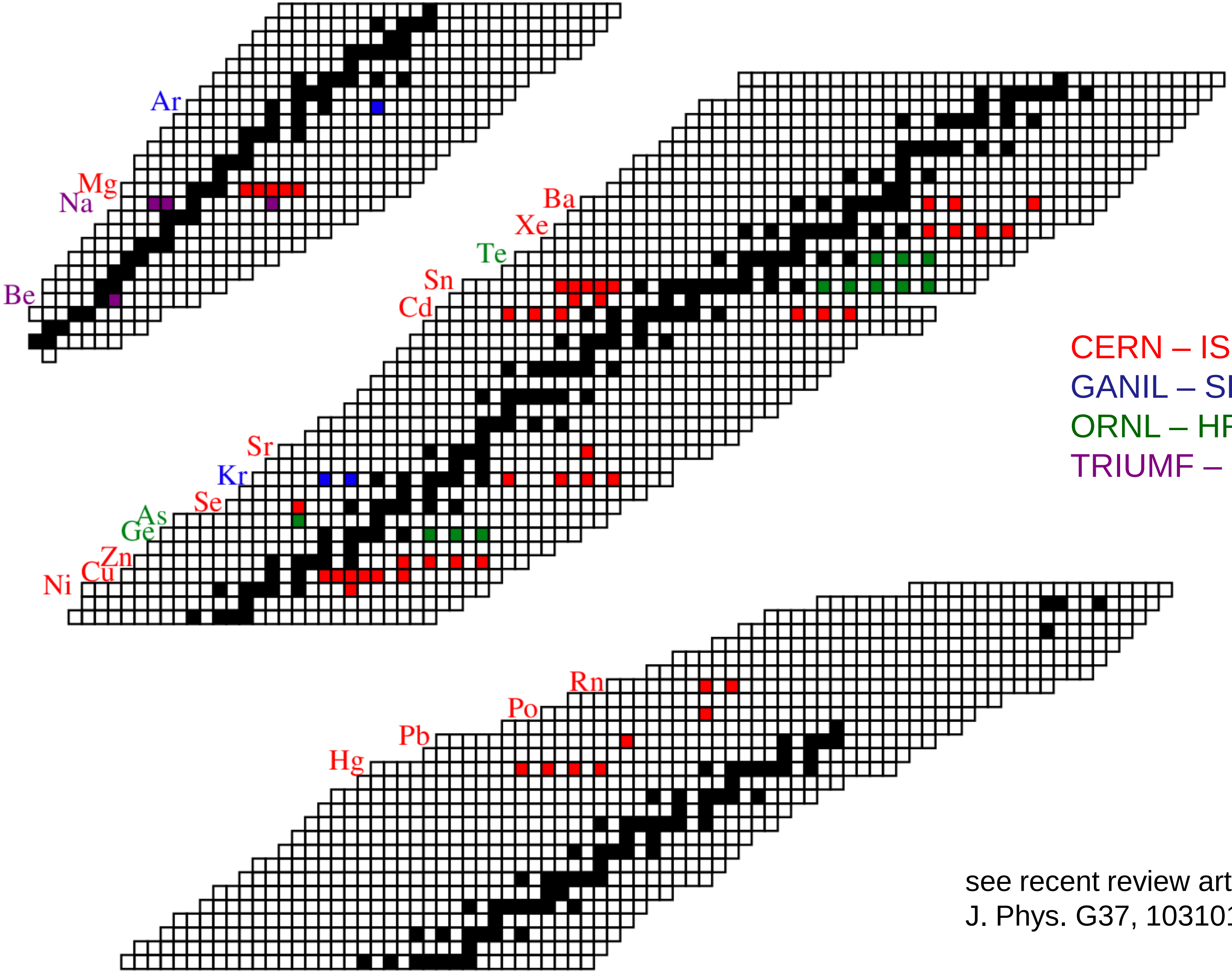


Exogam + QQQ2, SPIRAL, GANIL



Tigress + Bambino (S2), ISAC, TRIUMF

Low-energy Coulomb excitation with RIB



CERN – ISOLDE

GANIL – SPIRAL

ORNL – HRIBF

TRIUMF – ISAC

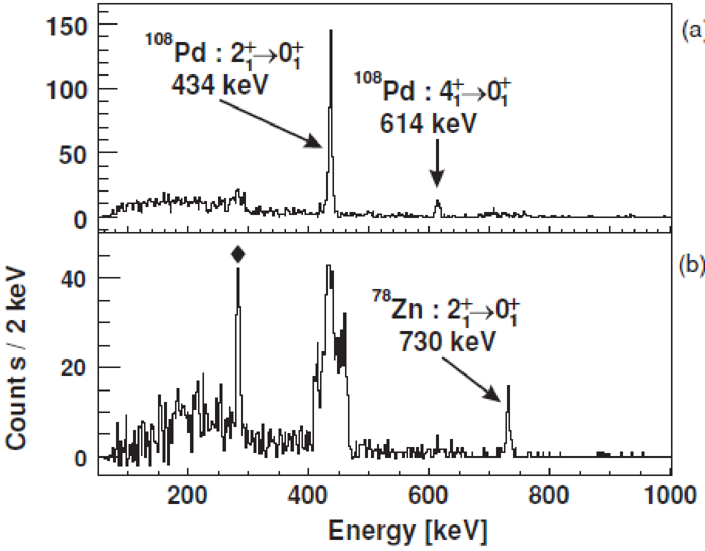
see recent review article:
J. Phys. G37, 103101 (2010)

Collectivity of neutron-rich Zn isotopes

- ISOLDE ^{78,80}Zn beam at 2.8 A MeV
- Coulomb excitation on ^{108}Pd target
- resonant laser ionization
- ^{78}Zn: 4300 ions/s, 64% purity
- ^{80}Zn: 3000 ions/s, 43% purity,
  $T_{1/2}$ = 540 ms ⇒ decay losses in trap and EBIS

easily excited target with well-known matrix elements

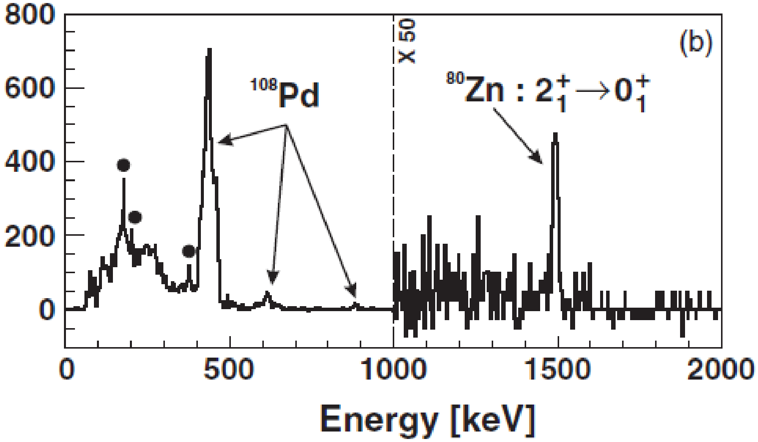
- target excitation as normalization
- efficiencies cancel out
- need to know beam composition (isobaric contaminants)

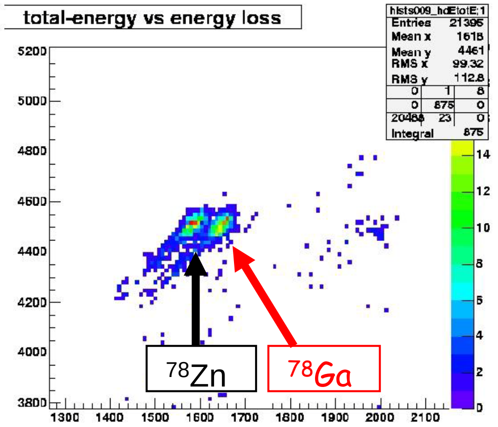


Doppler correction for target

Doppler correction for projectile

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

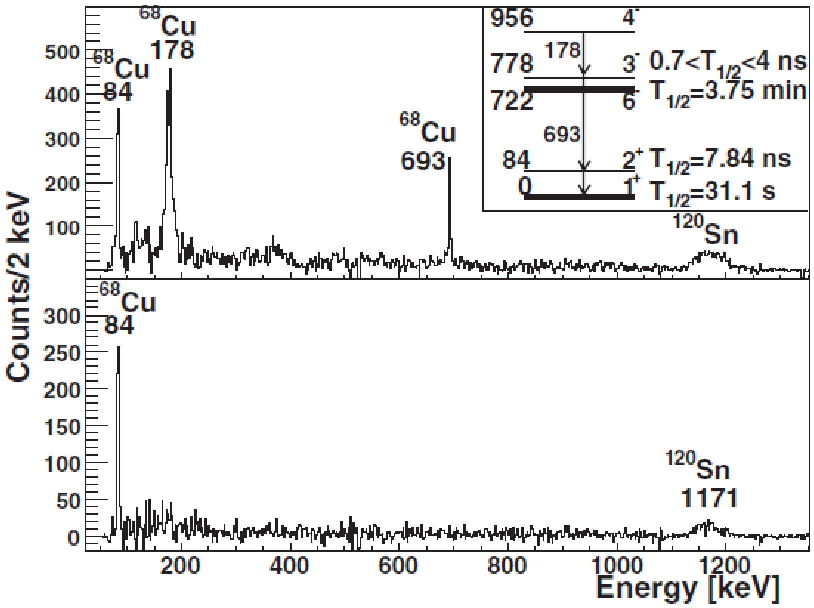


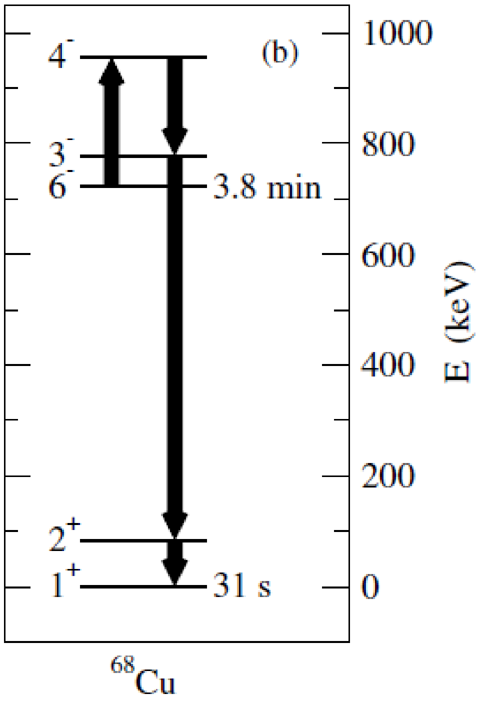


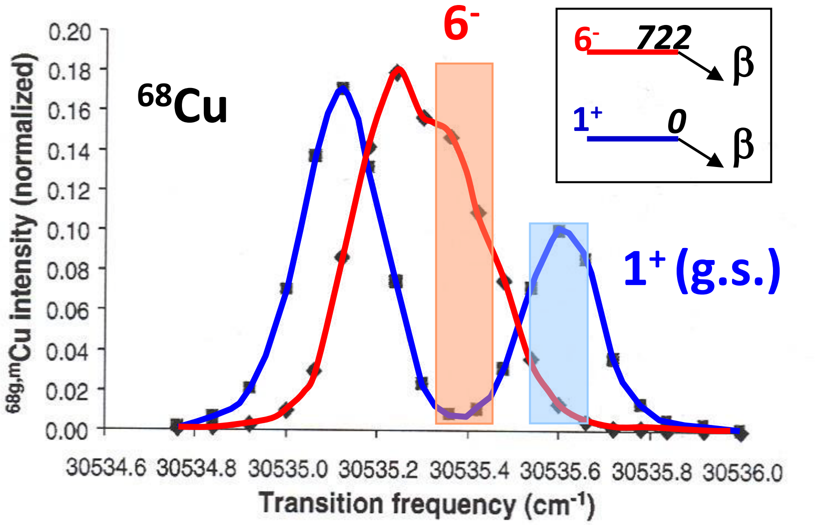
first observation of 2$^+$ state in ^{80}Zn$_{50}$

Coulomb excitation to measure fundamental properties in a very exotic nucleus

Coulomb excitation of isomeric beams produced by resonant laser ionization







I. Stefanescu et al.,
Phys. Rev. Lett. 98, 122701 (2007)

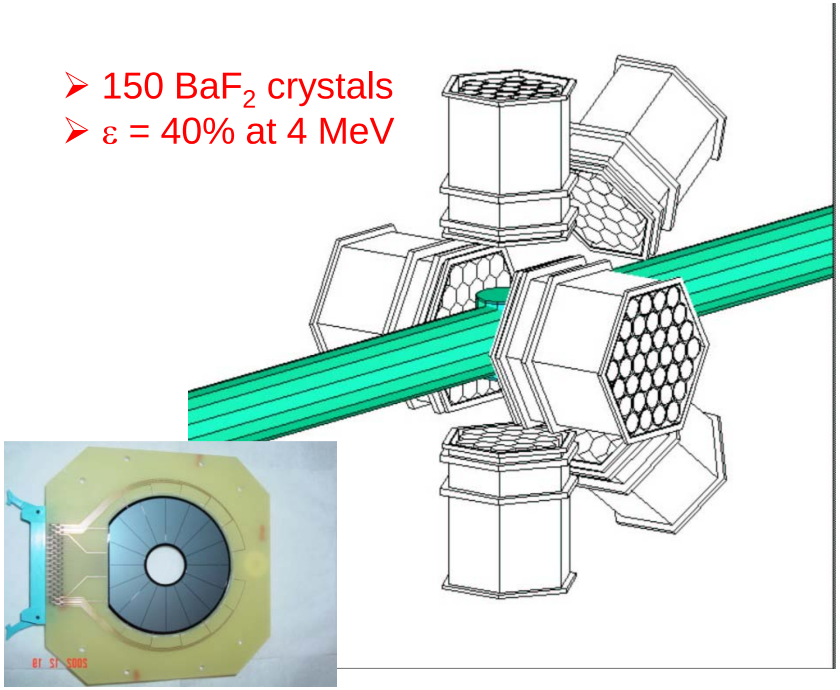
Coulomb excitation + laser ionization

Coulomb excitation of ^{132}Sn

- HRIBF ^{132}Sn beam at E=3.75 A MeV
- ^{132}Sn intensity: 10^5 ions/s
- Coulomb excitation on ^{48}Ti target
- unsafe energy, limit for scattering angle
- high-lying 2^+ state at 4 MeV

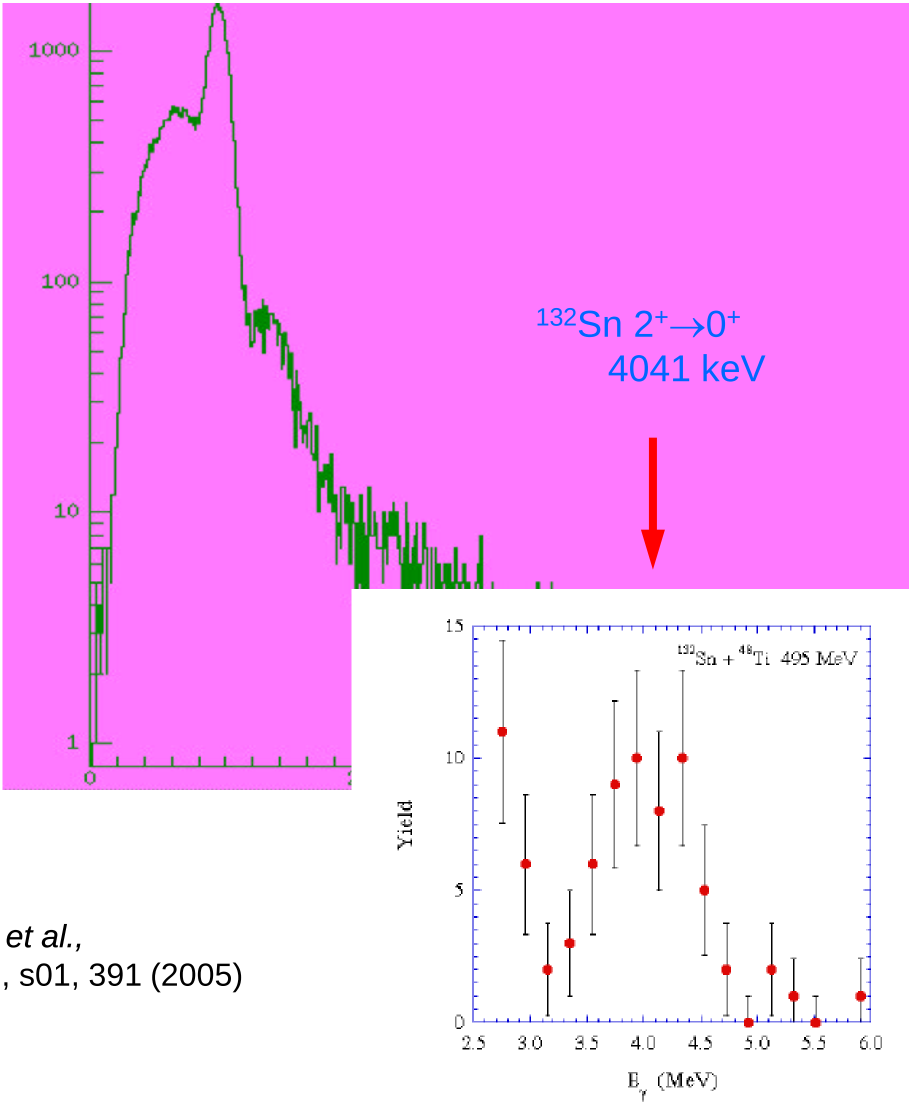
AGATA + PARIS ?

- 150 BaF_2 crystals
- ε = 40% at 4 MeV



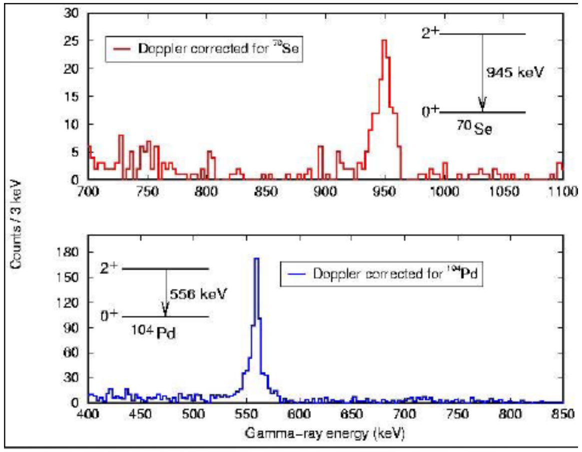
^{48}Ti $2^+ \rightarrow 0^+$
983 keV

^{132}Sn $2^+ \rightarrow 0^+$
4041 keV



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

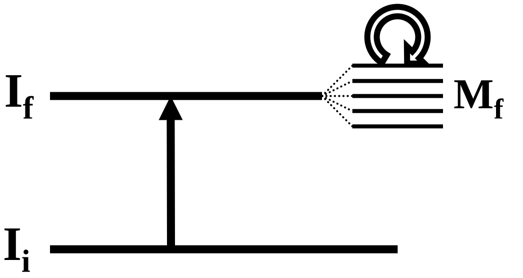
Shape of ^{70}Se

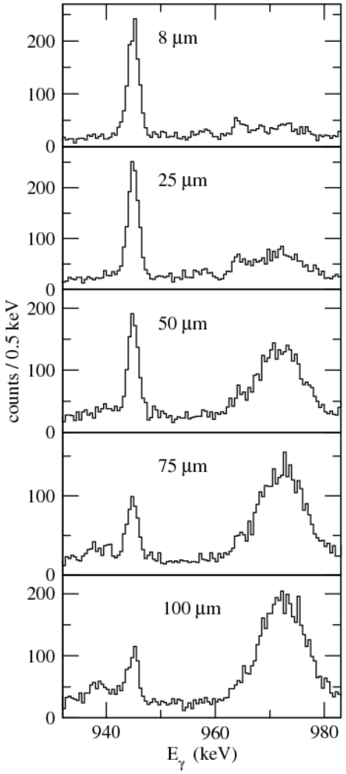


- ISOLDE ^{70}Se beam
- 10^4 pps at 2.94 A MeV
- excitation on ^{104}Pd target
- excitation probability P(2^+) via normalization to target

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

- P(2^+) depends on **B(E2)** and **Q_s**
- one measurement, two unknowns !

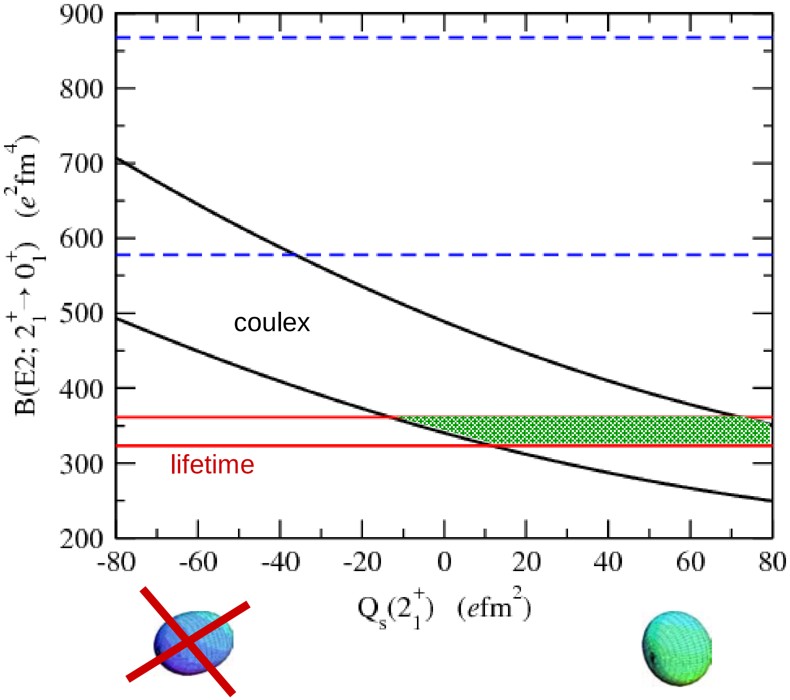




complementary
recoil-distance
lifetime measurement

J. Ljungvall et al.,
PRL 100, 102502 (2008)

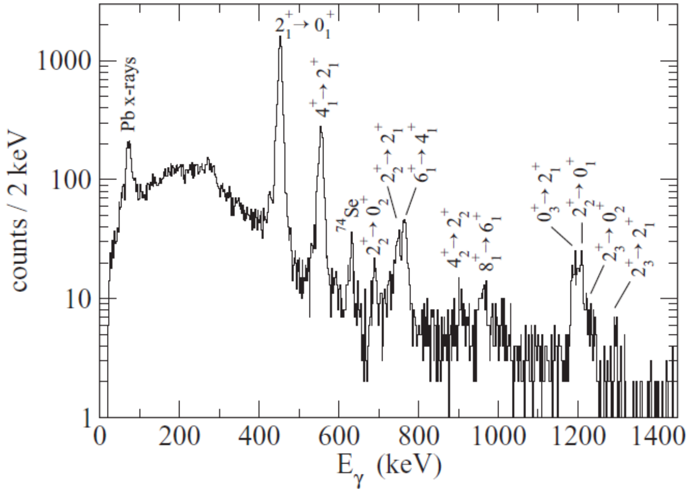
Coulomb excitation
+ lifetime measurement

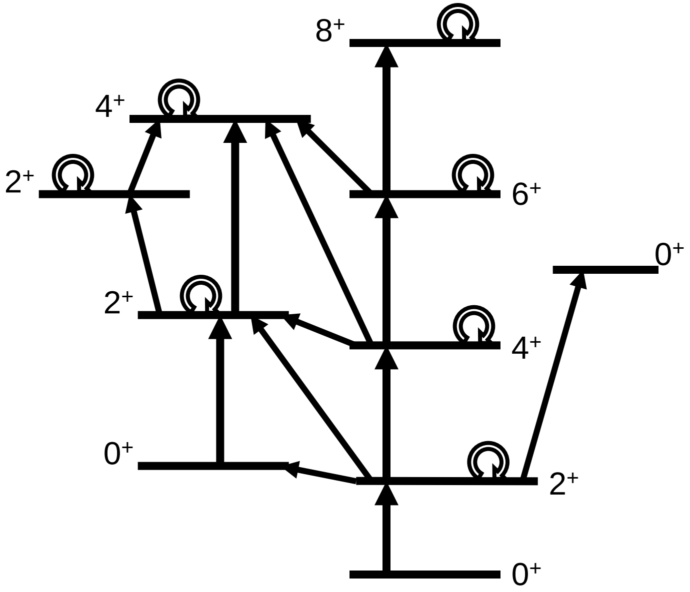


Multi-step Coulomb excitation of ^{74}Kr

- SPIRAL ^{74}Kr beam
- 10^4 pps at 4.7 A MeV
- scattered on ^{208}Pb target
- multi-step up to 8^+

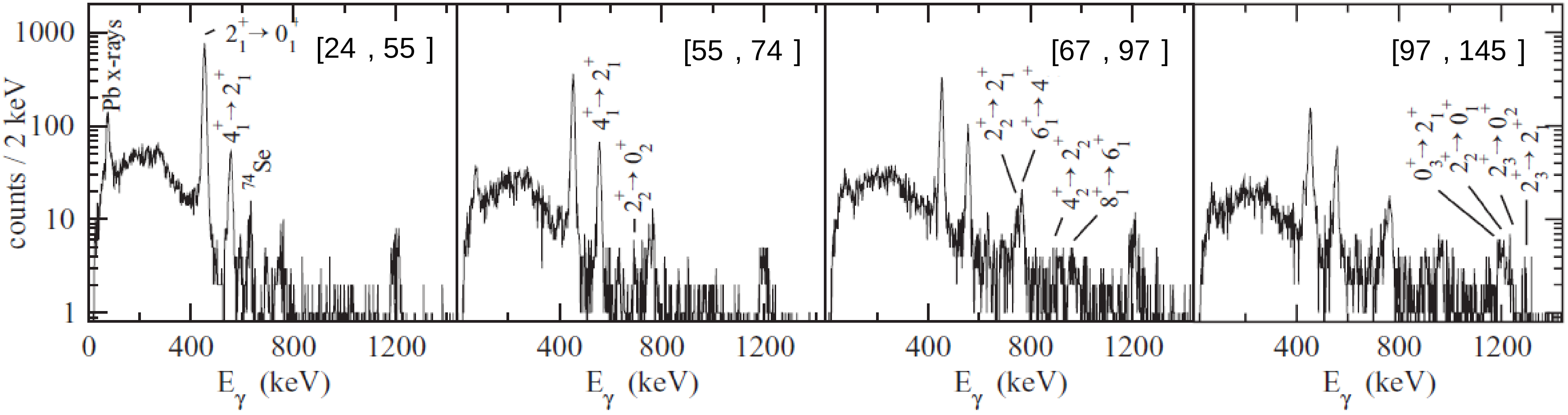
E. Clément et al.,
PRC 75, 054313 (2007)



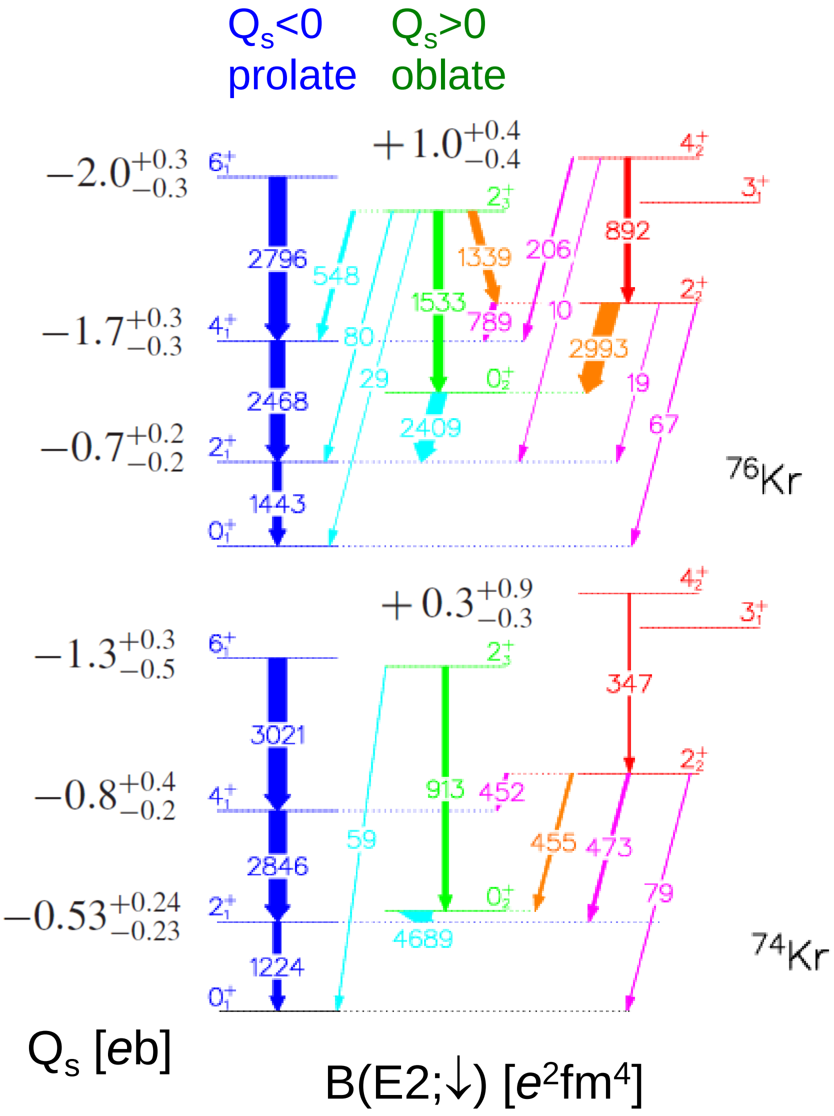


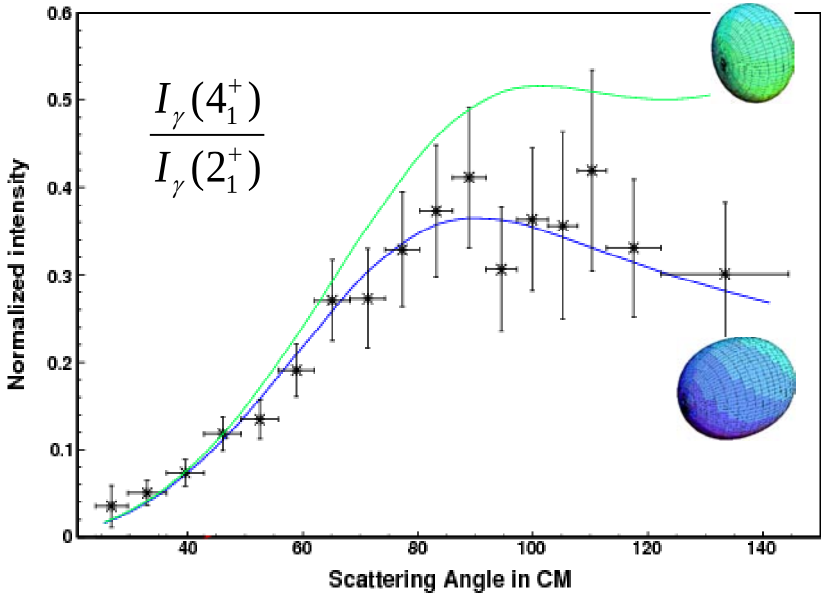
χ^2 minimization of matrix elements (transitional, diagonal) to reproduce experimental γ-ray yields

- differential measurement $\sigma(\theta)$



Shape coexistence in light Kr isotopes



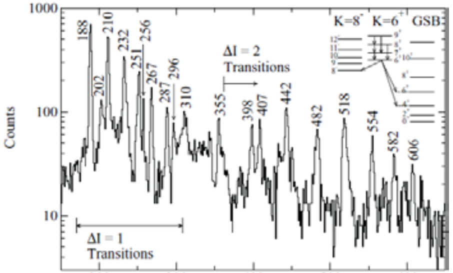


- ➢ complete set of matrix elements for low-lying states
- ➢ quadrupole moments via reorientation effect

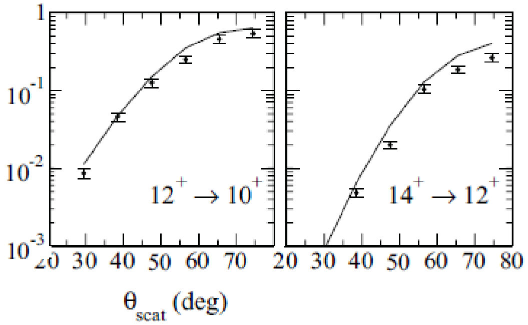
E. Clément et al., PRC 75, 054313 (2007)

Example for stable-beam Coulex: K mixing in ^{178}Hf

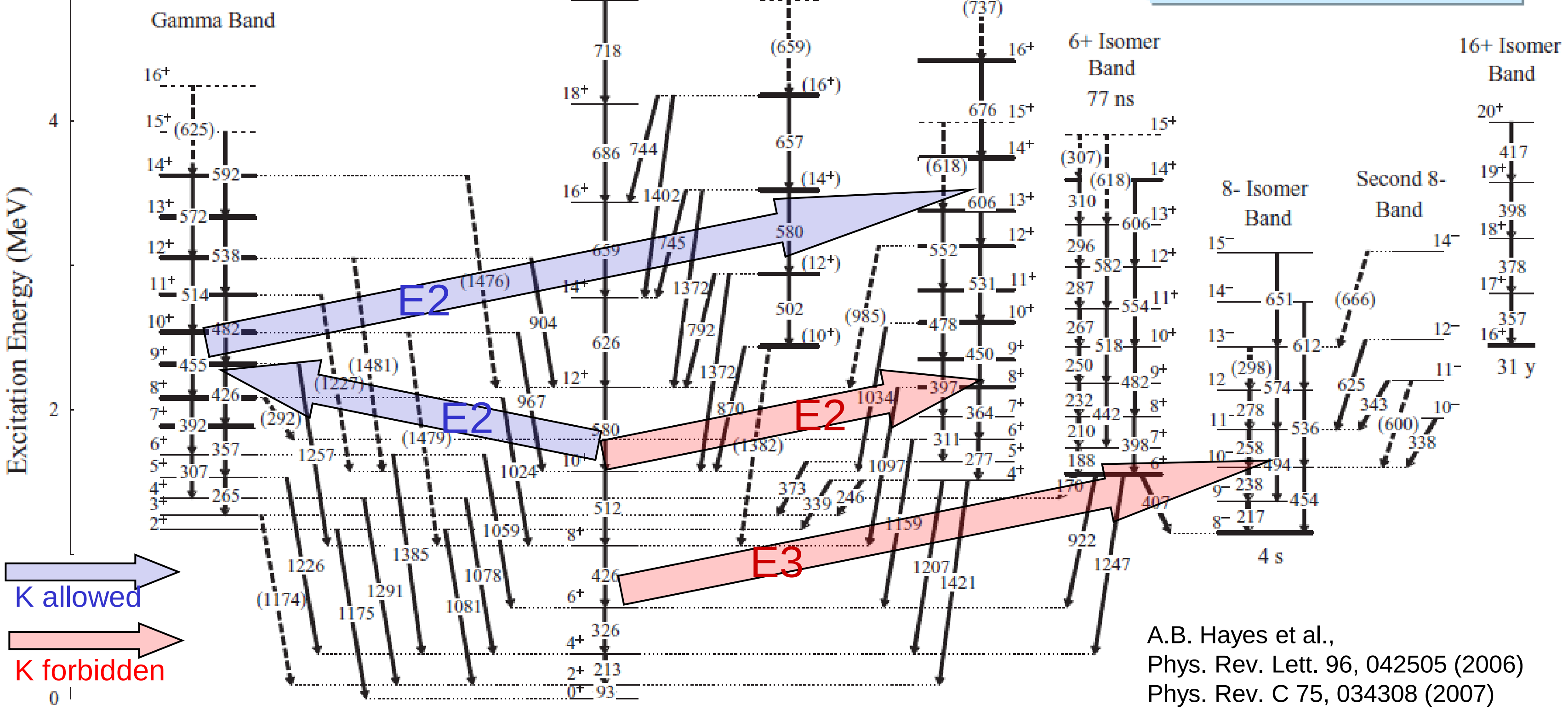
^{136}Xe + ^{178}Hf @ 4.8 A MeV
Gammasphere + CHICO @ ANL



γγ coincidence spectrum



High-intensity RIB
⇒ in-depth studies of collective excitations in unstable nuclei



K allowed

K forbidden

A.B. Hayes et al.,
Phys. Rev. Lett. 96, 042505 (2006)
Phys. Rev. C 75, 034308 (2007)

Summary

- Coulomb excitation: old technique for new physics with RIB
- fundamental properties $E(2^+)$, $B(E2;0^+\rightarrow2^+)$ of the most exotic nuclides
- in-depth studies when higher beam intensities are available
- even more powerful when combined with
  - laser ionization
  - lifetime measurements etc.