Experimental perspective: observables and detection set-ups

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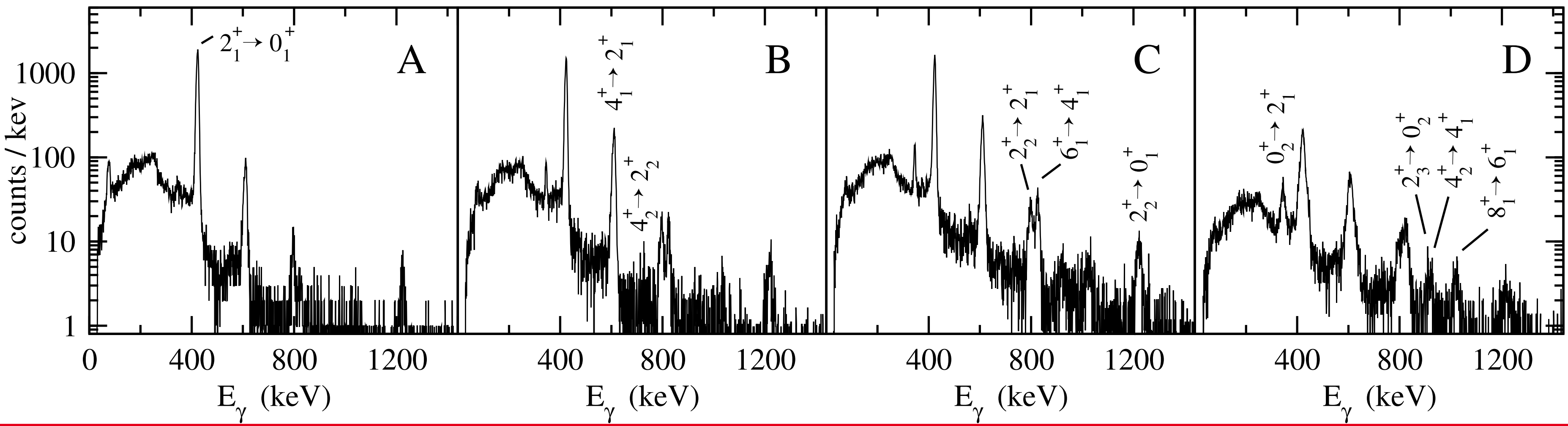
- What is measured and what effects we make use of?
- Examples of particle detectors
- Complementary experimental information

Low-Energy Coulomb Excitation and Nuclear Deformation, chapter in: *The Euroschool on Exotic Beams - Vol.6*, Lecture Notes in Physics 1005, 43 (2022).

Experiment step by step – what do we measure?

- velocity vectors of reaction partners (from scattering angle and energy or TOF measured by particle detectors)
  - selection of Coulomb-excitation events (high beam energy, exotic beam experiments, experiments with oxide targets...)
  - identification target-projectile
  - description of the excitation process (dependence on θ)
  - Doppler correction of gamma rays
  - possibility to study particle-gamma correlations

- γ-ray intensities following Coulomb excitation as a function of CM scattering angle



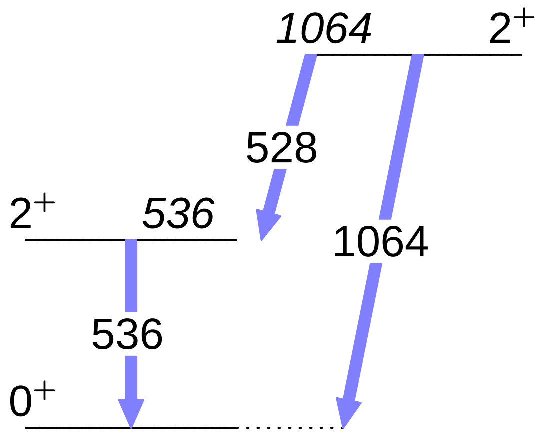
Once we have gamma-ray intensities...

...to convert them to cross sections normalisation is needed

- known B(E2) in the studied nucleus
- known B(E2) in the reaction partner
- Rutherford cross section

Final step: extraction of individual electromagnetic matrix elements from measured gamma-ray intensities

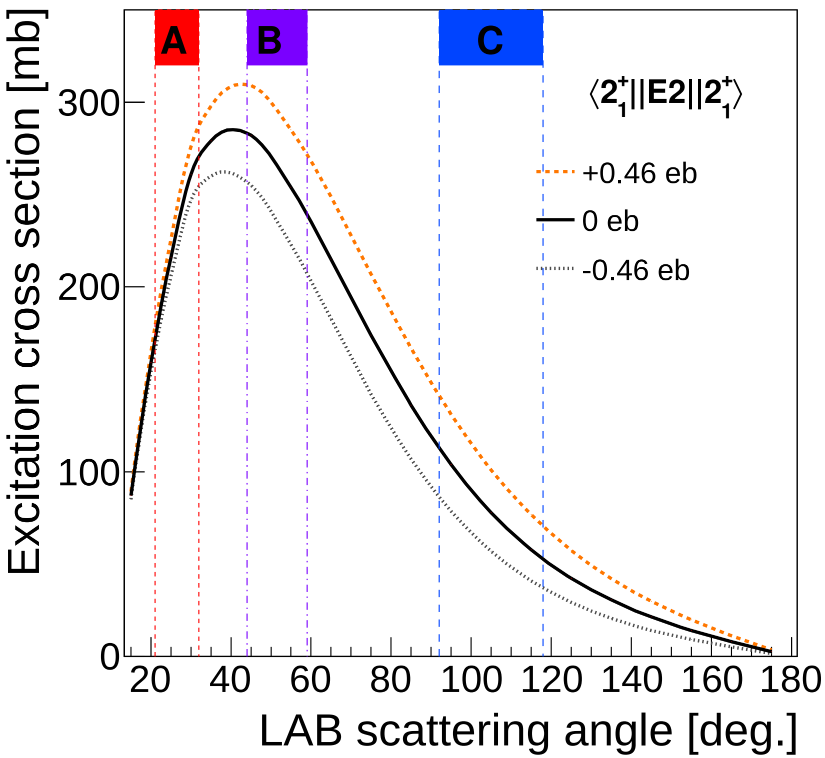
- simple cases (rare) : first/second order perturbation theory
- most cases too complicated: multiple Coulomb excitation
- excited states populated indirectly via intermediate states
- excitation probability of a given state may depend on many matrix elements
- set of coupled equations for excitation amplitudes – solved numerically with dedicated analysis codes

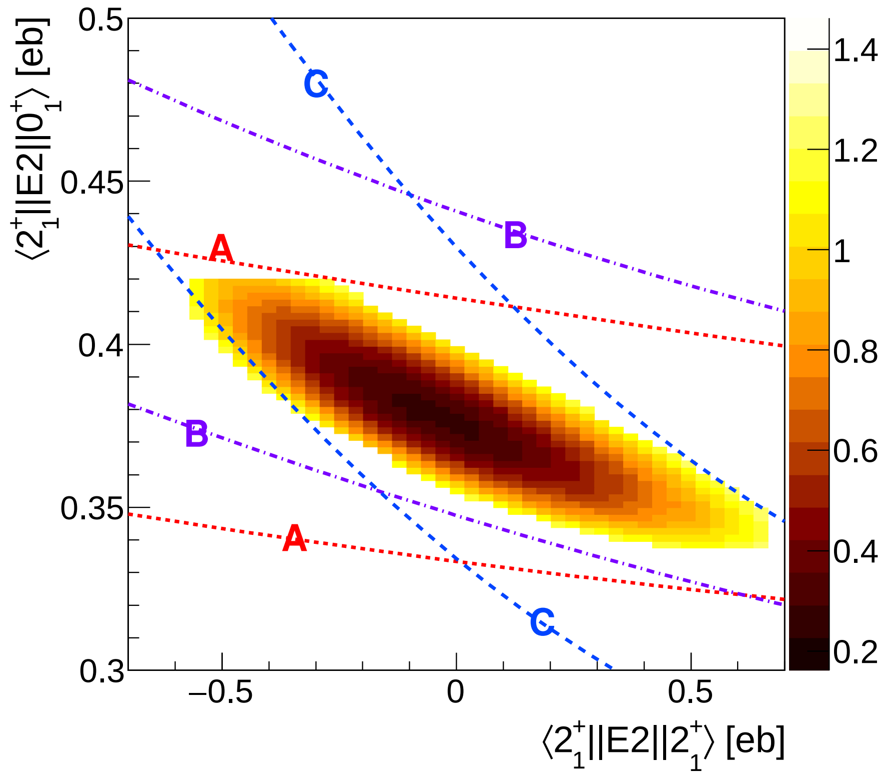


Measuring quadrupole moments of excited states

- reorientation effect: influence of the quadrupole moment on the excitation cross section

^{76}Zn, HIE-ISOLDE data from: A. Illana, MZ *et al.*, submitted to PRC





- differential cross section measurements possible at $\sim 10^4$ pps (statistics of at least 1000 counts needed)

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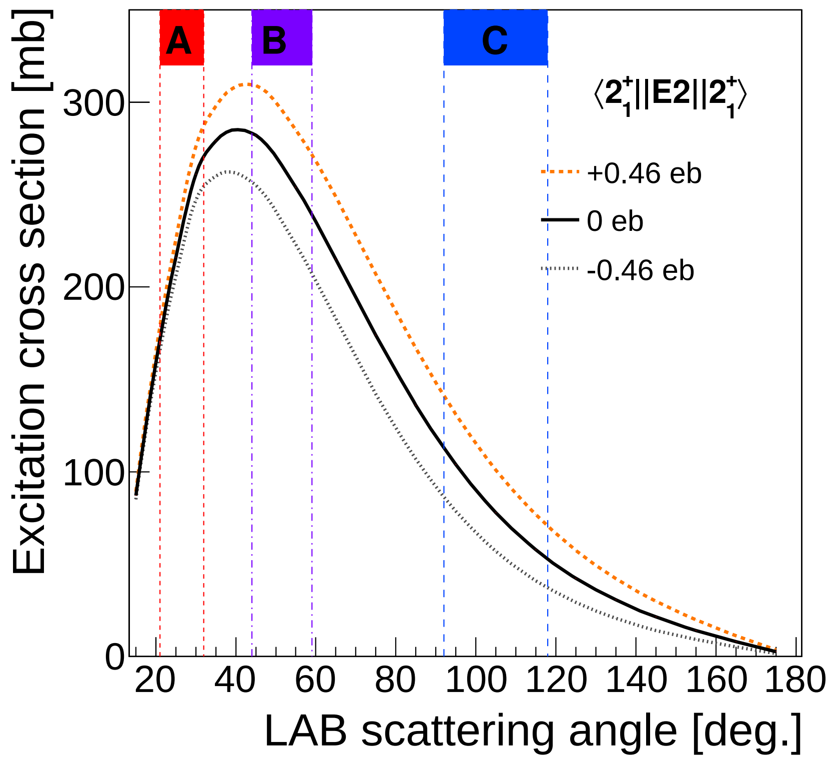
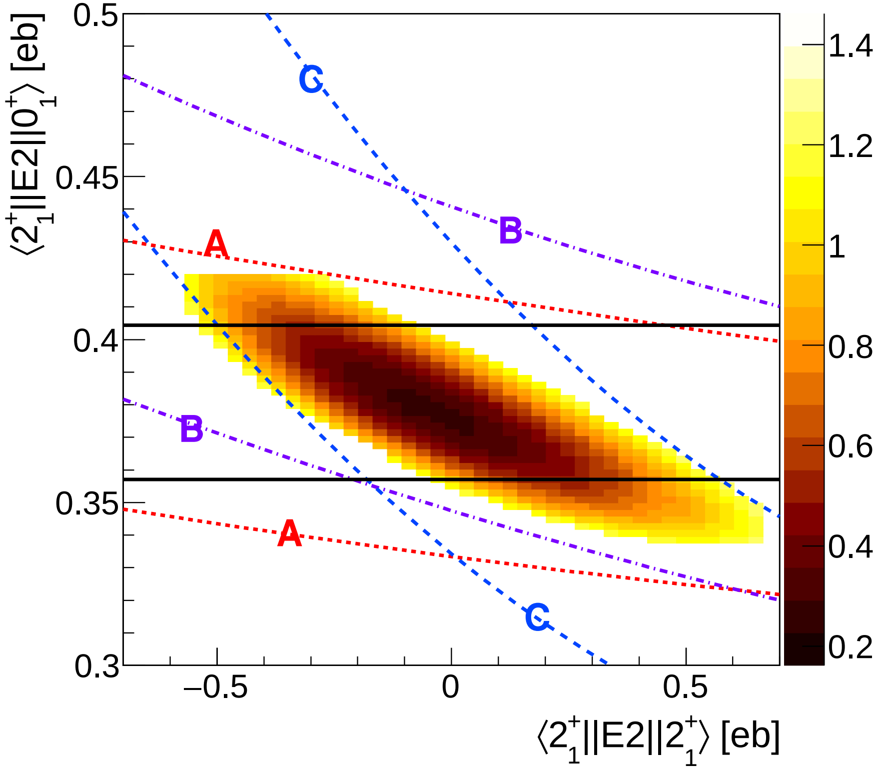
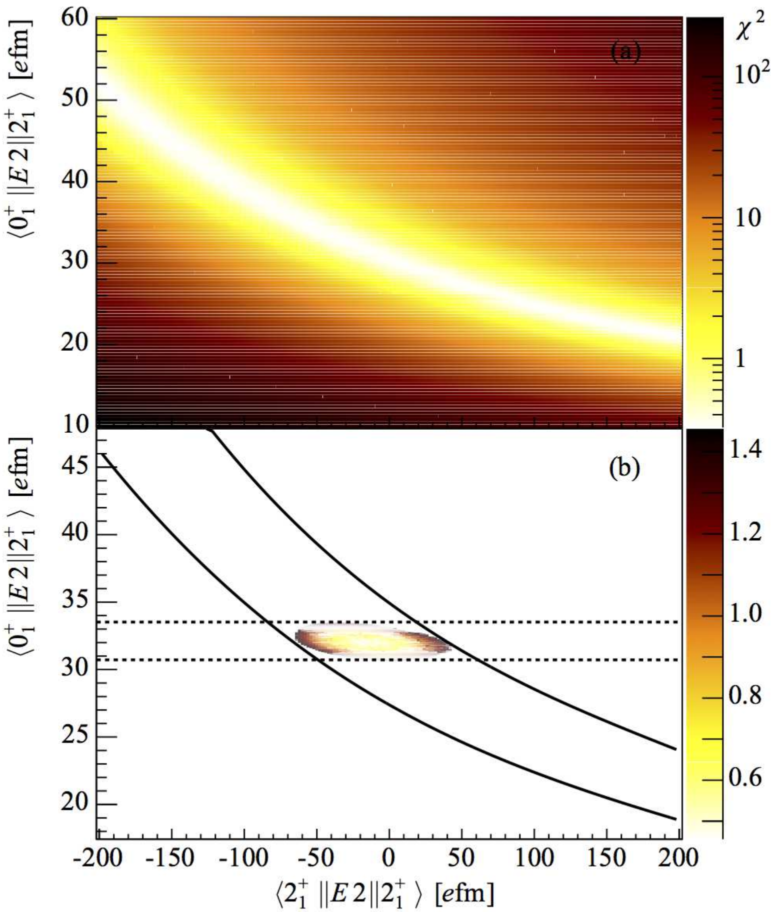




- differential cross section measurements possible at $\sim 10^4$ pps (statistics of at least 1000 counts needed)
- independent lifetime measurements increase precision of extracted quadrupole moments

Measuring quadrupole moments of excited states

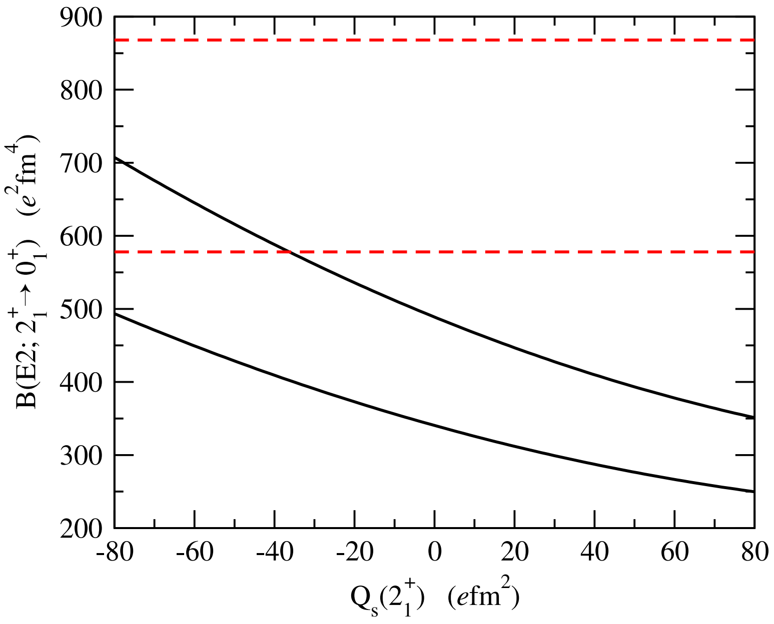
- integral cross section measurements combined with lifetimes: possible at $\sim 10^3$ pps (statistics of 100-500 counts needed)



^{62}Fe, ISOLDE

L. Gaffney *et al.* EPJA 51, 136 (2015)

Coulomb excitation of ^{70}Se, ISOLDE



A.M. Hurst *et al.*,

Phys. Rev. Lett. 98, 072501 (2007)

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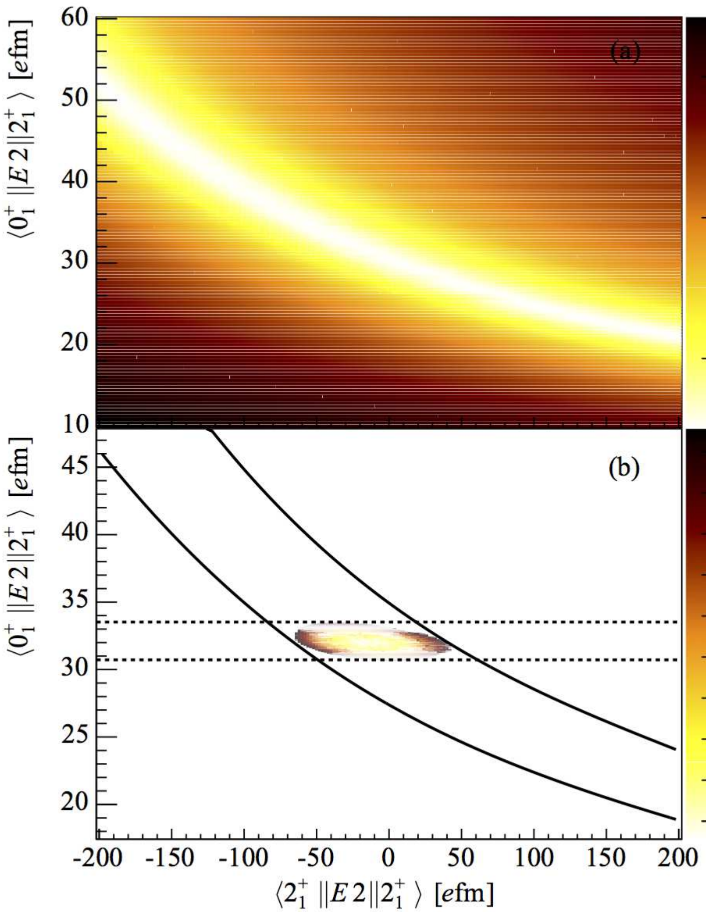
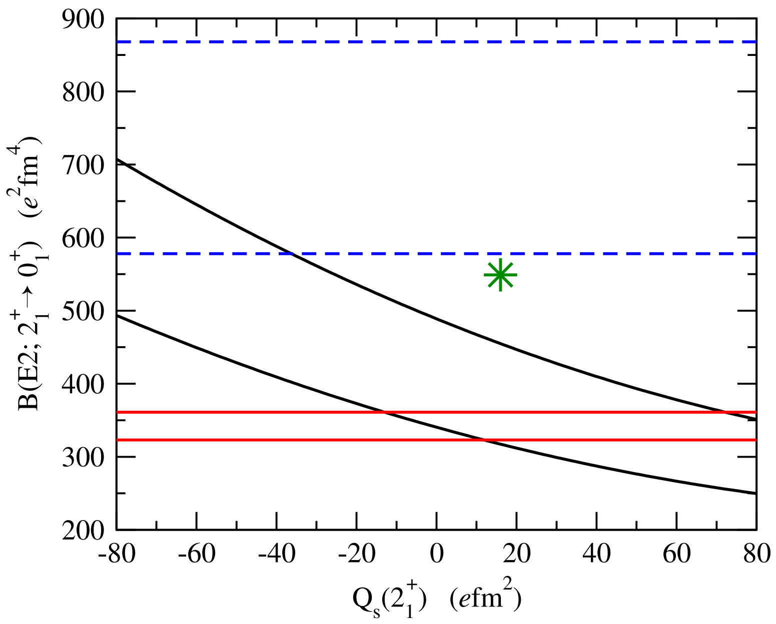


^{62}Fe, ISOLDE

L. Gaffney *et al.* EPJA 51, 136 (2015)

Coulomb excitation of ^{70}Se, ISOLDE

+ new lifetime



J. Ljungvall *et al.*,

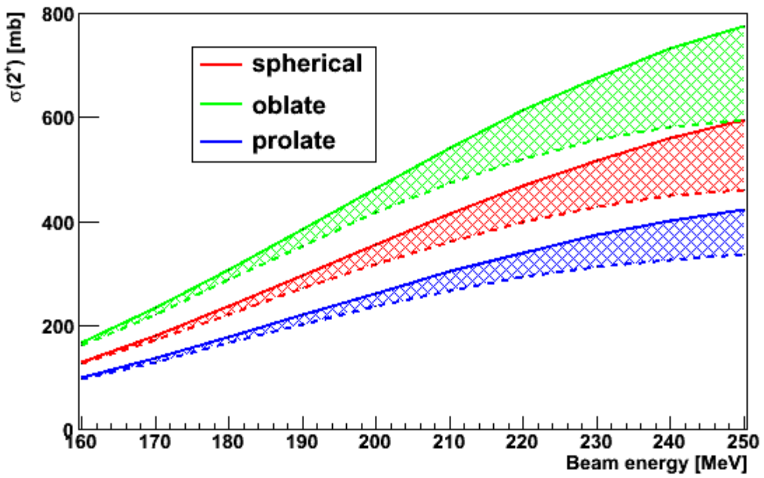
Phys. Rev. Lett. 100, 102502 (2008)

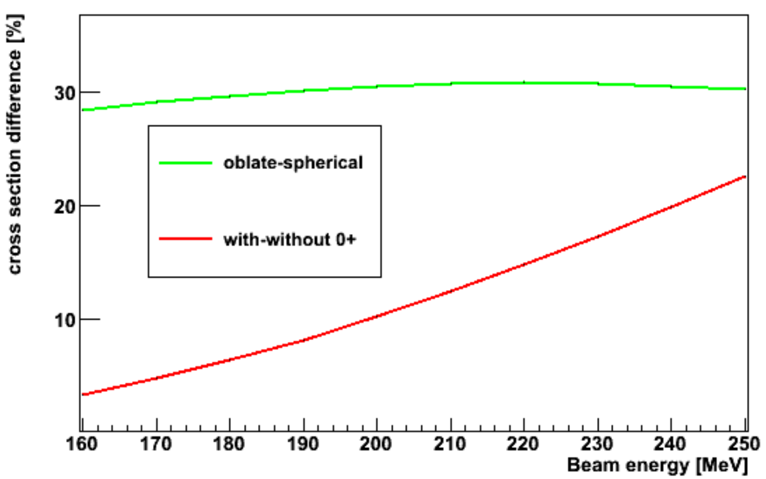
reliable lifetimes needed!

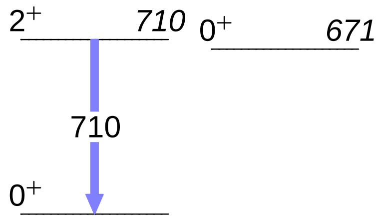
Measuring quadrupole moments of excited states: life is never simple

• influence of double-step excitation of other states may have the same effect on the cross section as the quadrupole moment

• measurements using different targets and/or beam energies may be necessary, especially if other states lie close in energy





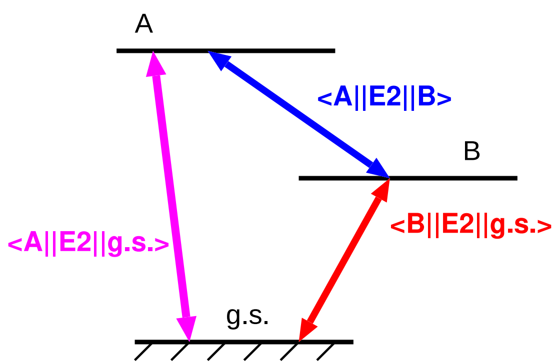


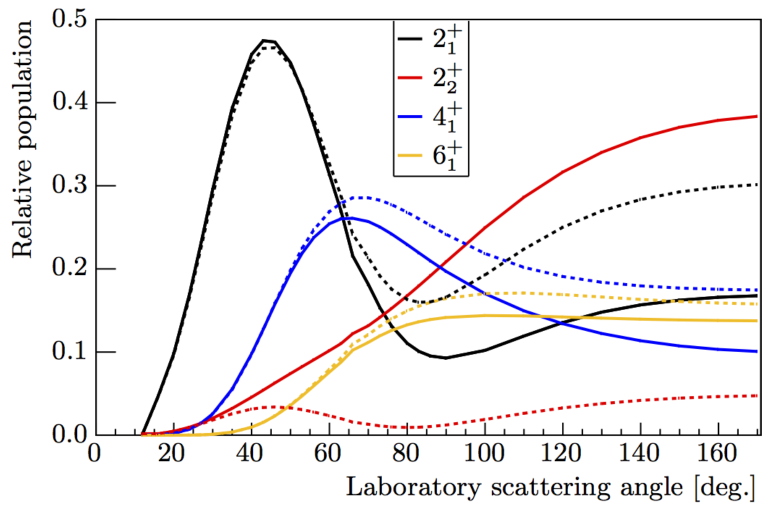
calculations for ^{72}Kr on ^{104}Pd

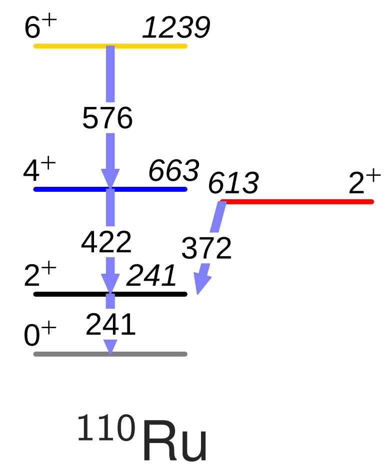
Multi-step excitation and relative signs

• sensitivity of Coulomb-excitation data to relative signs of MEs: result of interference between single-step and multi-step amplitudes:

- excitation amplitude of state A: $a_A \sim \langle A\|E2\|g.s.\rangle + \langle B\|E2\|g.s.\rangle\langle A\|E2\|B\rangle$
- excitation probability ($\sim a_A^2$) contains interference terms $\langle A\|E2\|g.s.\rangle\langle B\|E2\|g.s.\rangle\langle A\|E2\|B\rangle$





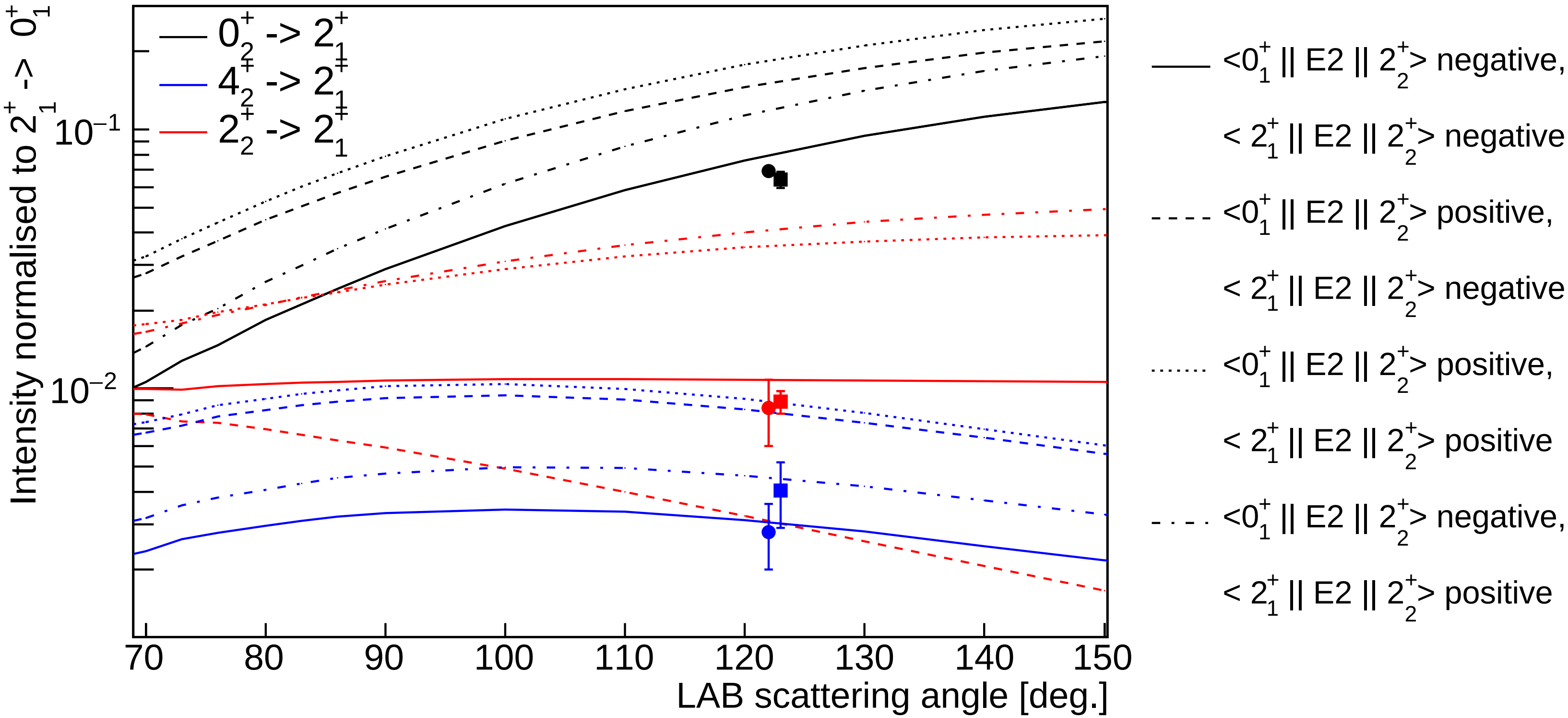


• negative $\langle 2_1^+\|E2\|2_2^+\rangle$ (solid lines): much higher population of 2_2^+ at high CM angles

• sign of a product of matrix elements is an observable

Sensitivity to relative signs of matrix elements: example of ^{42}Ca

MZ, K. Hadyńska-Klęk, EPJ Web Conf 178 (2018) 02014



- solid: final set of matrix elements, dashed: other combinations of signs
- different combinations of signs lead to changes in population of the states of a factor of two or more
- precision of the lifetimes: 2% - 20%

Summary: what we can get from a Coulomb-excitation experiment?

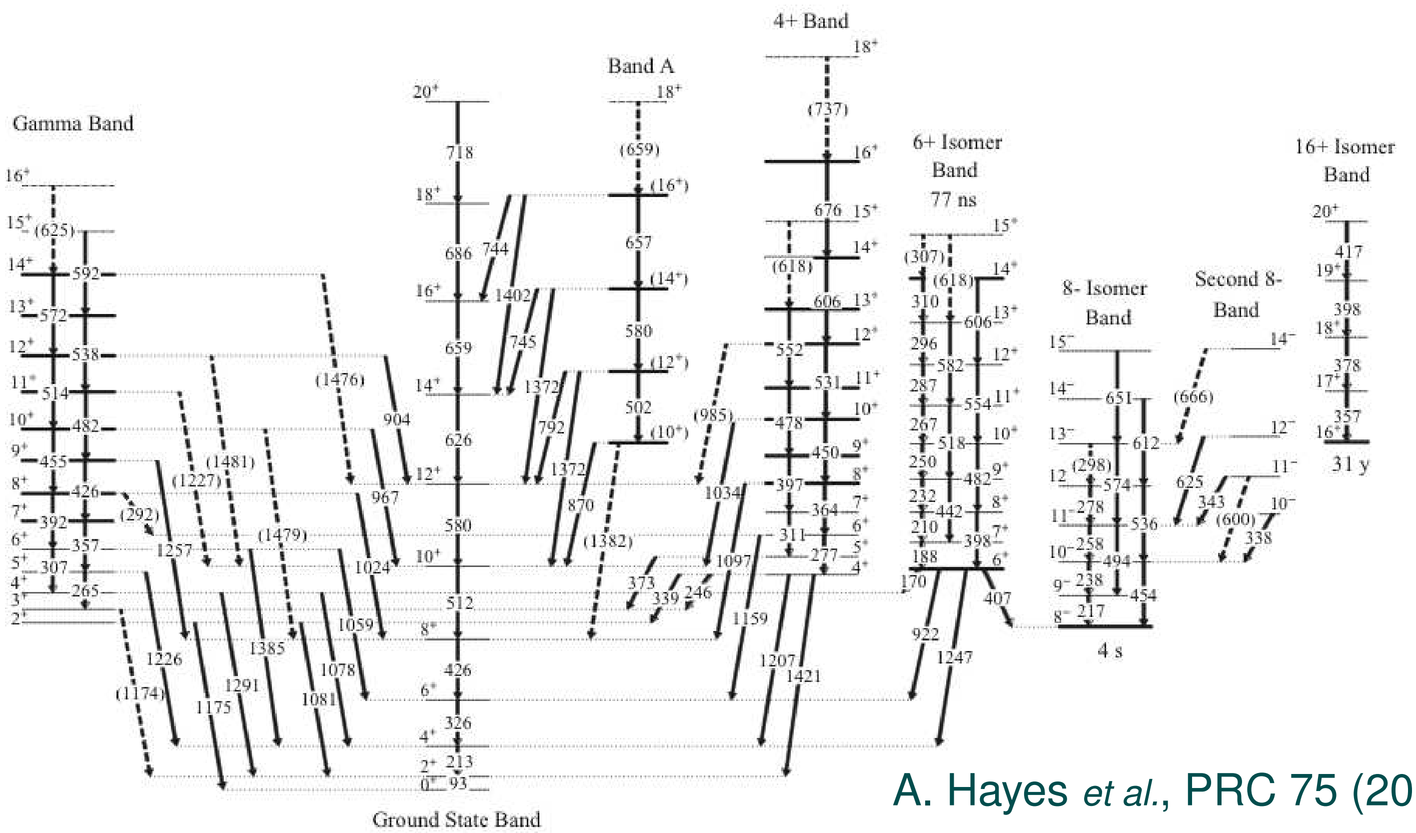
- observation of new excited levels, selective population of collective states
  - first excited state in ^{80}Zn (J. Van de Walle et al, PRL 99 (2007) 142501)
  - rotational band in ^{97}Rb (C. Sotty et al, PRL 115 (2015) 172501)
- B(E2) and B(E3) values between low-lying states, as well as B(M1)'s; in rare cases B(E4)
- relative signs of matrix elements
- signs and magnitudes of static E2 moments of excited states
- for complex level schemes up to 50 MEs that can be further interpreted using the quadrupole sum rules approach

Experimental considerations

What kinds of particle detectors are needed?

Coulomb-excitation experiments with stable beams

- usually multi-step excitation and complicated level schemes, search for subtle effects
- beam intensities of the order of pnA $\rightarrow 10^{10}$pps: particle detectors usually at backward angles
- lifetimes of several states known: no need for other kind of normalisation
- statistics enough for particle-gamma angular correlations



^{178}Hf

A. Hayes *et al.*, PRC 75 (2007) 034308

Coulomb-excitation experiments with exotic beams

• usually one- or two-step excitation; level schemes not well known on the neutron-rich side

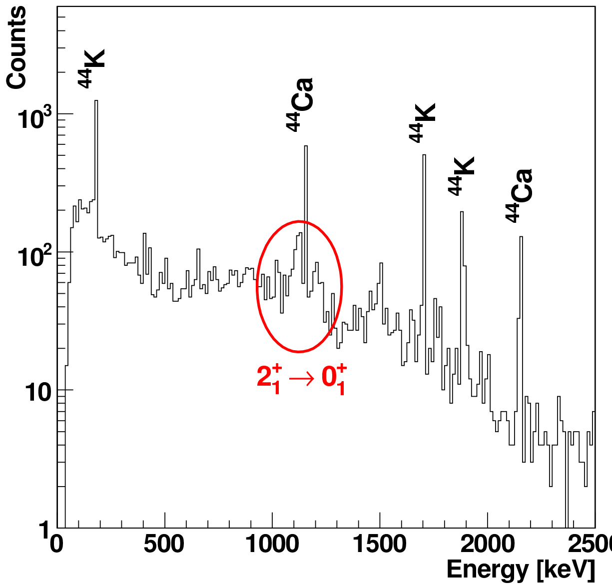
• beam intensities rather low: particle detectors at forward angles to maximise the statistics

• normalisation to target excitation or Rutherford scattering needed

• low statistics, sometimes only one gamma line observed

• differential measurements at the limits of feasibility

• high background from β decay
$\rightarrow$ experiments without particle detection impossible

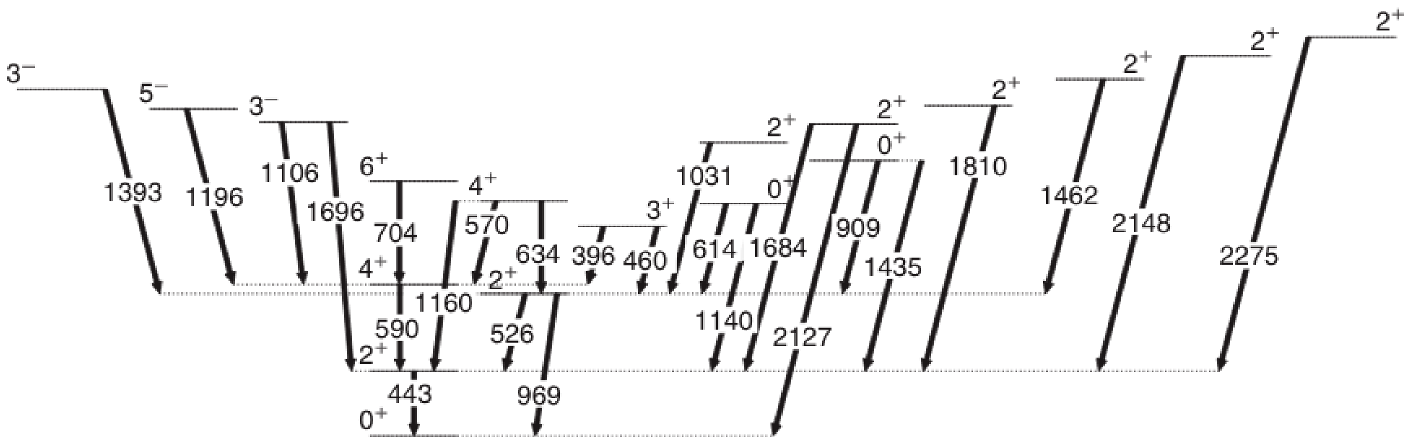


Simplest Coulomb-excitation detector: no detector at all

Doppler correction impossible; how can we manage?

- traditional "thick target" measurements
  $\rightarrow$ lifetimes should be long compared to stopping time

- strongly assymetric inverse kinematics, everything goes forward
  $\rightarrow$ favours one-step excitation - suitable for example to search for mixed symmetry 2^+ states

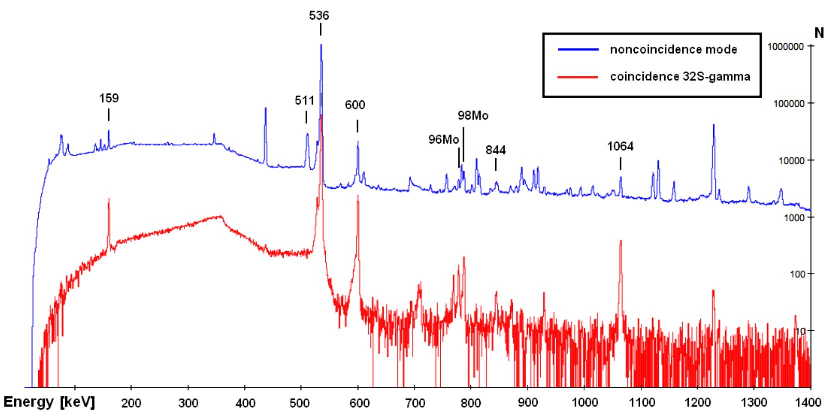


^{128}Xe on ^{12}C

L. Coquard *et al.*, PRC 80 (2009) 061304

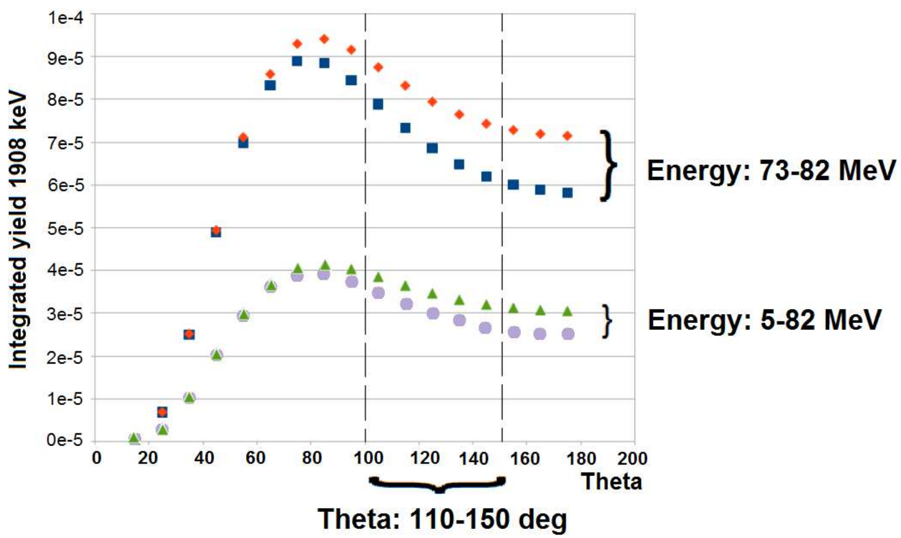
Simplest Coulomb-excitation detector: no detector at all

- possibility of collecting gamma singles in a particle-γ coincidence measurement:
  - independent data set (different ranges of incident energy and scattering angles)
  - can help to disentangle various excitation patterns!



^{32}S on ^{100}Mo

K. Hadyńska-Kłęk, MSc thesis

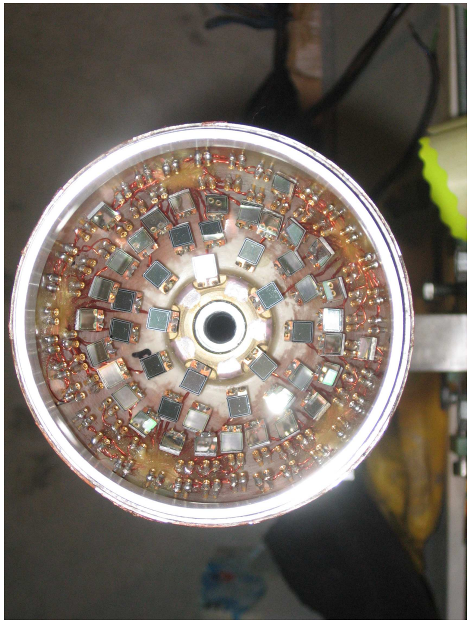


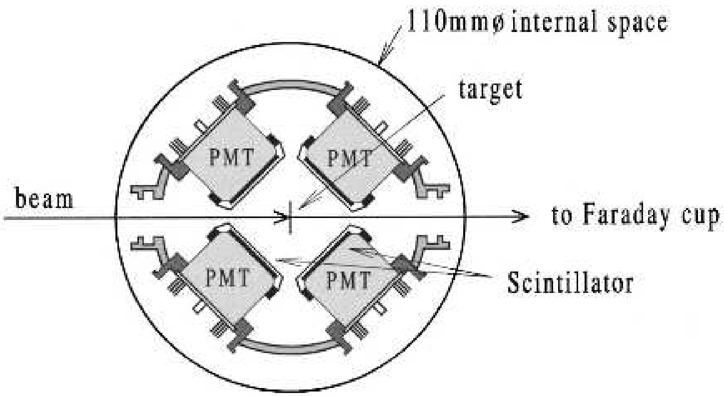
blue and violet: only single-step excitation of the 3^- state

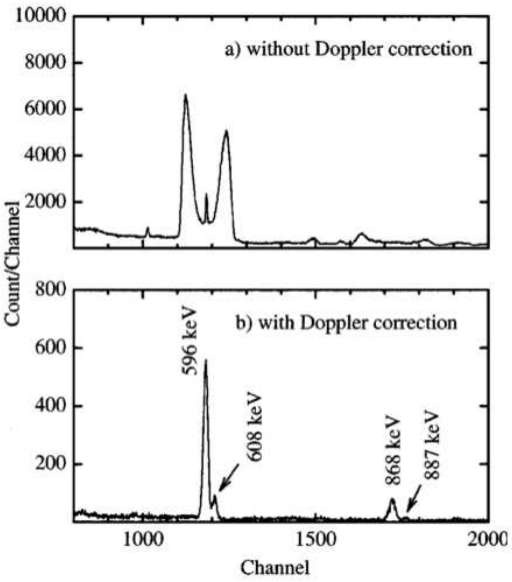
red and green: double-step excitation of the 3^- state (via 2^+) added

Stable beam Coulomb excitation: detectors at backward angles

- only scattered beam particles detected – in principle no need to know their energy
  - (although it may help – makes possible to make cuts on incident energy)
- very compact geometry possible (chambers of 5 cm radius)
- detectors used: Si (segmented/PIN diodes), plastic, solar cells, MCP,...







Munich Chamber, HIL Warsaw

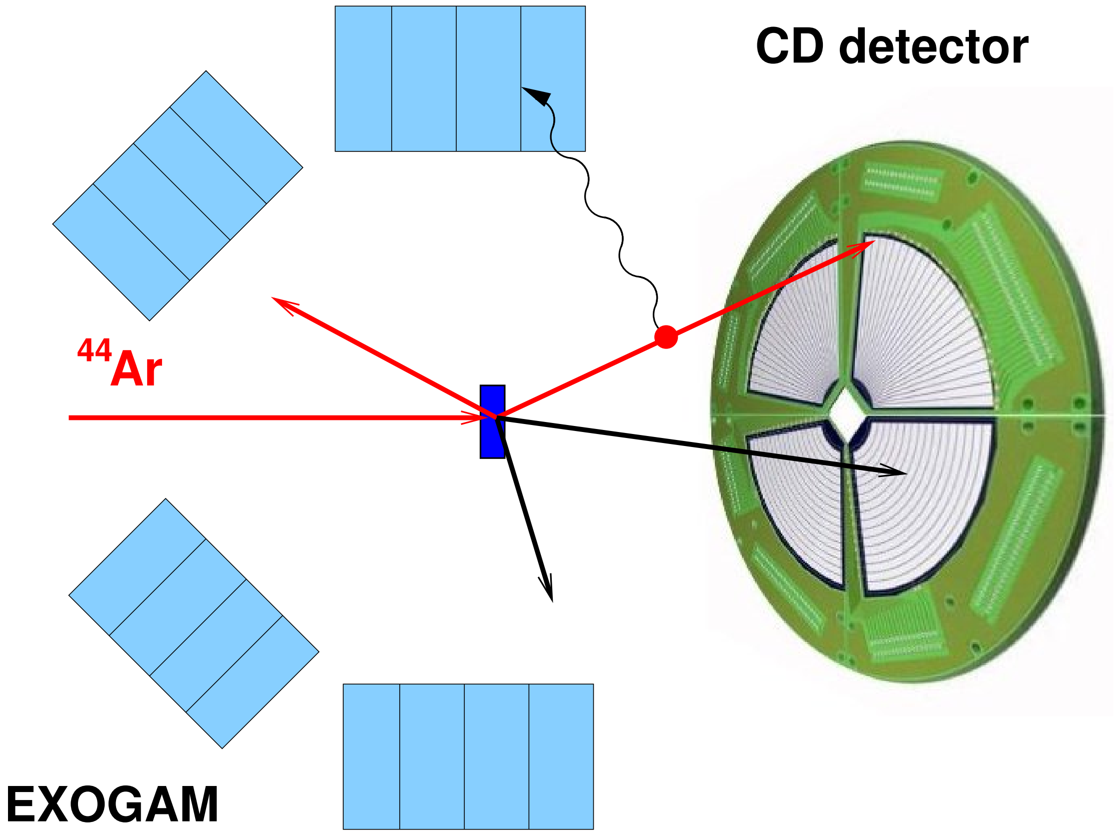
K. Wrzosek *et al.*, Acta Phys. Pol. B39 (2008) 513

LUNA, JAEA Tokai

Y. Toh *et al.*, Rev. Sci. Inst. 73 (2002)

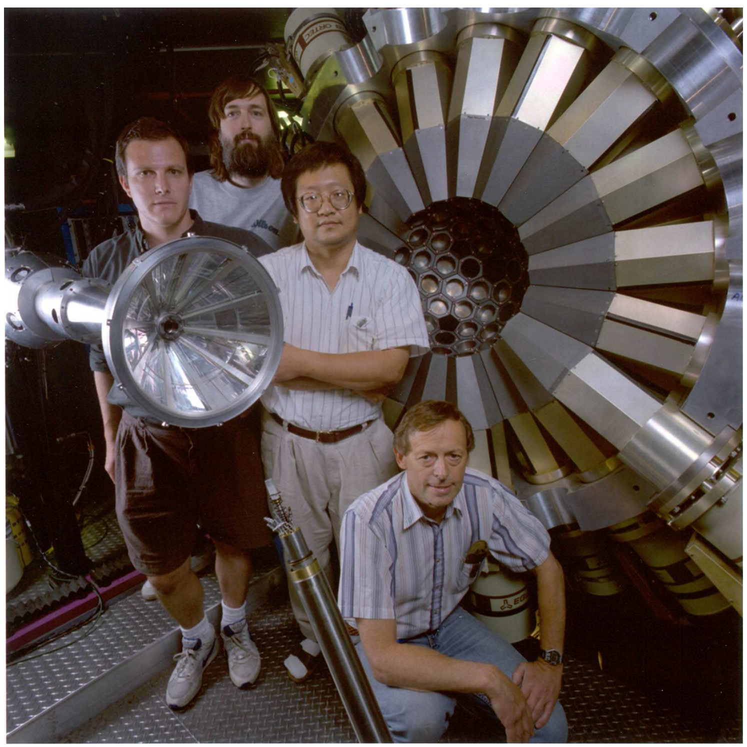
Exotic beam Coulomb excitation: detectors at forward angles

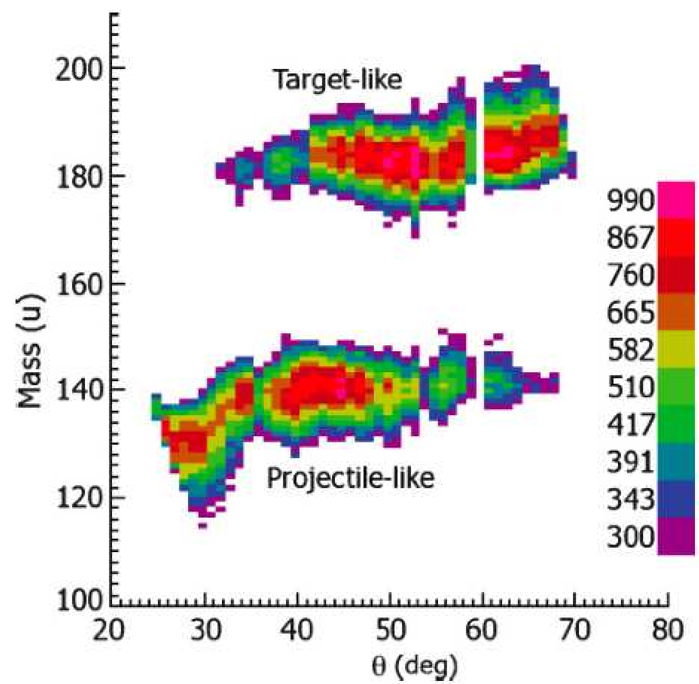
- simultaneous detection of scattered projectiles and recoils
- unambiguous identification necessary for excitation process description and Doppler correction
- detectors used: PPAC (stable and exotic beams), segmented Si / CsI(Tl) (exotic beams)



Identification ejectile-recoil: time

- CHICO: 4 π PPAC array designed for GAMMASPHERE
- chamber diameter 36 cm (distance target-detector 15 cm)
- timing resolution 500 ps
- for ^{136}Xe + ^{178}Hf Coulomb excitation: 10 ns TOF difference, ejectile and recoil well resolved

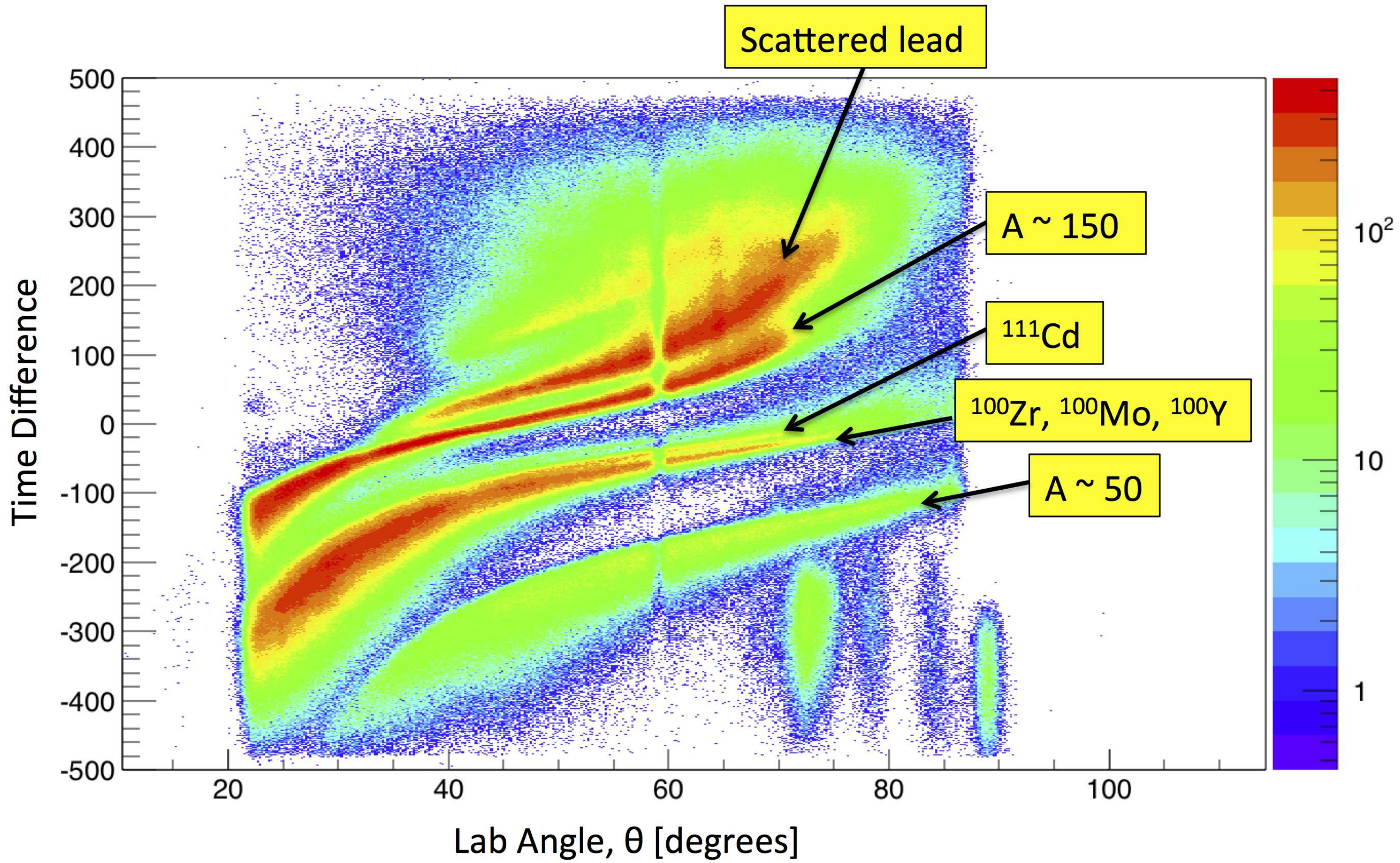




A. Hayes *et al.*, PRC 75 (2007) 034308

CHICO2 for exotic beam studies at CARIBU

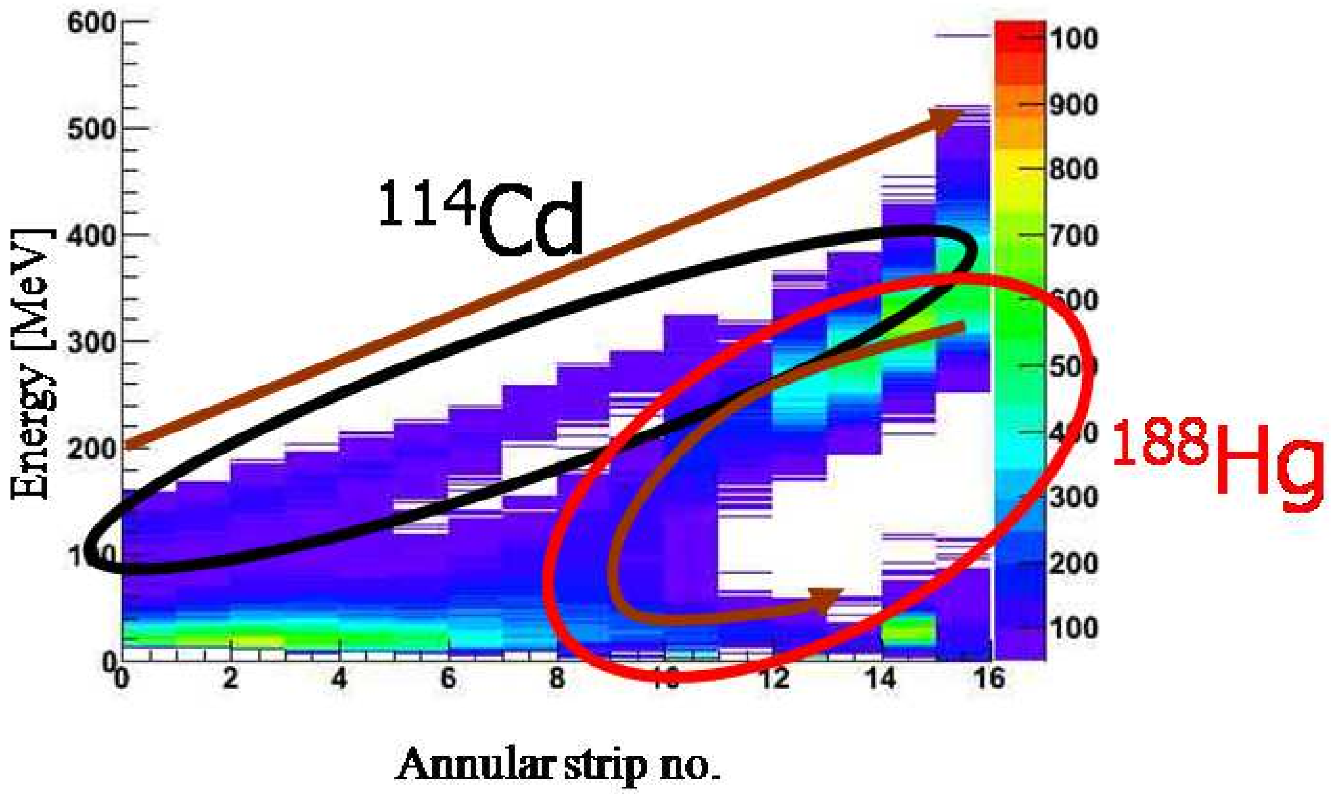
- clear separation of A $\sim$ 50, A $\sim$ 100, A $\sim$ 150 and A $\sim$ 200 nuclei
- for $\theta_{\mathrm{LAB}} > 60^{\circ}$ even possible to distinguish ^{111}Cd from A $\sim$ 100 nuclei!



D. Doherty, ^{100}Zr Coulomb-excitation analysis

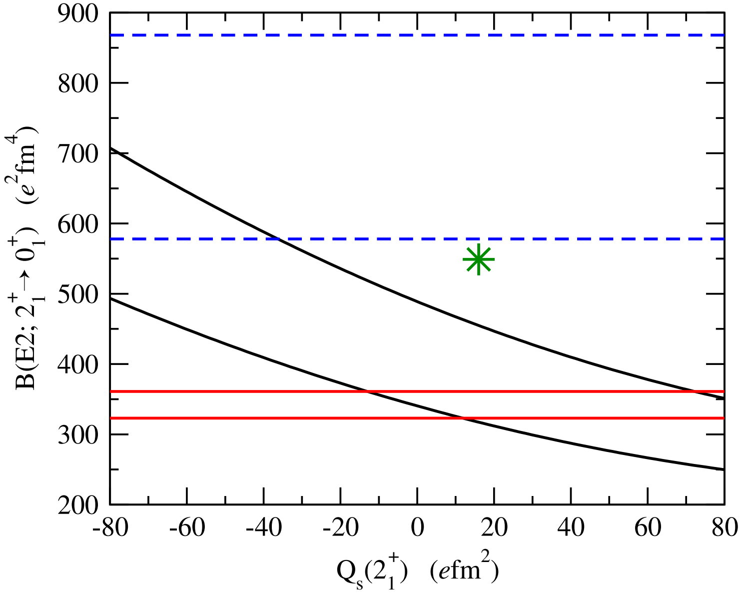
Identification ejectile-recoil: energy

- for Si detectors and targets of 1-2 mg/cm^2: ejectile and recoil should differ in mass by roughly a factor of two
- strong constraint for studies of A > 150 nuclei (heavy targets like Pt or Pb cannot be used, so excitation strength is limited)



Additional measurements needed for Coulomb-excitation data analysis...

- lifetime measurements
  - necessary for integral cross-section measurements

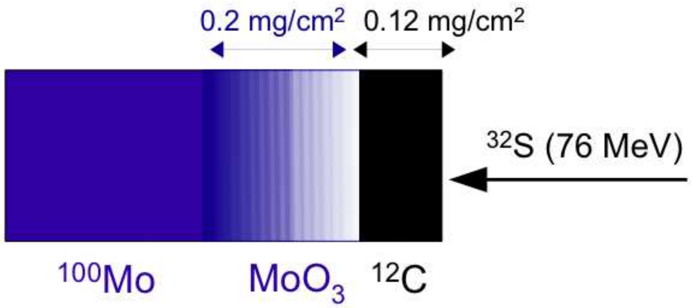


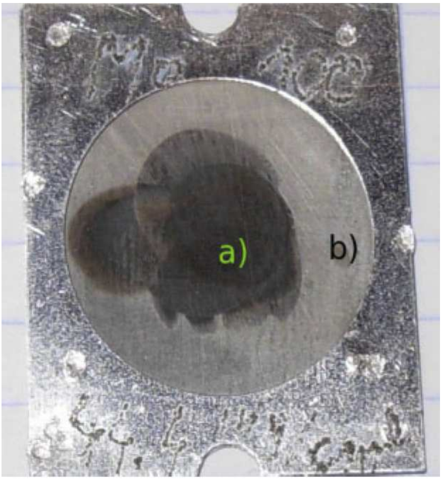
J. Ljungvall *et al.*,
Phys. Rev. Lett. 100, 102502 (2008)

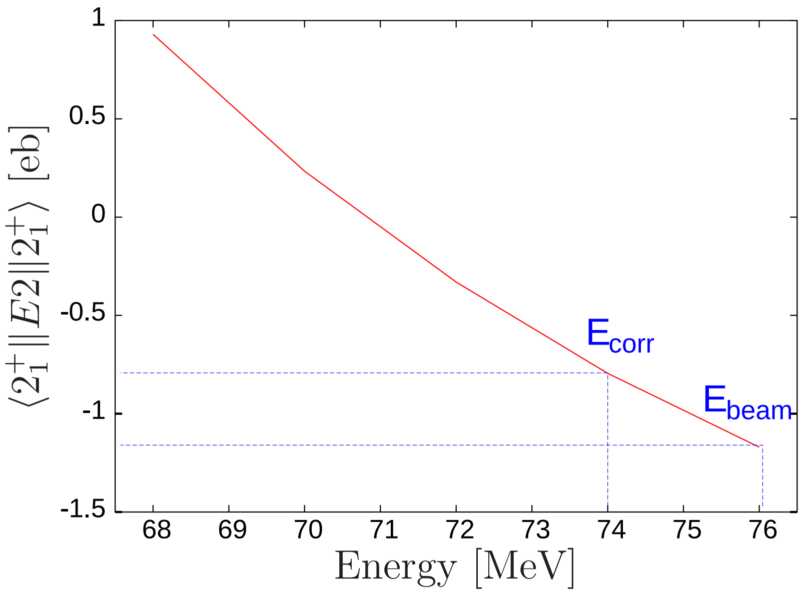
  - increase precision of quadrupole moments/intra-band matrix elements for differential measurements
- beam composition (isobaric contamination/isomeric ratio)
- beam energy
- conversion coefficients/E0 branchings

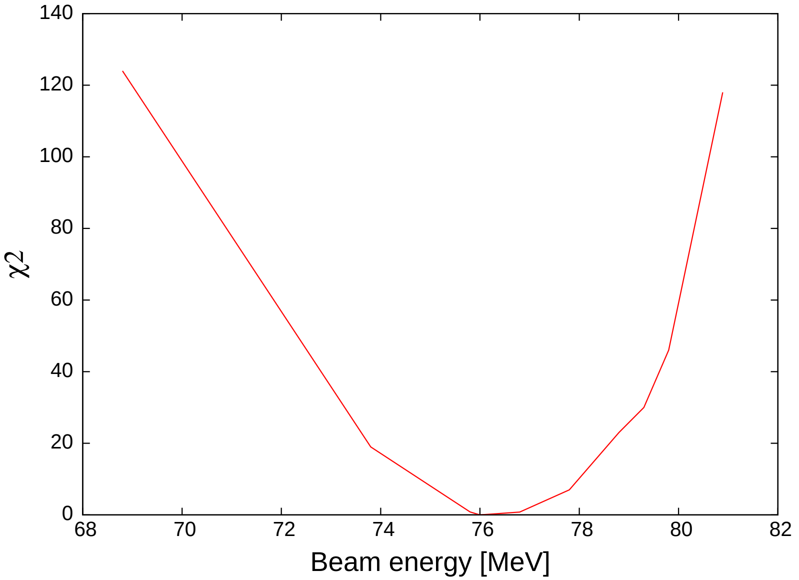
Incident energy

- strong dependence of multi-step excitation and reorientation effect on beam energy
- correct beam energy required!





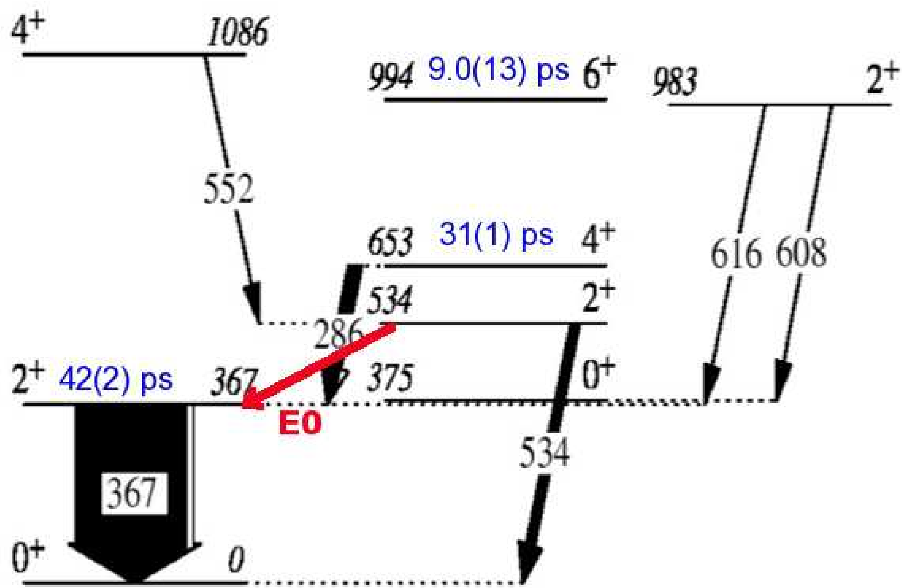




K. Wrzosek-Lipska, PhD thesis (2011)

E0 strengths

- decay branch unvisible for Ge detectors
- important for 0^+ states (^{74}Kr, ^{100}Mo,...) and heavy nuclei



$\alpha\ (2_2^+ \rightarrow 2_1^+)$ in ^{184}Hg: 14.2(36)

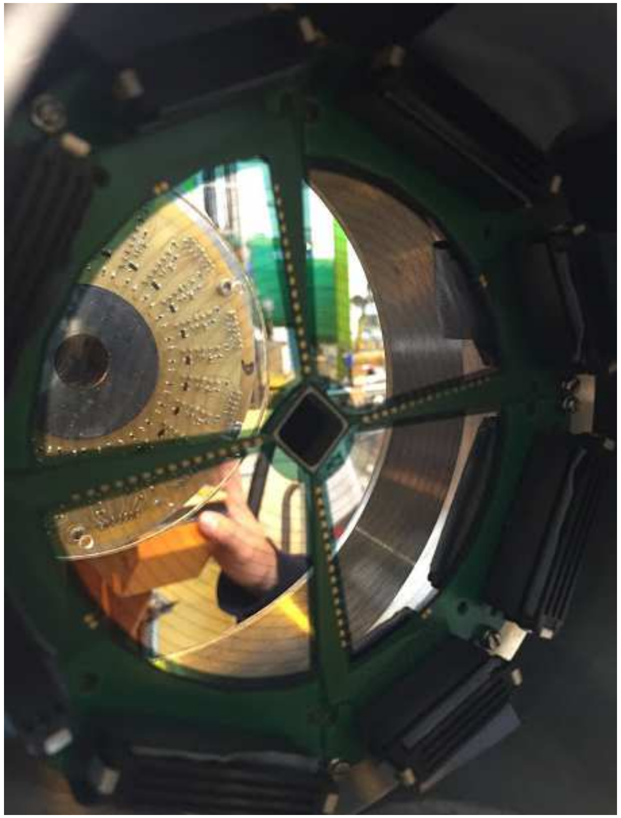
E. Rapisarda *et al.*, JPG 44 (2017) 074001

more recent value: 12.8(24)

M. Stryjczyk, PhD, KU Leuven, 2021.

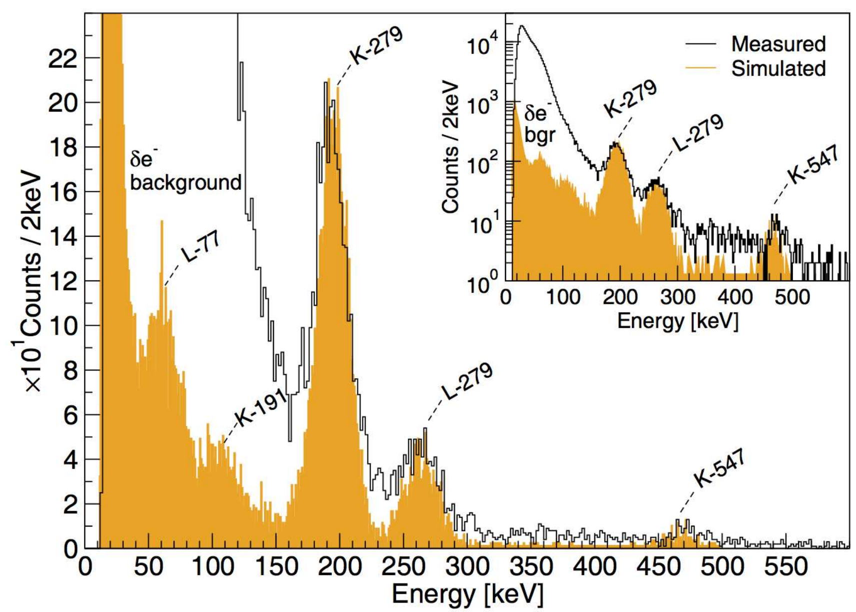
- electron spectroscopy measurements for strongly converted transitions?

SPEDE: new conversion electron detector for in-beam measurements



- First Coulomb-excitation measurement using SPEDE at HIE-ISOLDE: November 2022
- collaboration of Uni. Jyväskylä, Uni. Liverpool, KU Leuven

- very compact electron spectrometer that can be used together with a particle detector for Coulomb-excitation studies
- E0 transitions: measure of mixing of coexisting states and difference of their deformation
- internal conversion important for E2 and M1 transitions in heavy nuclei



P. Papadakis et al, EPJA 54 (2018) 42