Experimental perspective: observables and detection set-ups

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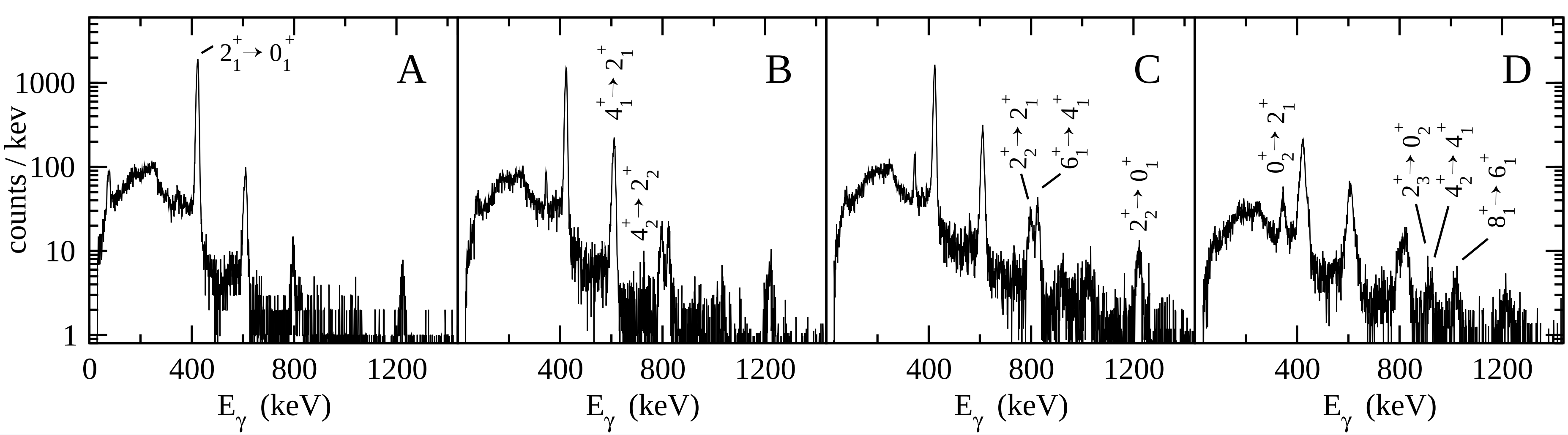
- What is measured and what effects we make use of?
- Examples of particle detectors for Coulex

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 Coulex as a function of CM scattering angle



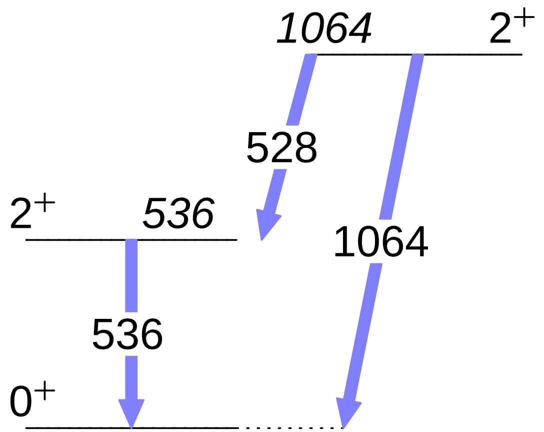
Once we have gamma-ray intensities...

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

- known B(E2) in the studied nucleus
- known B(E2) in the reaction partner   see my lecture tomorrow!
- Rutherford cross section

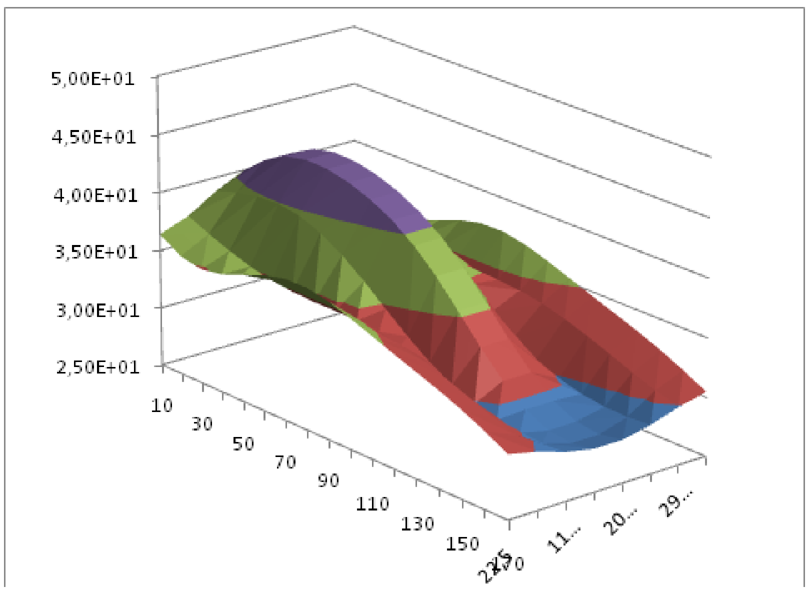
Final step: extraction of individual electromagnetic matrix elements from measured gamma-ray intensities

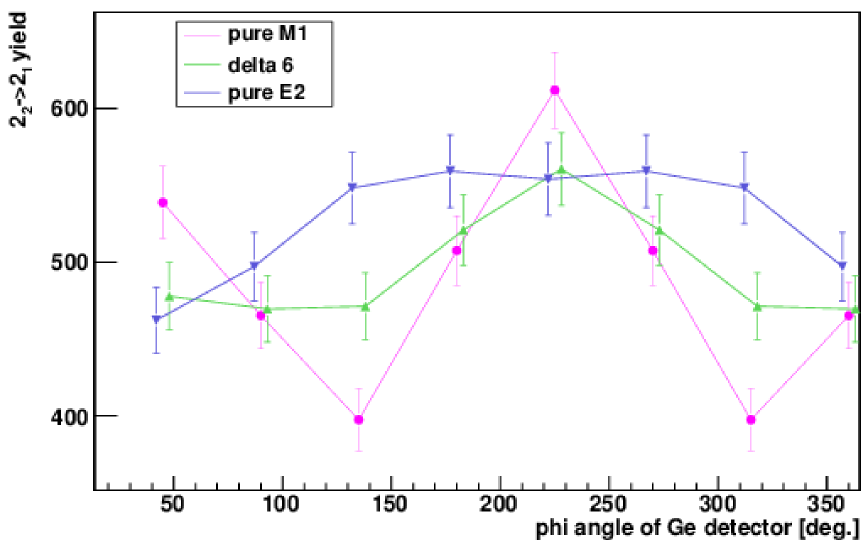
- simple cases (rare) : first/second order perturbation theory
- most cases too complicated: multiple Coulomb excitation
- excited states populated indirectly via intermediate states
- excitation probability of a given state may depend on many matrix elements
- set of coupled equations for excitation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



Gamma-particle angular correlations

- feasible at several thousands of counts in a given gamma line
- determination of E2/M1 mixing ratios
- determination of spin of a decaying level
- distribution in phi usually more conclusive than in theta



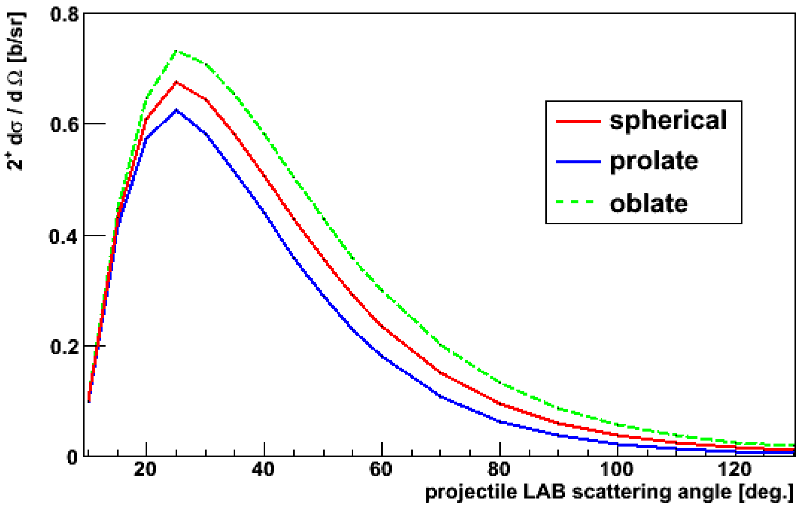


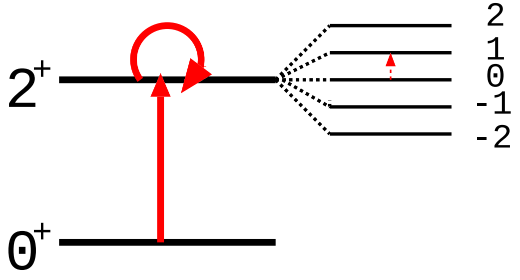
- the distributions are attenuated due to deorienation (recoil in vacuum) – possibility to measure g factors

Reorientation effect

• influence of the quadrupole moment of the excited state on its excitation cross-section: double excitation where "intermediate" states are the m substates of the state of interest

• dependence on scattering angle and beam energy

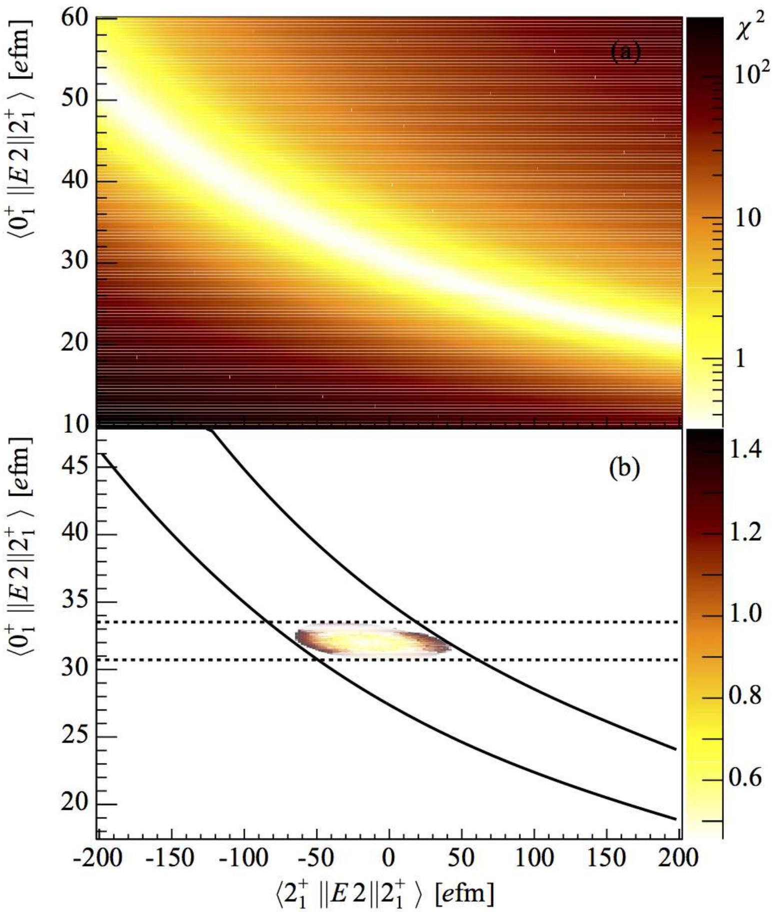




$\langle 2^+ \| E2 \| 2^+ \rangle \sim Q_{sp}$

Measuring quadrupole moments of excited states

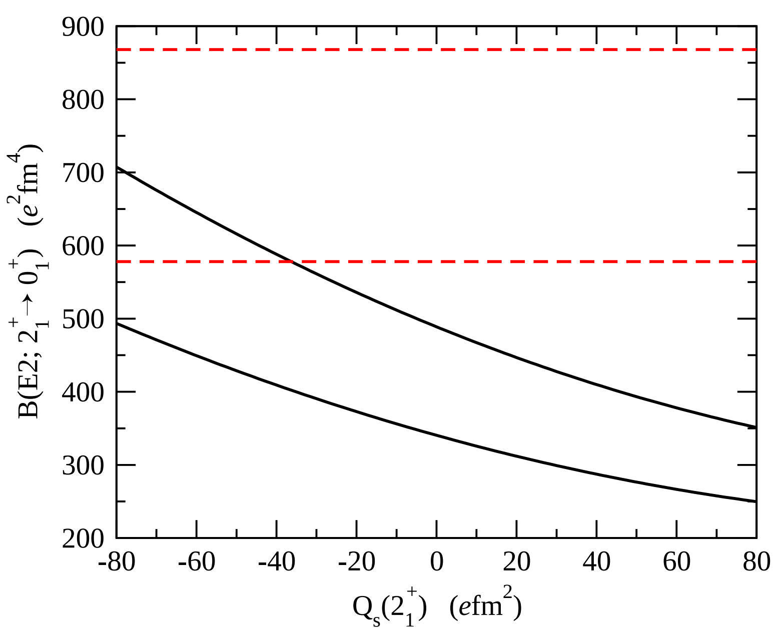
- integral cross section measurements combined with lifetimes: possible at $\sim 10^3$ pps (statistics of 100-500 counts needed)



^{62}Fe, ISOLDE

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

Coulex of ^{70}Se, ISOLDE



A.M. Hurst *et al.*,

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

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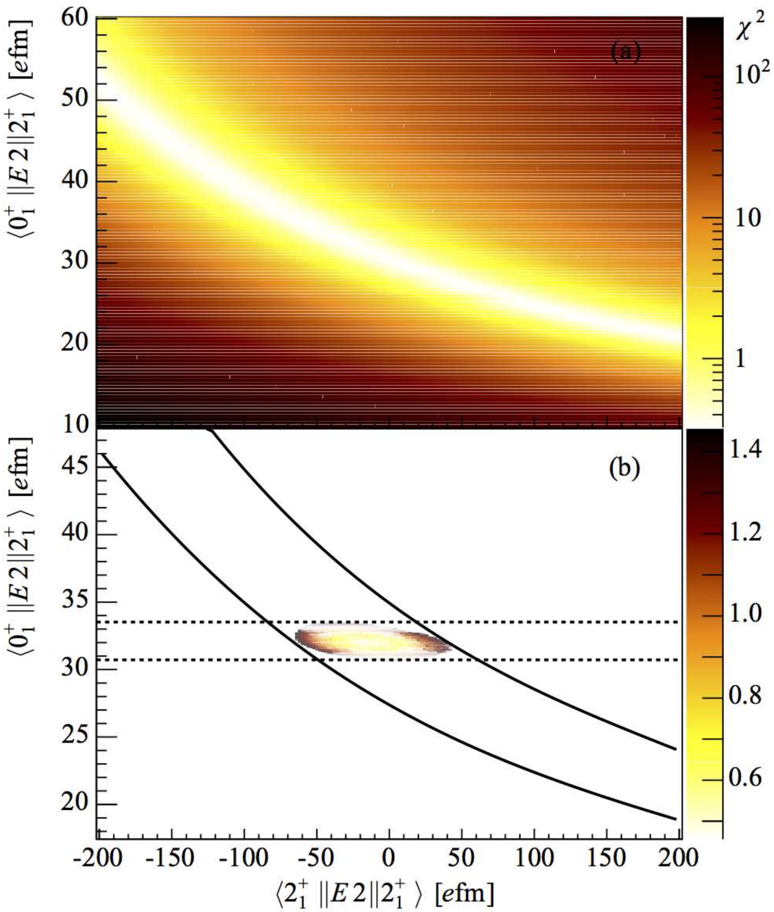
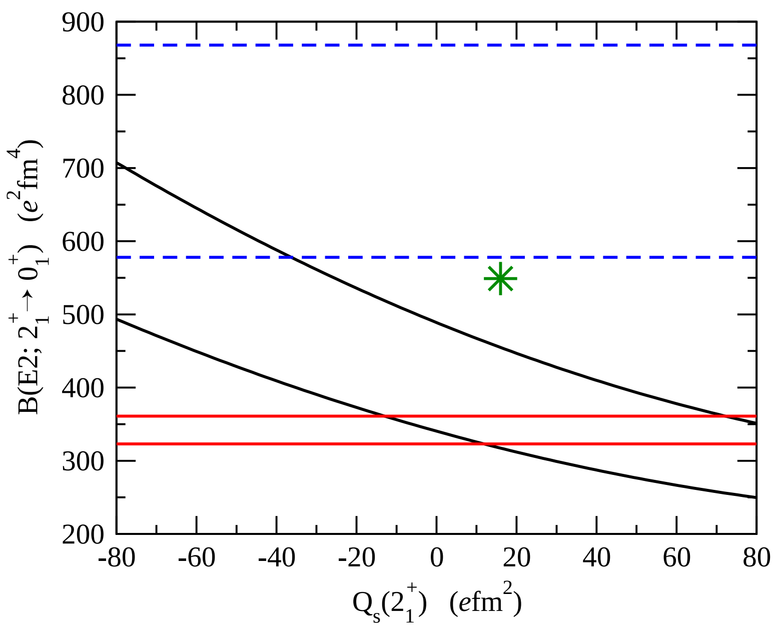


^{62}Fe, ISOLDE

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

Coulex of ^{70}Se, ISOLDE + new lifetime



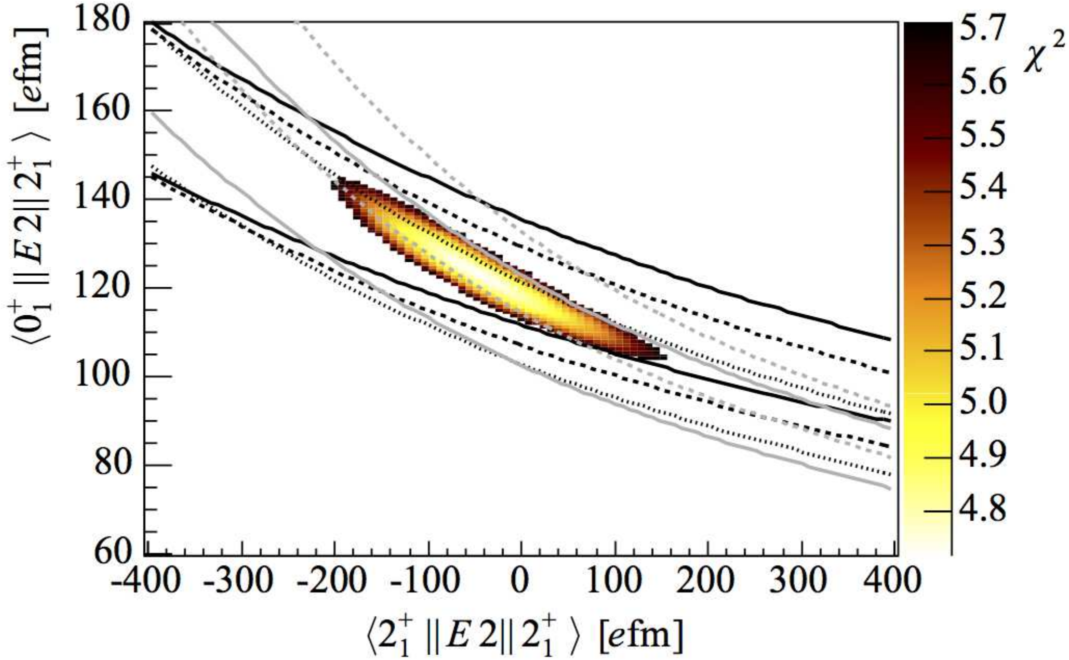
J. Ljungvall *et al.*,

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

reliable lifetimes needed!

Measuring quadrupole moments of excited states

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



^{202}Rn, ISOLDE

L. Gaffney *et al.* PRC 91, 064313 (2015)

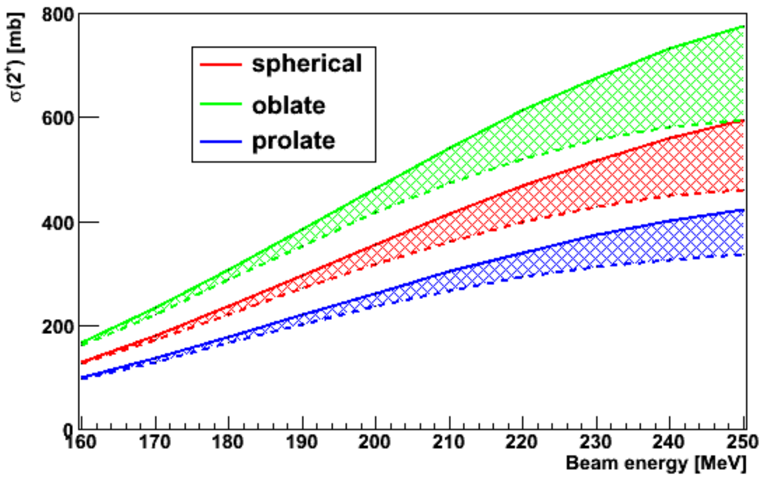
M. Zielińska *et al.* EPJA 52, 99 (2016)

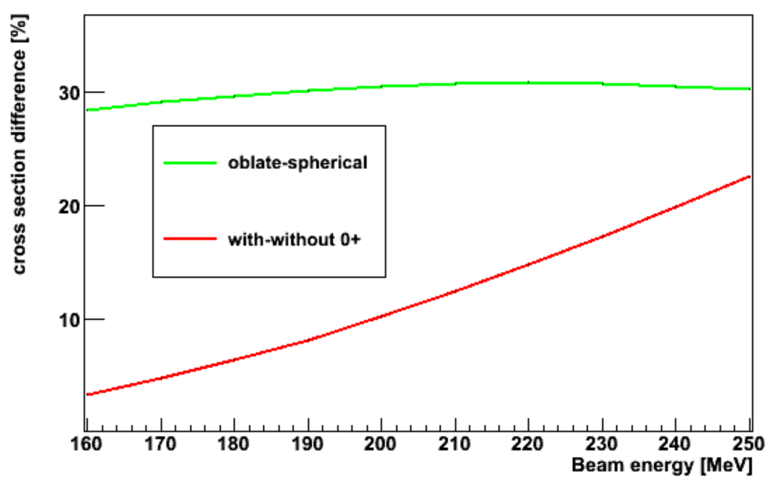
- lifetimes increase precision of quadrupole moments for differential measurements
- in most cases excitation of higher-lying states competes with the effect of Q_{sp}

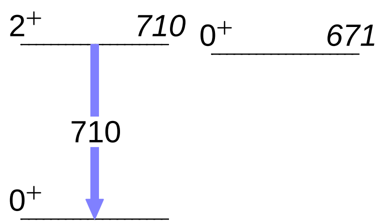
Reorientation effect

• 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, especpecyally if other states lie close in energy





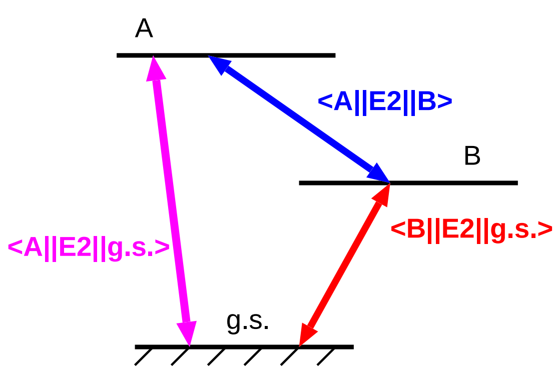


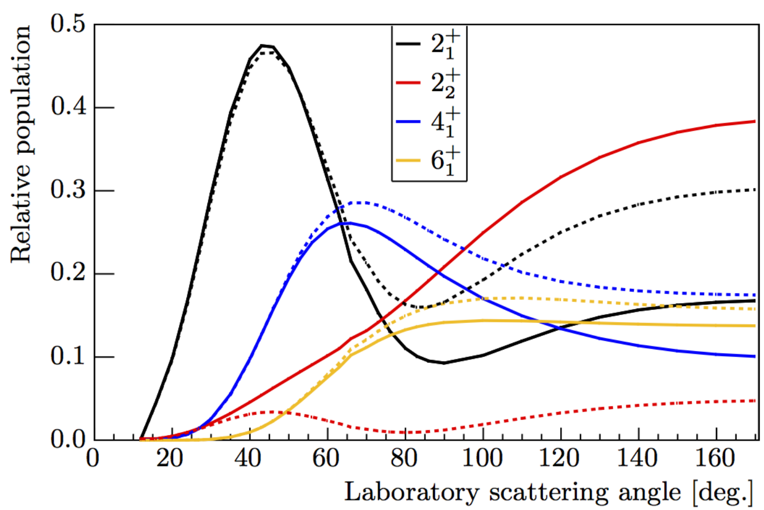
Multi-step excitation and relative signs

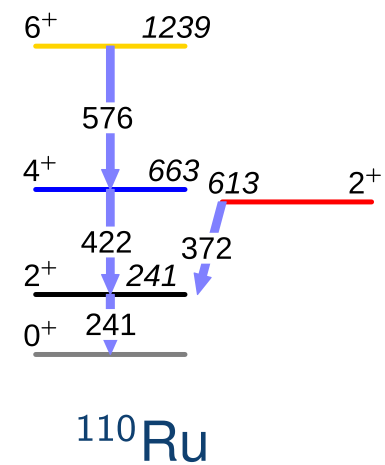
- sensitivity of Coulomb excitation data to relative signs of ME's:

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 $\langle A\|E2\|g.s.\rangle\langle B\|E2\|g.s.\rangle\langle A\|E2\|B\rangle$







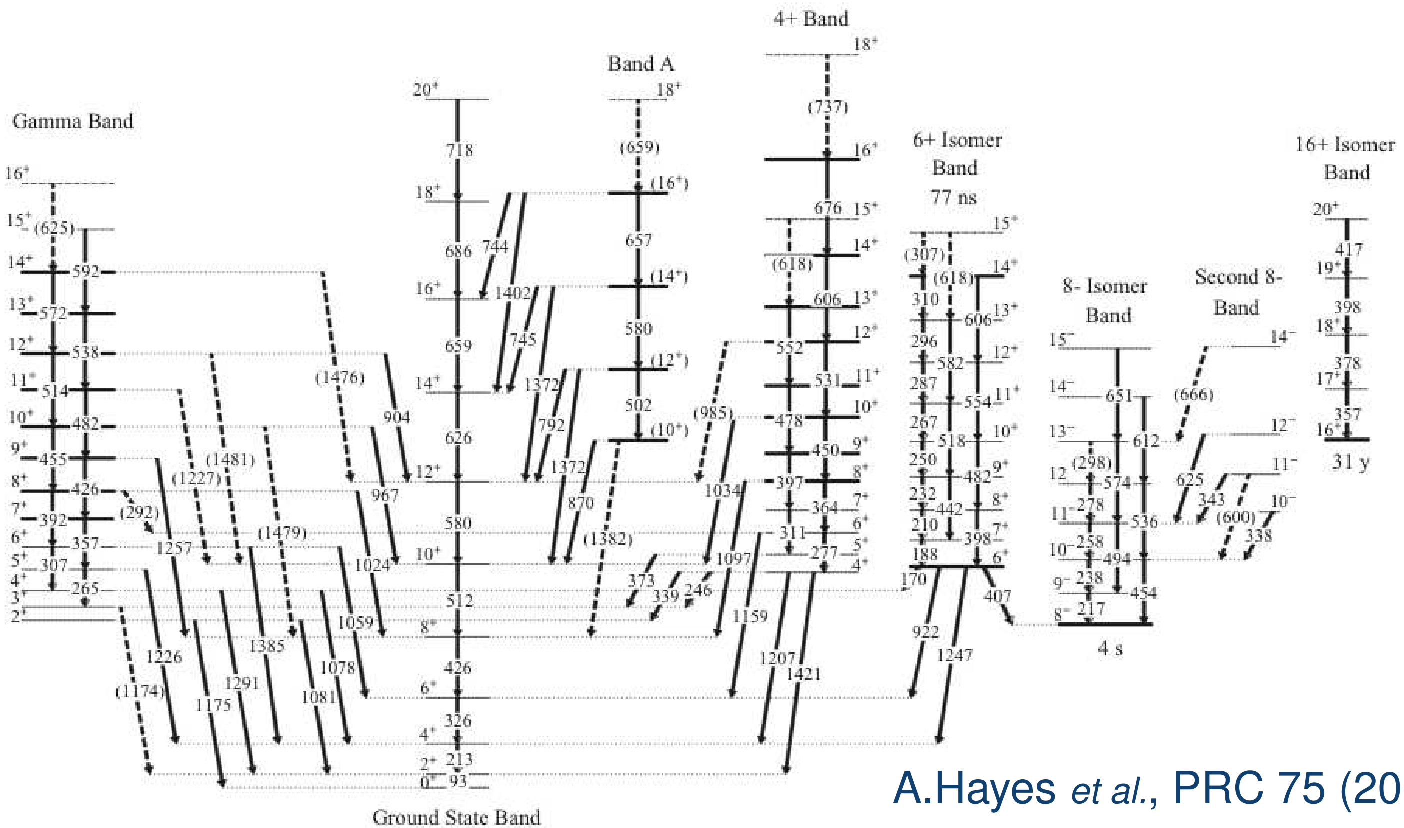
- negative $\langle 2_1^+\|E2\|2_2^+\rangle$ (solid lines): much higher population of 2_2^+ at high CM angles
- sign of a product of matrix elements is an observable

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

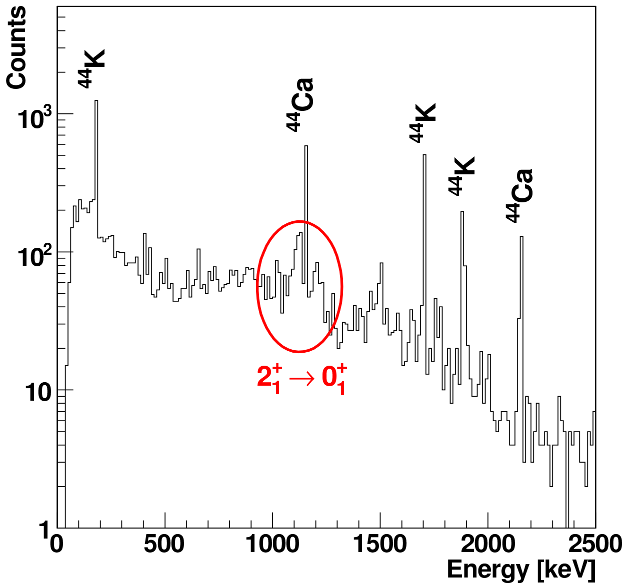
• beam intensities rather low: particle detectors at forward angles to maximise the statistics

• 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

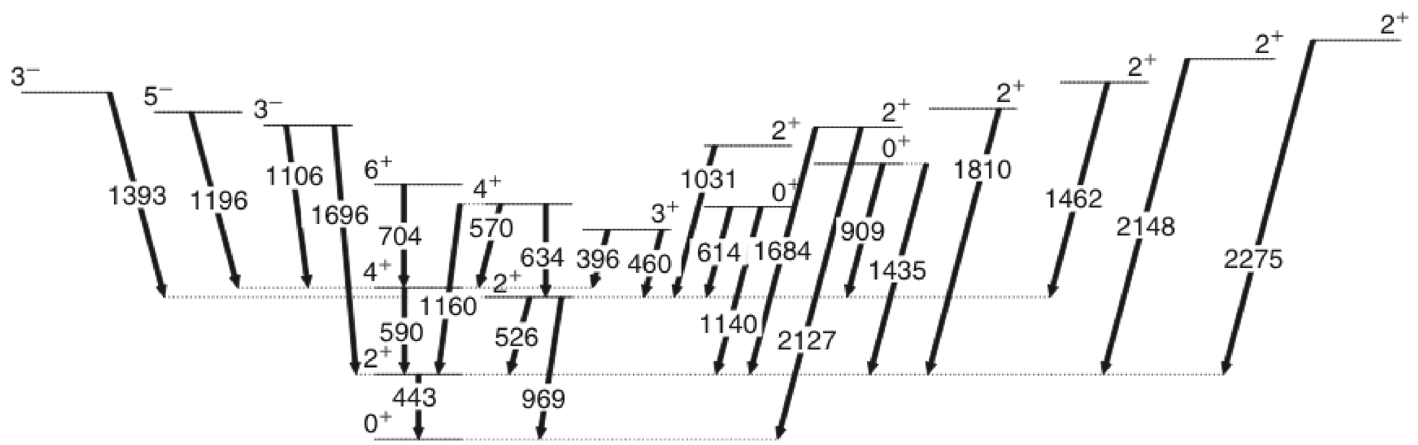


Simplest Coulex detector: no detector at all

Doppler correction impossible; how can we manage?

- traditional "thick target" measurements
  → lifetimes should be long compared to stopping time

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

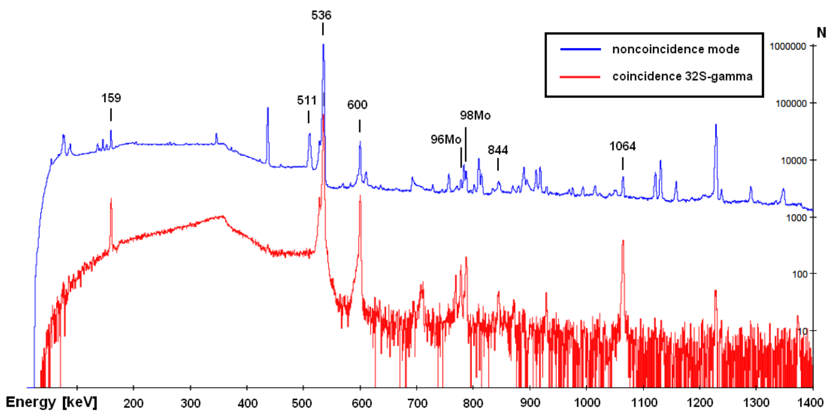


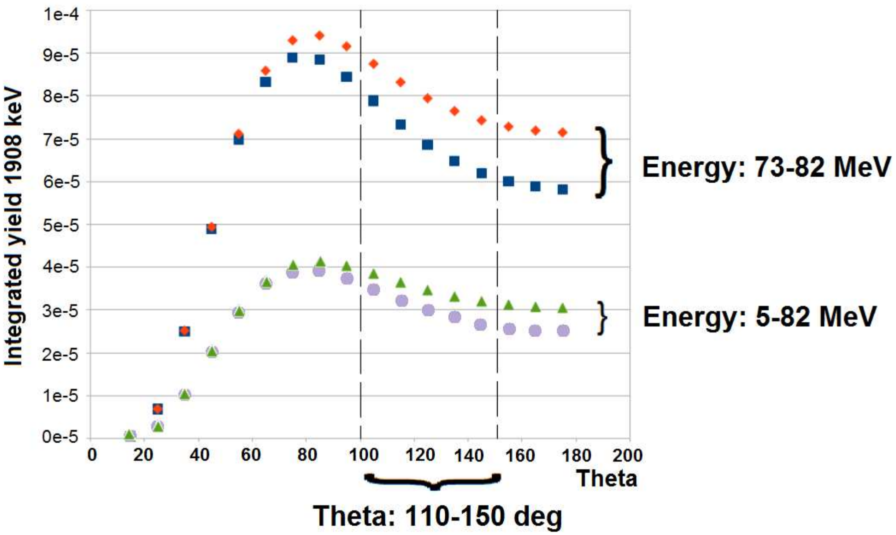
^{128}Xe on ^{12}C

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

Simplest Coulex 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!



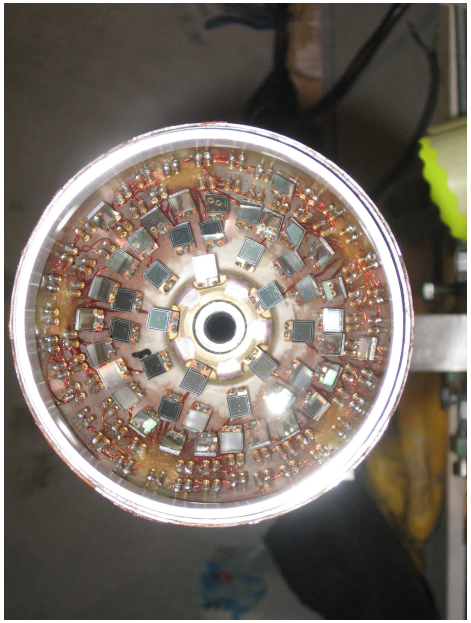


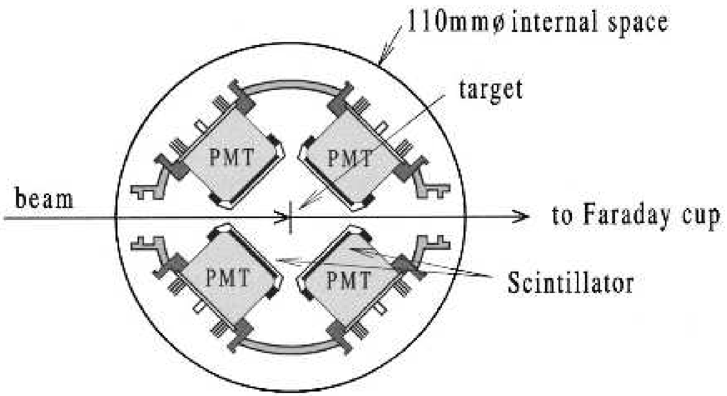
^{32}S on ^{100}Mo

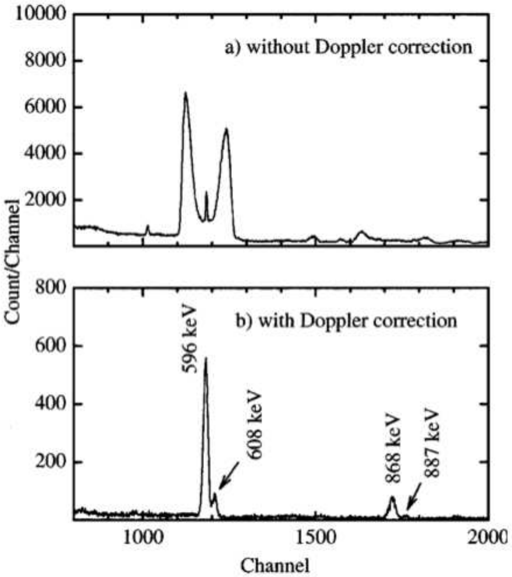
K. Hadyńska-Klęk *et al.*, MSc thesis

"Standard" stable beam Coulex: 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

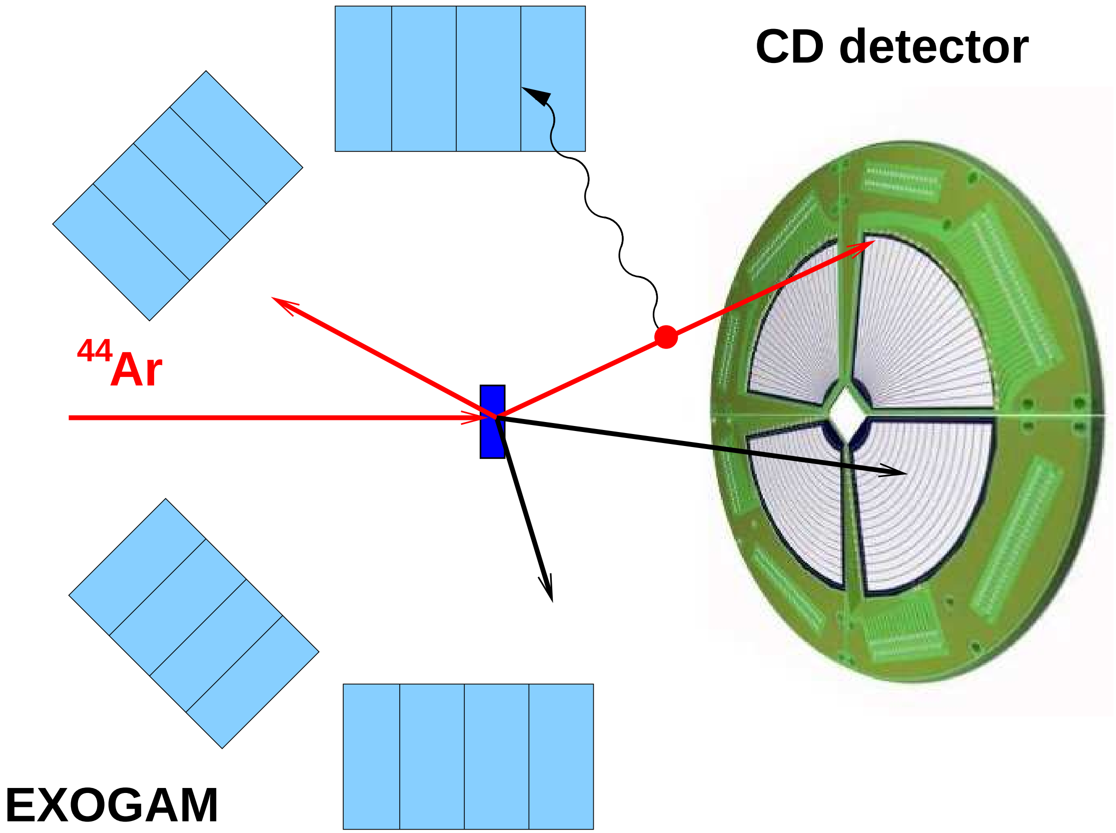
K. Wrzosek *et al.*, Acta Phys. Pol. B39 (2008) 513

LUNA, JAEA Tokai

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

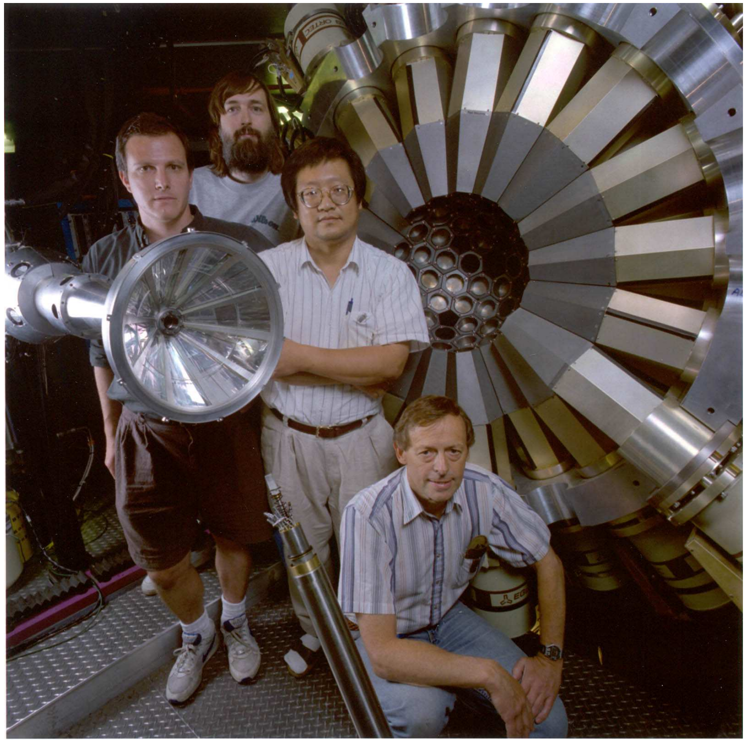
"Standard" exotic beam Coulex: detectors at forward angles

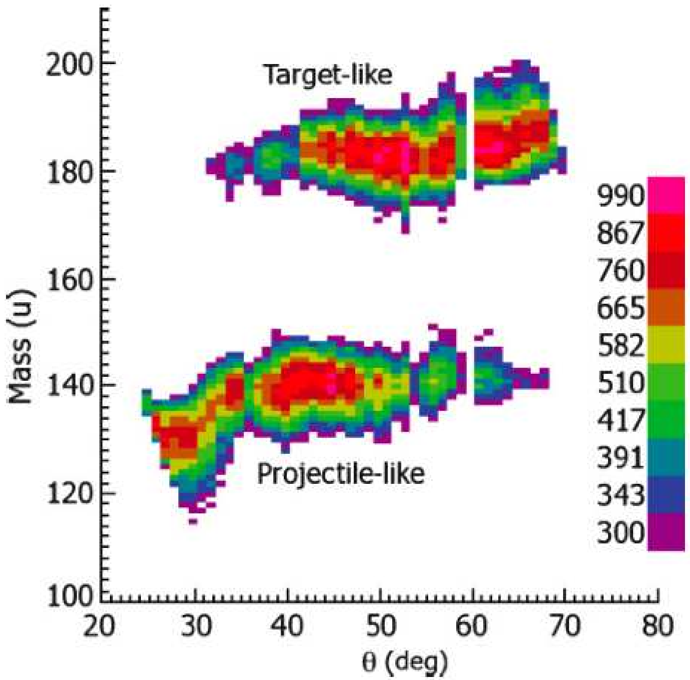
- simultaneous detection of scattered projectiles and recoils
- unambiguous identification necessary for excitation process description & Doppler correction
- detectors used: PPAC (stable and exotic beams), segmented Si / CsI(Tl) (exotic beams)



Identification ejectile-recoil: time

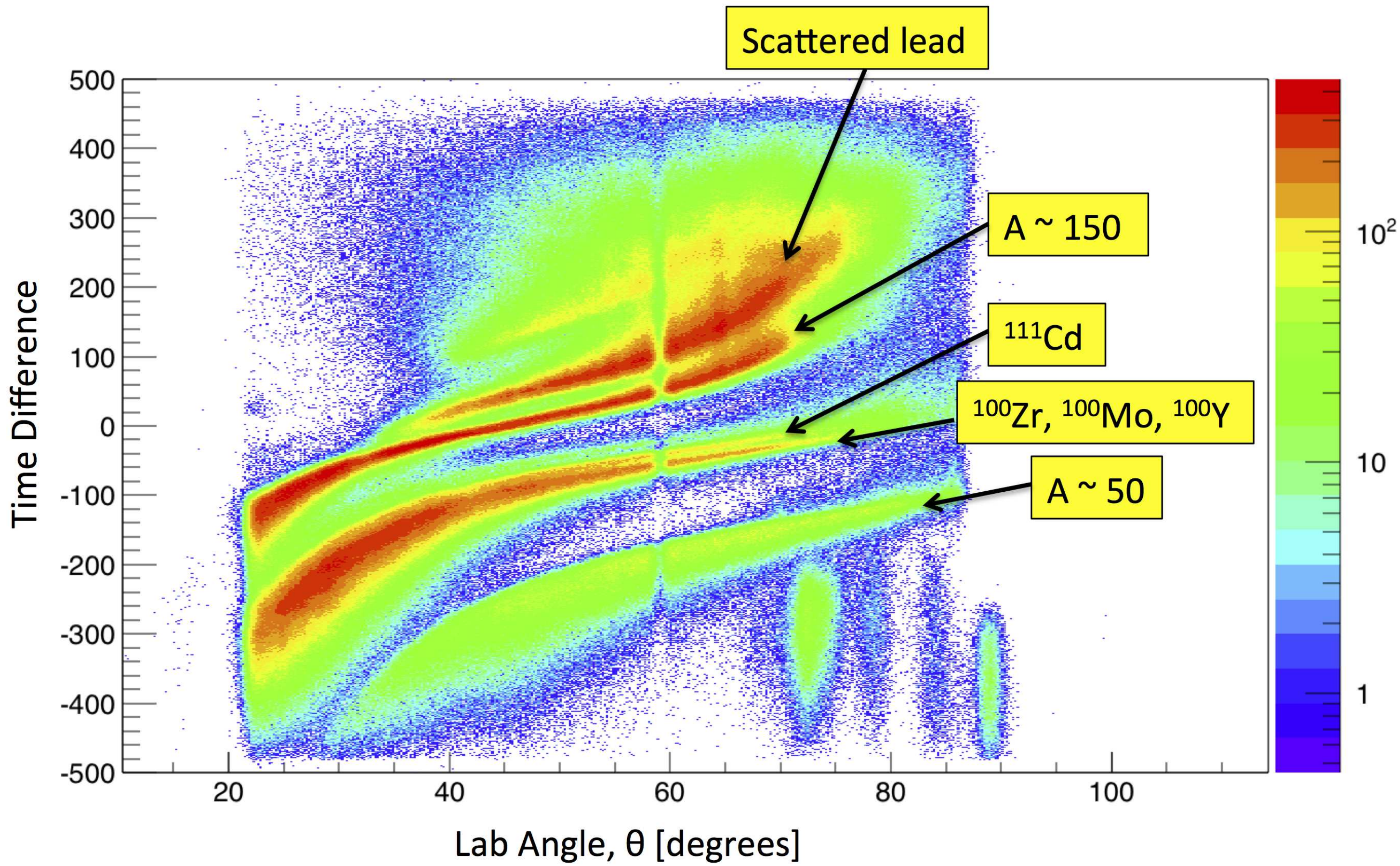
- CHICO: 4 π PPAC array designed for GAMMASPHERE
- chamber diameter 36 cm (distance target-detector 15 cm)
- timing resolution 500 ps
- for ^{136}Xe + ^{178}Hf Coulex: 10 ns TOF difference, ejectile and recoil well resolved





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

CHICO2 for exotic beam studies at CARIBU

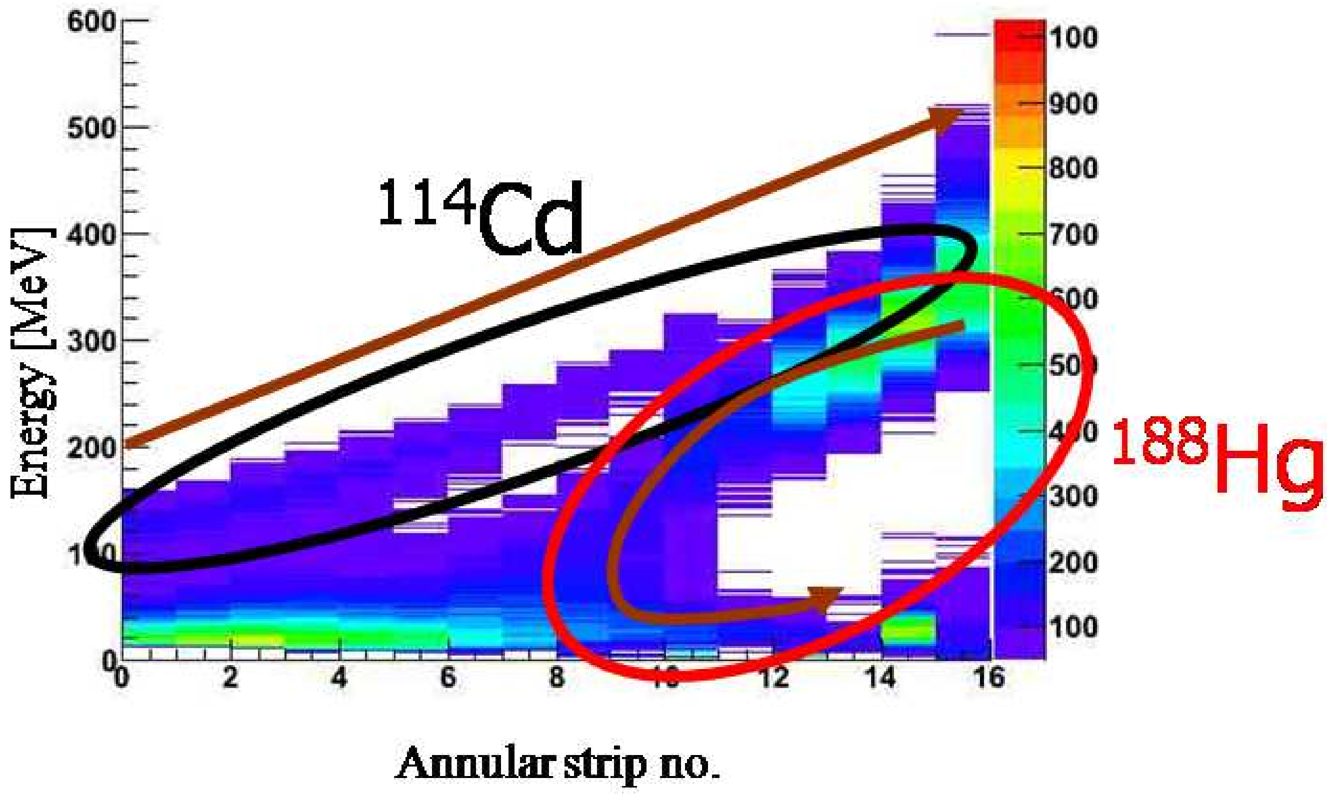


D. Doherty, ^{110}Ru Coulex analysis

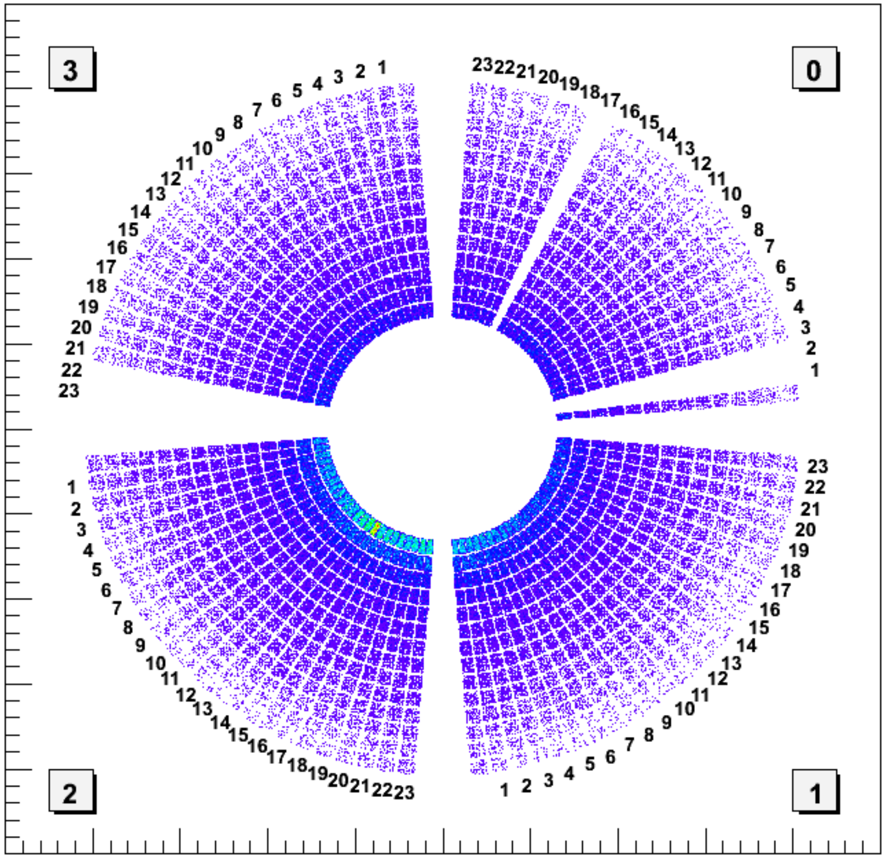
Identification ejectile-recoil: energy

- for Si detectors and targets of 1-2 mg/cm^2: ejectile and recoil should differ in mass by roughly a factor of two

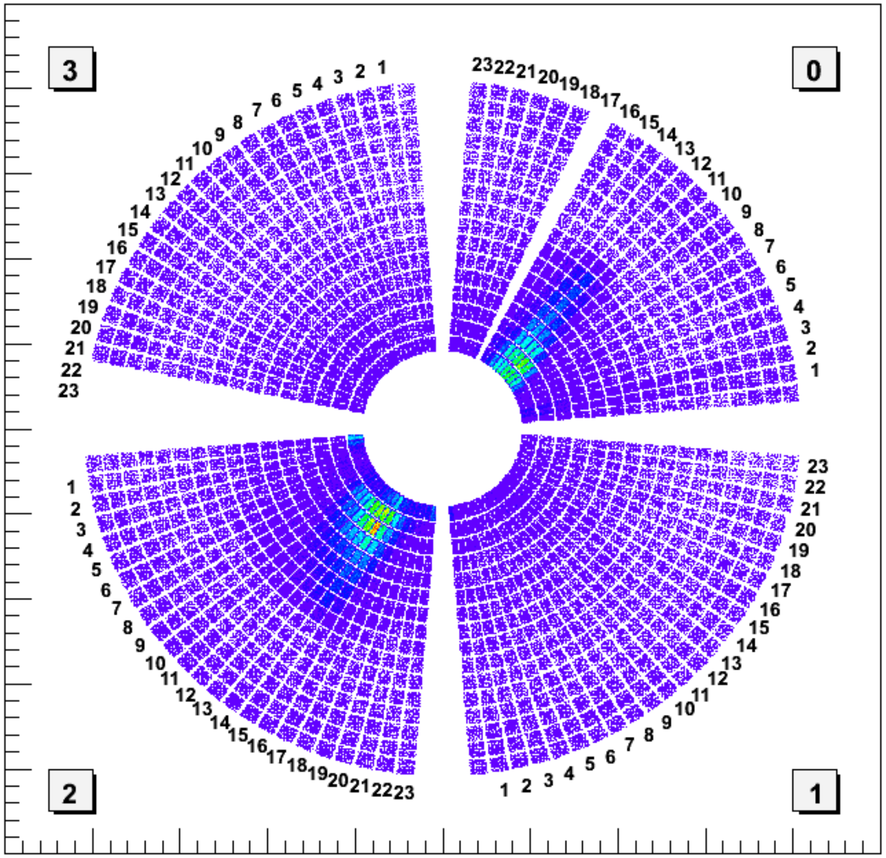
- this limits observed excitation for mass > 100 (heavy targets like Pt or Pb cannot be used)



Possible problems with particle data



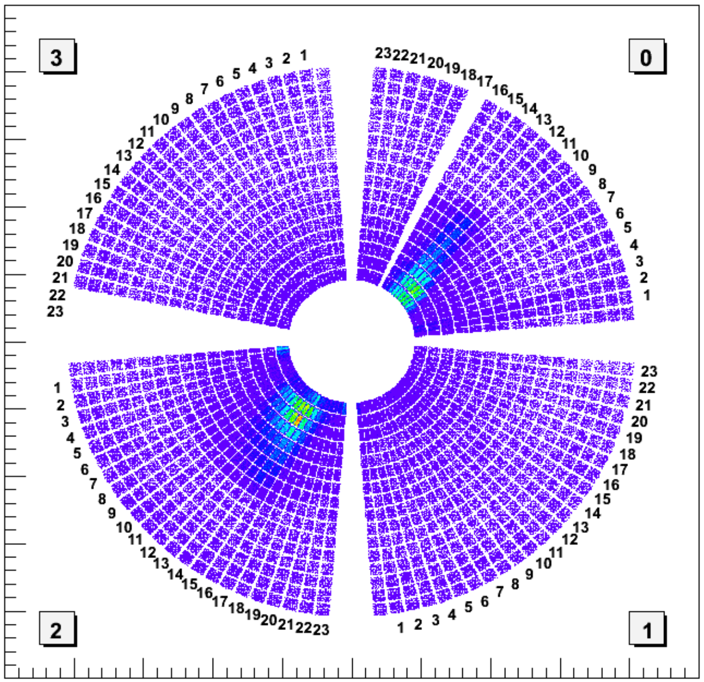
scattered beam

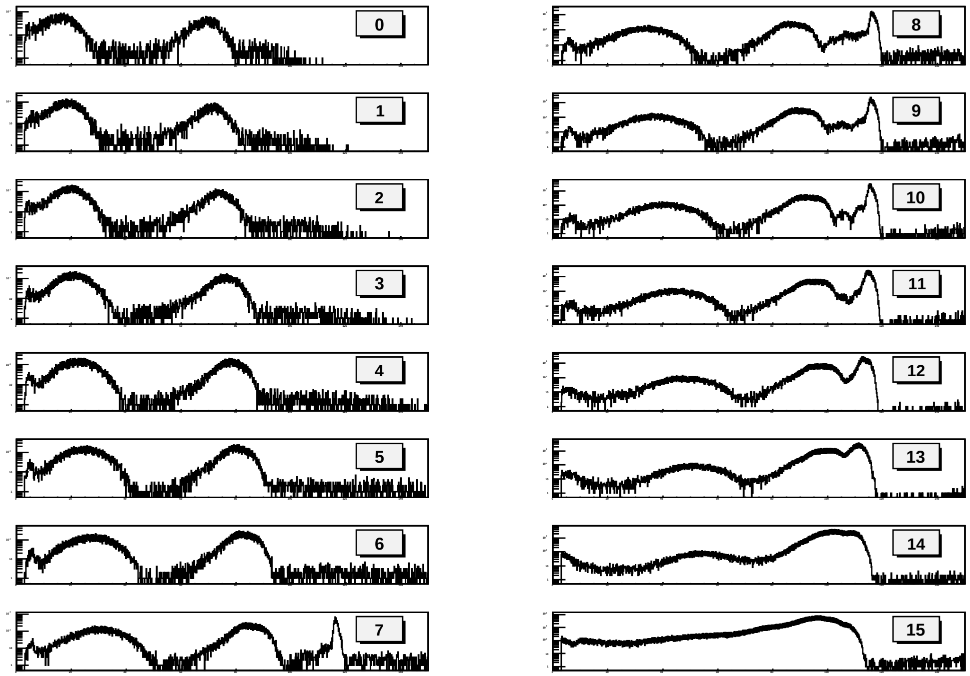


direct beam

Radiation damage due to direct beam

Coulomb excitation of ^{44}Ar

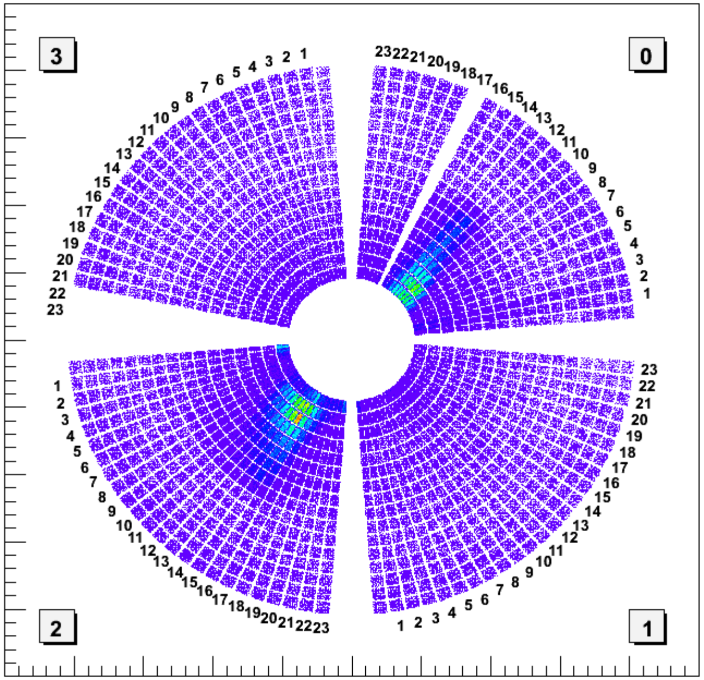


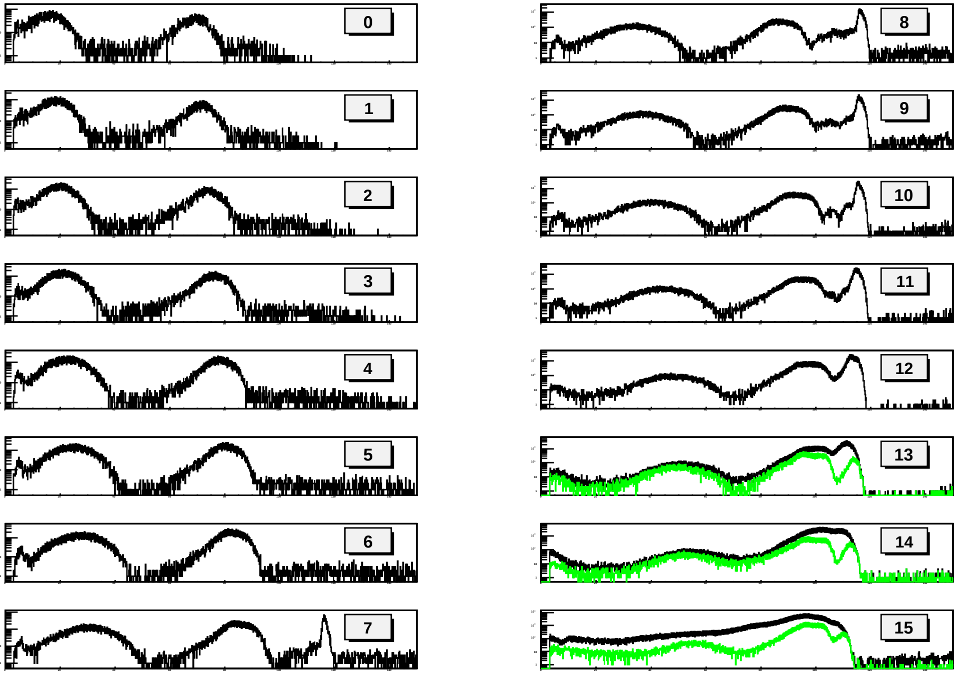


Direct beam of intensity 10^3 pps hitting 5-10% of detector area

Radiation damage due to direct beam

Coulomb excitation of ^{44}Ar

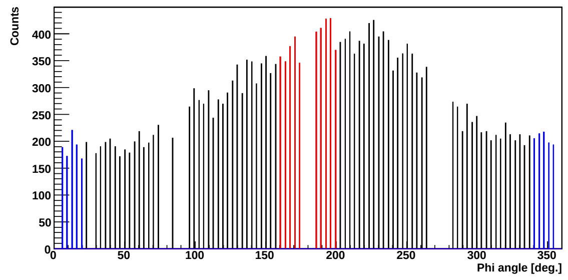


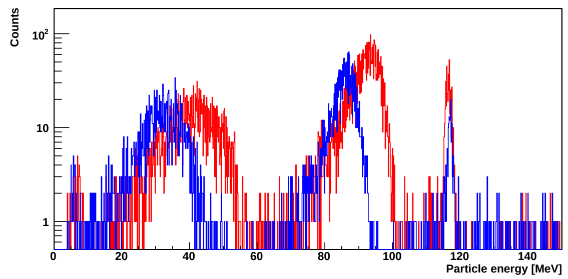


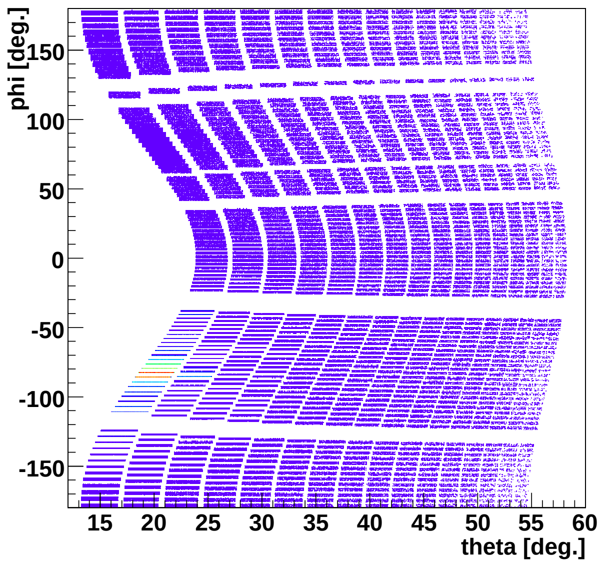
Direct beam of intensity 10^3 pps hitting 5-10% of detector area

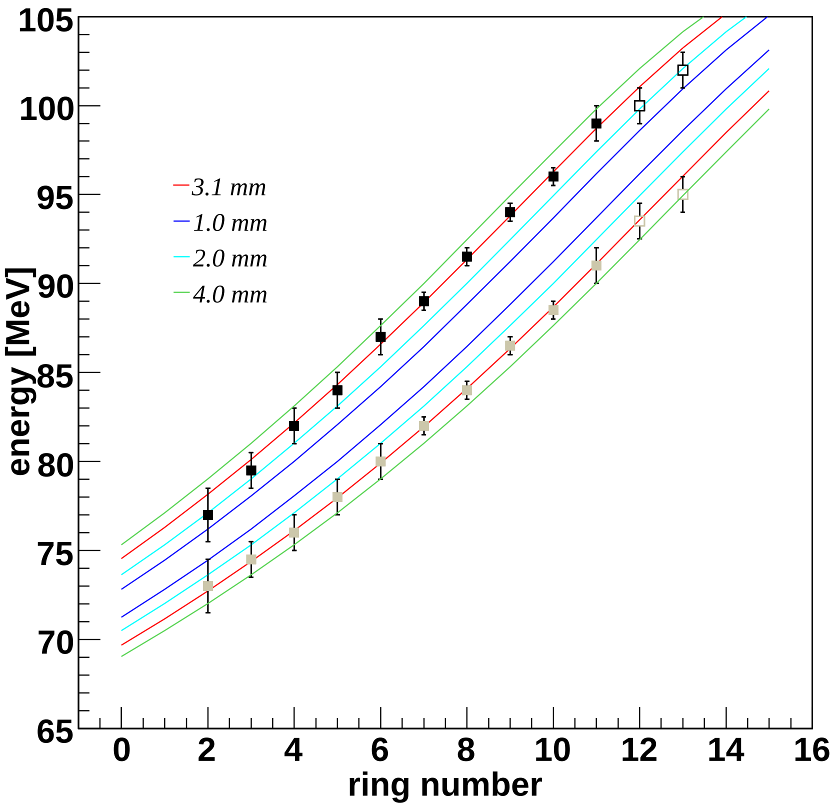
Rate equivalent to Rutherford scattering of 10^8 pps beam at $15^\circ < \theta < 25^\circ$

Estimation of detector displacement









- estimation confirmed by Doppler correction
- complicated shape of the detector due to its displacement

Exotic beam experiments: future

- increase in RIB intensities
- multi-step excitation experiments will become common
- Coulex one of the most important methods to measure transition probabilities on the neutron-rich side
- need for novel particle detectors