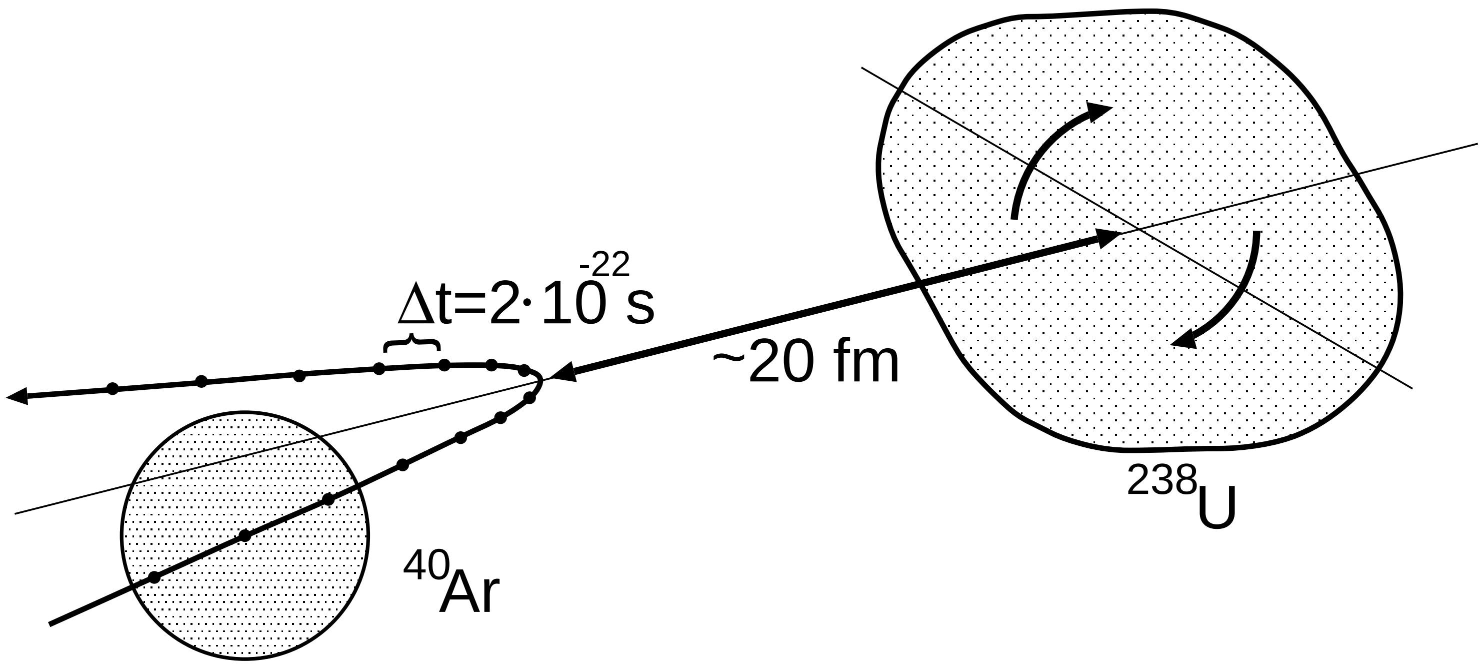
Why do we like Coulomb excitation?

- it's a very precise tool to measure the collectivity of nuclear excitations and in particular nuclear shapes
- shape = fundamental property of a nucleus, "condensed" information about its structure
- excitation mechanism purely electromagnetic, the only nuclear properties involved: matrix elements of electromagnetic multipole operators
- nuclear structure information extracted in a model-independent way

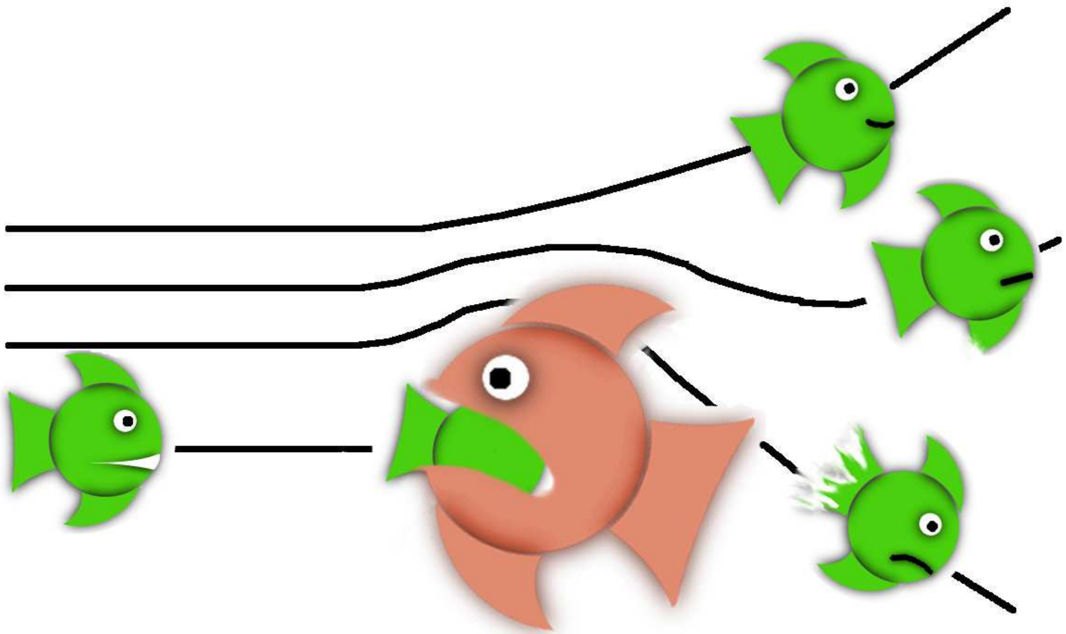


Coulomb excitation method

- Cline's "safe energy" criterion: purely electromagnetic interaction if the distance between nuclear surfaces is greater than 5 fm

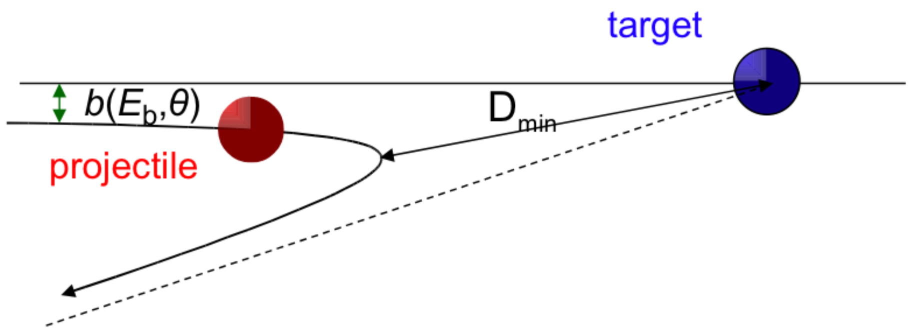
$$d = 1.25 \cdot (A_p^{1/3} + A_t^{1/3}) + 5.0 \quad [\mathrm{fm}]$$

- The observed excitation depends on:
  - (Z, A) of the collision partners,
  - beam energy,
  - scattering angle.



„Safe“ bombarding energy requirement

is a consequence of the D_{min} requirement



$$E_b(\theta_{cm}) = 0.72 \cdot \frac{Z_P Z_T}{D_{min}} \cdot \frac{A_p + A_t}{A_t} \cdot \left[1 + \frac{1}{\sin\left(\frac{\theta_{cm}}{2}\right)}\right] [\mathrm{MeV}]$$

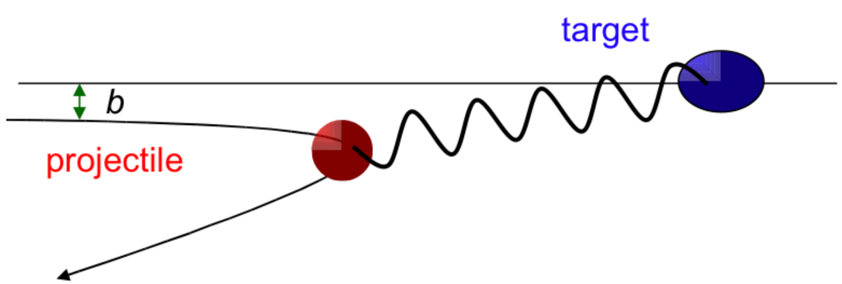
Two possibilities to prepare an experiment:

- choose adequate beam energy (D > D_{min} for all θ)
  low-energy Coulomb excitation
- limit scattering angle, i.e. select impact parameter b (E_b, θ) > D_{min}
  high-energy Coulomb excitation

- Electromagnetic interaction well-known $\rightarrow$ one can easily calculate Coulomb excitation cross section for any states of the investigated nucleus when its internal structure is known (i.e. matrix elements of electromagnetic transitions)
  - Straightforward method – quantum mechanical treatment: high number of partial waves, coupled channel equations... IMPRACTICAL !
  - Simplified and replaced by a semiclassical approach without any significant loss of accuracy

Semiclassical picture of the Coulomb excitation

- Projectile is moving along the hyperbolic orbit and the nuclear excitation is caused by the time-dependent electromagnetic field from the projectile acting on the target nucleus
- **Assumption:** trajectories can be described by the classical equations of motion, electromagnetic interaction is described using the quantum mechanic.



- Validity of semiclassical approach:

  1. $\lambda_{projectile} << D_{min}$ for a head on collision,

  2. small energy transfer,

  3. the excitation is induced only by the monopole-multipole interaction,

  4. time seperation of the collision (10^{-19} – 10^{-20} s) and deexcitation (10^{-12} s) process.

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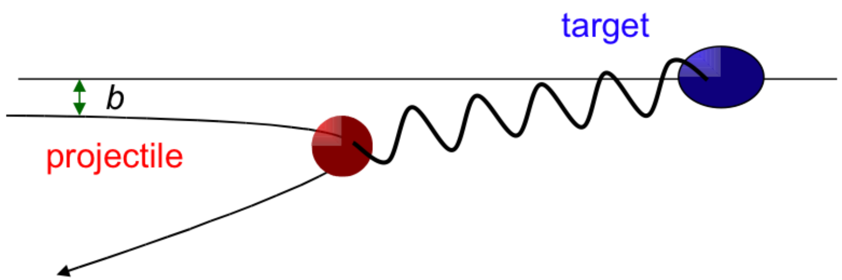

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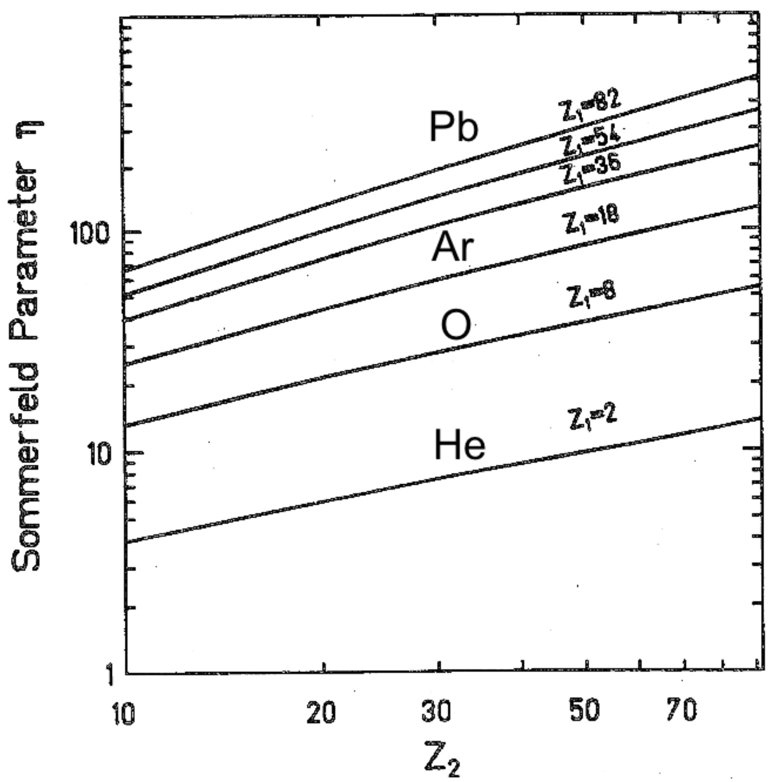
Validity of classical Coulomb trajectories

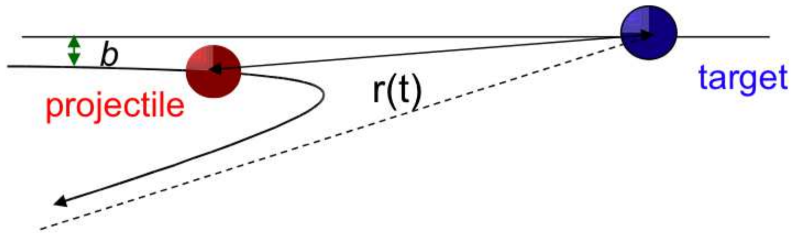
$\lambda_{projectile}$ << D => Sommerfeld parameter η

$$\eta = \frac{D}{2\lambda\!\!\!^{-}} = \frac{Z_P Z_T e^2}{\hbar v} >> 1$$

- η » 1 required for a semiclassical treatment of equations of motion $\rightarrow$hyperbolic trajectories
- condition well fulfilled in heavy-ion induced Coulomb excitation
- semiclassical treatment is expected to deviate from the exact calculation by terms of the order $\approx 1/\eta$



Coulomb excitation theory - the general approach



The excitation process can be described by the time-dependent **H**:

$$H = H_P + H_T + V(r(t))$$

with $H_{P/T}$ being the free Hamiltonian of the projectile/target nucleus
and V(t) being the time-dependent electromagnetic interaction
(remark: often only target or projectile excitation are treated)

Denoting the P/T wave function by $\psi(t)$ the time-dependent Schrödinger equation:

$$i\hbar \, d\psi(t)/dt = [H_P + H_T + V(r(t))] \, \psi(t)$$

During the collision, the wave function can be expressed as time-dependent expansion $\psi(t) = \sum_n a_n(t) \, \phi_n$ of the eigenstates ϕ_n of free $H_{P/T}$ what leads to a set of coupled equations for the **time-dependent excitation amplitudes $a_n(t)$**

$$i\hbar \, da_n(t)/dt = \sum_m \langle \phi_n | V(t) | \phi_m \rangle \exp[i/\hbar \, (E_n - E_m) \, t] \, a_m(t)$$

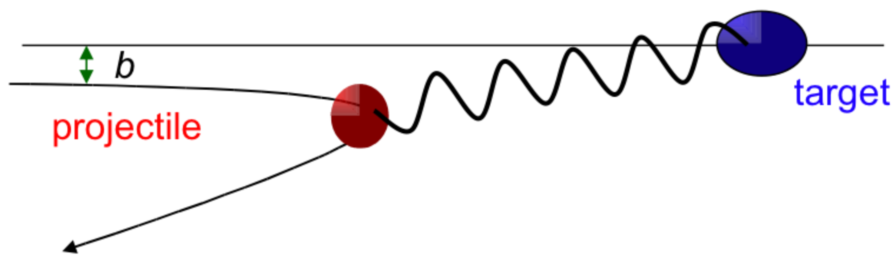
m - all states involved in the excitation process
→ nr. of coupled equations

can be written as an expansion of multipoles

Energies of initial and final states

Coulomb excitation theory - the general approach

The coupled equations for $a_n(t)$ are usually solved by a multipole expansion of the electromagnetic interaction $V(r(t))$



$V_{P\text{-}T}(r) = Z_T Z_P e^2/r$	monopole-monopole (Rutherford) term
$+ \sum_{\lambda\mu} \mathbf{V_P(E\lambda,\mu)}$	**electric multipole-monopole target excitation,**
$+ \sum_{\lambda\mu} \mathbf{V_T(E\lambda,\mu)}$	**electric multipole-monopole project. excitatio**n,
$+ \sum_{\lambda\mu} V_P(M\lambda,\mu)$	magnetic multipole project./target excitation
$+ \sum_{\lambda\mu} V_T(M\lambda,\mu)$	(but small at low v/c)
$+ O(\sigma\lambda,\sigma'\lambda'>0)$	higher order multipole-multipole terms (small)

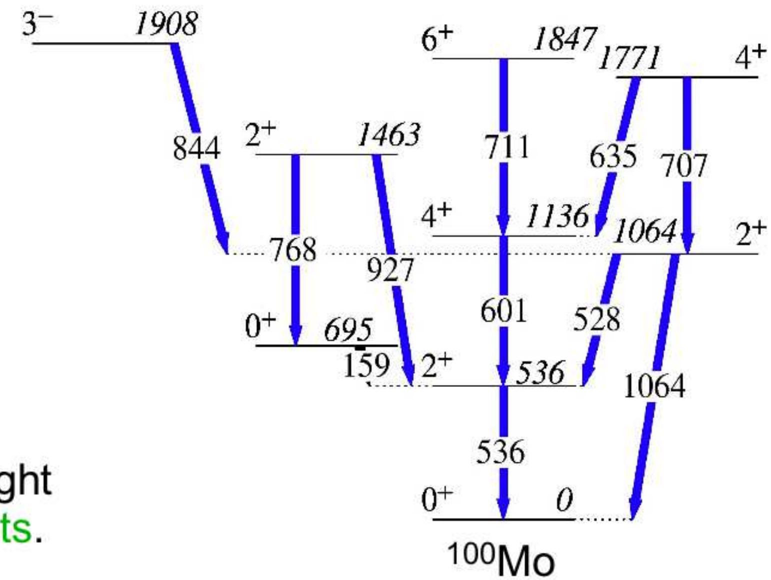
Coupled equations

$$i\hbar\, da_n(t)/dt = \sum_m \langle\phi_n|V(t,T\lambda,\mu)|\,\phi_m\rangle \exp[i/\hbar\,(E_n-E_m)\,t]\; a_m(t)$$

In the heavy ion induced Coulomb excitation the interaction strength gives rise to multiple Coulomb excitation

nuclear state can be populated indirectly, via several intermediate states

The exact excitation pattern is not known
The excitation probability of a given excited state might strongly dependent on many different matrix elements.



Coulex, HIL, Warsaw, 2007

High number of coupled equations for the $da_n(t)/dt$ -> **GOSIA** code

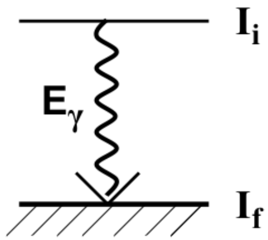
Deexcitation process

- For a given set of matrix elements **(Tλ,μ)** GOSIA solves differential coupled equations for the **time-dependent excitation amplitudes $a_n(t)$**

  $$i\hbar\, da_n(t)/dt = \sum_m \langle \phi_n | \sum_{\lambda,\mu} V(t, T\lambda,\mu) | \phi_m \rangle \exp[i/\hbar\, (E_n - E_m)\, t]\, a_m(t)$$

  to find level populations and gamma yields.

- The same set of **Tλ,μ** describes the deexcitation process



$$P(T\lambda; I_i \rightarrow I_f) = \frac{8\pi(\lambda+1)}{\lambda((2\lambda+1)!!)^2} \cdot \frac{1}{\hbar} \cdot \left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda+1} \cdot B(T\lambda; I_i \rightarrow I_f)$$

$$B(T\lambda; I_i \rightarrow I_f) = \frac{1}{2I_i+1} \cdot \langle I_f | M(T\lambda) | I_i \rangle^2$$

Calculation includes effects influencing γ-ray intensities: internal conversion, size of Ge, γ-ray angular distribution, deorientation

Basic facts about Coulex

- Due to the purely electromagnetic interaction the nucleus undergoes a transition from state $|i\rangle$ to $|f\rangle$.

- Then it decays to the lower state, emitting a γ-ray (or a conversion electron).

- The matrix elements $\langle f||M(E2)||i\rangle$ describe the excitation and decay pattern $\rightarrow$ they are directly connected with γ-ray intensities observed in the experiment.

- In the intrinsic frame of the nucleus they are related to the deformation parameters.

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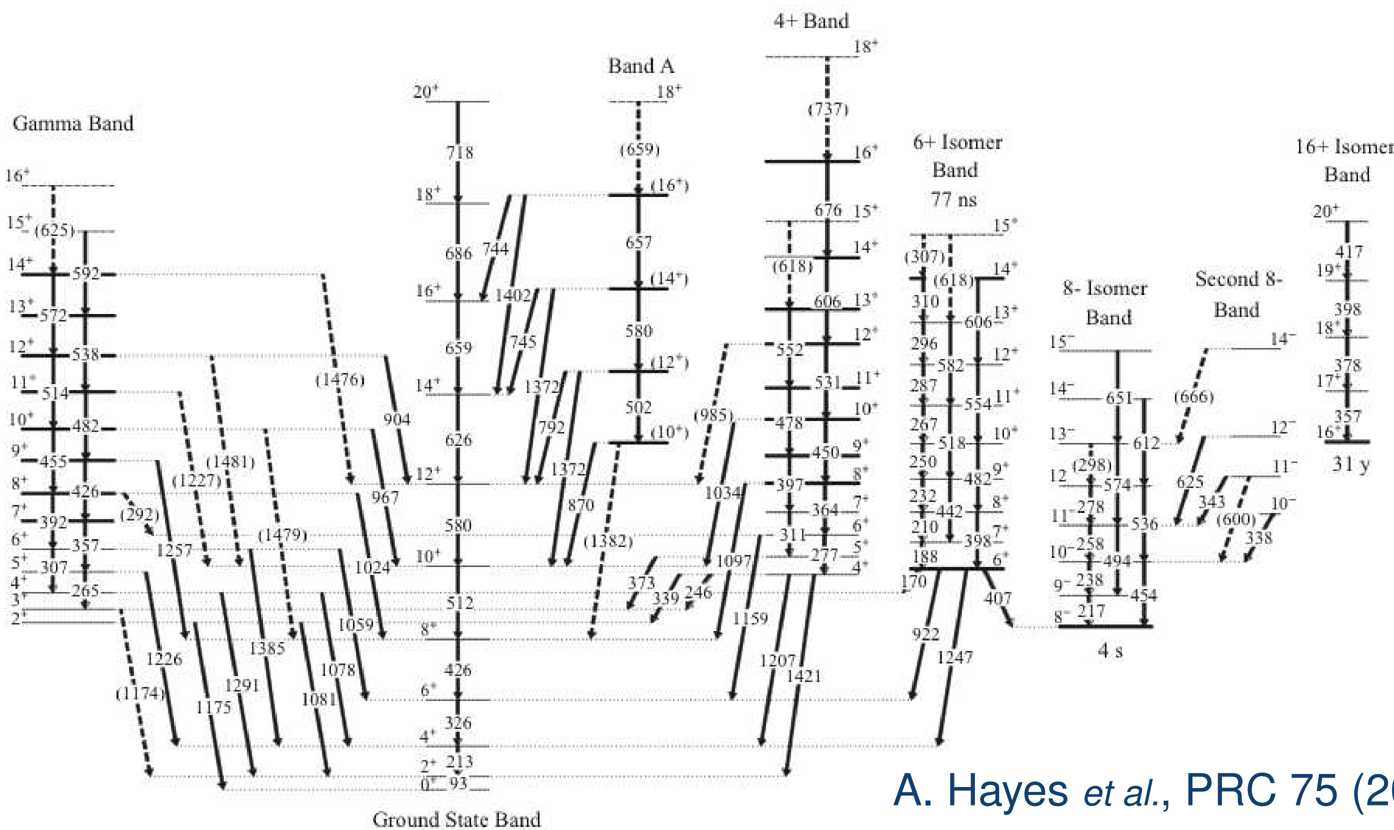
Stable beam experiments

- 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

Exotic beam experiments

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

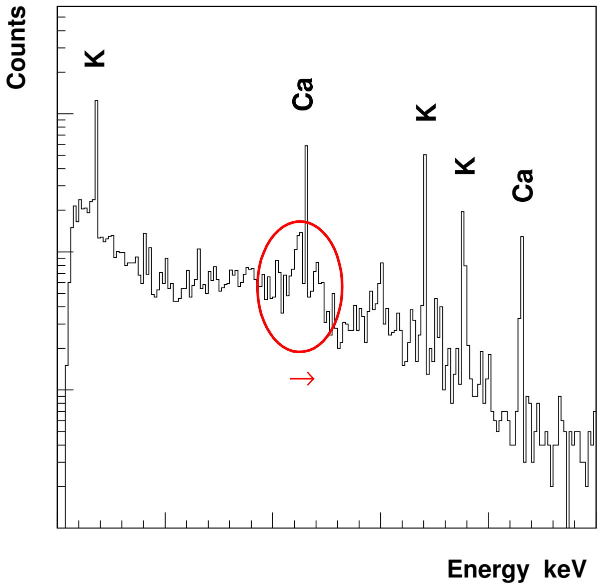
• beam intensities rather low: particle detectors at forward angles to maximise the statistics

• 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



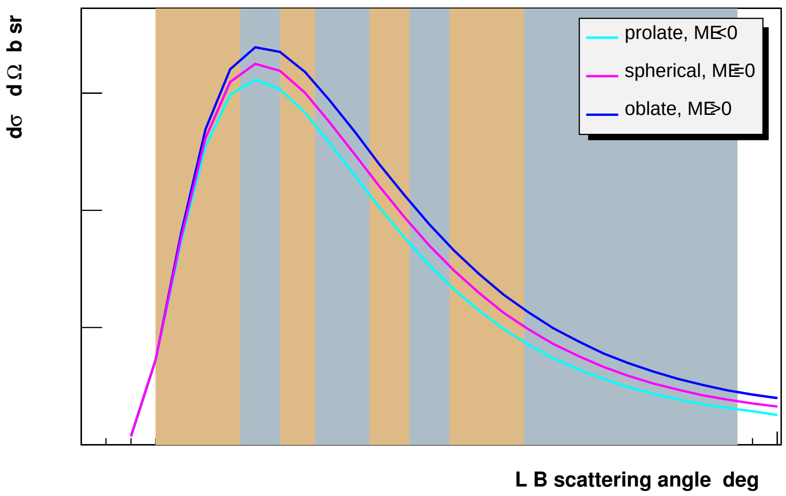
Reorientation effect

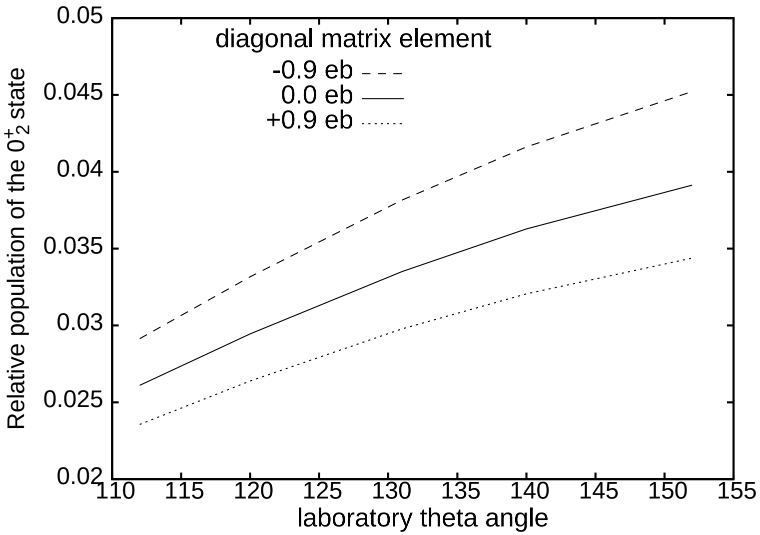
- influence of the quadrupole moment of the excited state on its excitation cross-section

- dependence on scattering angle and beam energy

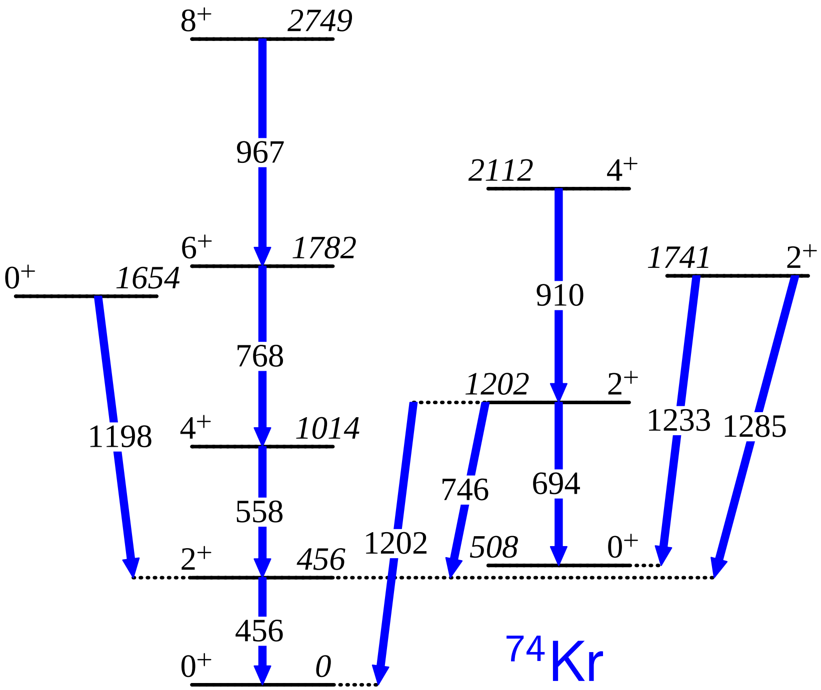
- direct measurement of the nuclear shape

- BE CAREFUL – influence of double-step excitation of higher states may have the same effect!

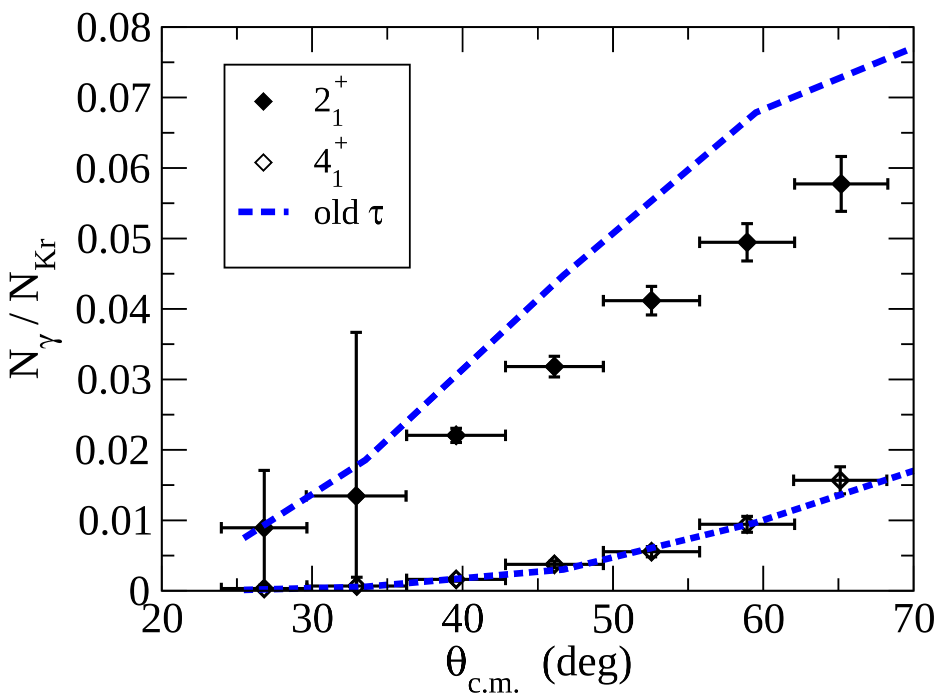




Coulomb excitation and lifetime measurements



- subdivision of data in several ranges of scattering angle
- spectroscopic data (lifetimes, branching and mixing ratios)
- least squares fit of $\sim$30 matrix elements (transitional and diagonal)



- results inconsistent with previously published lifetimes
- new RDM lifetime measurement: Köln Plunger & GASP
  ^{40}Ca (^{40}Ca,α2p) ^{74}Kr
  ^{40}Ca (^{40}Ca,4p) ^{76}Kr

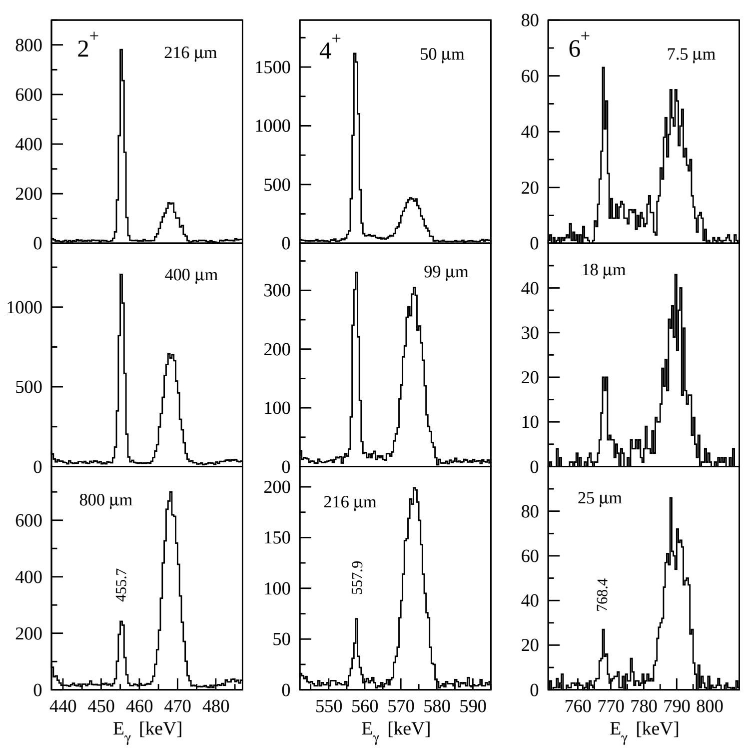
Lifetime measurement

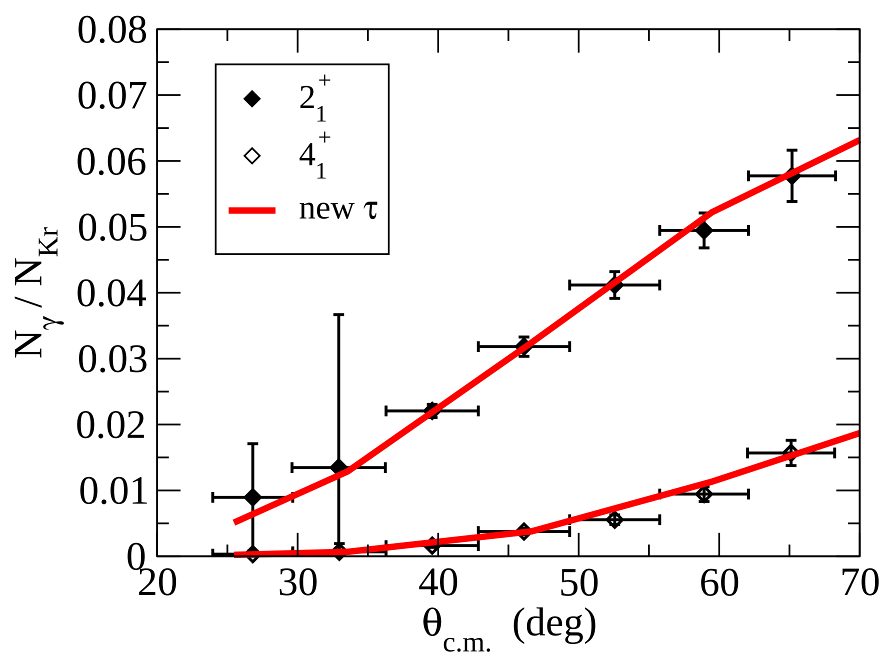
A. Görgen *et al.* EPJ A 26 153 (2005)

		old	new			old	new
^{76}Kr	2^+	35.3(10) ps	41.5(8) ps	^{74}Kr	2^+	28.8(57) ps	33.8(6) ps
	4^+	4.8(5) ps	3.87(9) ps		4^+	13.2(7) ps	5.2(2) ps

^{74}Kr, forward detectors (36°)

gated from above





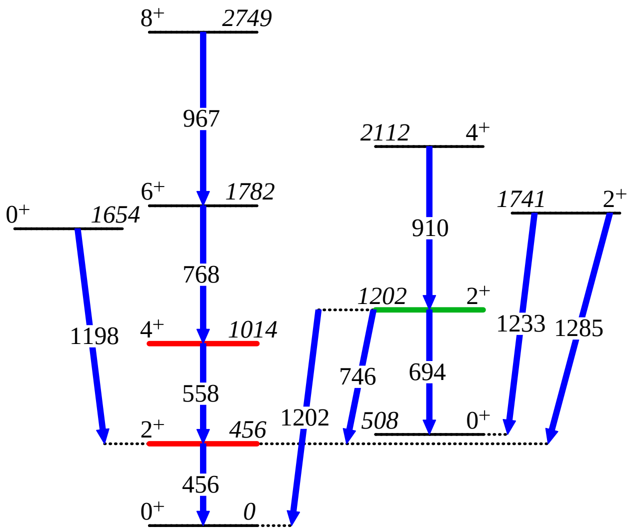
- new lifetimes in agreement with Coulex
- enhanced sensitivity for diagonal and intra-band transitional matrix elements

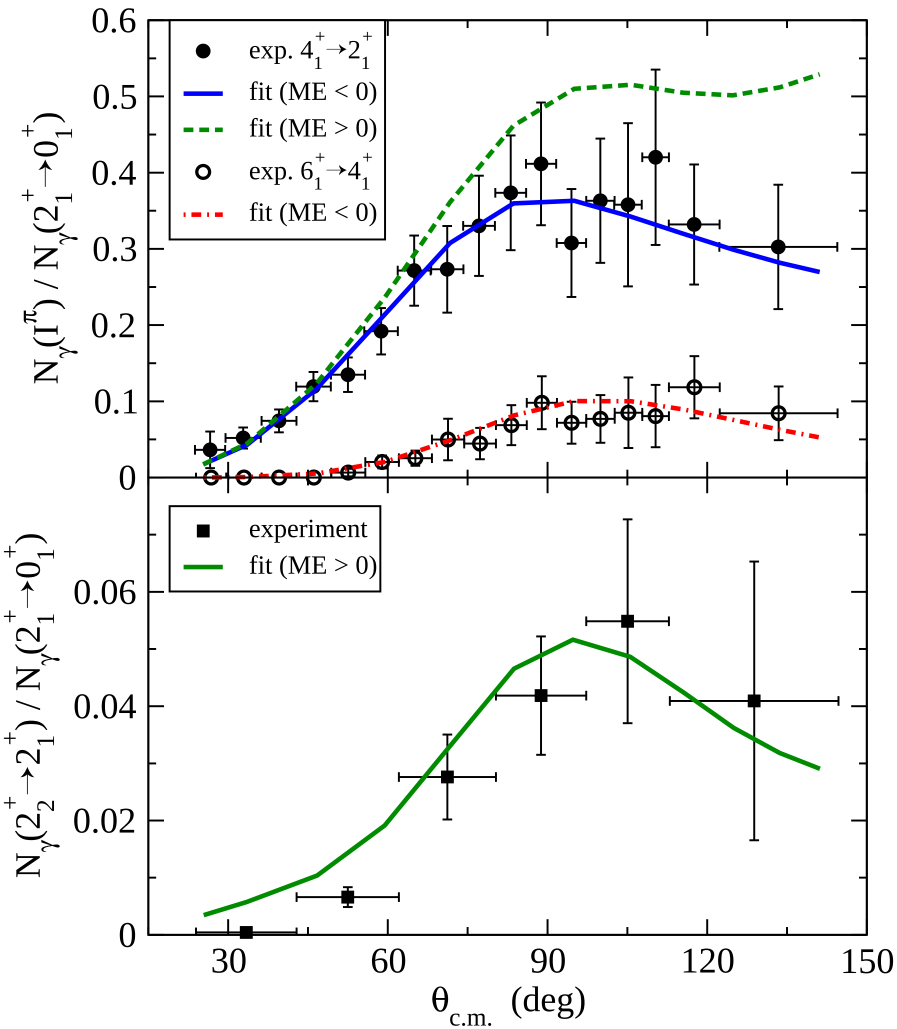
Results: shape coexistence in light Kr isotopes

^{76}Kr: 18 transitional + 5 diagonal ME
^{74}Kr: 14 transitional + 5 diagonal ME

$$\langle 2_1^+ \| E2 \| 2_1^+ \rangle = -\,0.70^{-0.33}_{-0.30}$$
$$\langle 4_1^+ \| E2 \| 4_1^+ \rangle = -\,1.02^{+0.59}_{-0.21}$$

$$\langle 2_2^+ \| E2 \| 2_2^+ \rangle = +\,0.33^{+0.28}_{-0.23}$$





First measurement of diagonal E2 matrix elements using Coulex of radioactive beam

E. Clément *et al.* Phys. Rev. C75, 054313 (2007)