Nuclear Shapes

Lectures I and II

Andreas Görgen
Department of Physics
University of Oslo, Norway
andreas.gorgen@fys.uio.no

Selected Topics in Nuclear and Atomic Physics
Fiera di Primiero
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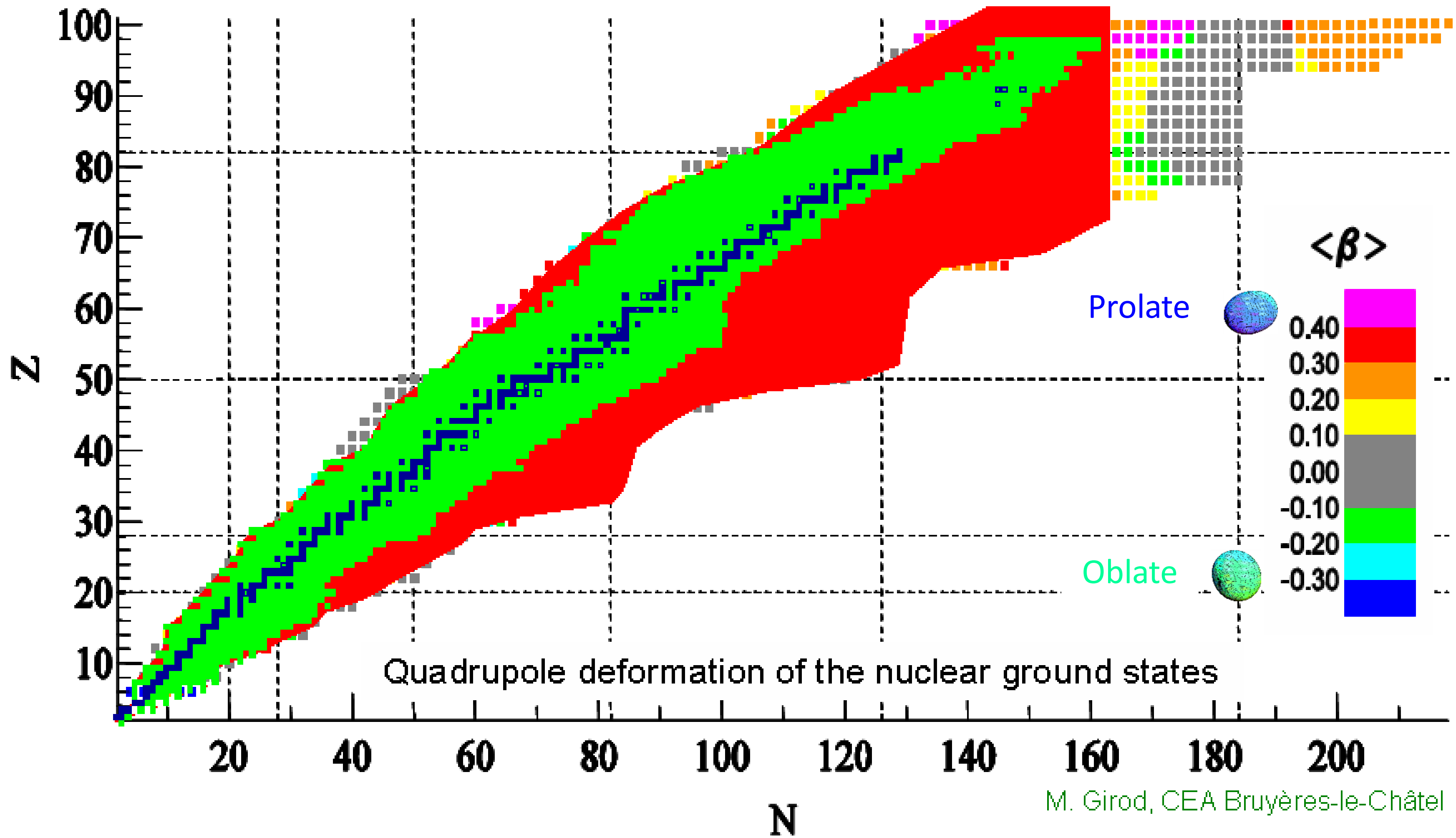
Why study nuclear shapes ?



fundamental property of the nucleus

- sensitive to the nuclear structure

benchmarks for nuclear theory

- shape evolution with N, Z, energy, spin
- shape coexistence
- evolution of shell structure far from stability

Program

Lecture 1:
- quadrupole moments
- low-energy Coulomb excitation
- lifetime measurements
- neutron-deficient Kr isotopes

Lecture 2:
- E0 transitions
- shape mixing and coexistence
- neutron-deficient Se isotopes
- intermediate-energy Coulomb excitation

Lecture 3:
- neutron-rich Sr and Zr isotopes
- lifetime measurements in fission fragments
- odd-mass nuclei
- triaxiality around ^{110}Ru and ^{140}Sm

Lecture 4:
- triaxial superdefomation
- wobbling motion
- Jacobi shape transition
- extreme deformation

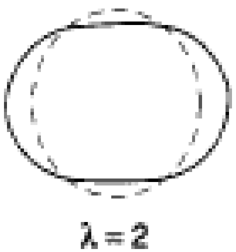
How can we describe the shape of a nucleus?

expansion in spherical harmonics: $$R(t) = R_0\left[1 + \sum_{\lambda}\sum_{\mu=-\lambda}^{+\lambda} a_{\lambda\mu}(t)Y_{\lambda\mu}(\vartheta,\varphi)\right]$$

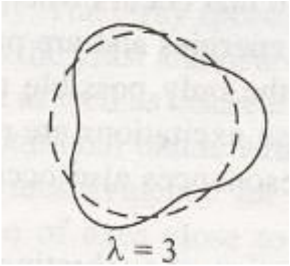
a_{00} describes the nuclear volume

$\lambda = 1$: translation of the whole system

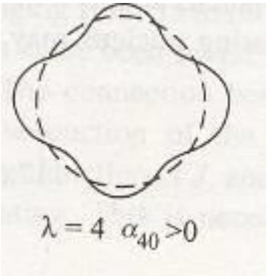
quadrupole



octupole

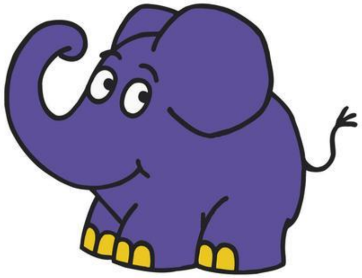


hexadecapole



most important shape

sufficiently large λ:



Quadrupole shapes

$$R(t) = R_0 \left[1 + \sum_{\lambda} \sum_{\mu=-\lambda}^{+\lambda} a_{\lambda\mu}(t) Y_{\lambda\mu}(\vartheta, \varphi) \right]$$

for $\lambda = 2$: five parameters $a_{2\mu}$

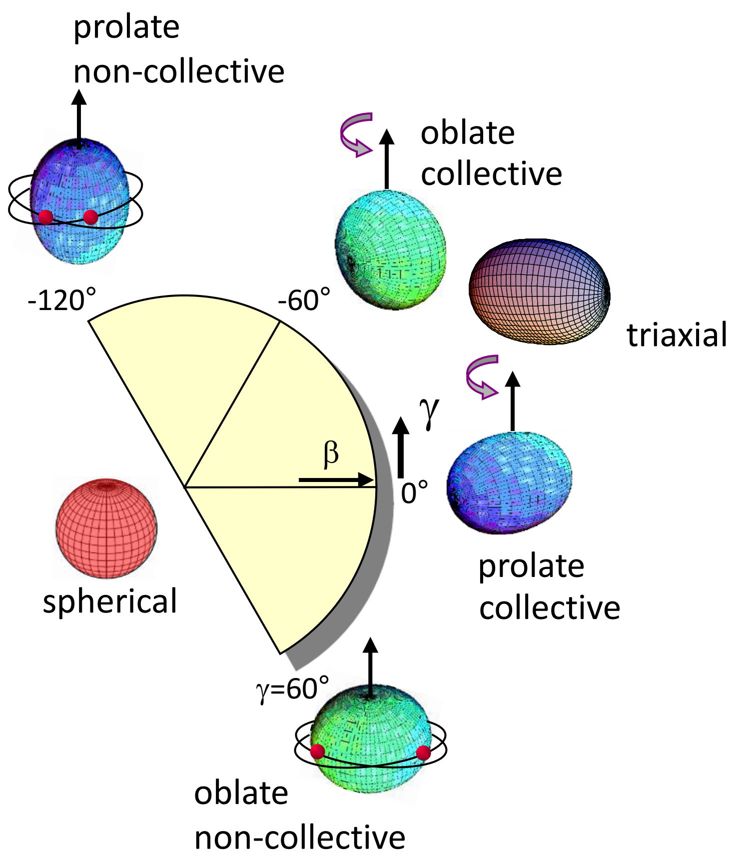
- only two parameters describe the shape
- three describe the orientation in space (Euler angles)

with a rotation we can achieve

$$a_{21} = a_{2,-1} = 0$$

$$a_{22} = a_{2,-2}$$

leaving two independent parameters a_{20} and a_{22}



$$a_{20} = \beta \cos\gamma$$

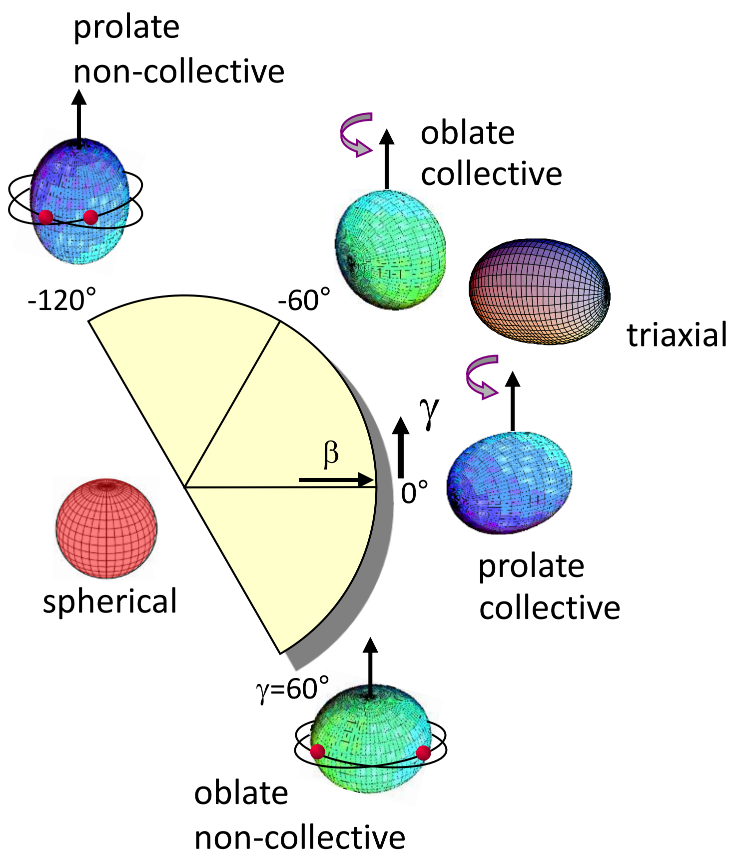
$$a_{22} = \frac{1}{\sqrt{2}} \beta \sin\gamma$$

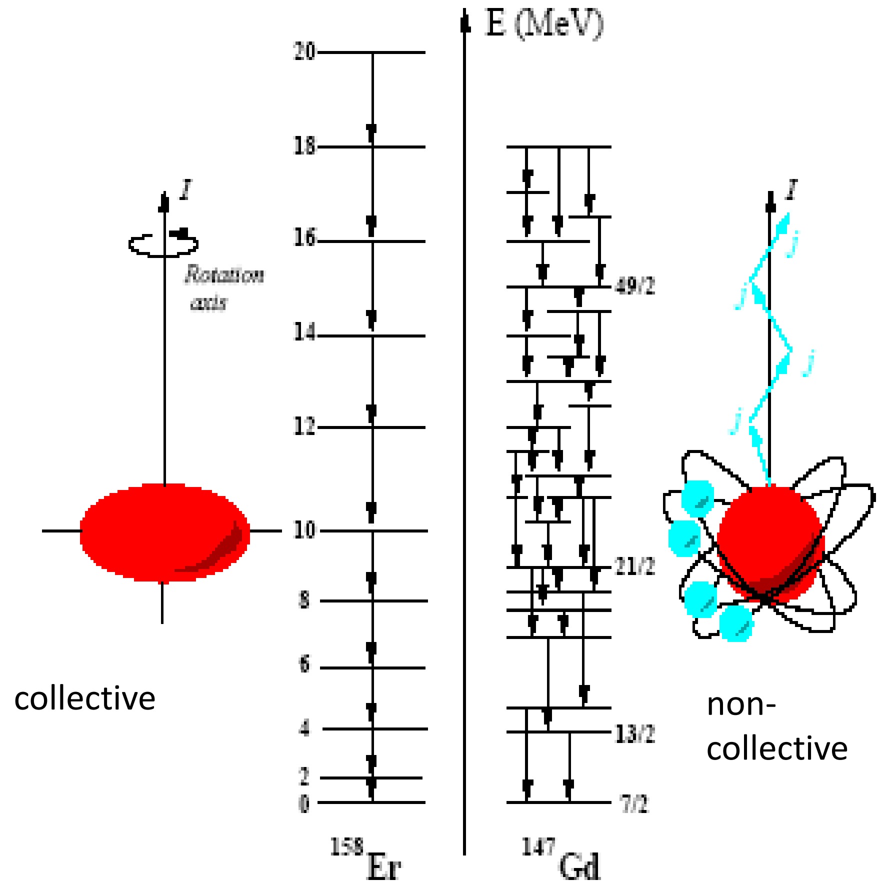
β axial deformation

γ triaxial deformation

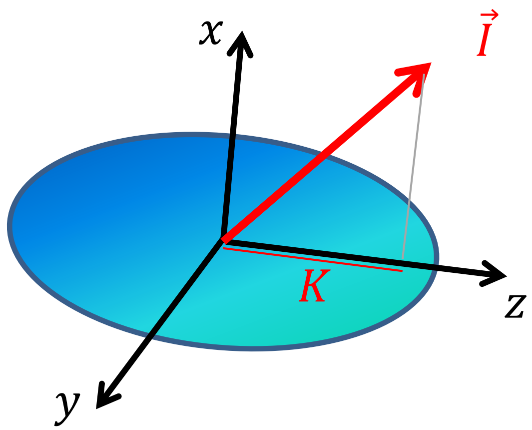
Quadrupole shapes

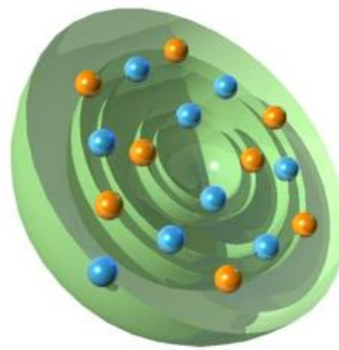
$$R(t) = R_0\left[1 + \sum_{\lambda}\sum_{\mu=-\lambda}^{+\lambda} a_{\lambda\mu}(t)Y_{\lambda\mu}(\vartheta,\varphi)\right]$$

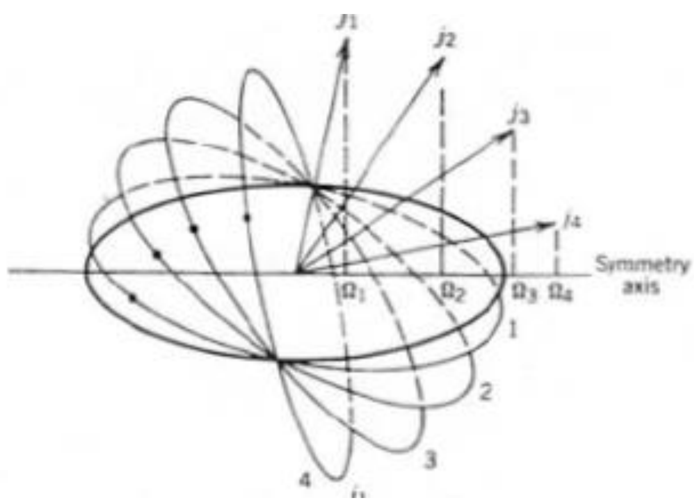


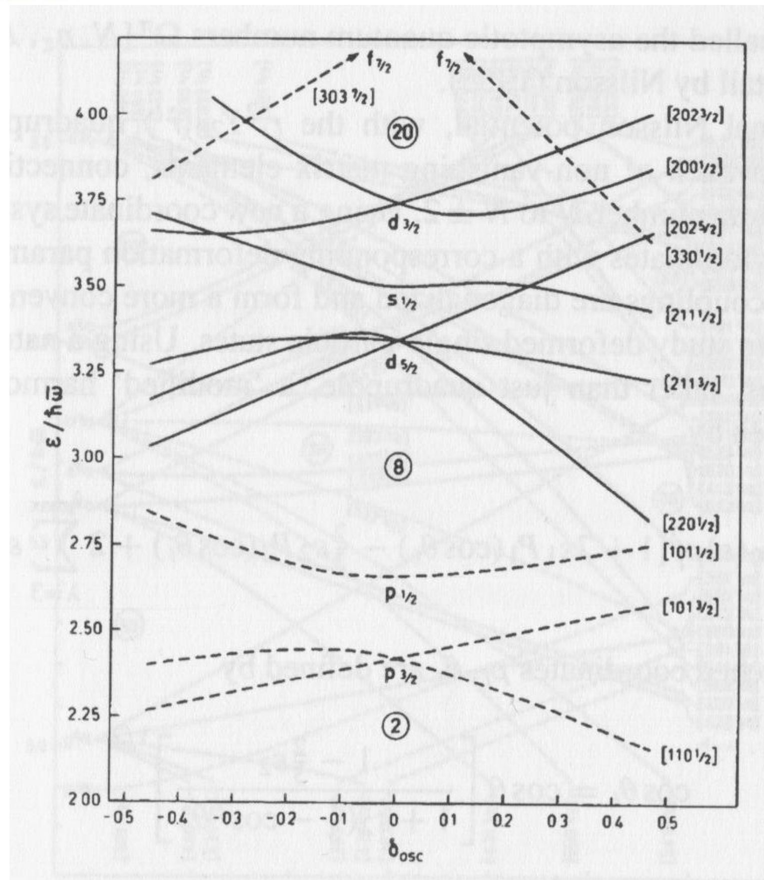


Macroscopic shape ⇔ microscopic structure?

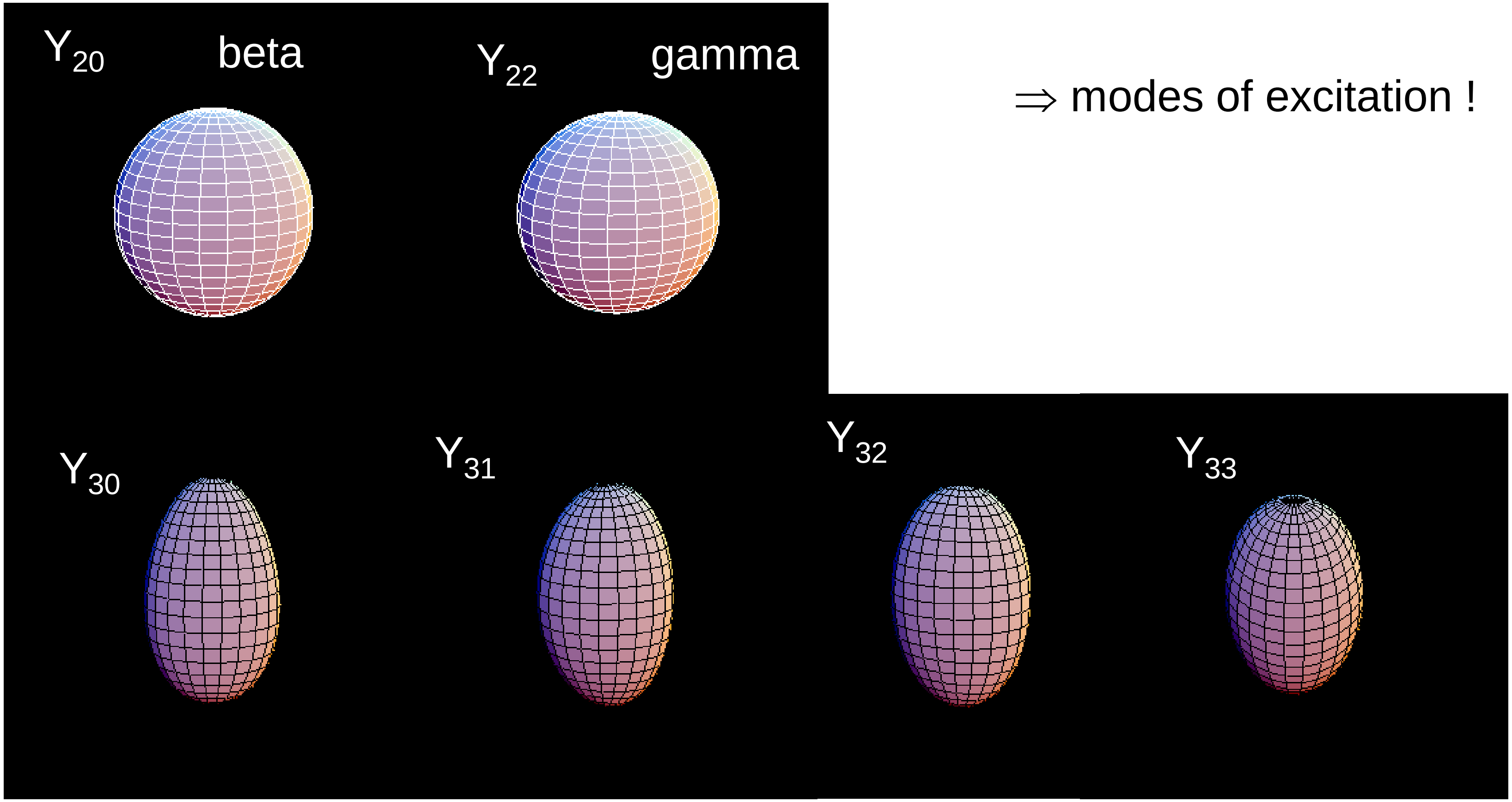






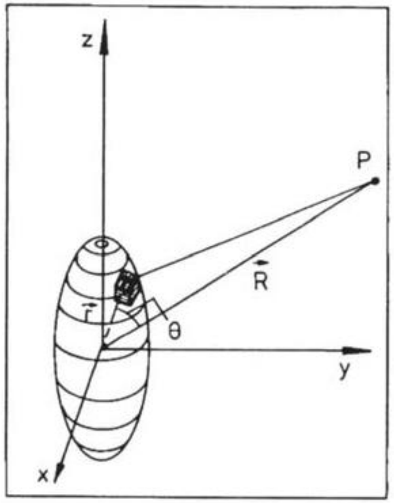


deformation can be dynamic: $a_{\lambda\mu}(t)$



$\Rightarrow$ modes of excitation !

- difficult to measure mass distribution
- electromagnetic interaction sensitive to charge distribution $\rho(\vec{r})$

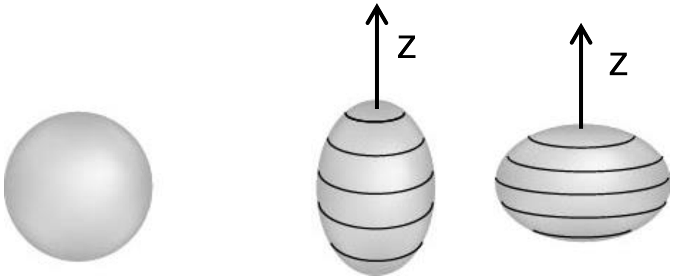


electric quadrupole tensor $Q_{ij} = \int \rho(\vec{r})\left(3x_i x_j - r^2\delta_{ij}\right)dV$

rotation to principal axis frame $\Rightarrow$ Q_{ij} becomes diagonal

in case of axial symmetry: symmetry axis z

$$Q_z = \int \rho(\vec{r})(3z^2 - r^2)dV = \int \rho(\vec{r})r^2(3\cos^2\vartheta - 1)dV = \sqrt{\frac{16\pi}{5}}\int \rho(\vec{r})r^2 Y_{20}(\vartheta,\varphi)dV = Q_0$$



spherical $Q_z = 0$

prolate $Q_z > 0$

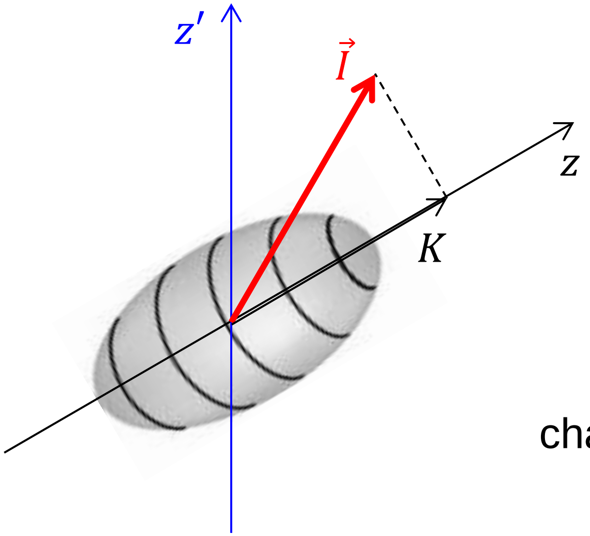
oblate $Q_z < 0$

in the same way we can define:

$$Q_2 = \sqrt{\frac{16\pi}{5}}\int \rho(\vec{r})r^2 Y_{22}(\vartheta,\varphi)dV$$

all quadrupole shapes can be described by Q_0 and Q_2

described in the body-fixed frame of reference !



axial deformation

body-fixed frame (x, y, z) with symmetry axis z

laboratory frame (x', y', z')

angular momentum $\vec{I}$

angular momentum projection K onto the symmetry axis

charge distribution in laboratory frame ⇔ body-fixed frame

the **spectroscopic quadrupole moment Q_s** observed in the laboratory frame is related to the **intrinsic quadrupole moment Q_0** via:

$$Q_s = \frac{3K^2 - I(I+1)}{(I+1)(2I+3)} Q_0$$

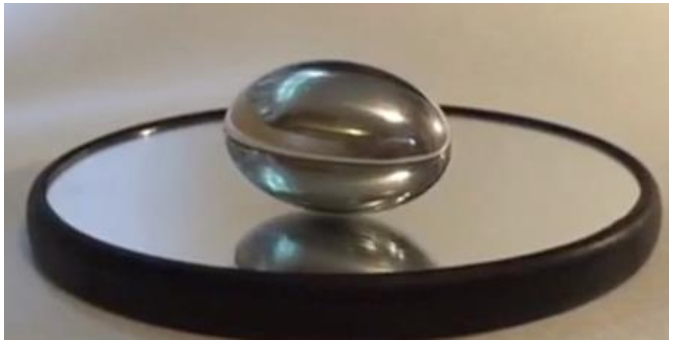
special cases:

$$I = 0 \quad \Rightarrow \quad K = 0 \quad \Rightarrow \quad Q_s = 0$$

$$I = \tfrac{1}{2} \quad \Rightarrow \quad K = \tfrac{1}{2} \quad \Rightarrow \quad Q_s = 0$$

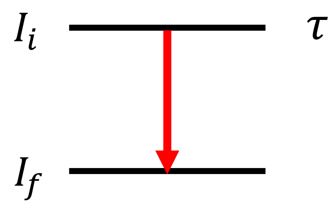
$$I = 2, K = 0 \quad \Longrightarrow \quad Q_s = -\frac{2}{7} Q_0$$

It is impossible to measure the quadrupole moment of an even-even nucleus in its ground state



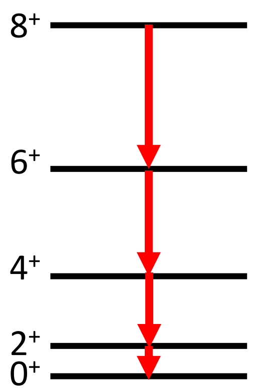
Transition probabilities

$$T_{i\to f}(\sigma\lambda\mu) = \frac{8\pi(\lambda+1)}{\lambda\hbar[(2\lambda+1)!!]^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda+1} B\left(\sigma\lambda; I_i \to I_f\right) = \frac{1}{\tau}$$



reduced transition probability: $B\left(\sigma\lambda; I_i \to I_f\right) = \frac{1}{2I_i+1}\left|\langle I_f \| \hat{O}(\sigma\lambda) \| I_i\rangle\right|^2$

for a rotational band:



$$B\left(E2; I_i \to I_f\right) = \frac{1}{2I_i+1}\left|\langle I_f \| \hat{O}(E2) \| I_i\rangle\right|^2 = \frac{5}{16\pi} Q_t^2 \langle I_i K 2 0 | I_f K\rangle^2$$

transitional quadrupole moment Q_t

- for purely rotational states: $Q_t = Q_0$
- Q_t is a good approximation of the deformation for rotational bands
- we cannot get the sign of the quadrupole moment in this way

Strategies

lifetime measurement $\Rightarrow$ transition probabilities $\Rightarrow$ model-dependent information on shape

↕

comparison with theoretical models
e.g. beyond-mean field theories

$\Rightarrow$ quantitative test of the model

↕

Coulomb excitation $\Rightarrow$ transition probabilities

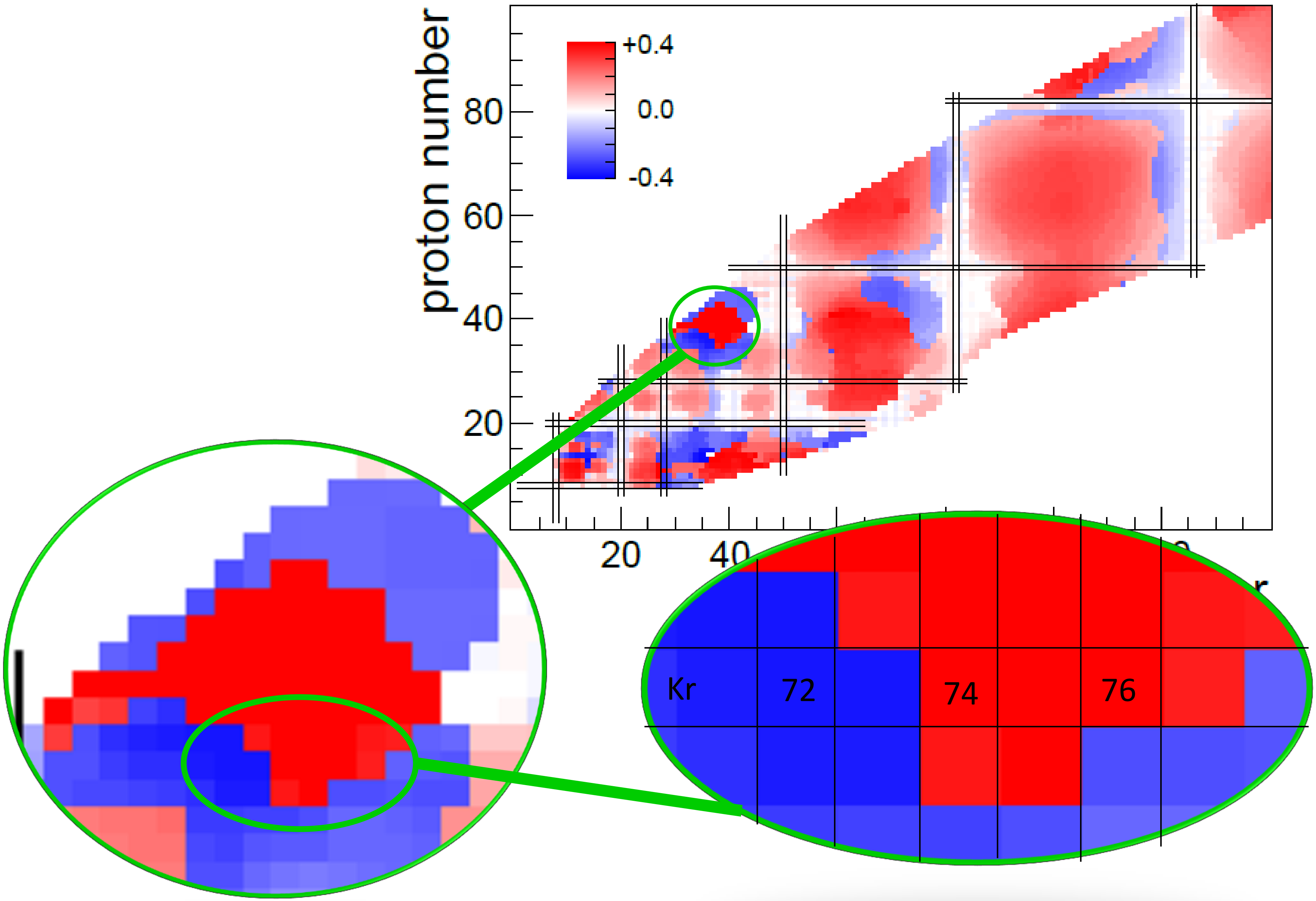
$\Rightarrow$ spectroscopic quadrupole moments

↳ model-independent information on shape

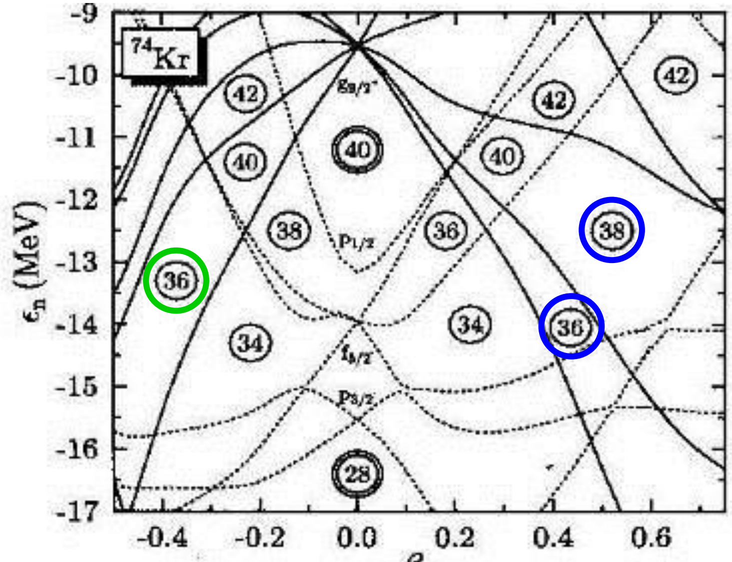
also sensitive to the sign of Q_s

Example: neutron-deficient Kr isotopes

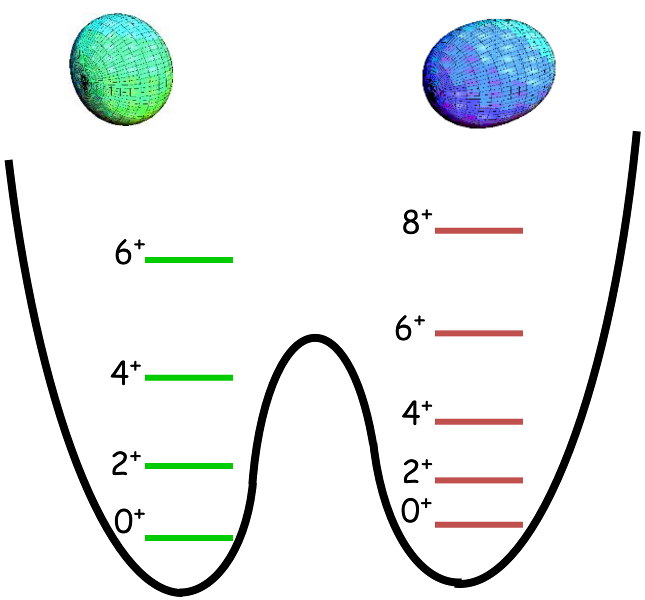
P. Möller et al., ADNDT 109, 1 (2016)



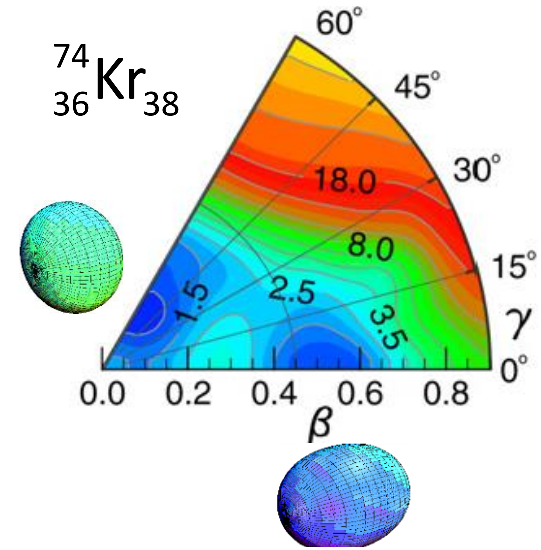
Shape coexistence in light Kr isotopes

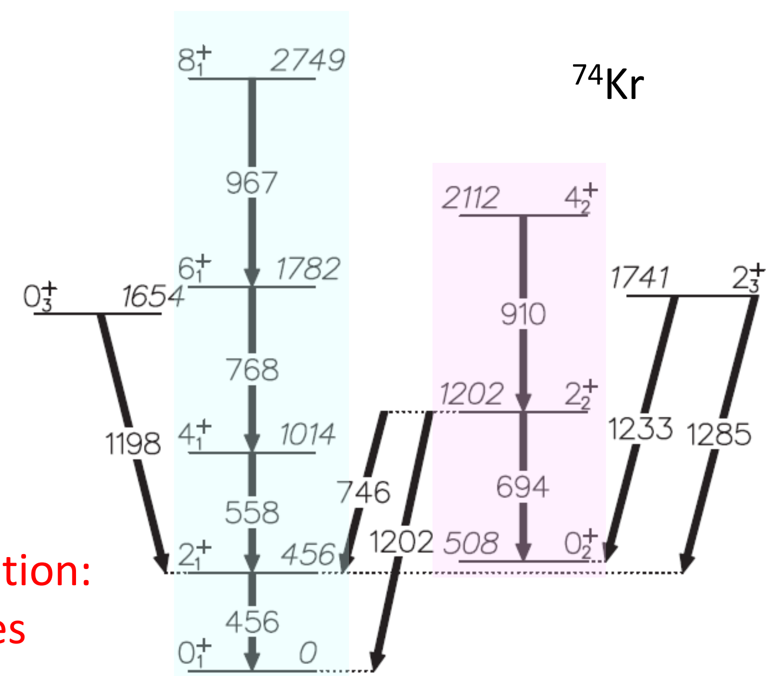


oblate prolate



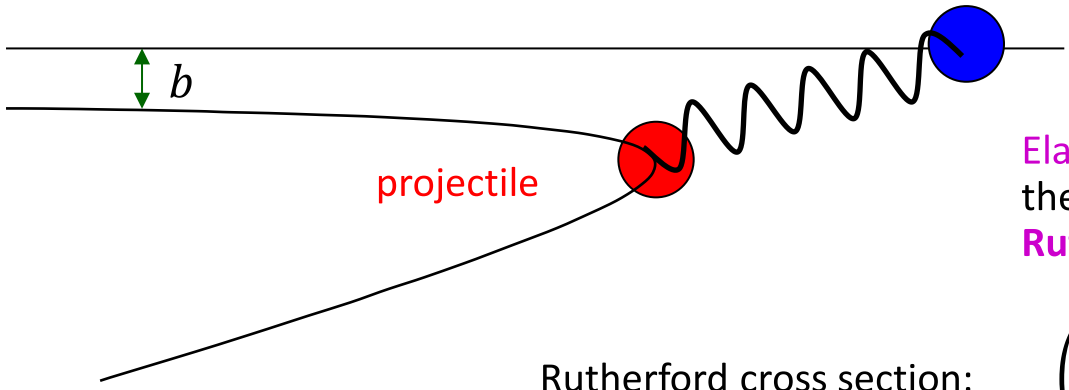
potential energy surface
mean-field calculation
Gogny D1S interaction





Coulomb excitation:
- $B(E2)$ values
- Q_s

Coulomb excitation



Elastic scattering of charged particles under the influence of the Coulomb field:
Rutherford scattering

Rutherford cross section: $$\left(\frac{d\sigma}{d\Omega}\right)_{el} = \left(\frac{a_0}{2}\right)^2 \sin^{-4}\left(\frac{\theta_{cm}}{2}\right)$$

with $2a_0$ the distance of closest approach for head-on collisions

Nuclear excitation by the electromagnetic interaction acting between two colliding nuclei:
Coulomb excitation

excitation of both target and projectile possible
often magic nucleus (e.g. ^{208}Pb) as
- projectile $\Rightarrow$ target Coulomb excitation
- target $\Rightarrow$ projectile Coulomb excitation
  important technique for radioactive beams

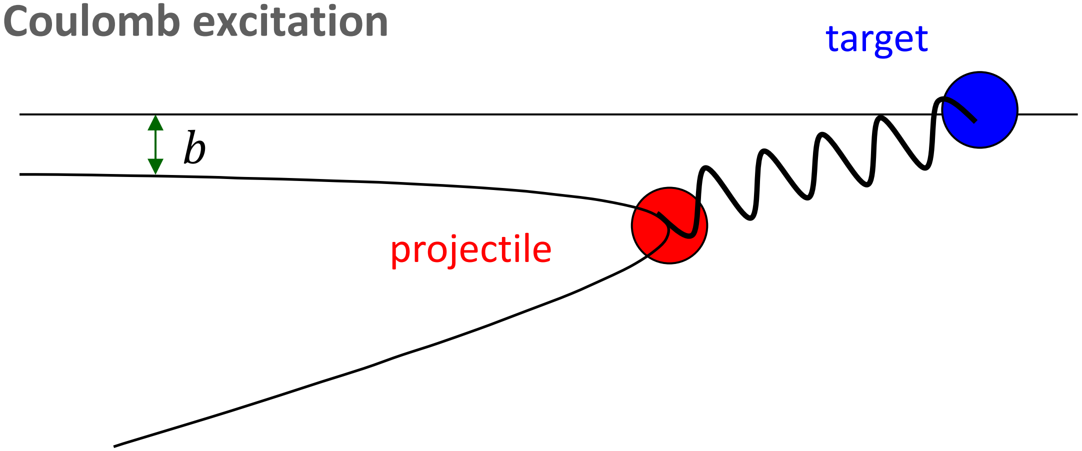
“safe” Coulomb excitation at low energy: purely electromagnetic process

safe condition: distance of closest approach $2a_0 > 1.25\left(A_p^{1/3} + A_t^{1/3}\right) + 5\ \mathrm{fm}$

$\Rightarrow$ choose beam energy and scattering angle (i.e. impact parameter) accordingly

$\Rightarrow$ purely electromagnetic process, can be calculated with high precision

Coulomb excitation



Coulomb excitation cross section:

$$\left(\frac{d\sigma}{d\Omega}\right)_{CE} = \left(\frac{d\sigma}{d\Omega}\right)_{el} P_{i\to f}$$

with excitation probability $P_{i\to f}$

first-order perturbation $\Rightarrow$ excitation amplitude $$b_{i\to f} = \frac{1}{i\hbar}\int_{-\infty}^{\infty} \exp\left(\frac{i}{\hbar}(E_f - E_i)t\right)\langle f|V(\vec{r}(t))|i\rangle dt$$

excitation probability: $$P_{i\to f} = \frac{1}{2I_i + 1}\left|b_{i\to f}\right|^2$$

multipole expansion of $V(\vec{r}(t))$: $$\sigma_{E\lambda} = \left(\frac{Z_t e}{\hbar v}\right)^2 a_0^{-2\lambda+2} B(E\lambda) f_{E\lambda}(\xi)$$

$$\sigma_{M\lambda} = \left(\frac{Z_t e}{\hbar c}\right)^2 a_0^{-2\lambda+2} B(M\lambda) f_{M\lambda}(\xi)$$

magnetic excitations suppressed by $(v/c)^2$

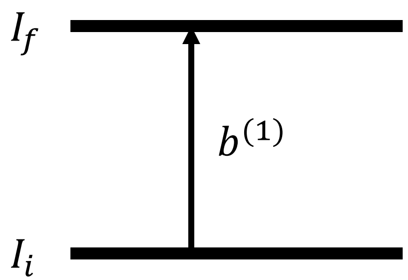
with Coulomb excitation function $f_{E\lambda}(\xi)$
and adiabacity parameter ξ

K. Alder and A.Winther, *Electromagnetic Excitation, Theory of Coulomb Excitation with Heavy Ions* (1975)

to first order: $\boldsymbol{\sigma_{\pi\lambda} \propto B\left(\pi\lambda; I_i \to I_f\right) \propto \left|\langle I_f | M(\sigma\lambda) | I_i\rangle\right|^2}$

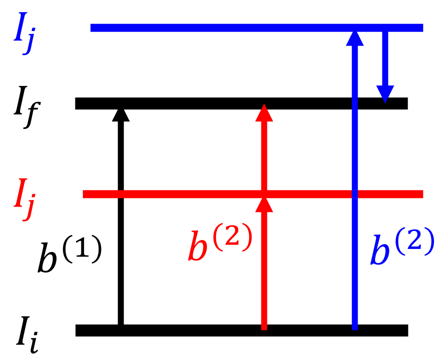
Second-order effects

$$P_{i\to f} = \frac{1}{2I_i+1}\left|b^{(1)}_{i\to f}\right|^2$$



1st order:

$$b^{(1)}_{i\to f} \propto \langle I_f|M(\sigma\lambda)|I_i\rangle$$



2nd order:

$$b^{(2)}_{i\to f} \propto \sum_j \langle I_f|M(\sigma\lambda)|I_j\rangle\langle I_j|M(\sigma\lambda)|I_i\rangle$$

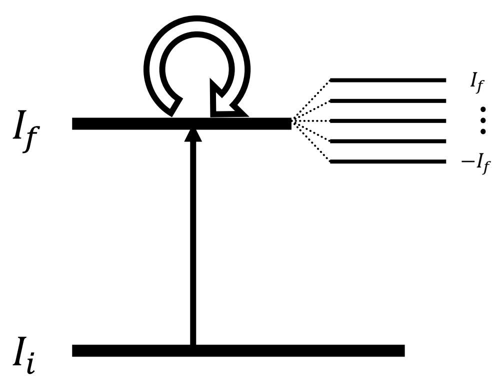
$$P_{i\to f} = \frac{1}{2I_i+1}\left|b^{(1)}_{i\to f} + b^{(2)}_{i\to f}\right|^2$$

$\Rightarrow$ interference terms

special case:
intermediate state
another magnetic substate

"reorientation effect"

$$b^{(2)}_{i\to f} \propto \langle I_f|M(\sigma\lambda)|I_f\rangle\langle I_f|M(\sigma\lambda)|I_i\rangle$$

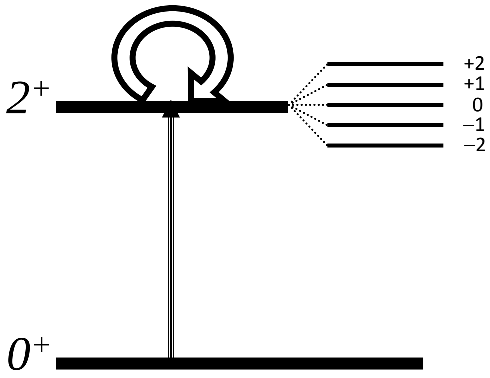


$P_{i\to f}$ depends on:

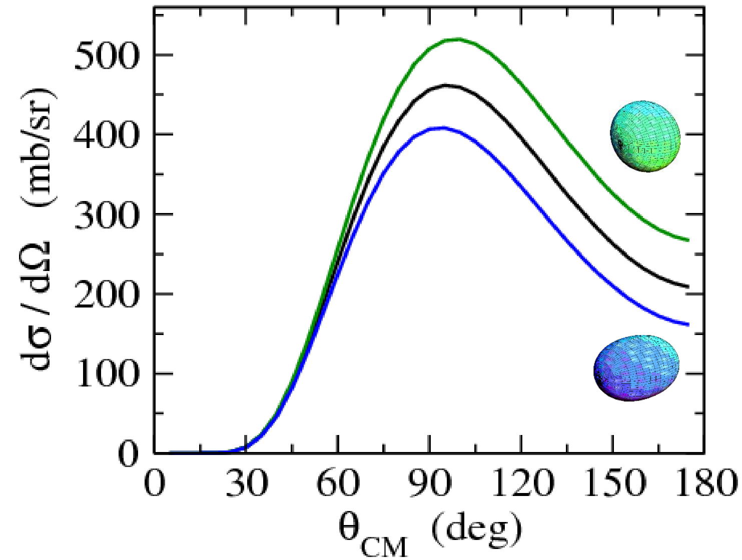
- transitional matrix element
  $B(\sigma\lambda; I_i \to I_f) = \left|\langle I_f|M(\sigma\lambda)|I_i\rangle\right|^2$
- diagonal matrix element
  $\langle I_f|M(\sigma\lambda)|I_f\rangle \propto Q_s(I_f)$

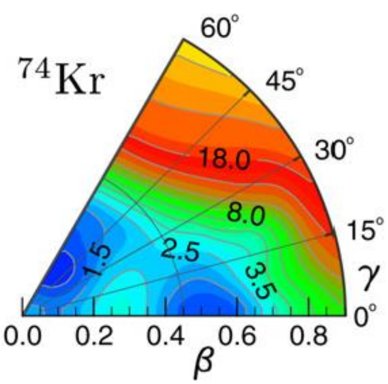
Coulomb excitation sensitive
to spectroscopic quadrupole moments

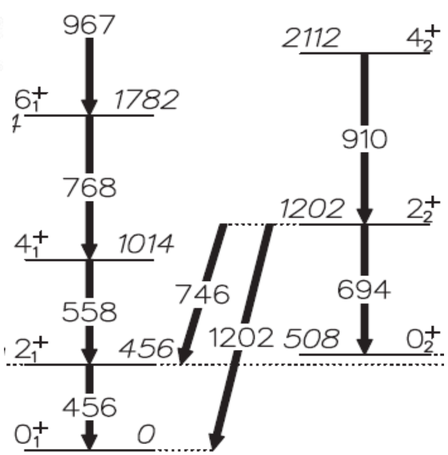
Reorientation effect



$$b^{(2)}_{0^+\to 2^+} \propto \langle 2^+|M(E2)|2^+\rangle\langle 2^+|M(E2)|0^+\rangle$$







to extract *B(E2)* and Q_s

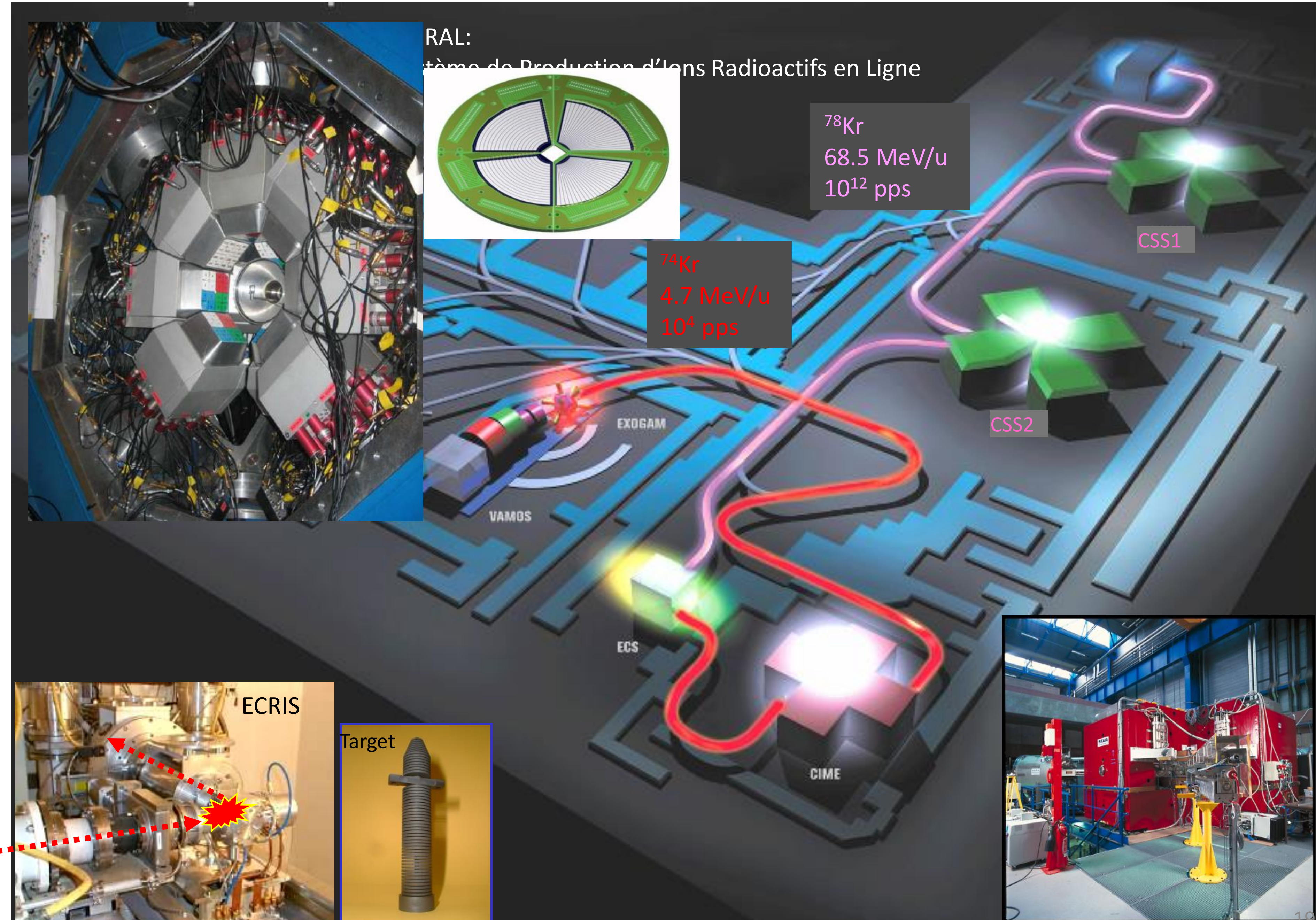
- ➢ differential measurement of cross section (as a function of scattering angle)
- ➢ large θ_{cm} most sensitive

Idea: measure $Q_s(2^+_1)$ and $Q_s(2^+_2)$

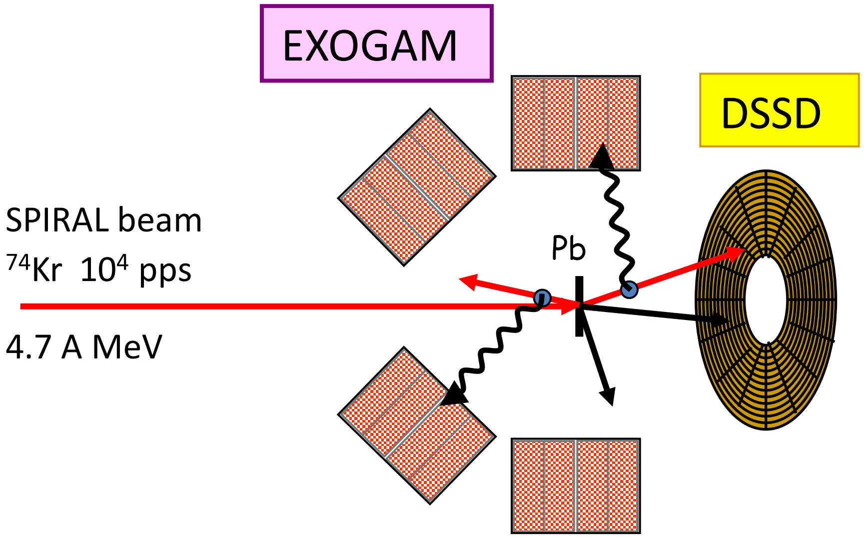
(remember: $Q_s(0^+) = 0$)

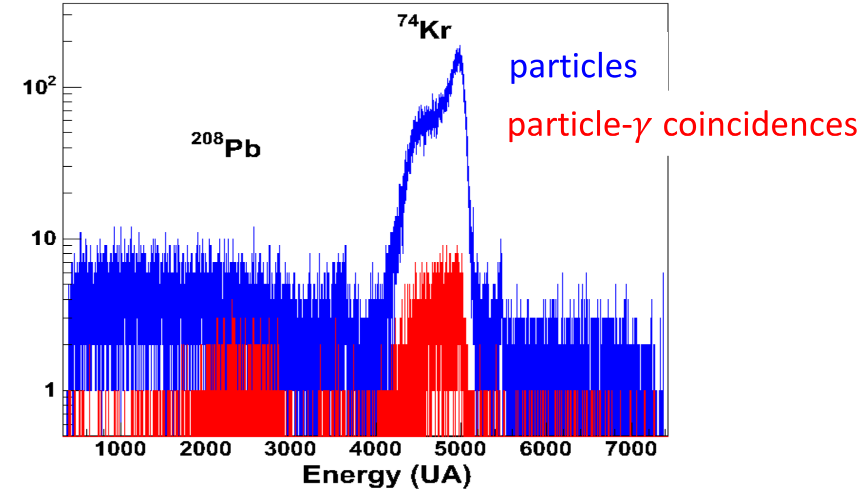
Problem: ^{74}Kr is radioactive ($T_{1/2}$=11.5 min)
➢ radioactive beam

GANIL – SPIRAL: Isotope separation on-line (ISOL)

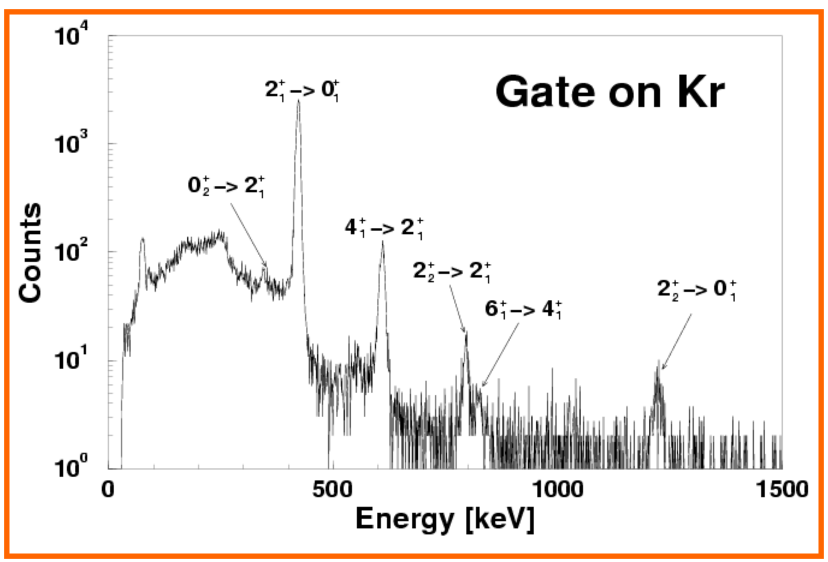


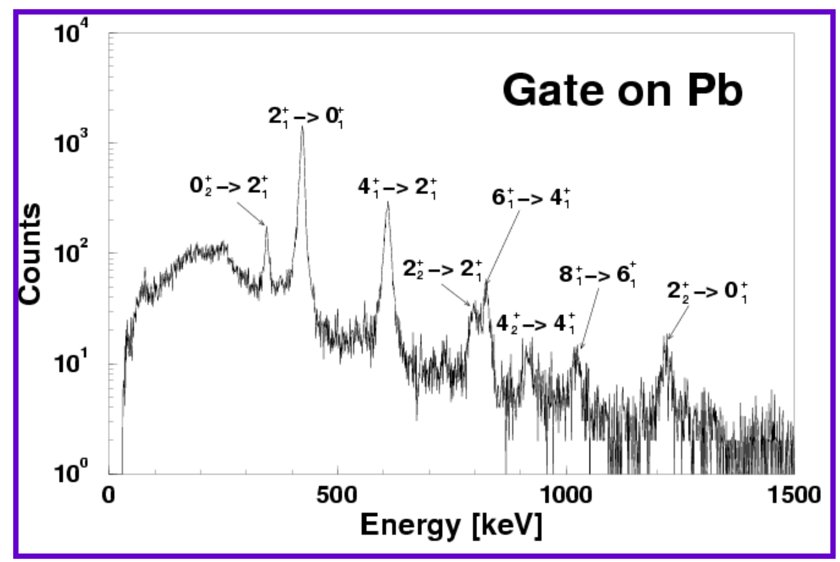
Coulomb excitation of ^{74}Kr





Differential Coulomb excitation cross section for $35° < \theta_{cm} < 130°$

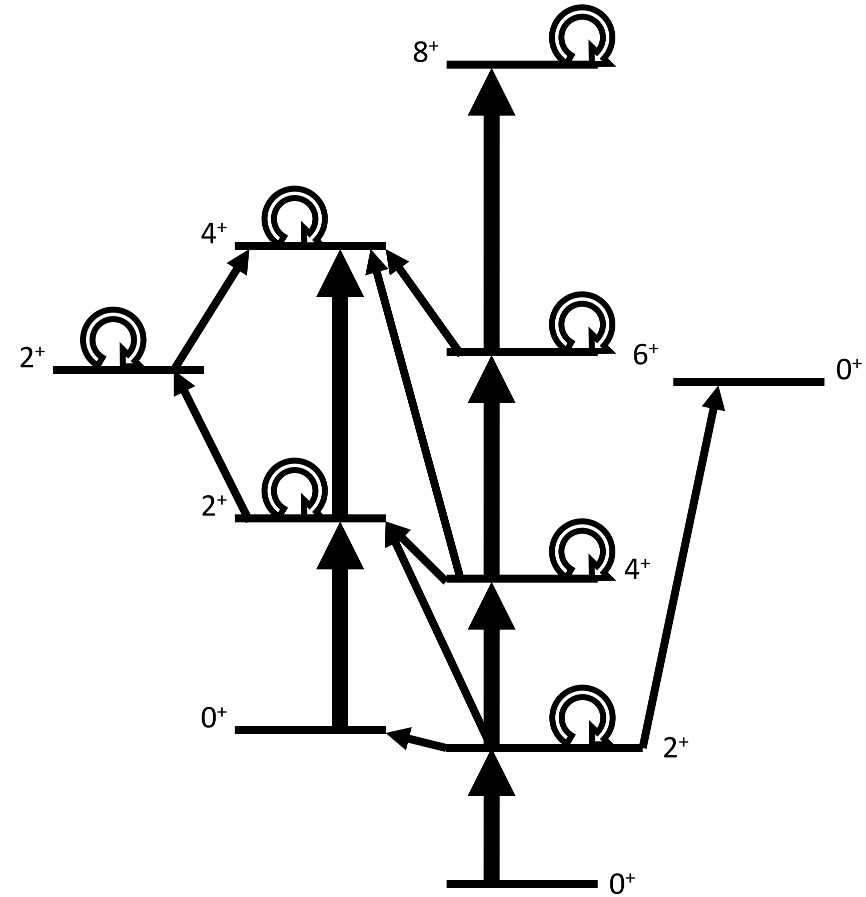


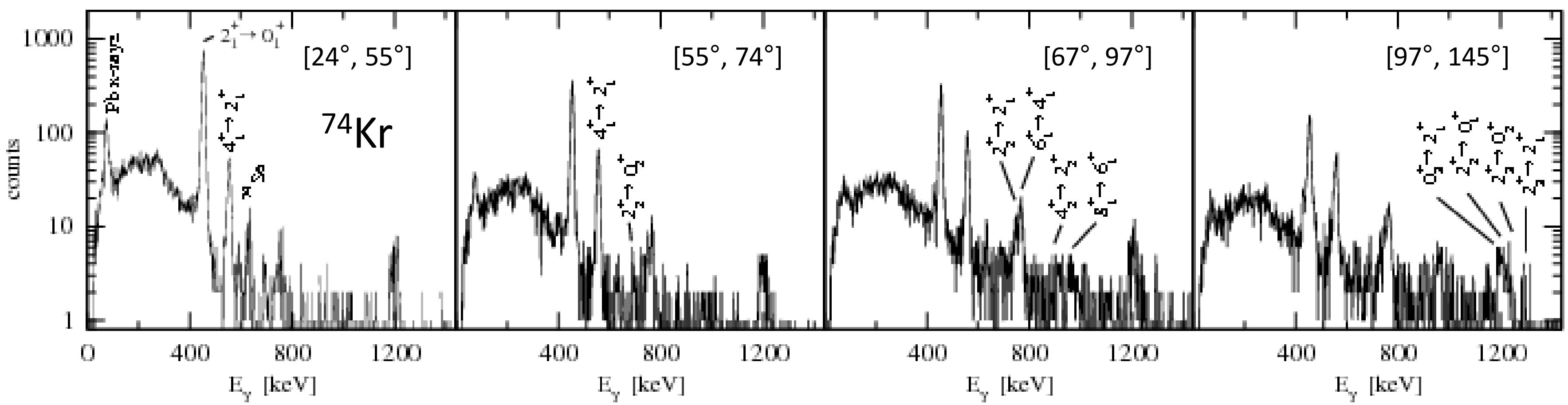


Multi-step Coulomb excitation of ^{74}Kr

- γ yields as function of scattering angle: differential cross section
- least squares fit of ~ 30 matrix elements (transitional and diagonal)
- experimental spectroscopic data
  - lifetimes, branching and mixing ratios

GOSIA: Coulomb excitation and least-squares fitting code





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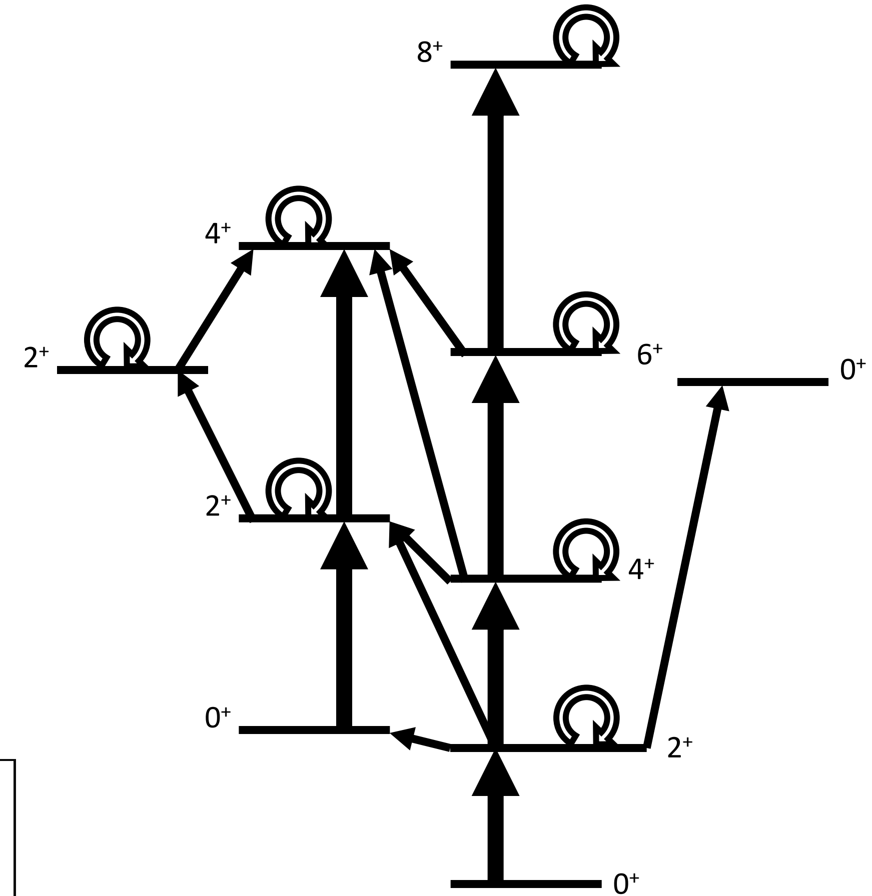
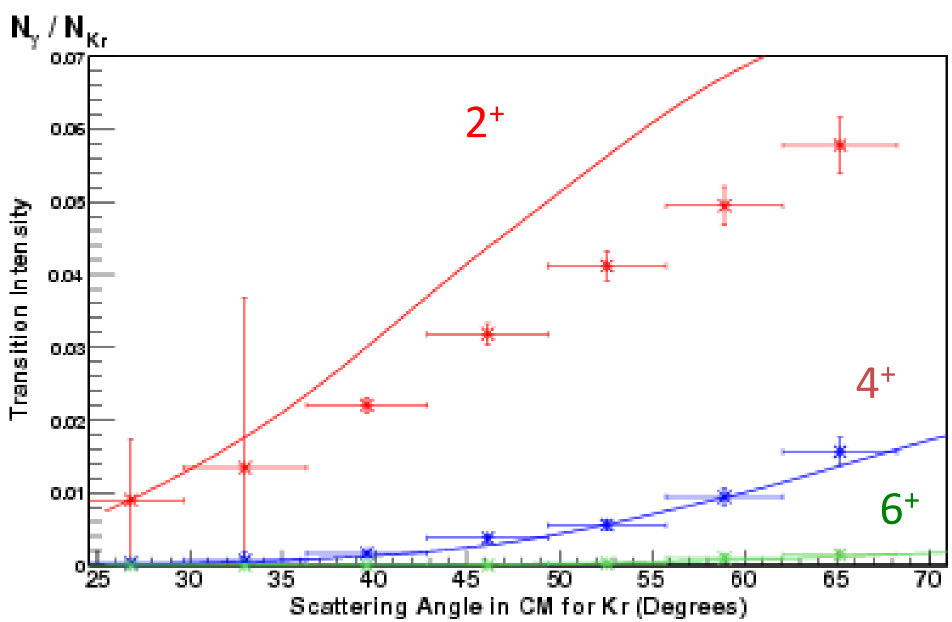
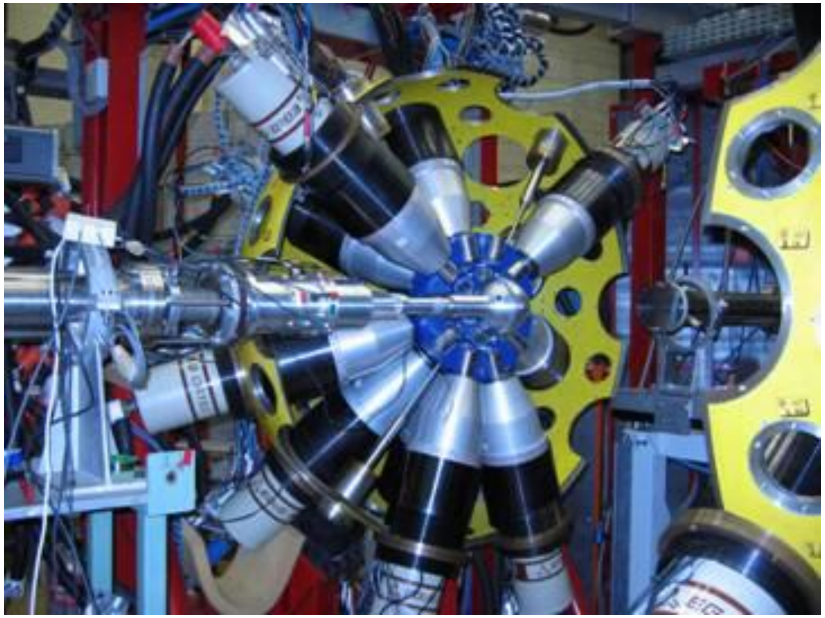
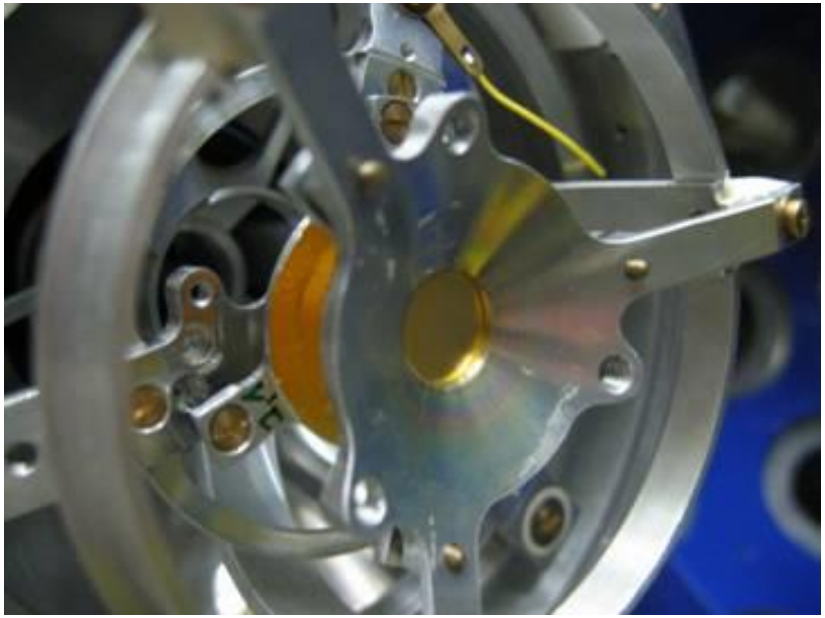




- Results inconsistent with published lifetimes

Lifetime measurement with GASP and the Köln Plunger

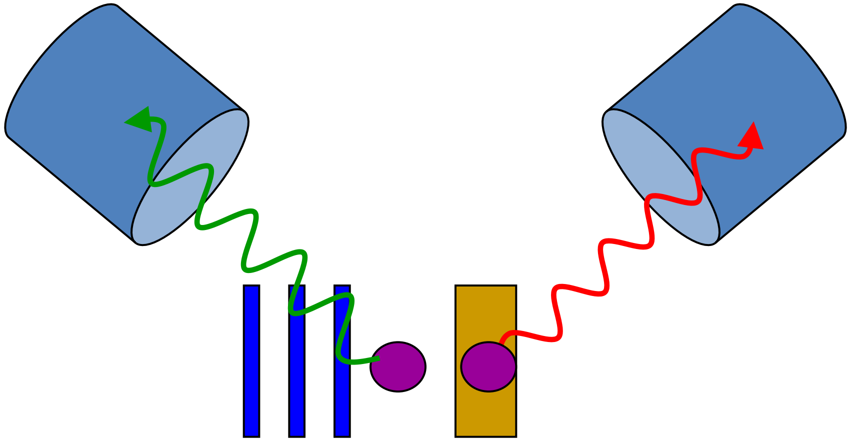


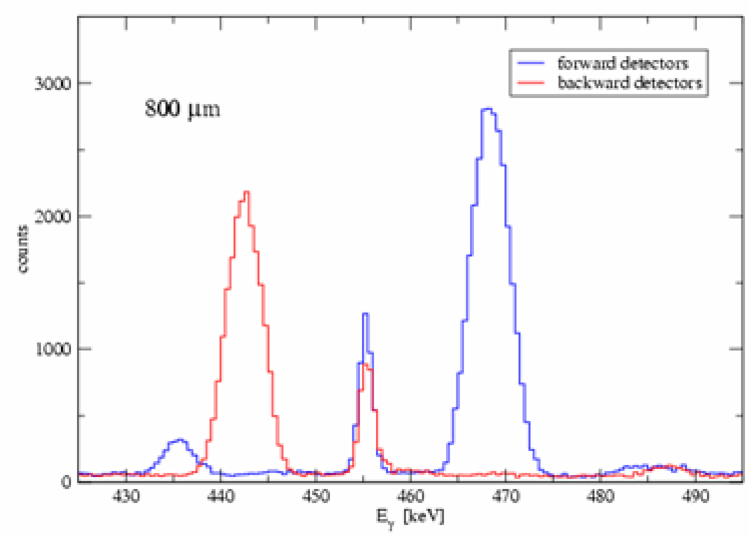


$^{40}Ca(^{40}Ca,a2p)^{74}Kr$

$^{40}Ca(^{40}Ca,4p)^{76}Kr$

124 MeV





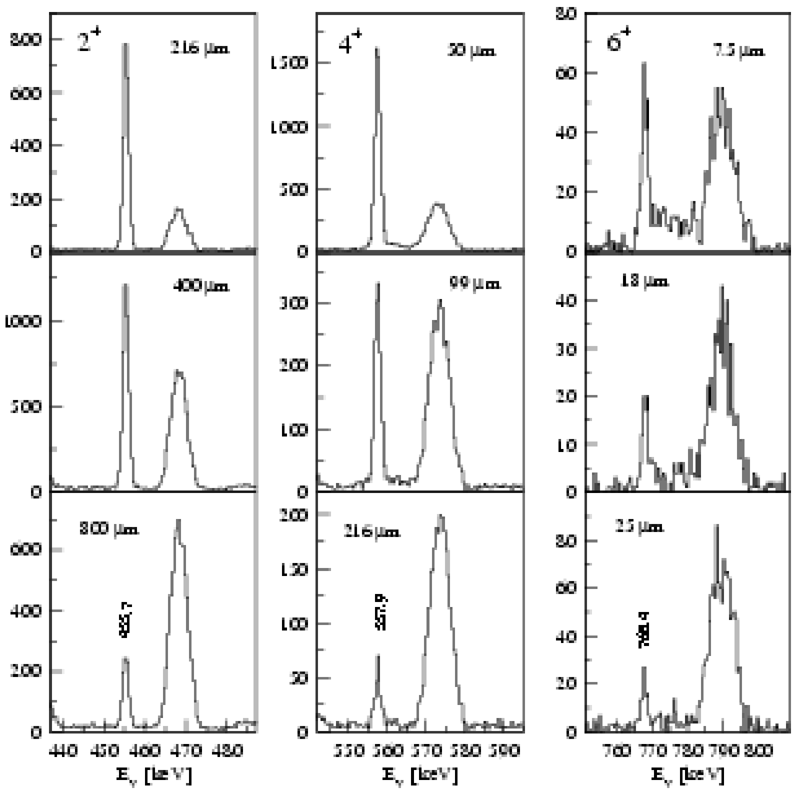
Lifetime results

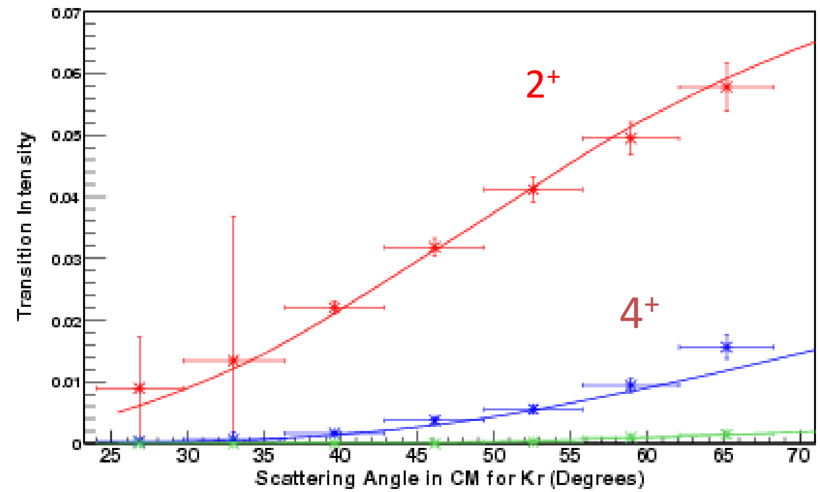
A. Görgen, Eur. Phys. J. A 26, 153 (2005)

^{74}Kr	2^+	4^+	^{76}Kr	2^+	4^+	
new	33.8(6)	5.2(2)	new	41.5(8)	3.67(9)	[ps]
	28.8(57)	13.2(7)		35.3(10)	4.8(5)	[ps]
	J. Roth et al., J.Phys.G, L25 (1984)			B. Wörmann et al., NPA 431, 170 (1984)		

^{74}Kr

- forward detectors (36˚)
- gated from above





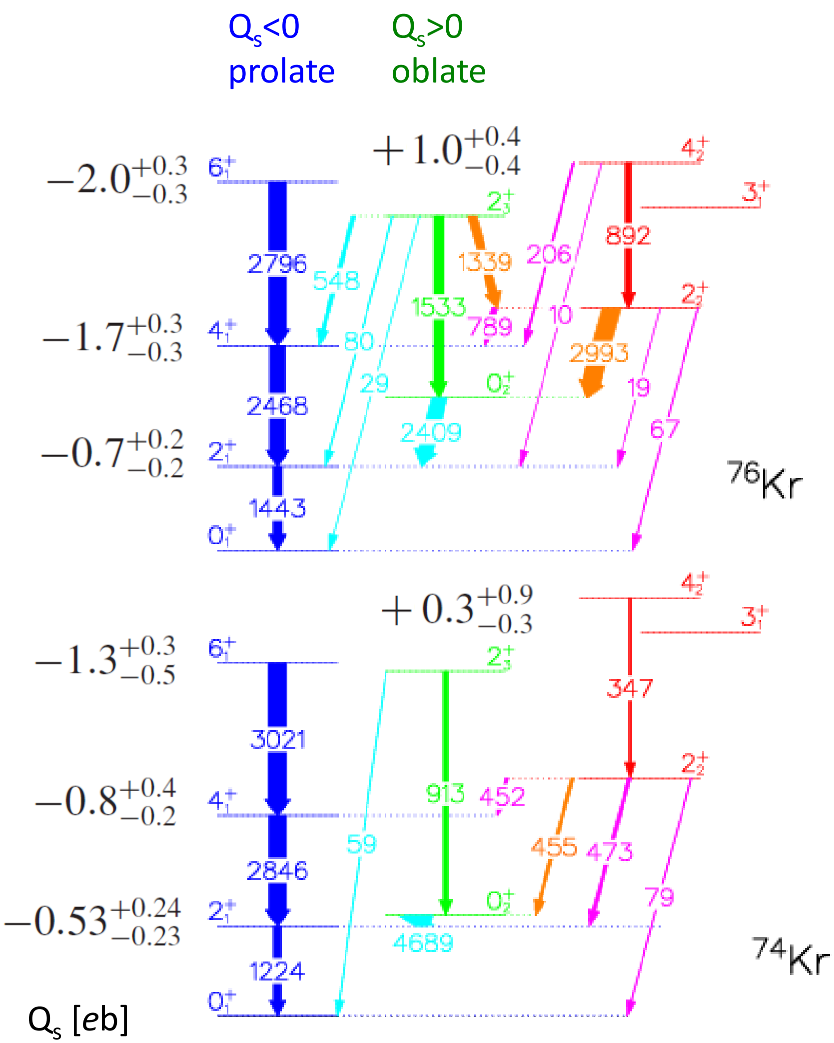
Results consistent with Coulomb excitation.

Lifetimes constrain GOSIA fit.

⇒ enhanced sensitivity for non-yrast transitions and diagonal matrix elements

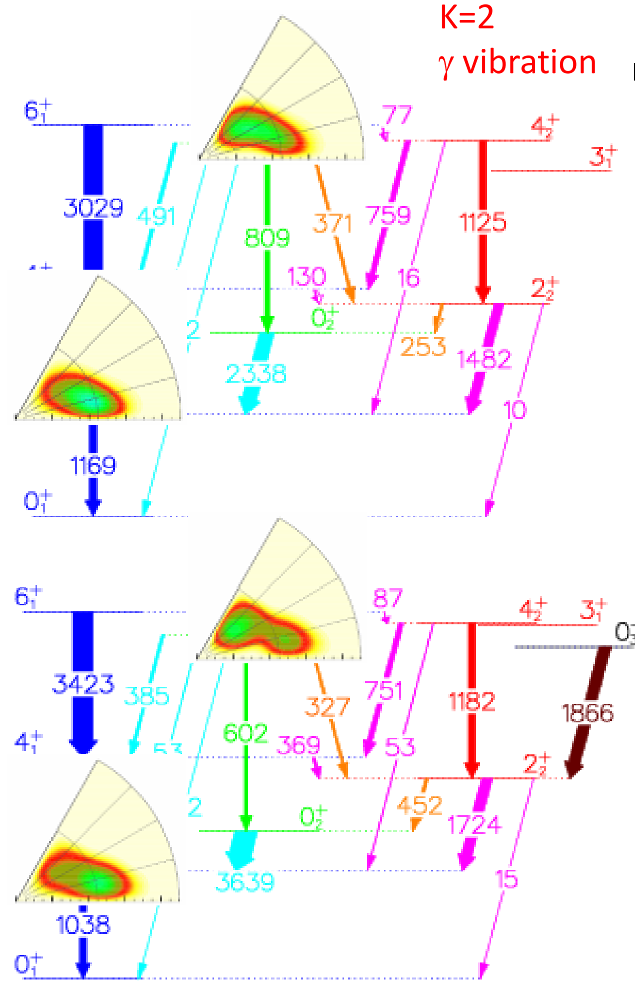
Prolate – oblate shape coexistence

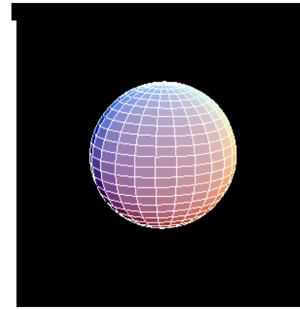
- no free parameters in the calculation (except for the globally derived D1S interaction)



experimental B(E2;↓) [e^2fm^4]

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





GCM (GOA) calculation with Gogny D1S
q_0, q_2: triaxial deformation

M. Girod et al.,
Phys. Lett. B 676, 39 (2009)

Quadrupole sum rules

We measure $B(E2)$ and Q_s values in the laboratory frame.

How can we determine the **intrinsic shape**?

$$\mathcal{M}(E2,\mu=0) = Q\cos\delta$$
$$\mathcal{M}(E2,\mu=\pm1) = 0$$
$$\mathcal{M}(E2,\mu=\pm2) = \tfrac{1}{\sqrt{2}}Q\sin\delta$$

rotate electric quadrupole tensor into principal axis frame
$\Rightarrow$ only two non-zero quadrupole moments
$\Rightarrow$ two parameters (Q,δ) in analogy with Bohr's parameters (β,γ)

Zero-coupled products of the E2 operators are rotationally invariant (the same in the lab and intrinsic frames):

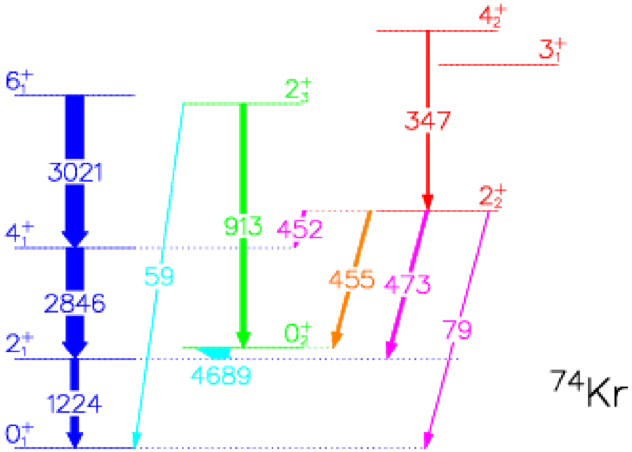
$$\langle s|[E2\times E2]_0|s\rangle = \frac{1}{\sqrt{5}}Q^2 = \frac{(-1)^{2s}}{\sqrt{2s+1}}\sum_t \langle s||E2||t\rangle\langle t||E2||s\rangle \begin{Bmatrix} 2 & 2 & 0 \\ s & s & t \end{Bmatrix}$$

$$\langle s|[[E2\times E2]_2\times E2]_0|s\rangle = -\sqrt{\frac{2}{35}}Q^3\cos(3\delta) = \frac{1}{2s+1}\sum_{tu} \langle s||E2||t\rangle\langle t||E2||u\rangle\langle u||E2||s\rangle \begin{Bmatrix} 2 & 2 & 2 \\ s & t & u \end{Bmatrix}$$

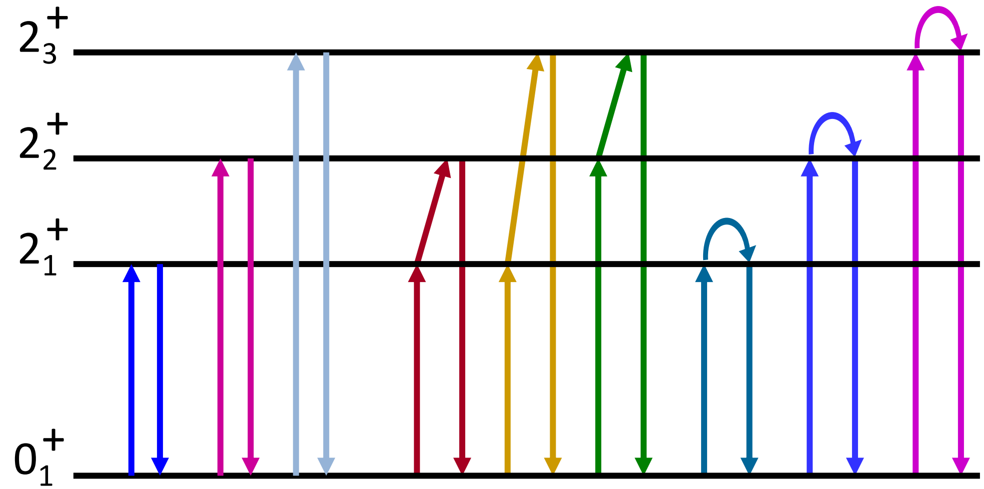
D. Cline, Ann. Rev. Nucl. Part. Sci. 36, 683 (1986)

Model-independent method to determine the intrinsic quadrupole shape of the charge distribution from a set of E2 matrix elements

Example for ^{74}Kr, ^{76}Kr



experimental B(E2;↓) [e^2fm^4]



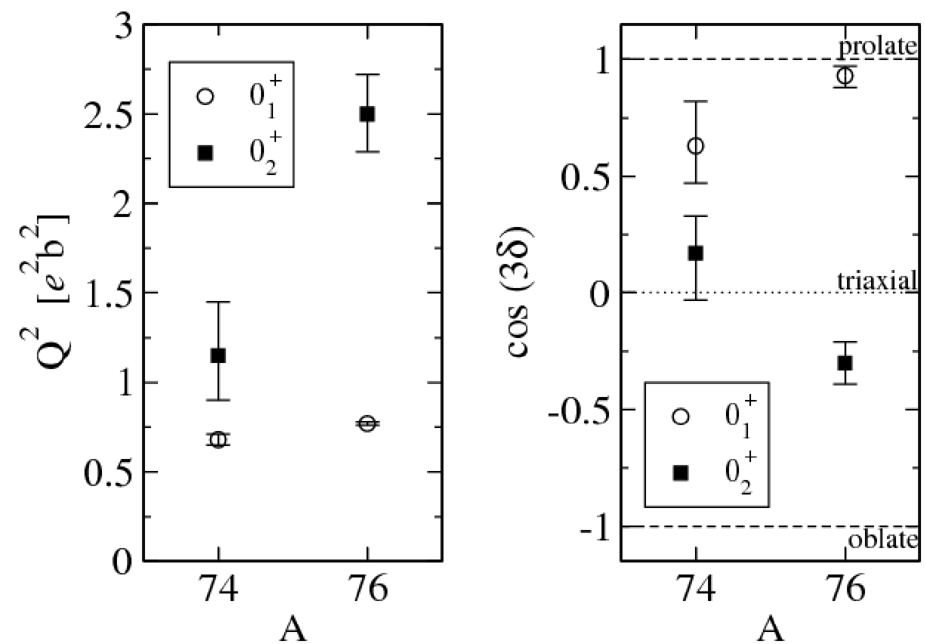
$$\sum_t \langle s||E2||t\rangle \langle t||E2||s\rangle \left\{ \begin{array}{ccc} 2 & 2 & 0 \\ s & s & t \end{array} \right\}$$

$$\sum_{tu} \langle s||E2||t\rangle \langle t||E2||u\rangle \langle u||E2||s\rangle \left\{ \begin{array}{ccc} 2 & 2 & 2 \\ s & t & u \end{array} \right\}$$

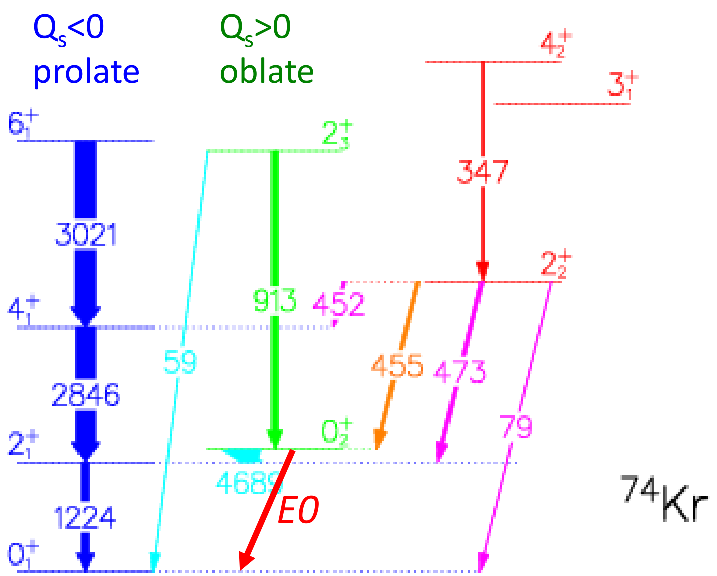
needs complete set of matrix elements

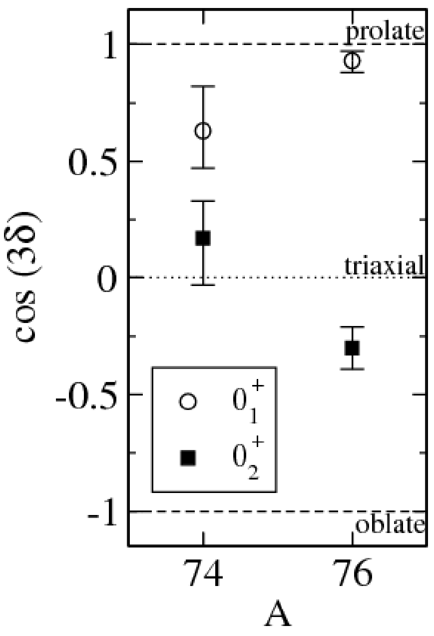
⇒ usually only feasible for 0^+ states

more mixing in ^{74}Kr ?



Prolate – oblate shape coexistence





- evidence for shape coexistence
- indication of mixing
- electric monopole transition?

⇒ conversion electron spectroscopy

electric monopole (E0) transitions

- between states of the same spin and parity, in particular $0^+ \rightarrow 0^+$
- non-radiative: only internal conversion or internal pair creation (E >1.022 MeV) possible
- related to changes in the rms radius of the charge distribution

E0 transition rate:

$$\frac{1}{\tau(E0)} = \rho^2(E0; i \rightarrow f)\left(\Omega_K + \Omega_{L_1} + \cdots + \Omega_{IP}\right)$$

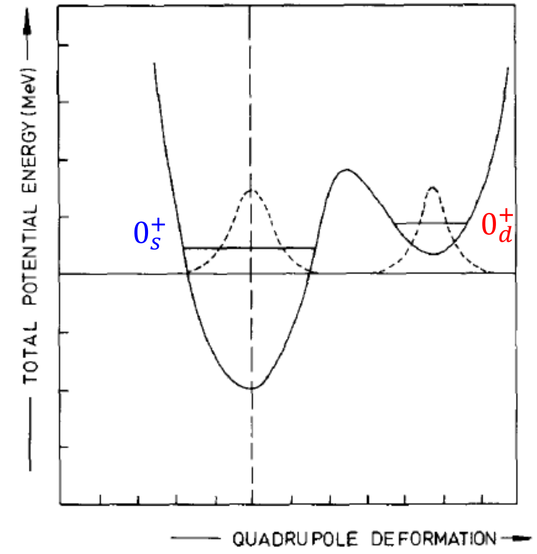
with electronic factors Ω http://bricc.anu.edu.au/index.php

and the E0 matrix element

$$\rho(E0; i \rightarrow f) = \frac{\left|\left\langle f\left|\hat{T}(E0)\right|i\right\rangle\right|}{eR^2} = \frac{\left|\langle f|\sum_k e_k r_k{}^2\,|i\rangle\right|}{eR^2}$$

with $R = r_0 A^{1/3}$ and sum over all protons
or valence nucleons with effective charge e_k

shape coexistence and E0 transitions



two 0^+ states with different intrinsic deformation: $|0_s^+\rangle$, $|0_d^+\rangle$

mixing of the two configurations gives two eigenstates:

$$|0_2^+\rangle = a|0_s^+\rangle + b|0_d^+\rangle$$

$$|0_1^+\rangle = -b|0_s^+\rangle + a|0_d^+\rangle$$

$$\rho(E0; 0_2^+ \to 0_1^+) = \frac{1}{eR^2}\left[ab\left(\langle 0_d^+|\hat{T}(E0)|0_d^+\rangle - \langle 0_s^+|\hat{T}(E0)|0_s^+\rangle\right) + (a^2 - b^2)\langle 0_s^+|\hat{T}(E0)|0_d^+\rangle\right]$$

the wave functions $|0_s^+\rangle$ and $|0_d^+\rangle$ have different deformation $\Rightarrow \langle 0_s^+|\hat{T}(E0)|0_d^+\rangle \approx 0$

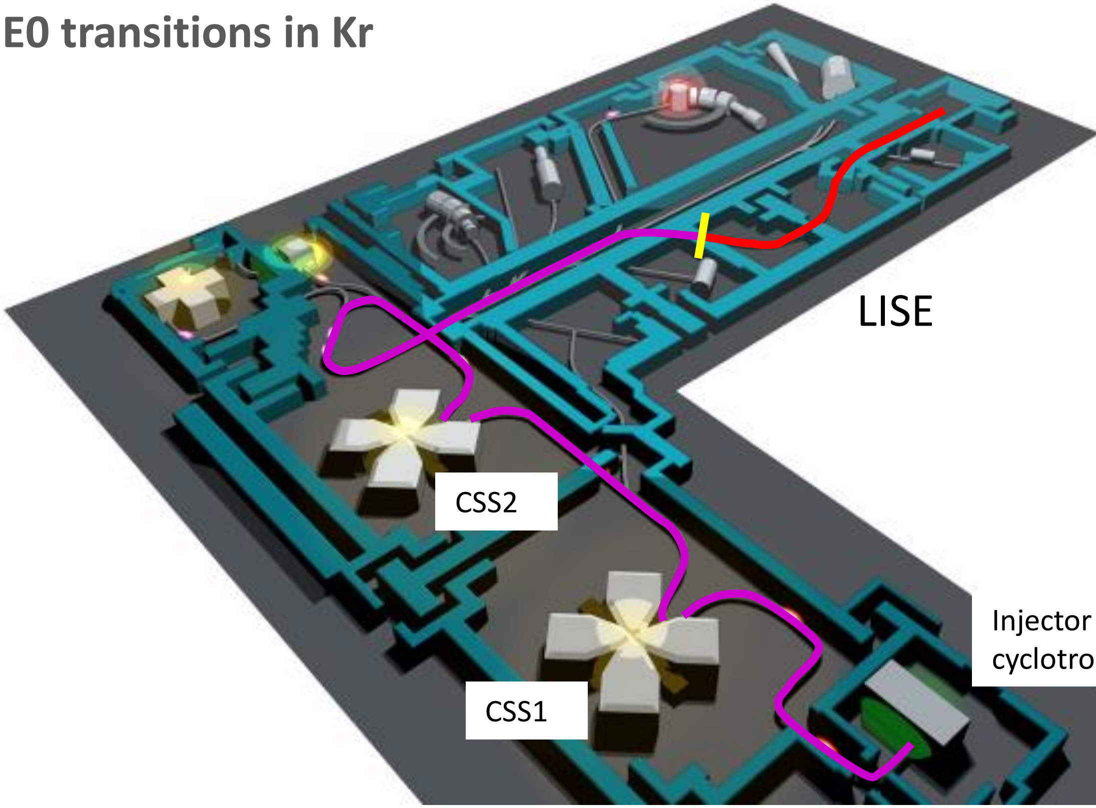
no mixing: $a = 1, b = 0 \Rightarrow ab = 0 \quad \Rightarrow \rho(E0; 0_2^+ \to 0_1^+) \approx 0$ no E0 transition

mixing: $$\rho(E0; 0_2^+ \to 0_1^+) = \frac{1}{eR^2}\left[ab\left(\langle 0_d^+|\hat{T}(E0)|0_d^+\rangle - \langle 0_s^+|\hat{T}(E0)|0_s^+\rangle\right)\right]$$

$$\rho^2(E0) = \left(\frac{3Z}{4\pi}\right)^2 a^2 b^2 \left({\beta_2}^2 - {\beta_1}^2\right)^2$$

E0 transition requires mixing and change in deformation

E0 transitions in Kr



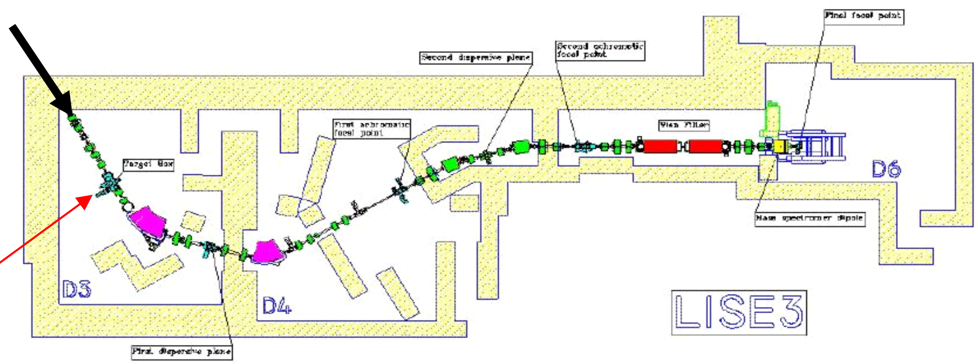
dipole magnets: $B\rho = \frac{mv}{q}$

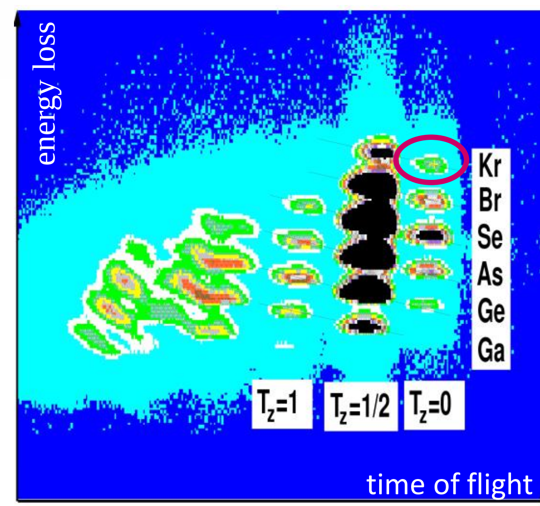
degrader: Z-dependent energy loss

Wien filter: $\vec{E} \perp \vec{B} \;\Rightarrow\; qE = qvB$

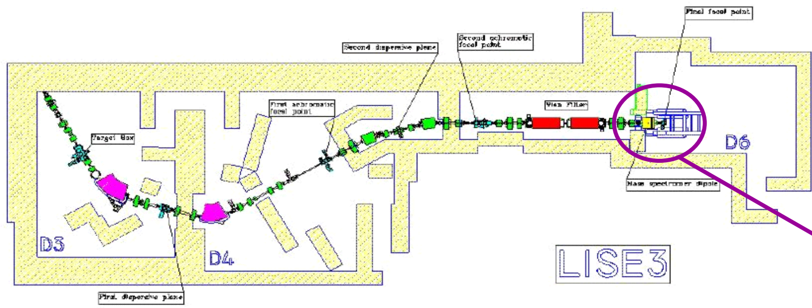
^{78}Kr
70 MeV/u
~10^{12} pps

^{9}Be target

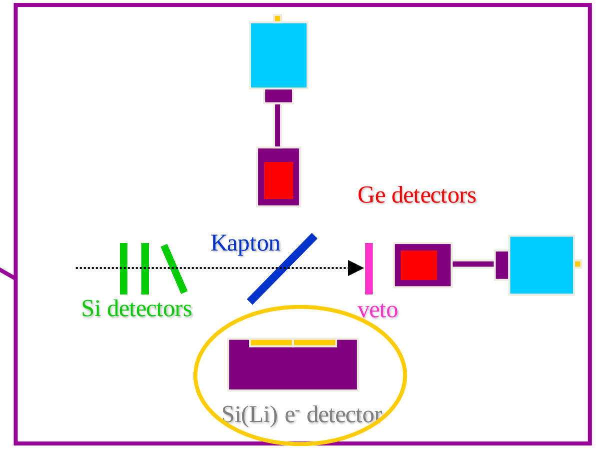


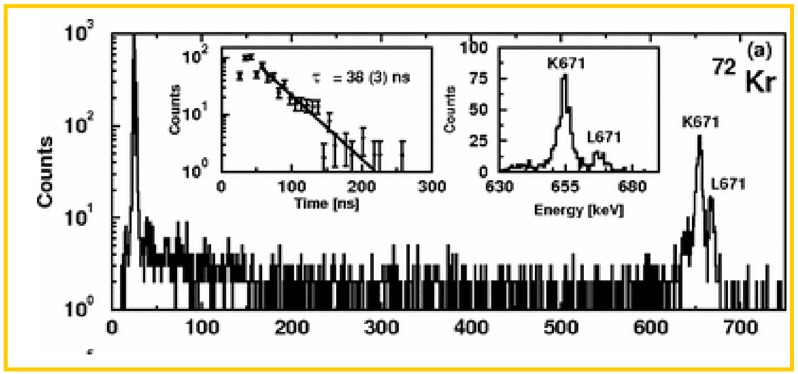


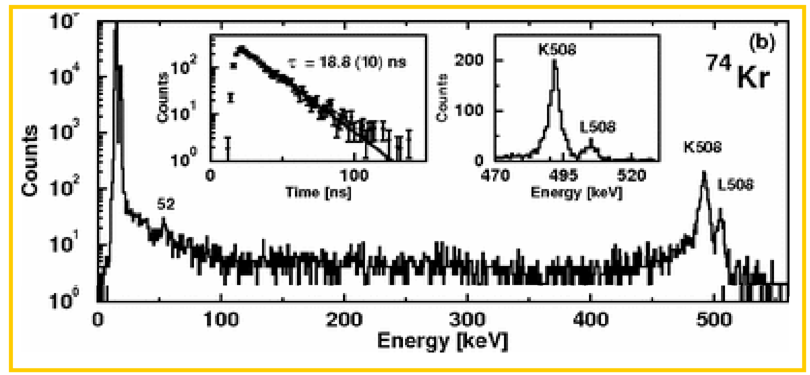
^{72}Kr : ~2 ions/sec

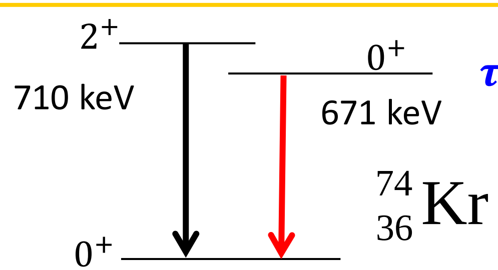


E. Bouchez et al.,
PRL 90, 082502 (2003)

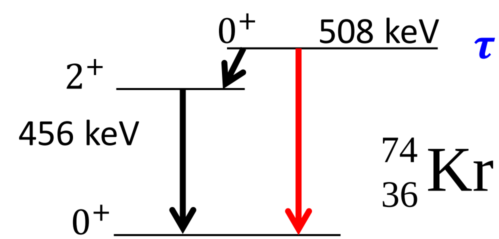








$\tau = 38(3)$ ns



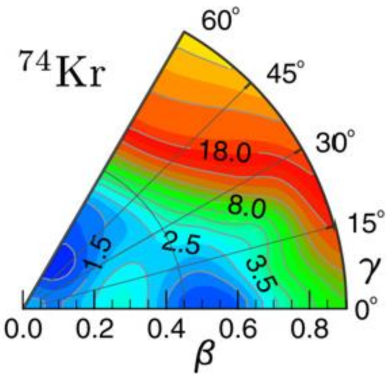
$\tau = 18.8(10)$ ns

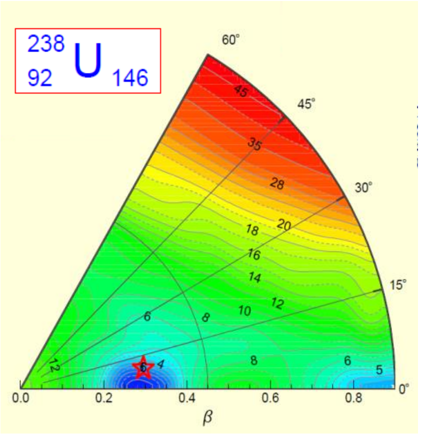
$\rho(E0; 0_2^+ \rightarrow 0_1^+) = 72(6) \cdot 10^{-3}$

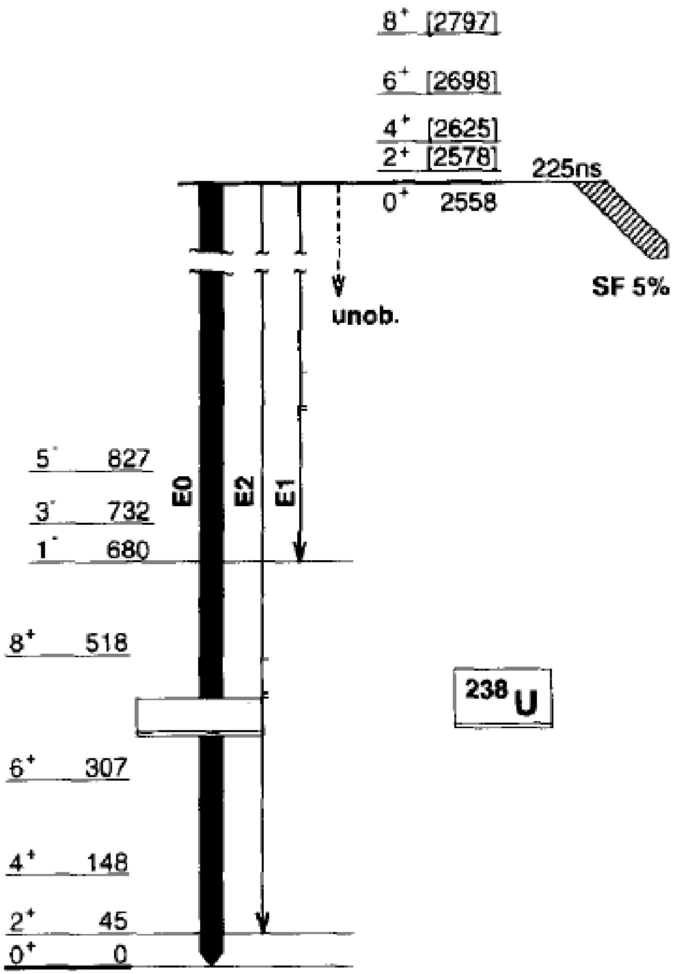
$\rho(E0; 0_2^+ \rightarrow 0_1^+) = 85(19) \cdot 10^{-3}$

E0 transitions ⇒ shape coexistence

⇒ shape isomers





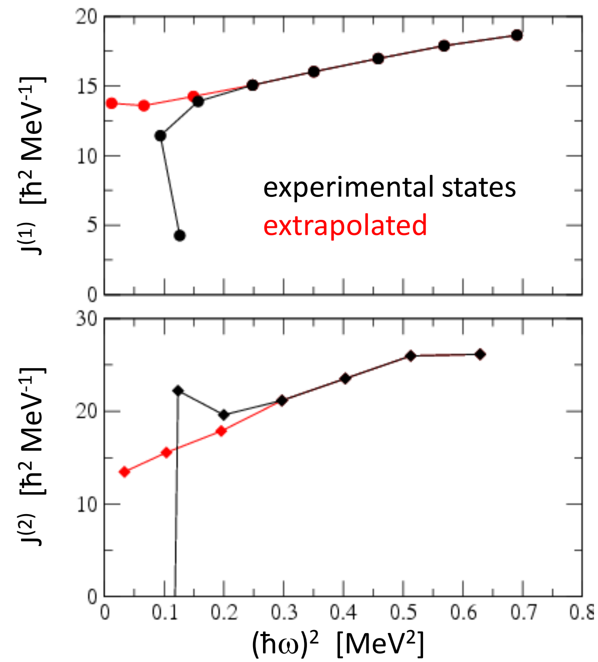


For ^{74}Kr it is: $\rho^2(E0; 0_2^+ \to 0_1^+) = 85 \cdot 10^{-3}$.
What E0 strength do you expect for the superdeformed fission isomer at 2.558 MeV in ^{238}U ?

1. much smaller: $1.7 \cdot 10^{-6}$
2. about the same: $85 \cdot 10^{-3}$
3. much larger: 3.8

large difference in deformation
but: very little mixing

Two-level mixing

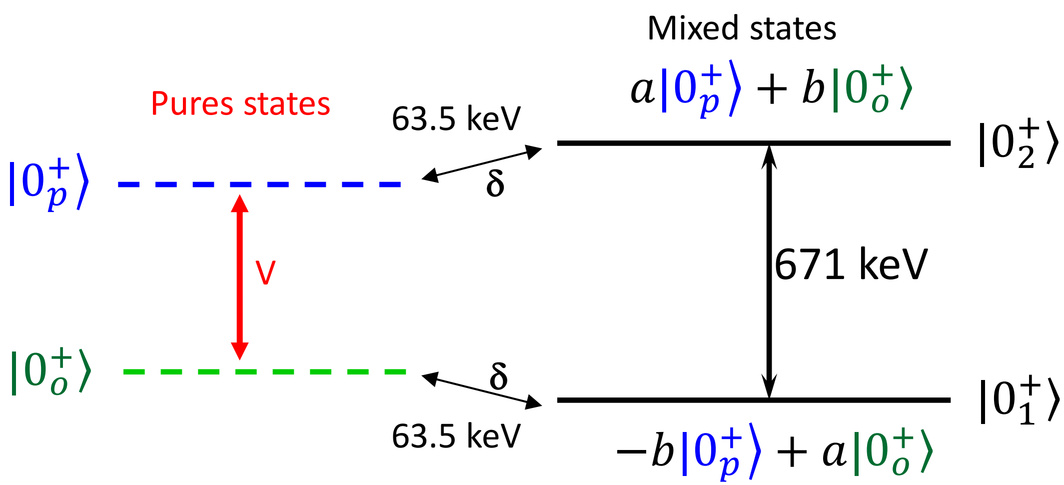


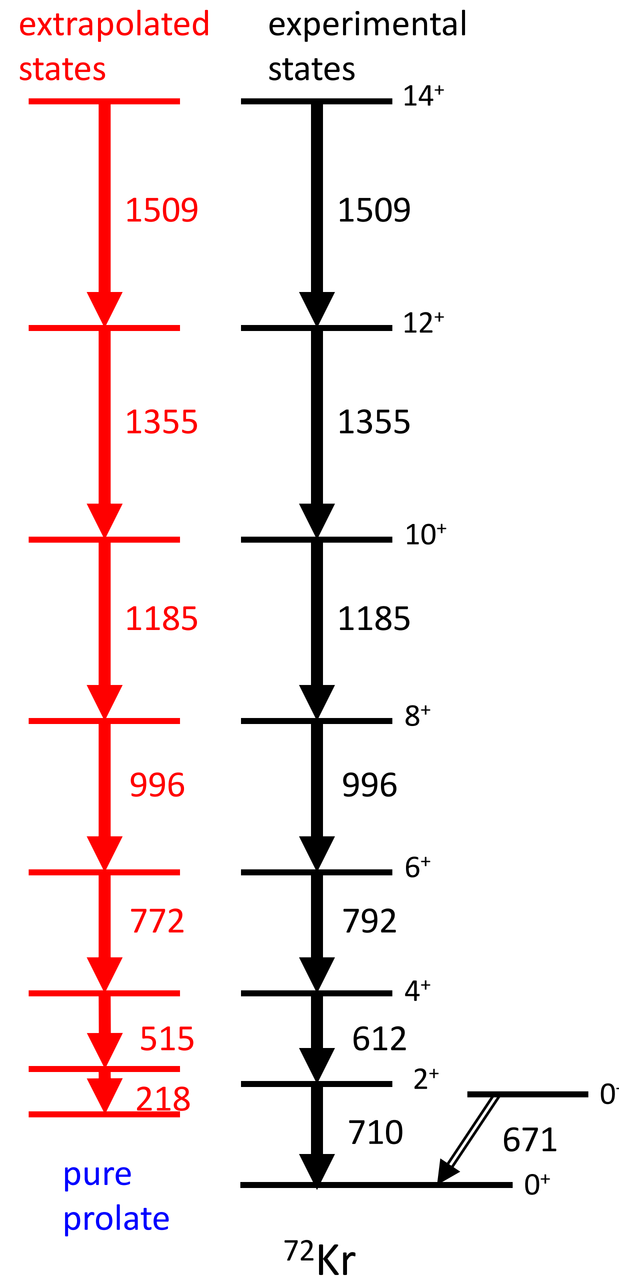
Regular rotational cascade at high spin:

$$E(I) = \frac{\hbar^2}{2\Im} I(I+1)$$

Rotational band is distorted at low spin.
⇒ influence of mixing

- Interaction V
- mixing amplitudes a, b



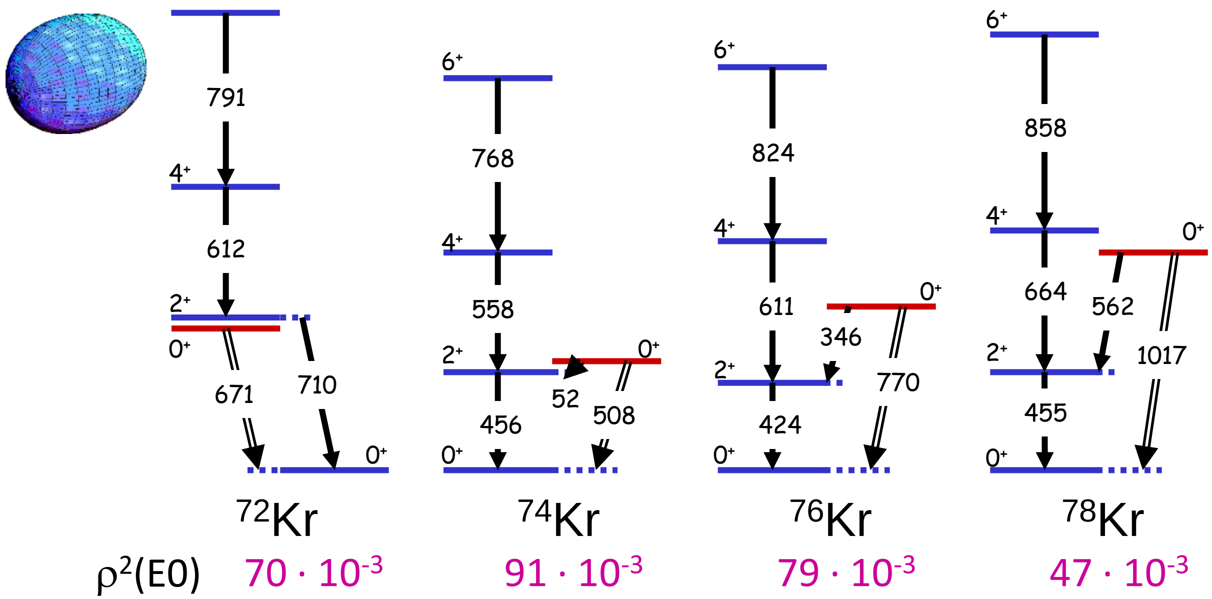


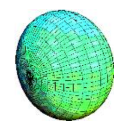
Systematics of the light krypton isotopes

- energy of excited 0^+
- E0 strengths $\rho^2(E0)$
- configuration mixing

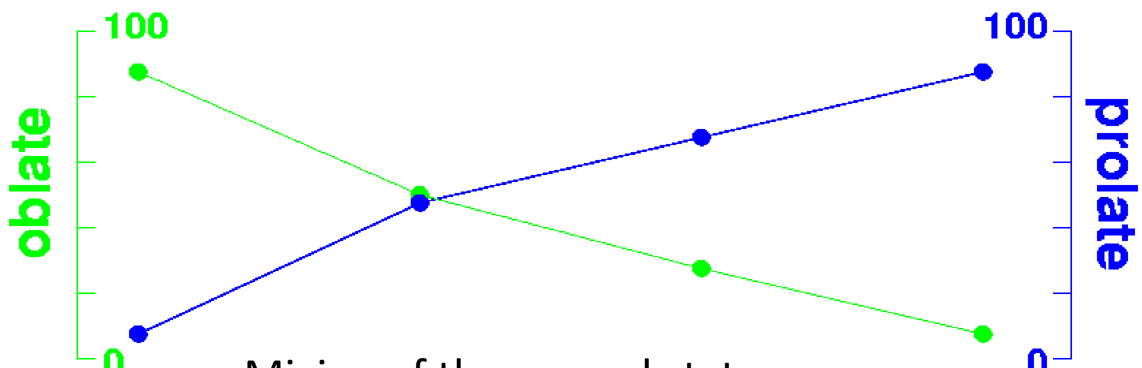
- Inversion of ground state shape for ^{72}Kr

prolate





oblate



Mixing of the ground state
(two-level mixing extrapolated
from distortion of rotational bands)

E. Bouchez et. al.,
Phys. Rev. Lett. 90, 082502 (2003)

Matrix elements from Coulomb excitation

$$|0_1^+\rangle = a_0|0_p^+\rangle + b_0|0_o^+\rangle \qquad |2_1^+\rangle = a_2|0_p^+\rangle + b_2|0_o^+\rangle$$

$$|0_2^+\rangle = -b_0|0_p^+\rangle + a_0|0_o^+\rangle \qquad |2_2^+\rangle = -b_2|0_p^+\rangle + a_2|0_o^+\rangle$$

$$a_0^2 + b_0^2 = 1 \qquad a_2^2 + b_2^2 = 1$$

no transitions between intrinsic prolate and oblate states:

$$\langle I_p^+|E2|J_o^+\rangle = 0$$

4 equations:

$$\langle 2_1^+|E2|0_1^+\rangle = b_0 b_2\langle 2_o^+|E2|0_o^+\rangle + a_0 a_2\langle 2_p^+|E2|0_p^+\rangle$$

$$\langle 2_1^+|E2|0_2^+\rangle = a_0 b_2\langle 2_o^+|E2|0_o^+\rangle - a_2 b_0\langle 2_p^+|E2|0_p^+\rangle$$

$$\langle 2_2^+|E2|0_1^+\rangle = a_2 b_0\langle 2_o^+|E2|0_o^+\rangle - a_0 b_2\langle 2_p^+|E2|0_p^+\rangle$$

$$\langle 2_2^+|E2|0_2^+\rangle = a_0 a_2\langle 2_o^+|E2|0_o^+\rangle + b_0 b_2\langle 2_p^+|E2|0_p^+\rangle$$

4 unknowns:

2 mixing amplitudes: a_0, a_2

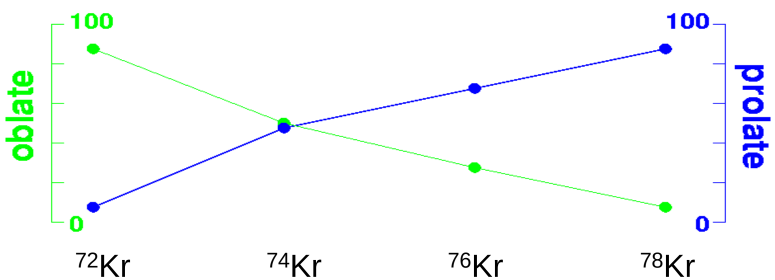
$$Q_{0,p} = \sqrt{\frac{16\pi}{5}}\langle 2_p^+|E2|0_p^+\rangle$$

$$Q_{0,o} = \sqrt{\frac{16\pi}{5}}\langle 2_o^+|E2|0_o^+\rangle$$

using experimental coulex matrix elements for ^{74}Kr:

$$a_0^2 = 0.48(2)$$
$$a_2^2 = 0.82(20)$$
$$Q_{0,p} = 3.62(48)\ e\text{b}$$
$$Q_{0,o} = -0.66(86)\ e\text{b}$$

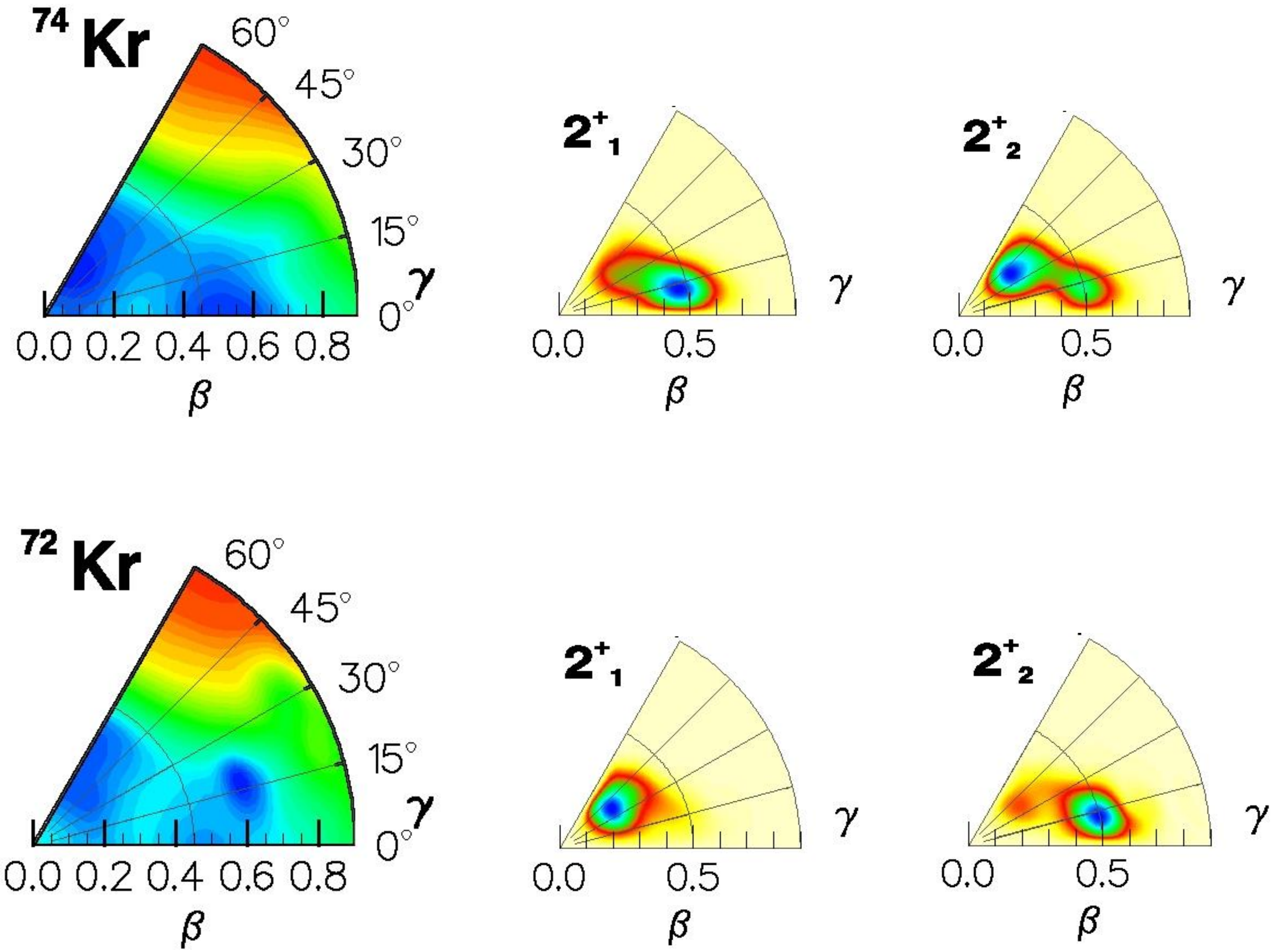
E. Clément et al., PRC 75, 054313 (2007)



consistent with mixing obtained from E0 transitions

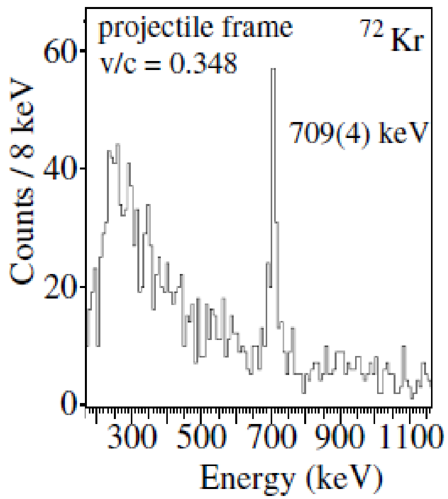
Composition of the wave functions

Inversion of prolate and oblate configurations in ^{72}Kr reproduced by "beyond mean field" calculations
5DCH / Gogny D1S

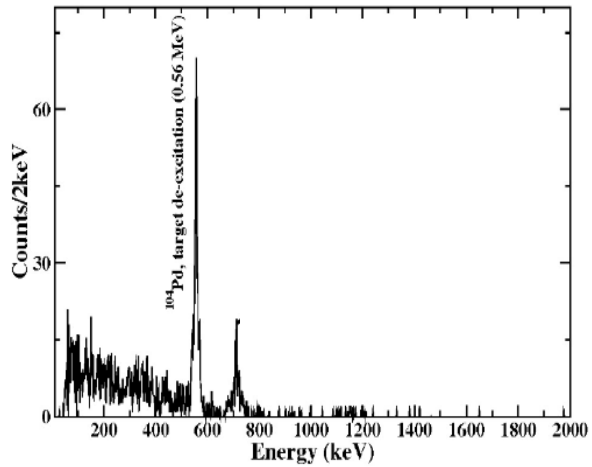


M. Girod et al., Phys. Lett. B 676, 39 (2009)

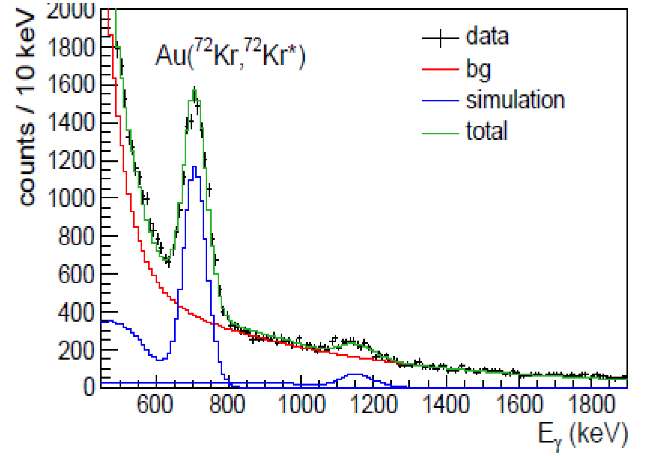
$B(E2; 0^+ \rightarrow 2^+)$ measurements for ^{72}Kr



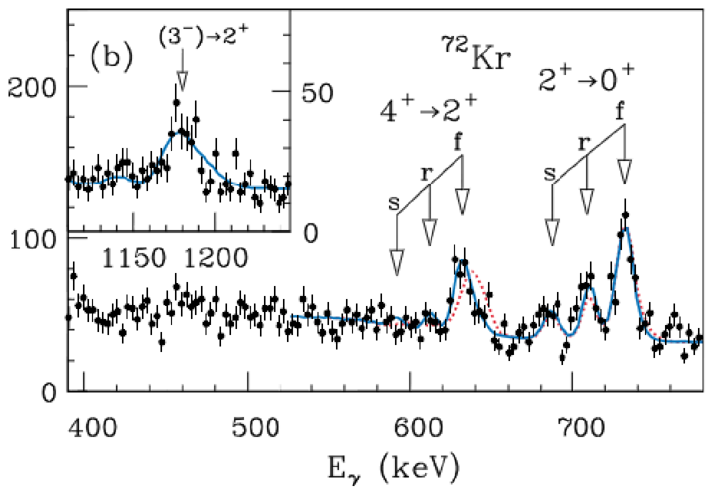
A.Gade et al., PRL 95, 022502 (2005)
Au(^{72}Kr,^{72}Kr'), 70 MeV/u, MSU



B.S.Nara Singh et al. (unpublished)
ISOLDE IS478 (2012)
^{104}Pd(^{72}Kr,^{72}Kr'), 2.8 MeV/u



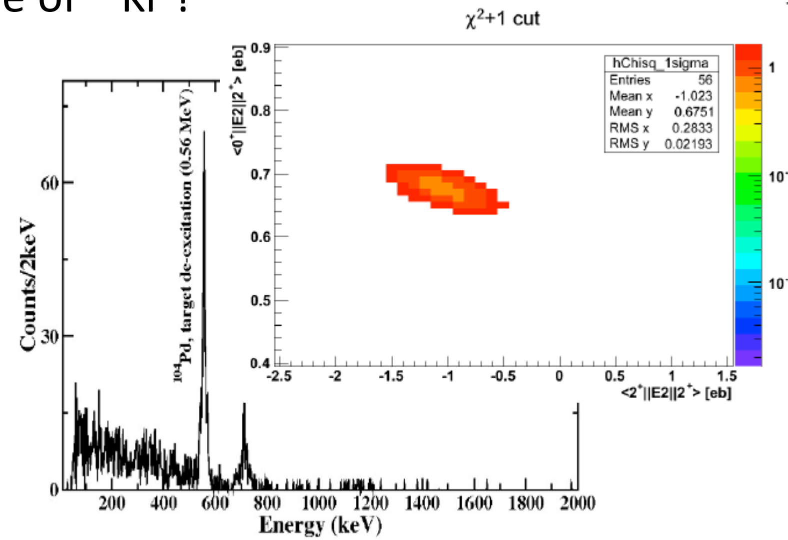
T.Arici, PhD Univ. Giessen (2017)
Au(^{72}Kr,^{72}Kr'), 150 MeV/u, RIKEN



H.Iwasaki et al., PRL 112, 142502 (2014)
^{9}Be(^{74}Kr,^{72}Kr), RDDS lifetime, MSU

$B(E2; 0^+ \rightarrow 2^+)$ [e^2fm^4]	
4997(647)	Gade
4600(600)	Nara Singh
4050(750)	Iwasaki
4910(700)	Arici

Shape of ^{72}Kr ?

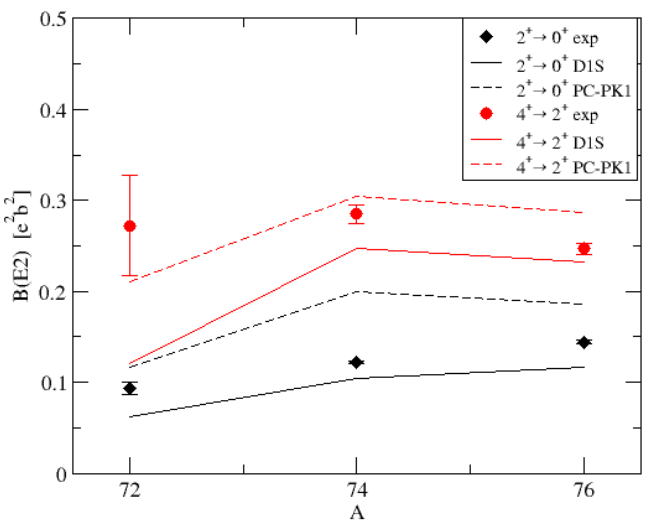


B.S.Nara Singh, HIE-ISOLDE Workshop 2016

high-energy Coulomb excitation (MSU, RIKEN)
- not sensitive to Q_s

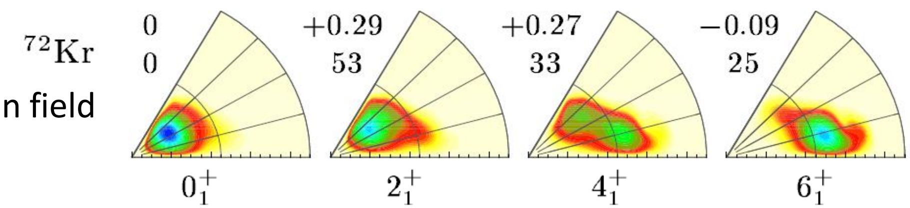
low-energy Coulomb excitation (ISOLDE)
- sensitive to $Q_s(2^+)$
- very low statistics
- favors prolate shape for 2^+ state

lifetime measurement (MSU)
- not sensitive to $Q_s(2^+)$
- large $B(E2; 4^+ \rightarrow 2^+)/B(E2; 2^+ \rightarrow 0^+)$



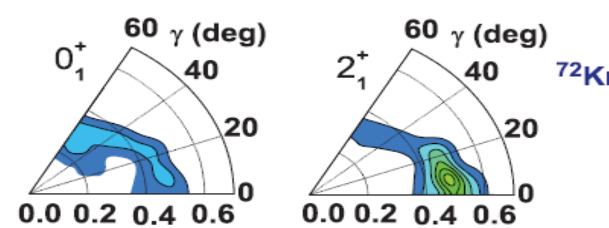
^{74,76}Kr: E.Clément et al., PRC 75, 054313 (2007)
^{72}Kr: H.Iwasaki et al., PRL 112, 142502 (2014)

beyond mean field
Gogny D1S
5DCH



M.Girod et al., PLB 676, 39 (2009)

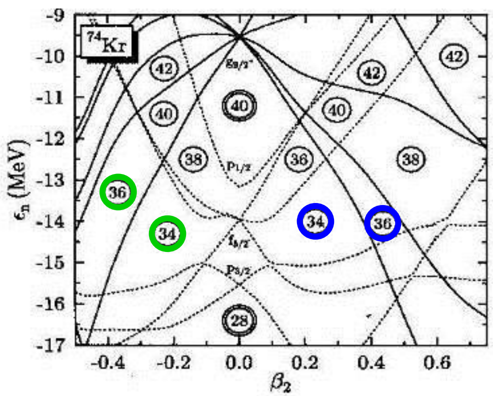
beyond mean field
RMF PC-PK1
5DCH

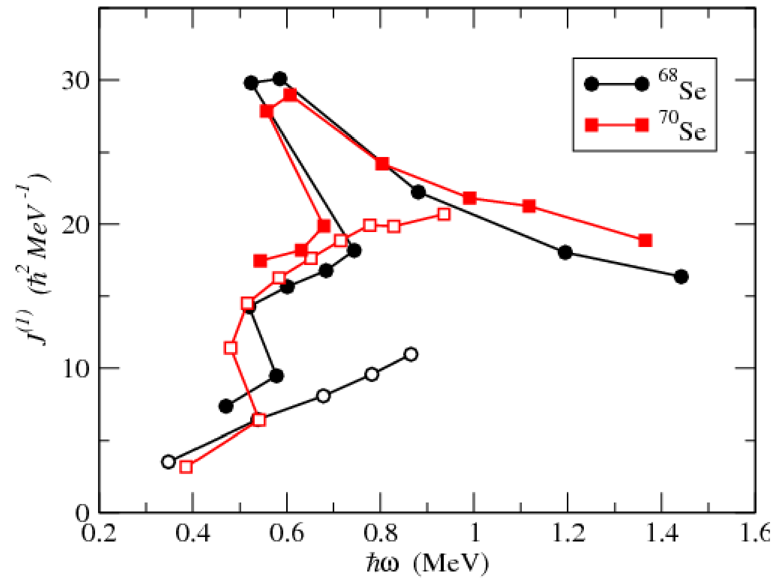


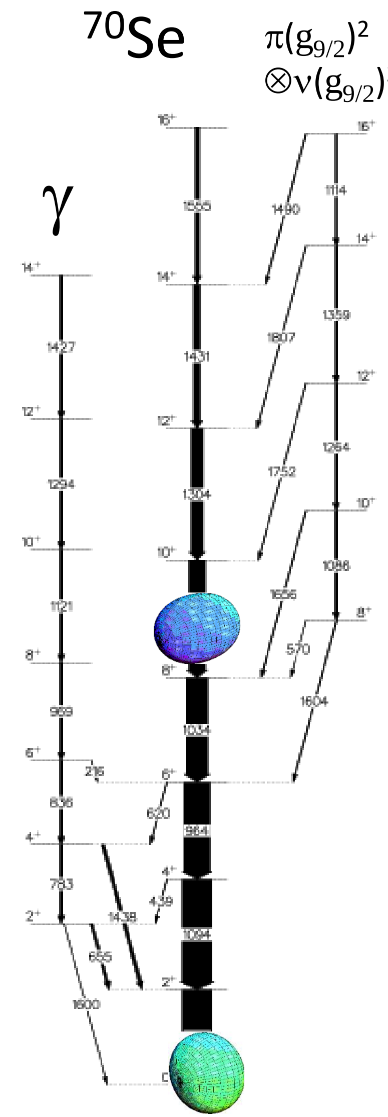
Y.Fu et al., PRC 87, 054305 (2013)

- rapid transition from oblate ground state to prolate 2^+ in ^{72}Kr ?

Shape coexistence in light Selenium isotopes

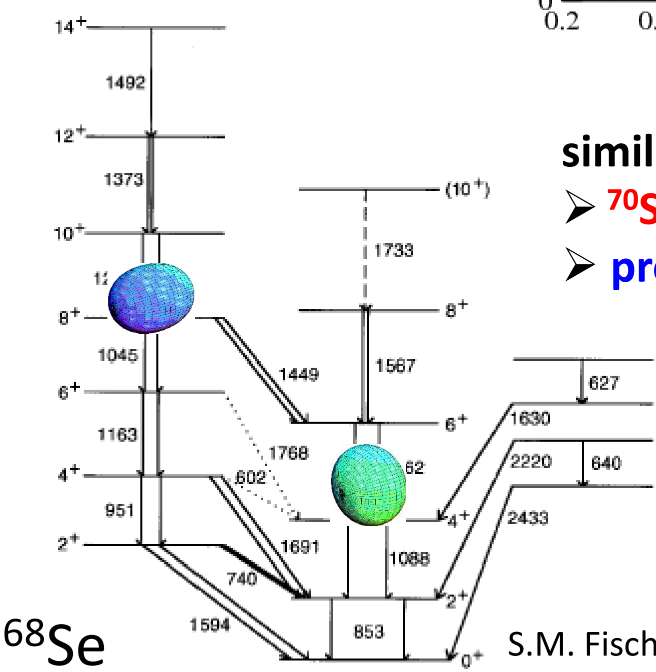






similar $J^{(1)}$ in ^{68}Se and ^{70}Se:

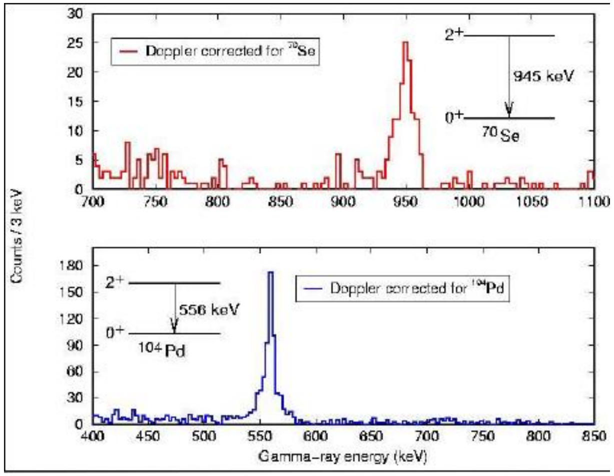
- **^{70}Se oblate near ground state**
- **prolate at higher spin**



S.M. Fischer et al.,
PRC 67, 064318 (2003)

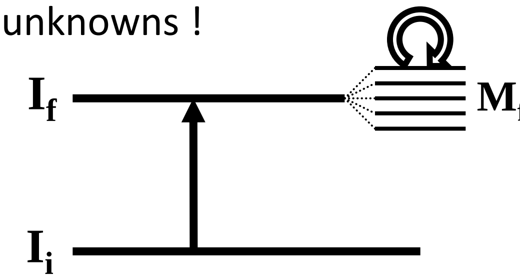
G. Rainovski et al.,
J.Phys.G 28, 2617 (2002)

Coulomb excitation of ^{70}Se at CERN / ISOLDE

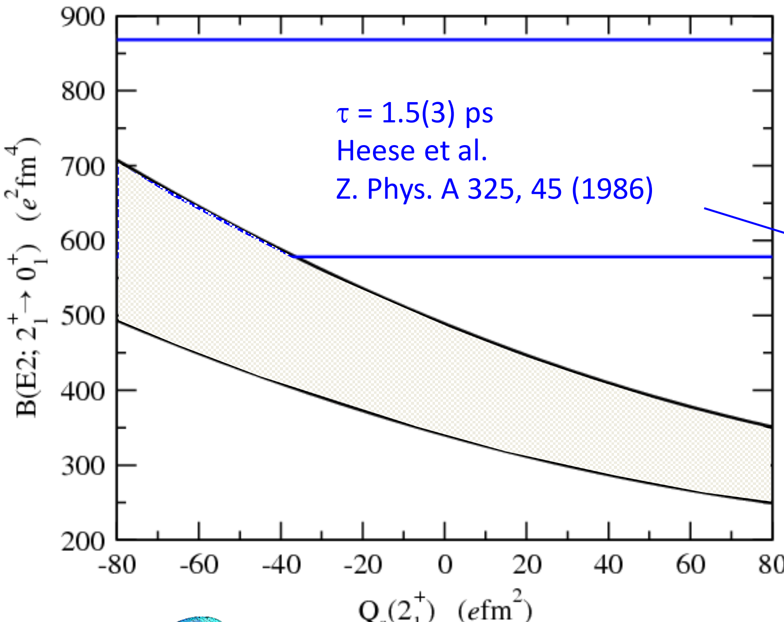


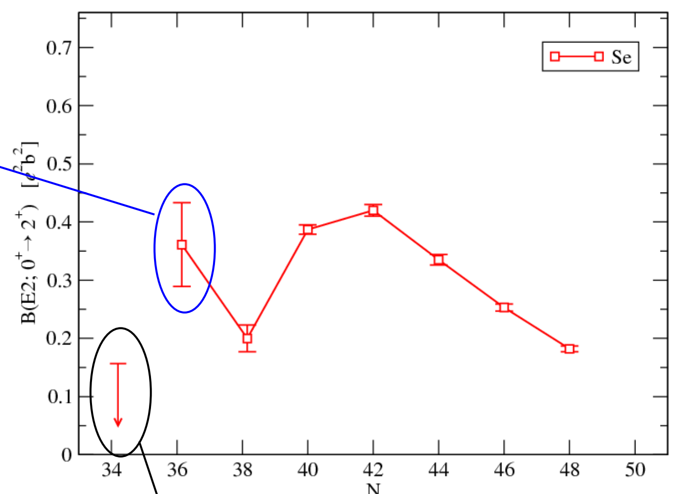
- ^{70}Se on ^{104}Pd at 2.94 MeV/u
- integral measurement of excitation probability $P(2^+)$
- normalization to target

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

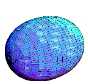


A.M. Hurst et al.,
PRL 98, 072501 (2007)





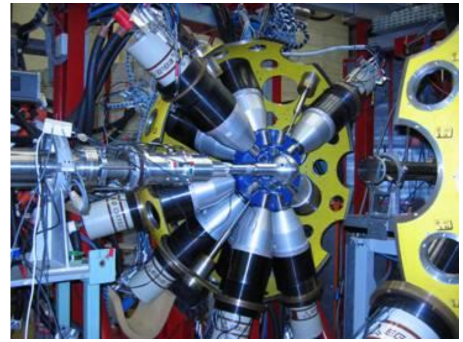
GANIL intermediate-energy Coulex
E. Clément et al., NIM A 587, 292 (2008)

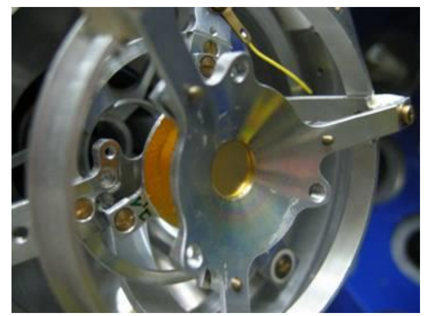


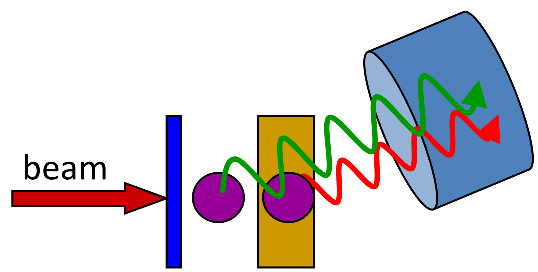
⇒ **only prolate shape consistent with both Coulex and lifetime measurement**

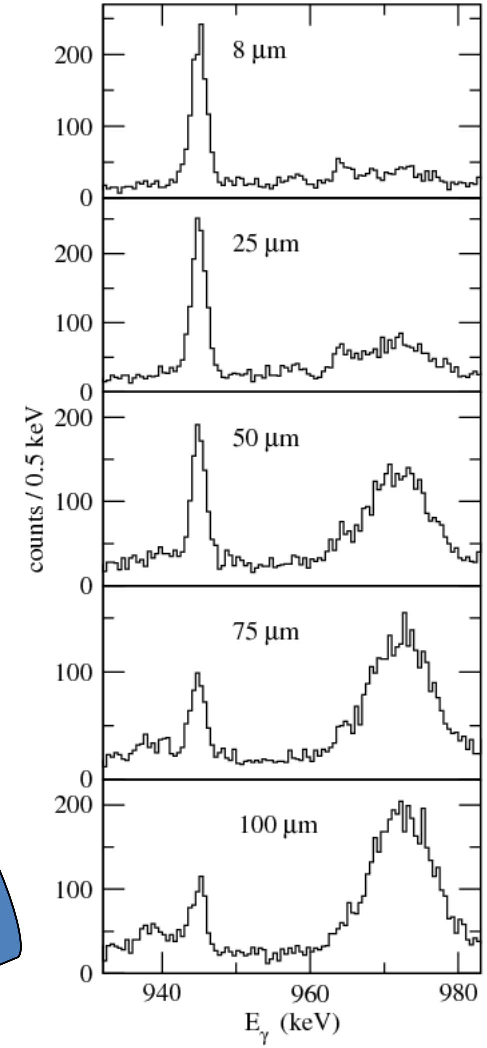
Lifetimes in ^{70}Se and ^{72}Se revisited

- Recoil-distance Doppler Shift
- GASP and Köln Plunger at Legnaro
- ^{40}Ca(^{36}Ar,α2p)^{70}Se
- 12 distances between 8 and 400 μm
- gated from above
  $\Rightarrow$ side feeding effects eliminated





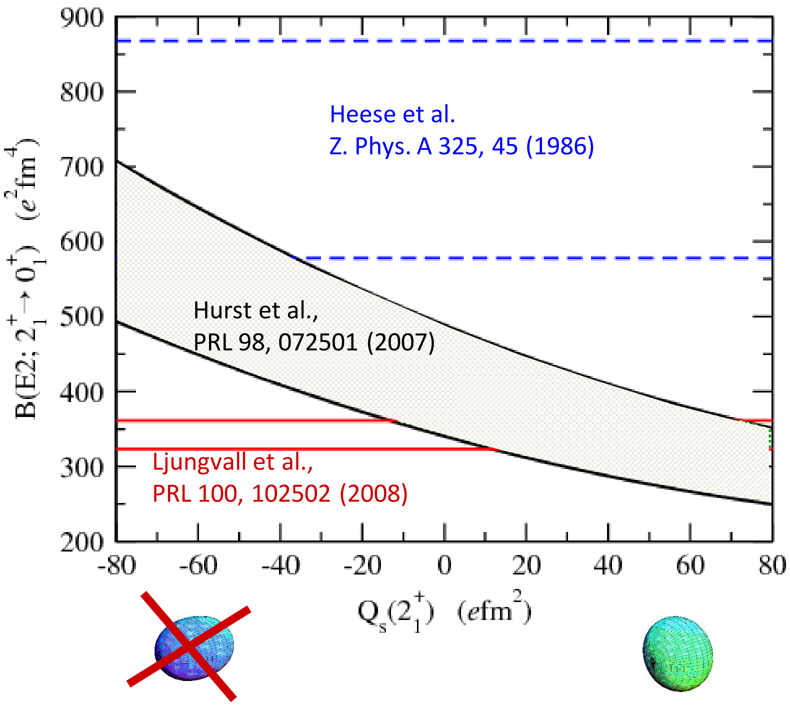




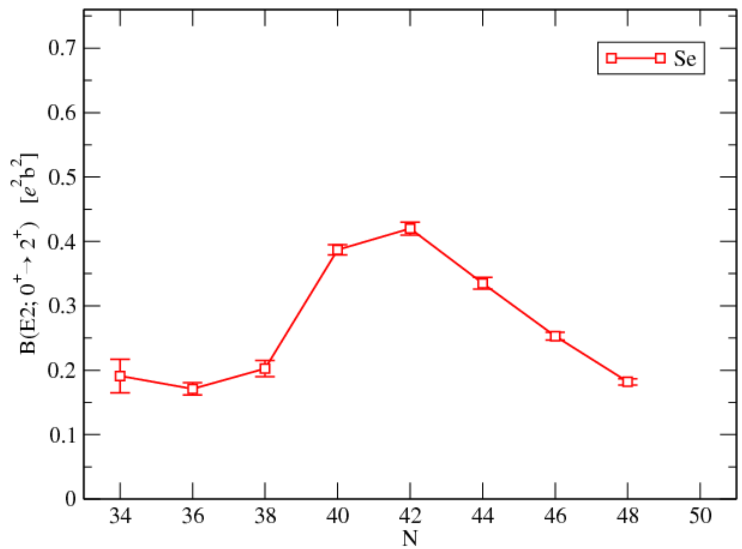
	old [1] τ (ps)	new[2] τ (ps)	B(E2;↓) (e^2fm^4)
^{70}Se	**^{40}Ca(^{36}Ar,α2p)^{70}Se**		
2^+	**1.5(3)**	**3.2(2)**	342(19)
4^+	1.4(3)	1.4(1)	370(24)
6^+	3.9(9)	1.9(3)	530(96)
^{72}Se	**^{40}Ca(^{36}Ar,4p)^{72}Se**		
2^+	4.3(5)	4.2(3)	405(25)
4^+	2.7(4)	3.3(2)	882(50)
6^+	2.3(2)	1.7(1)	1220(76)

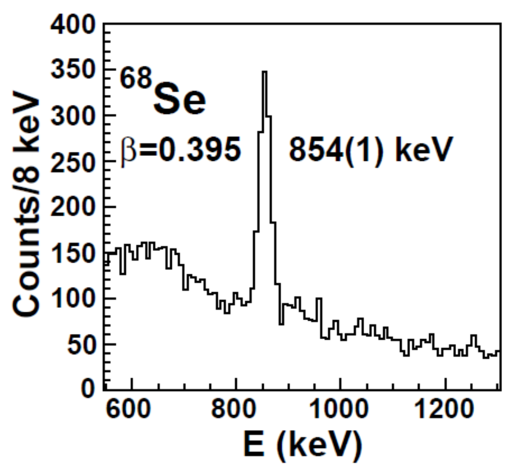
[1] J. Heese et al., Z. Phys. A 325, 45 (1986)
[2] J. Ljungvall et al., PRL 100, 102502 (2008)

Consequences for the shape of ^{70}Se



- oblate shape in ^{70}Se near the ground state
- Coulomb excitation and lifetime measurements are complementary techniques



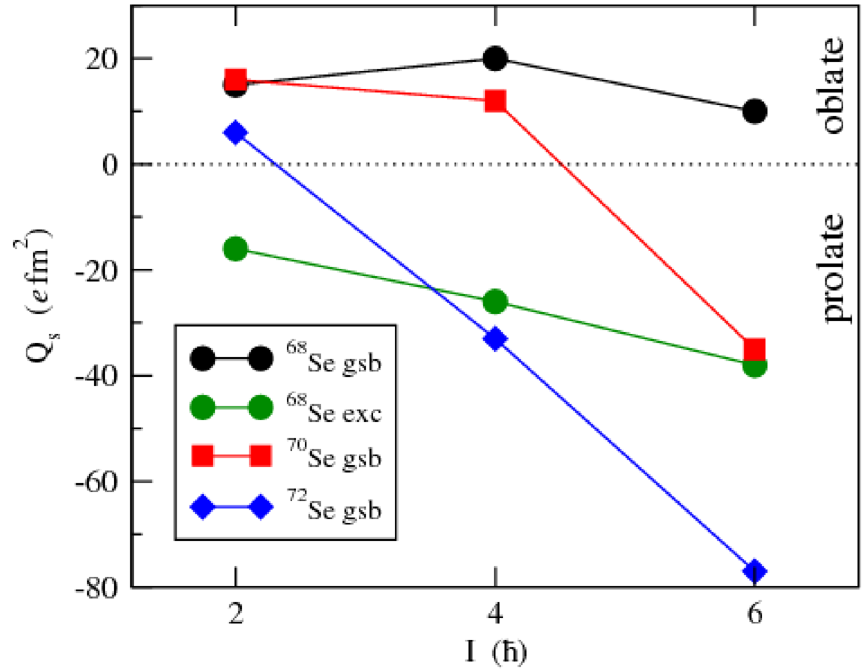


intermediate-energy Coulomb excitation MSU
$B(E2;\uparrow) = 1911(260)$ e^2fm^4

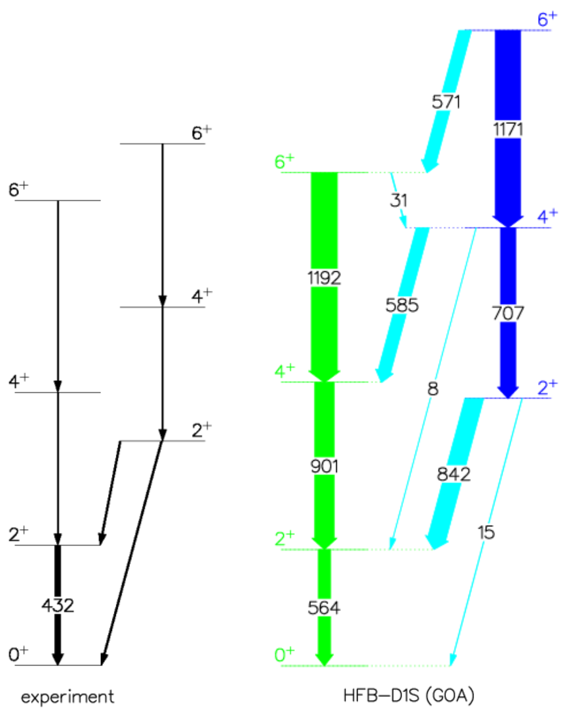
A. Obertelli et al.
PRC 80 (2009) 031304(R)

Shape evolution in the light Selenium isotopes

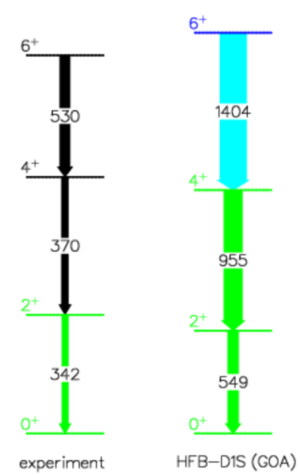
- **oblate rotation prevails only in ^{68}Se**
  ⇒ best example for shape coexistence in A=70 region
- **experimental quadrupole moments needed**



Q_s from Gogny configuration mixing calculation

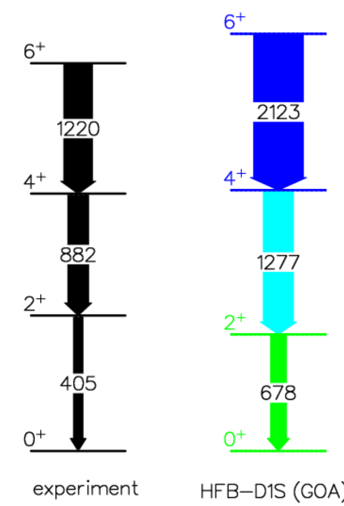


^{68}Se



^{70}Se

B(E2,↓) in e^2fm^4



^{72}Se