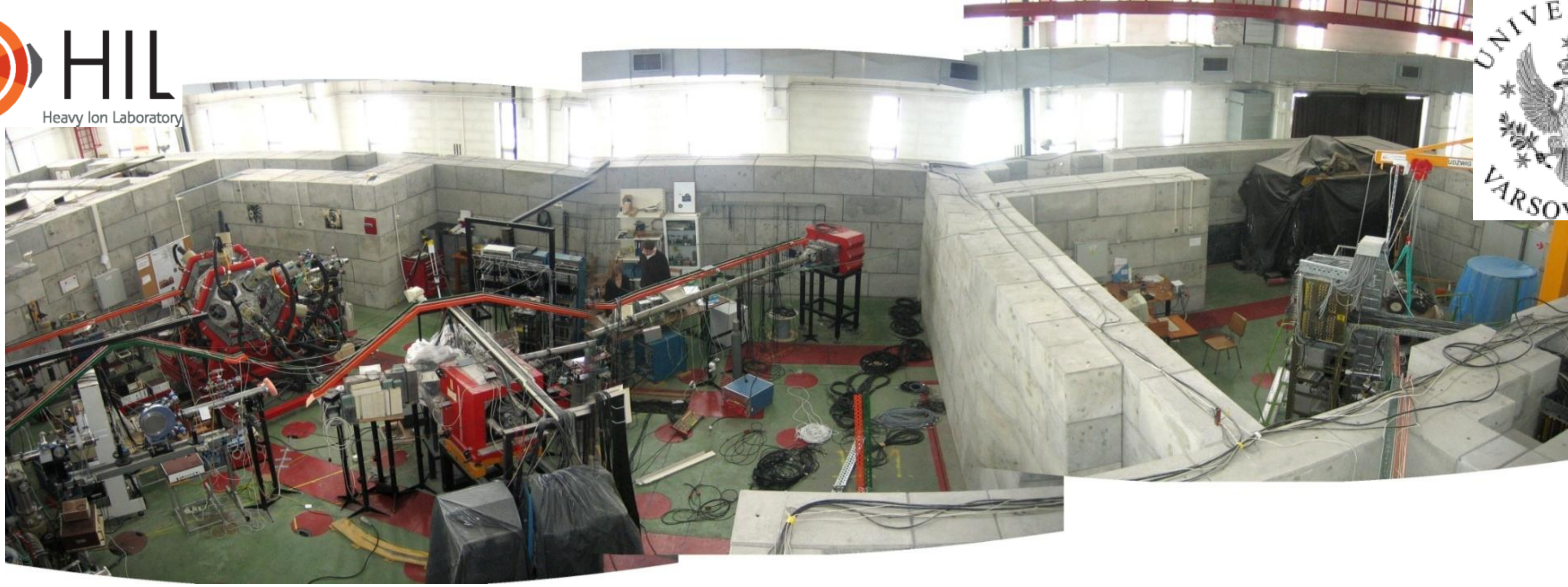
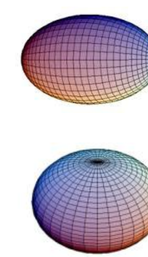
HIL Heavy Ion Laboratory



Deformations of atomic nuclei studied with Coulomb excitation - perspectives and experimental needs

Katarzyna Wrzosek-Lipska

Heavy Ion Laboratory, University of Warsaw, Poland

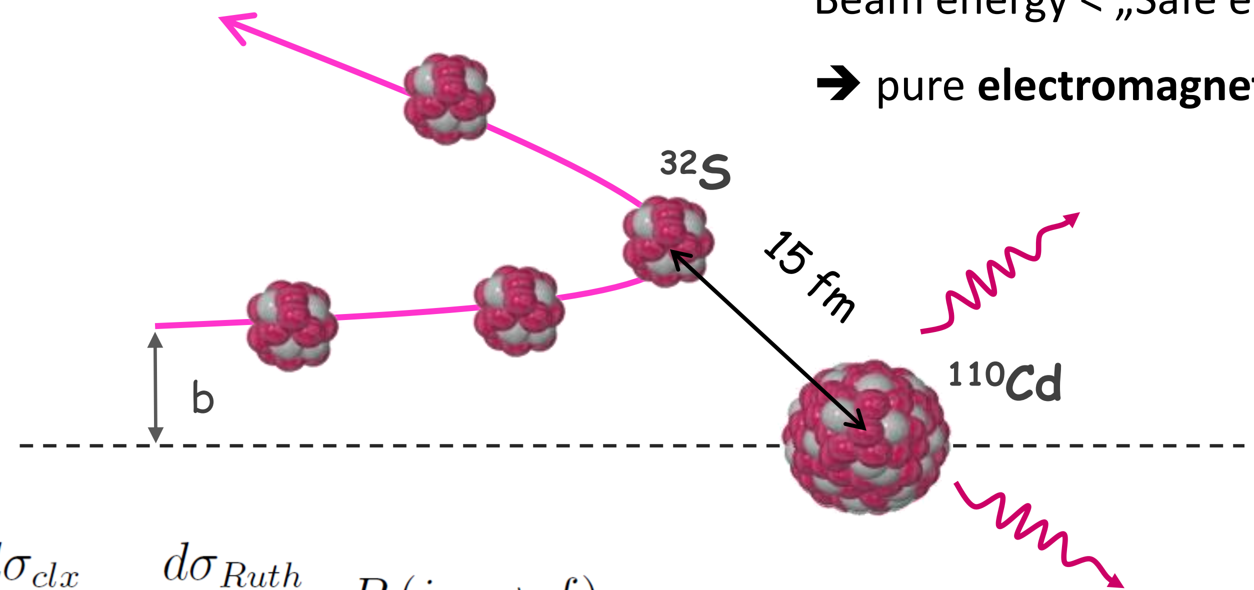


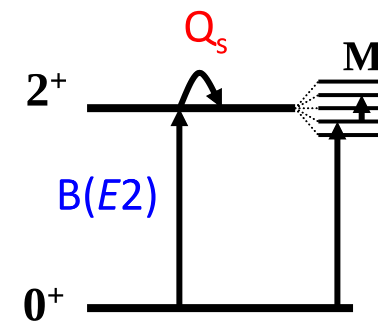
PRZYSZŁOŚĆ FIZYKI JĄDROWEJ NISKICH ENERGII W POLSCE A ROZWÓJ KRAJOWEJ INFRASTRUKTURY BADAWCZEJ
14-15 stycznia 2019, ŚLCJ UW

Low-Energy Coulomb Excitation

Beam energy < „Safe energy" (3-5 MeV/A)

➔ pure **electromagnetic** interaction





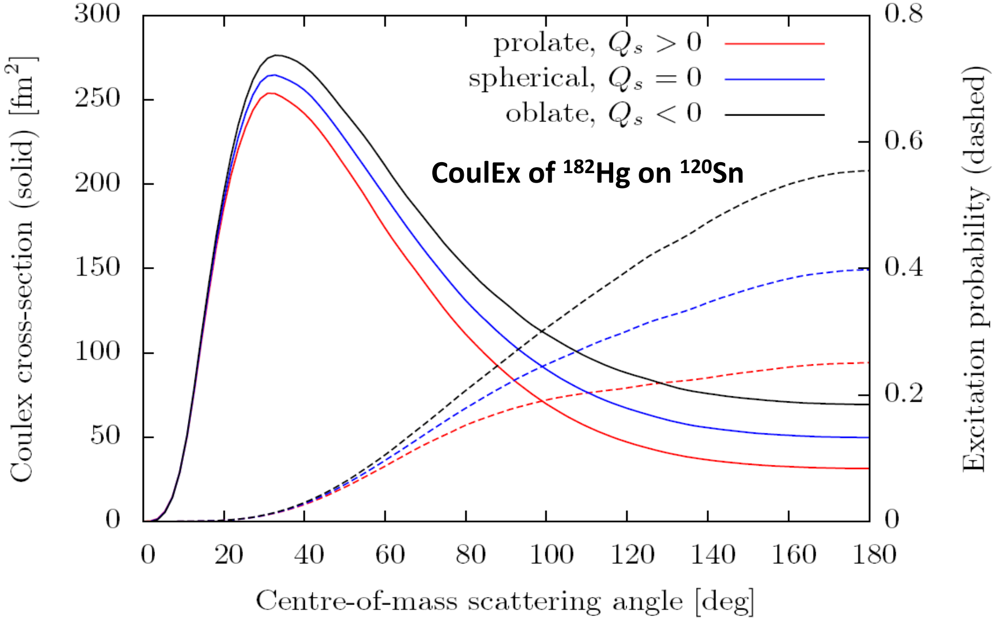
$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega} \cdot P\left(i \longrightarrow f\right)$$

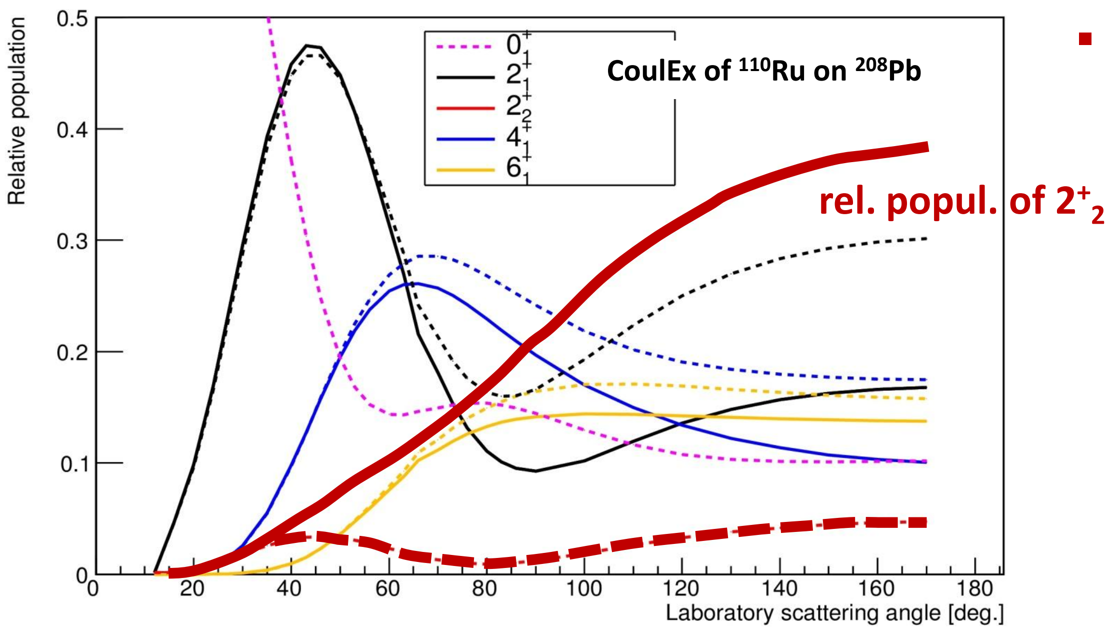
$$P_{2_1^+} \propto |\langle 2_1^+||\mathrm{E2}||0_1^+\rangle|^2 \cdot \left(1 + \langle 2_1^+||E2||2_1^+\rangle \cdot K(\theta, \mathrm{E}_p)\right)$$

Access to: reduced transition probabilities and spectrosopic quadrupole moments of excited yrast and non-yrast states in the **model independent way.**

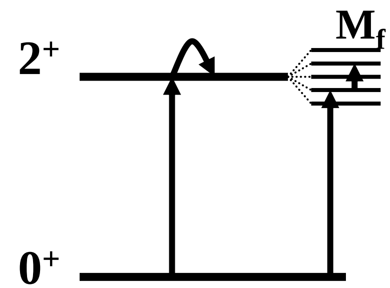
Reorientation effect and relative signs

M. Zielińska, L. P. Gaffney, K. Wrzosek-Lipska et al.,Eur.Phys.J. A 52, 99 (2016)

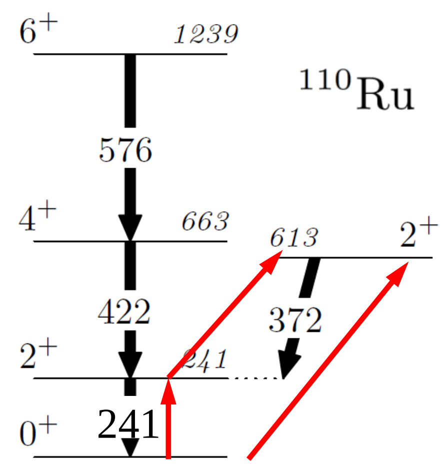




Coulex cross-section depends on both
$<0^+||E2||2^+>$ and $<2^+||E2||2^+>$ ~ Q_{sp}



- Sensitivity of Coulex data to relative signs of ME's
- Sign of a product of matrix elements is an observable !



Reorientation effect and relative signs

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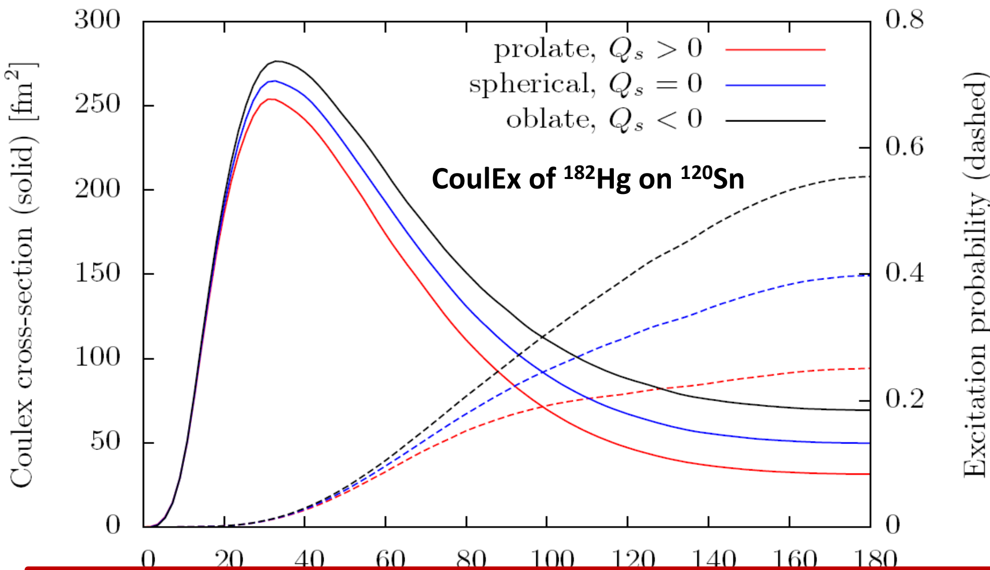
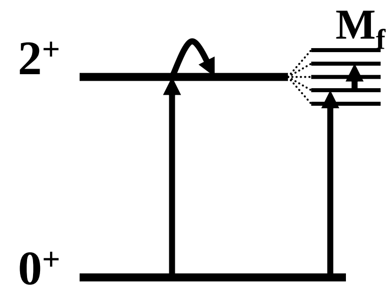
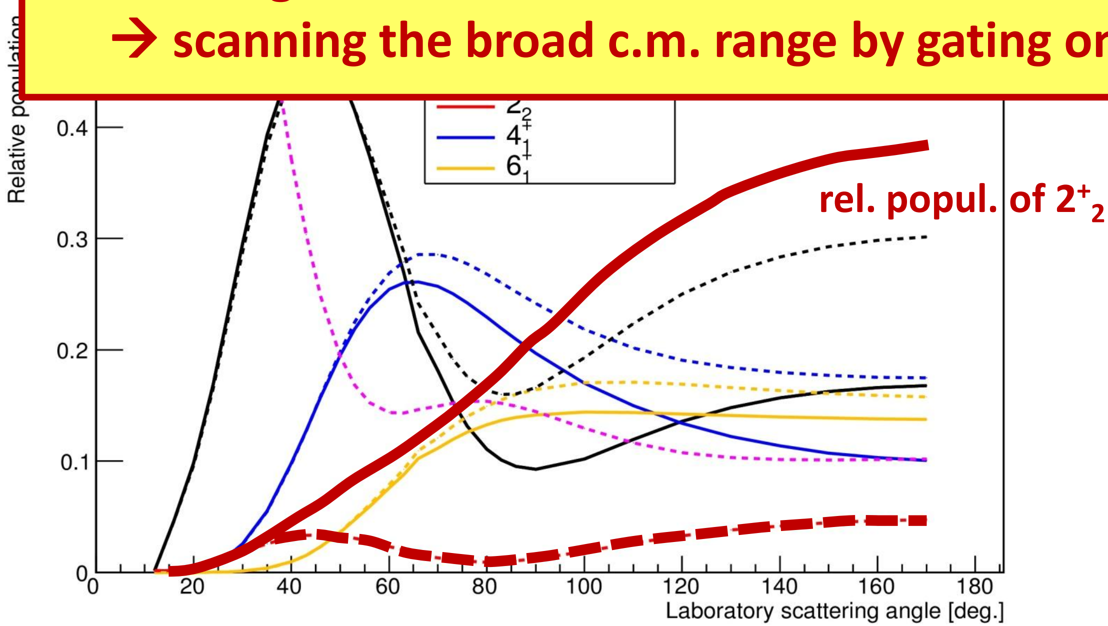


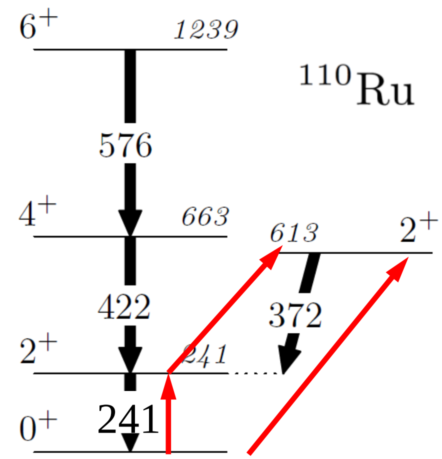
Coulex cross-section depends on both $\langle 0^+ || E2 || 2^+ \rangle$ and $\langle 2^+ || E2 || 2^+ \rangle \sim Q_{sp}$



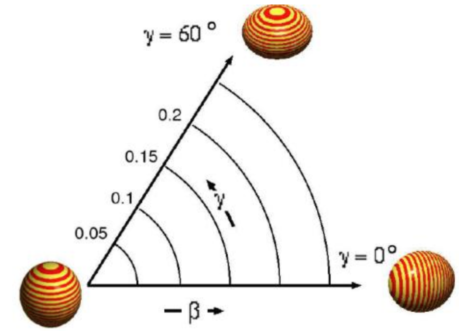
High – statistics differential CoulEx measurements are crucial
→ scanning the broad c.m. range by gating on different angular ranges!

is an observable ?



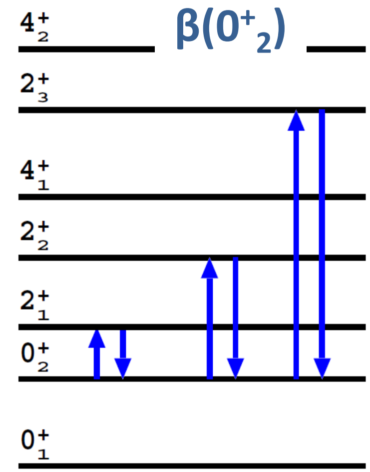


CoulEx and nuclear deformation



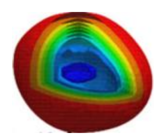
Quadrupole invariants method ➔ nuclear shape from matrix elements

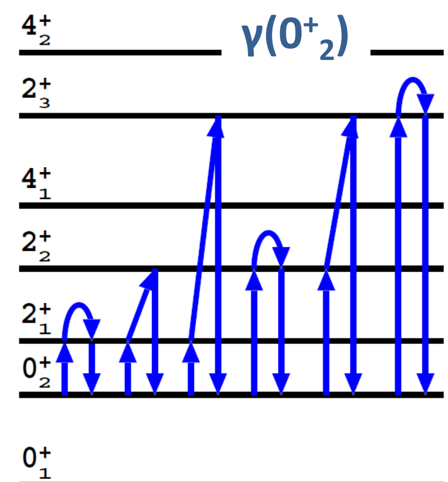
→ **overall deformation** (analogous to β Bohr's parameter)



$$\frac{\langle Q^2 \rangle}{\sqrt{5}} = \langle i|\, [\mathrm{E2} \times \mathrm{E2}]^0 \,|i\rangle = \frac{1}{\sqrt{(2I_i+1)}} \sum_t \langle i\|\mathrm{E2}\|t\rangle \langle t\|\mathrm{E2}\|i\rangle \begin{Bmatrix} 2 & 2 & 0 \\ I_i & I_i & I_t \end{Bmatrix}$$

→ **triaxiality** (analogous to γ Bohr's parameter)





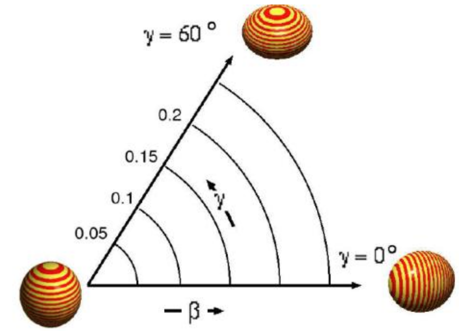
$$\sqrt{\frac{2}{35}} \langle \mathrm{Q}^3 \cos 3\delta \rangle = \langle i|\{[\mathrm{E2} \times \mathrm{E2}]^2 \times \mathrm{E2}\}^0|i\rangle$$

$$= \frac{1}{(2I_i+1)} \sum_{t,u} \langle i\|\mathrm{E2}\|u\rangle \langle u\|\mathrm{E2}\|t\rangle \langle t\|\mathrm{E2}\|i\rangle \begin{Bmatrix} 2 & 2 & 2 \\ I_i & I_t & I_u \end{Bmatrix}$$

D. Cline, Ann. Rev. Nucl. Part. Sci. 36 (1986)
K. Kumar, PRL 28 (1972)

CoulEx and nuclear deformation

Quadrupole invariants method ➔ nuclear shape from matrix elements



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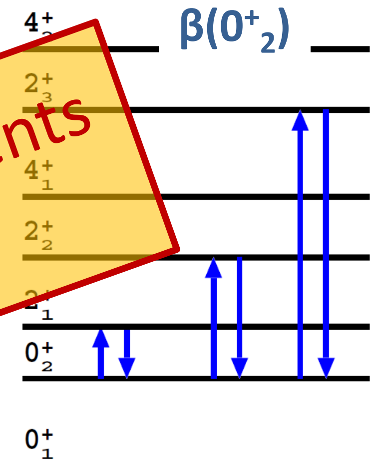
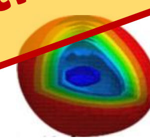


→ **triaxiality** (analogous to γ Bohr's parameter)



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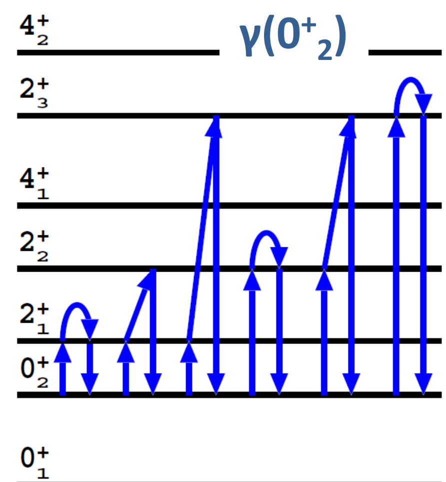
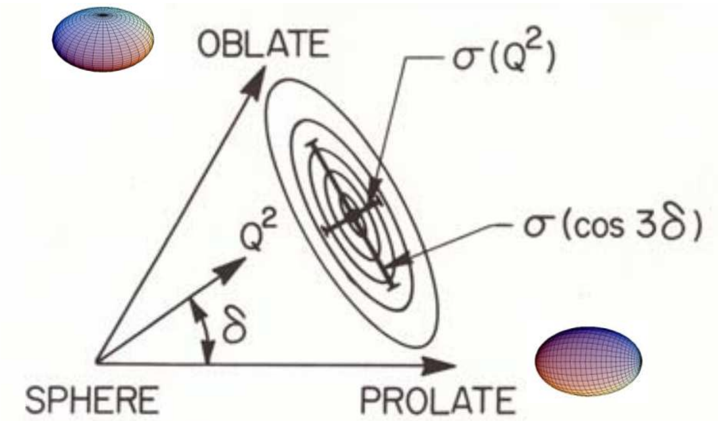
$$= \frac{1}{(2I_i+1)}\sum_{t,u}\langle i||\mathrm{E2}||u\rangle\langle u||\mathrm{E2}||t\rangle\langle t||\mathrm{E2}||i\rangle \begin{Bmatrix} 2 & 2 & 2 \\ I_i & I_t & I_u \end{Bmatrix}$$



Important role of **relative signs** of matrix elements when determining the **triaxiality** !

D. Cline, Ann. Rev. Nucl. Part. Sci. 36 (1986)
K. Kumar, PRL 28 (1972)

Next step: Q^2 („β”)/ cos3δ („γ”) softness or stiffness ?

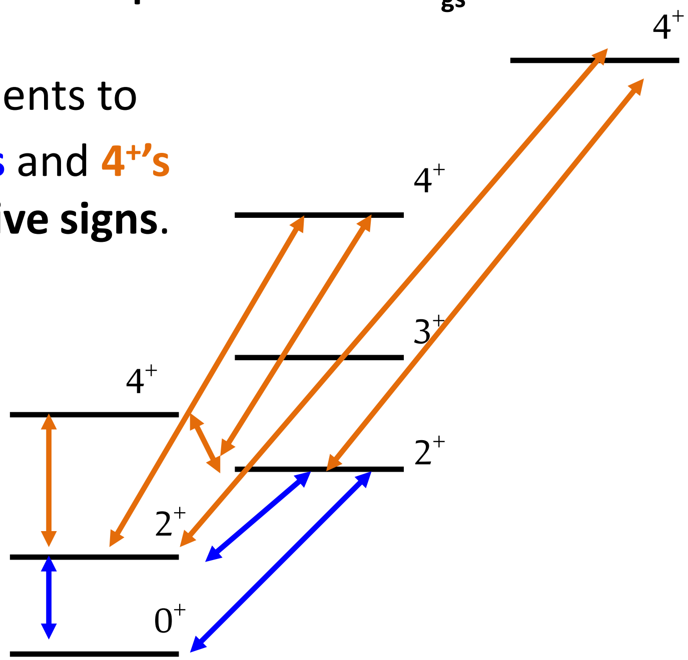


Softness in β:

$$\sigma(Q^2) = \sqrt{\langle Q^4 \rangle - \langle Q^2 \rangle^2}$$

What is needed softness parameters for 0^+_{gs} ?

*E*2 matrix elements to the excited **2^+’s** and **4^+’s** and their **relative signs**.



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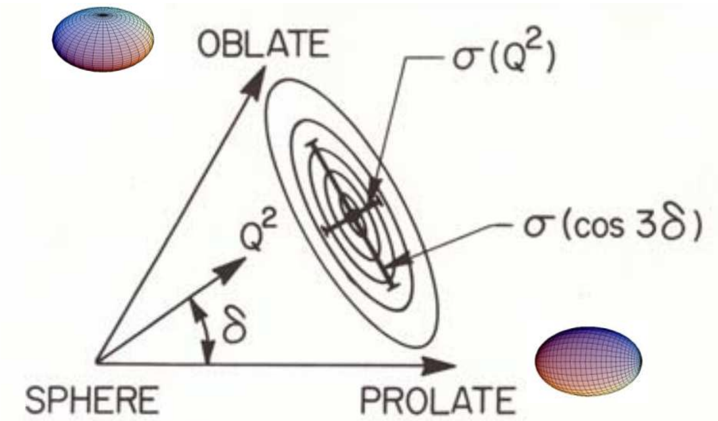
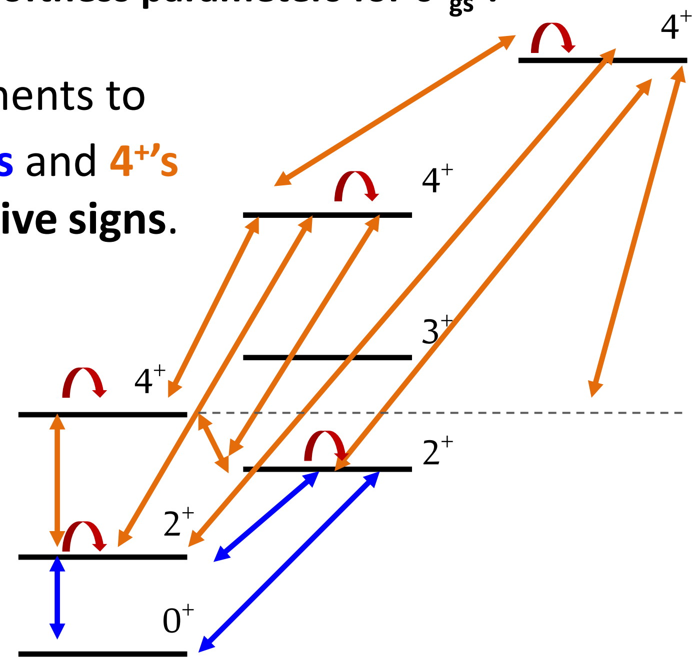


What is needed softness parameters for 0^+_{gs} ?

*E*2 matrix elements to the excited **2⁺'s** and **4⁺'s** and their **relative signs**.



Softness in β:

$$\sigma(Q^2) = \sqrt{\langle Q^4\rangle - \langle Q^2\rangle^2}$$

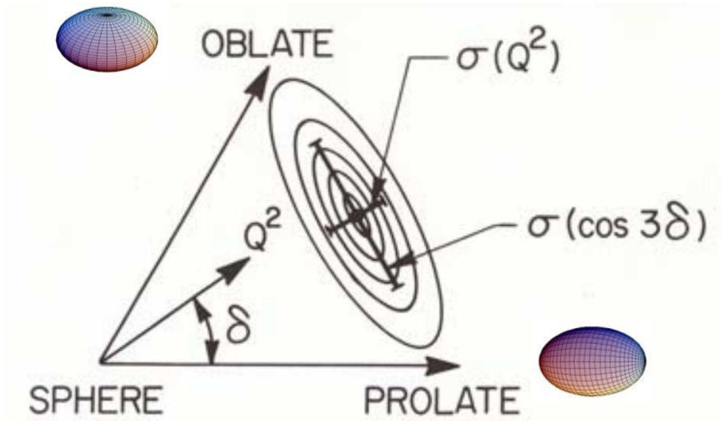
Softness in γ:

$$\sigma(\cos 3\delta) \cong \sqrt{\frac{\langle Q^6 \cos^2 3\delta\rangle}{\langle Q^6\rangle} - \frac{\langle Q^3 \cos 3\delta\rangle}{\langle Q^3\rangle}}$$

Additionaly Q_{sp} moments for excited 2^+ and 4^+ states are important.

This requires much more detailed studies yielding a **larger set of *E*2 matrix elements.**

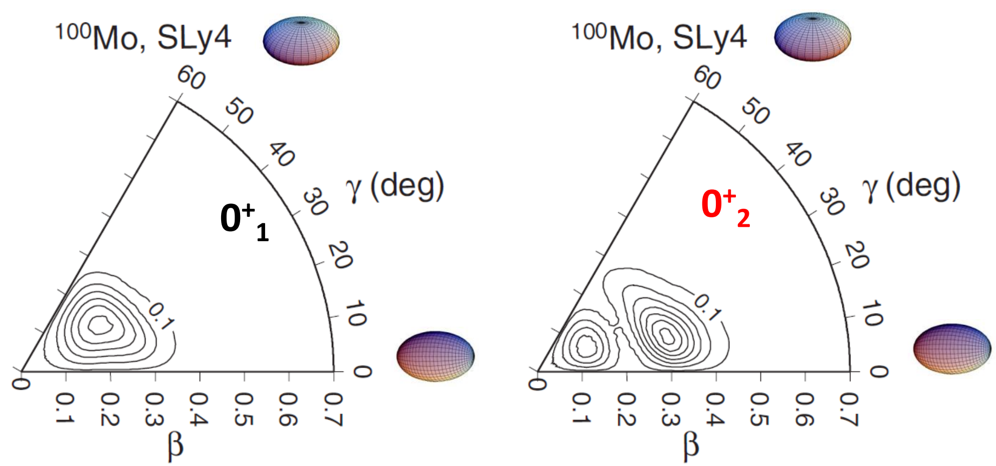
Next step: Q^2 („β”)/ cos3δ („γ”) softness or stiffness ?



Direct comparison to the theoretical predictions:

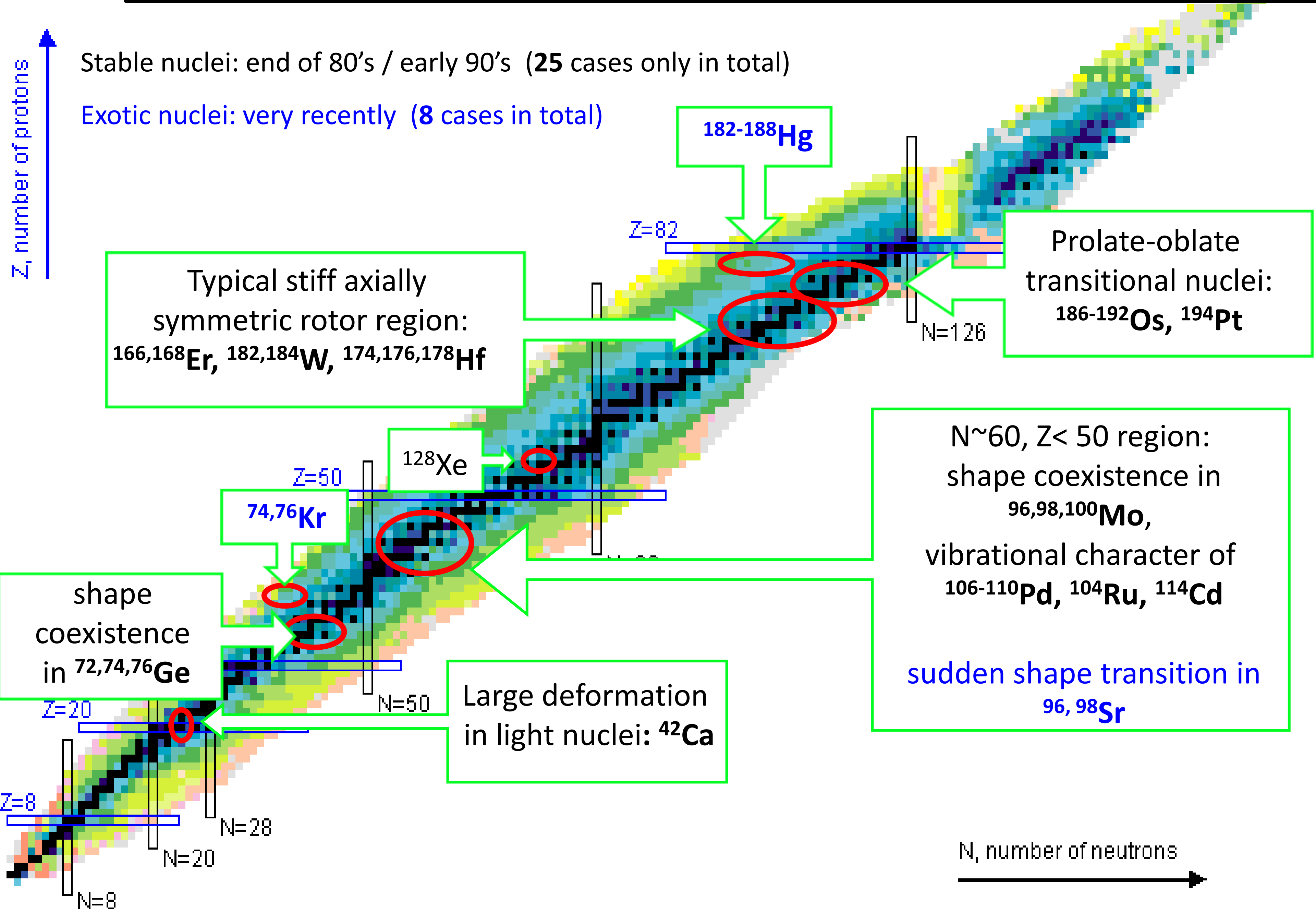
Probability density for the $\mathbf{0^+_1}$ and $\mathbf{0^+_2}$

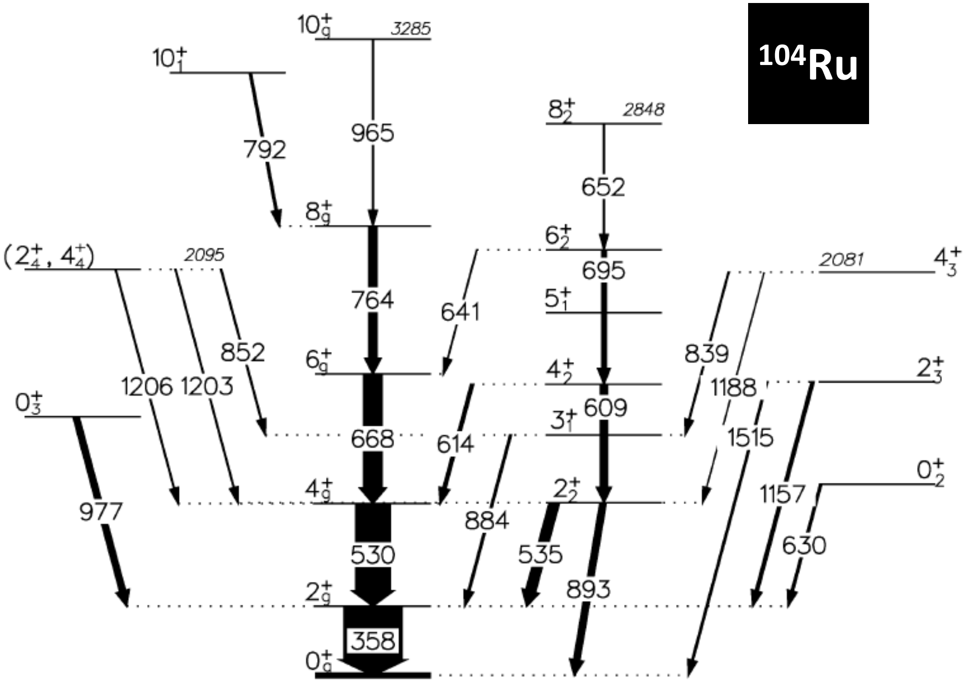
General Bohr Hamiltonian; calculations perfomed by L. Próchniak for ^{100}Mo



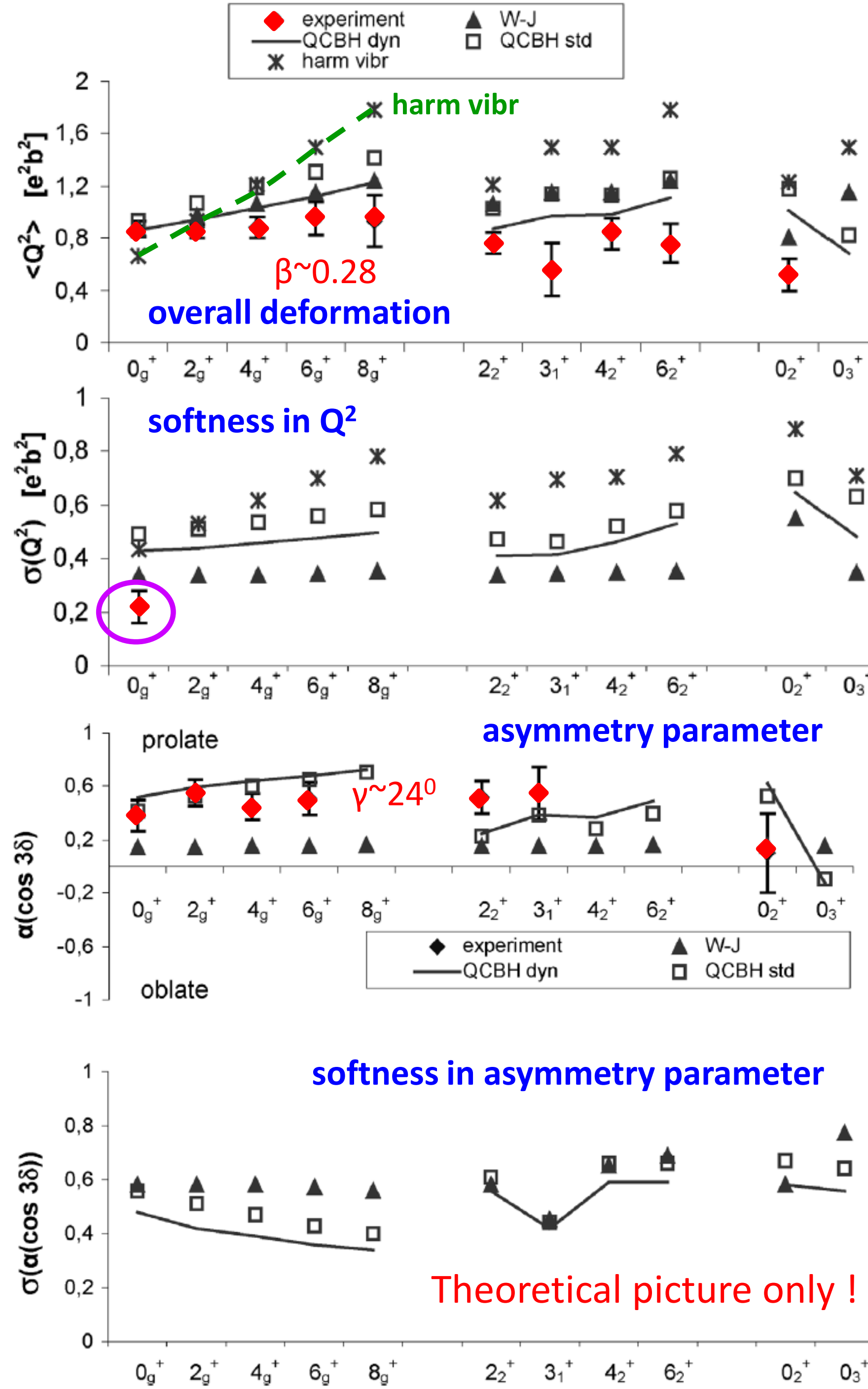
K. Wrzosek-Lipska , L. Próchniak et al., PRC 86 (20__,

Application of the quadrupole invariants method:



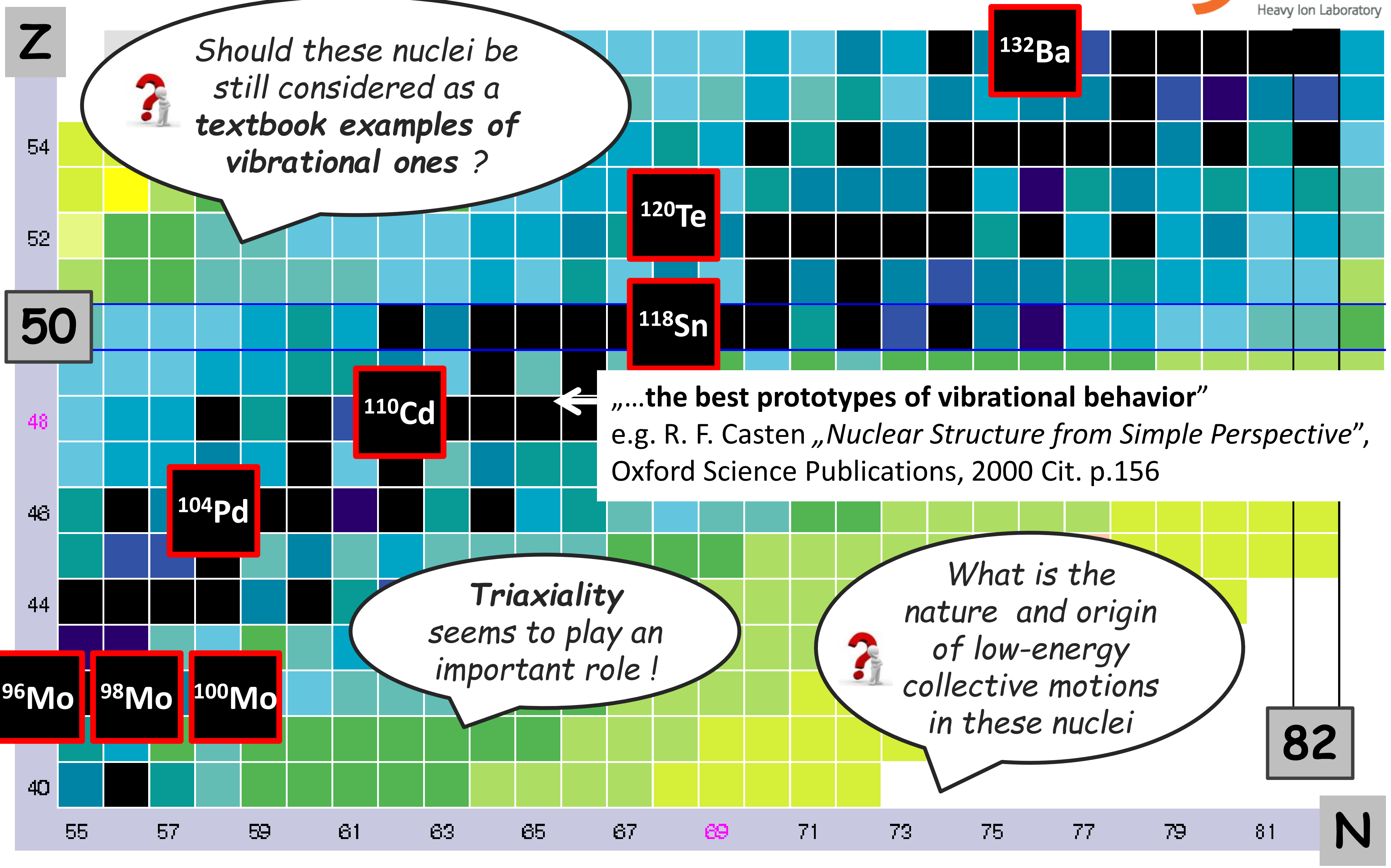


J. Srebrny et al., NPA 766 (2006) 25



- CoulEx of ^{104}Ru : **Lawrence Berkeley Laboratory**
- **various beams** used: **^{208}Pb, ^{136}Xe and ^{58}Ni** ions.
- 17 low-lying excited states measured by Coulex
- The magnitudes and signs of **28 *E*2 and 3 *M*1 matrix elements** extracted.
- *Data are consistent with a non-harmonic vibrational structure that exhibits some quasi-rotational features*.

CoulEx studies @ HIL : A~100 region



The Cadmium Enigma

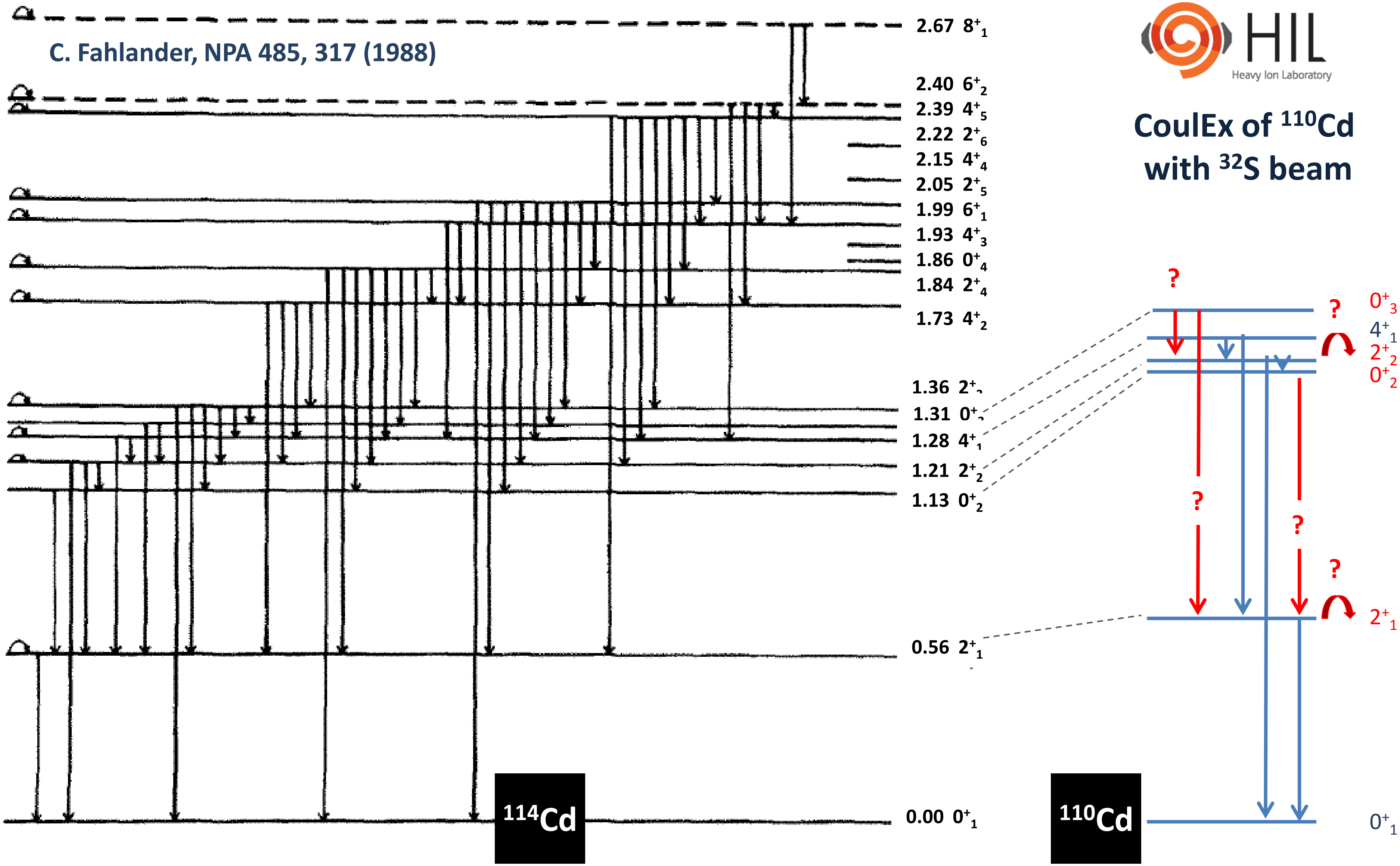
On the robustness of surface vibrational modes: case studies in the Cd region

data [14] and these have been reduced to diagonal and transition $E2$ matrix elements. The large diagonal $E2$ matrix element for the 2_1^+ and 4_1^+ states are particularly notable: they correspond to $Q(2_1^+) = -0.27$ eb and $Q(4_1^+) = -0.72$ eb [18], i.e. they suggest that ^{114}Cd may be deformed! This interpretation is contrary to the belief that nuclei near to closed shells are spherical. We look further at this new perspective below.

The data sets presented here illustrate that a wide suite of experimental probes may be necessary in order to understand even the most apparently simple patterns of excitation energy in nuclei. By far the most promising probe is very-high-statistics multi-step Coulomb excitation; but to date for the Cd isotopes this has only been carried out for ^{114}Cd, quite possibly because these isotopes were considered so obviously to be vibrational that there was no point in such measurements. The discrepancies between some $B(E2)$ values deduced

P. E Garrett and J. L. Wood J. Phys. G: Nucl. Part. Phys. 37 (2010) 064028

- Most detailed CoulEx study to date on Cd isotopes perfomed with ^{16}O, ^{40}Ca, ^{58}Ni, ^{208}Pb beams on ^{114}Cd (Uppsala EN tandem & Rochester and Brookhaven & UNILAC@GSI)
- In total **40** *E*2 matrix elements determined !



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CoulEx of ^{110}Cd with ^{32}S beam

CoulEx with stable beams @ HIL : perspectives

- Large demand for Coulomb excitation data for stable nuclei.
- Fundamental questions concerning nuclei from the **(A~100, Z~40,50) region**:

Spherical vibrators or deformed nuclei ?
Are there vibrational nuclei at all ?
Nature and origin of low-energy collectivity ?
Role of triaxiality ? Shape coexistence ?

} *the debate is still on-going.*

- A detailed Coulomb excitation studies are surprisingly scarce and critically needed !

- **The aim of the future projects:**

1. extensive, high-statistics multi-step Coulomb excitation experiments

   → a rich, <u>complete and precise</u> set of reduced matrix elements in stable nuclei;

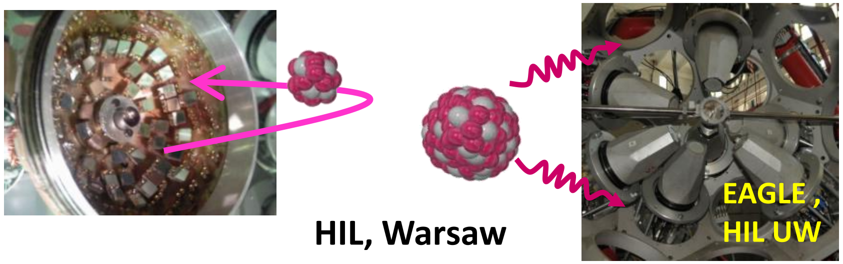
2. **differential measurements** of Coulomb excitation cross sections:

   → to disantangle **contribution from various excitation paths ,**

   → to gain sensitivity on **subtle effects** (quadrupole moments, signs of M*E*2's).

*Combining such a rich, high-precision data sets will consequently yield **shape parameters**, including **triaxiality**, and opens a possibilities to describe their **softnesses**.*

Experimental needs:



1. The use of **various beam ions** differing with Z,

   e.g.: **^{16}O (Z=8), ^{32}S(Z=16), ^{58}Ni (Z=28), … , ^{208}Pb(Z=82)**

2. Beam energies: **2.5 – 4.5 MeV /A** , beam intensities: **1 pnA**

3. Efficient γ detection array:

   EAGLE (30 HPGe of 70% eff., GAMMAPOOL), **AGATA**

4. Experiments with **normal** and **inverse kinematics**, e.g.:

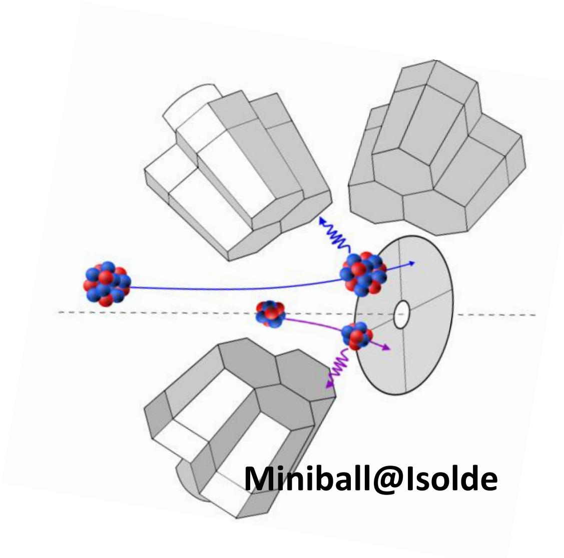
   ^{208}Pb(^{104}Pd,^{104}Pd) or **^{104}Pd(^{208}Pb,^{208}Pb)**

   → forward particle detection geometry.

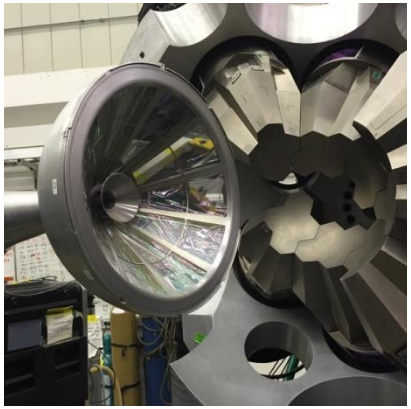
5. **Broad C.M. angular range** covered by particle detectors (incl.~90^0)

6. Type of detectors: **segmented Si** and/or **CVD** (12 μm) → ϑ, E information

7. Simultanues measurements of **conversion electrons** (*E*0 transitions)

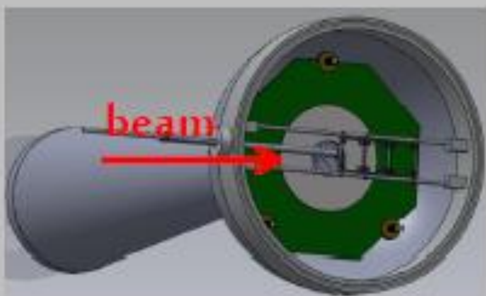


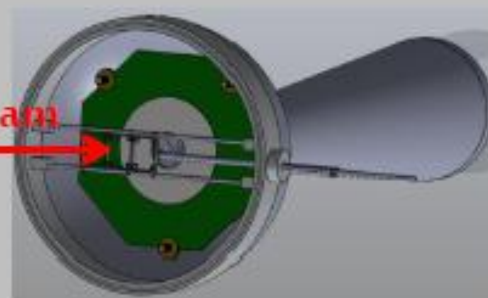
CHIC0@ANL, 20 PPAC's
12^o < θ < 85^o & 95^o < θ < 168^o



New CouLEx chamber

under construction

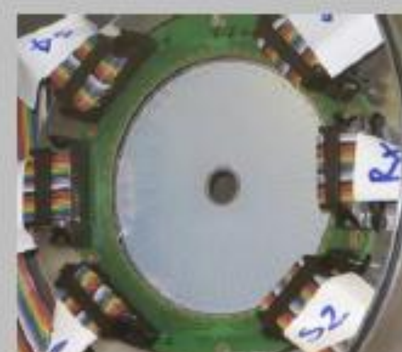




20° < **θ** < 45° & 135° < **θ** < 160°

DSSSD
CD type
64 phi sectors
32 theta rings

CVD SC
diamond detector
5 mm x 5 mm
Ultra thin membrane (12 um)
possible to be applied
as a radiation resist HI detector
at forward scattering angles



DSSSD
CD type
other
possible
solution form
CEA Saclay

Courtosy of P. J. Napiorkowski

Outlook

- **High-statistics, detailed, multi-step Coulomb excitation** experiments are of critical need for many stable nuclei.

- **Fundamental questions** still need to be answered for a number of stable, „well-known" nuclei concerning the nature and origin of their low-energy collective structure (*e.g. region of* ***Cd, Ru, Pd, Te*** *isotopes*).

- What is needed ?
  Precise measurements of particular $\mathbf{Q_{sp}}$ **, B(*E*2)** values of excited states as well as **relative signs** of M(*E*2)'s.

- **Nuclear-model independent** extraction of quadrupole **deformation** parameters, including **asymmetry parameter**, of individual excited nuclear states.

- Such detailed experimental information opens as well the possibilities to extract **softnesses** of the quadrupole shape parameters.

- Veryfication and comparison with state-of-art nuclear models (GBH, MCSM, BMF, …)