06/01/2020

Exotic nuclear shapes with radioactive ion beams

@lpgaff

Liam Gaffney (University of Liverpool)

UK Nuclear Physics Community Meeting

6th January 2020 – Warwick, UK

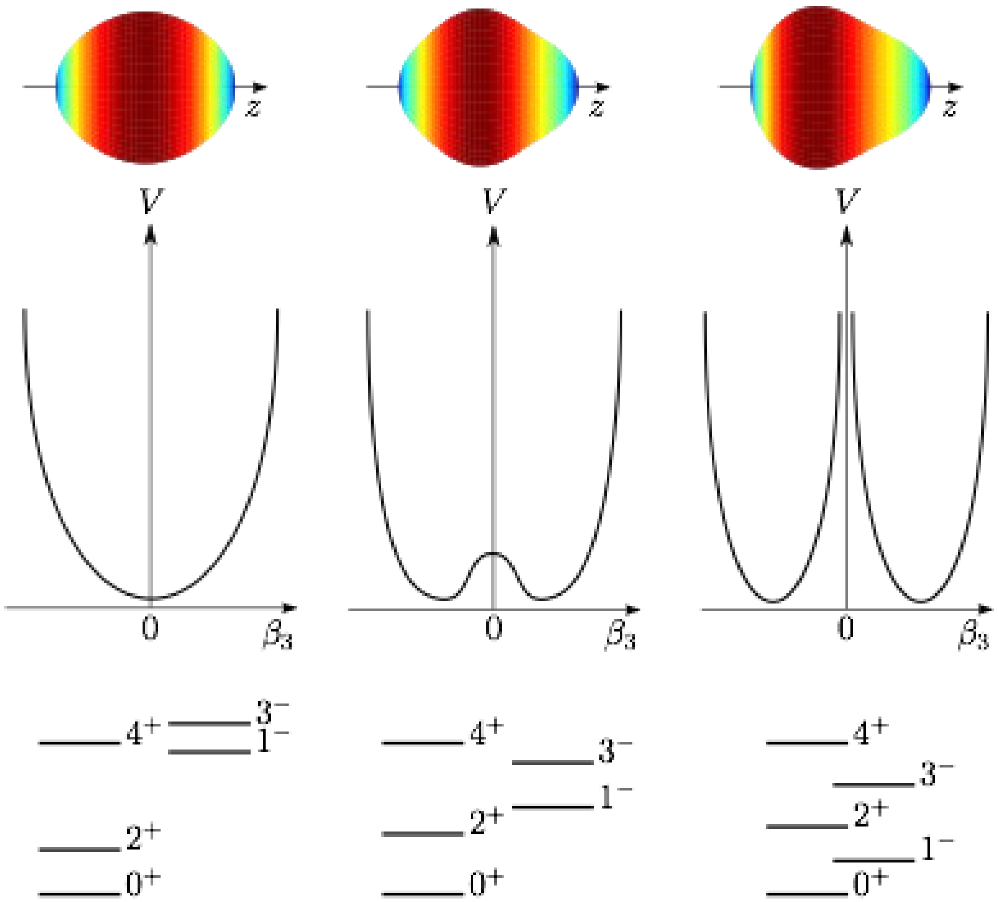
Exotic shapes ≡ octupole

Macroscopically…

- Nuclei take on a “pear” shape
- Reflection asymmetric
  - β_3-vibration
  - Static β_3-deformation
  - Rigid β_3-deformation…

Signatures…

- Odd-even staggering, -ive parity
- Parity doublets in odd-A nuclei
- Collective B(E3) transitions



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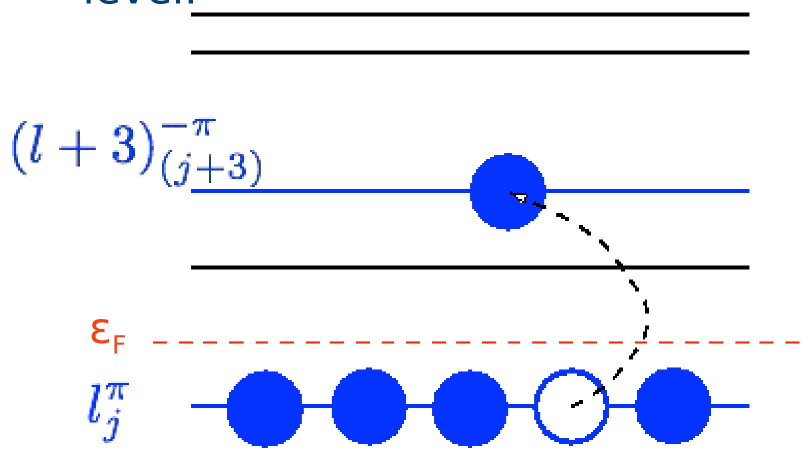
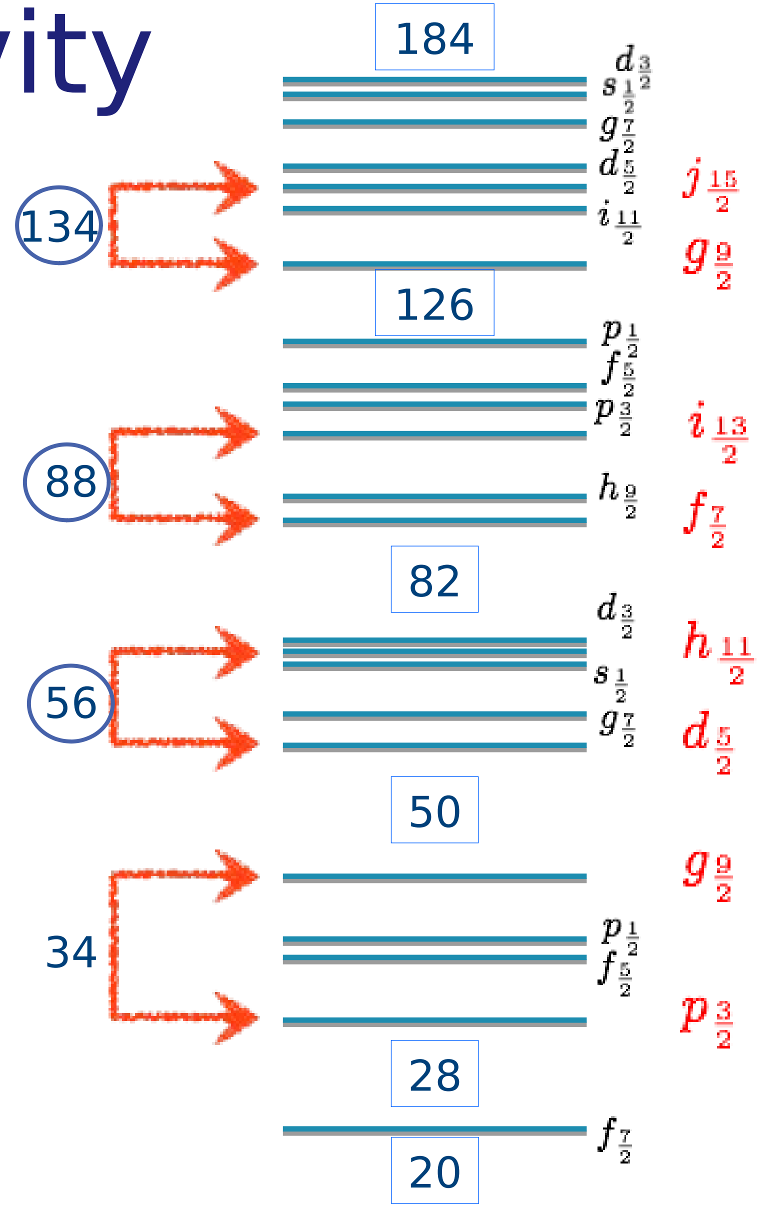
Octupole Collectivity

Microscopically driven

- Intruder orbitals of opposite parity and ΔJ, ΔL = 3 close to the Fermi level.





^{224}Ra (actinides)
Z = 88, *N* = 134 region

^{144}Ba (lanthanides)
Z = 56, *N* = 88 region

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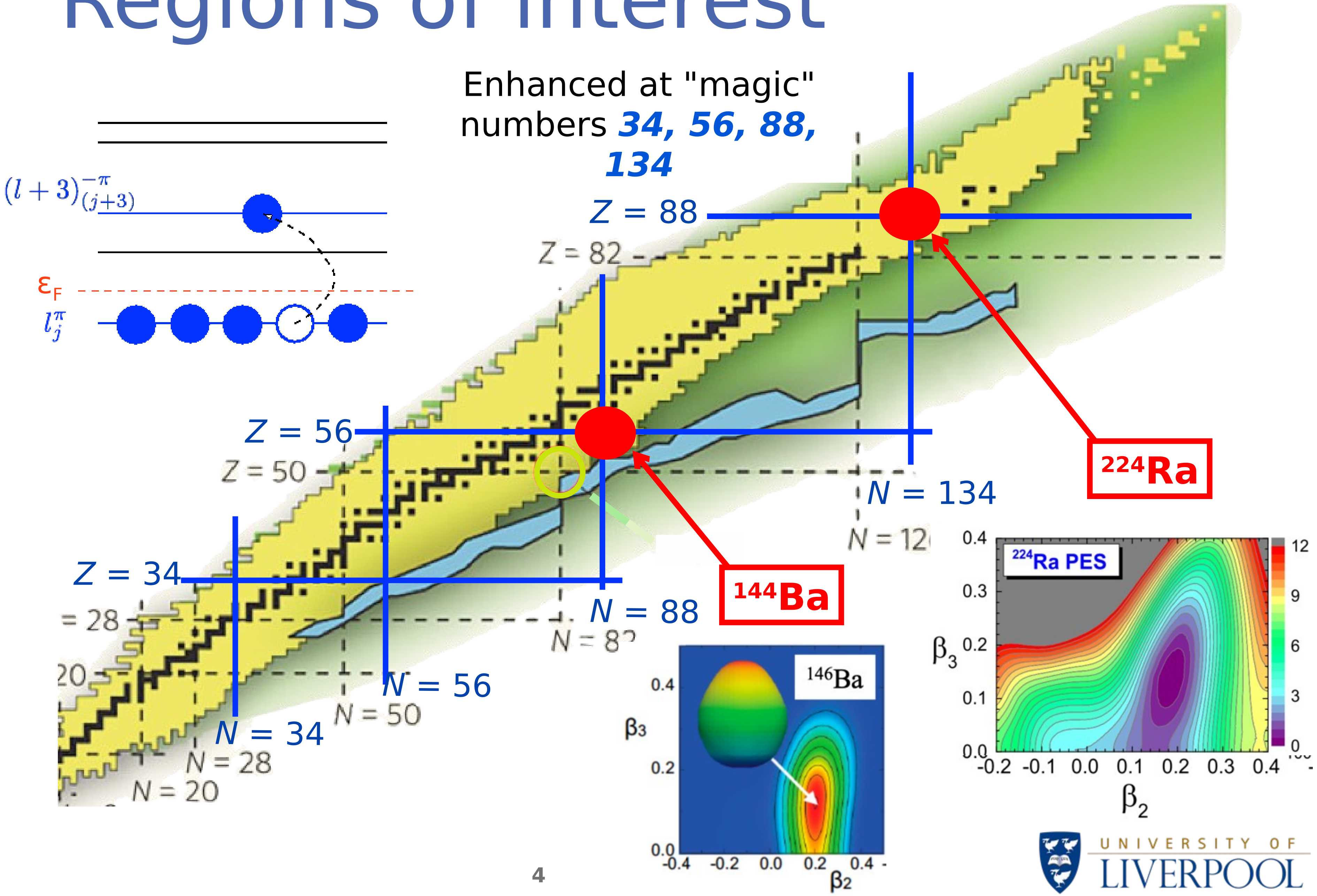
Regions of interest

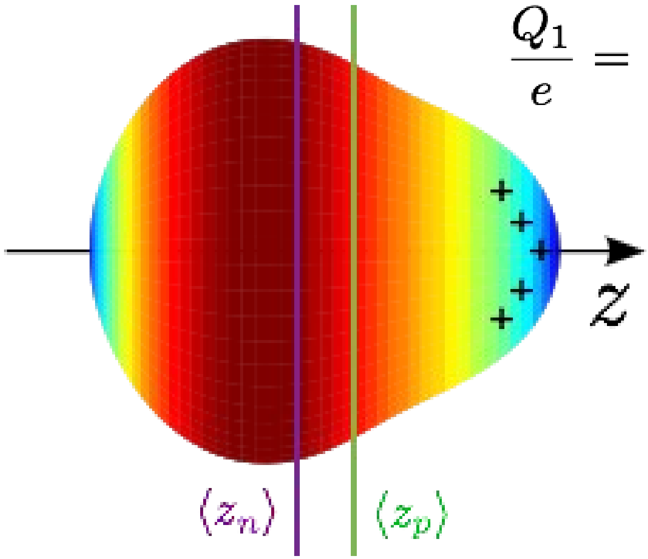
Enhanced at "magic" numbers ***34, 56, 88, 134***

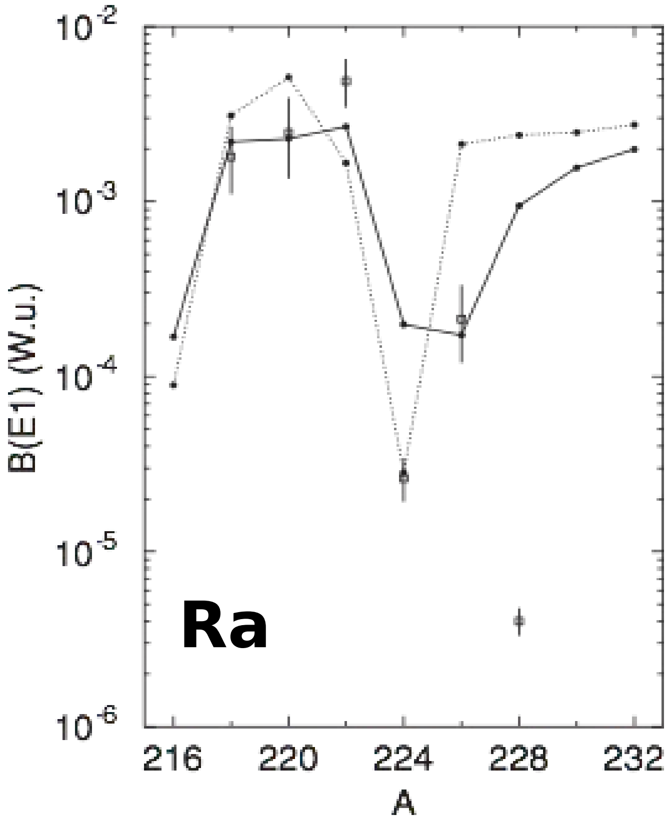


Quantifying octupole collectivity, *B(E1)*

$$B(E1; I_i \rightarrow I_f) = \frac{3}{4\pi}(I_f 010|I_i 0)^2 Q_1^2$$

$$\frac{Q_1}{e} = \frac{N}{A}\langle z_p \rangle - \frac{Z}{A}\langle z_n \rangle$$





- Two contributions to Q_1:
  - *Macroscopic* of the order **+0.1 fm**
  - *Microscopic* of the order **-0.1 fm**

- Cancellation gives small *B(E1)* in ^{224}Ra and ^{146}Ba; both strong octupole candidates.

L.M. Robledo et al., *Phys. Rev. C* **81**, 034315 (2010)

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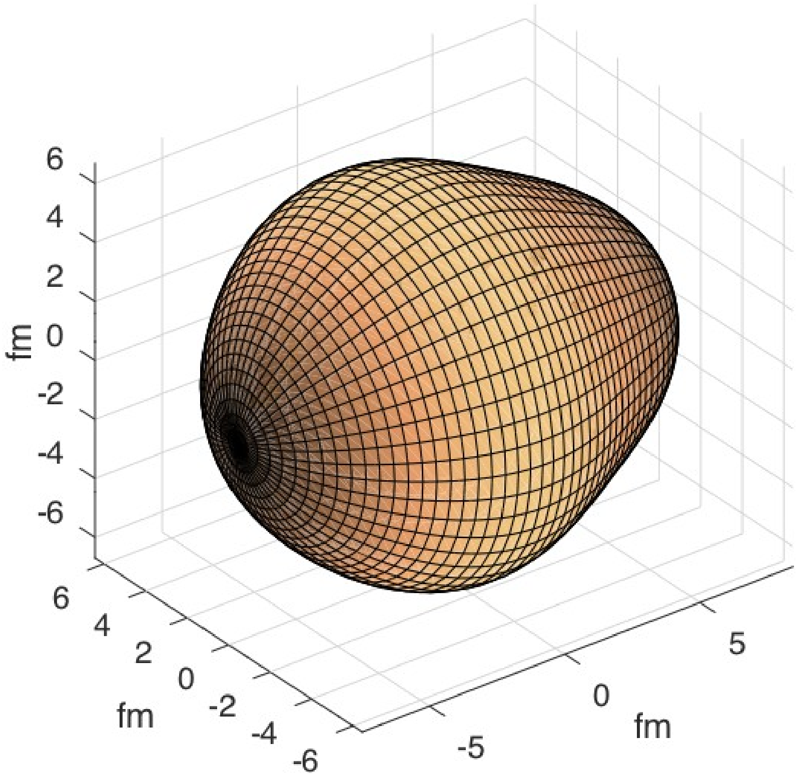
Quantifying octupole collectivity
B(*E3*)

Pros:

- Insensitive to single-particle effects
- Direct measure of octupole collectivity
- Linked to deformation via β_3 parameter



Cons:

- Difficult to access *E3* transitions
- Excited state decay dominated by *E1*/*E2*

Solved! Use **Coulomb excitation** from the ground state!

$$Q_3 = \frac{3}{\sqrt{7\pi}} ZeR_0^3\overline{\beta_3}$$

$$B(E3; I_i \rightarrow I_f) = \frac{1}{2I_i+1}\langle I_f||E3||I_i\rangle^2$$

B(E3) >~ 30 W.u. gives significant β_3

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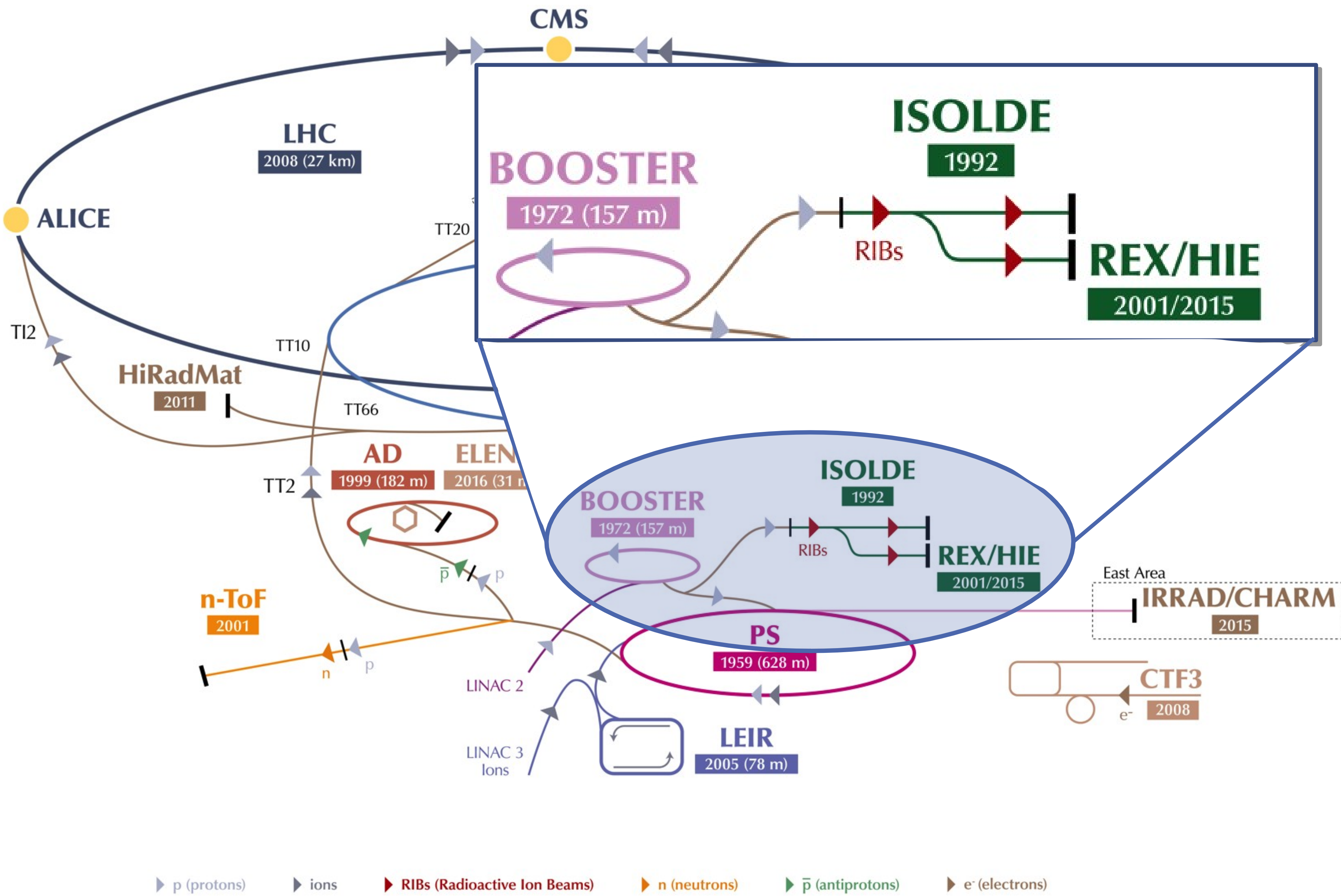
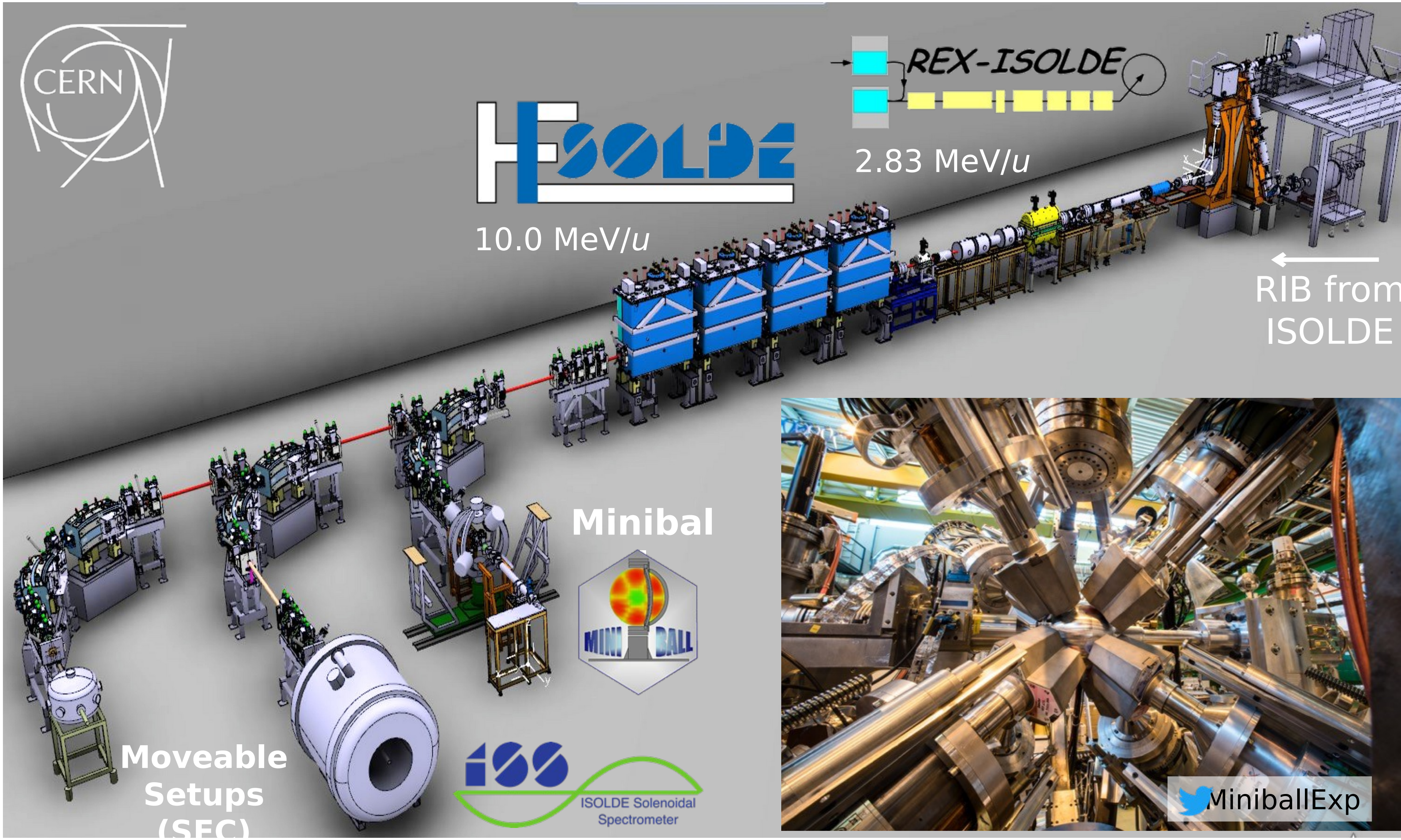
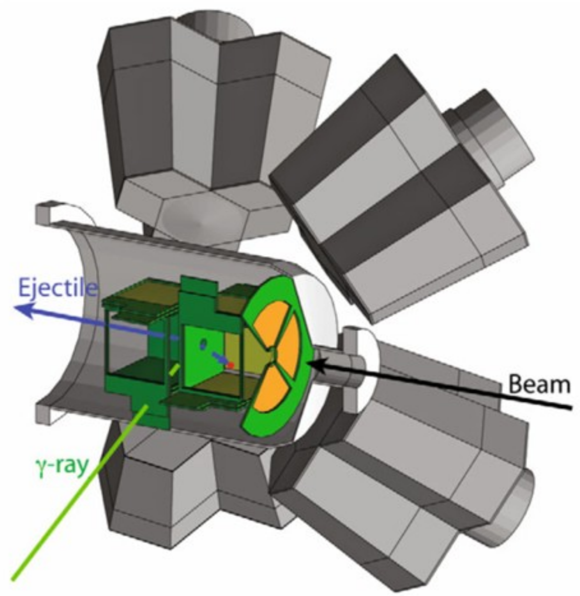
CERN accelerator complex



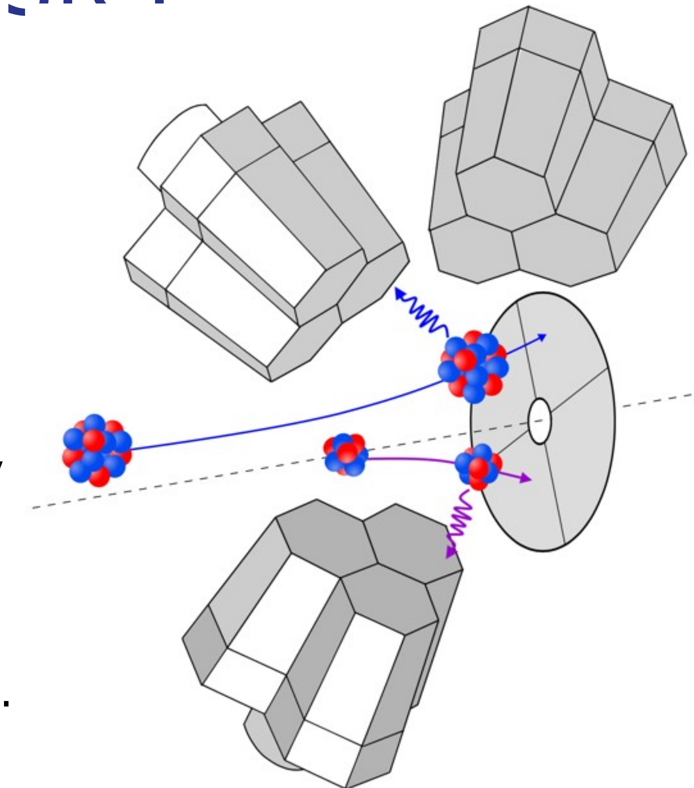
HIE-ISOLDE Phase 2 (2018)



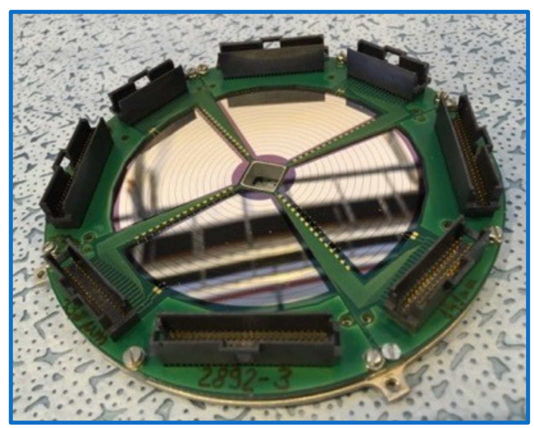
Miniball: Coulex or transfer



- Array of HPGe of 8 x triple clusters
- 6-fold electronic segmentation
- ε > 7% for 1.3MeV γ-rays
- Event-by-event Doppler correction.



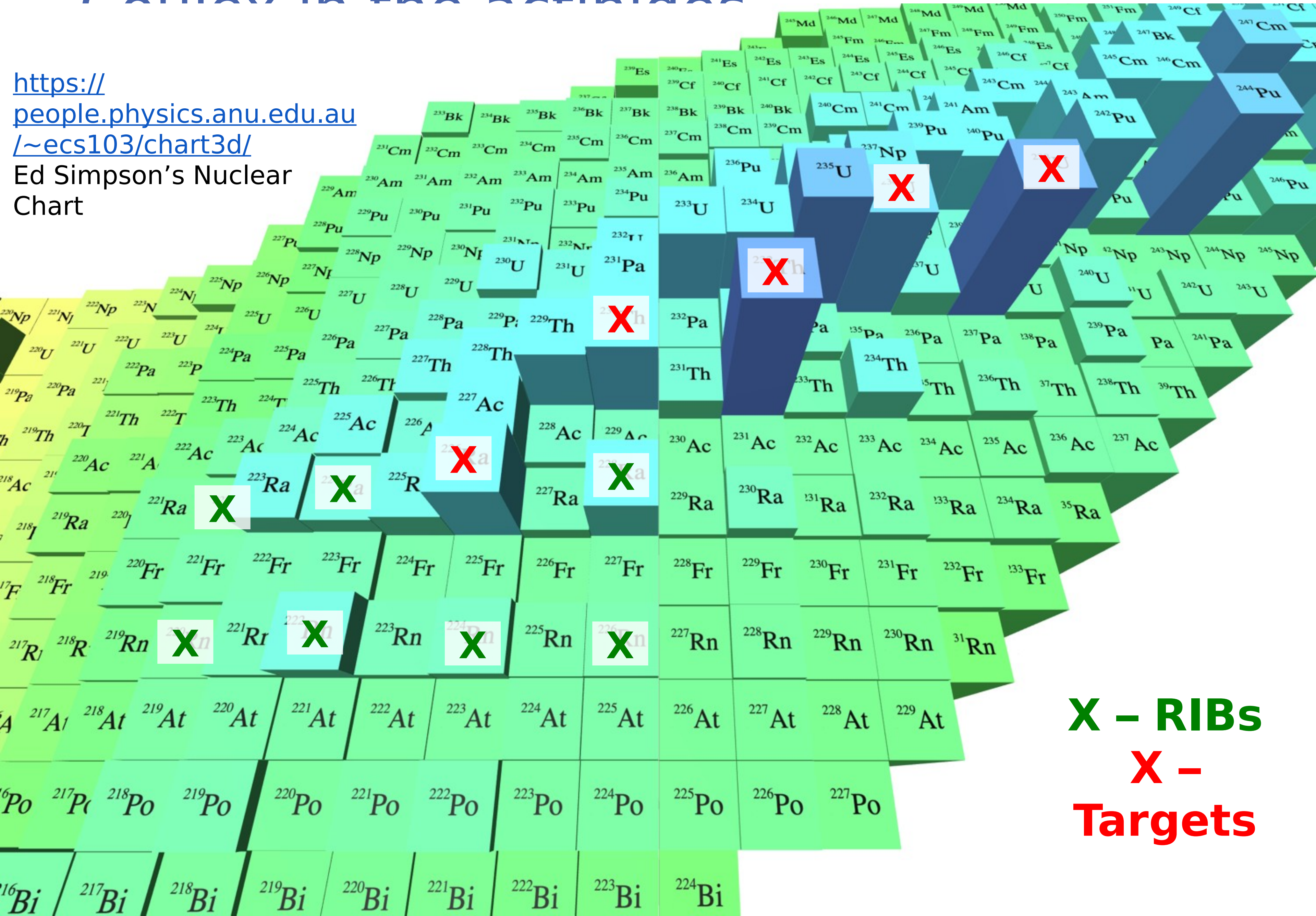
- Particle ID in segmented Si detectors, telescope configuration.
  - Forward CD only; plunger possible.
  - Barrel configuration; large coverage.
  - Complementary to new ISS setup!



N. Warr et al., EPJ **49** (2013)

Coulex in the actinides

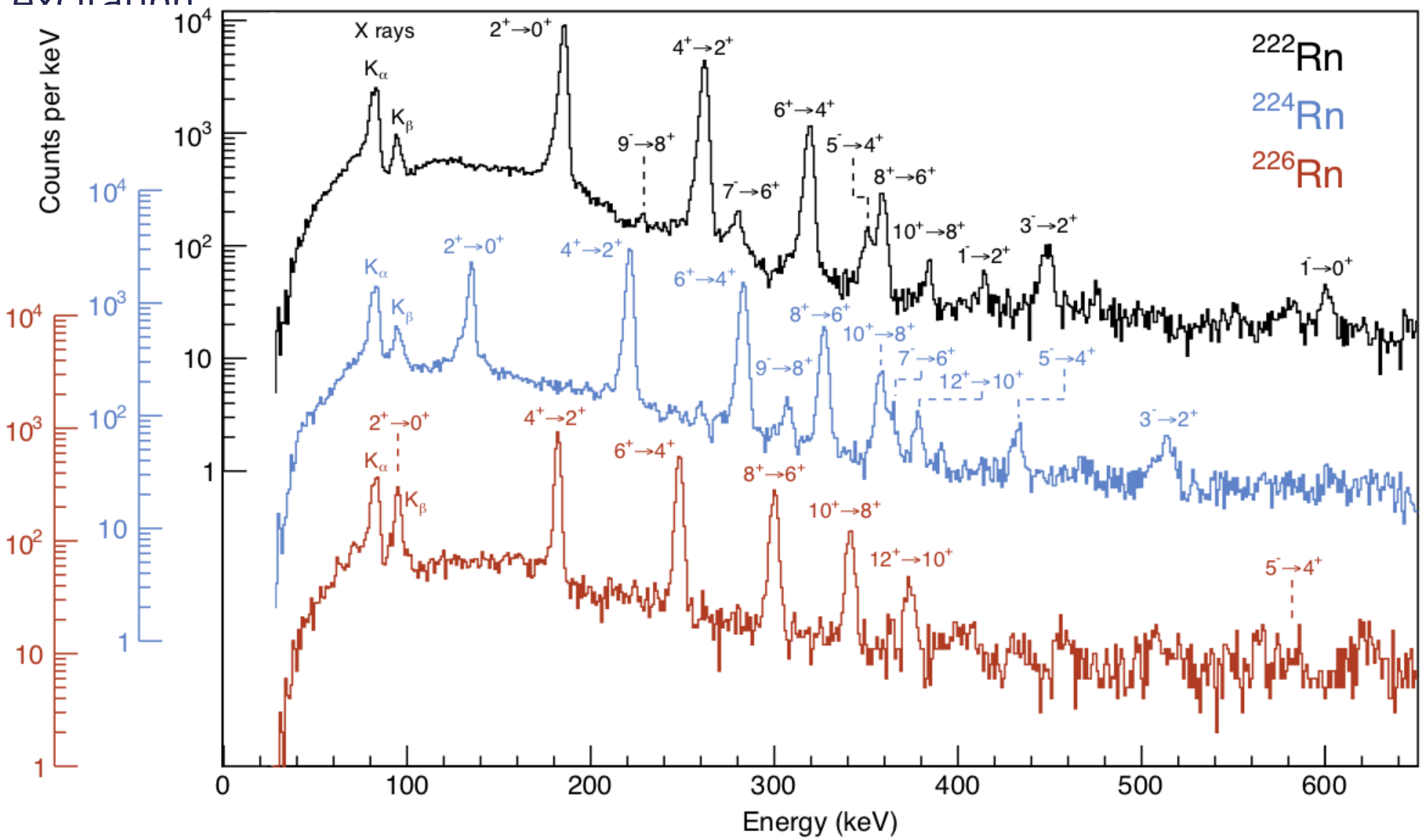
https://people.physics.anu.edu.au/~ecs103/chart3d/
Ed Simpson’s Nuclear Chart



X – RIBs
X – Targets

^{224,226}Rn – Virgin nuclei

- Higher beam energy (5.1 MeV/*u*), with aim of maximising multi-step excitation

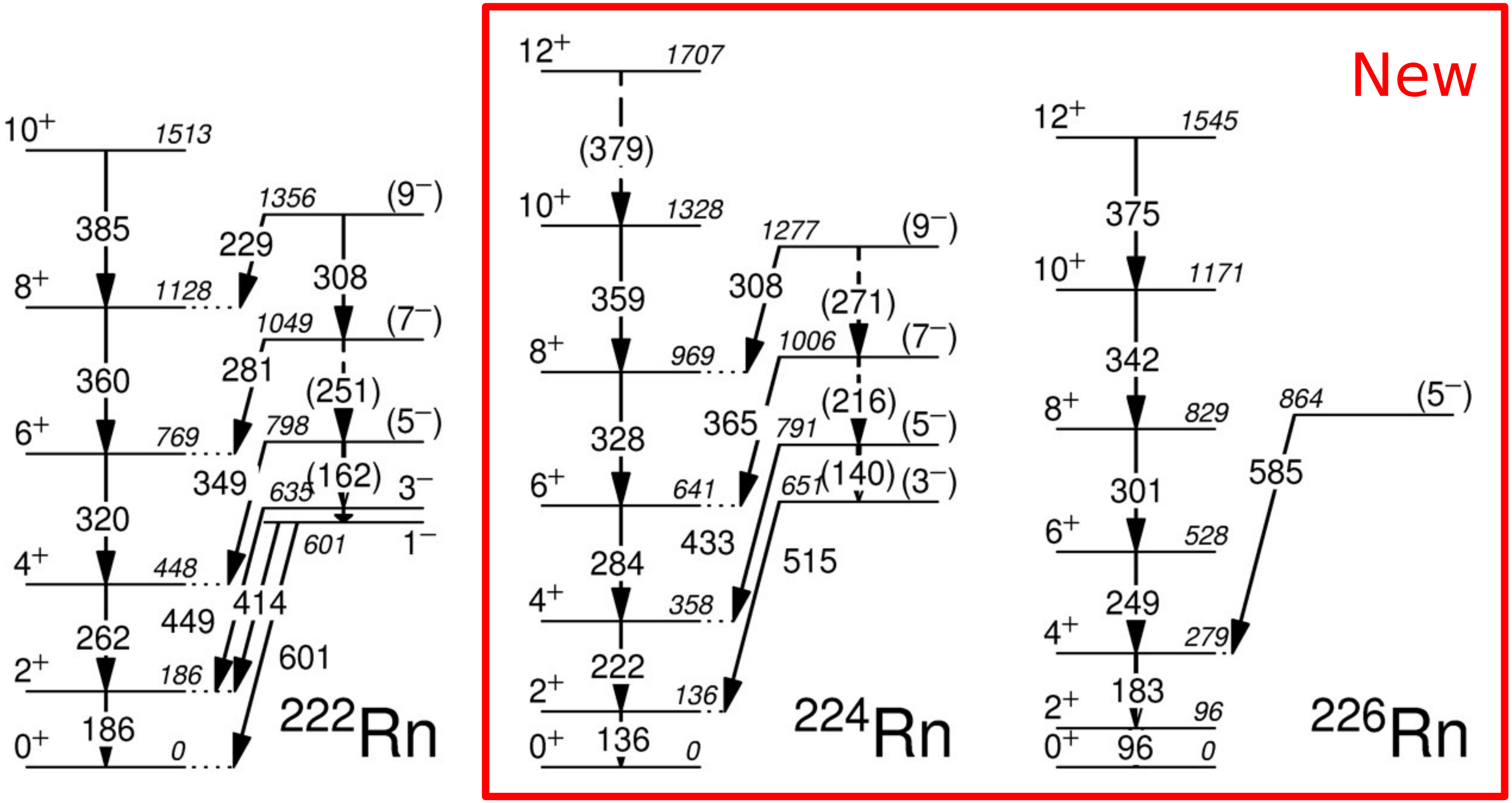


P. A. Butler, et al, *Nature Comm.* **10**, 2473 (2019).

Building level schemes with Coulex

- Looking for low-lying negative-parity states, using p-γ-γ coincidences.
- Where is the 3^- state in the heavy Rn nuclei? □ EDM searches

P. A. Butler, et al, *Nature Comm.* **10**, 2473 (2019).



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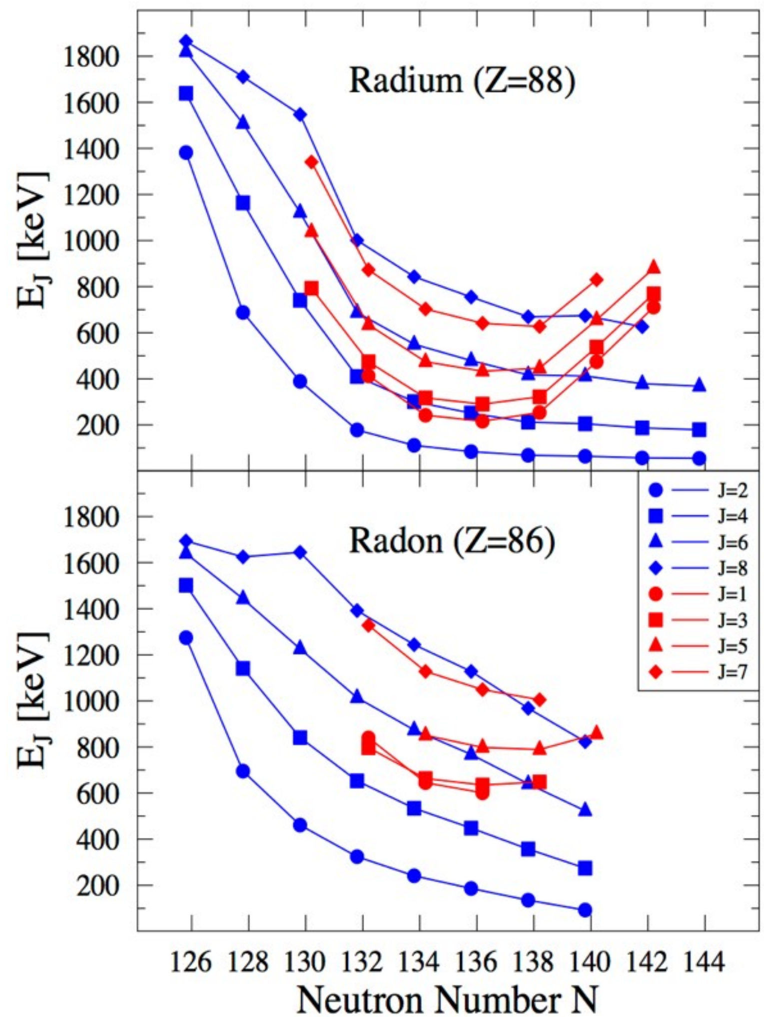
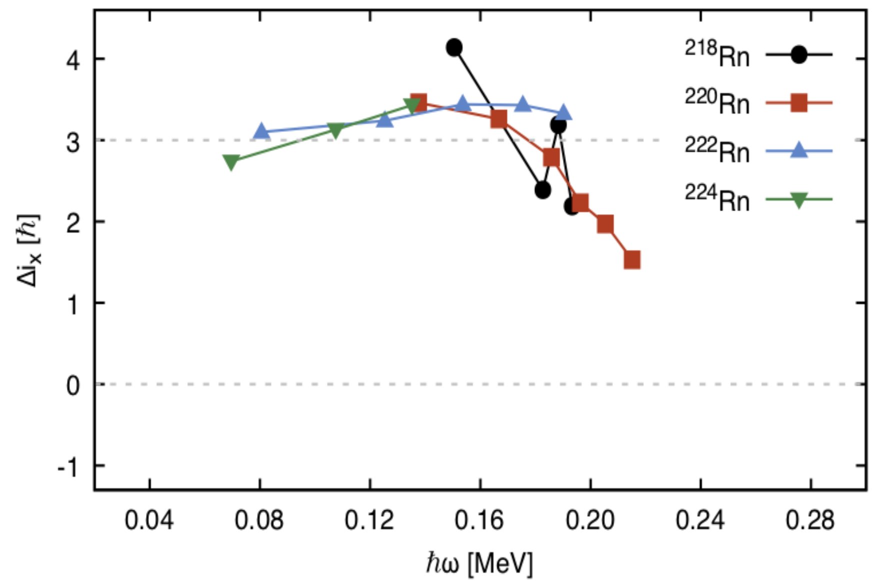
Vibrational or deformed?

ERF □ Direct $\Delta E_{\pm}$ measurements in odd-mass Rn isotopes

- Are ^{221,223,225}Rn good candidates for the EDM measurements?

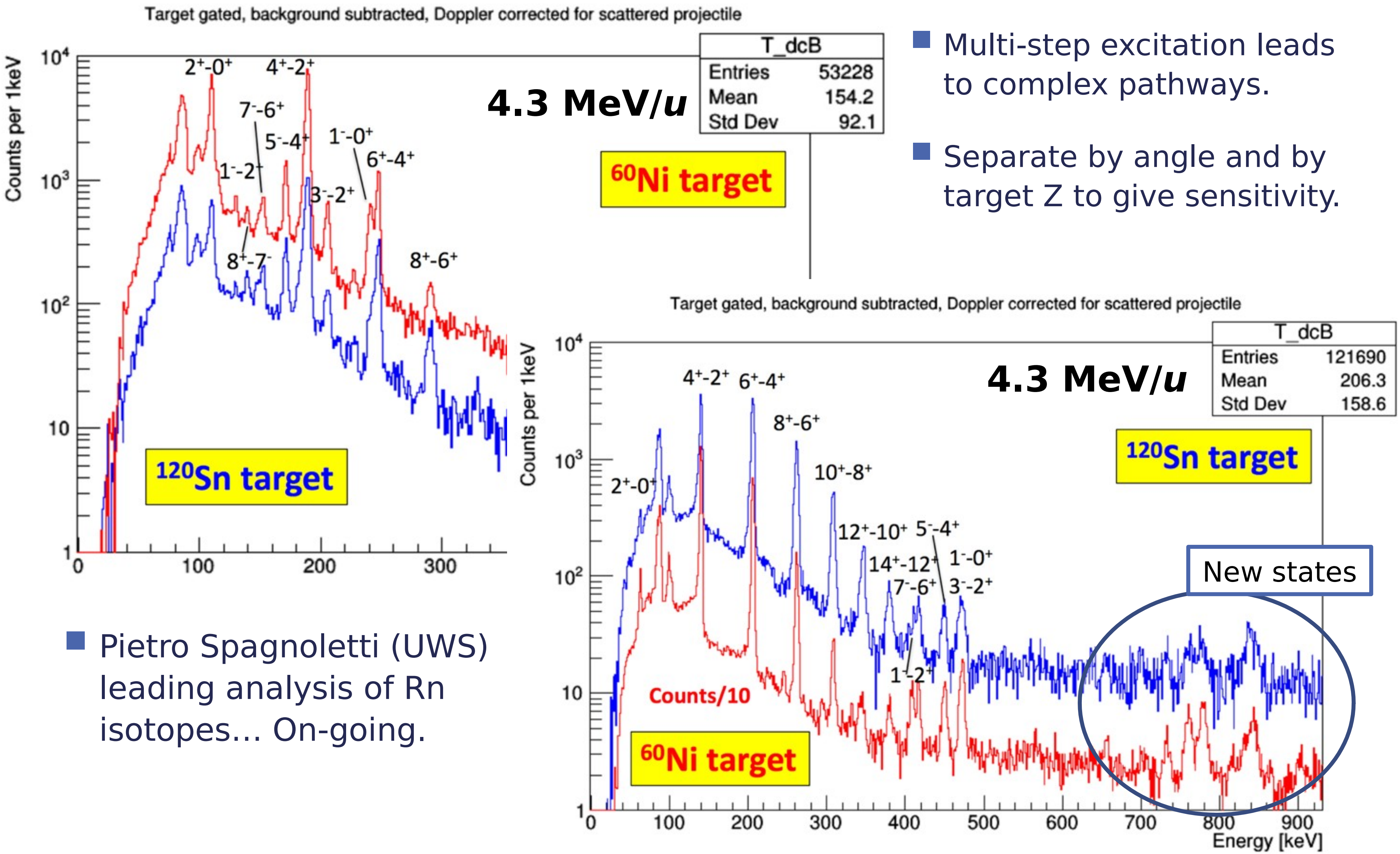


- Relative alignment of positive- and negative-parity bands…
- $\Delta i_x = 3\hbar$ is vibrational limit?



E3 matrix elements needed!

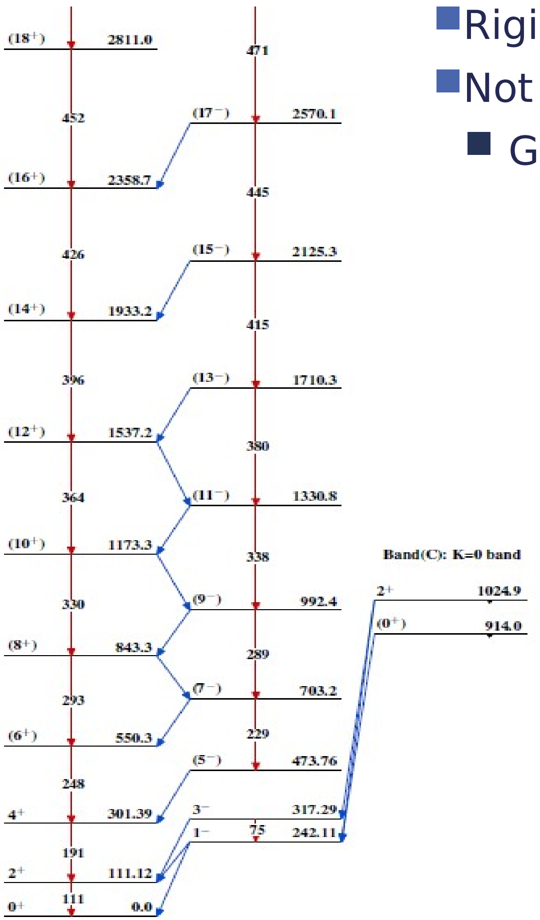
^{222,228}Ra @ HIE-ISOLDE

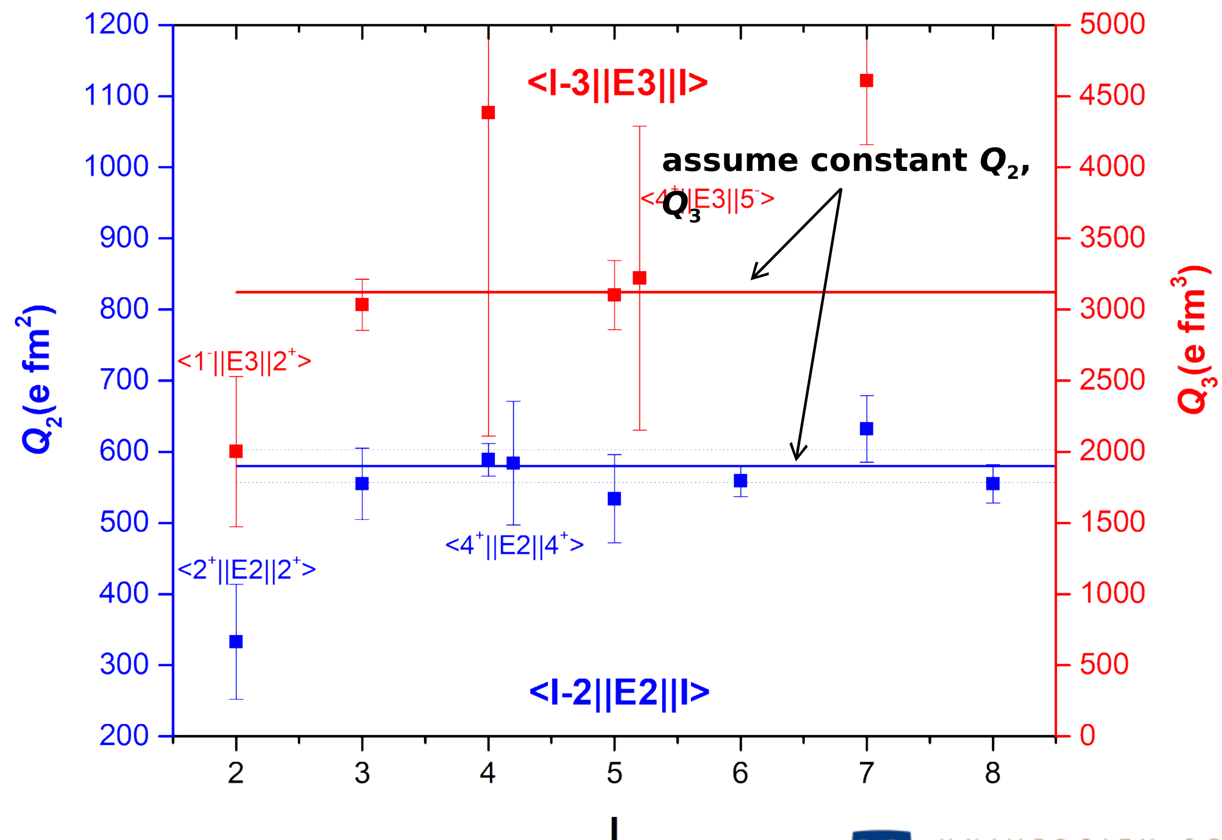


- Multi-step excitation leads to complex pathways.
- Separate by angle and by target Z to give sensitivity.
- Pietro Spagnoletti (UWS) leading analysis of Rn isotopes… On-going.

Coulex analysis of ^{222}Ra

- Rigid-rotor model good predictor for *E2* and *E3* matrix elements.
- Not a constraint in the final analysis!
  - GOSIA: least-squares fitting code, established techniques





4 angles x 2 targets
9 branching ratios
114 data, 42 variables

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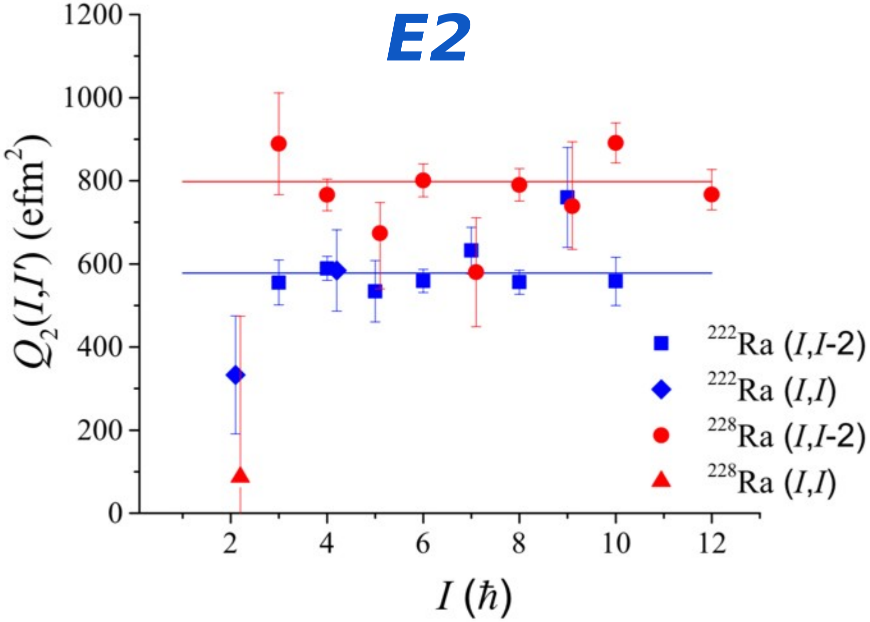
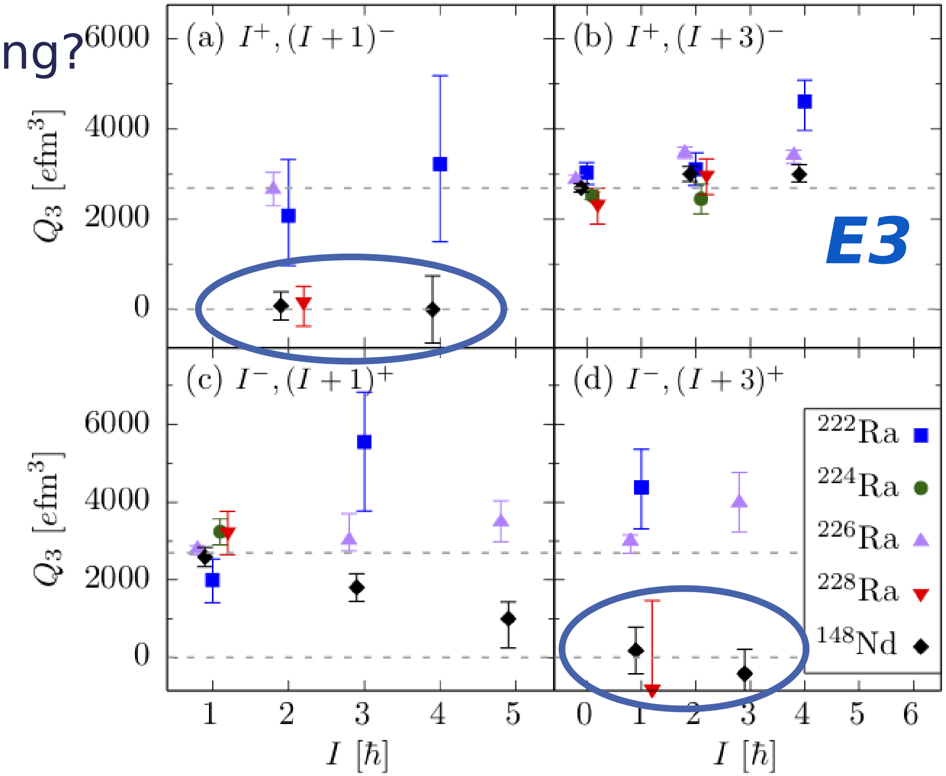
$E\lambda$ matrix elements – ^{228}Ra

- Similar behaviour of *E2* matrix elements between ^{222}Ra and ^{228}Ra.
- Remarkable differences in some *E3* matrix elements for ^{228}Ra.
  - **Deviation** from rotational model.
  - Evidence of **vibrational** coupling?

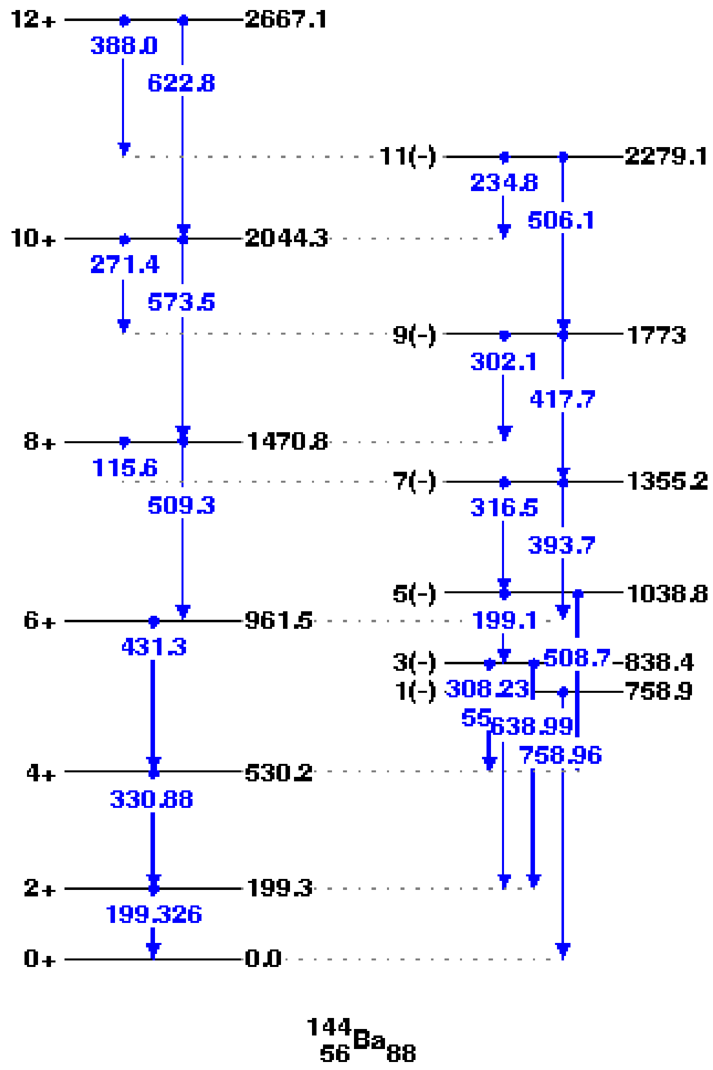
e.g. $\langle 1^{-} || E3 || 4^{+} \rangle = 0$





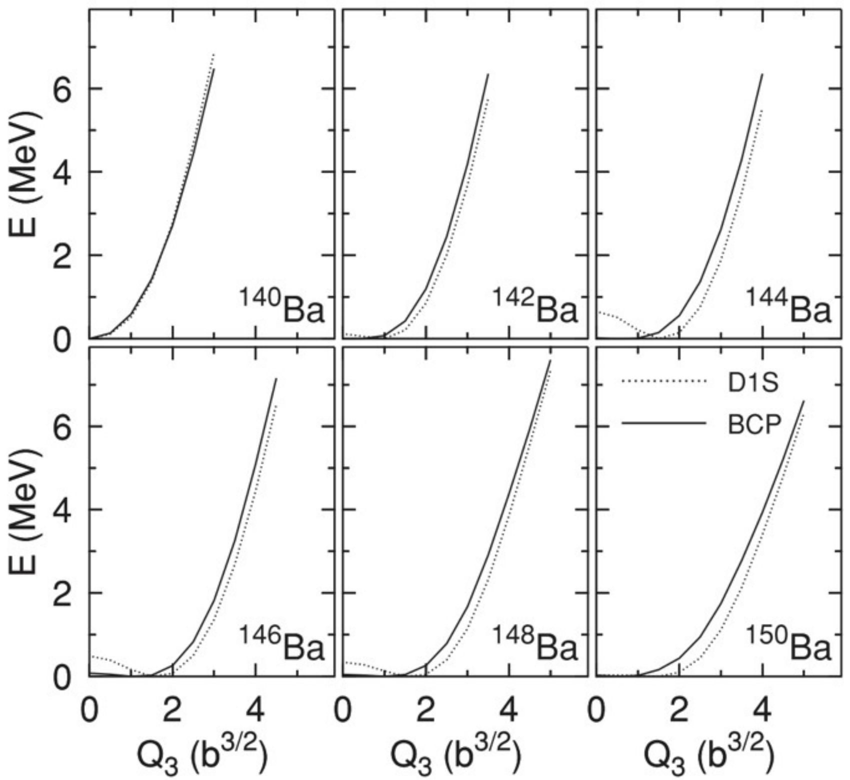
Submitted to *PRL*

Lanthanides: ^{142,144}Ba



- Predicted by mean-field approaches to be most likely candidates for β_3 deformation in lanthanide region.

L. M. Robledo, M. Baldo, P. Schuck, and X. Viñas, Phys. Rev. C **81**, 34315

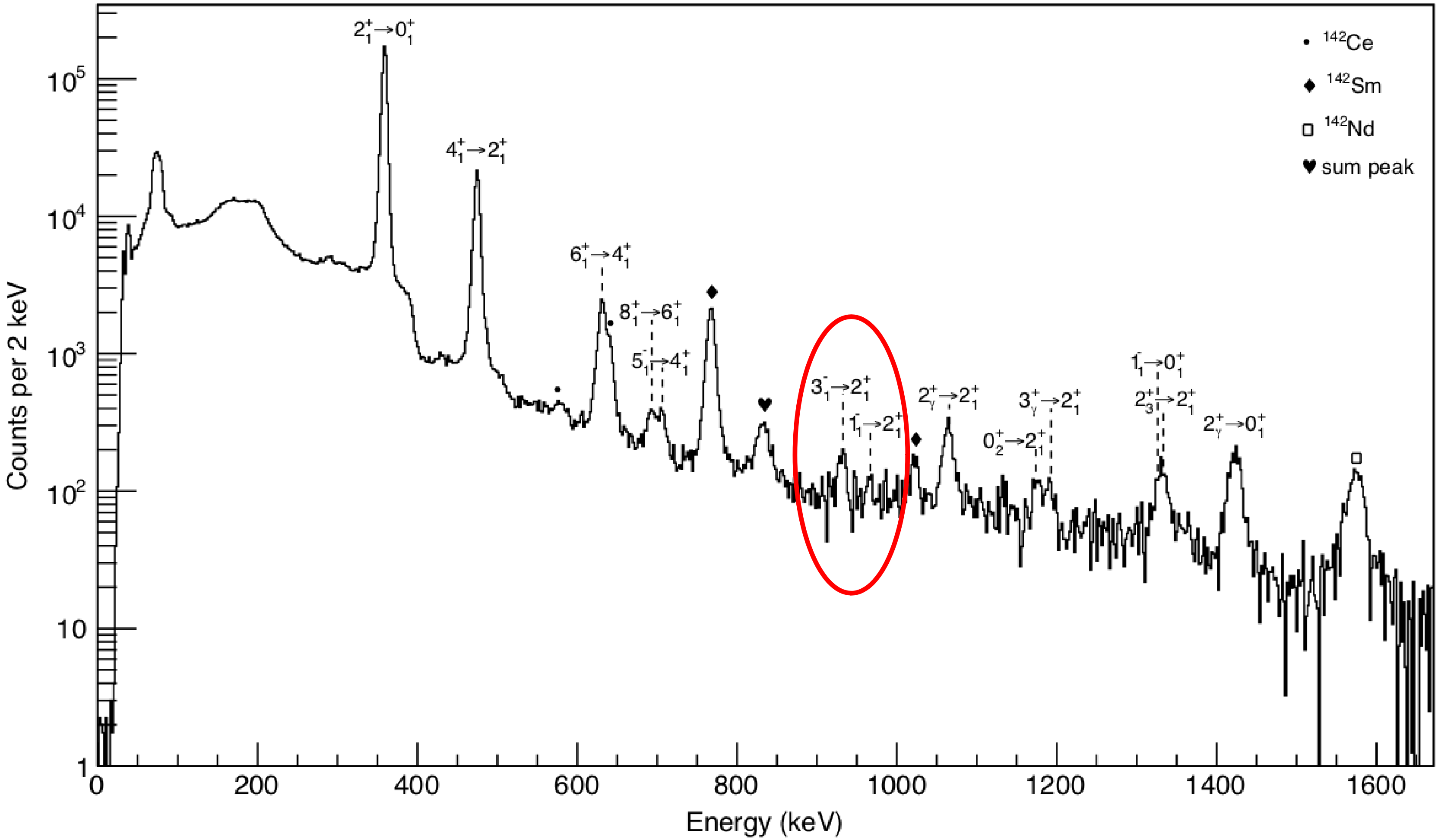


Spokesperson: M. Scheck (UWS)

^{142}Ba on ^{208}Pb

2018 data

- Laser ionised (RILIS) with Cs suppressed using beam gate.
- Small contamination from isobars, but 50% duty cycle from beam gate.



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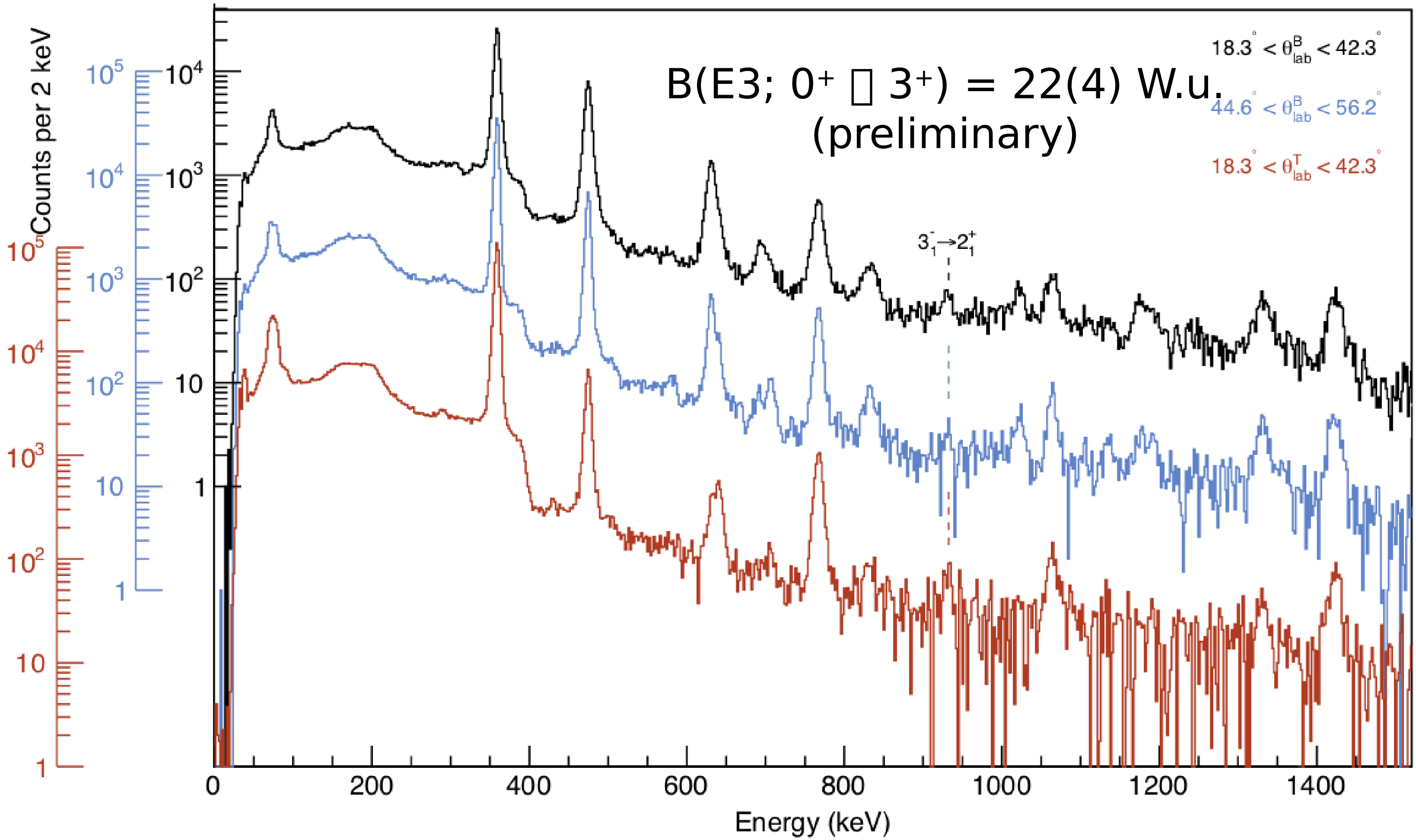

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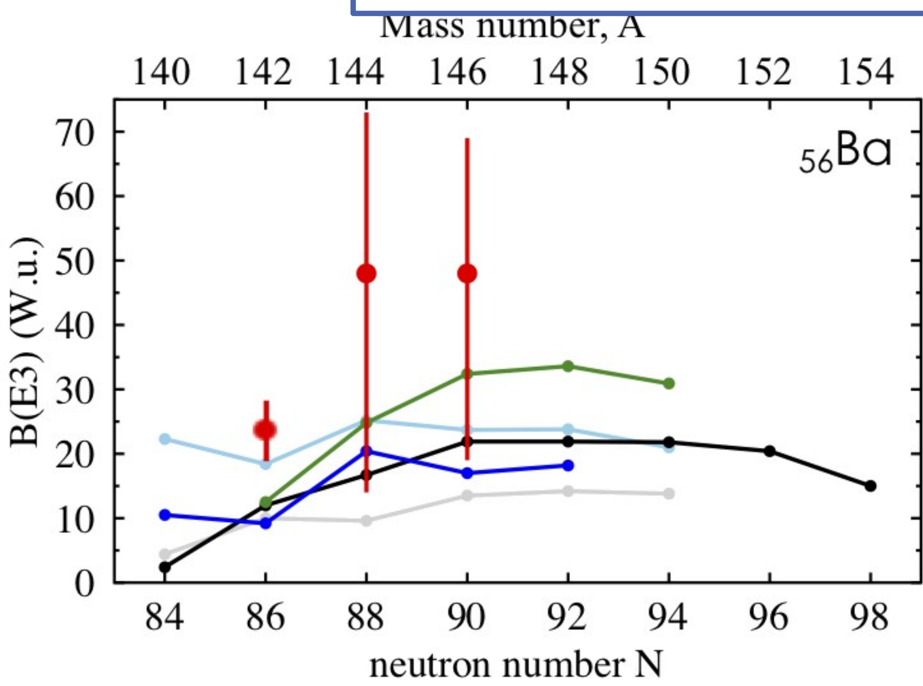
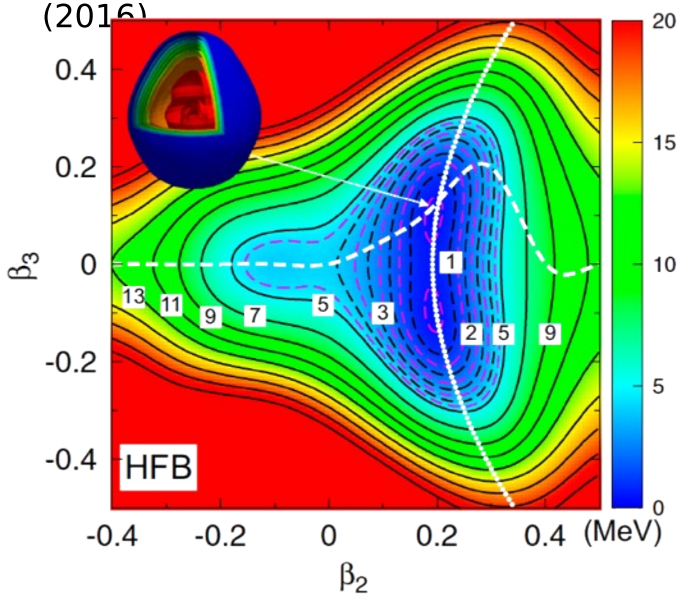
*B(E3)*s in Ba isotopes

Marcus Scheck (UWS) defended remaining ^{144}Ba shifts to run in 2021

- Many recent theoretical calculations…
  - Self-consistent mean-field basis, with beyond MF correlations.
  - Gogny and Skyrme functionals.
- Discussions on-going…



R. N. Bernard et al., *PRC* **93**, 061302 (2016)



B. Bucher et al., *PRL* **116**, 112503 (2016) & **118**, 152504 (201
L. P. Gaffney, M. Scheck et al., *to be published*

J.L. Egido and L.M. Robledo, *Nucl. Phys. A* **518**, 475 (1990)
J.L. Egido and L.M. Robledo, *Nucl. Phys. A* **545**, 589 (1992)

S.Y. Xia et al, *Phys. Rev. C* **96**, 054303 (2017)

L.M. Robledo et al., *Phys. Rev. C* **81**, 034315 (2010)

R. N. Bernard et al., *Phys. Rev. C* **93**, 061302 (2016)
T.R. Rodríguez, private communications

K. Nomura et al. *Phys. Rev. C* **89**, 024312 (2014)

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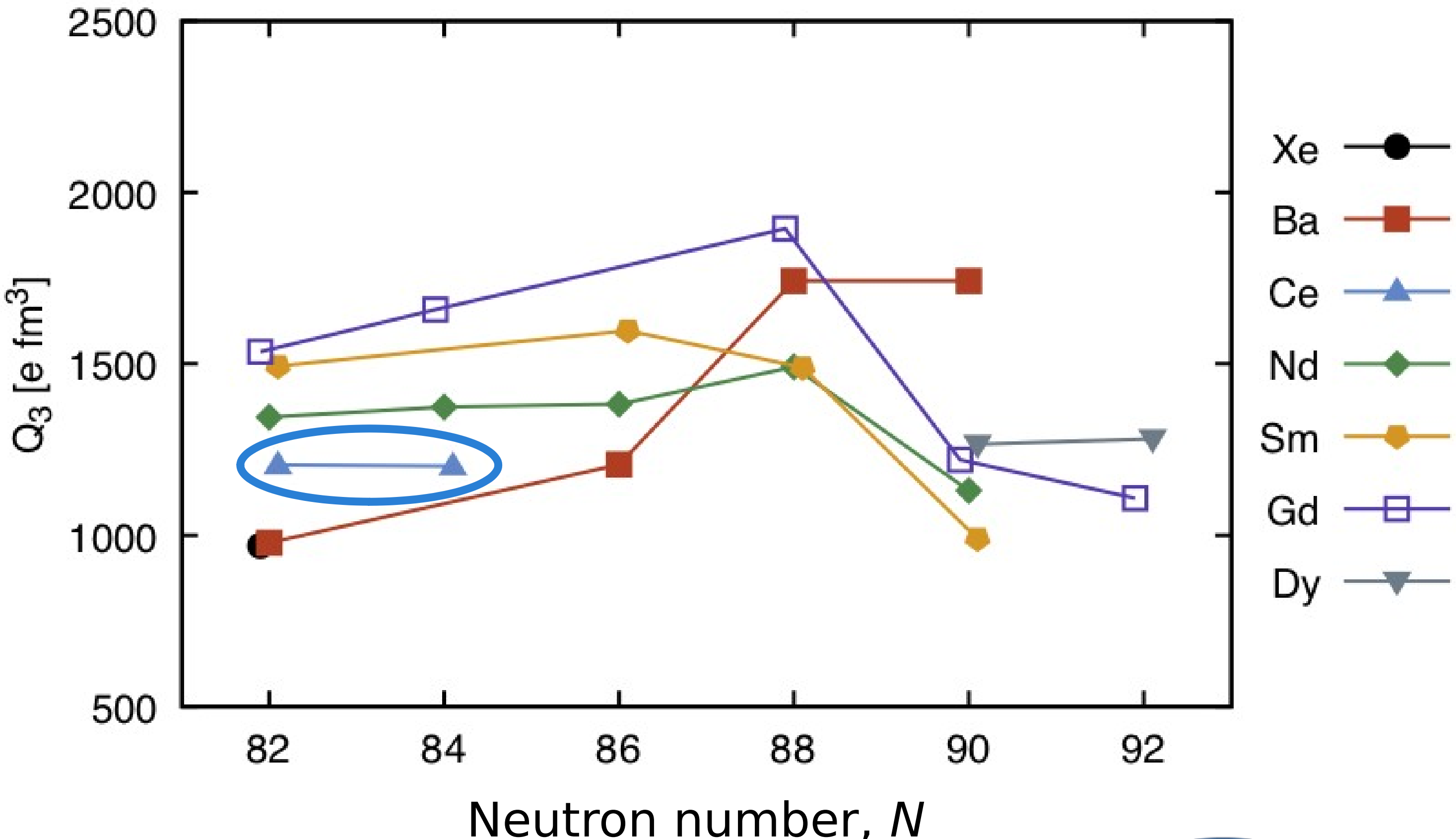
Experimental Q_3 - Lanthanides

- Summary of experimental *B(E3)*s in the lanthanides.
- Does Q_3 simply scale with Z? Where is the enhancement?
- Need more systematic data and more ***precise*** data!

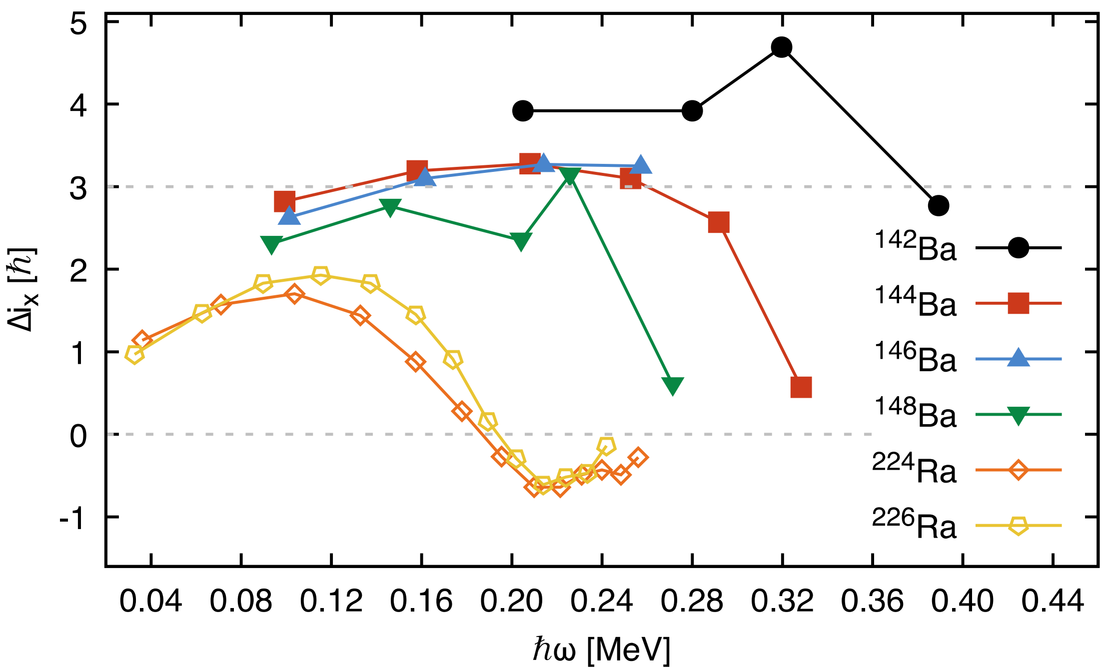
ERF Ce isotopes!



P. A. Butler, *J. Phys. G Nucl. Part. Phys.* **43**, 073002 (2016).

Vibrational or deformed?

- A lot of complementary evidence to say that Ba isotopes are octupole soft.
- Our *B(E3)* data are consistent with other values in the region.
  - Also consistent with large error bars from CARIBU.
- Can the relative alignment plots tell us enough information?
  - Does Q_3 provide the definitive argument?
  - What about □1^{-}||*E3*||4^{+}□ like in ^{228}Ra? □ Difficult in lanthanide region.



- Try to identify a signature of vibration or deformation.
- Experiment and theory consistency.
  - Conversation on-going…

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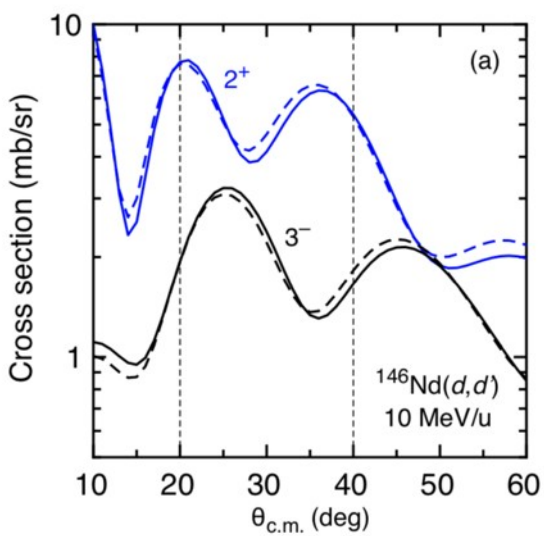
Alternative methods?

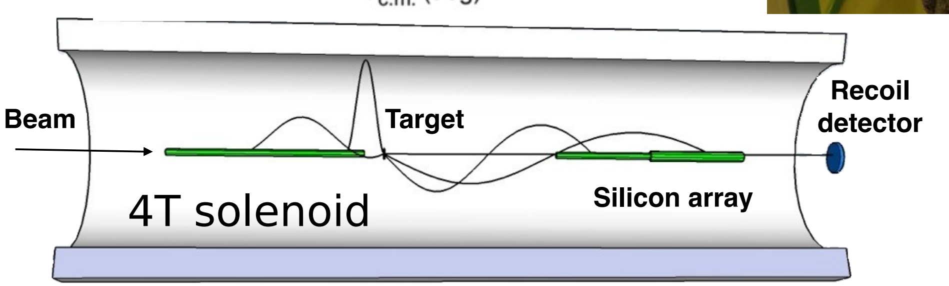
- What about (*d*,*d*′)?
  - Large cross sections.
  - Proportionality to deformation length or $\langle Q_3 \rangle^2$.

$$\left(\frac{d\sigma}{d\Omega}\right) \propto \langle Q_3 \rangle^2$$

ISOLDE Solenoidal Spectrometer



eng Yang



Helical orbit spectrometer principle

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ISOLDE Solenoidal Spectrometer

Solenoid with target on field axis.

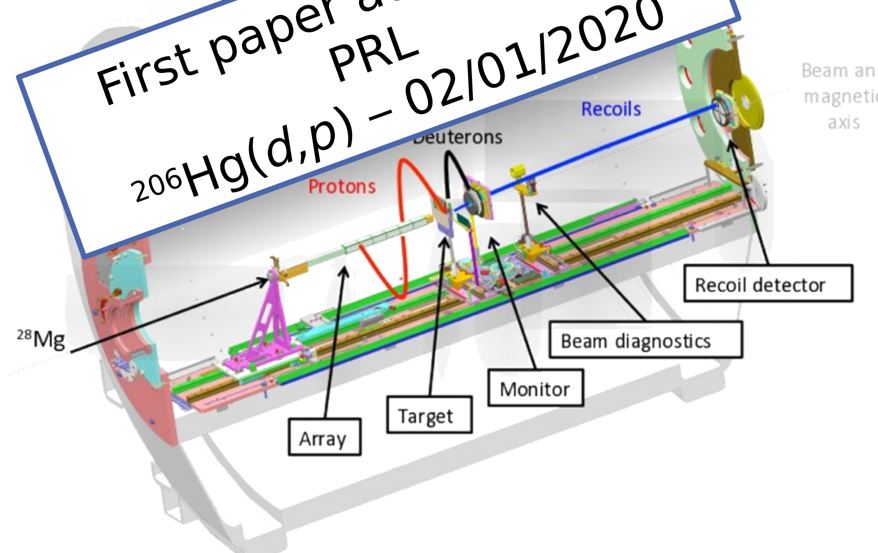
MEASURED QUANTITIES: position *z*, cyclotron period T_{cyc} and lab particle energy E_p

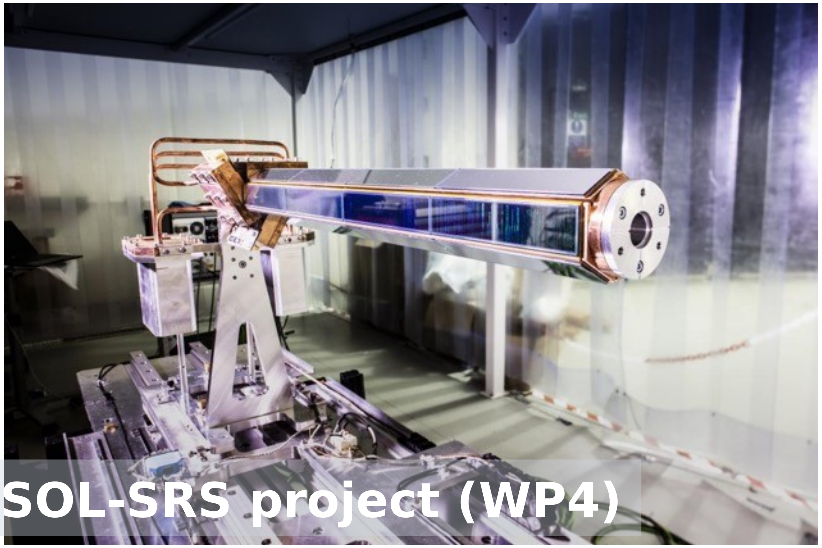
Suffers no kinematic compression of the Q-value spectrum.

Linear relationship between E_{cm} and E_{lab}

$$E_{\rm cm} = E_{\rm lab} + \frac{mV_{\rm cm}^2}{2} - \frac{mzV_{\rm cm}}{T_{\rm cyc}}$$

First paper accepted to PRL
$^{206}Hg(d,p)$ – 02/01/2020





Outgoing protons from (*d,p*) reaction follow helical orbits backwards to the beam/magnetic axis.
(*d,d'*) reaction goes forwards.
Detected by position sensitive silicon array.

Recoils detected downstream in dE-E silicon detector, or a gas-filled ionization chamber.

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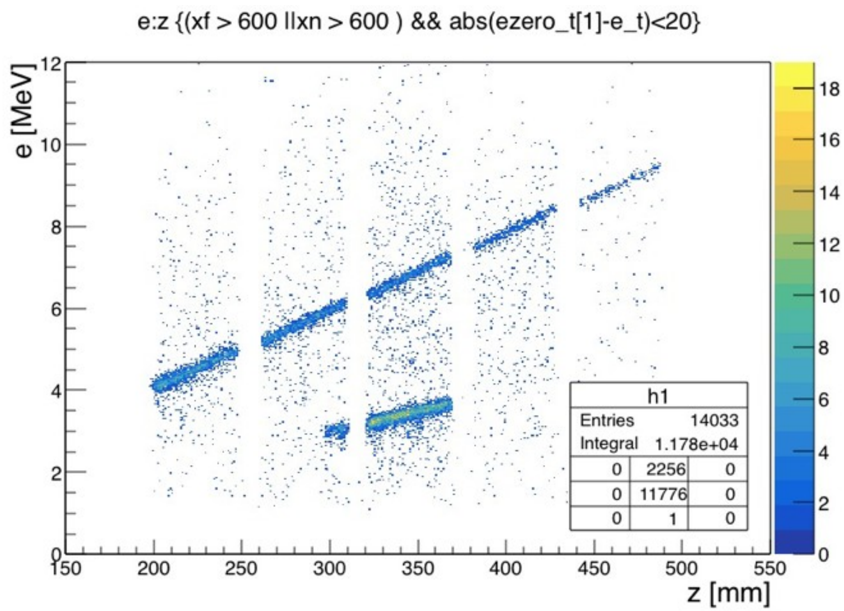
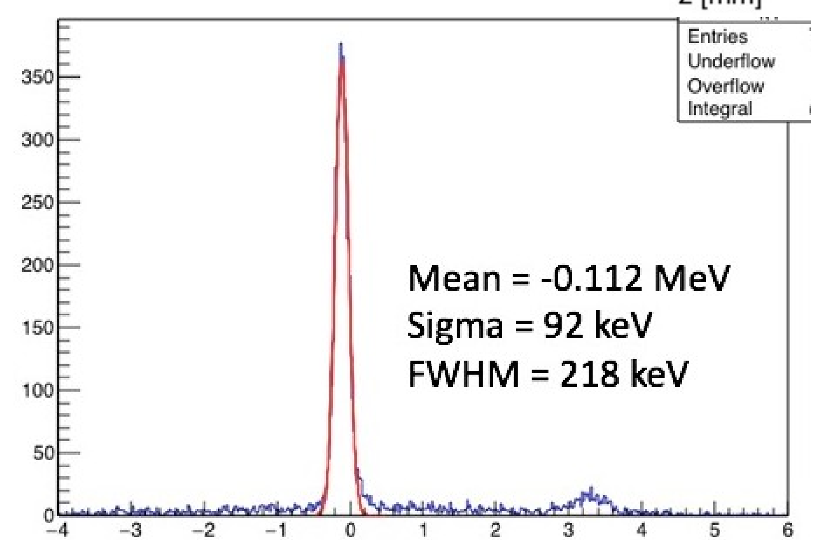
Proof-of-principle experiment: (*d*,*d'*)

- ^{136}Xe beam at 10.0 MeV/*u* to HELIOS
  - ATLAS at Argonne National Lab.
  - Original plan to use ^{146}Nd.
- Coincidence with ionisation chamber
  - Selection of ~Z and ~A
  - Effectively a fusion veto, timing gate.
  - No reaction selectivity, but different kinematics see gradient in plot
- (*d*,*d*) elastic scattering observed
  - Small inelastic cross section in ^{136}Xe
- Stable beam tests at HIE-ISOLDE: 2020





HELIOS

ISOLDE Solenoidal Spectrometer

Ben Kay and Ryan Tang (ANL)

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Summary

- **Octupole collectivity** is investigated in the actinide and lanthanide regions.
- *B(E3)* **most direct** way to quantify deformation/collectivity □ Q_3.
- Existence of a *B(E3)* is **not unambiguous evidence of deformation**, must be taken in context with other observables.
- **Coulomb excitation** is the key tool for measuring octupole nuclei and it is enjoying a renaissance with the advent of radioactive ion beams.
- New methods are proposed, including **inelastic scattering** in a solenoidal field, utilizing the new **ISOLDE Solenoidal Spectrometer**.
- Complementary **β-decay** experiments at TRIUMF and ISOLDE.

Thank you!

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Backup slides

Schiff moment and EDMs

Intrinsic Schiff moment, *S*, gives rise to atomic EDM

P,T-odd nucleon-nucleon interaction

$$S = \frac{\eta \beta_2 \beta_3^2 Z A^{2/3} r_0^3}{E_+ - E_-} = \frac{\langle \Psi_+ | S_z | \Psi_- \rangle \langle \Psi_+ | V_{PT} | \Psi_- \rangle}{E_+ - E_-}$$

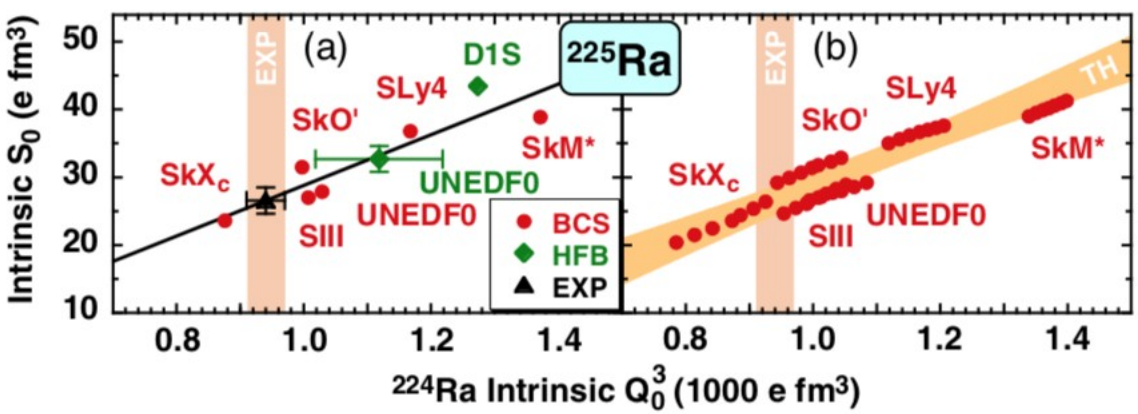
Theory!

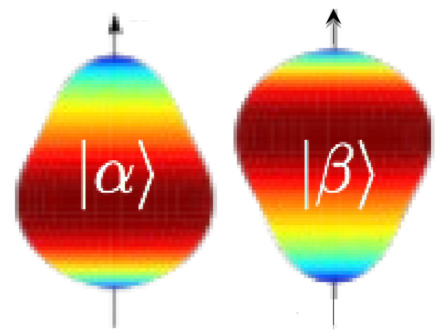
Theory + Experiment

Schiff moment of opposite parity states

Experiment

ΔE: Energy splitting of opposite parity states





^{225}**Ra**

ΔE = 55 keV

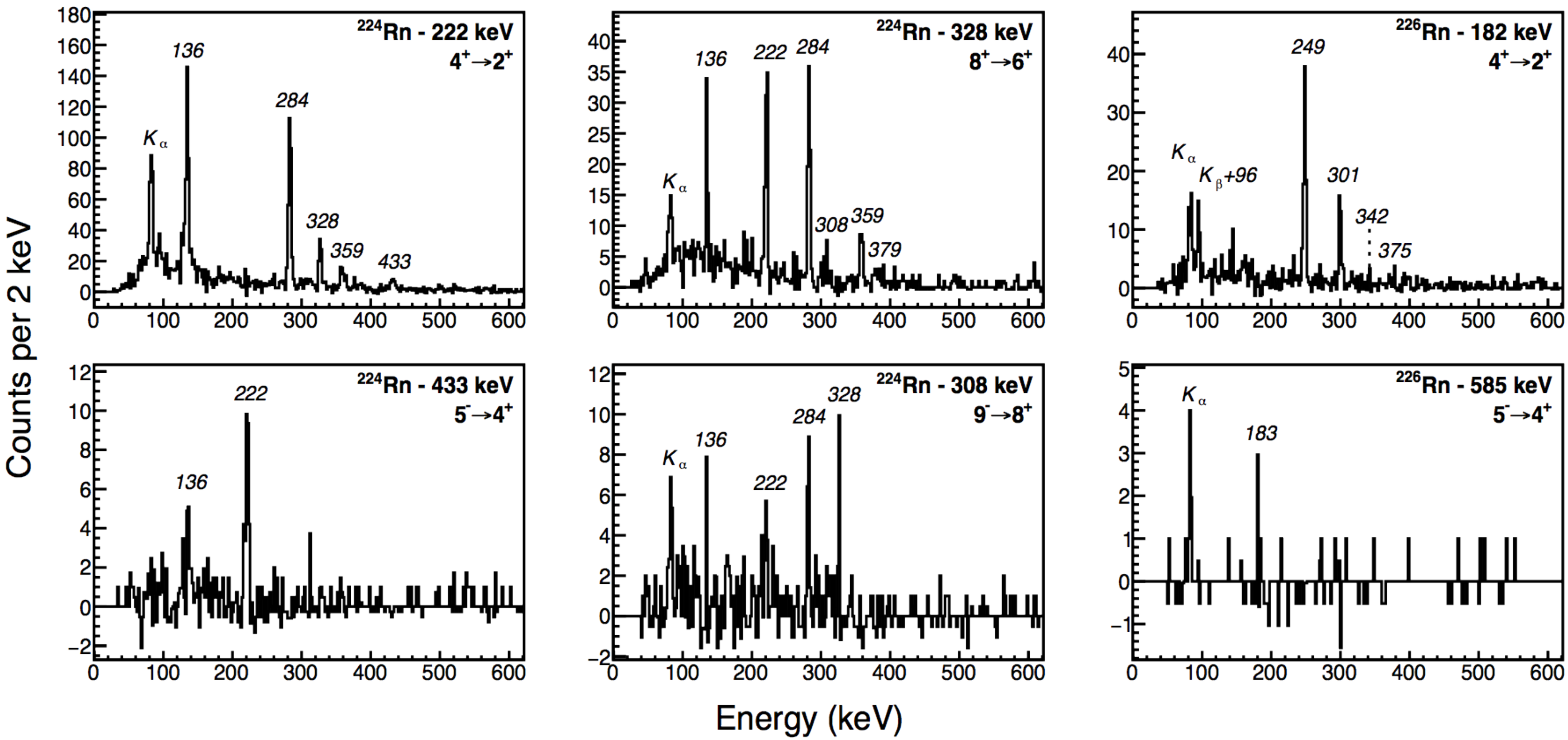
J. Dobaczewski, J. Engel, M. Kortelainen, and P. Becker, Phys. Rev. Lett. **121**, 232501 (2018).

T. E. Chupp, P. Fierlinger, M. J. Ramsey-Musolf, and J. T. Singh, Rev. Mod. Phys. **91**, 015001 (2019).

Current *S* limit □ ^{199m}Hg

Finding negative-parity states

- Gamma-gamma coincidences can pick out the negative-parity states.
- Combine these spectra with the knowledge of ^{222}Rn.



P. A. Butler, et al, *Nature Comm.* **10**, 2473 (2019)

Future ISS developments

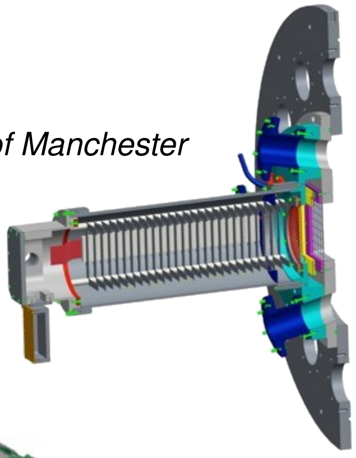
- New array (Liverpool)

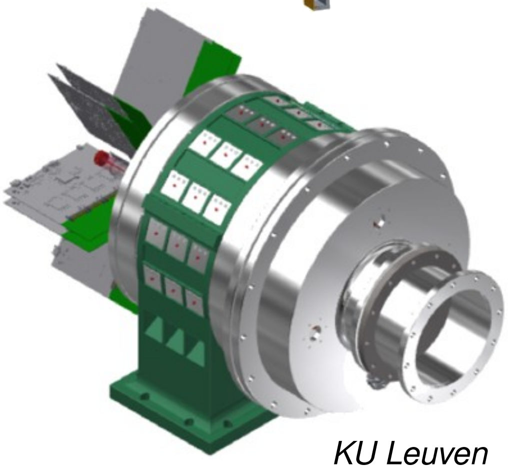
- New fast-counting ionisation chamber to be constructed at The University of Manchester 2019/20.
  - Up to 100 kHz counting.
  - Segmented with digital readout
  - Sample dE/dx along track of recoils.

- SpecMat – time projection chamber with gamma-ray detection.

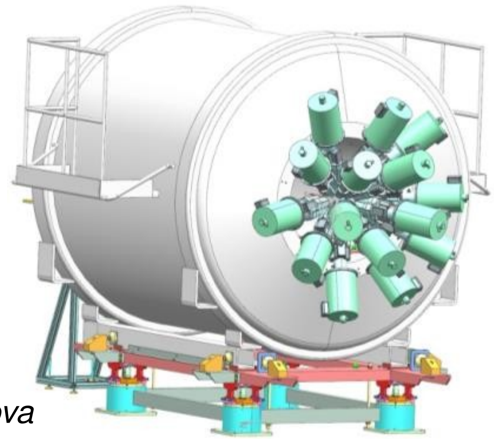
- Germanium spectrometer tests in the solenoid field. Design full array at back of ISS.

University of Manchester





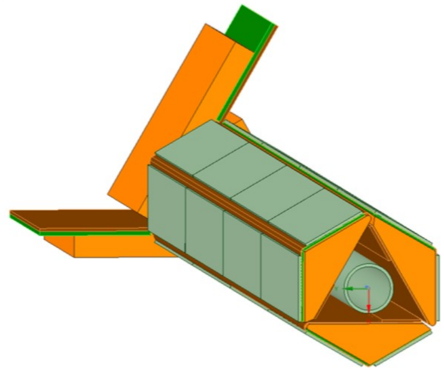
KU Leuven



University of Padova

Advanced Liverpool Array (ISS)

- DSSDs + ASIC readout.
  - 1mm thick, 4 x 6 wafers.
  - x: 128 x 0.95mm.
  - y: 11 x 2mm.



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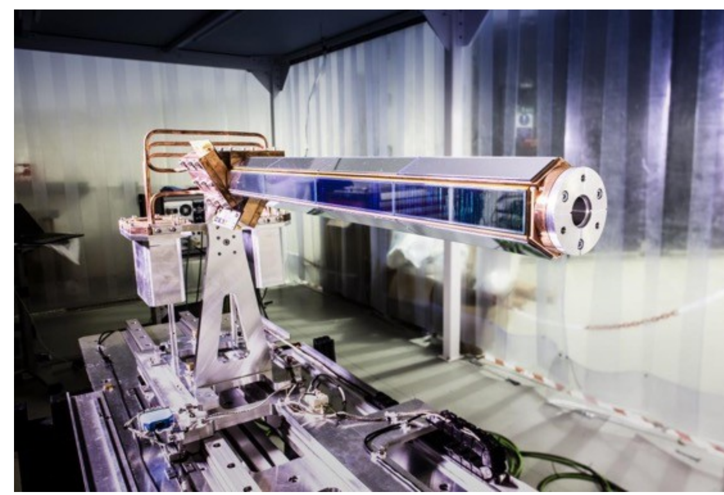
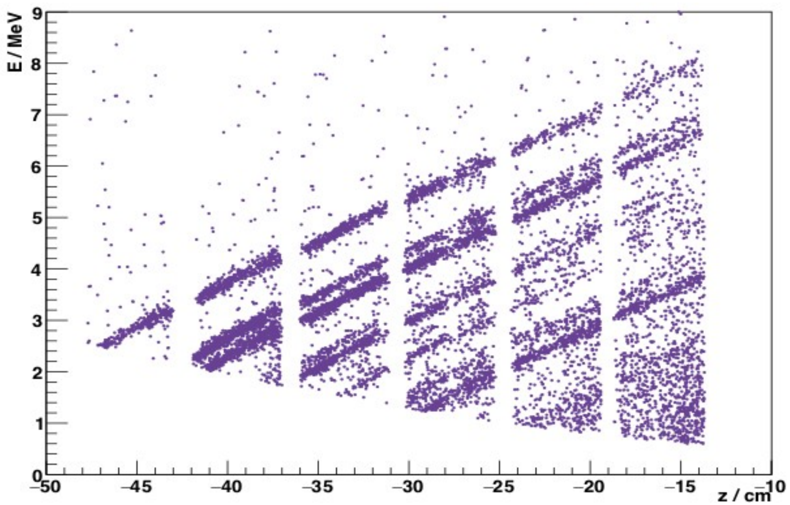
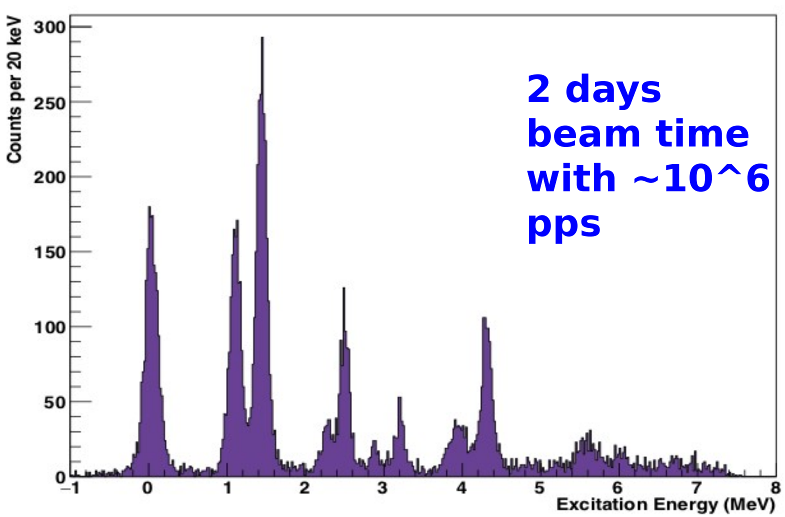
ISOLDE Solenoidal Spectrometer

- Alpha source tests at University of Liverpool
- Assembled, tested and shipped to ISOLDE in 2019

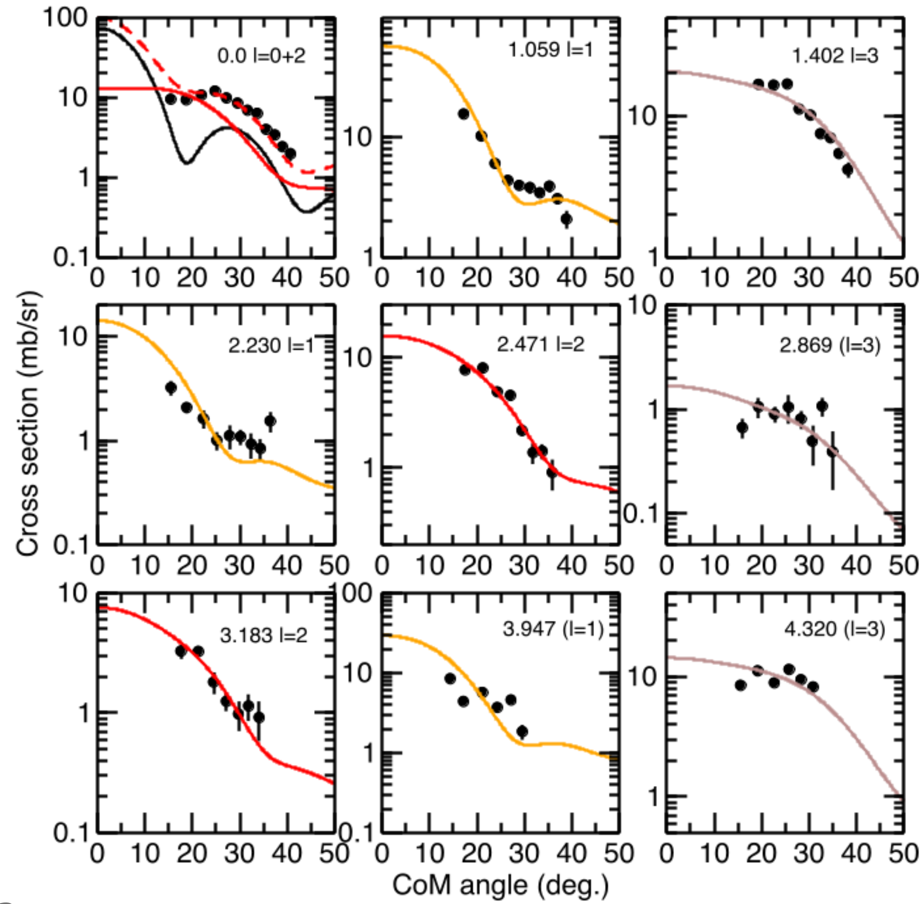


Results– ^{28}Mg(d,p)





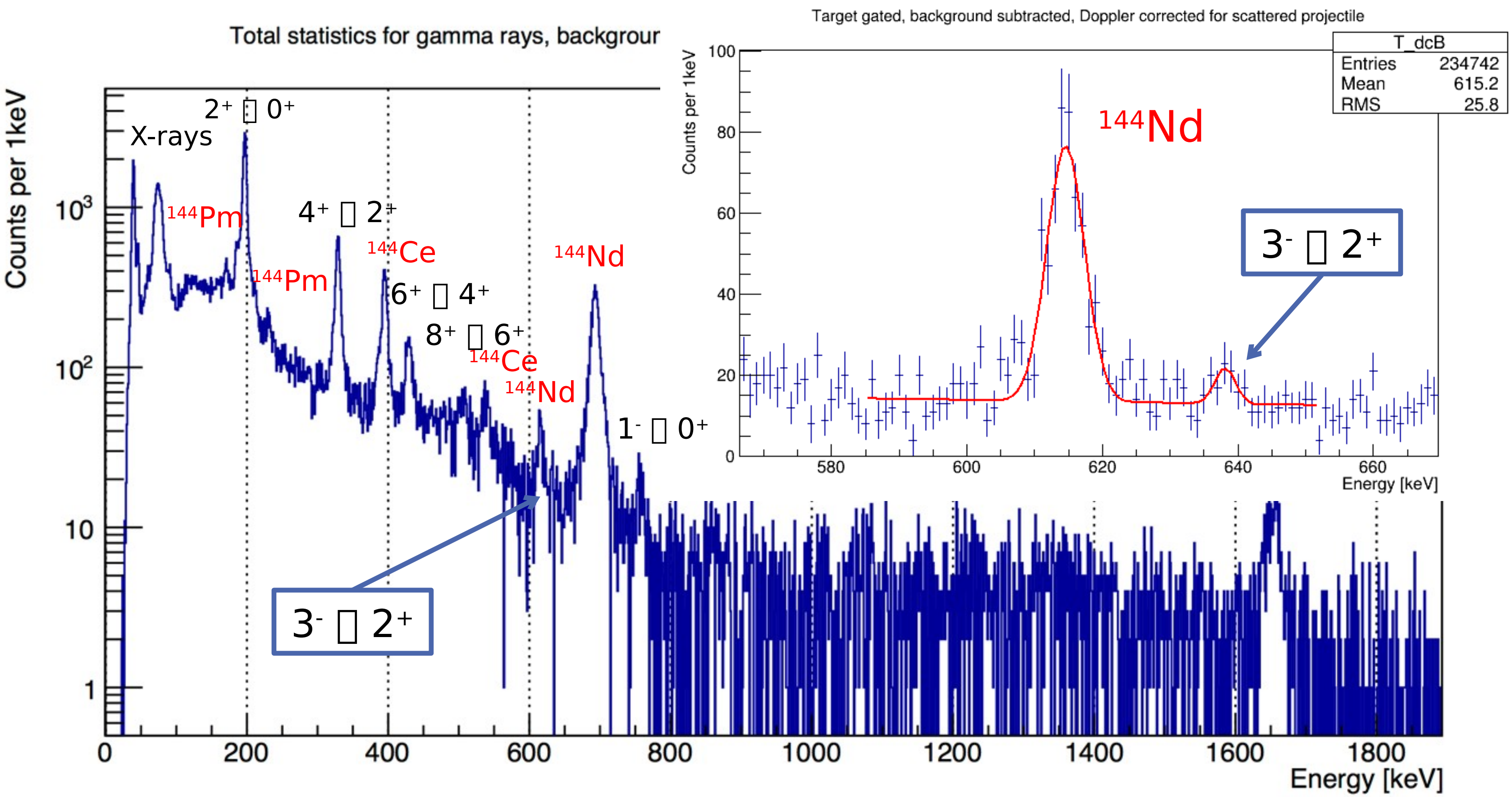
- Excitation energy resolution of ~140 keV.
- Compared to DWBA calculations to make ℓ assignments.



^{144}Ba on ^{208}Pb

2017 data

- BaF molecular beam Contamination from stable isobars.
- Data also taken with ^{58}Ni target… 3^{-} state is weakly populated.



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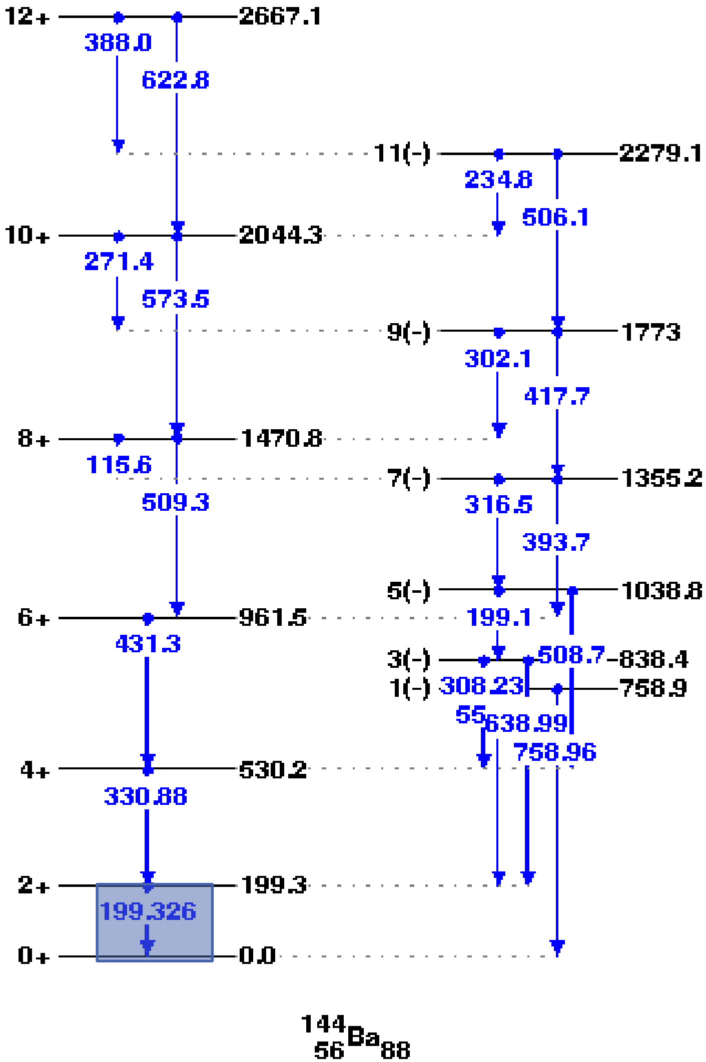
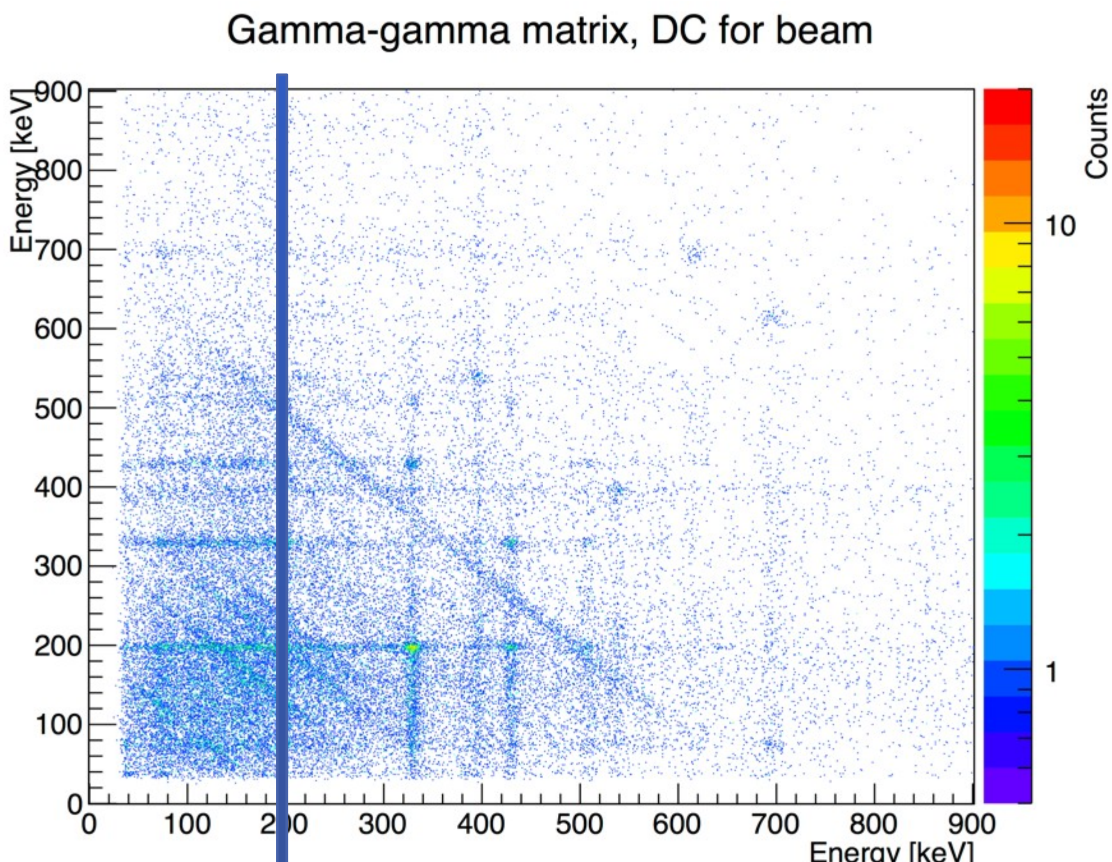
$\gamma\gamma$ matrix: ^{144}Ba on ^{208}Pb



- Particle-gamma-gamma spectrum.
- Doppler-corrected for ^{144}Ba
- 17 counts in 3^- → 2^+ peak.



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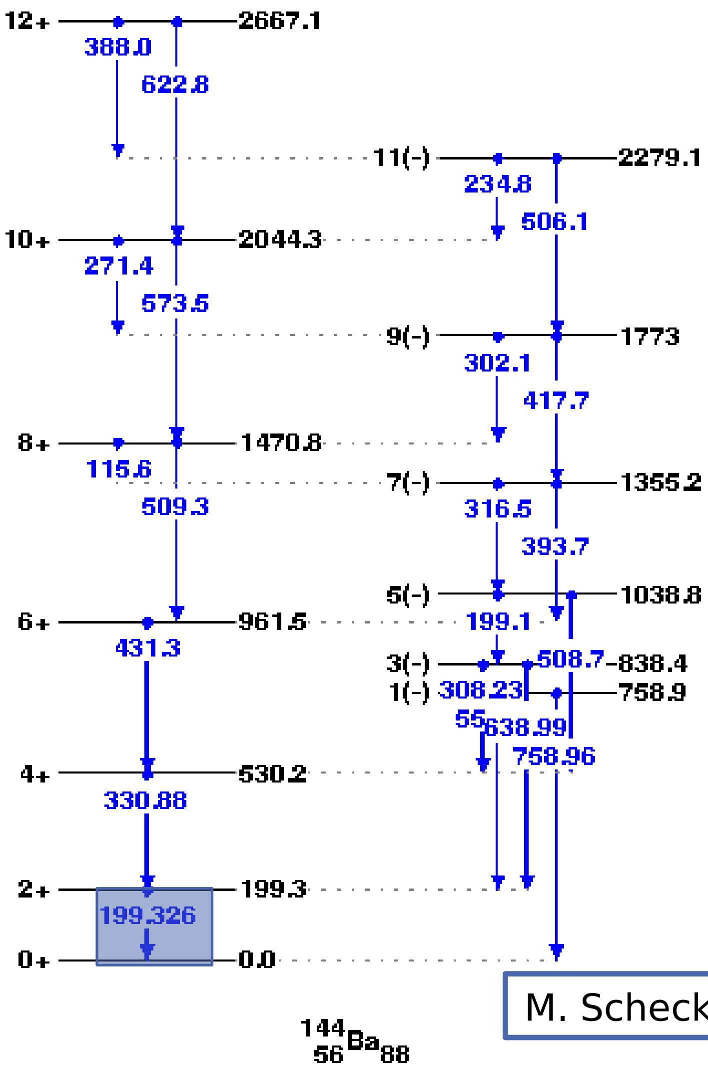
$\gamma\gamma$ matrix: ^{144}Ba on ^{208}Pb



- Particle-gamma-gamma spectrum.
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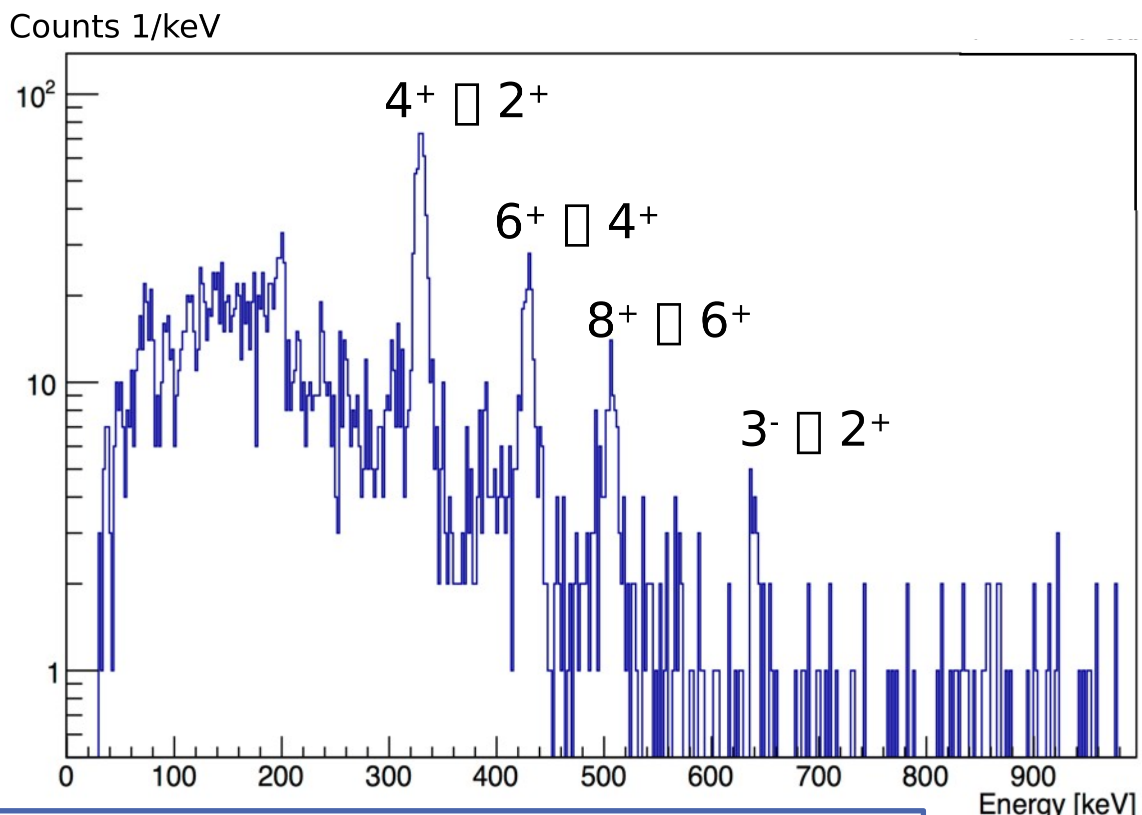

M. Scheck (UWS) defended remaining shifts to run in 2021

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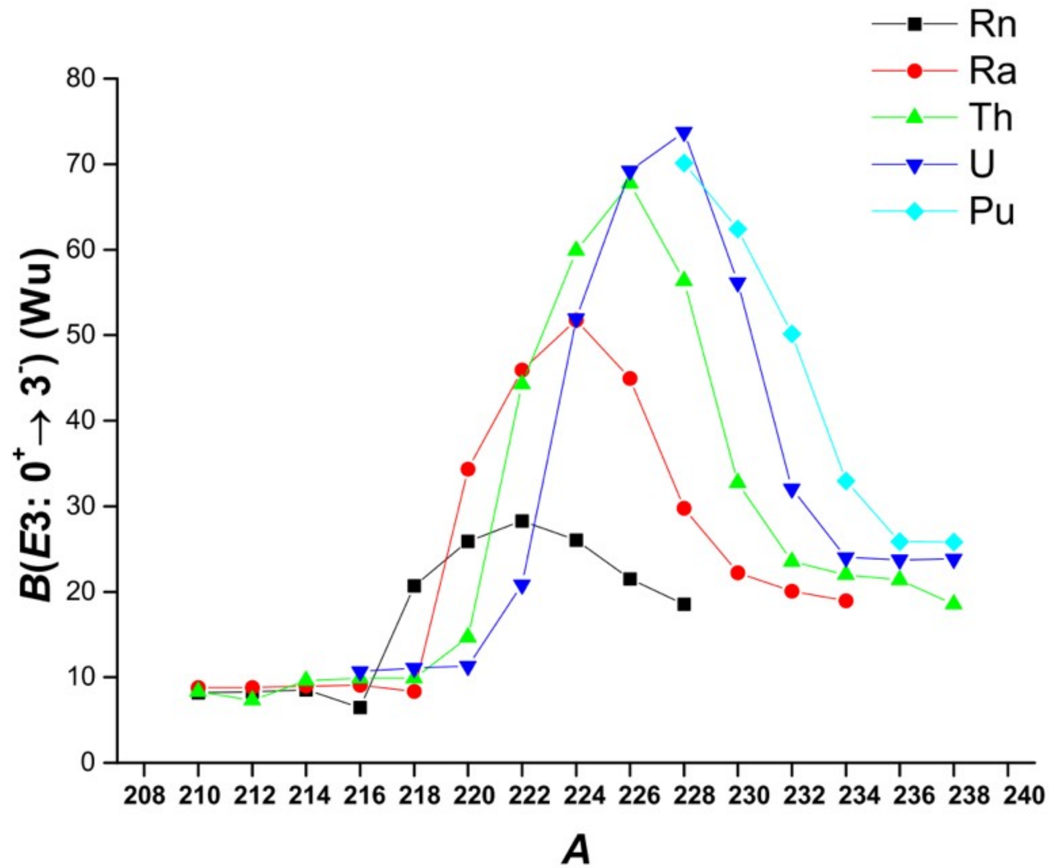
Theoretical Q_3 systematics

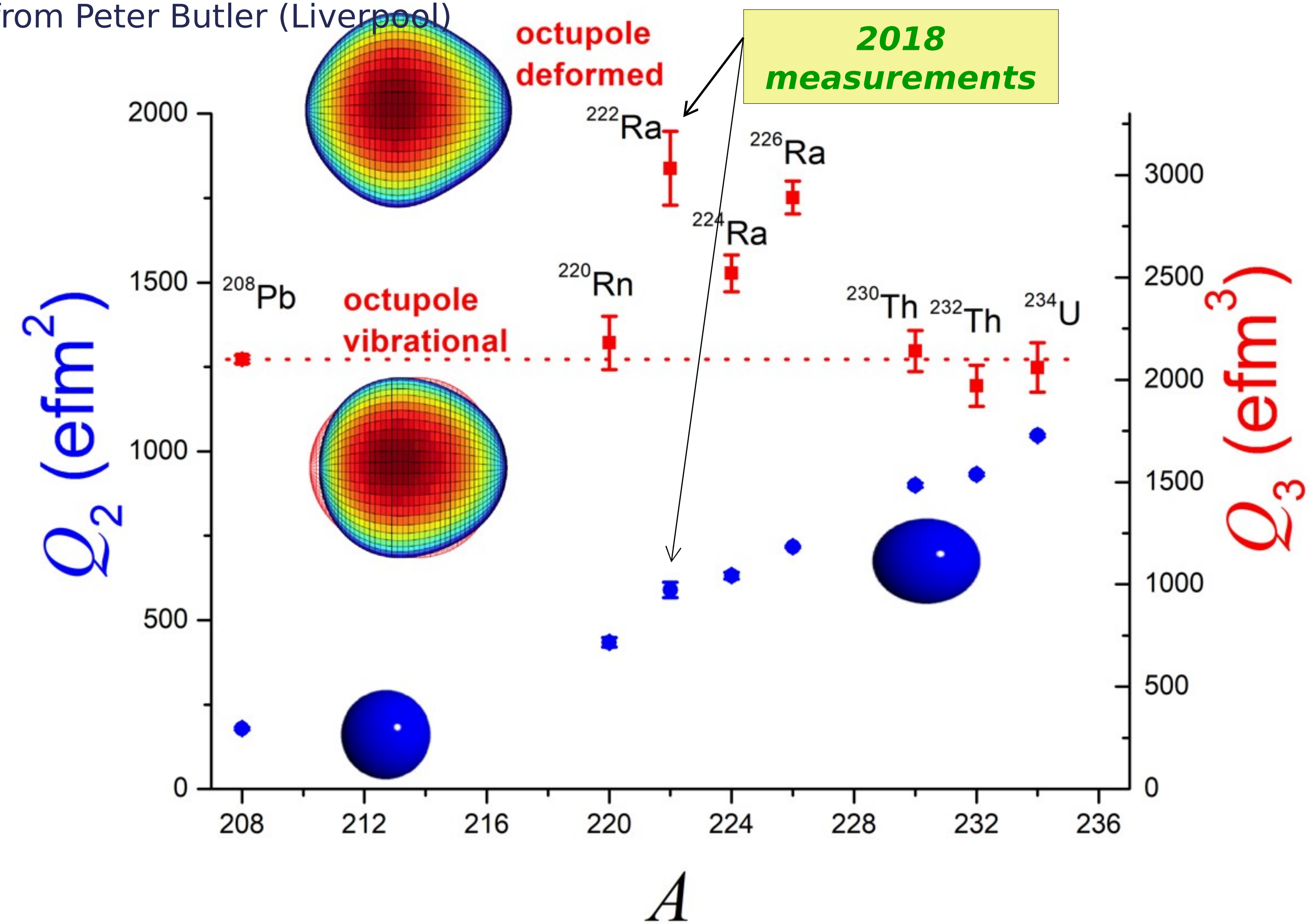
- Beyond mean-field theory calculations give global systematics.
- World-record values expected in Th, U and Pu not at ISOLDE.
- Defining the Ra peak is needed to add weight to calculations.
- Potential for a future program at ReA6 at FRIB, using GRETA.



P.A. Butler, *J. Phys. G Nucl. Part. Phys*. **43**, 073002 (2016).
L.M. Robledo and G.F. Bertsch, *Phys. Rev. C* **84**, 54302 (2011).

Q2 and Q3 systematics

- Slide from Peter Butler (Liverpool)



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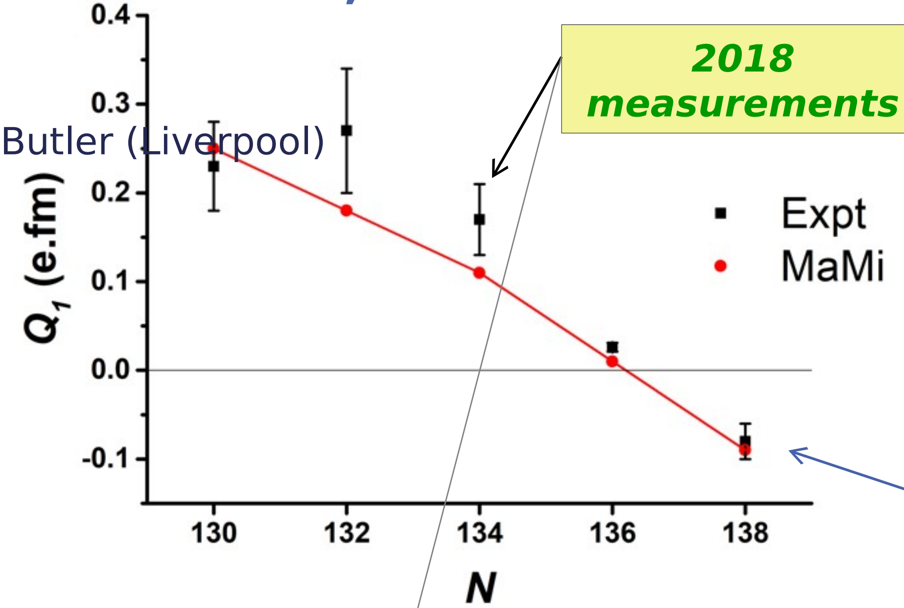
Theory for E1s, E2s - Ra

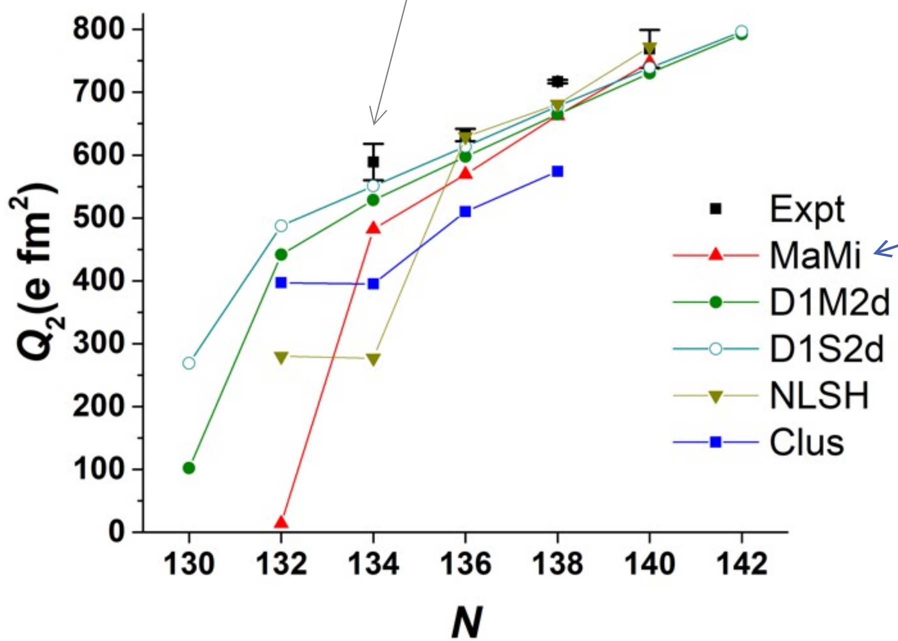
- Slide from Peter Butler (Liverpool)



2018 measurements

PAB & Nazarewicz et al
NP A533 (1991) 249

See Amzal et al
NP A734 (2004) 465



Nazarewicz et al.
Strut. WS
NP A429 (1984) 269

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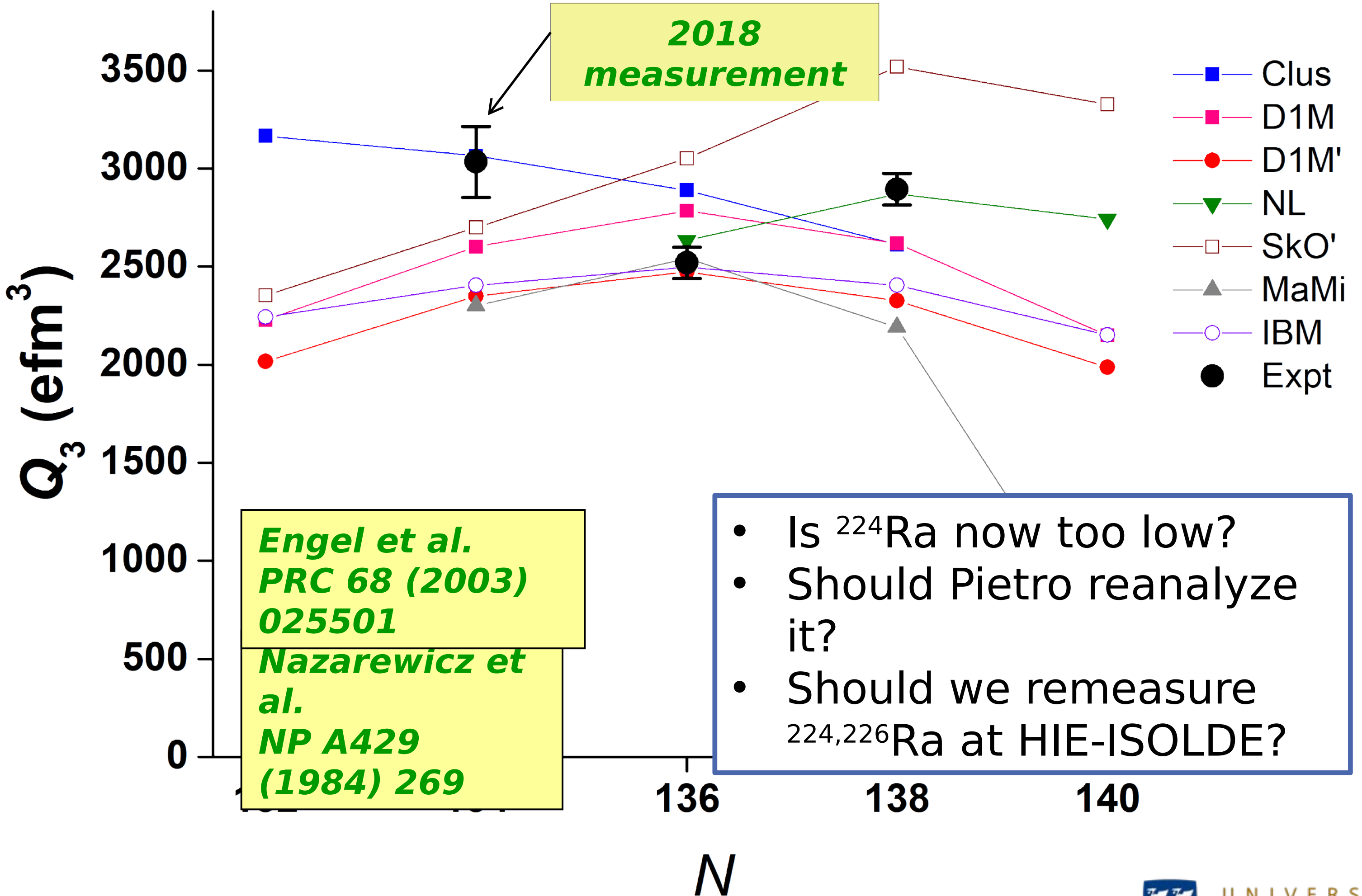
Theoretical Q_3 systematics

- Slide from Peter Butler (Liverpool)



- Is ^{224}Ra now too low?
- Should Pietro reanalyze it?
- Should we remeasure ^{224,226}Ra at HIE-ISOLDE?

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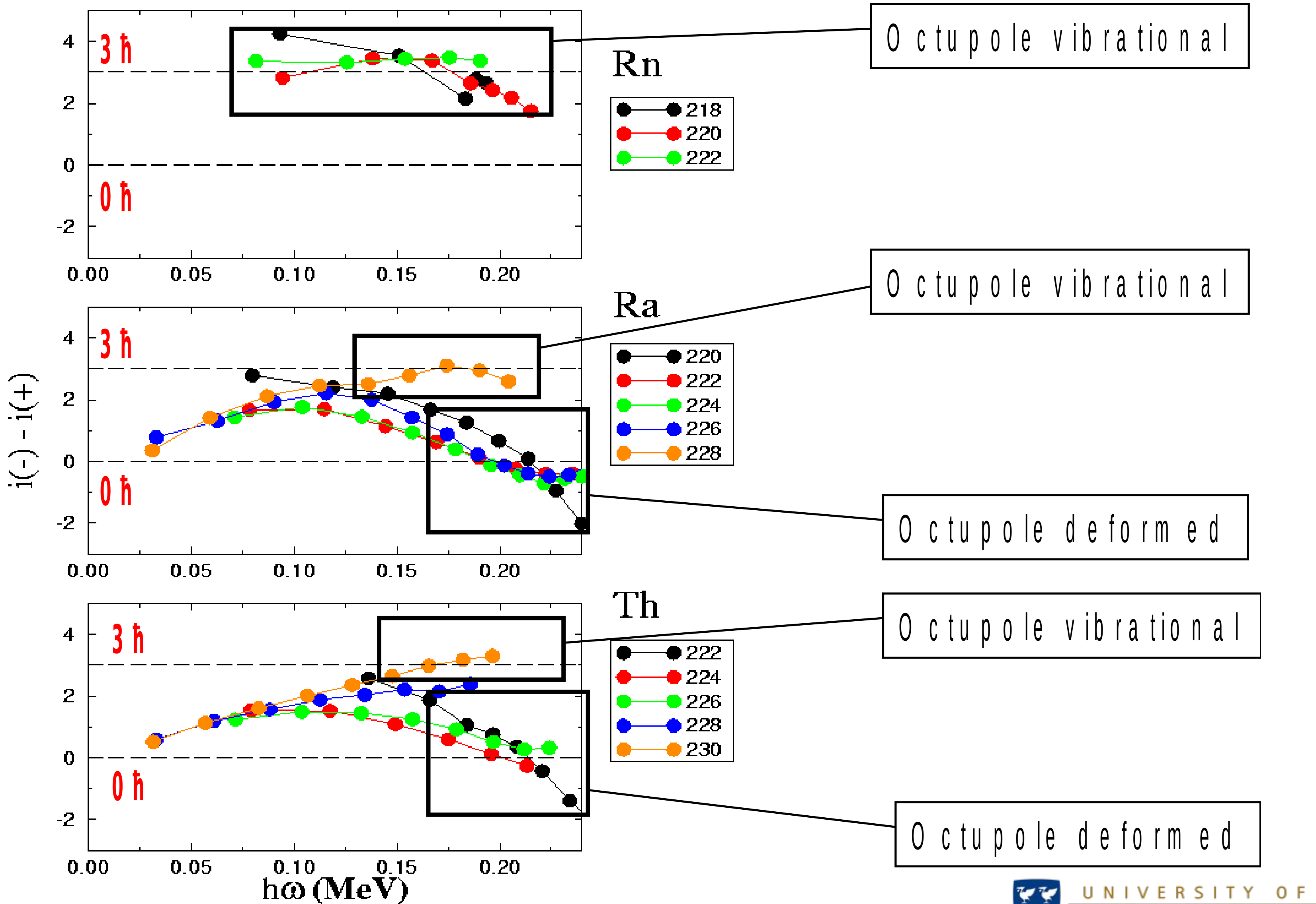

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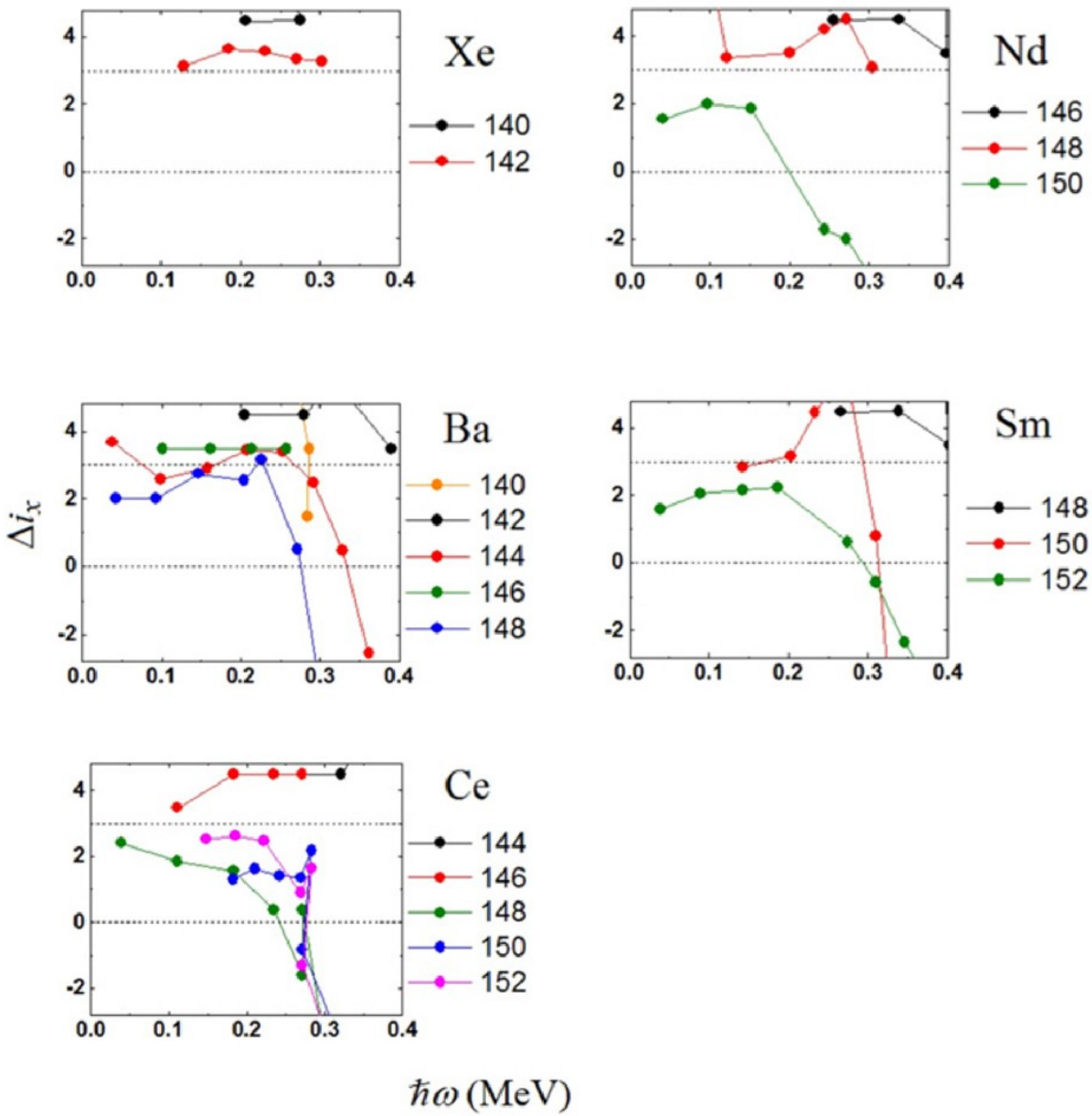

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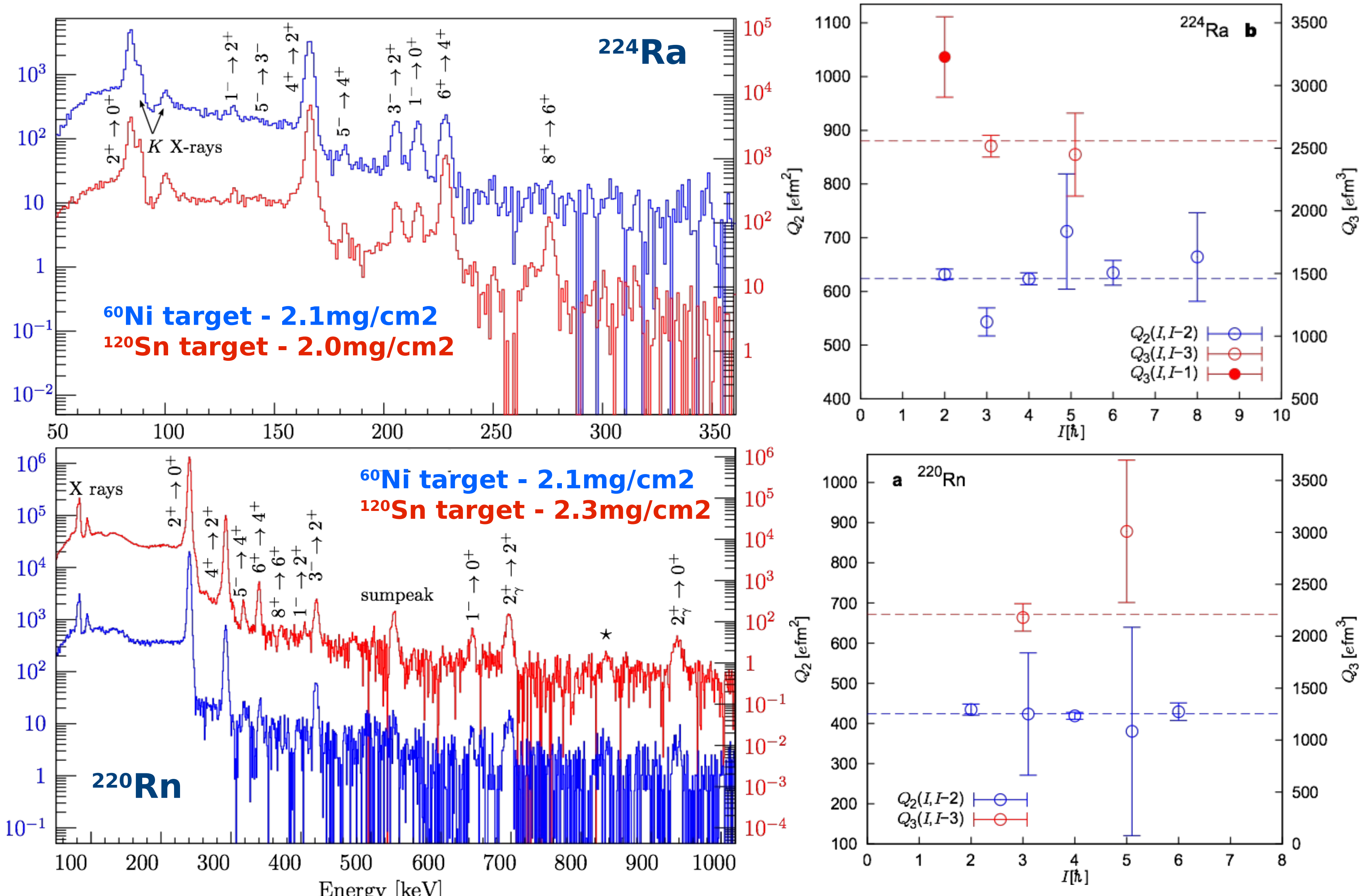
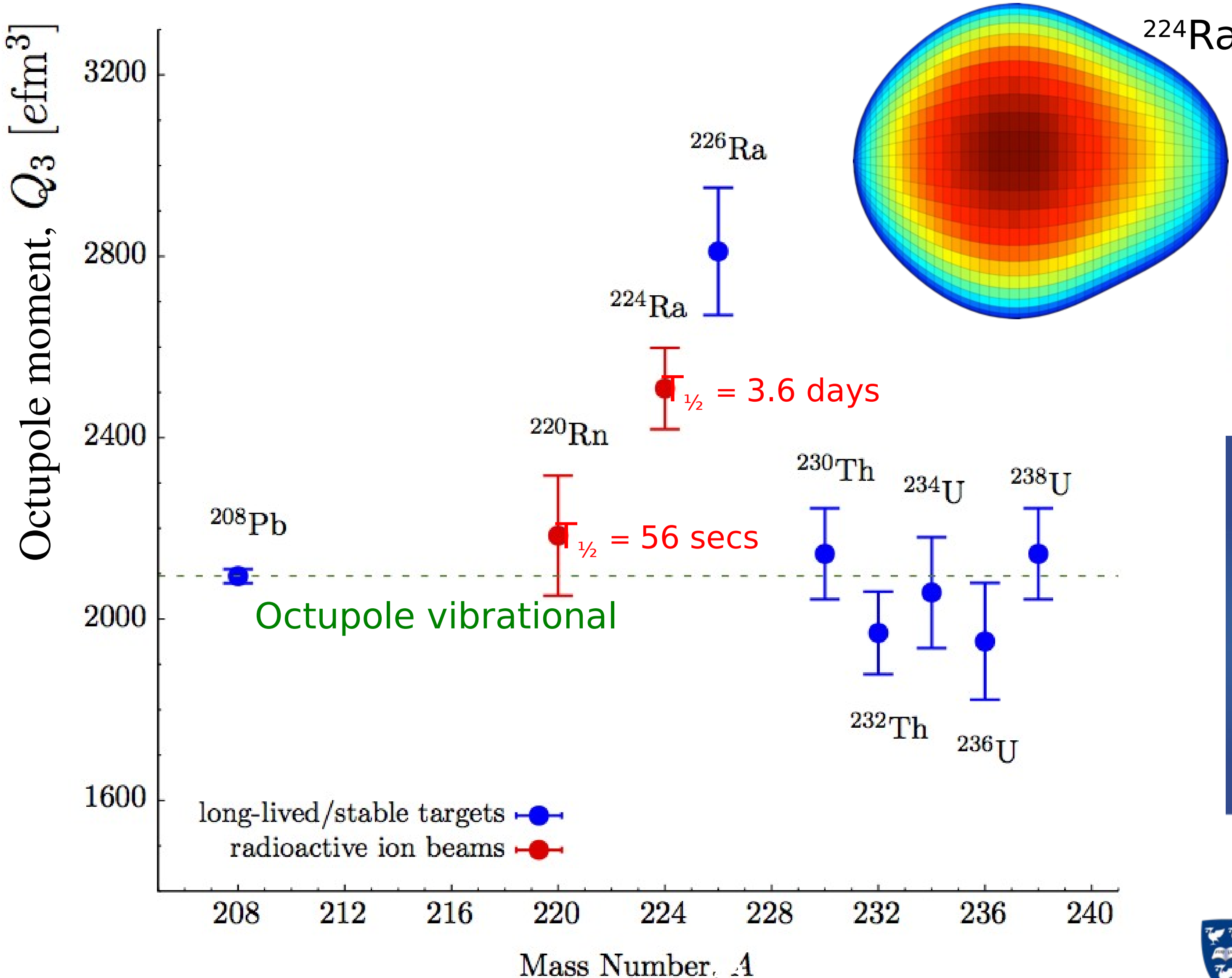
Actinides: ^{220}Rn & ^{224}Ra



L. P. Gaffney et al., Nature **497**, 199 (2013).

Dynamic or static deformation?



L. P. Gaffney et al., Nature ***497****, 199 (2013)*

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