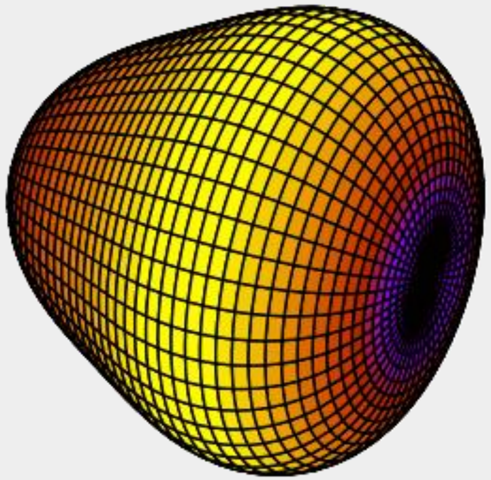
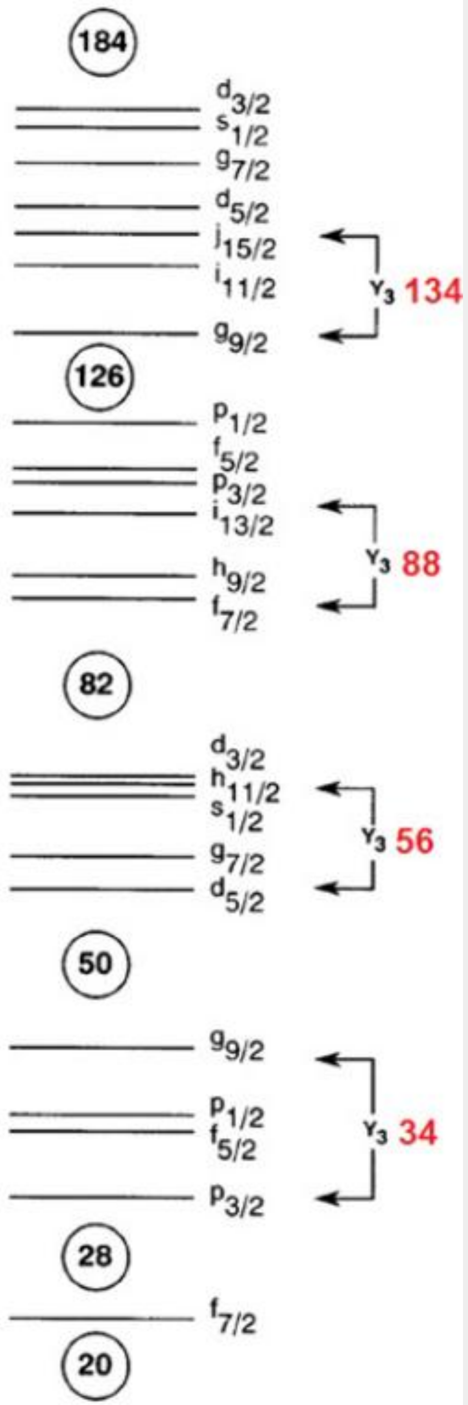
Measurements of octupole collectivity in ^{144}Ba



Ben Jones
University of Liverpool

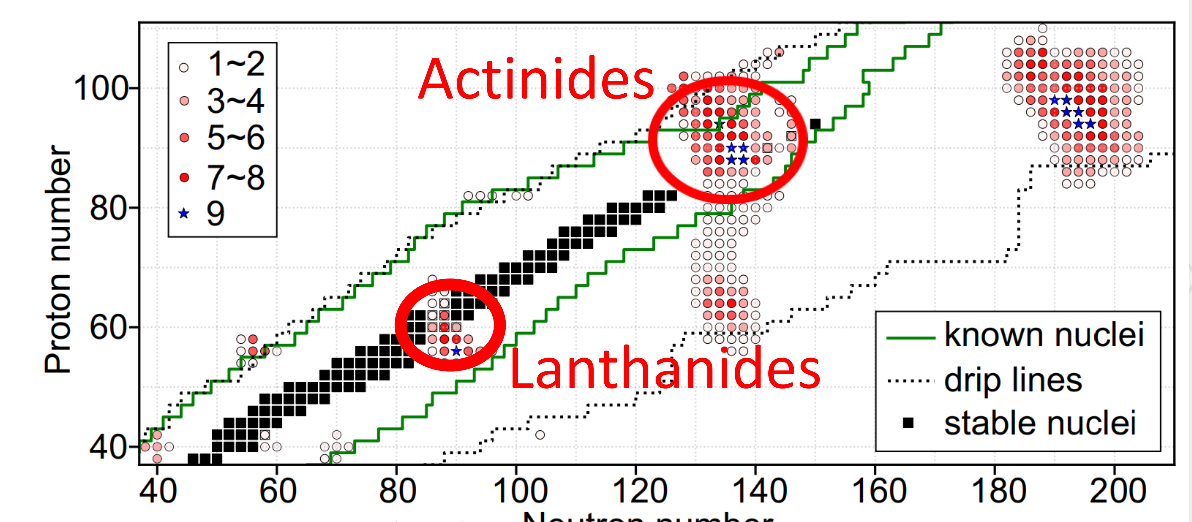
Intruder orbitals



Origins of octupole correlations in nuclei

- Octupole deformations are thought to arise from particle-hole interactions with intruder orbitals of opposite parity with $\Delta j, \Delta l = 3$, coupled by the octupole interaction.
- Octupole magic numbers: 34, 56, 88, 134.
- Octupole deformation is greatest when both proton and neutron numbers are near these octupole magic numbers.

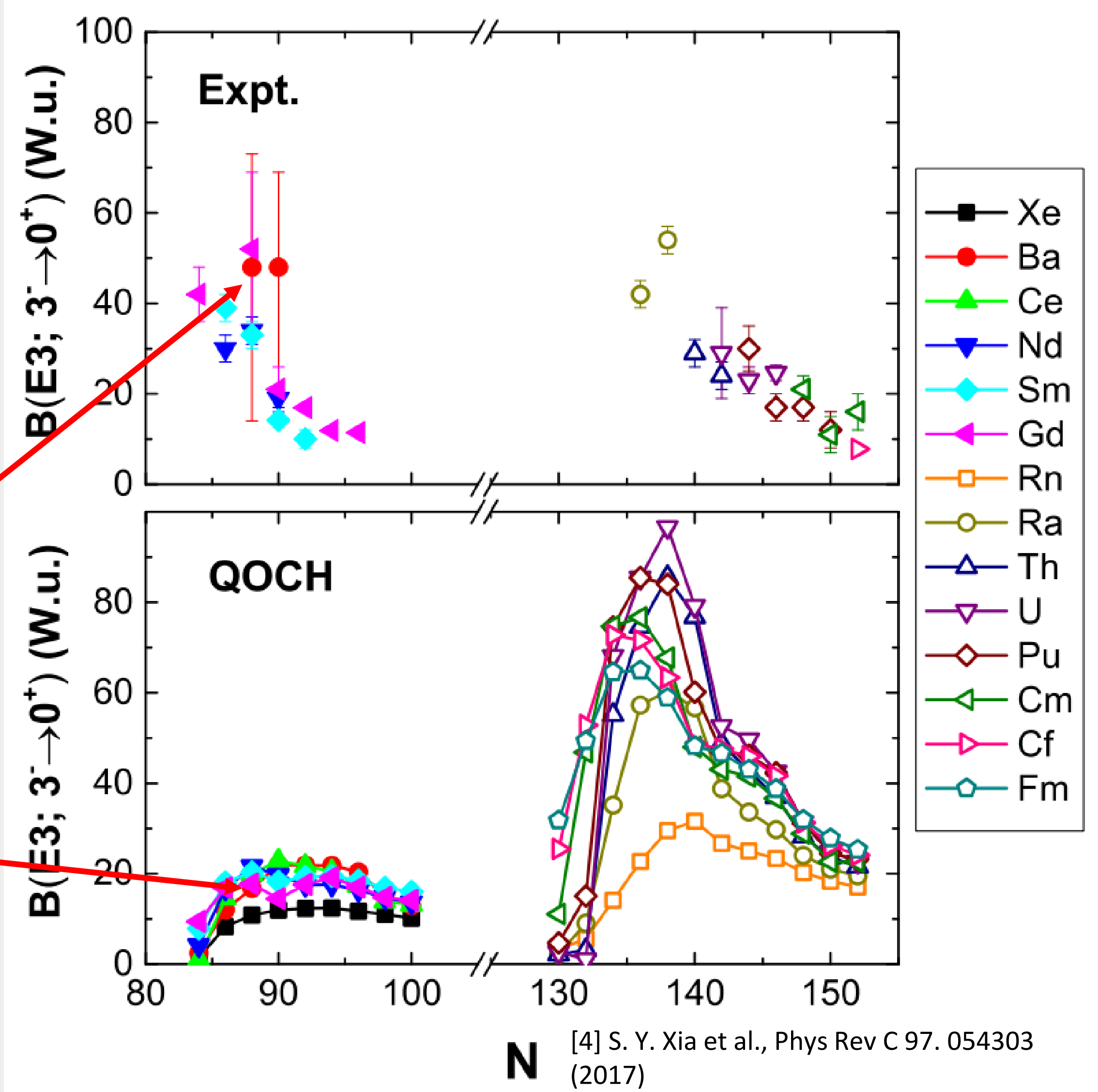
- $^{144}_{56}\boldsymbol{Ba} \leftarrow$
- $^{222}_{88}Ra$



[1] Y.Cao et al., Phys Rev C 102 (2020)

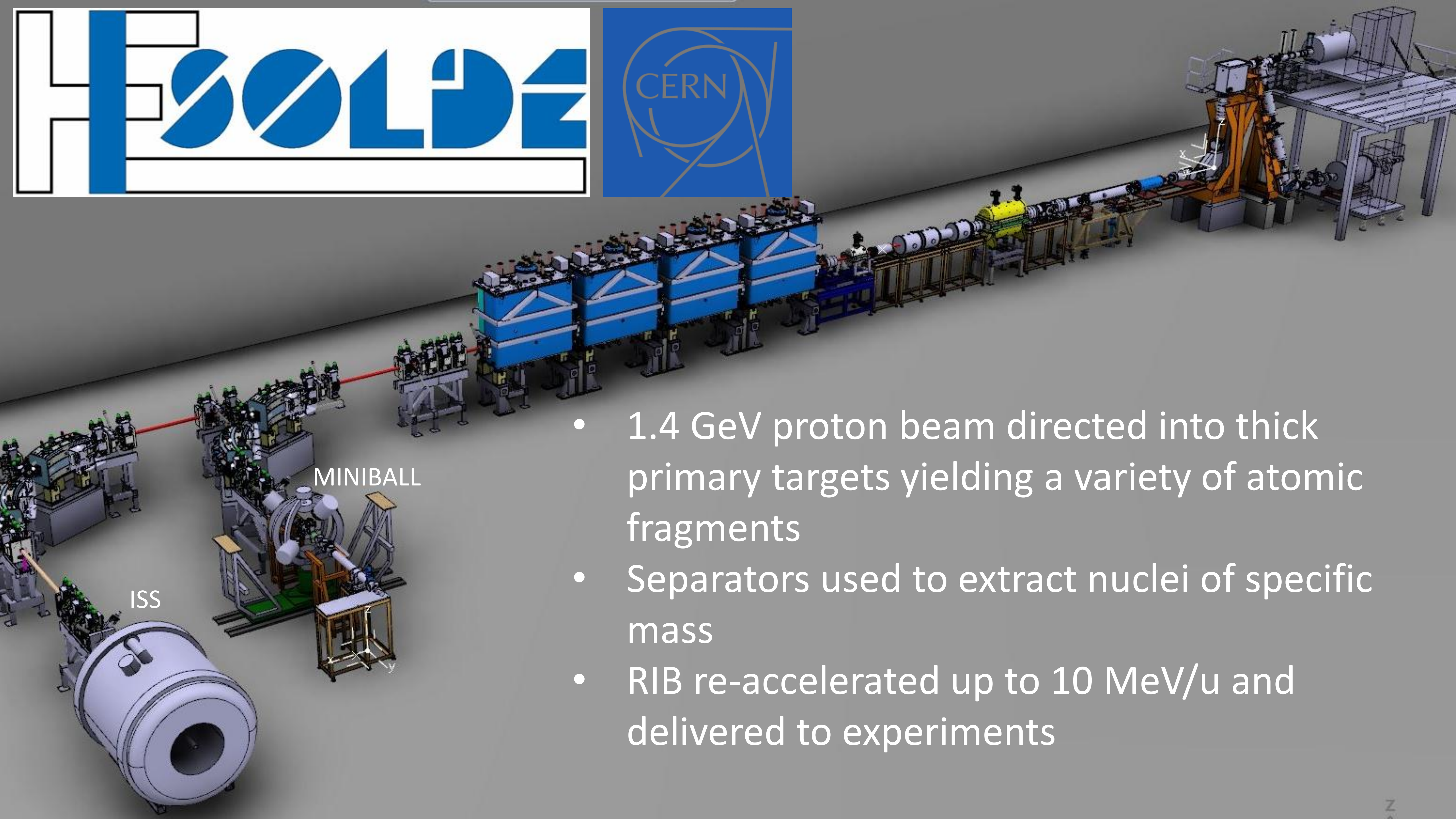
B(E3) systematics: Lanthanides and Actinides

- Several Rn isotopes are shown to behave as octupole vibrators [1], and ^{222,224,226}Ra exhibit static octupole deformation in their ground state [2].
- Very little experimental data of the $B(E3)$ exists for isotopes in the Lanthanide region.
- Previous measurement of the $B(E3)$ for ^{144}Ba near by Bucher et al., ANL [3] is significantly enhanced over theory and has a large associated uncertainty.



[4] S. Y. Xia et al., Phys Rev C 97. 054303 (2017)

[1] P. A. Butler et al., Nat Commun. 2019 Jun 6;10(1):2473
[2] P. A. Butler et al., Phys. Rev. Lett. 124, 042503 – Published 31 January, 2020
[3] B. Bucher et al., Phys. Rev. Lett. 116, 112503 – Published 17 March, 2016

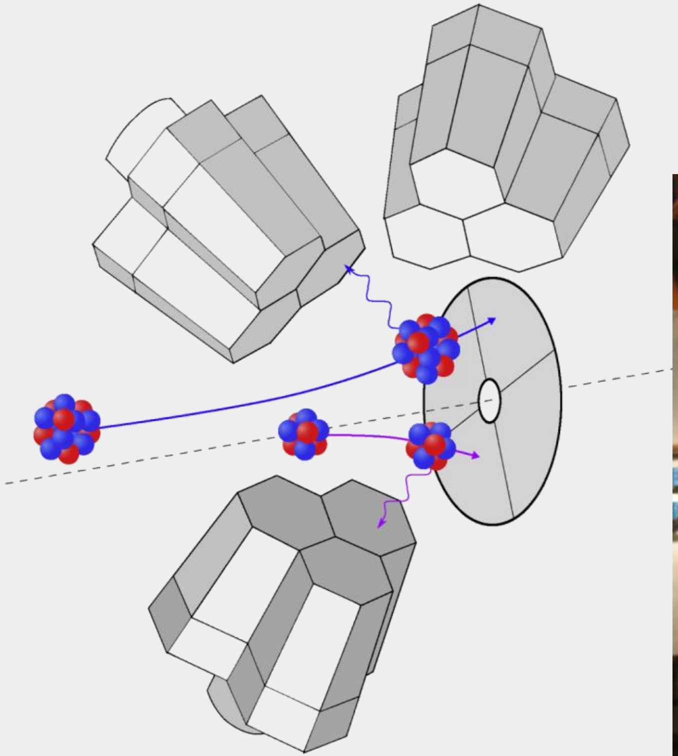


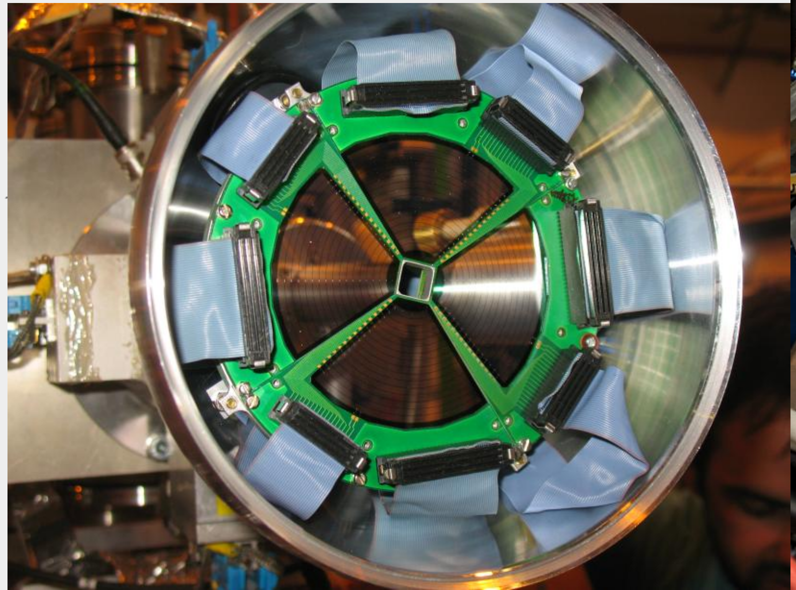
- 1.4 GeV proton beam directed into thick primary targets yielding a variety of atomic fragments
- Separators used to extract nuclei of specific mass
- RIB re-accelerated up to 10 MeV/u and delivered to experiments

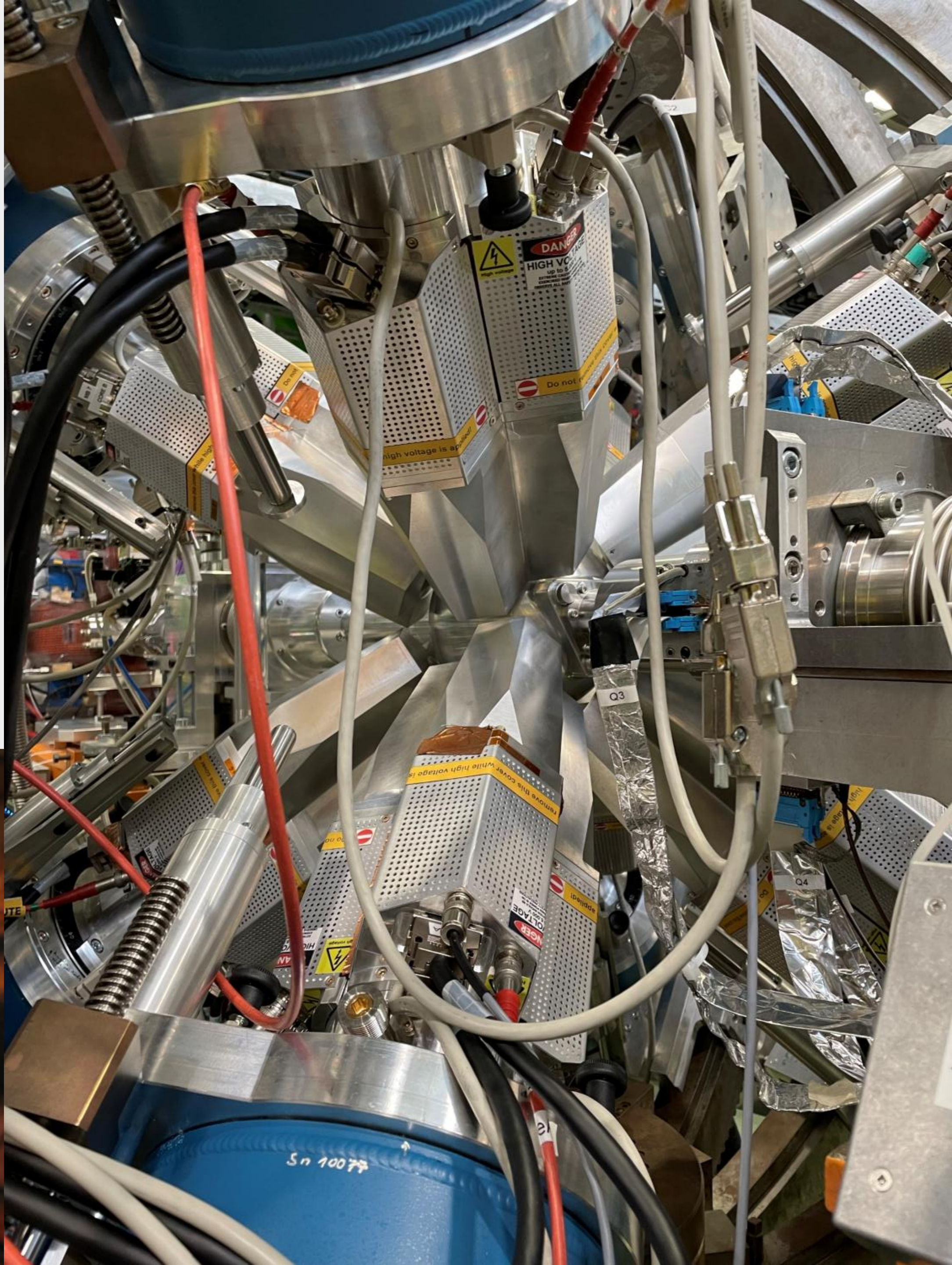
MINIBALL

Coulomb excitation setup:

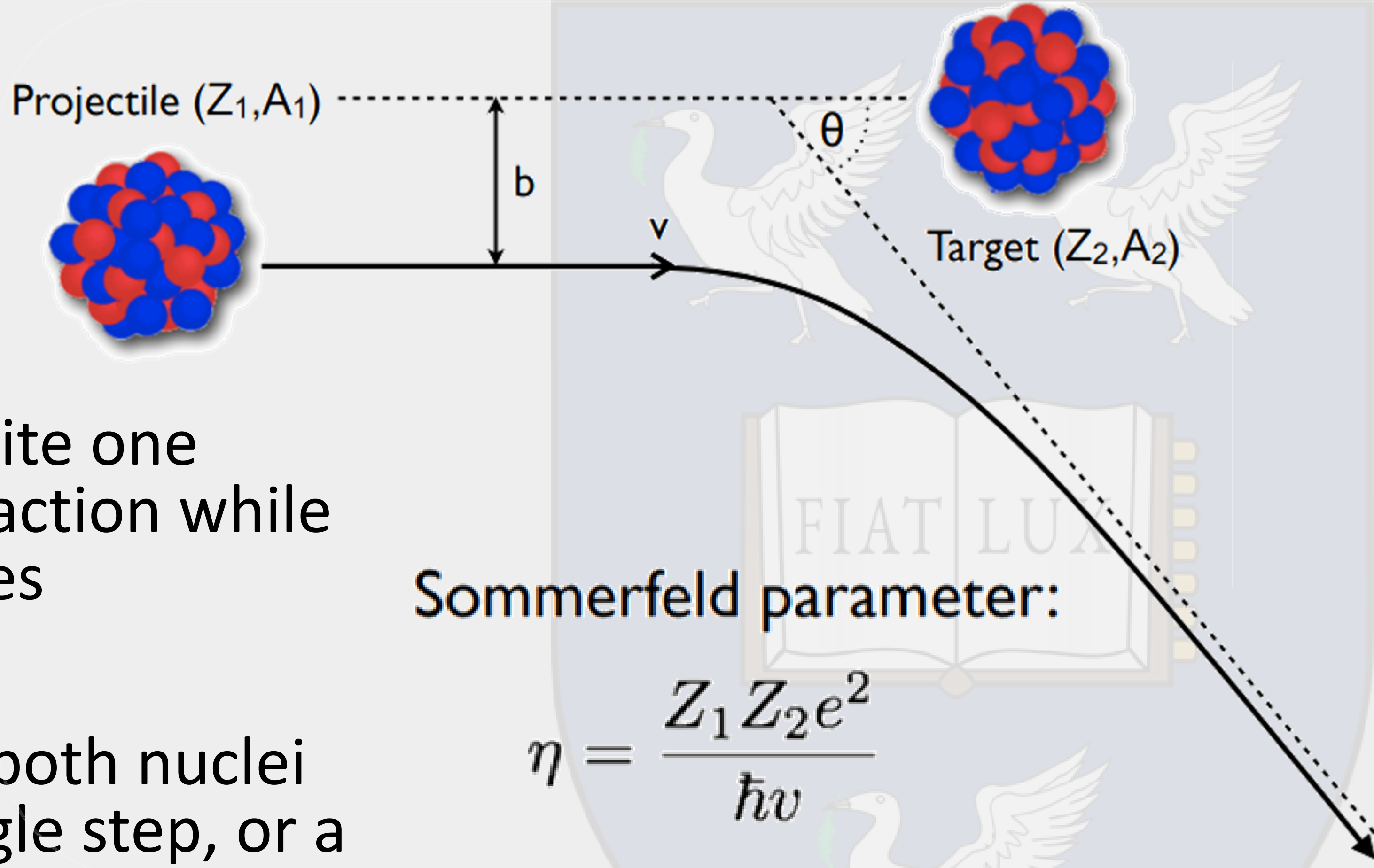
- HPGe clusters centred around the target
- Position sensitive silicon CD detector placed downstream of the target







Coulomb excitation



- Projectile and target nuclei excite one another via the Coulomb interaction while following hyperbolic trajectories

- While in each others EM-field both nuclei have a chance to excite via single step, or a series of multi-step transitions

- Direct probe for EM (E1, E2, E3, M1…) M.E.'s coupling states in a nucleus

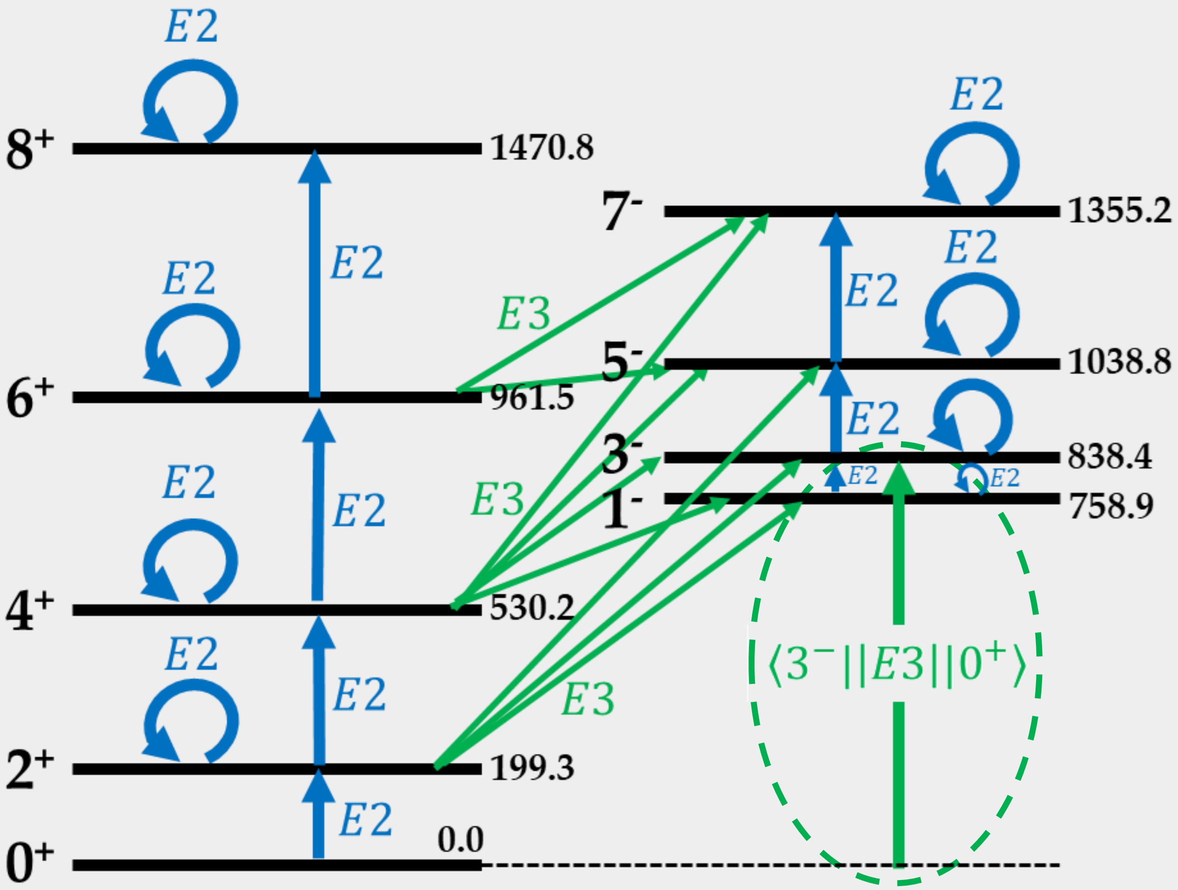
Sommerfeld parameter:

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$

"Safe" Coulex:

$$\eta \gg 1$$

^{144}Ba excitation

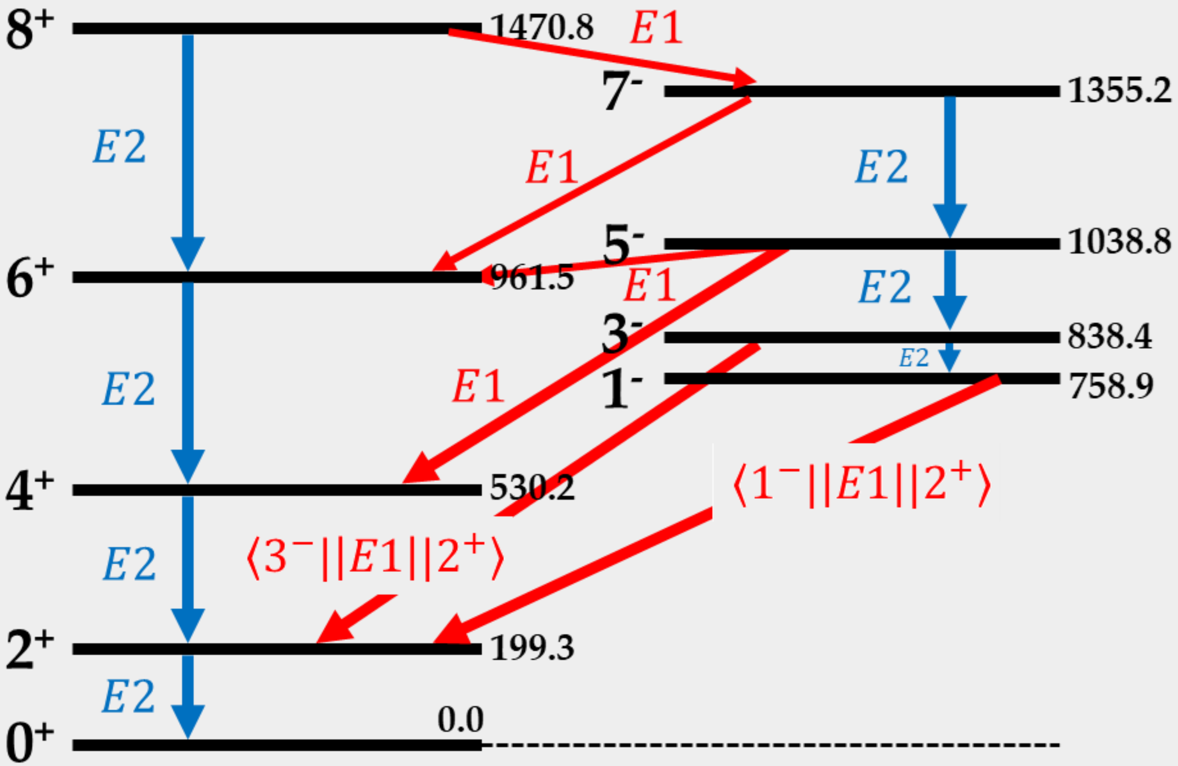


- $E2$ and $E3$ transitions dominate the excitation process

- Magnitude of the $\langle 3^- || E3 || 0^+ \rangle$ M.E. is an unambiguous measure of octupole collectivity

$$B(E3; 3^- \rightarrow 0^+) = \frac{\langle 3^- || E3 || 0^+ \rangle^2}{7}$$

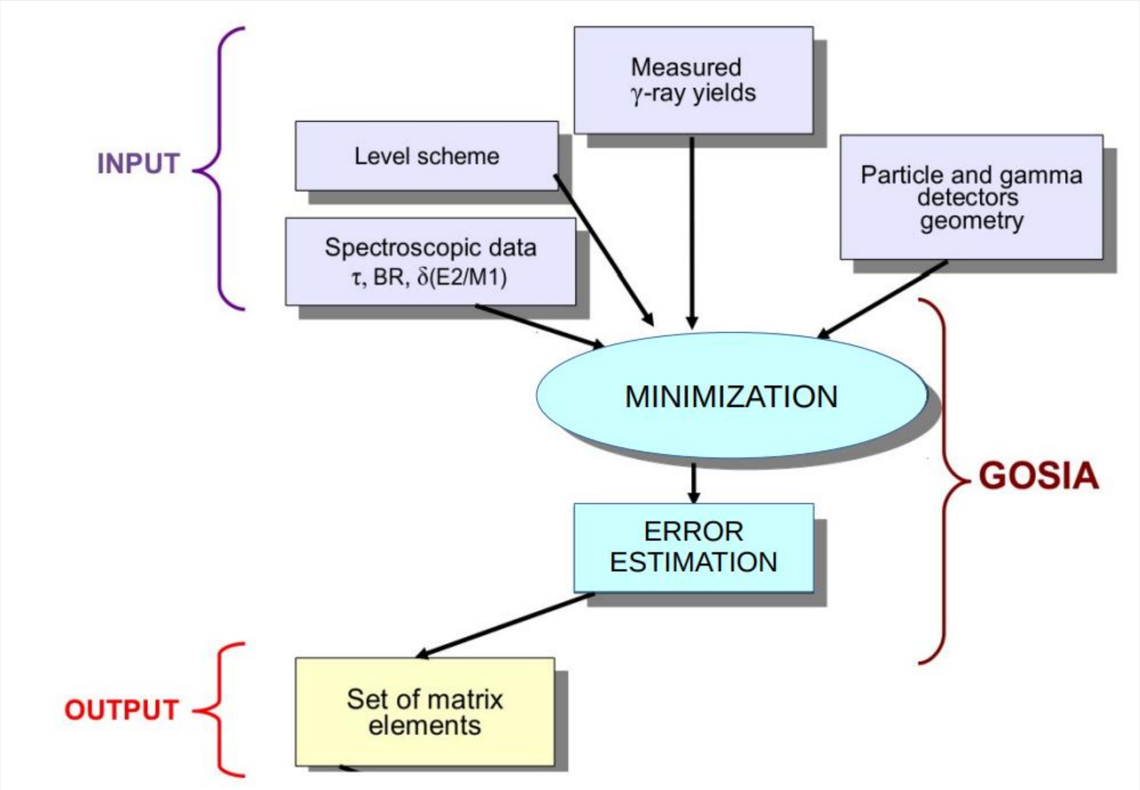
^{144}Ba de-excitation

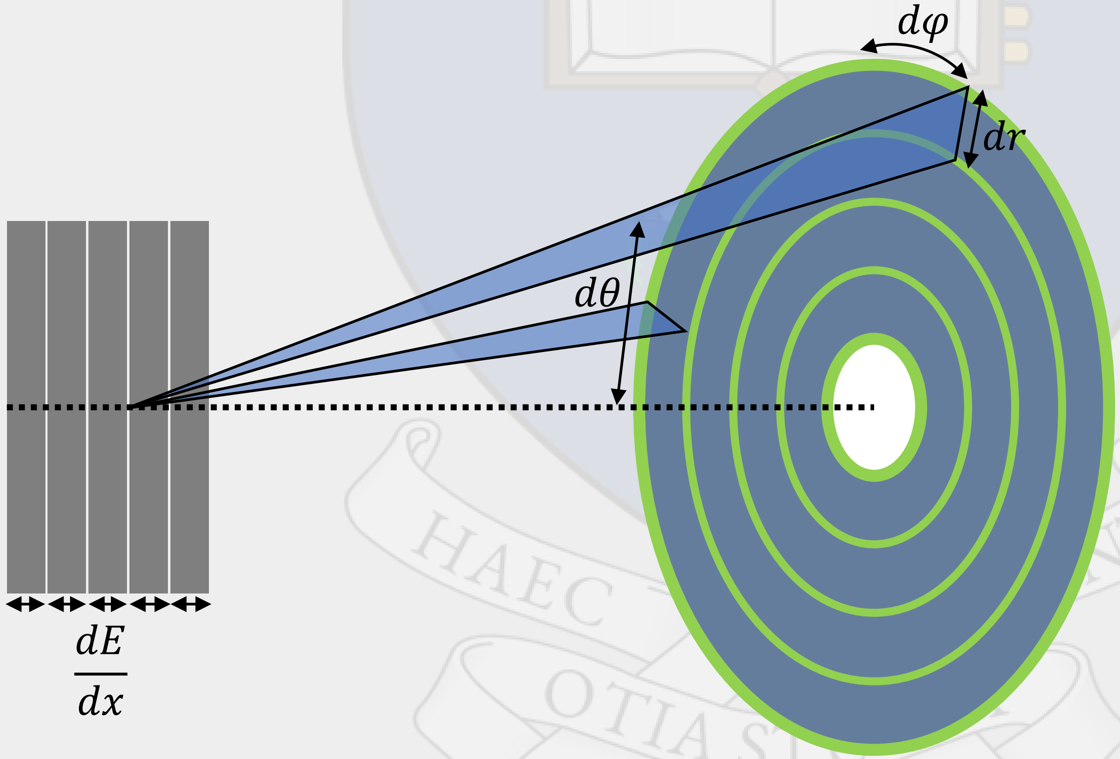


- $E2$ and $E1$ transitions dominate the de-excitation process i.e. the observed γ-rays
- $3^{-} \rightarrow 2^{+}$ γ-ray yield experimental observable used to probe occupation of the 3- state

GOSIA

- Used to model both excitation and de-excitation process
- Integrates over target thickness and scattering angles, considering the geometry and efficiency of the detector setup
- Fits the matrix elements to the experimental particle-gated γ-ray yields and additional spectroscopic data

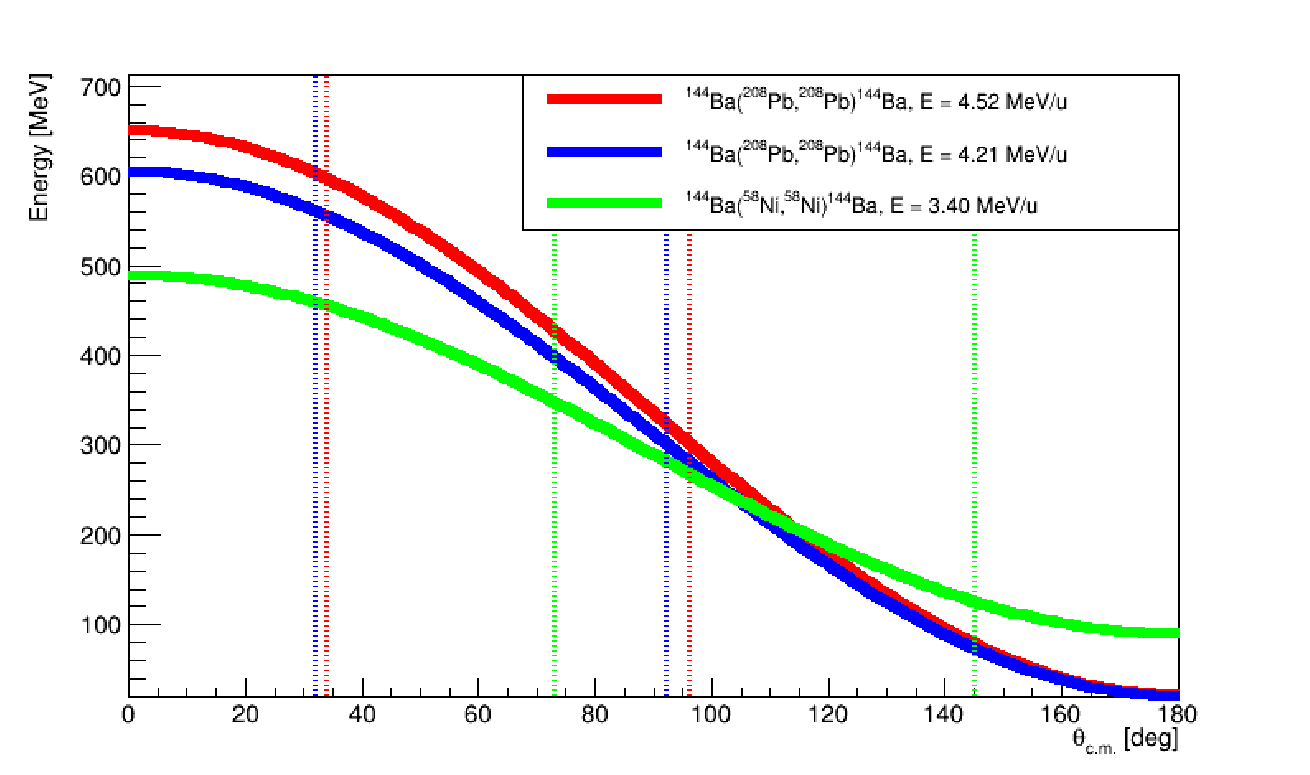




Experimental data

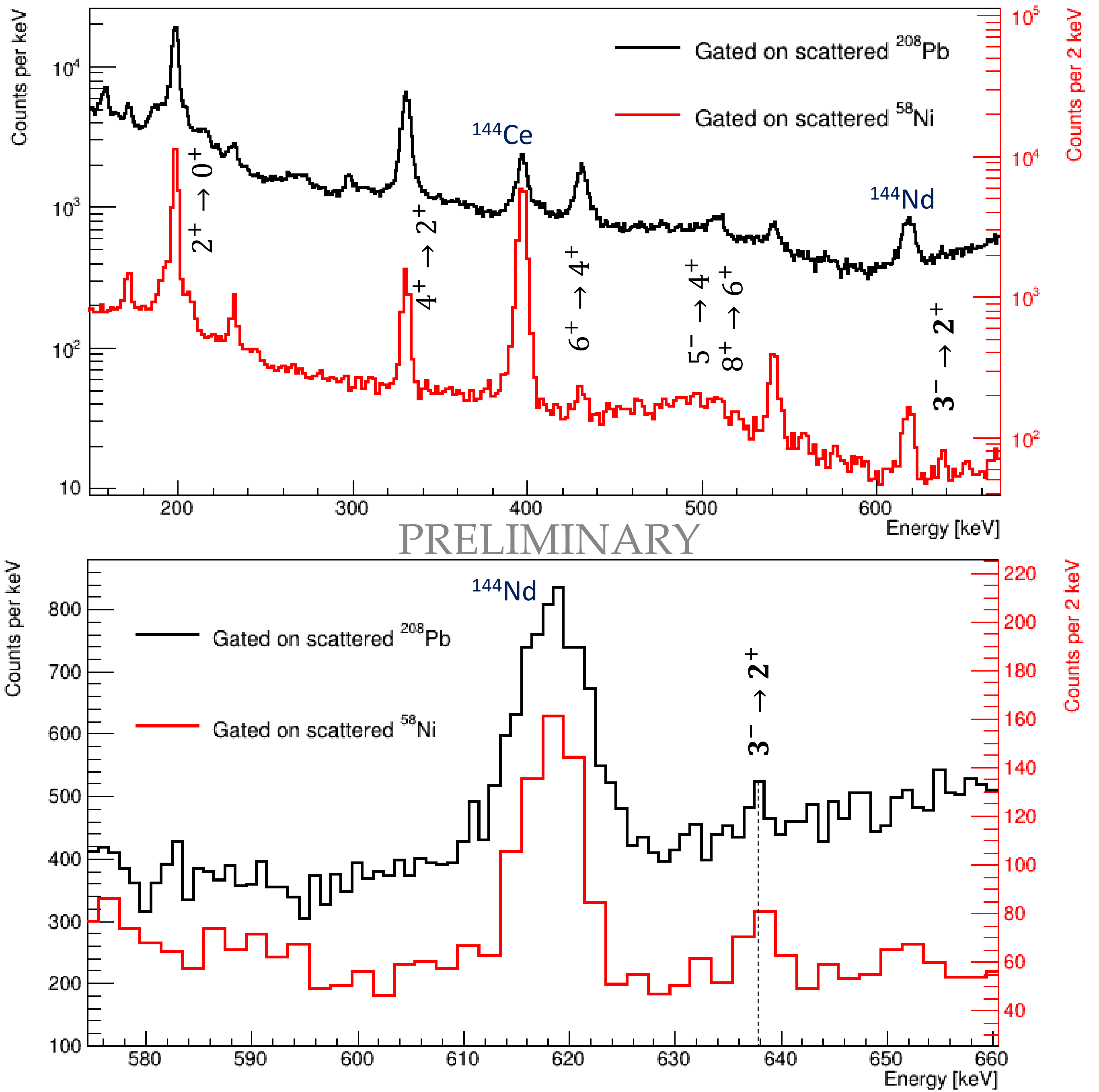
Three experiments performed on ^{144}Ba over 2017 and 2024 with a mix of beam energies and target isotope to cover a greater centre-of-mass scattering angle, gaining sensitivity to the angular distributions of the excitation:

- Beam E = 4.21 MeV/u, Target : ^{208}Pb
- Beam E = 4.52 MeV/u, Target : ^{208}Pb
- Beam E = 3.40 MeV/u, Target : ^{58}Ni



Particle gated spectra

- Singles and γγ yields checked for consistency for low stats peaks
- ^{208}Pb target favours multistep excitation and has higher Coulomb excitation cross section
- ^{58}Ni target favours single step excitation and has fewer counts, but cleaner spectrum
- $\gamma(2^+ \rightarrow 0^+)$ made up of a doppler shifted and unshifted component

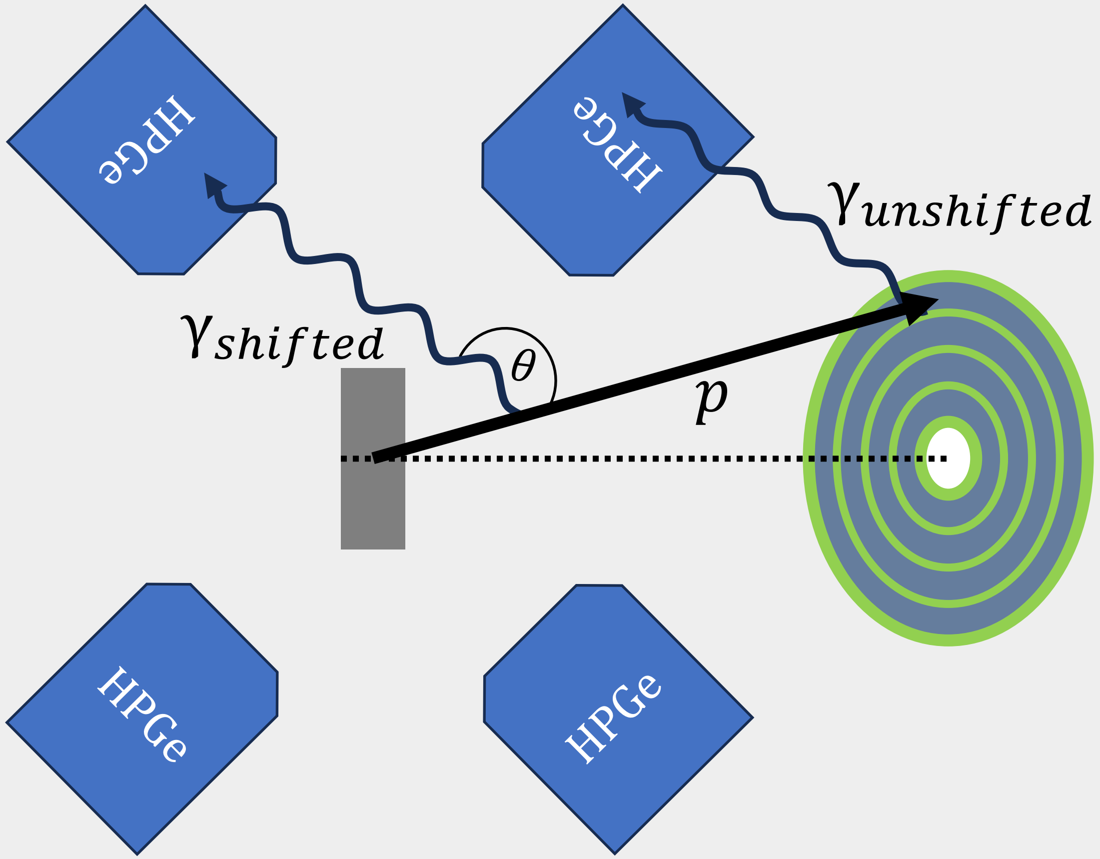


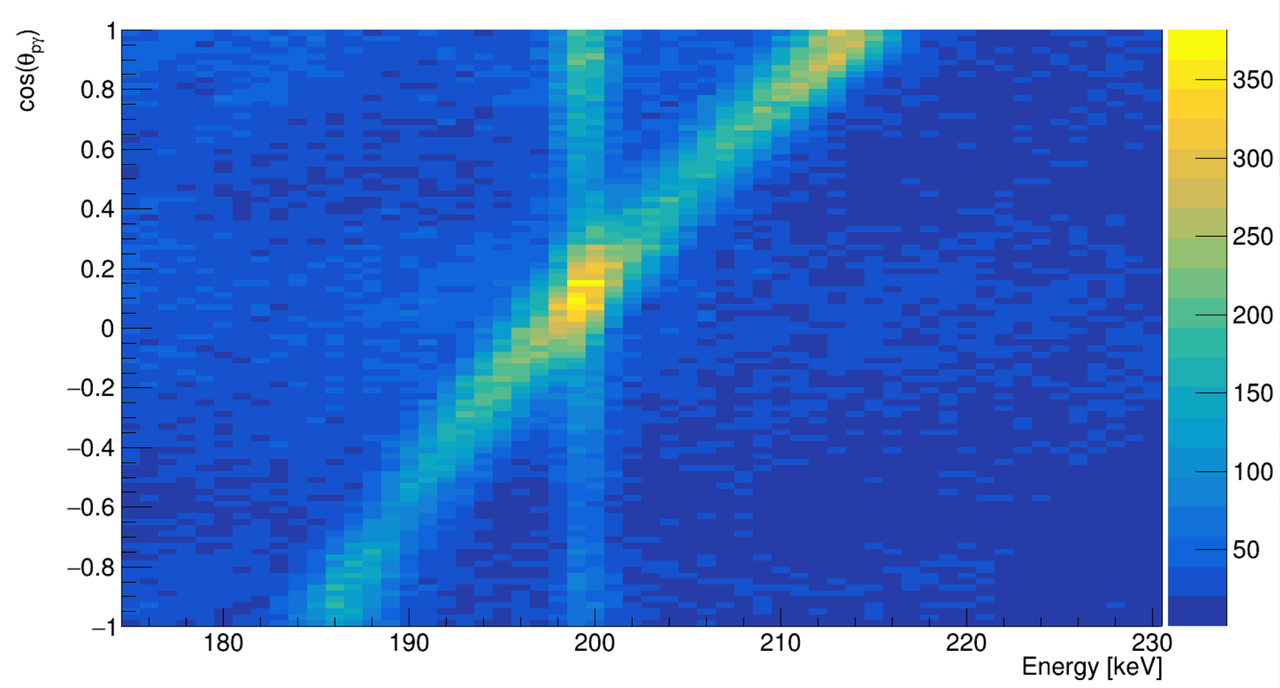
Doppler shifted/unshifted $\gamma(2^+ \rightarrow 0^+)$

$$\lambda = \lambda_0 \frac{(1-\beta cos(\theta_{p\gamma}))}{\sqrt{1-\beta^2}}$$

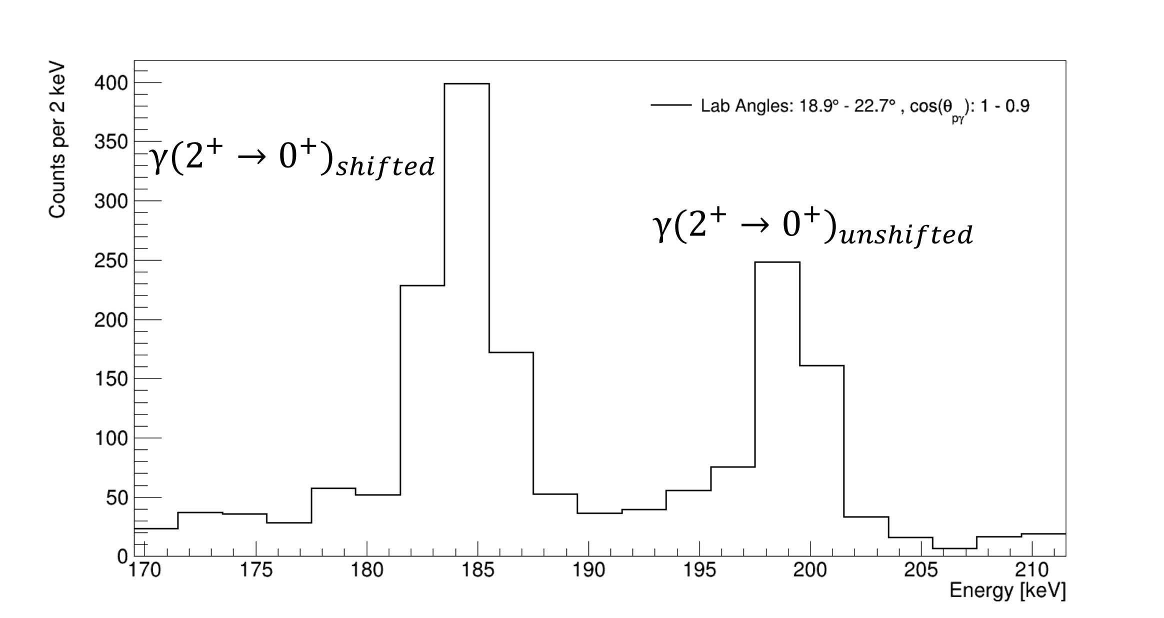
$$\frac{N(t)}{N_0} = \frac{\gamma(2^+ \rightarrow 0^+)_{shifted}}{\gamma(2^+ \rightarrow 0^+)_{shifted} + \gamma(2^+ \rightarrow 0^+)_{unshifted}}$$

$$\frac{N(t)}{N_0} = \exp\left({}^{-t(T.O.F.)}/_{\tau(2^+ \rightarrow 0^+)}\right)$$

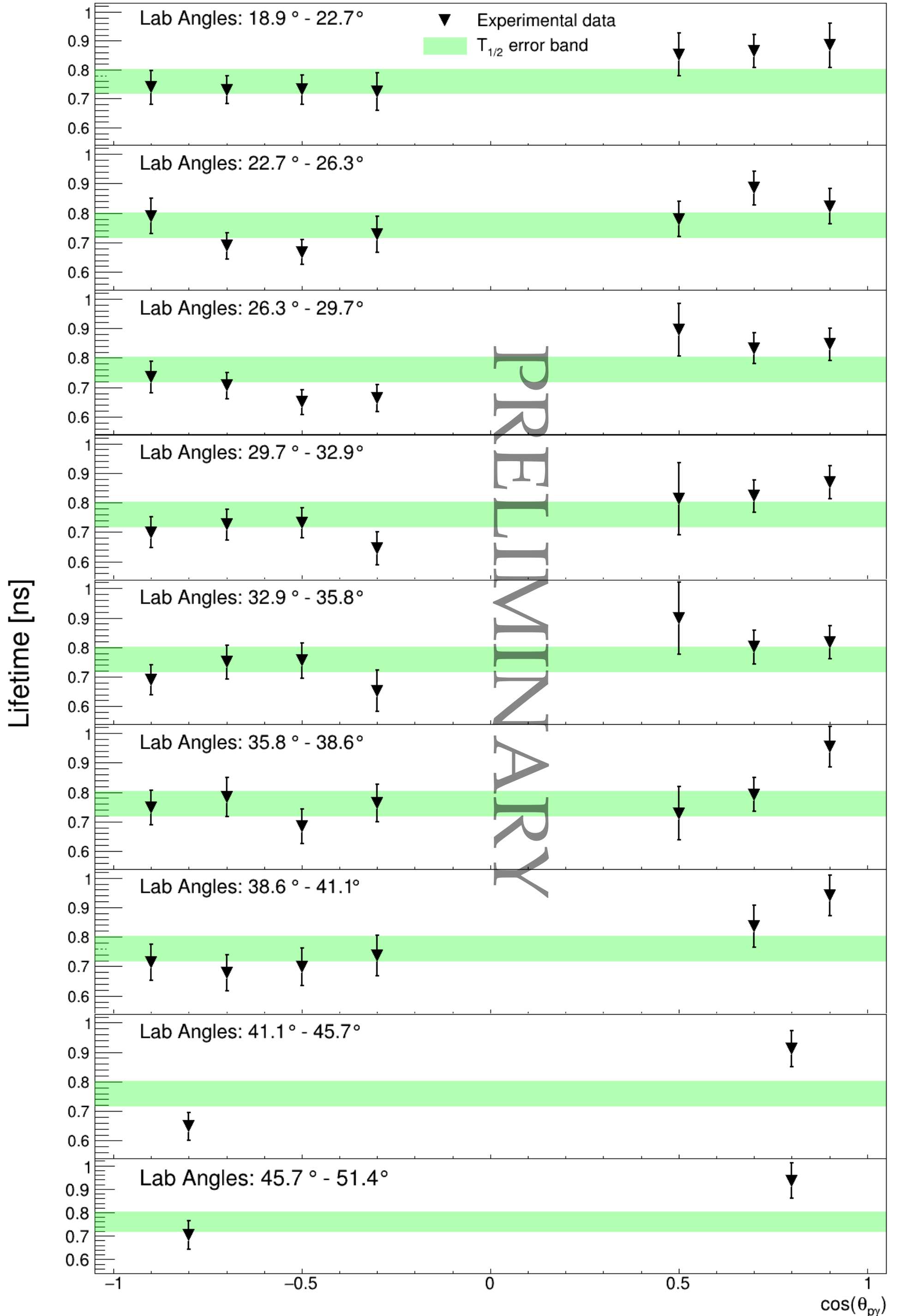




^{144}Ba - $T_{1/2}(2^+)$ level lifetime



Measurement	$T_{1/2}(2^+)$ [ps]
*This work.	740(30)
B.Olaizola et al, Phys Rev C 104, 034307 (2021)	740(90)
A. Sonzogni, Nucl Data Sheets 93, 599 (2001)	710(20)

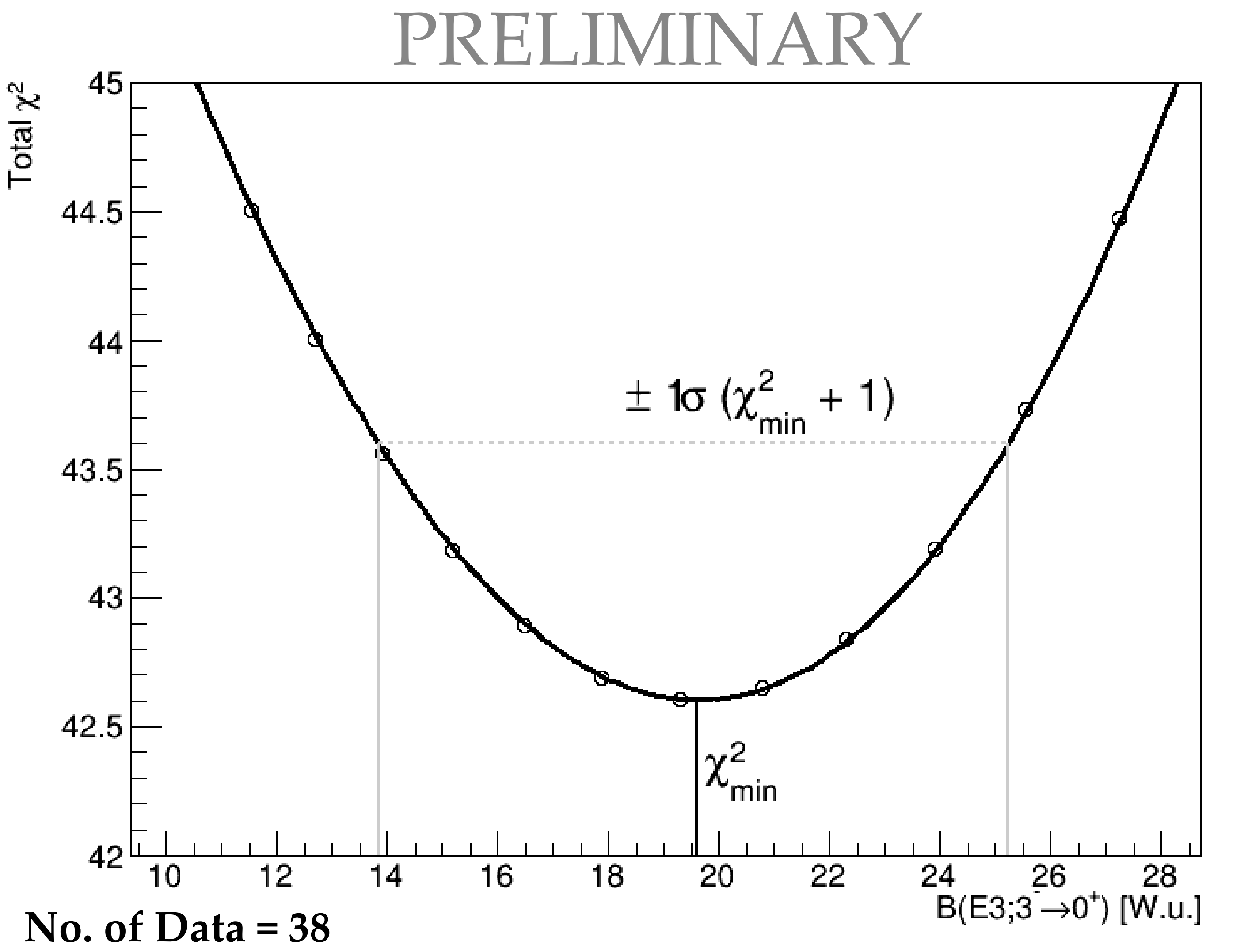


GOSIA – χ^2 minimisation

- Data normalised to the lifetime of the $T_{1/2}(2^+)$ in ^{144}Ba *

- χ^2 scan of $\langle 3^- || E3 || 0^+ \rangle$, all other M.E.'s are allowed to vary during the minimisation

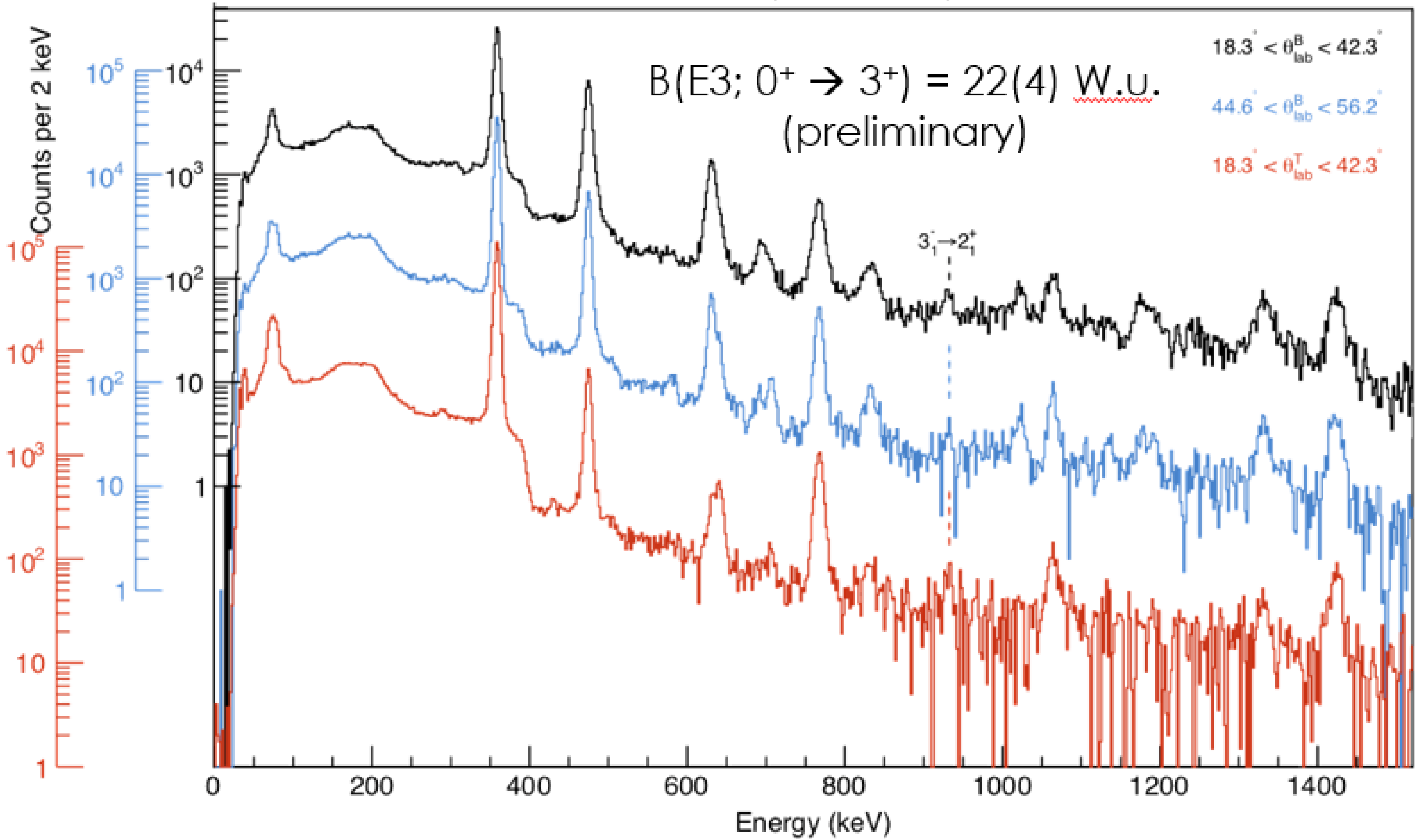
$$B(E3; 3^- \rightarrow 0^+) = \frac{\langle 3^- || E3 || 0^+ \rangle^2}{7}$$



^{142}Ba on 208Pb (2018) – unpublished

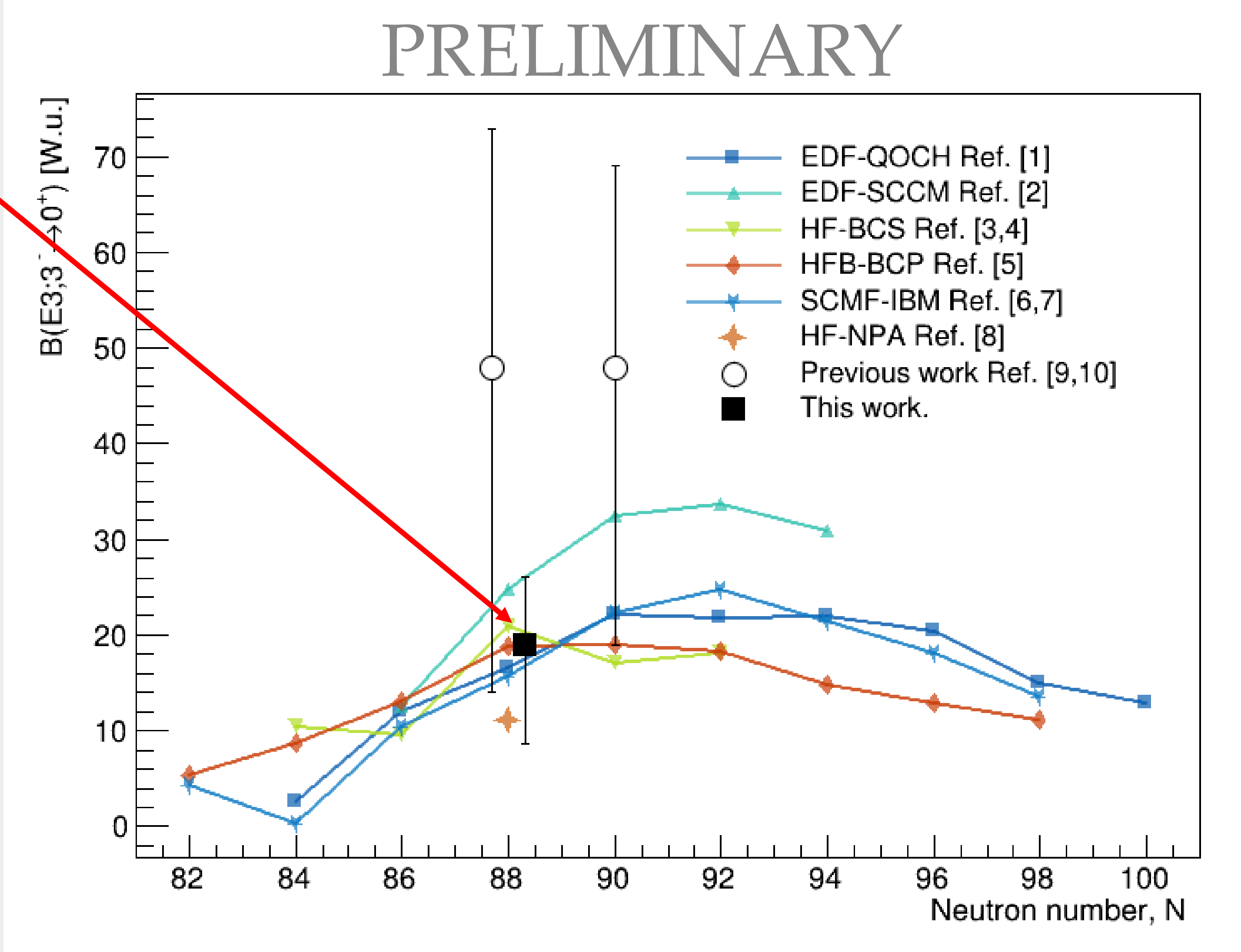
- Similar contamination from isobars (Sm, Nd & Ce)
- Much greater statistics for the $\mathbf{3^-} \rightarrow \mathbf{2^+}$ compared to the measurement on ^{144}Ba
- Measured B(E3) for ^{142}Ba and ^{144}Ba comparable to each other

Provided by L. Gaffney



Measured B(E3) vs theory

- Extracted B(E3) consistent with current theory
- Systematic errors yet to be included (Beam energy, target thickness etc.)



References:

[1] S. Y. Xia et al., Phys. Rev. C 96, 054303 (2017)

[2] R. N. Bernard, L. M. Robledo and T. R. Rodríguez, Phys. Rev. C 93, 061302 (2016)

[3] J. Egido and L.M. Robledo, Nucl. Phys. A 518, 475 (1990)

[4] J. Egido and L.M. Robledo, Nucl. Phys. A 545, 589 (1992)

[5] L. M. Robledo, M. Baldo, P Schuk, and T. R. Rodríguez, Phys. Rev. C 81, 034315 (2010)

[6] K. Nomura, D. Vretenar, T. Nikšić and Bing-Nan Lu, Phys. Rev. C 89, 024312 (2014)

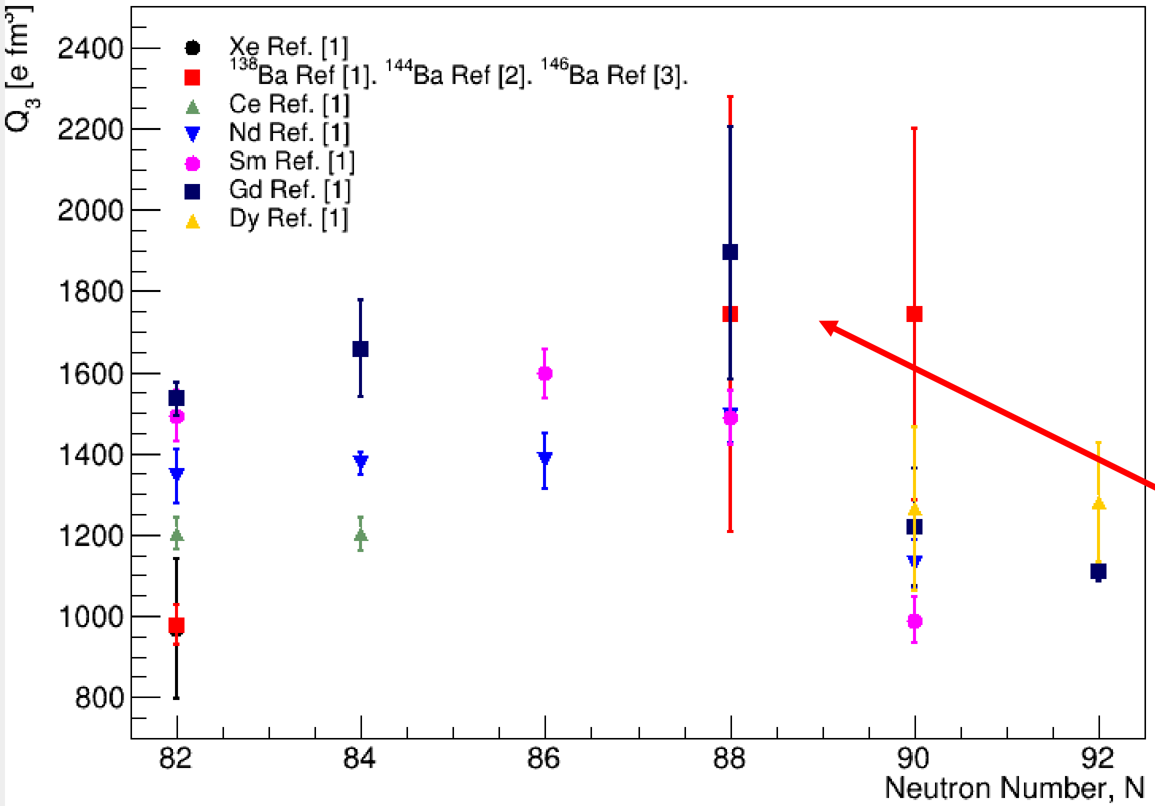
[7] K. Nomura, T. Nikšić and D. Vretenar, Phys. Rev. C 97 024317 (2014)

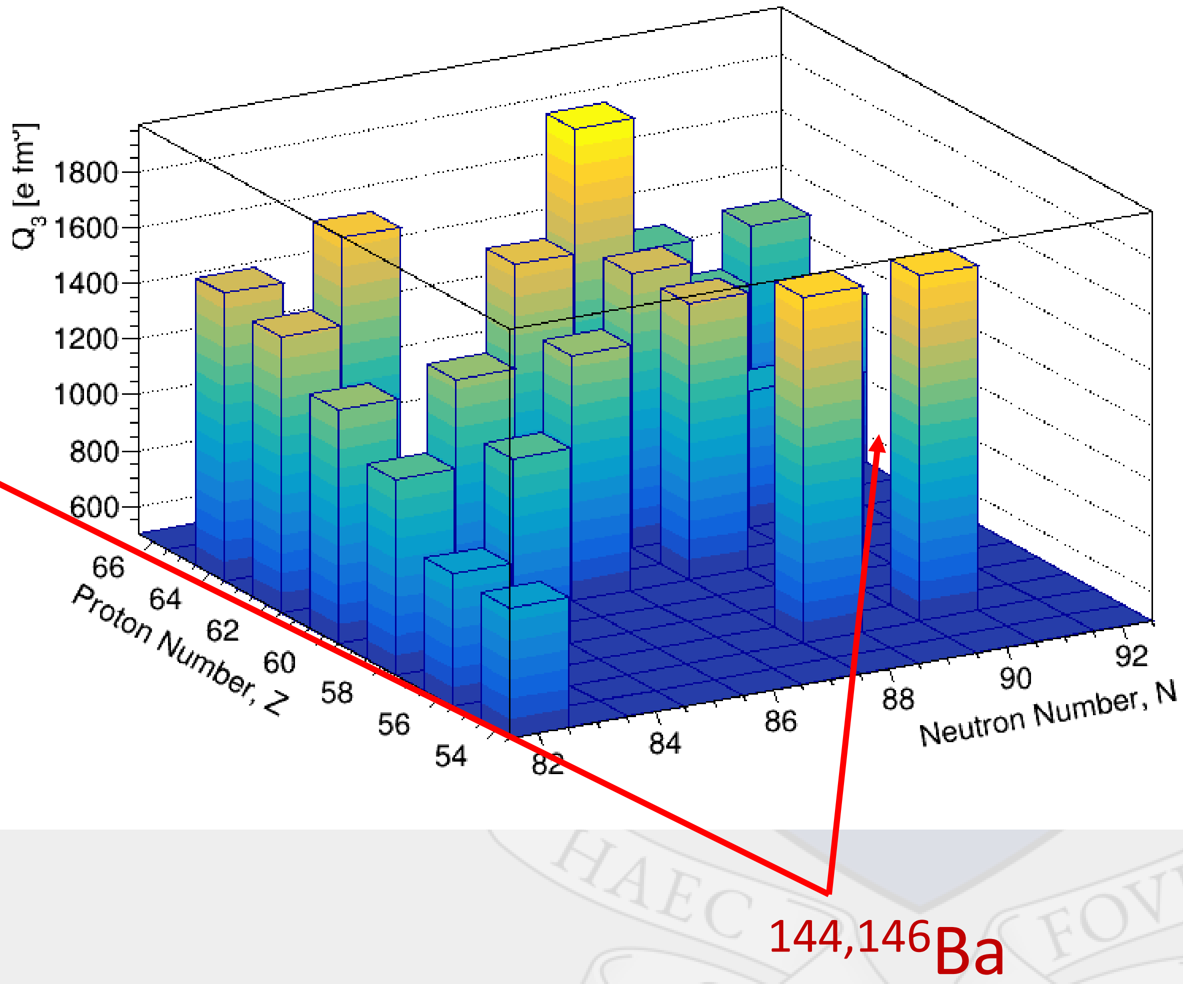
[8] X. Yin, M. Q. Lin, C. Ma, and Y. M. Zhao, Phys. Rev. C 111, 044310 (2025)

[9] B. Bucher et al., Phys. Rev. Lett. 116. 112503 (2016)

[10] B. Bucher et al., Phys. Rev. Lett. 118. 152504 (2017)

Experimental Q_3 in the Lanthanides - Previous work





References:

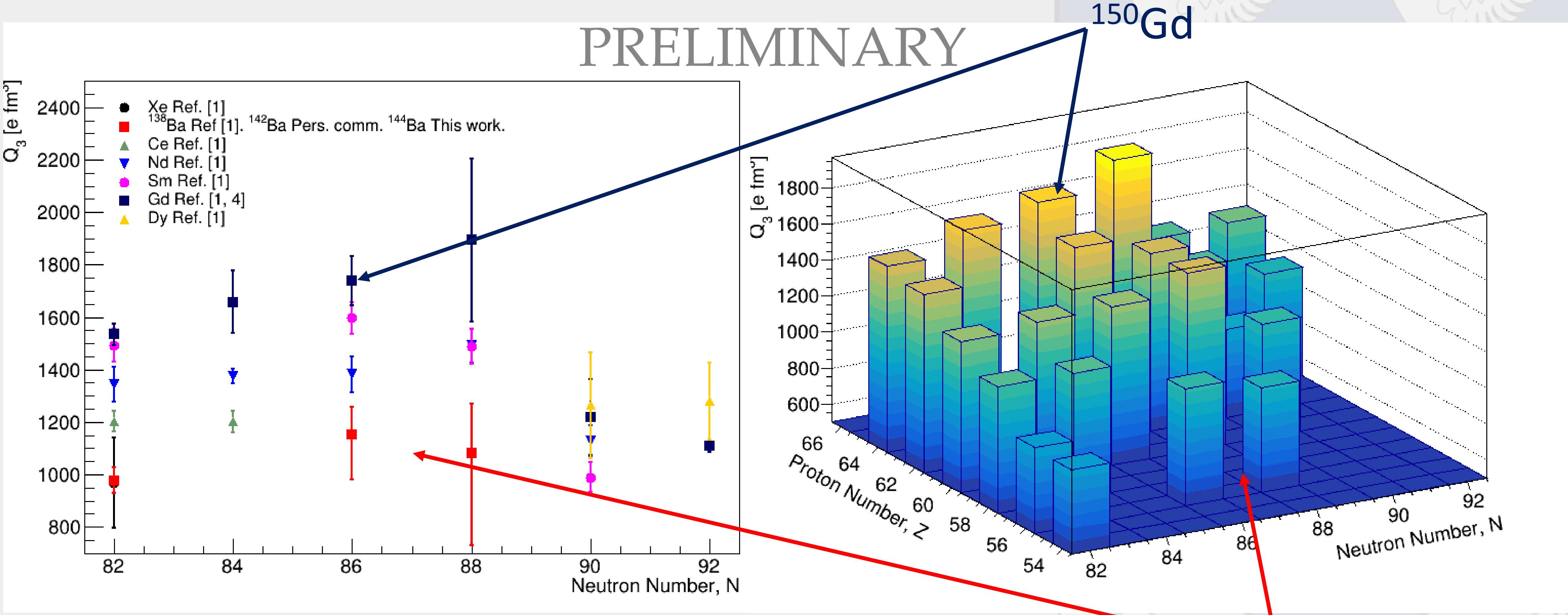
[1] Kibédi T and Spear R H, At. Data Nucl. Data Tables 80 35 (2002)

[2] B. Bucher et al., Phys. Rev. Lett. 116. 112503 (2016)

[3] B. Bucher et al., Phys. Rev. Lett. 118. 152504 (2017)

[4] S. Pascu et al., Phys. Rev. Lett. 134, 092501 (2025)

Experimental Q_3 in the Lanthanides - Recent work



References:

[1] Kibédi T and Spear R H, At. Data Nucl. Data Tables 80 35 (2002)

[2] B. Bucher et al., Phys. Rev. Lett. 116. 112503 (2016)

[3] B. Bucher et al., Phys. Rev. Lett. 118. 152504 (2017)

[4] S. Pascu et al., Phys. Rev. Lett. 134, 092501 (2025)

Thanks for listening and thanks to all the collaborators!

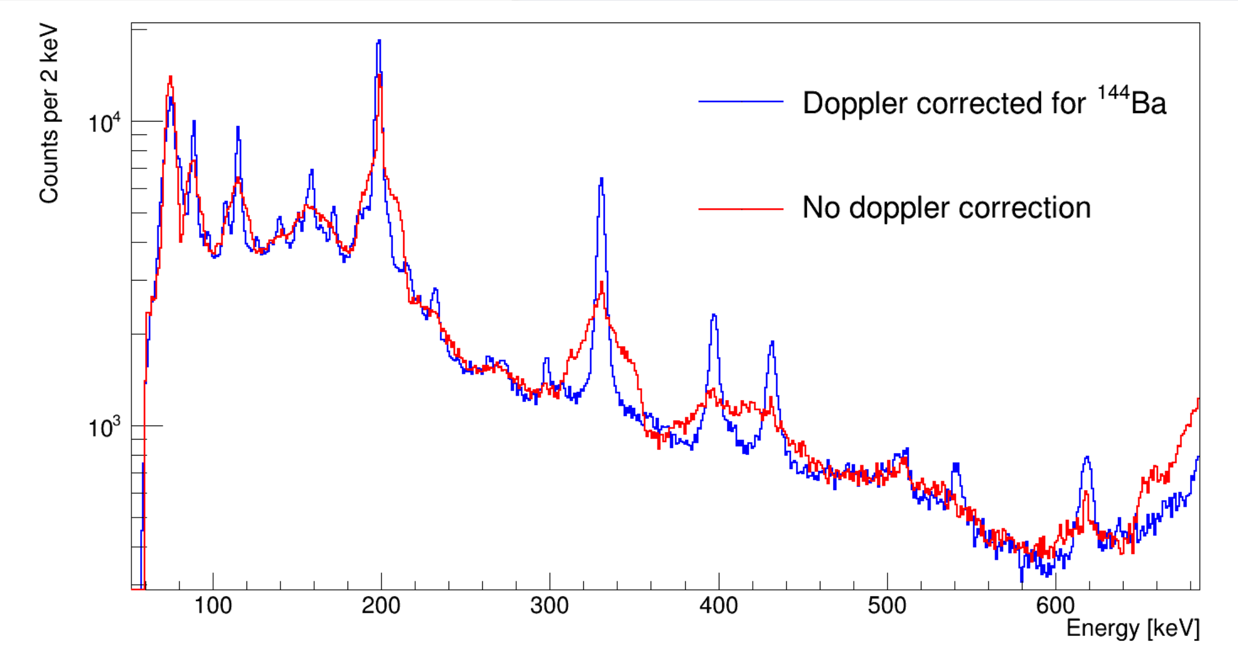
Summary

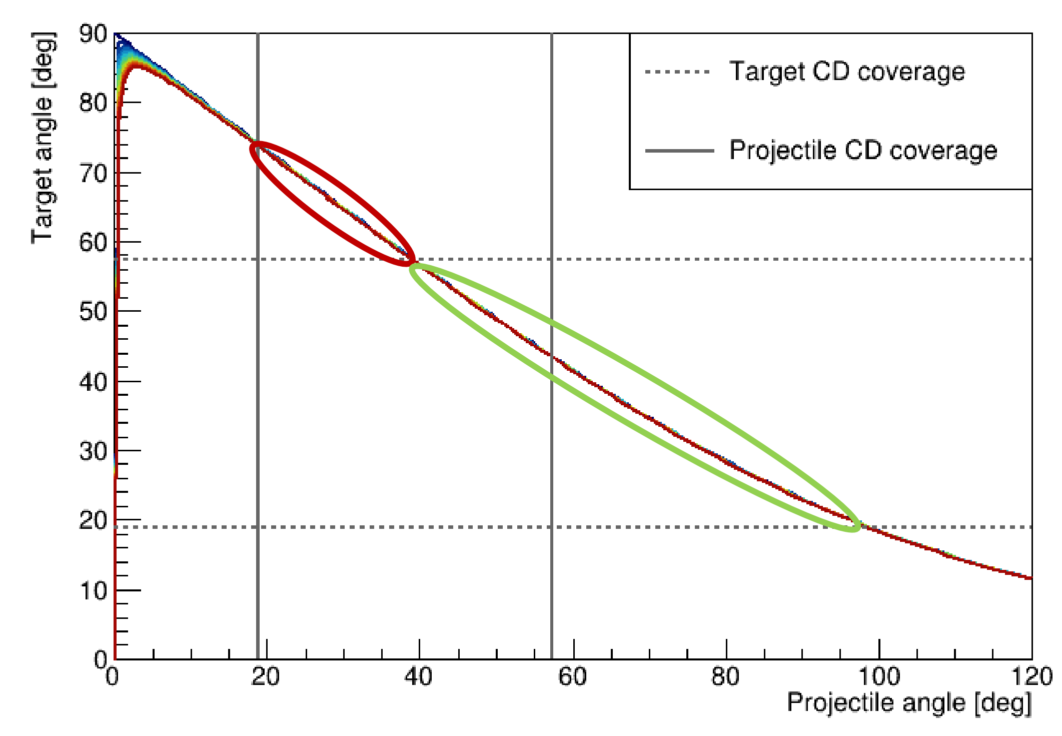
- Measured B(E3) for ^{144}Ba now consistent with mean-field theory calculations
- Experimental systematics indicate ^{144}Ba is likely not the centre of octupole collectivity in this region

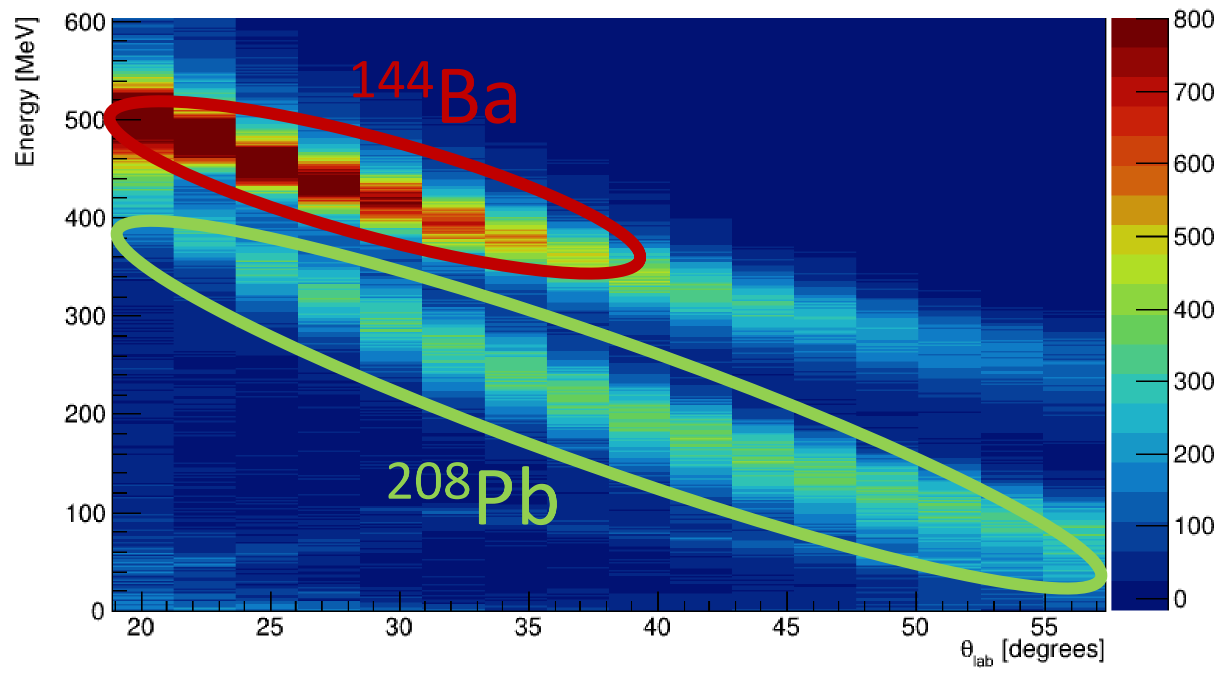
Backup slides

Particle gating

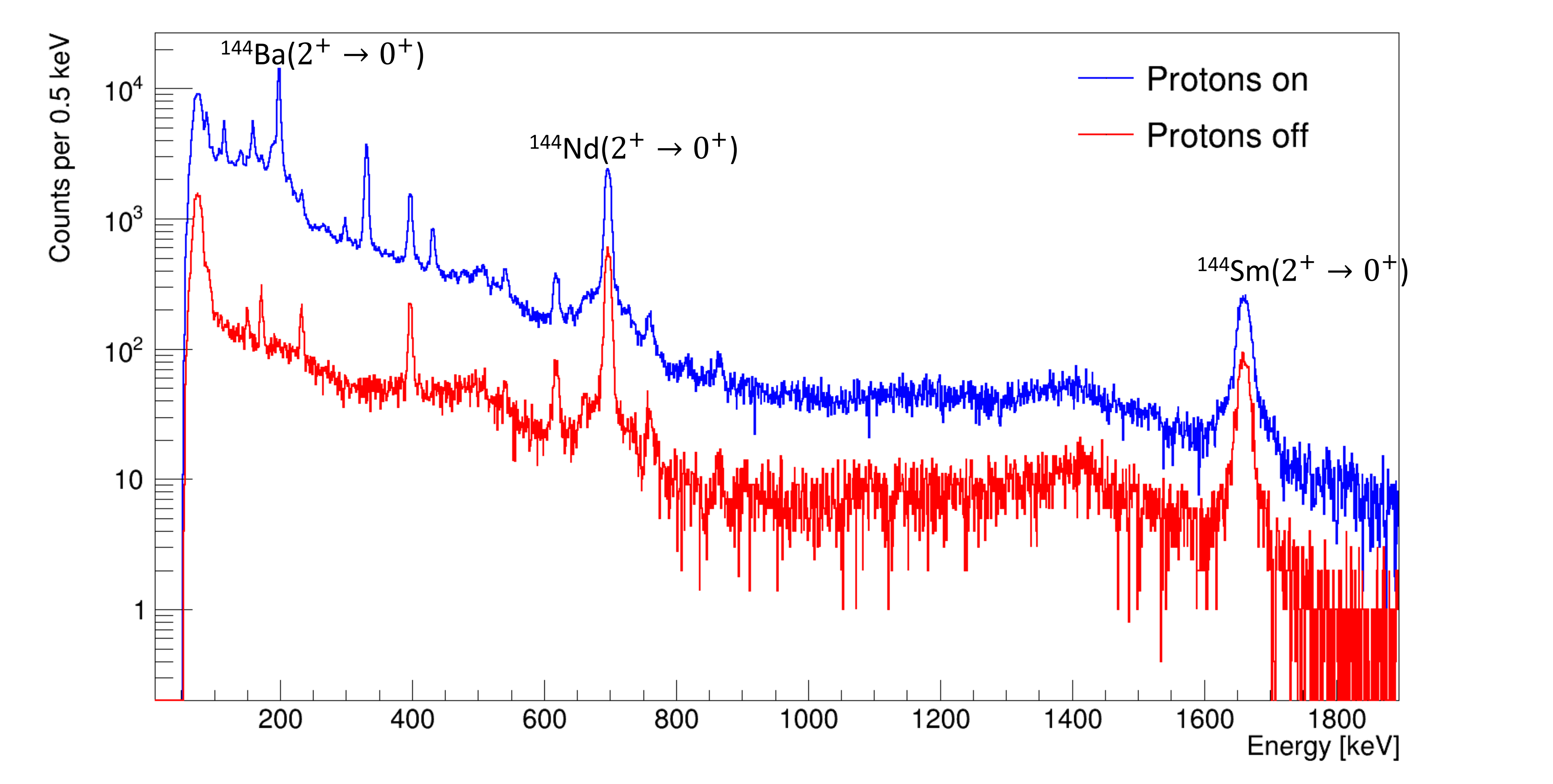
- γ-rays are doppler corrected for the coincident projectile/target nucleus
- Gating on both the projectile and target effectively increases the lab angle coverage of the CD detector



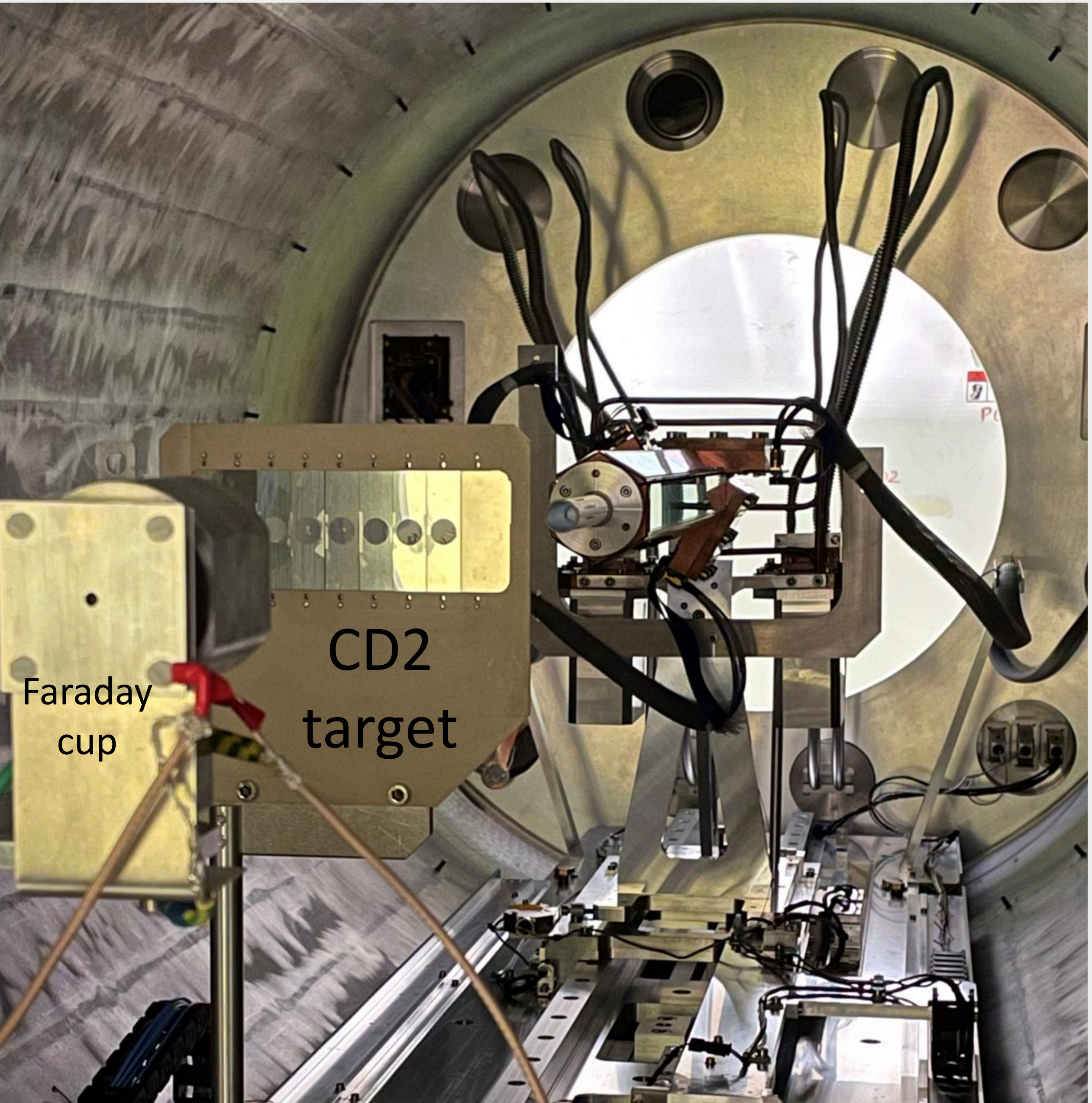




Isobaric contaminants - 2024 Data



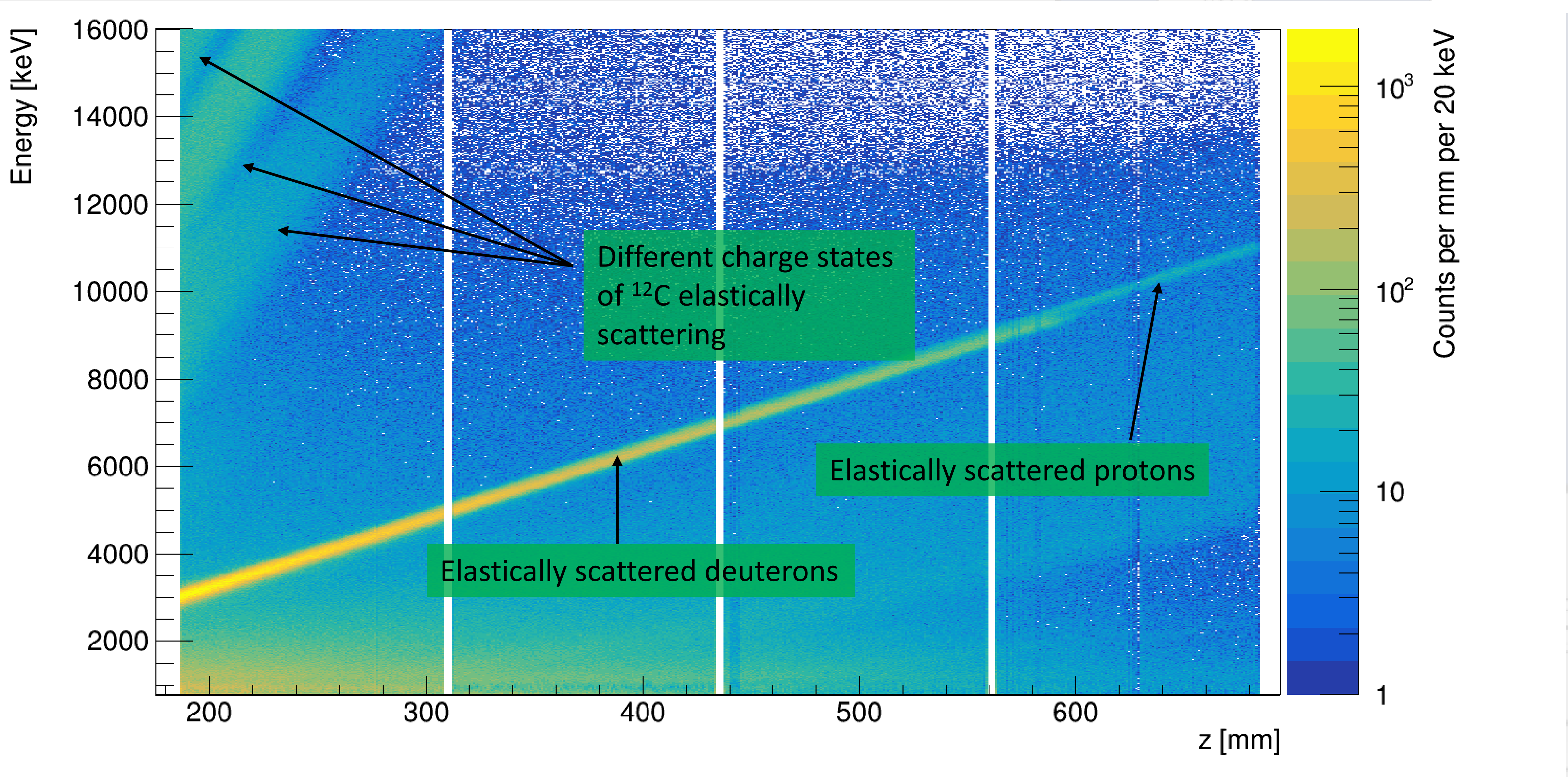
ISS



Setup

- ISS silicon array placed in the downstream position (for the first time)
- Target: 200 µg/cm^2, CD_2
- Beam Energy: 8.38 MeV/u
- Magnetic field: 2.5 T
- Faraday cup for beam tuning

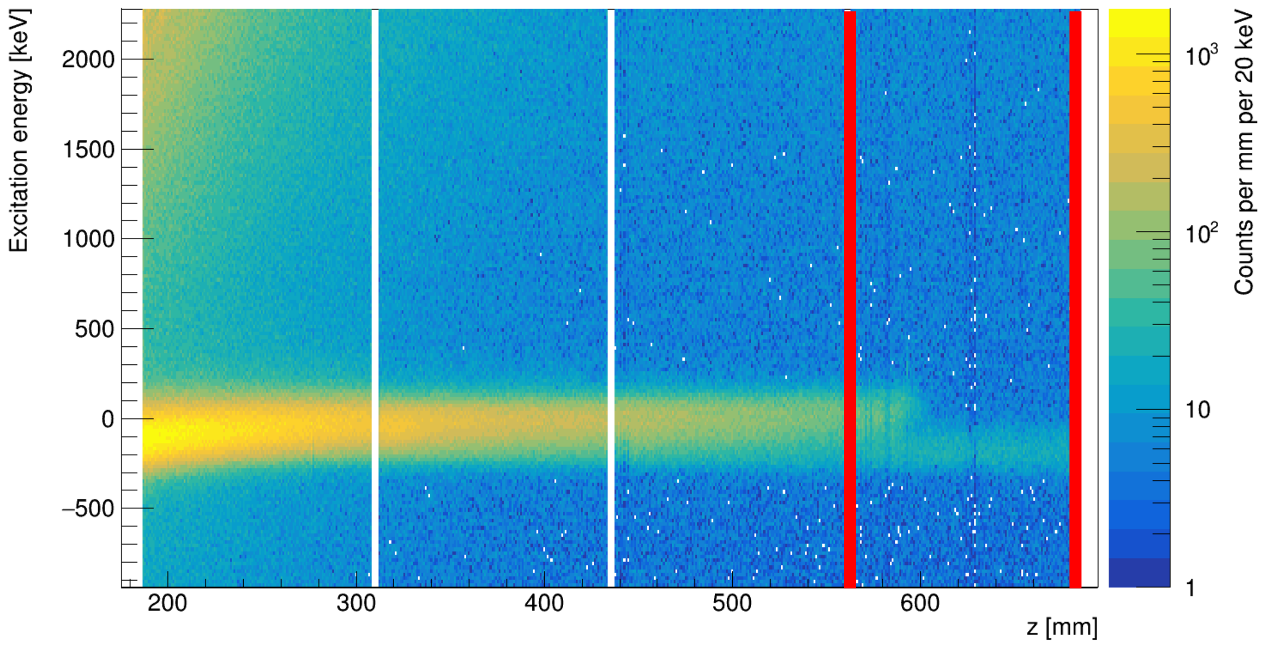
ISS data

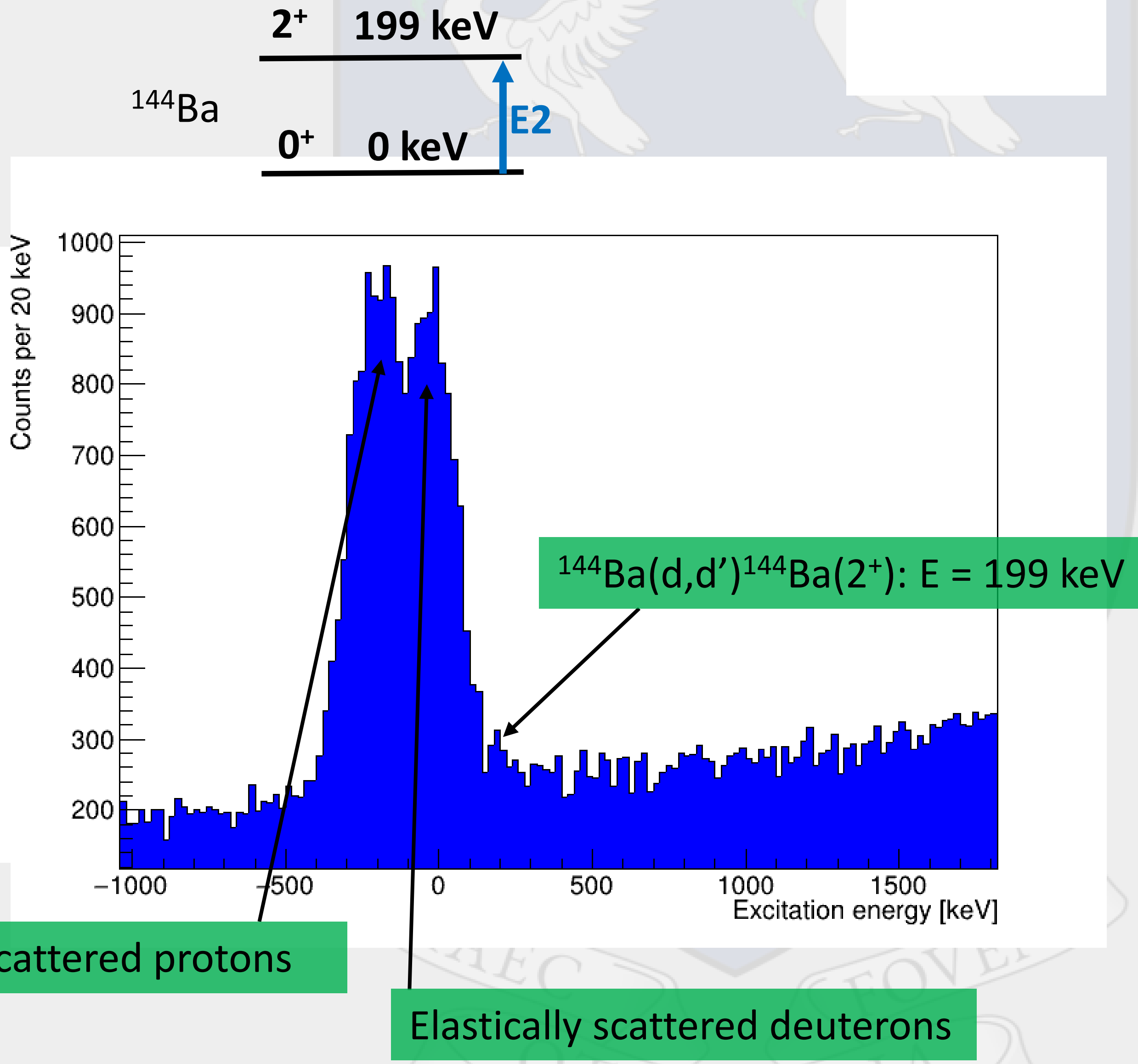


Energy [keV]
16000
14000
12000
10000
8000
6000
4000
2000
200
300
400
500
600
z [mm]
Counts per mm per 20 keV
10^3
10^2
10
1
Different charge states of ^{12}C elastically scattering
Elastically scattered protons
Elastically scattered deuterons

Excitation energy reconstructed from the kinematics

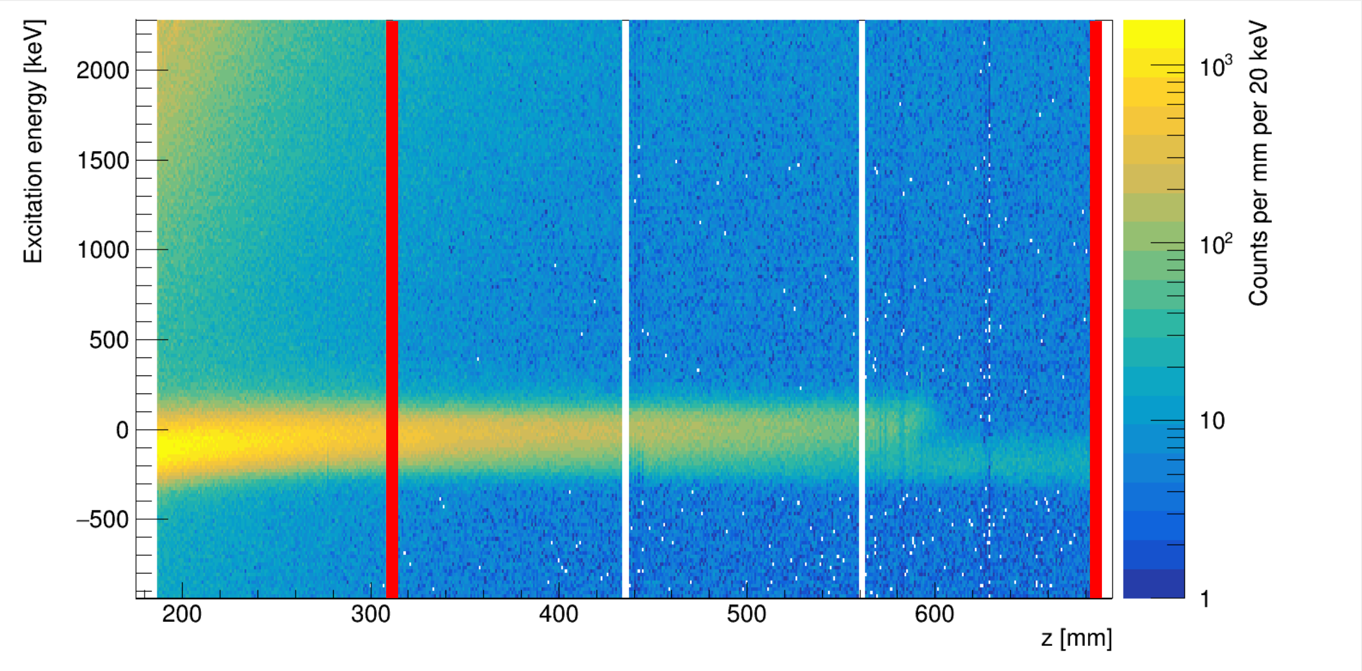
Slice of events from 570 mm to 684 mm

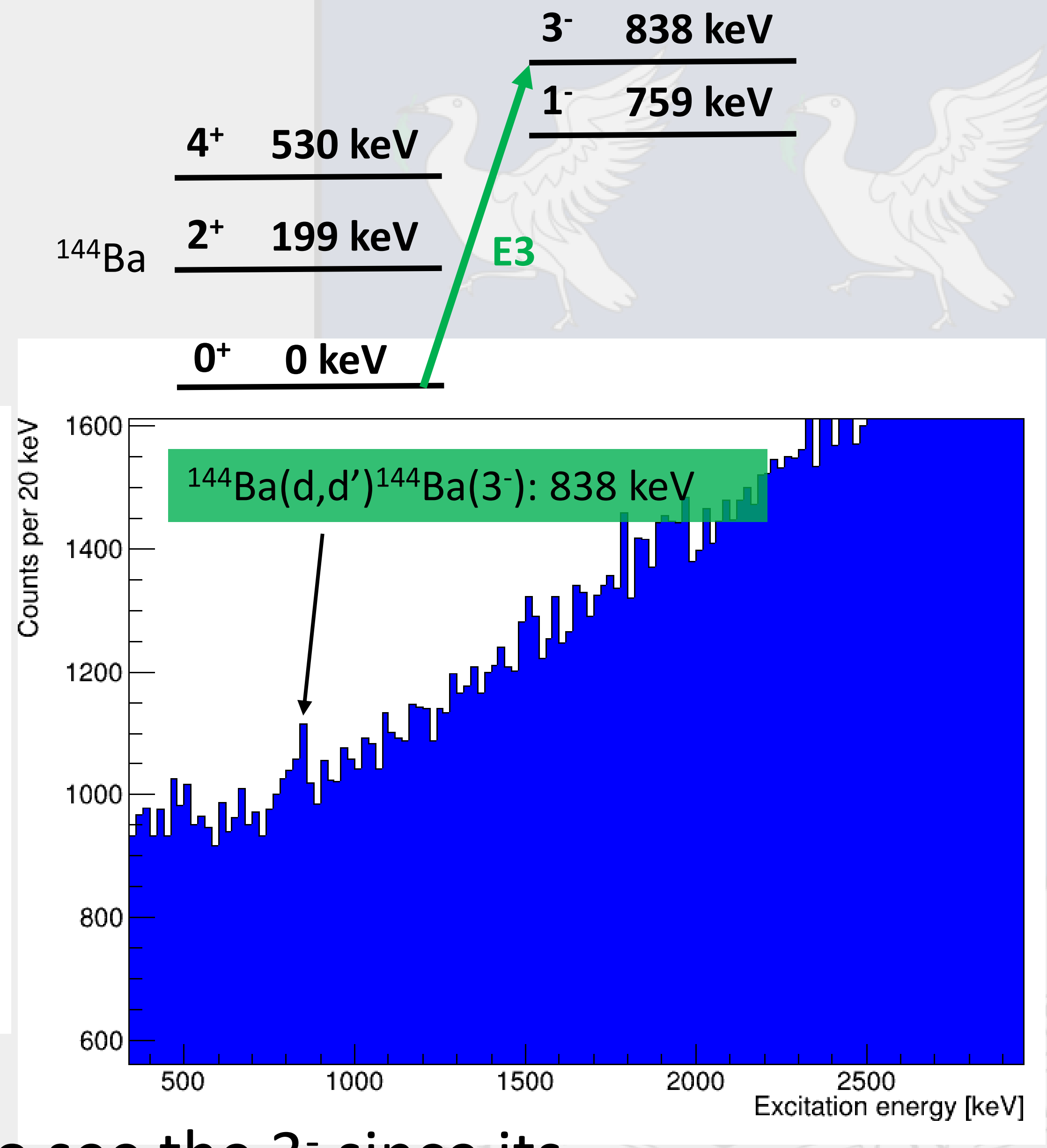




The 2^+ is only visible on the last row due to the resolution and size of the elastic peak.

Slice of events from 312 mm to 684 mm

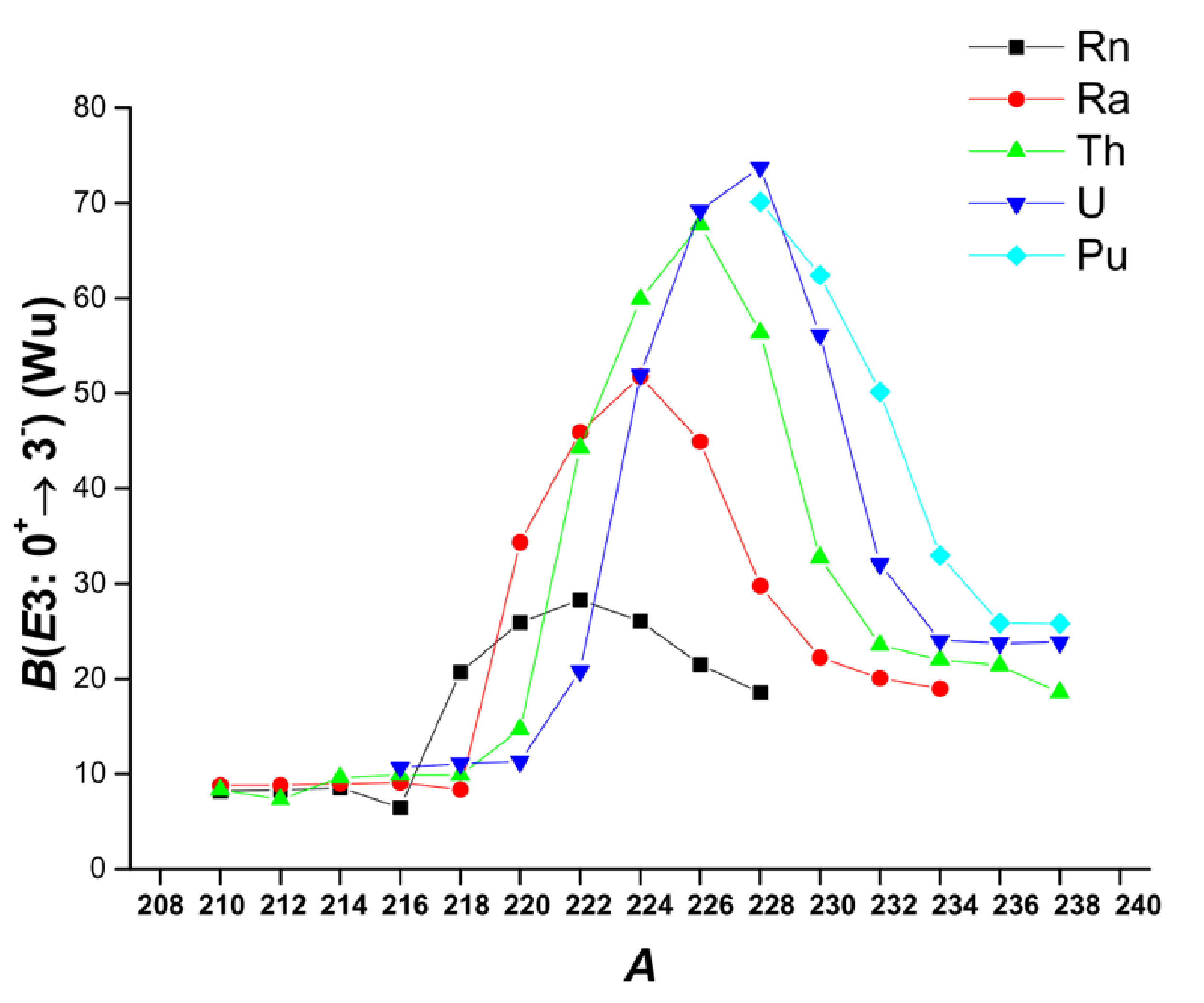




Almost the entire detector can be used to see the 3^- since its far enough away from the rutherford scattering peak.

Theoretical Q_3 in the Actinides

- Theoretical systematics in the actinides predict the expected peak for the B(E3) is past the Z=88, N=134 (A=222) doubly octupole magic ^{222}Ra and scales with Z
- Predicted yields from FRIB should be sufficient to measure transition strengths for isotopes such as ^{226}Th and ^{228}U

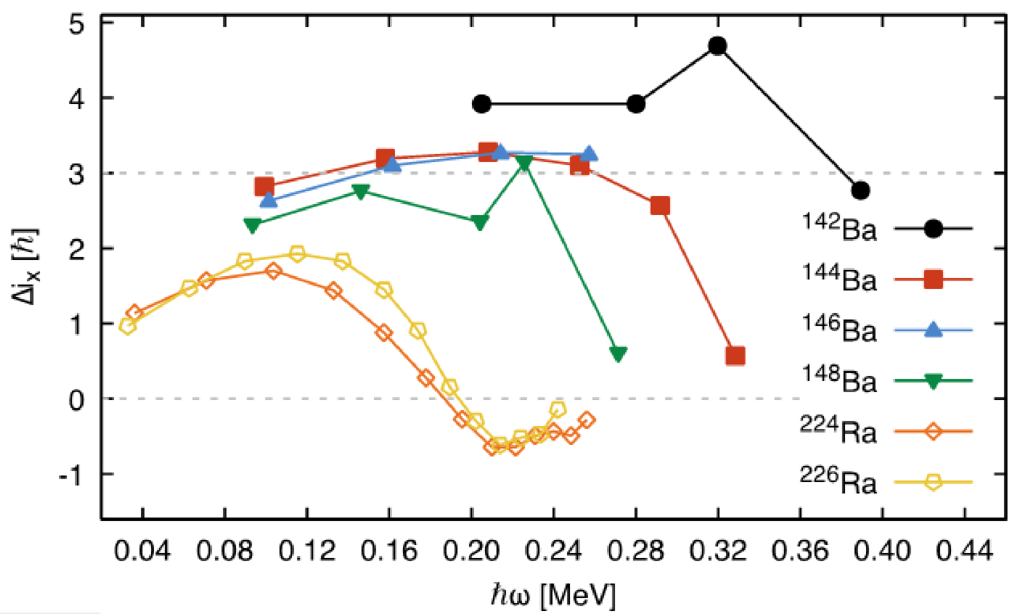


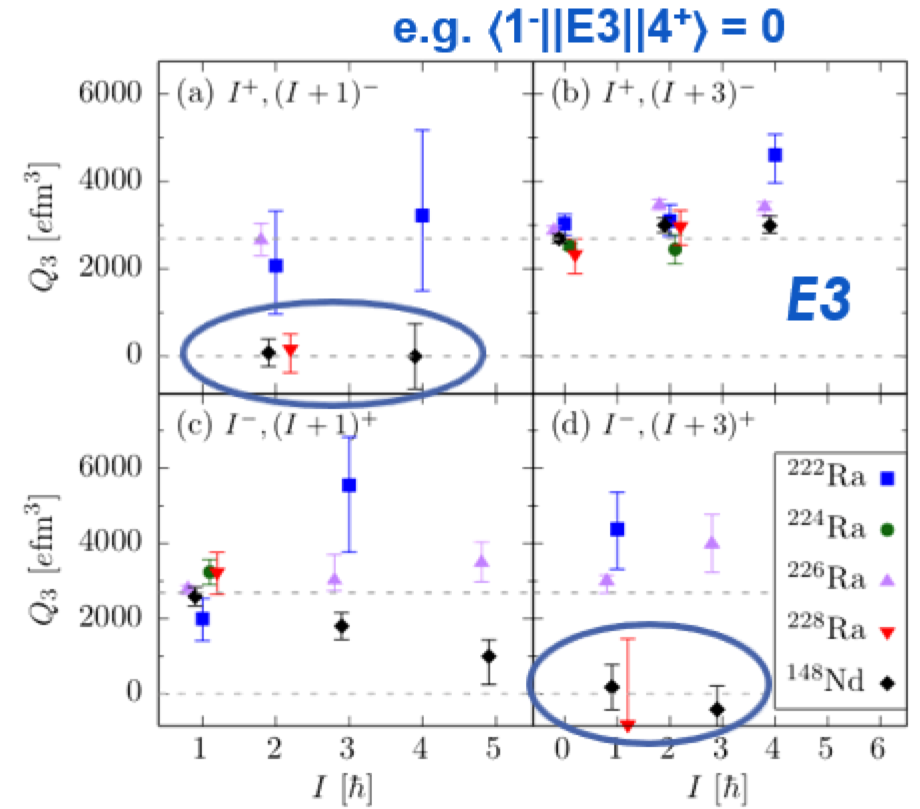
P.A. Butler, *J. Phys. G Nucl. Part. Phys*. **43**, 073002 (2016).
L.M. Robledo and G.F. Bertsch, *Phys. Rev. C* **84**, 54302 (2011).

Vibrational or deformed?

- Spin alignment plots provide information on the nature of the octupole correlations in nuclei – a value of $\Delta i_x = 3\hbar$ for all $\hbar\omega$ is expected for octupole vibrators where an octupole phonon aligned with the rotation axis

- A Q_3 of zero for some transitions (e.g. $\langle 1^- || E3 || 4^+ \rangle$ = 0) is a signature of vibrational octupole coupling, however measuring this is the Lanthanides would be very challenging





P.A. Butler, L.P. Gaffney, P. Spagnoletti, et al., *Phys. Rev. Lett.* **124**, 042503 (2020)