Octupole deformation in neutron-deficient plutonium isotopes

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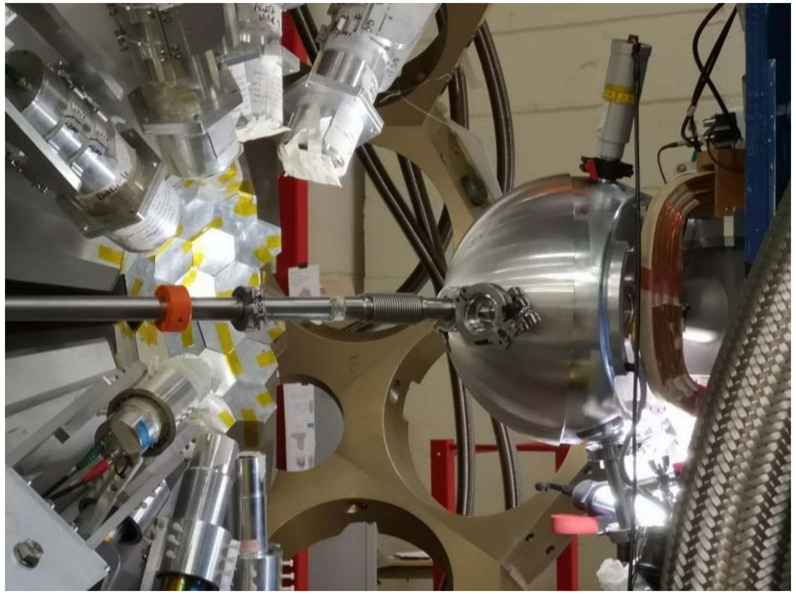
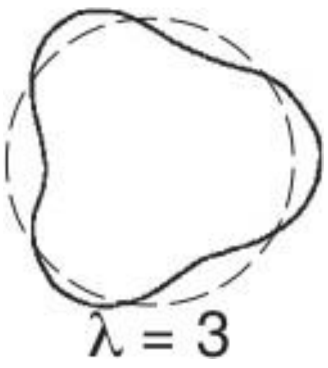


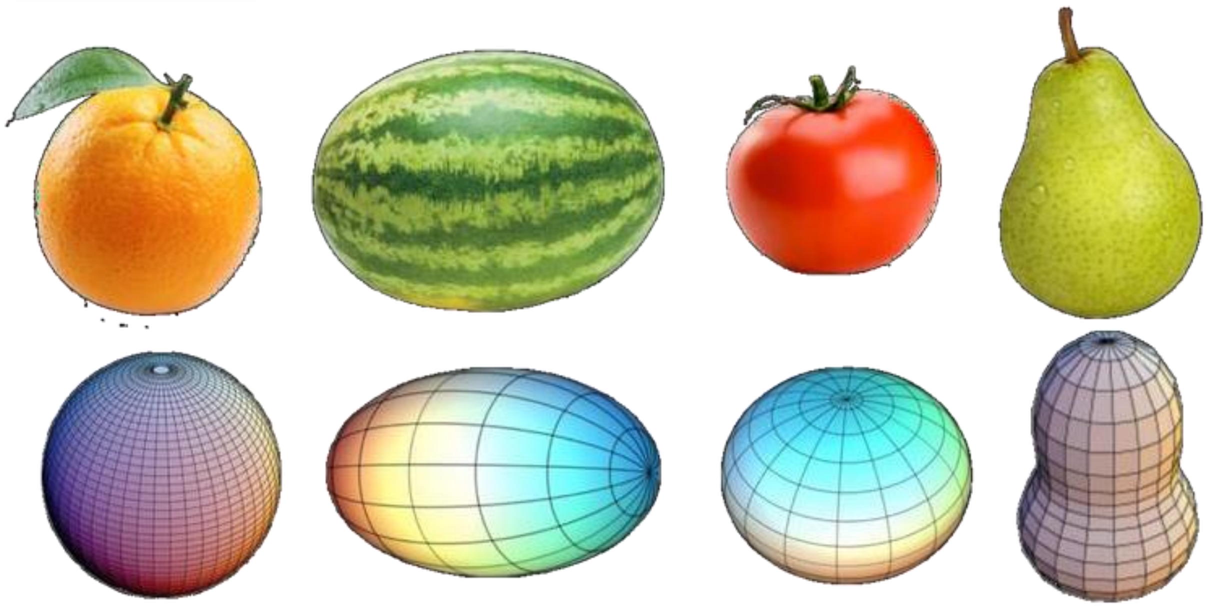
Octupole deformation

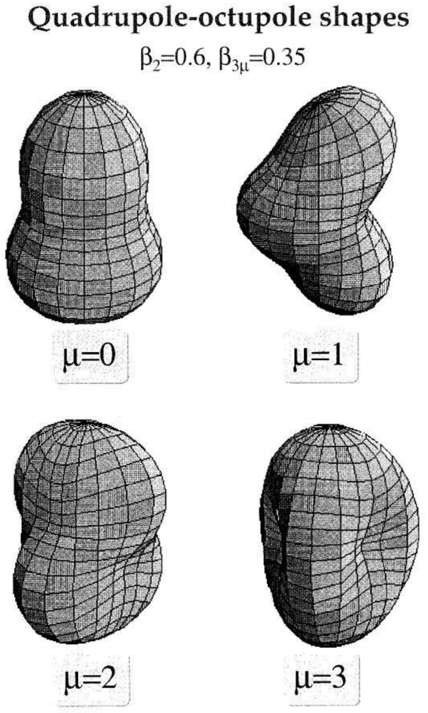
The nuclear shape is described by spherical harmonics multiplied by an expansion coefficient (deformation parameter).

$$R(\theta,\phi) = R_0[1 + \sum_{\lambda,\mu} \alpha_{\lambda,\mu} Y_\lambda^\mu]$$

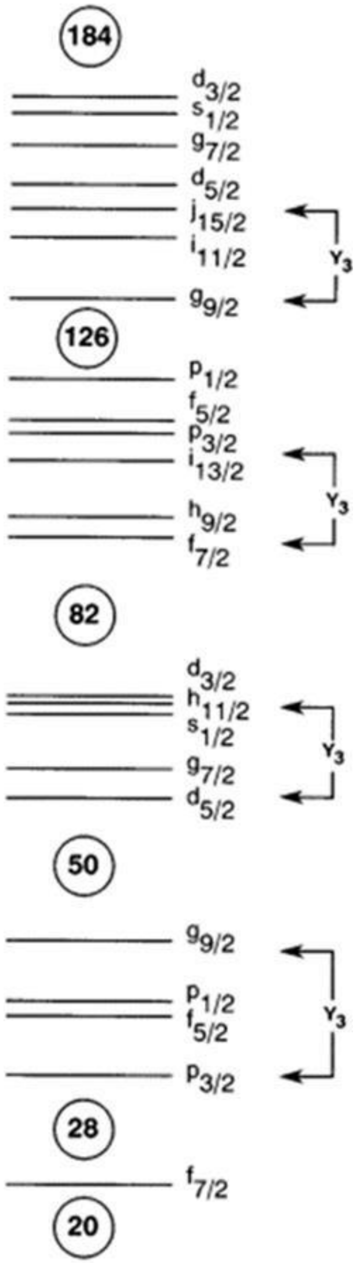


Spherical | Prolate | Oblate | Pear-shaped





Octupole deformation



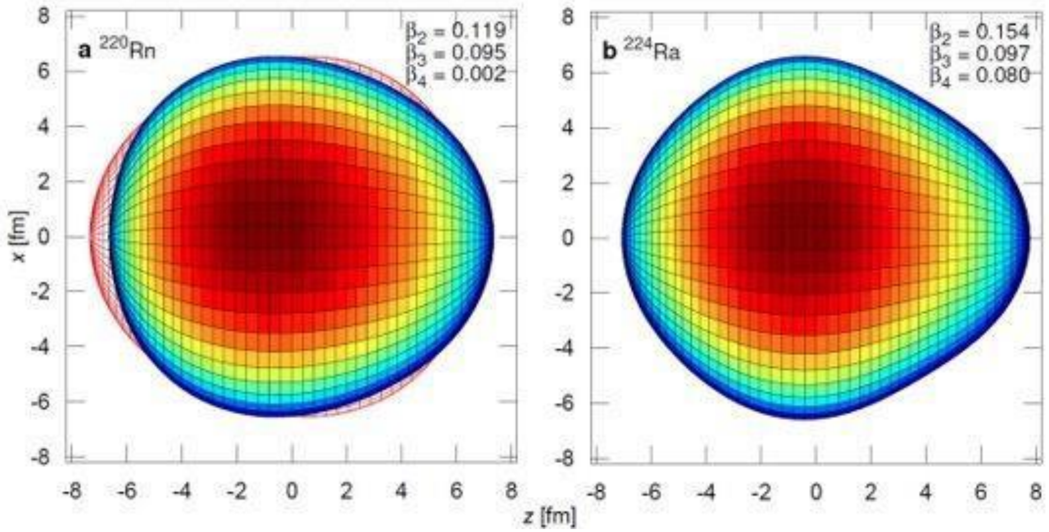
134 ($j_{15/2}$, $g_{9/2}$)

88 ($i_{13/2}$, $f_{7/2}$)

56 ($h_{11/2}$, $d_{5/2}$)

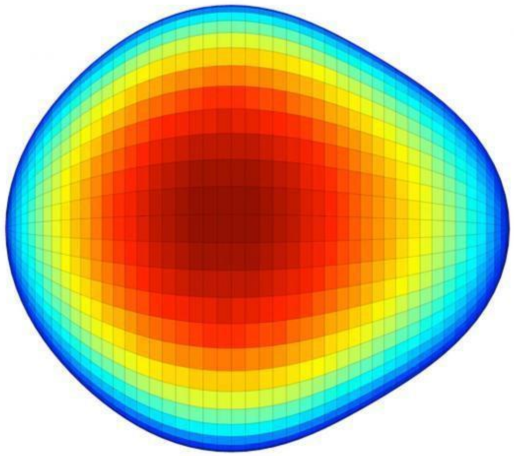
34 ($g_{9/2}$, $p_{3/2}$)

- $\Delta j = \Delta \ell = 3$
- Reflection-asymmetric nuclei
- Octupole magic numbers: 34, 56, 88, 134

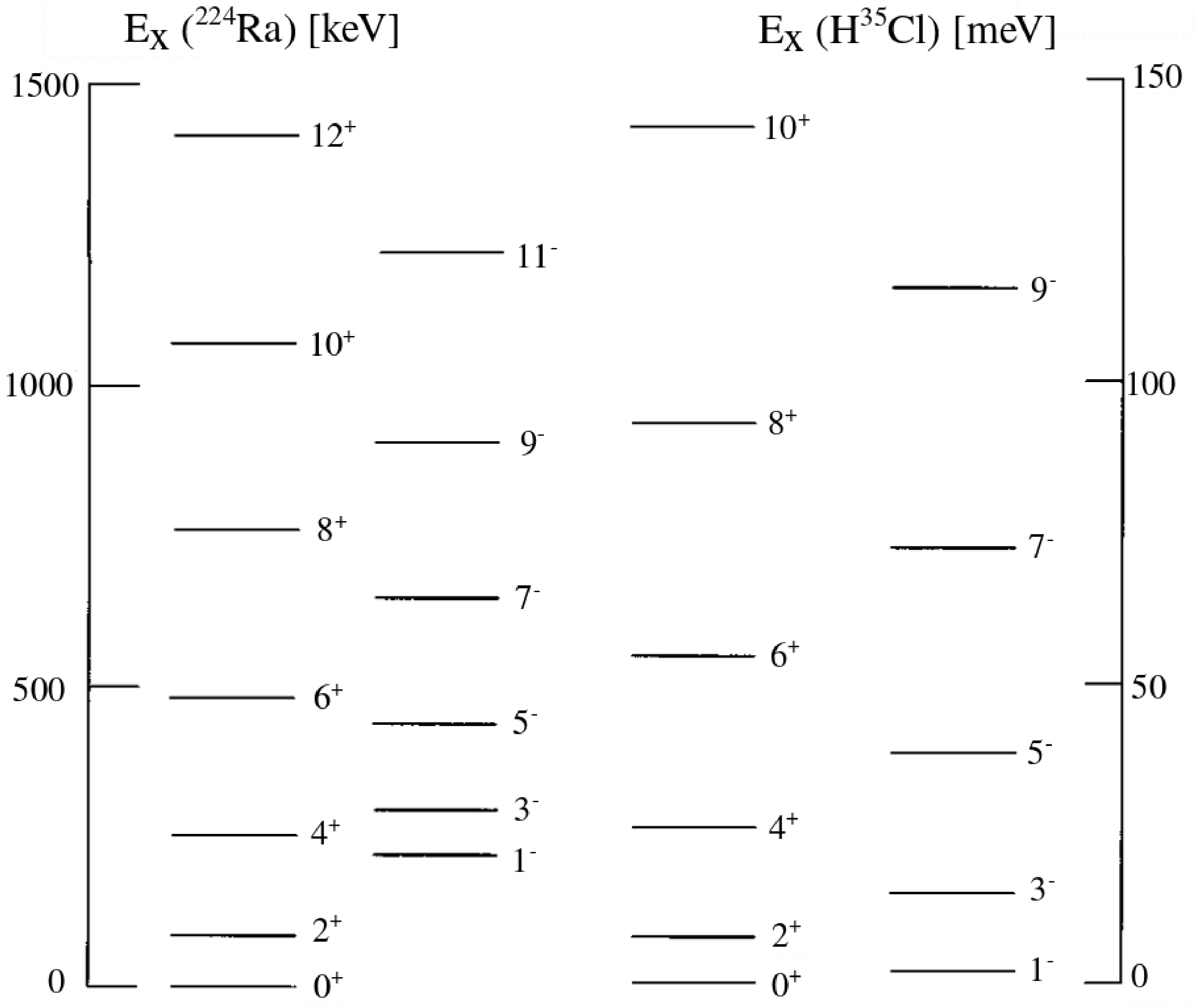


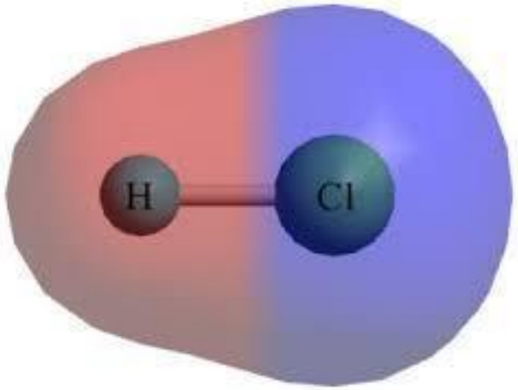
- N=Z=56 close to ^{112}Ba
- Z=56 N=88 close to ^{146}Ba
- Z=88 N=134 close to ^{224}Ra

Spectroscopic features of octupole deformation



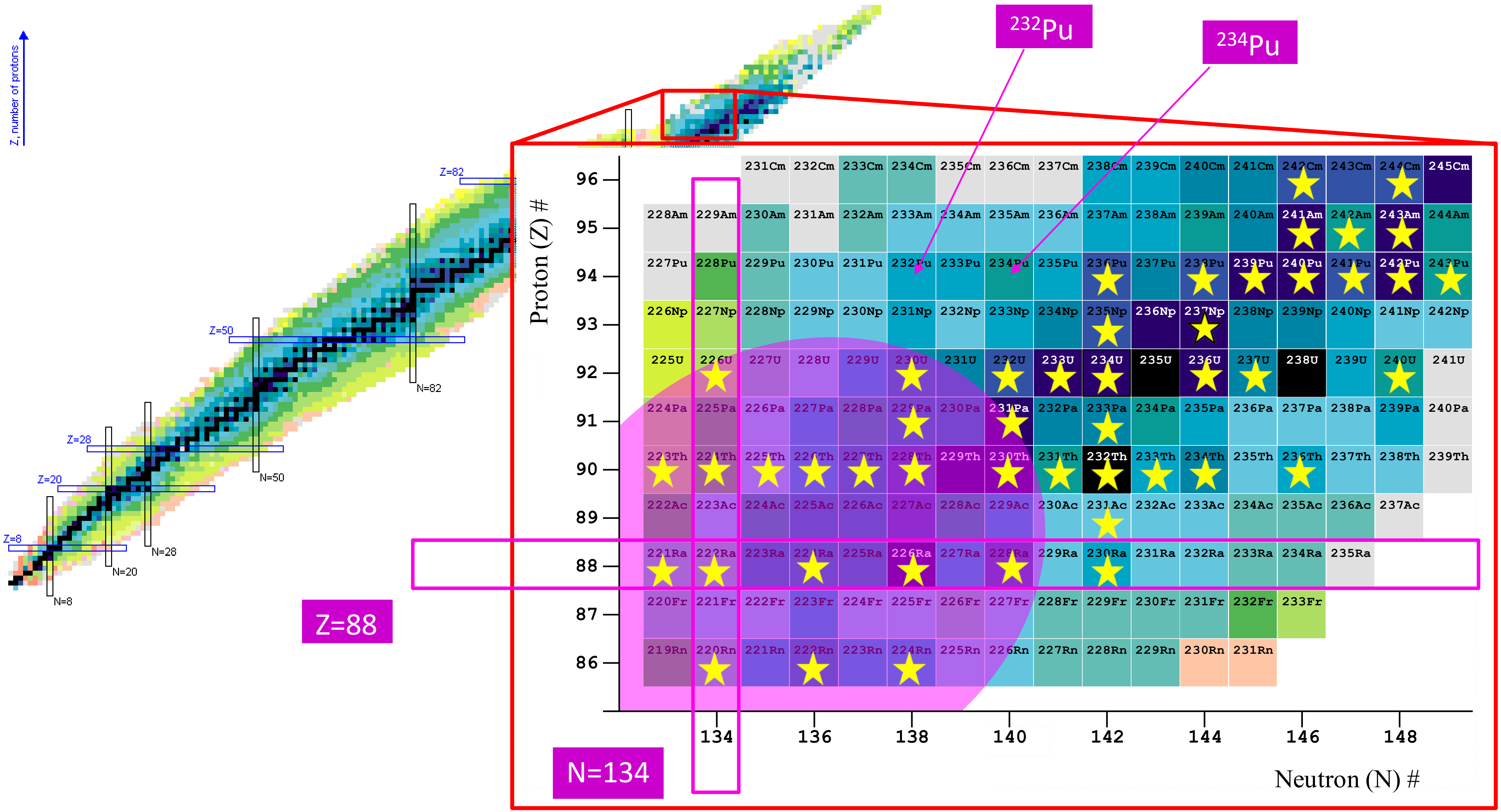
^{224}Ra





HCl

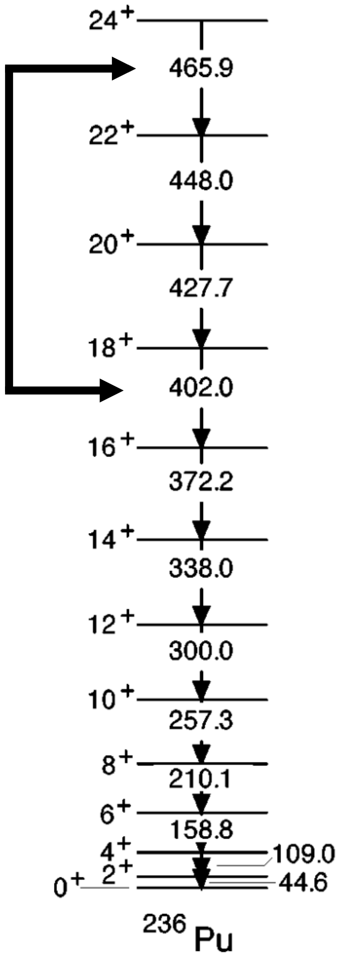
Regional understanding

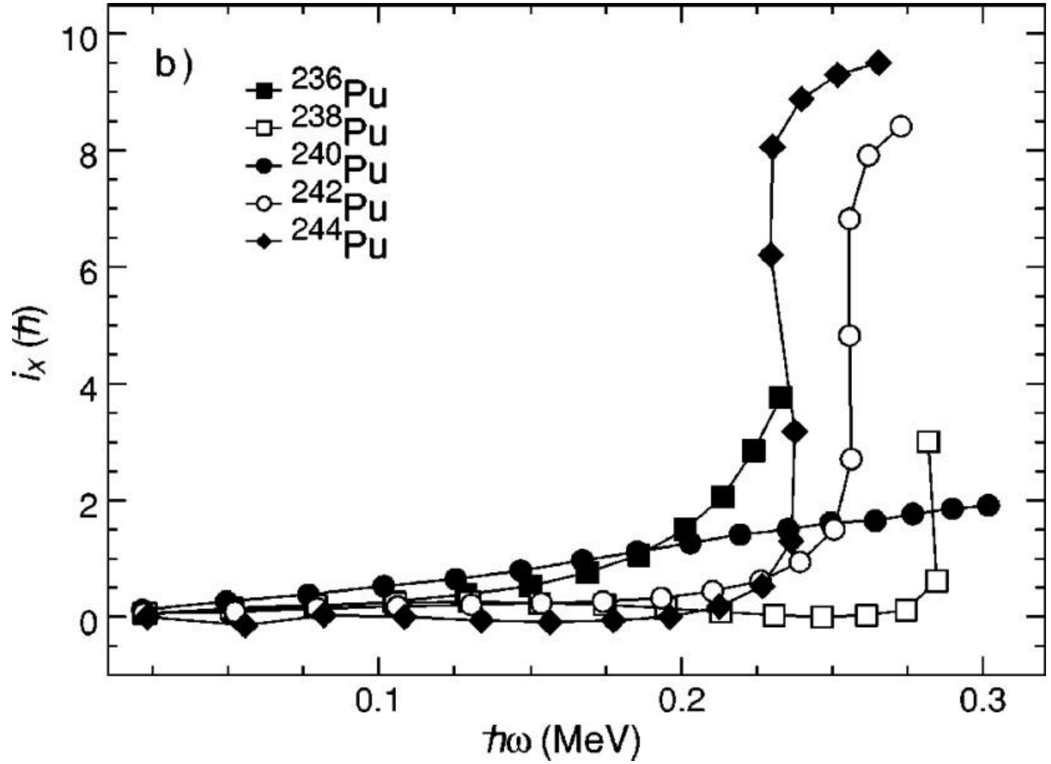


Previous plutonium studies

- An experiment by K. Abu Saleem et al. studied the ^{236}Pu isotope [K. Abu Saleem et al., Phys. Rev. C 70, 024310 (2004)] using the ^{237}Np(^{209}Bi,^{210}Pb) transfer reaction.
- Additional four γ-ray transitions identified in ^{236}Pu adding to established level scheme.

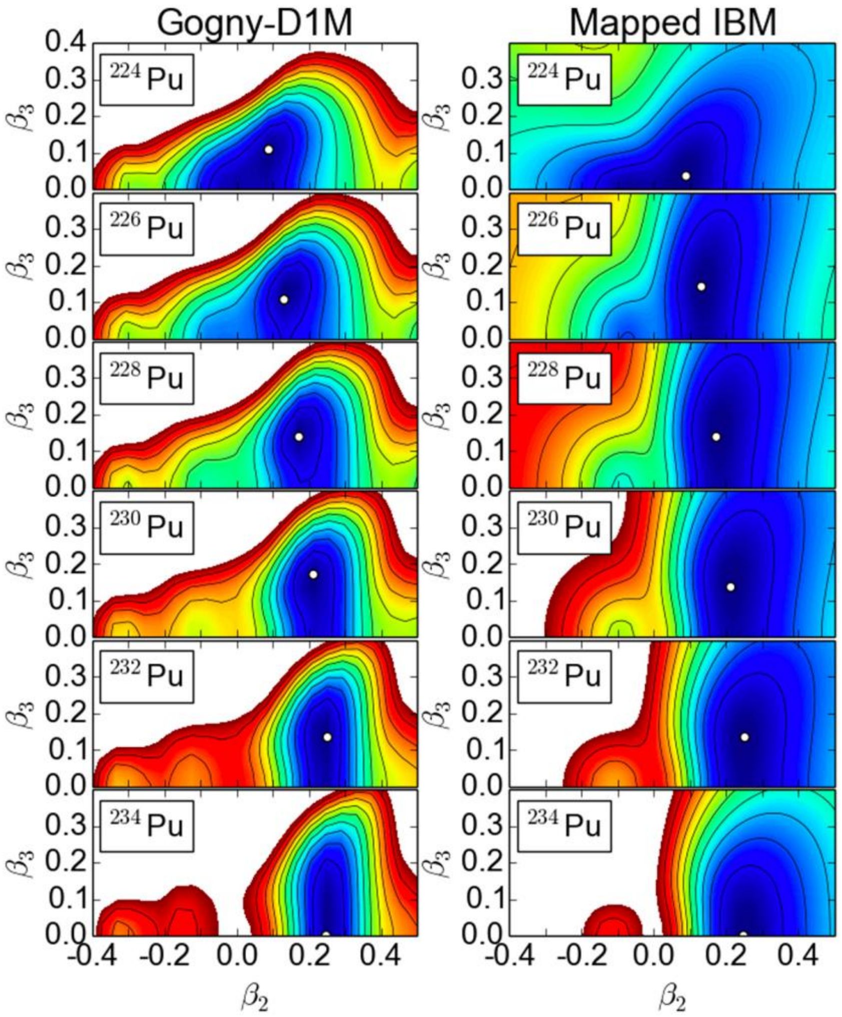
added γ rays





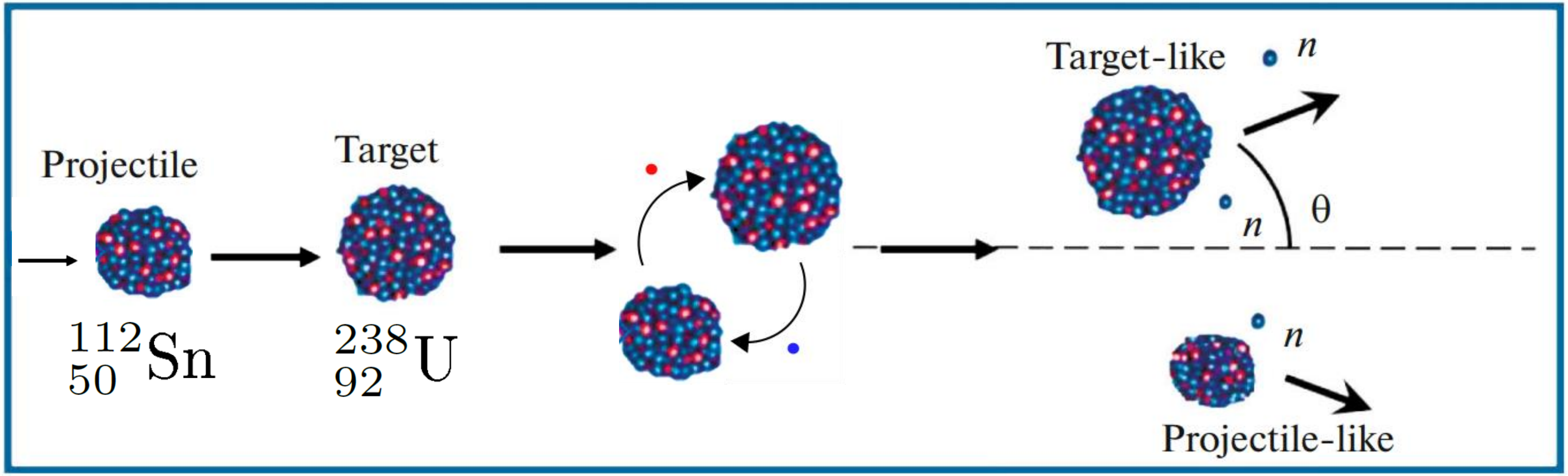
- Alignments show delayed backbending for plutonium isotopes with ^{236}Pu and ^{238}Pu.
- Only $^{238\text{-}240}$Pu show interleaving alternating parity states indicating stronger octupole effects.

Theoretical predictions



- Potential-energy surfaces by Nomura et al. (Phys. Rev. C **103,** 044311 (2021)) for ^{234}Pu has $\beta_3 \simeq 0$ whereas for ^{232}Pu, $\beta_3 \simeq 0.22$.

Multi-nucleon transfer reactions



- Able to probe exotic nuclei past the current experimental limit when using fusion, fragmentation and other methods.
- Combination of MNT reactions with AGATA-PRISMA detector setup allows improved efficiency and selectivity.

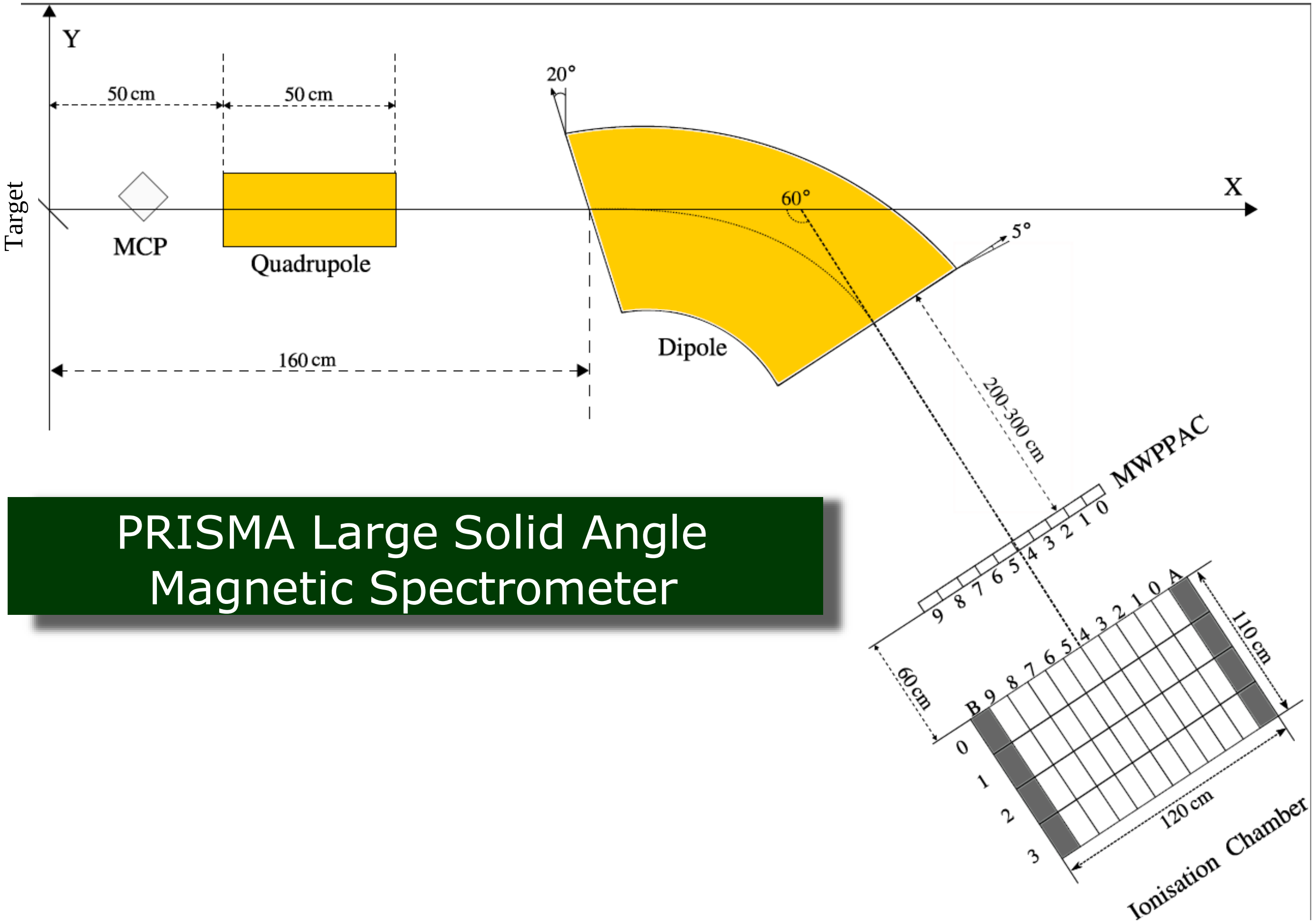
Experimental details

$$^{112}_{50}\mathrm{Sn} + \, ^{238}_{92}\mathrm{U}$$

808 MeV

$$\rightarrow \; ^{116}_{48}\mathrm{Cd} + \, ^{234}_{94}\mathrm{Pu} \quad (\sigma \sim 0.7 \text{ mb})$$

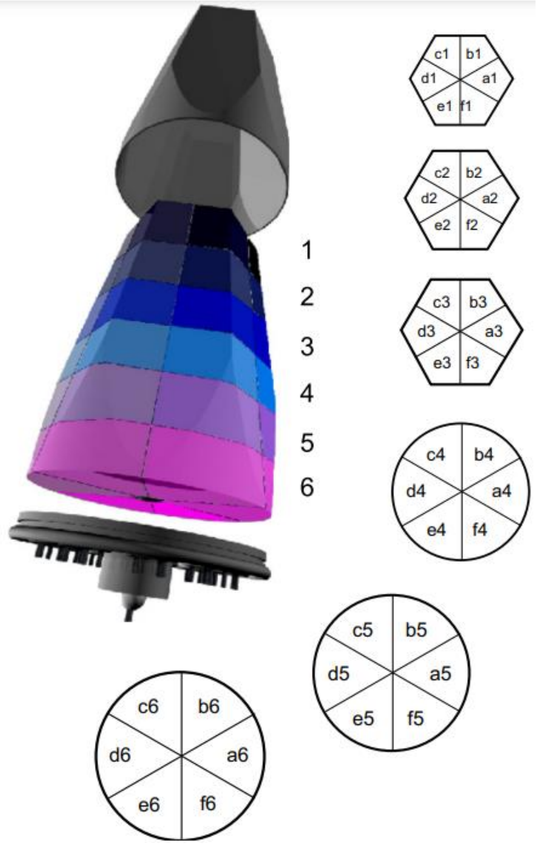
$$\rightarrow \; ^{118}_{48}\mathrm{Cd} + \, ^{232}_{94}\mathrm{Pu} \quad (\sigma \sim 0.4 \text{ mb})$$



PRISMA Large Solid Angle Magnetic Spectrometer

AGATA
(Advanced GAmma Tracking Array)

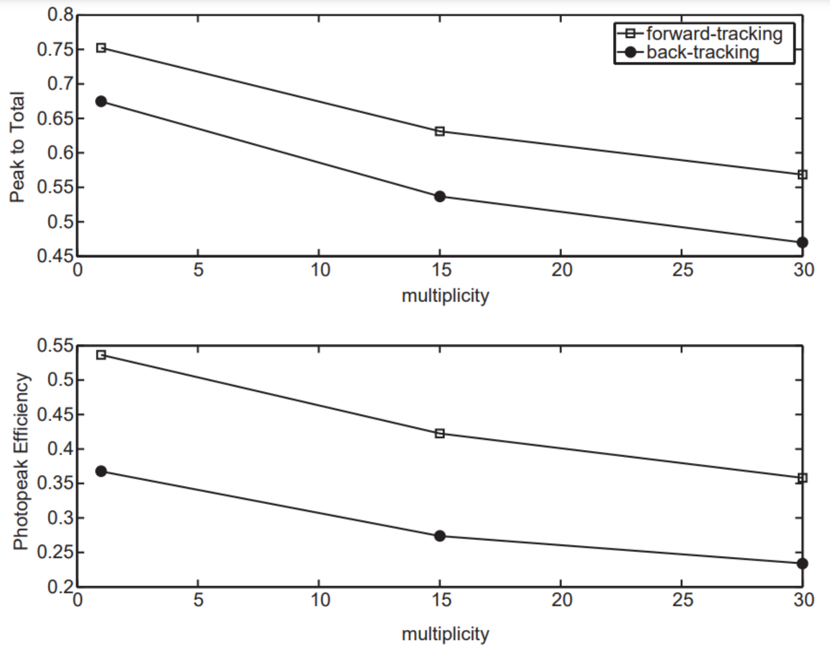
AGATA- Advanced Gamma-ray Tracking Array



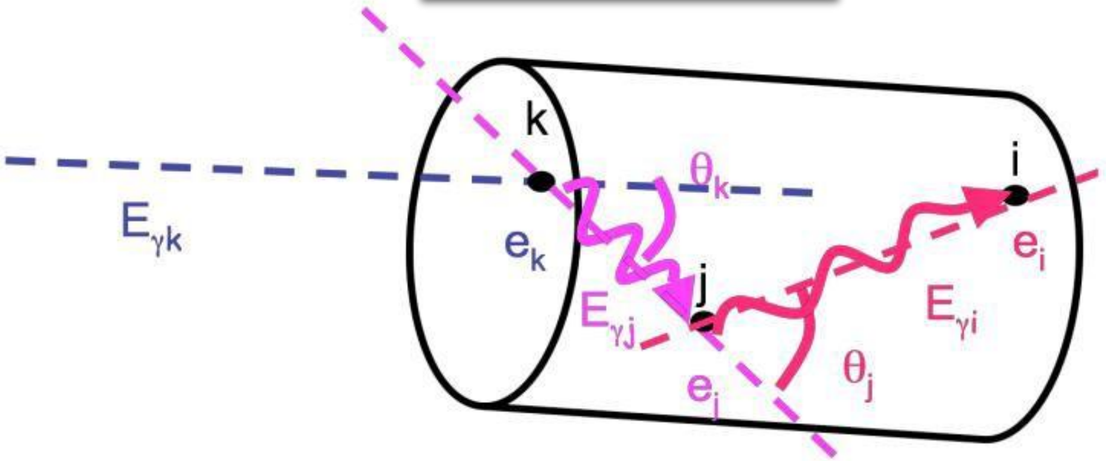
- New generation of gamma-ray spectrometers.
- Employs the novel technique of gamma-ray tracking to reconstruct events.
- 13 triple clusters.
- 36-fold segmentation.

AGATA - Gamma-ray tracking

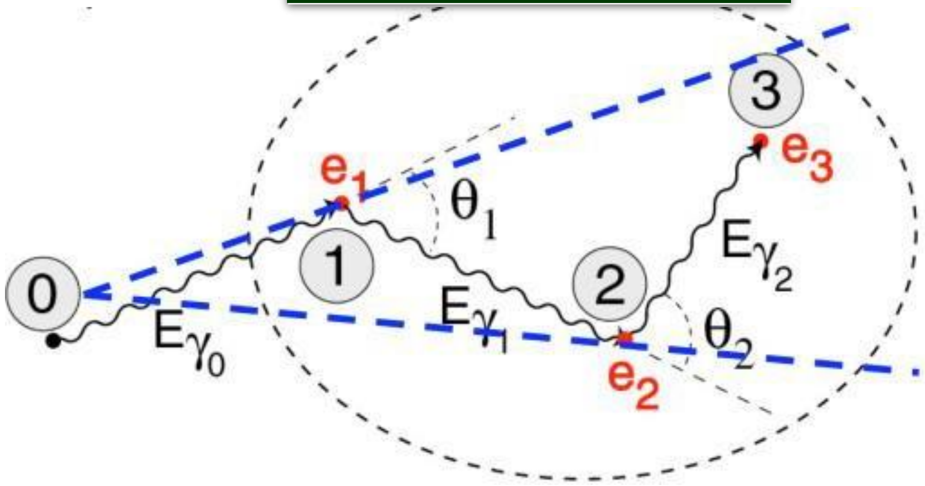
- Segmented germanium crystals allows reconstruction of gamma-ray energy.
- Two algorithms are employed to determine correct interaction sequence.
- Negates the requirement for Compton suppression and improves the overall detection efficiency of the apparatus.



Backtracking



Forward Tracking



Experimental details

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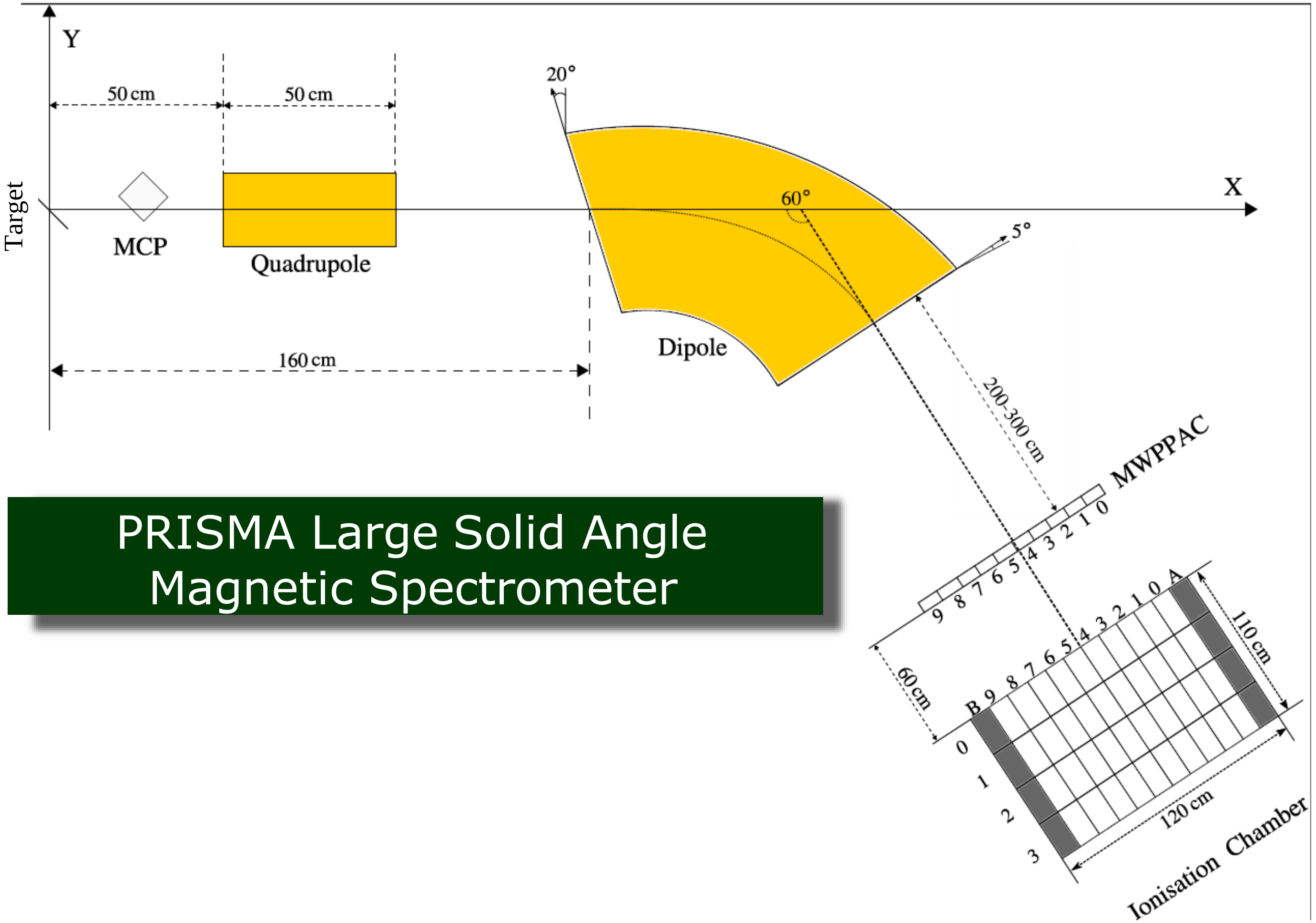

PRISMA Large Solid Angle Magnetic Spectrometer

AGATA
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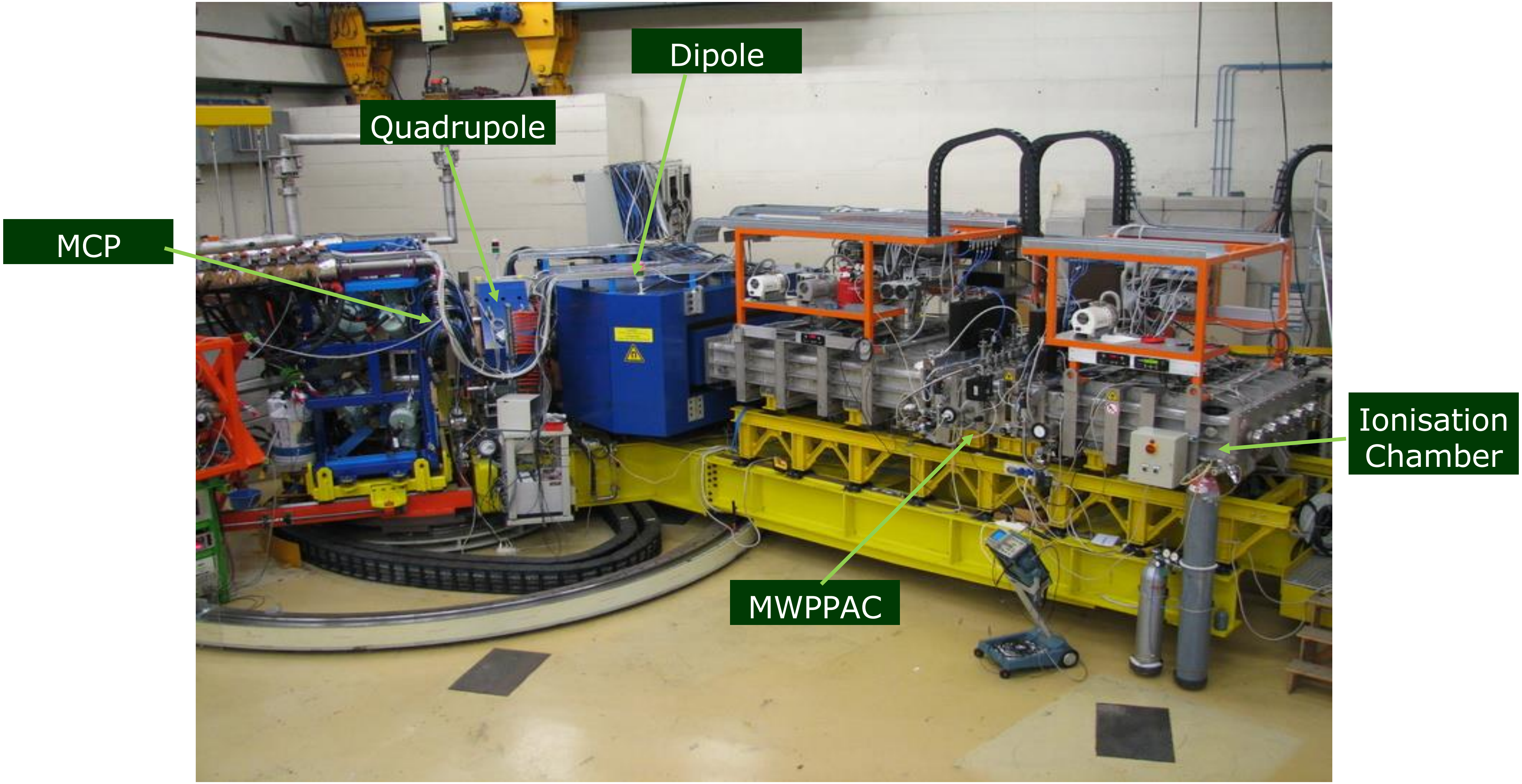
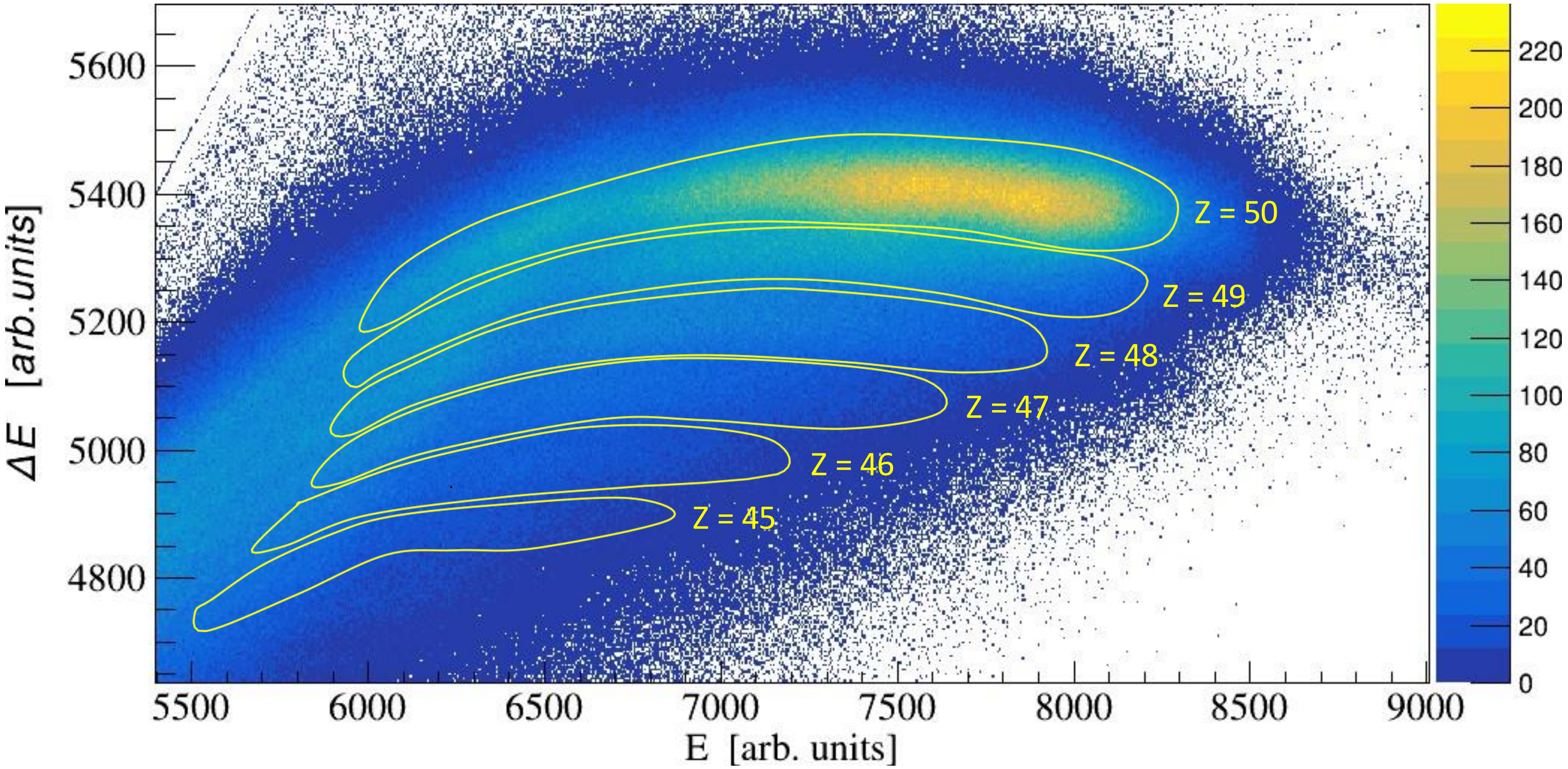
PRISMA Magnetic Spectrometer



PRISMA - Z identification

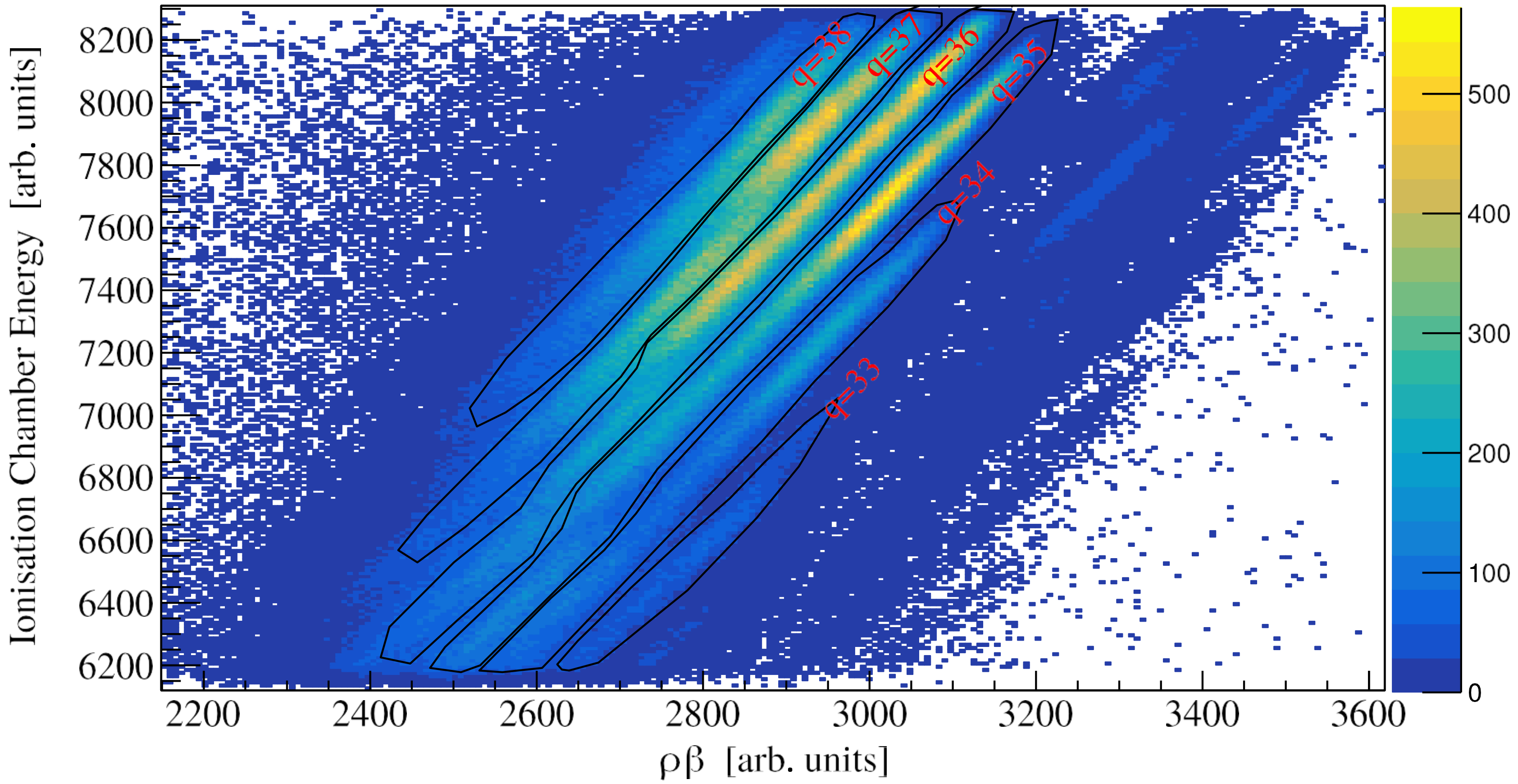


PRISMA - q selection

$$B\rho = \frac{p}{q}$$

$$p = mv\ ,\quad E_k = \frac{1}{2}mv^2,\quad v = \beta c$$

$$E_k \propto q \cdot \rho\beta$$

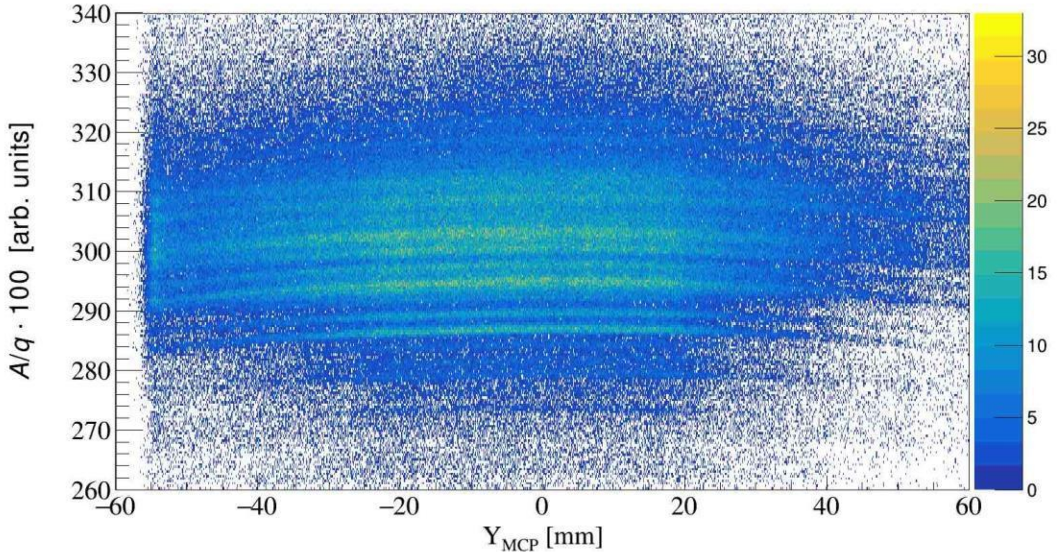


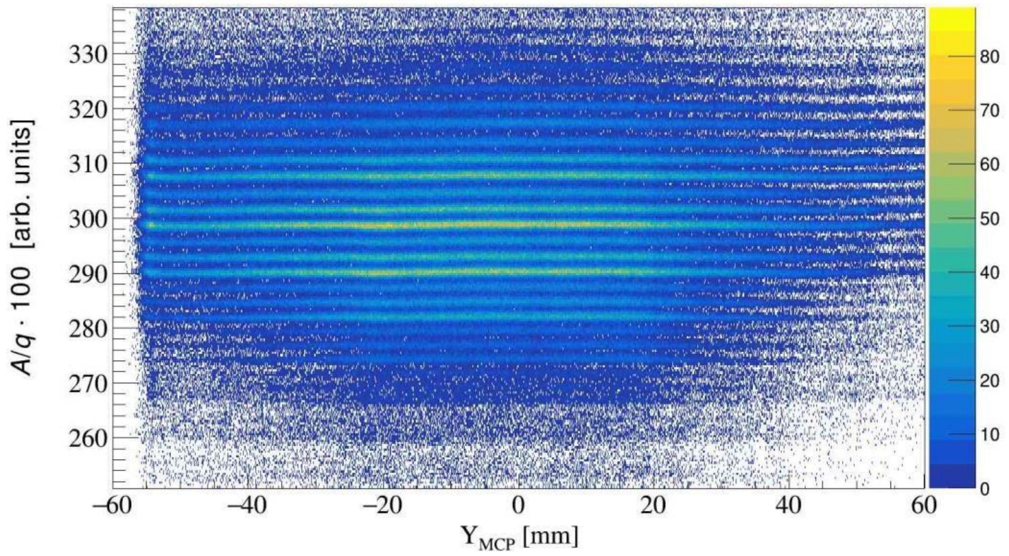
Charge state (q) gates applied to each Z gated distribution

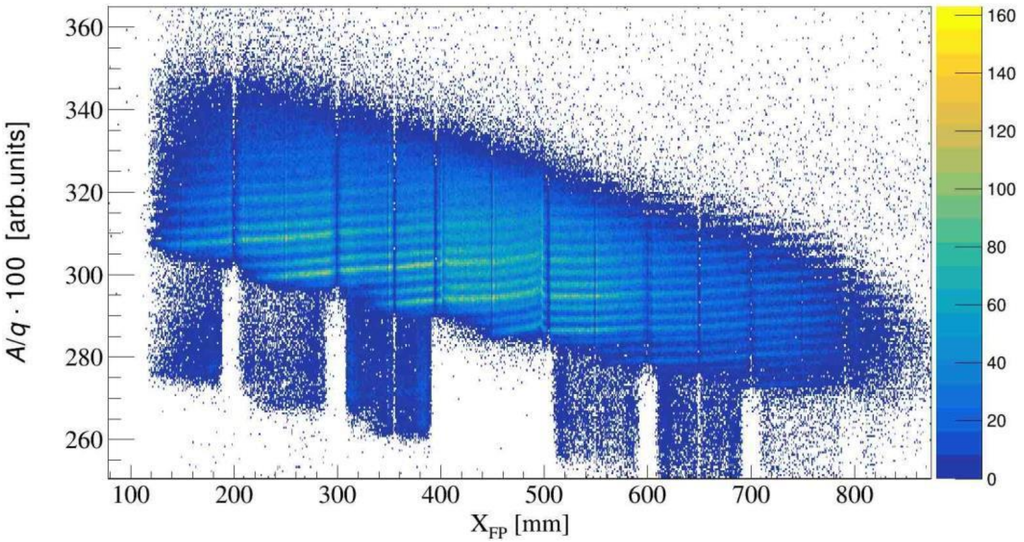
PRISMA - A/q calibration

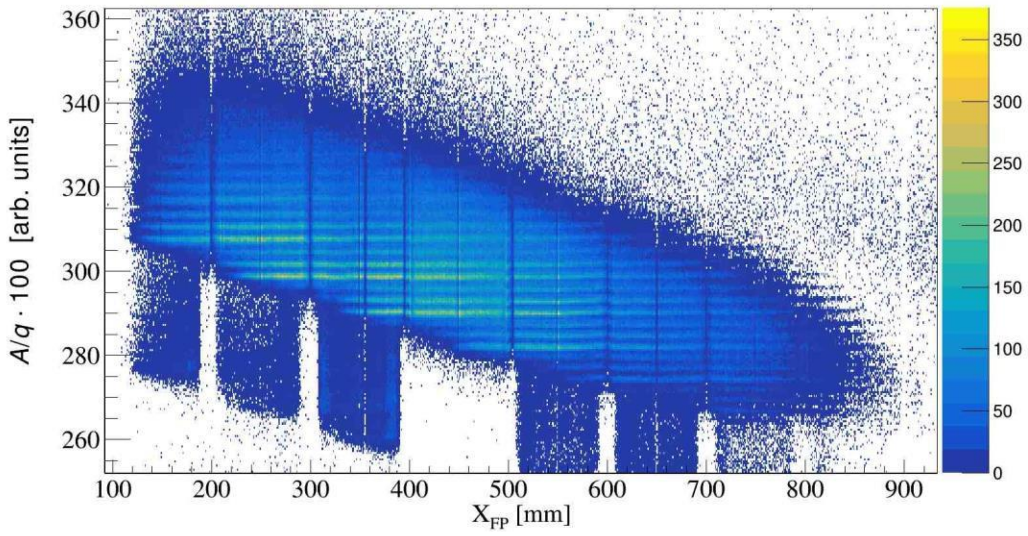
Before Aberrational corrections

After aberrational corrections

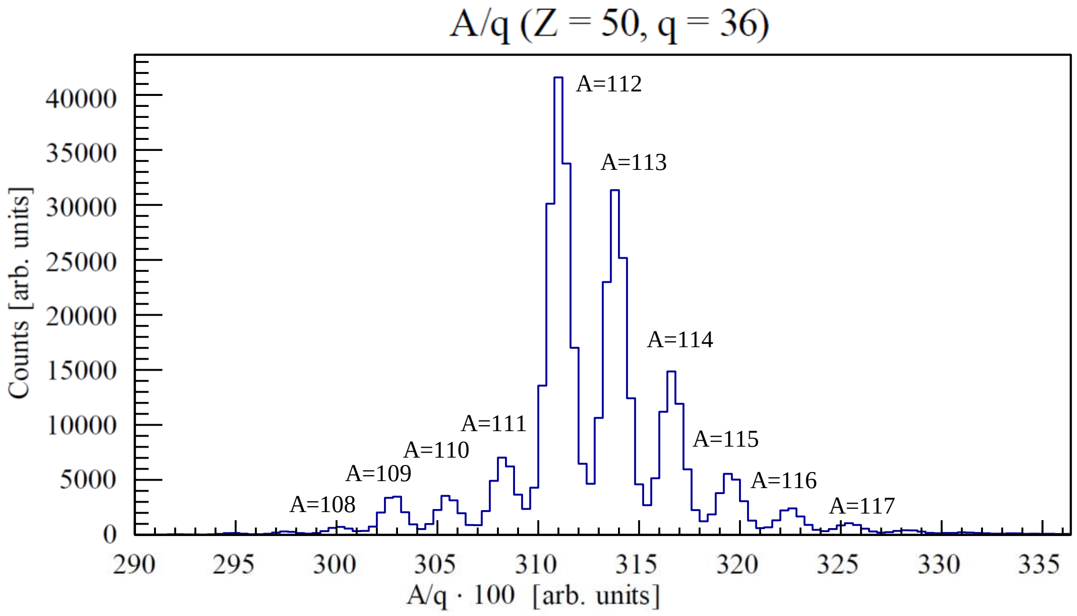






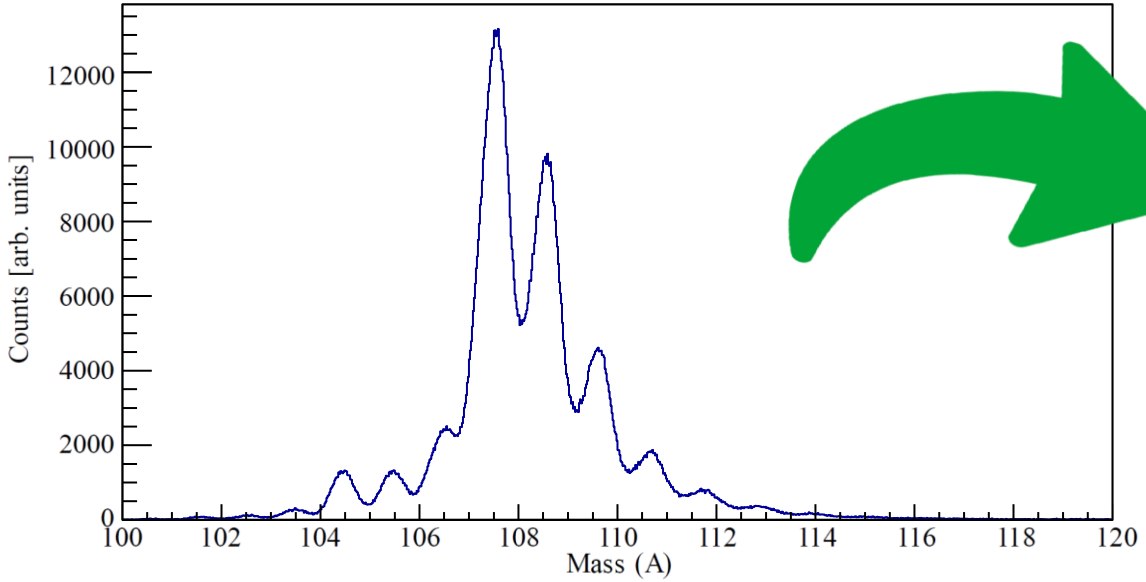


PRISMA - Mass calibration

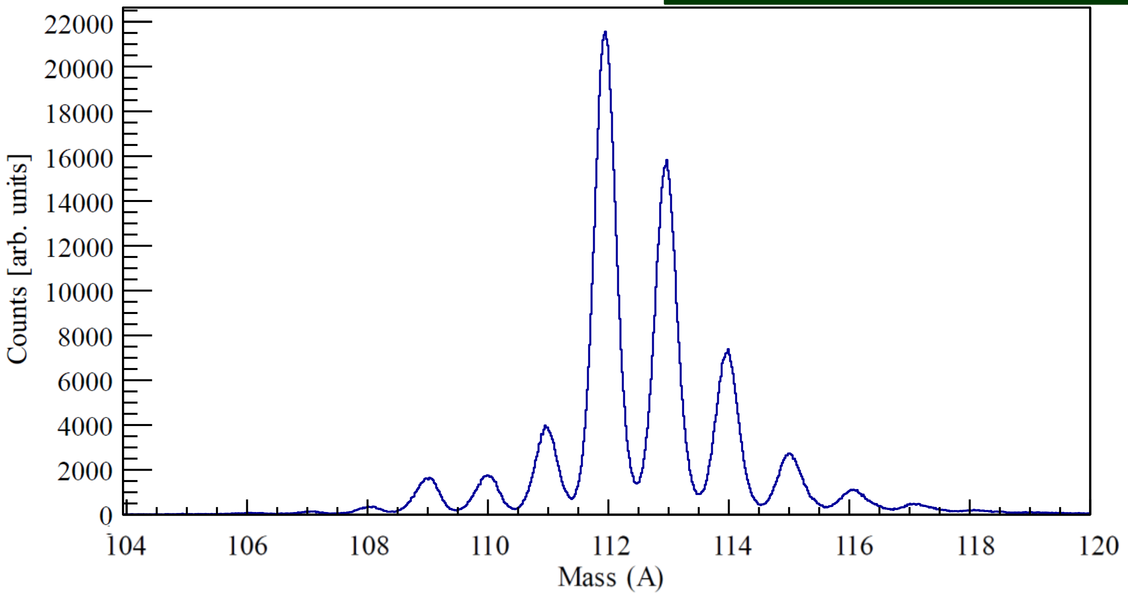


A/q linear calibration applied by measuring centroid of ZQ-gated 1D A/q distributions and comparing observed with expected.

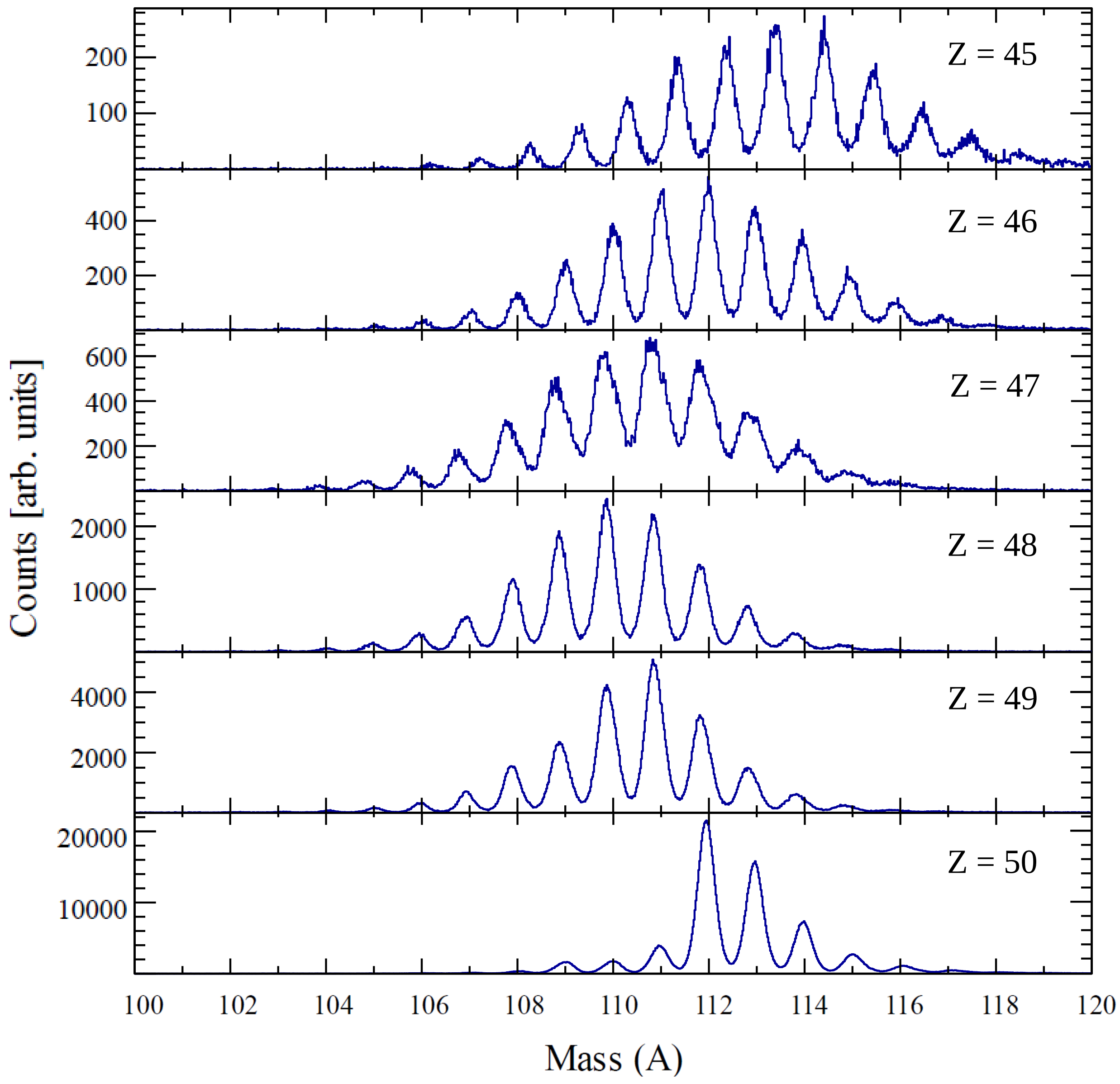
Mass (Z = 50) before linear calibration



Mass (Z = 50) after linear calibration



PRISMA - Mass distributions



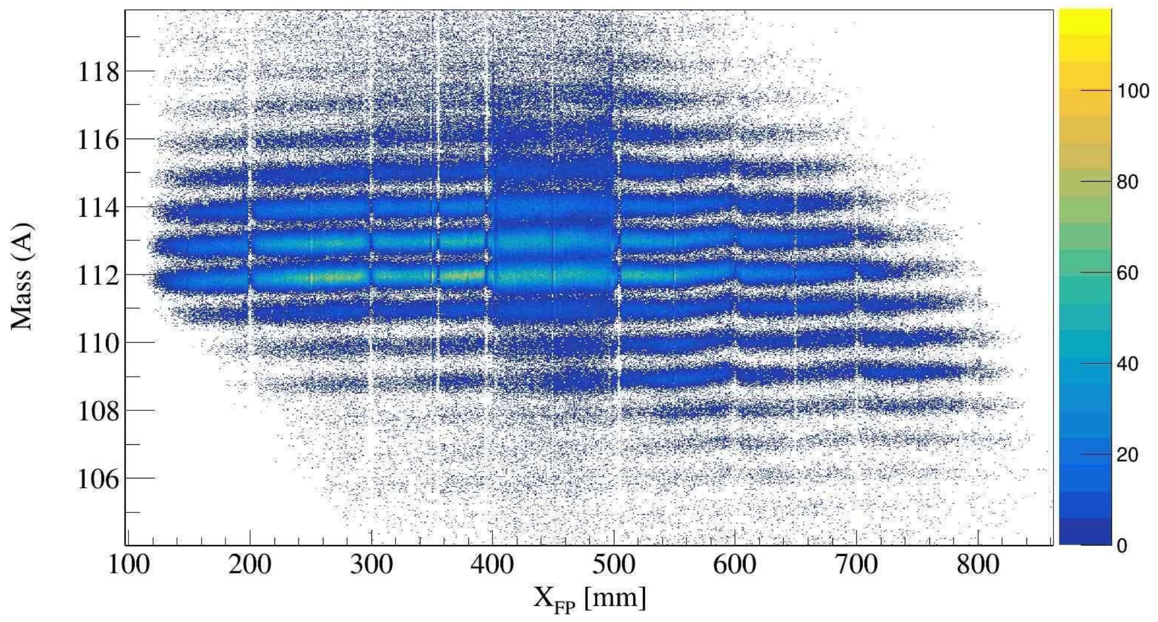
Mass resolutions

$Z = 50 \rightarrow \frac{1}{250}$

$Z = 49 \rightarrow \frac{1}{231}$

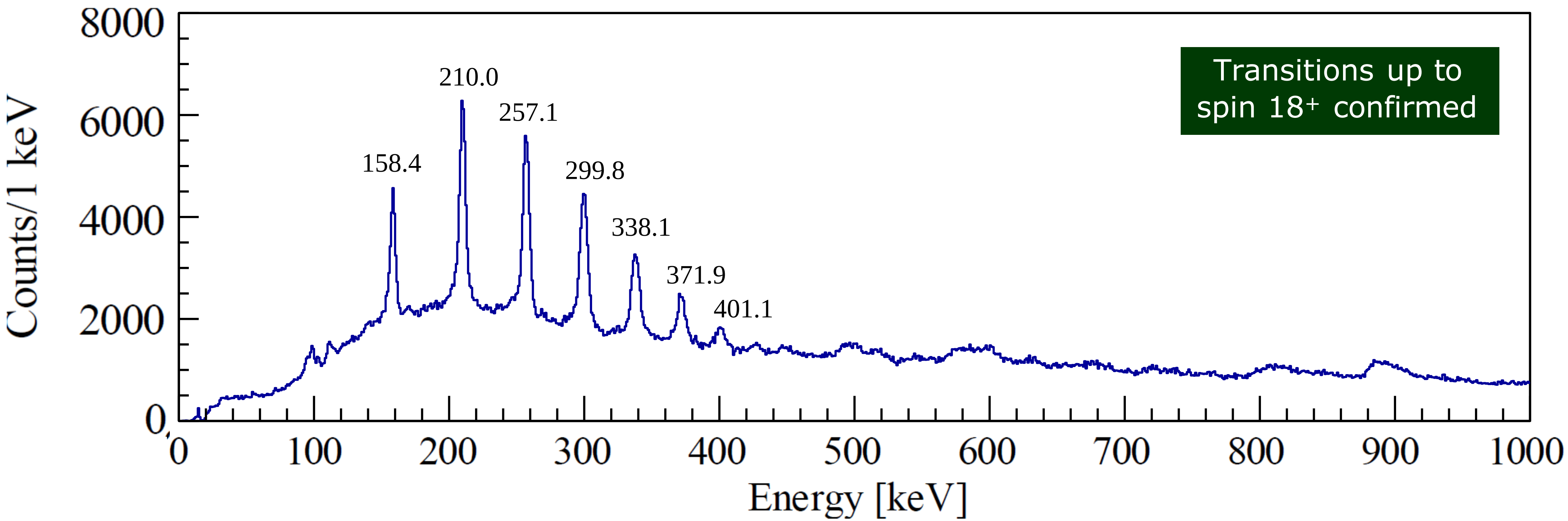
$Z = 48 \rightarrow \frac{1}{229}$

Mass assignments are gated on to look at coincidence gamma-ray spectra either using 2D gate or rounding to nearest integer.



Preliminary Analysis results – AGATA

AGATA-PRISMA coincidence spectra Analysis ongoing



Transitions up to spin 18^+ confirmed

^{238}U Doppler-corrected tracked γ-ray spectra gated on binary partner Sn (Z = 50, A=112).

Summary

With thanks to all collaborators:

H. Ayatollahzadeh [1, 2], J. M. Keatings [1, 2], J. F. Smith [1, 2], D. Mengoni [3], P. Aguilera [3, 4], G. Andreetta [3, 5], F. Angelini [3, 4], M. Balogh [4], J. Benito [3, 4], M. A. Bentley [6], A. J. Boston [7], H. C. Boston [7], S. Bottoni [8, 9], M. Bowry [1, 2], P. A. Butler [7], D. Brugnara [4], S. Carollo [3], G. Corbari [8], L. Corradi [4], R. Escudeiro [5], P. T. Greenlees [10], R. Chapman [1, 2], D. M. Cullen [1, 2], G. de Angelis [4], A. Ertoprak [4], C. Everett [7], L. P. Gaffney [7], F. Galtarossa [5], A. Goasduff [4], B. Góngora Servıń [4, 11], A. Gottardo [4], A. Gozzelino [4], J. Hackett [7], S. D. Hart [12], F. Holloway [7], P. M. Jones [12], S. Jongile [12], D. Judson [7], M. Labiche [13], M. S. R. Laskar [9], K. L. Malatji [12], A. McCarter [7], G. Montagnoli [3], N. Marchini [14], B. S. Nara Singh [1, 2], D. R. Napoli [4], R. Nicolás del Álamo [3, 5], D. O'Donnell [1, 2], J. Pellumaj [4], R. Pérez [4], S. Pigliapoco [3], E. Pilotto [5], M. Polettini [3], F. Recchia [3], K. Rezynkina [4], E. Rintoul [7], M. Rocchini [14], M. Sedlak [4], M. Siciliano [15], A. Stefanini [4], D. Stramaccioni [3, 4], C. Sullivan [7], J. J. Valliente-Dobon [4], F. van Niekerk [12], L. Zago [3, 4], and I. Zanon [4].

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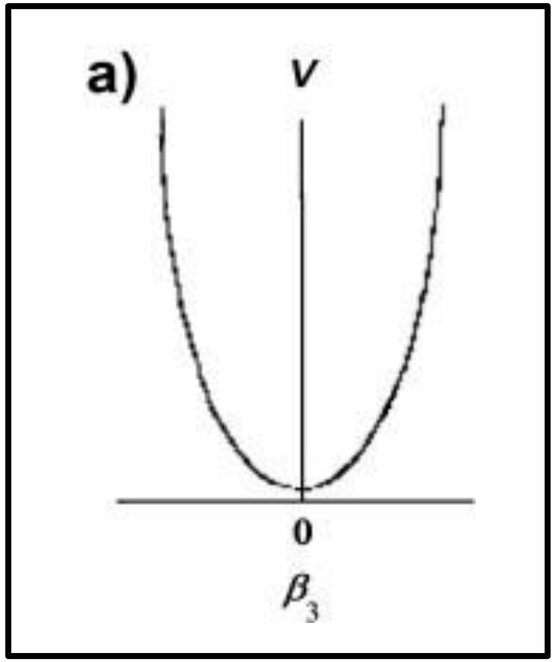
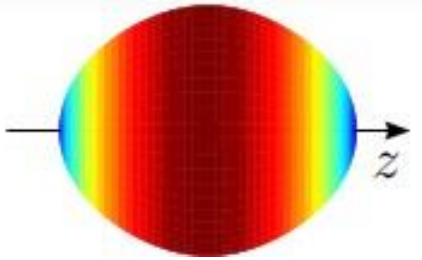
[15]Physics Division, Argonne National Laboratory, Argonne, USA

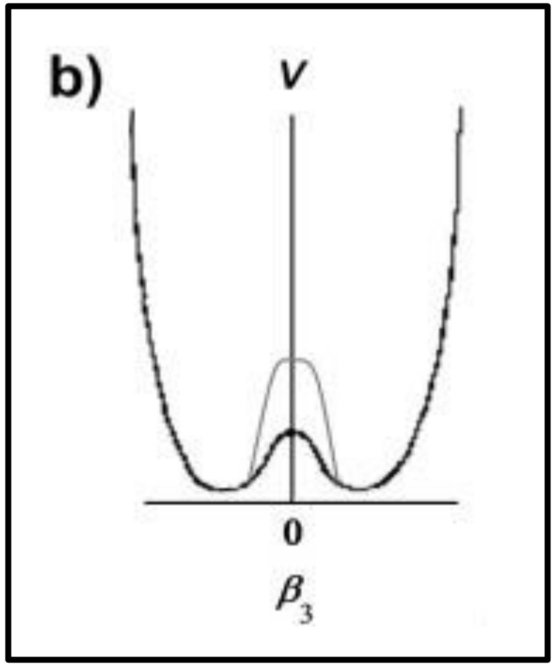
Spectroscopic features of octupole deformation

Angular momentum increasing

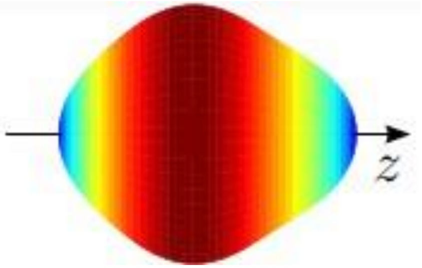


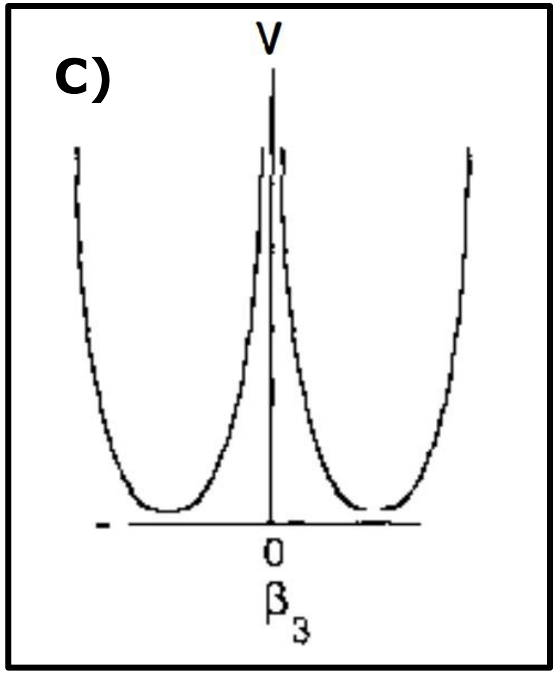
Octupole vibrational



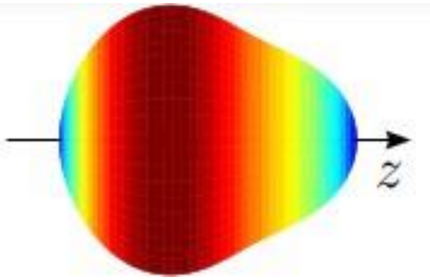


Octupole deformed (static)



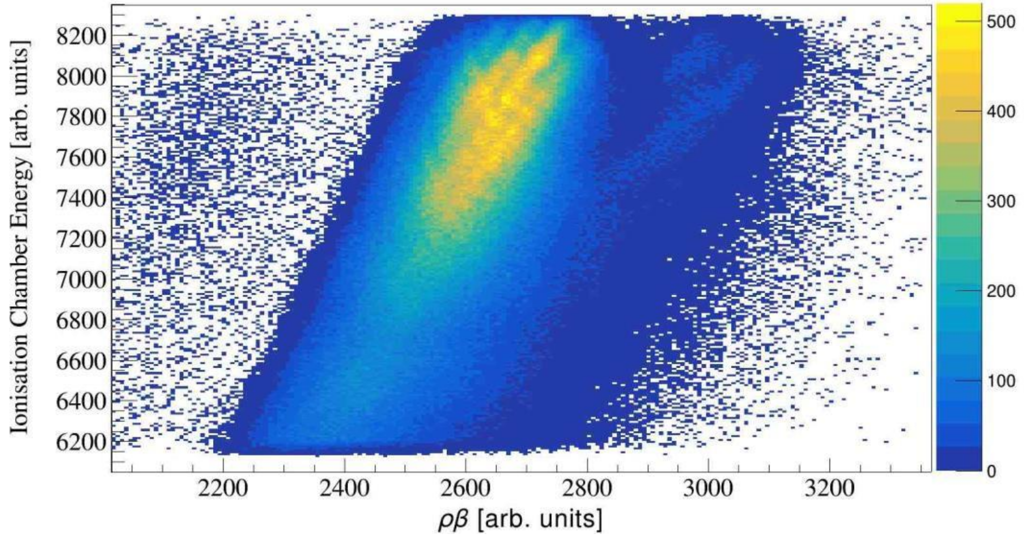


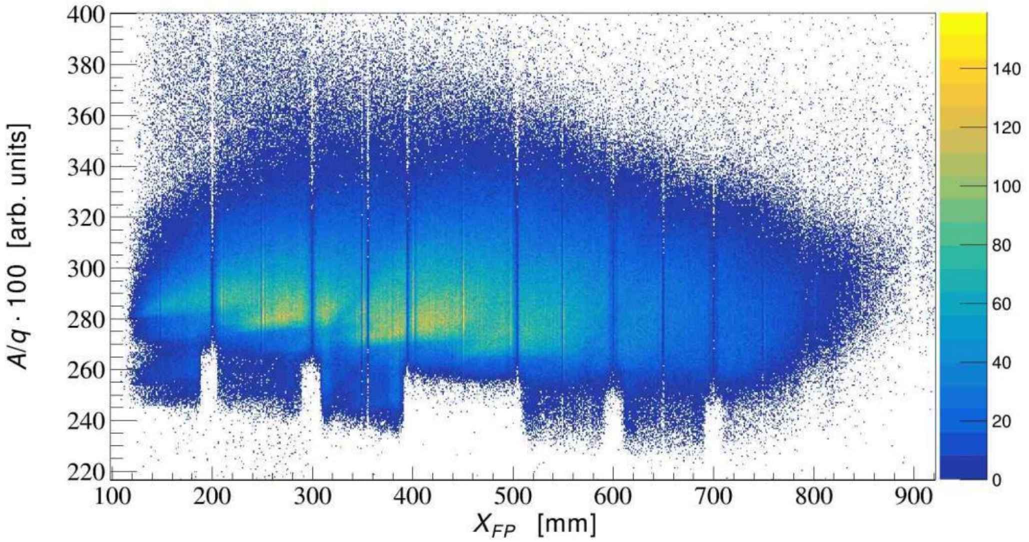
Octupole deformed (rigid)



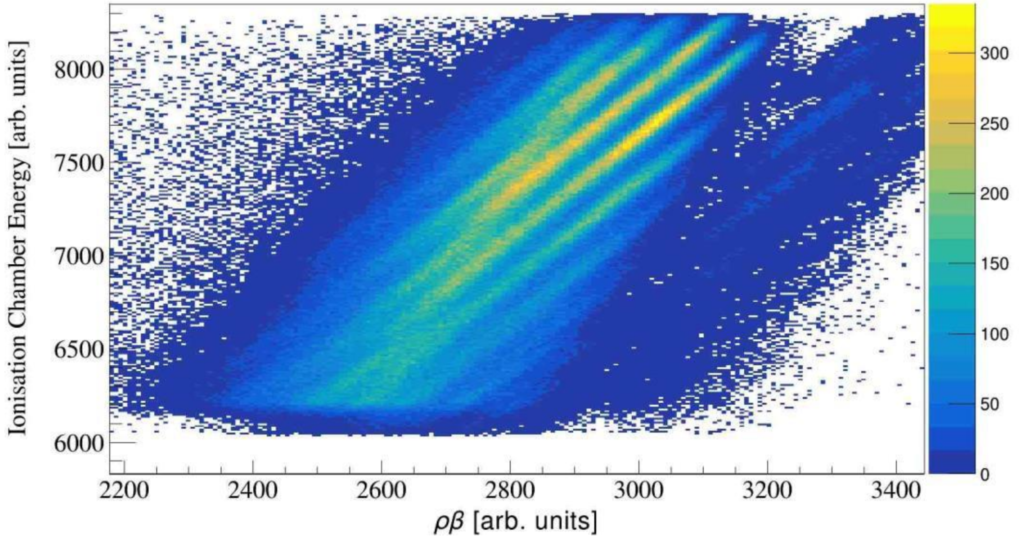
PRISMA – Trajectory reconstruction

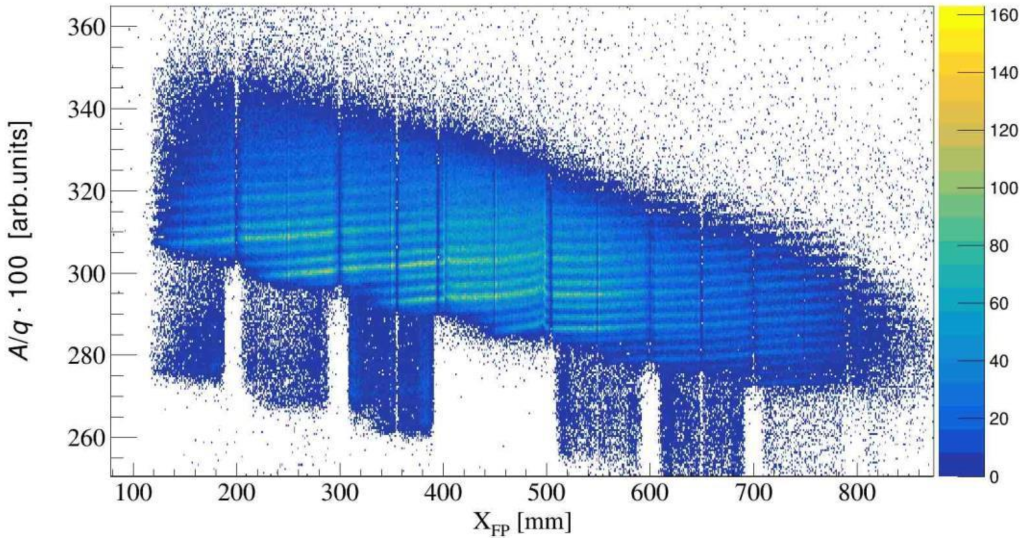
Bad optical parameters





Good optical parameters





Forward tracking vs. backtracking