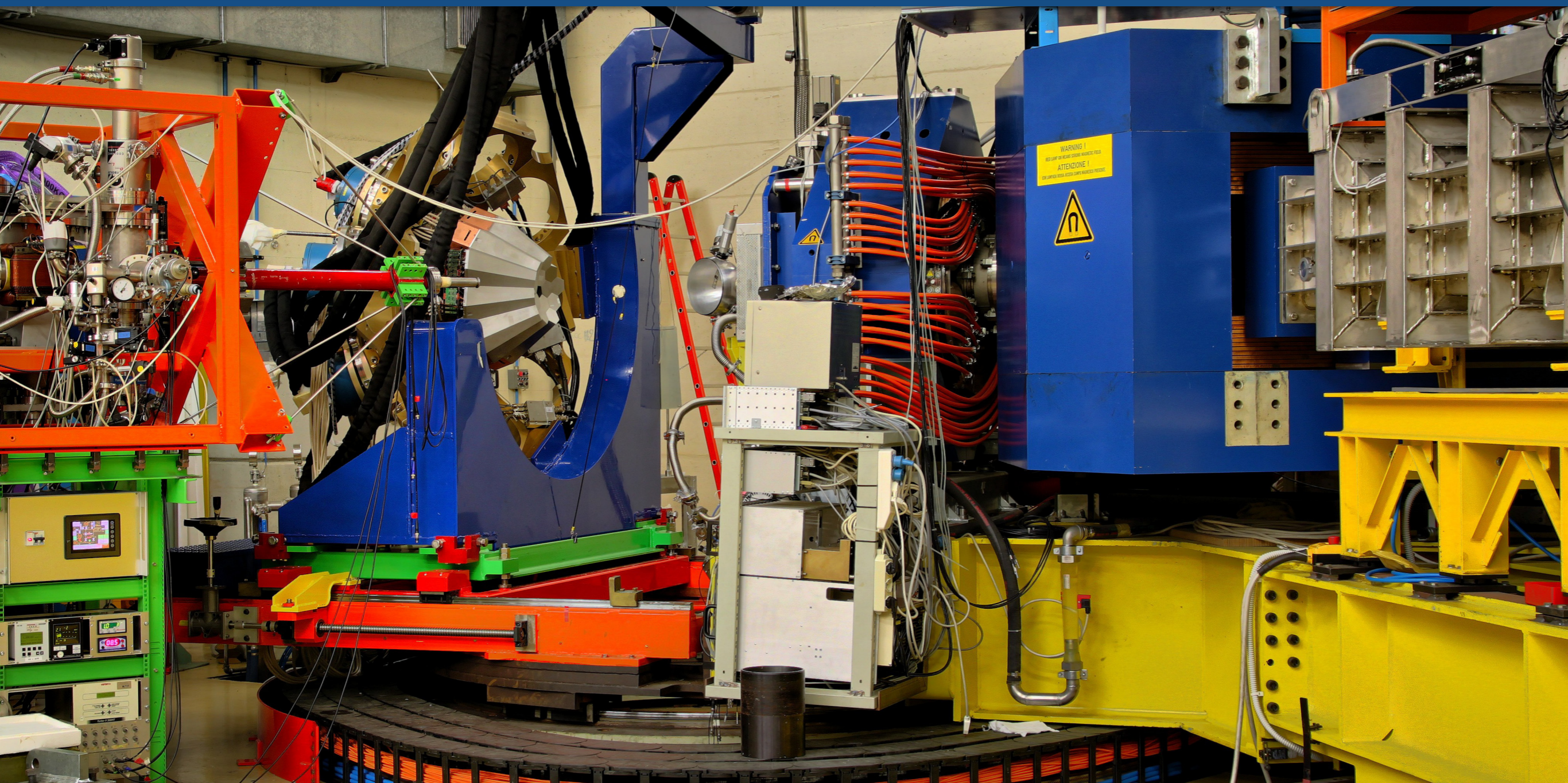


# Gamma-ray spectroscopy of neutron-rich actinides after multi-nucleon transfer reactions

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Institute for Nuclear Physics  
University of Cologne



# Spectroscopy of neutron-rich $Z=90-92$ actinides



Shell Correction Energy

A.Sobiczewski, I. Muntian,  
Z. Patyk,  
PRC, 63 (2001) 034306

Alternative Parity States

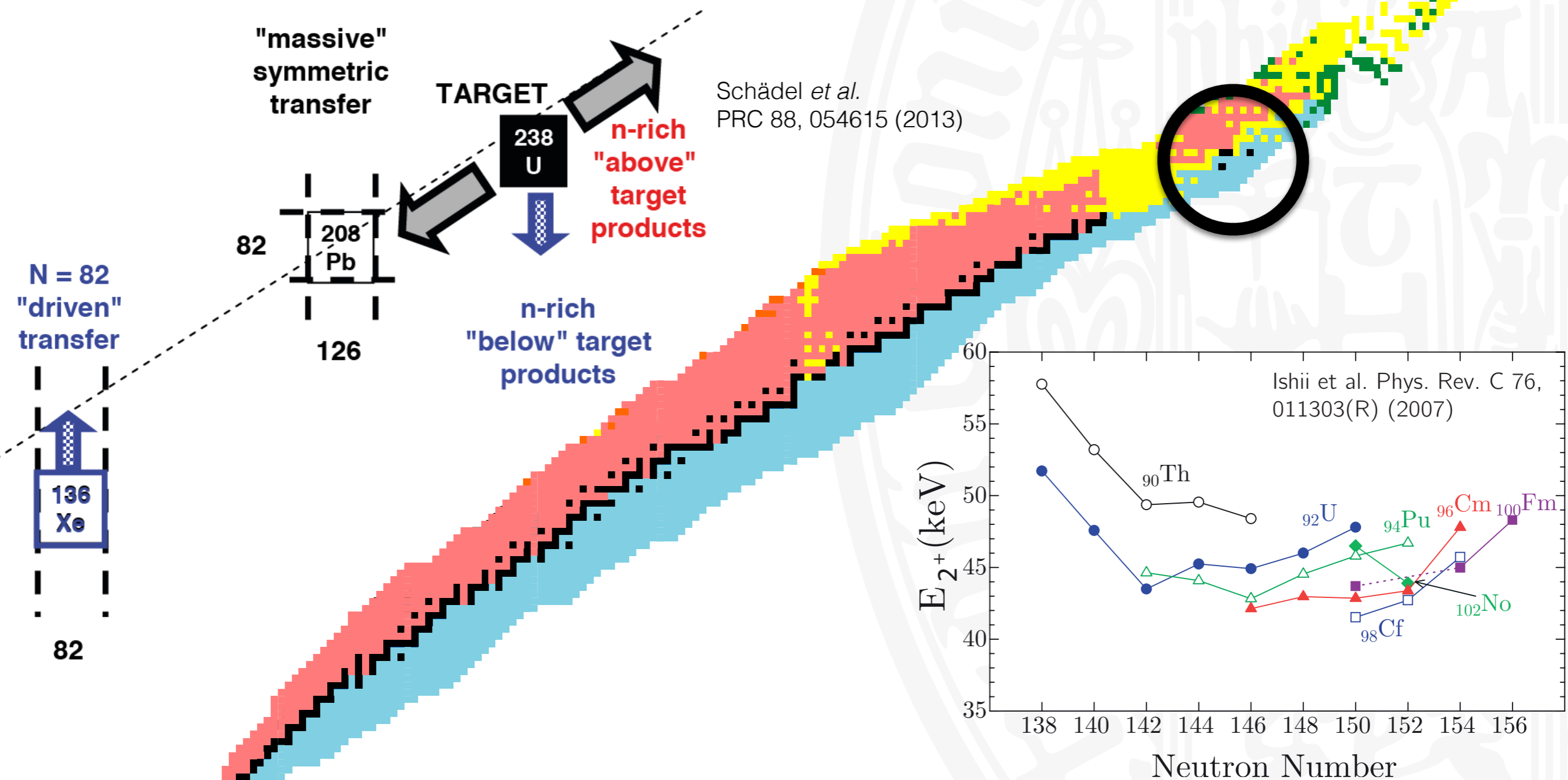
Shneidman, et al.  
PRC 74,  
034316 (2006)

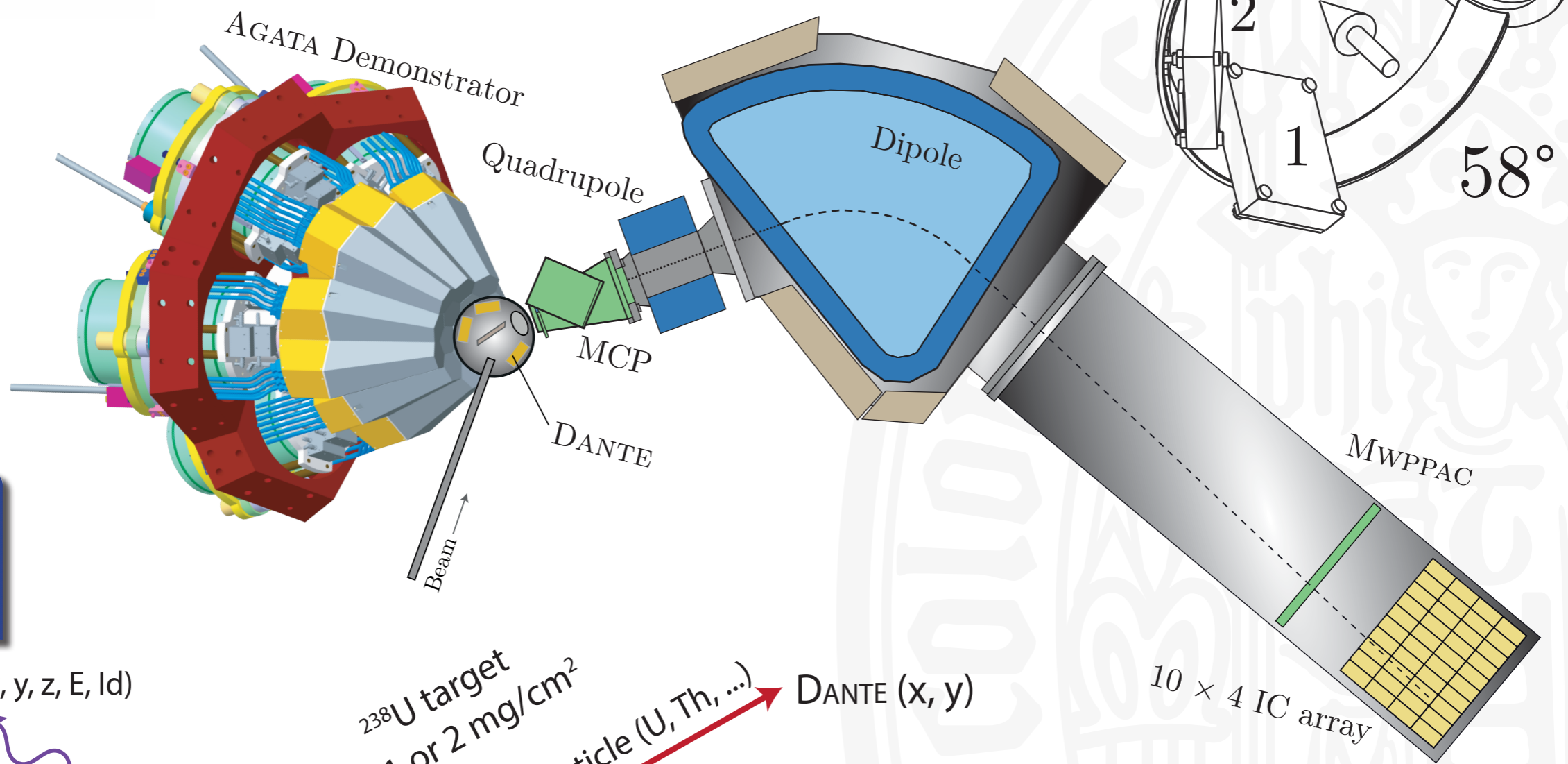
MF and beyond-MF methods, Gogny Force

J.-P. Delaroche, M. Girod.  
Nucl. Phys. A 771 (2006) 103–168

Relativistic Nuclear Energy Density Functionals

D. Vretenar, et al.,  
Int. J. Mod. Phys. E (2010)





AGATA (x, y, z, E, Id)

$^{238}\text{U}$  target  
1 or 2 mg/cm<sup>2</sup>

Target-like particle (U, Th, ...)

DANTE (x, y)

10 × 4 IC array

Doppler correction  
for both beam- and  
target-like spectra

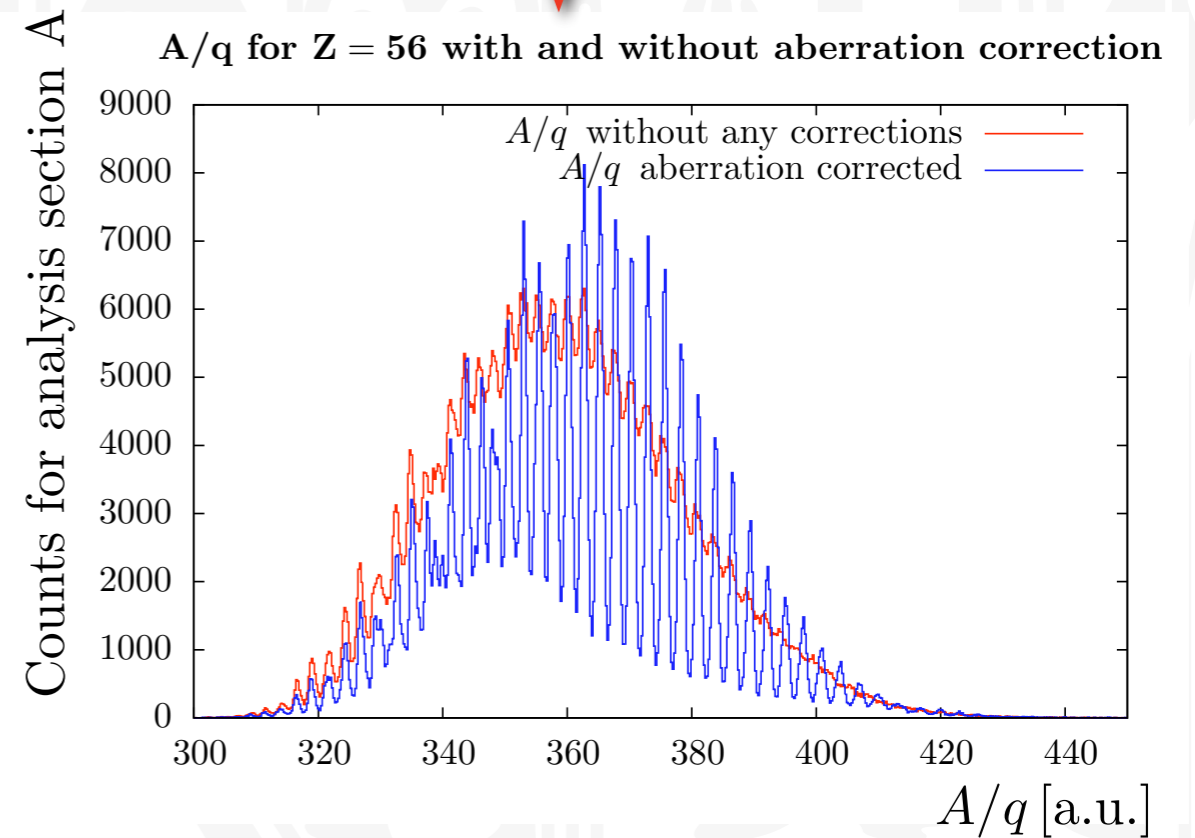
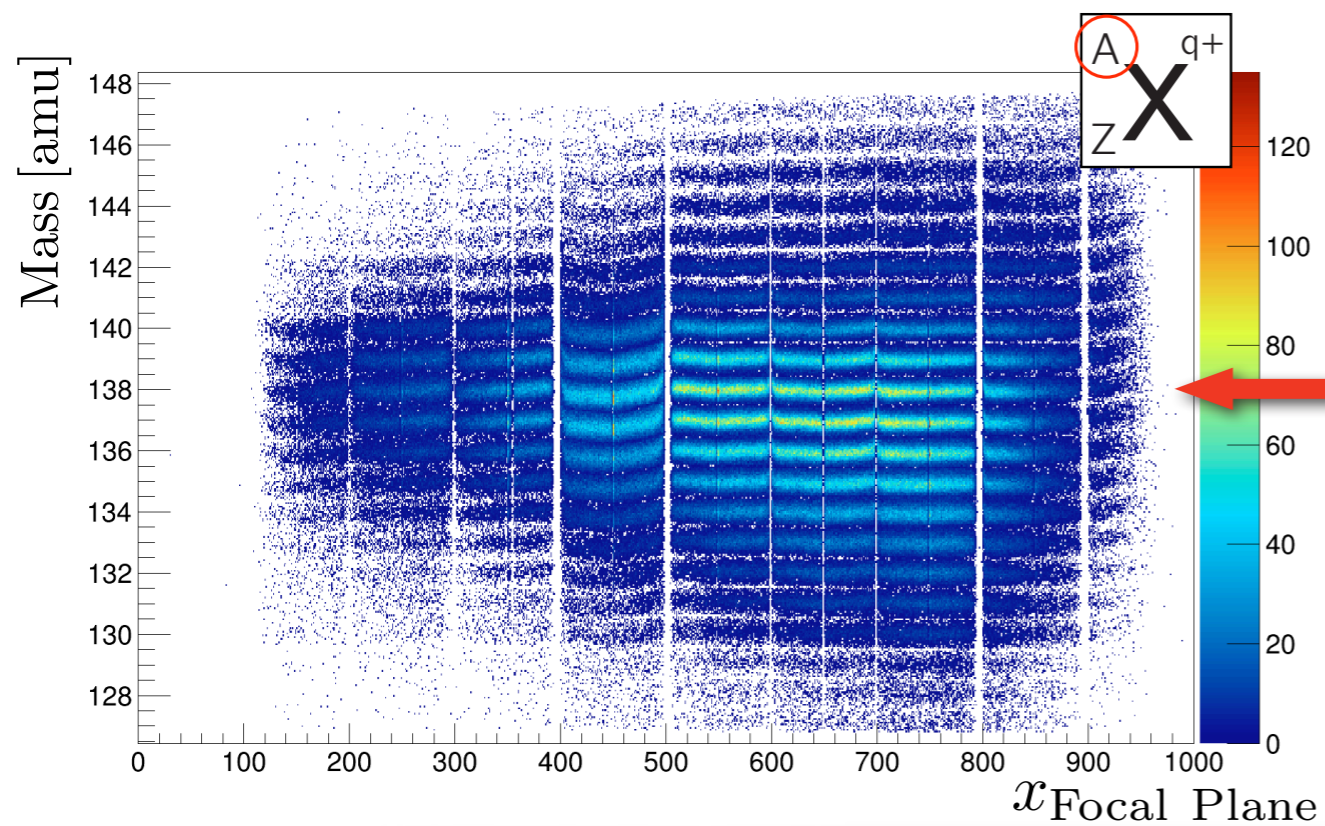
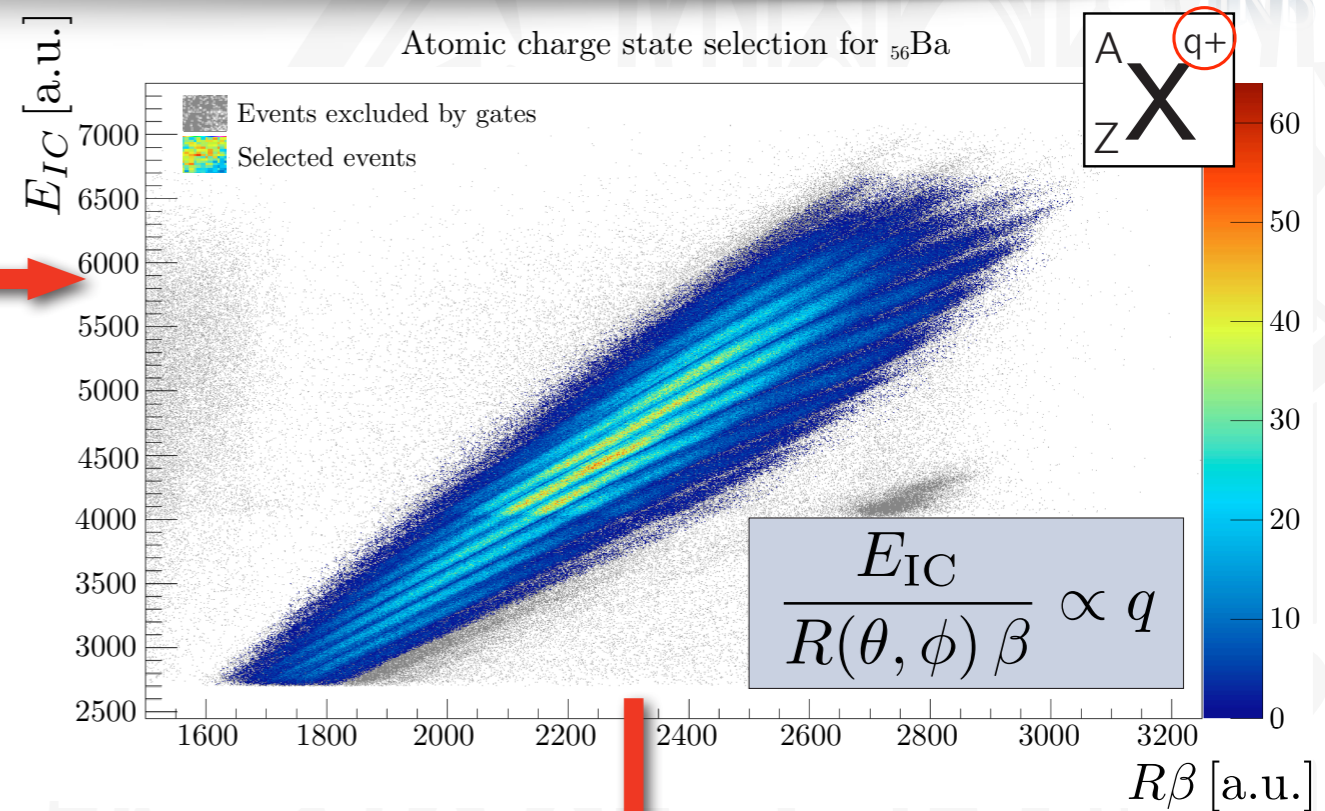
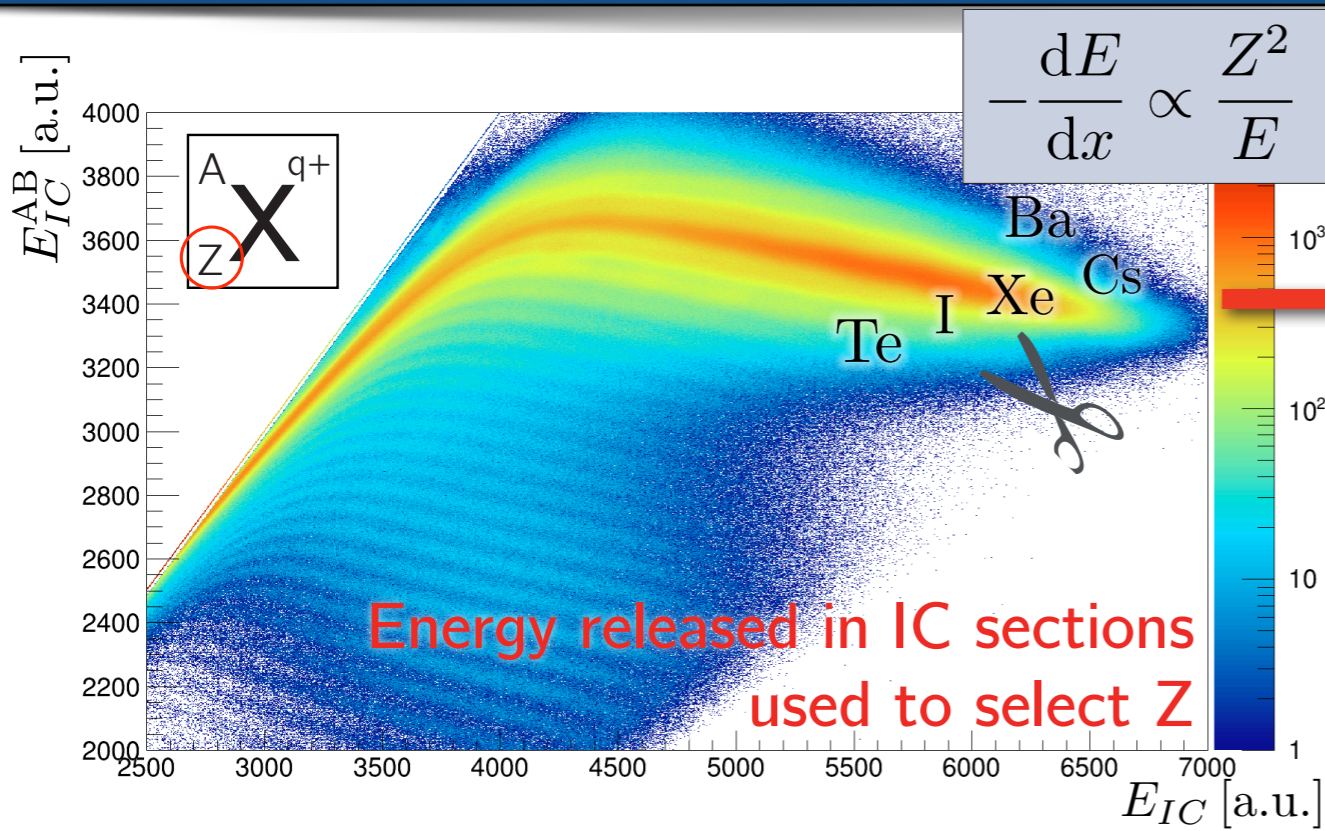
$$E_{\gamma} = E_{\gamma,0} \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \theta}$$

Nb backing  
1 mg/cm<sup>2</sup>

Beam-like particle (Xe, Ba, ...)  
PRISMA (x, y,  $\beta$ , A, Z)

Beam ( $^{136}\text{Xe}$ , 1 GeV, 2 pnA)

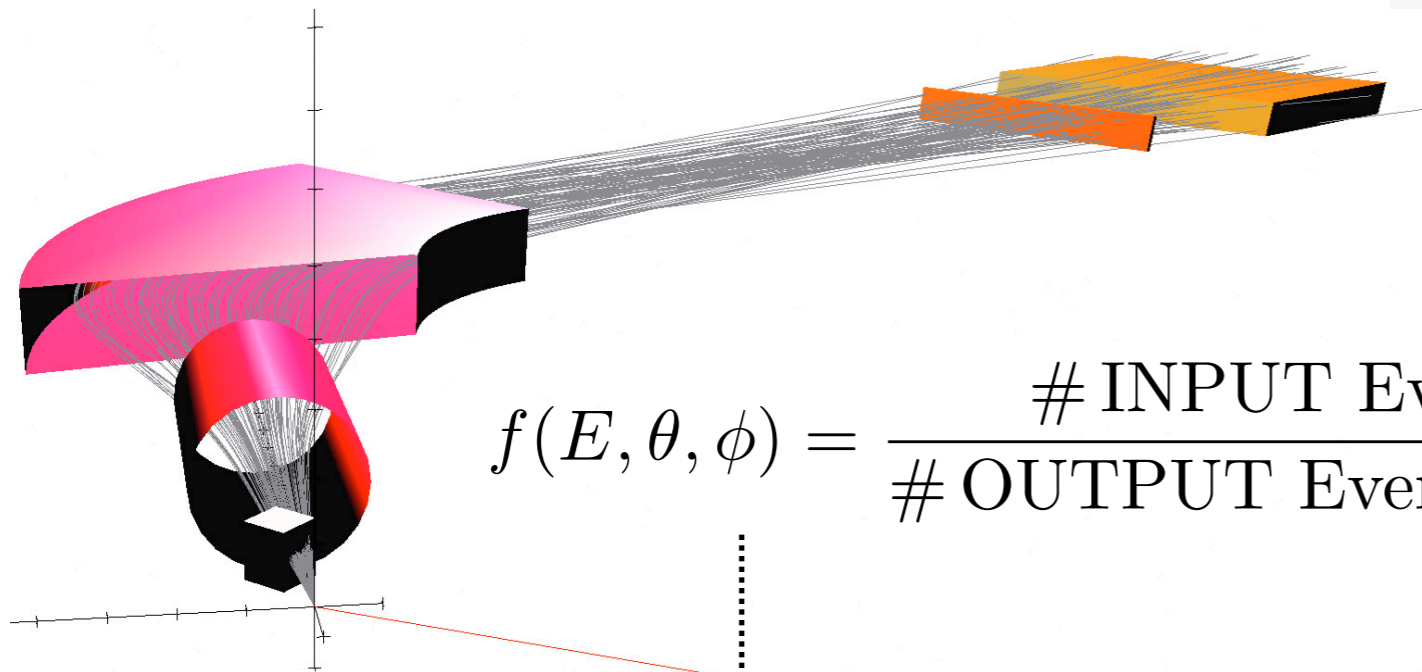
# PRISMA Analysis Procedure



# PRISMA Response Function

Transport of uniform event distribution in  $[E, \vartheta, \phi]$  with Monte Carlo simulation

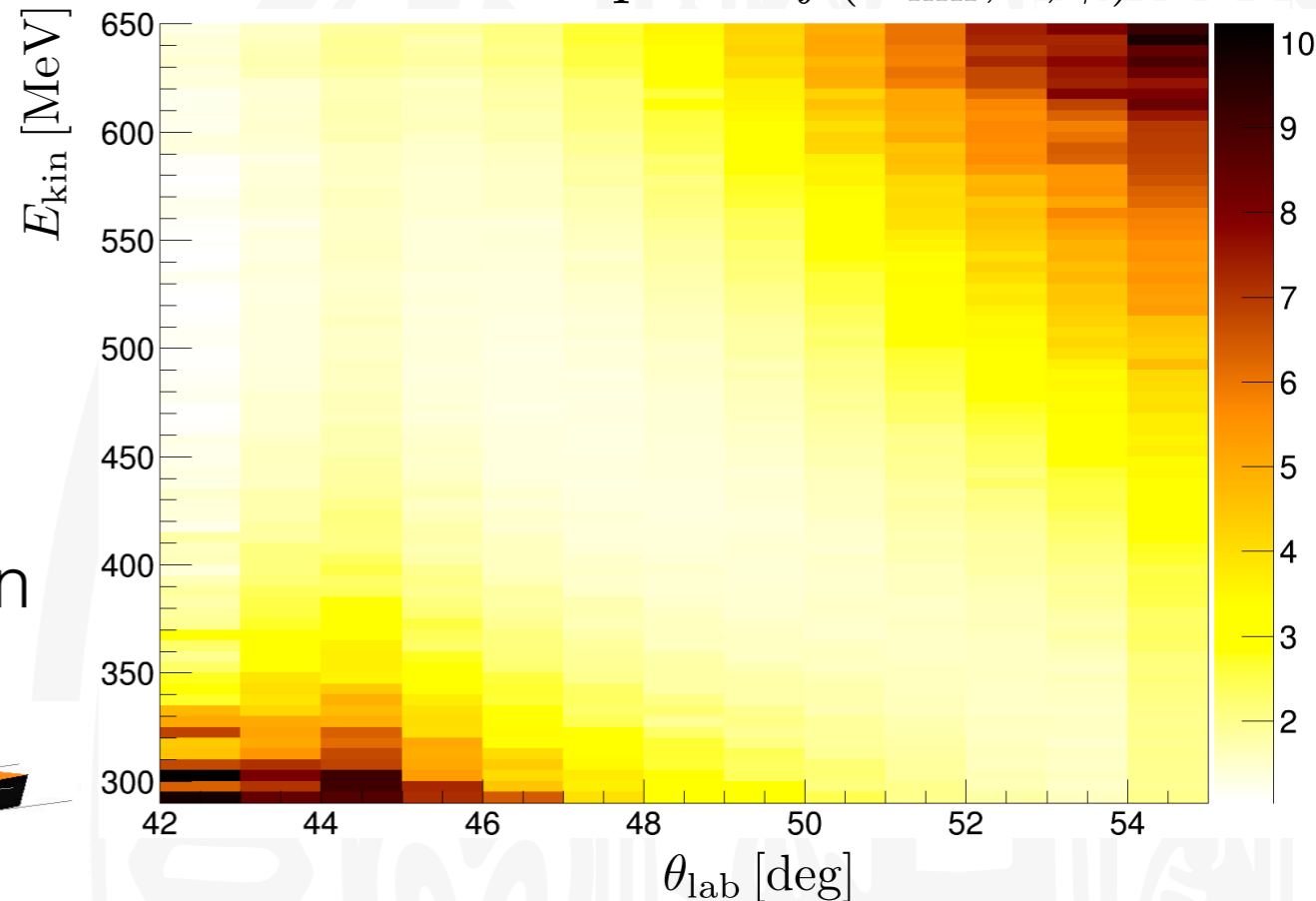
- ray-tracing code of PrismaLibrary
- adjust dipole and quadrupole fields to match experimental event distribution



$$f(E, \theta, \phi) = \frac{\# \text{ INPUT Events: at MCP}(E, \theta, \phi)}{\# \text{ OUTPUT Events: at Focal Plane}(E, \theta, \phi)}$$

$$Y = f(E_{\text{kin}}, \theta, \phi) \times Y_{\text{measured}}$$

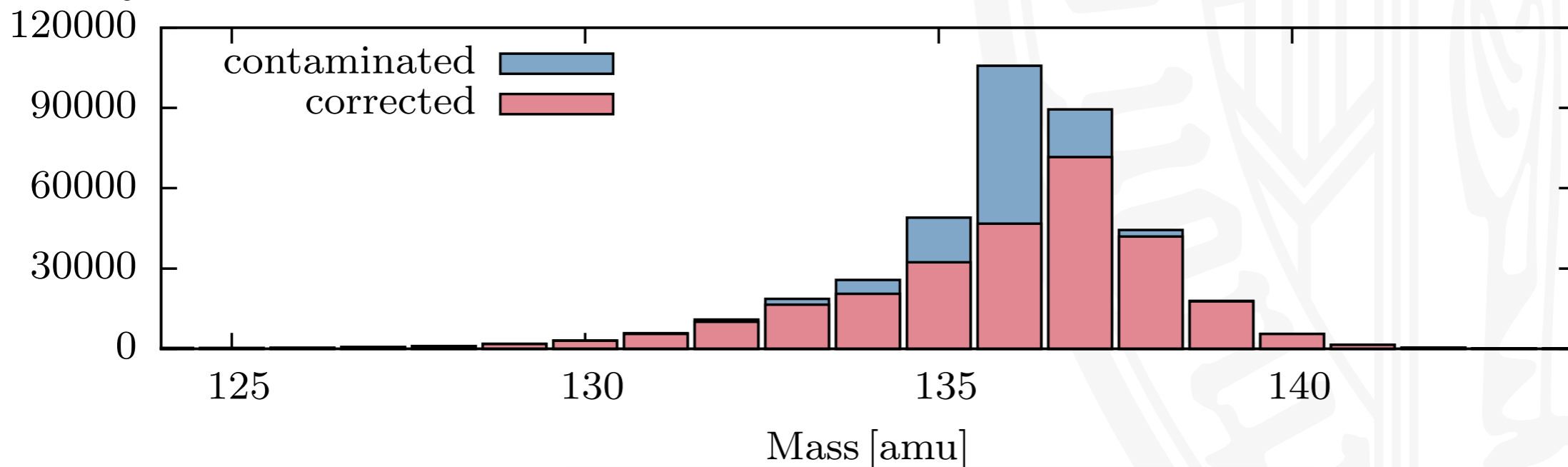
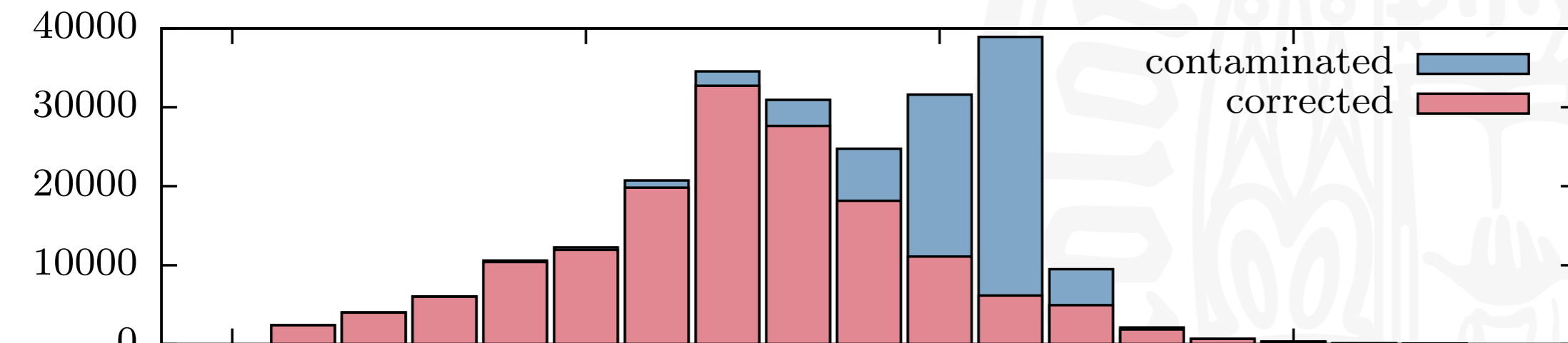
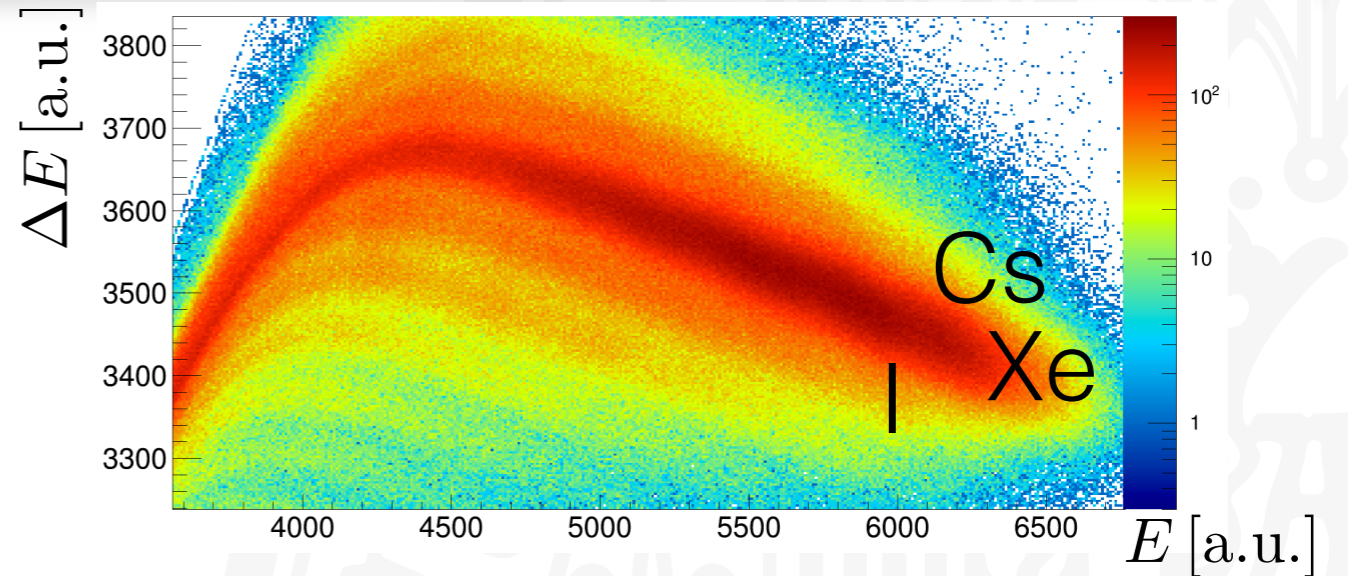
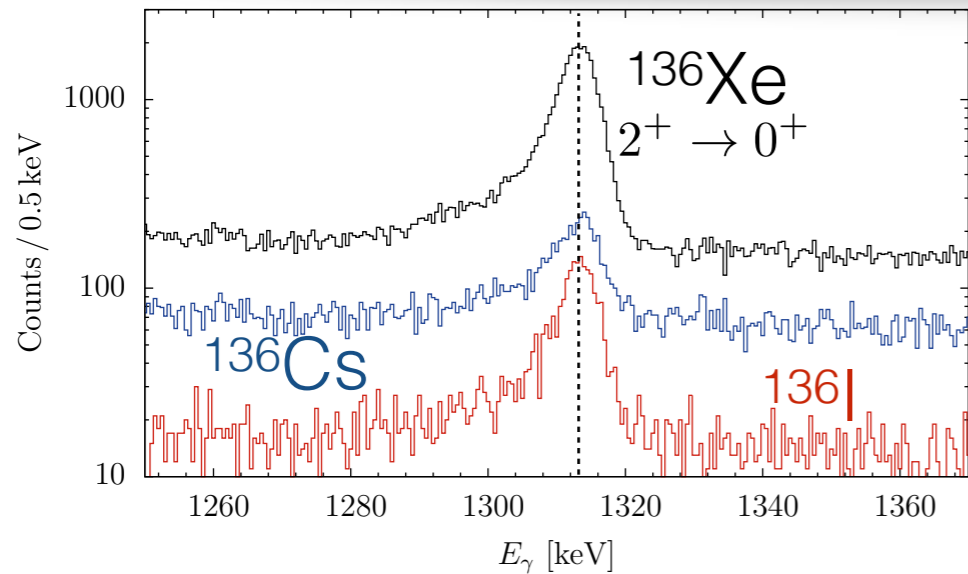
PRISMA Response  $f(E_{\text{kin}}, \theta, \phi)$



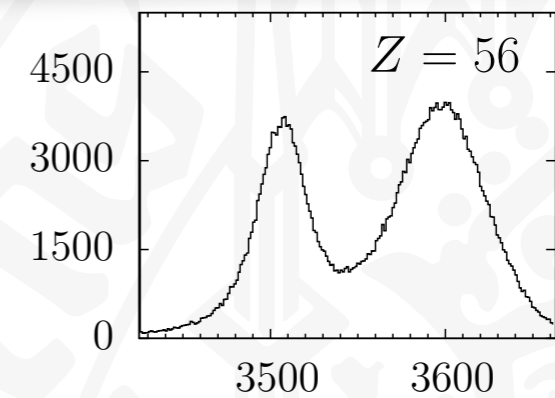
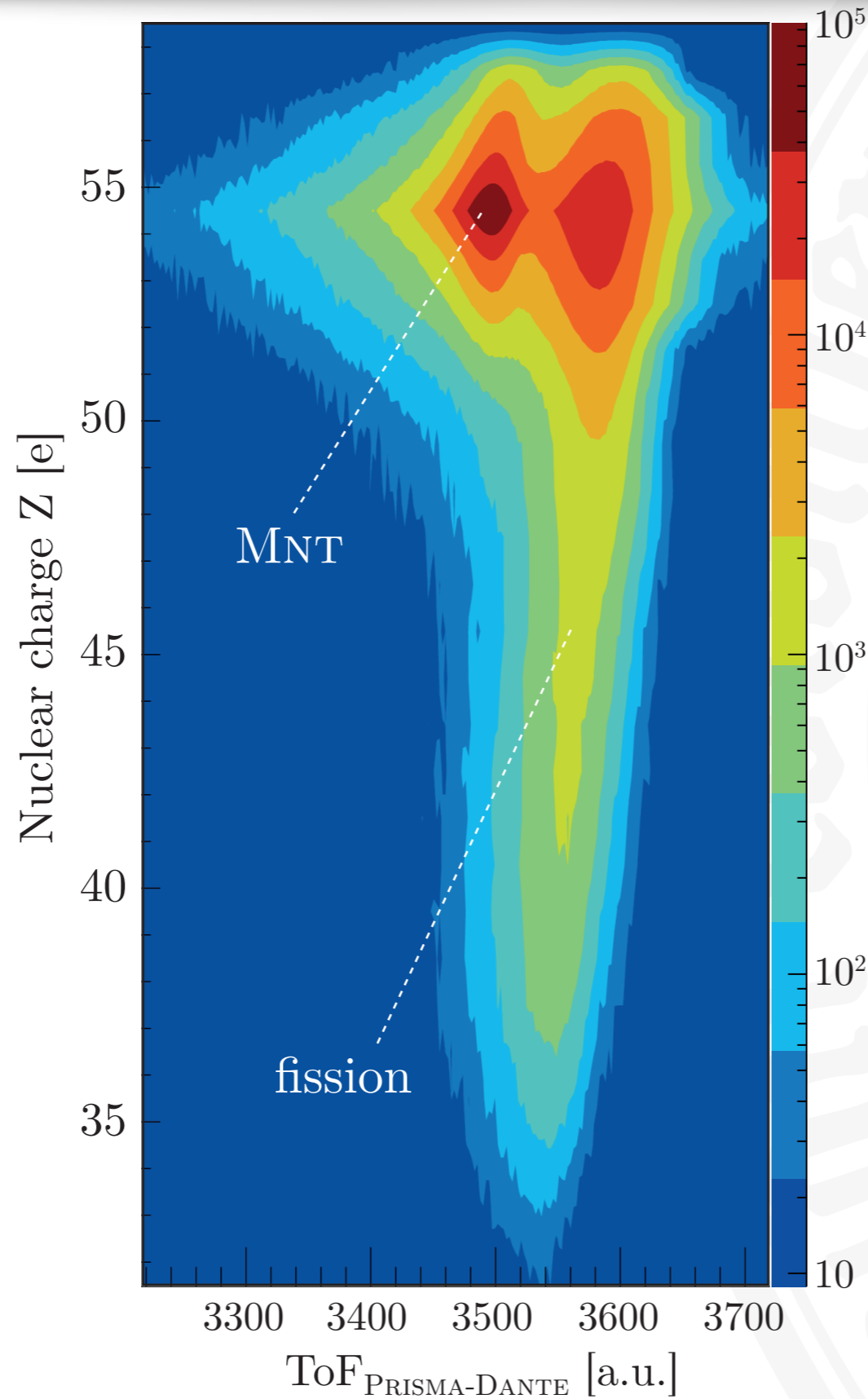
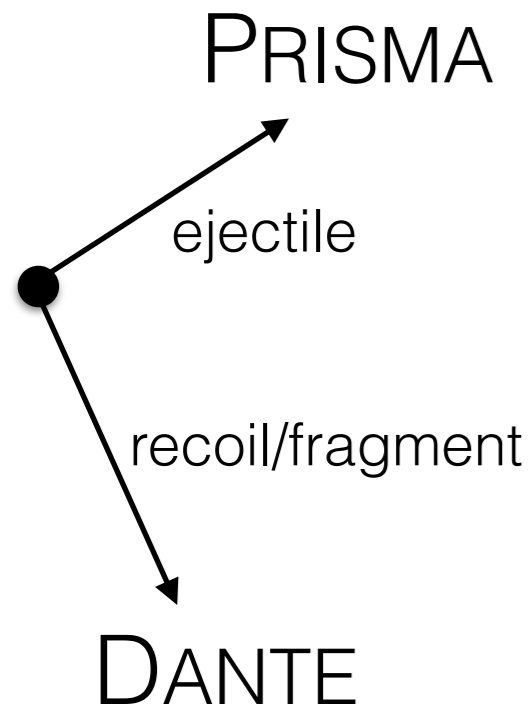
MCP input

transported to PPAC, signal in IC, no IC veto

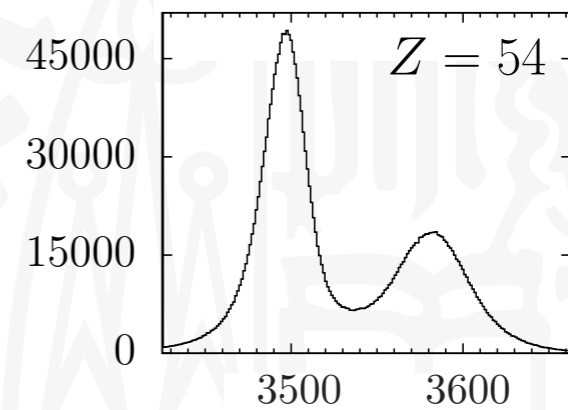
# PRISMA Contamination Correction



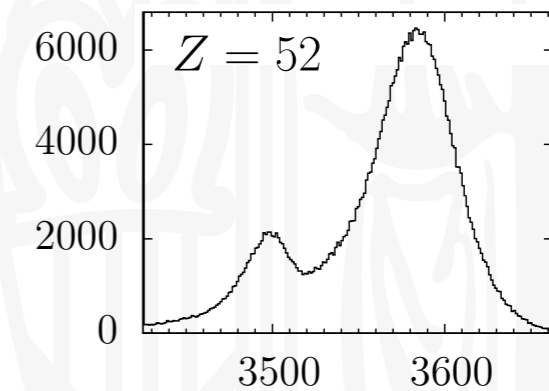
# Discriminating Fission & Transfer



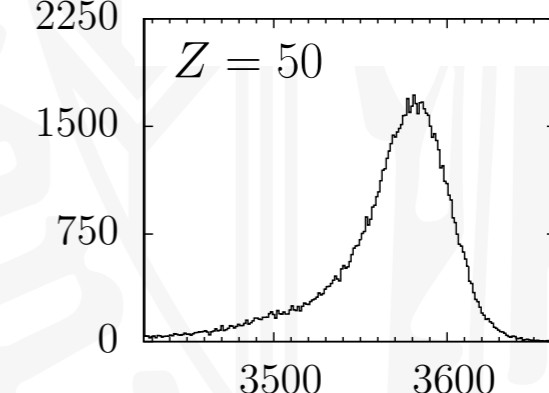
↔ Th



↔ U

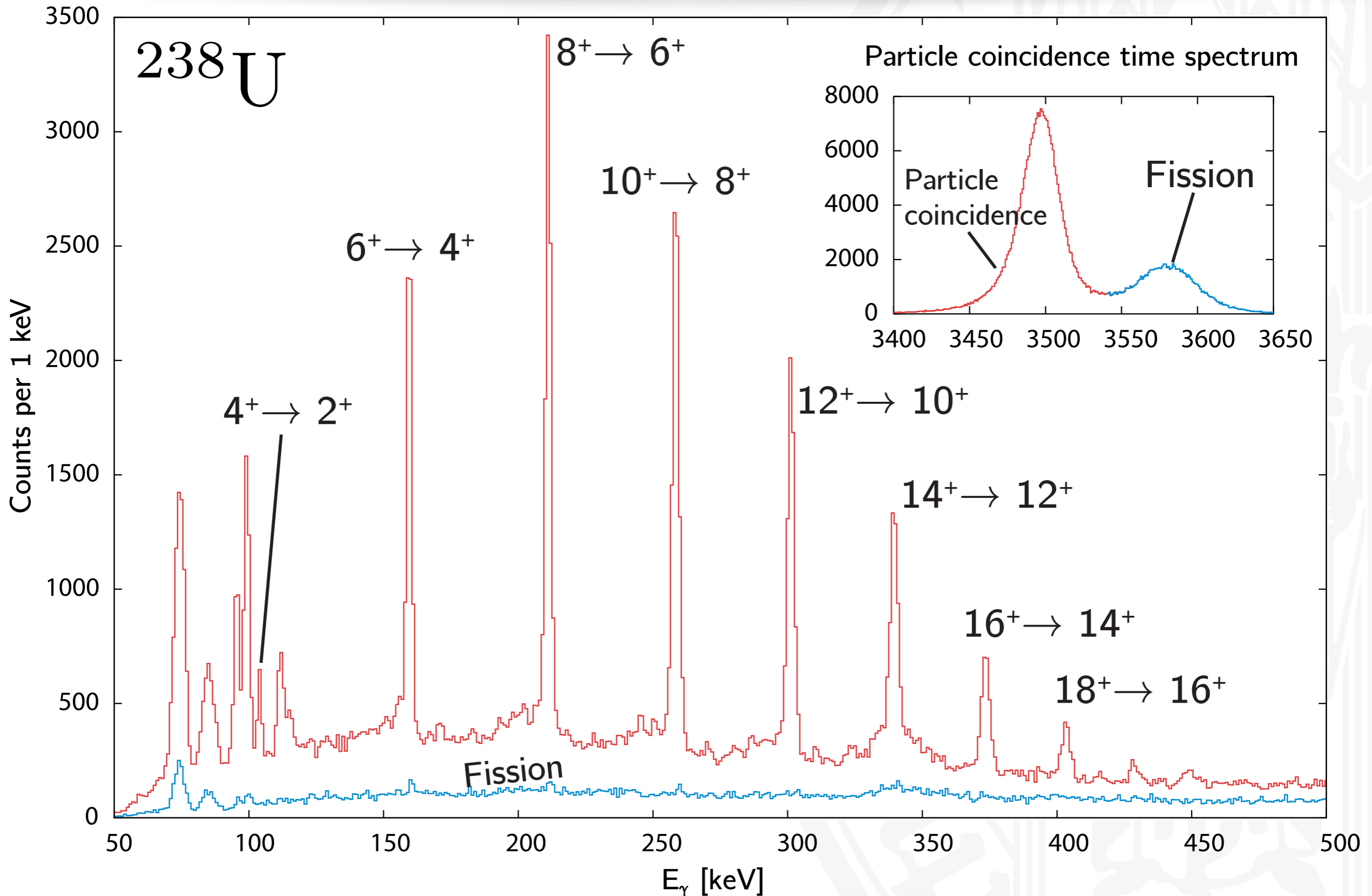


↔ Pu



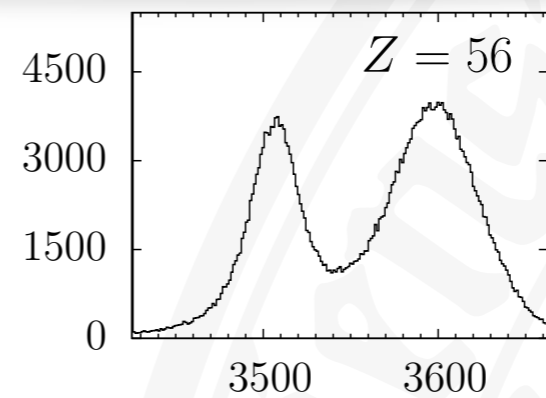
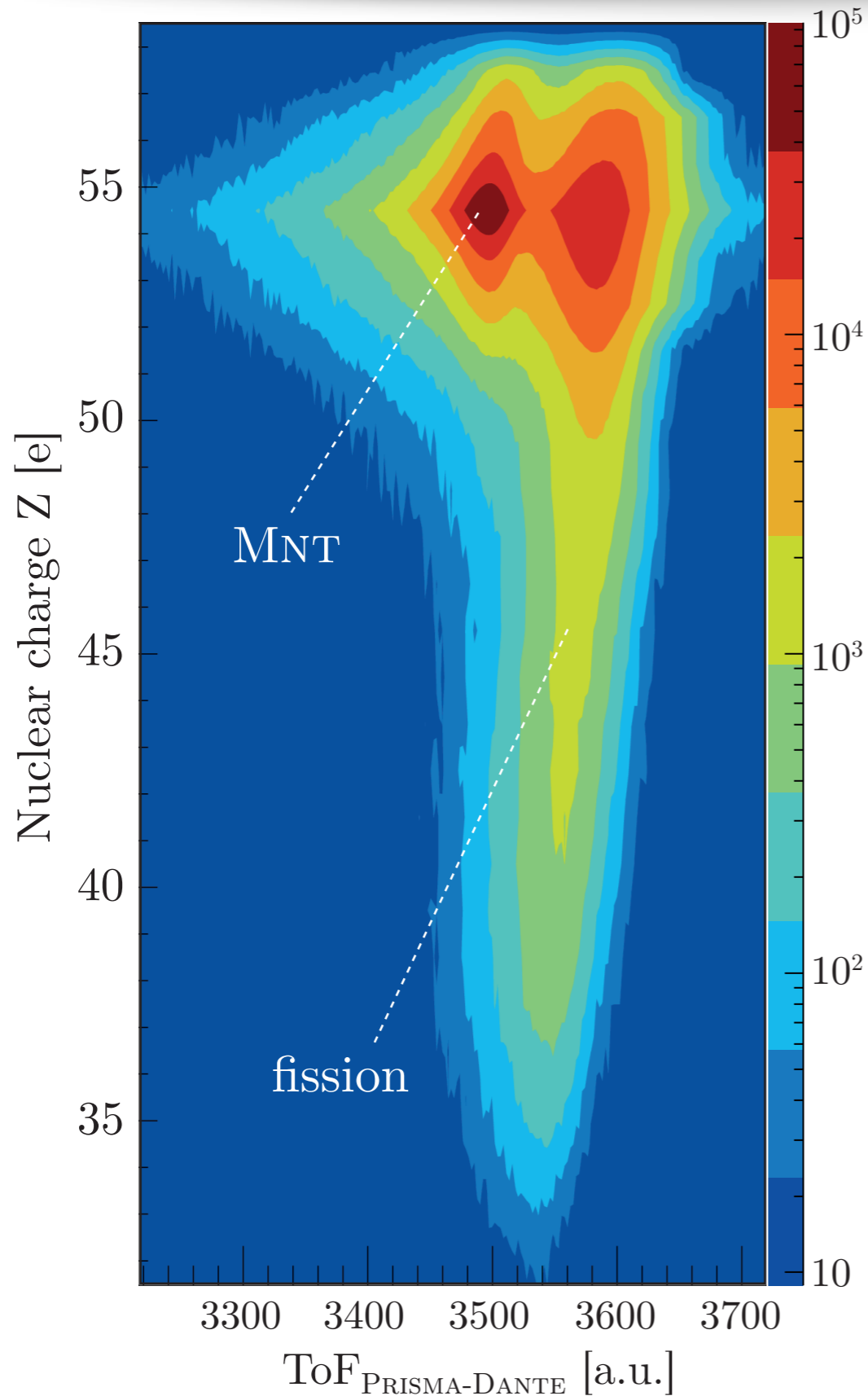
↔ Cu

# Discriminating Fission & Transfer

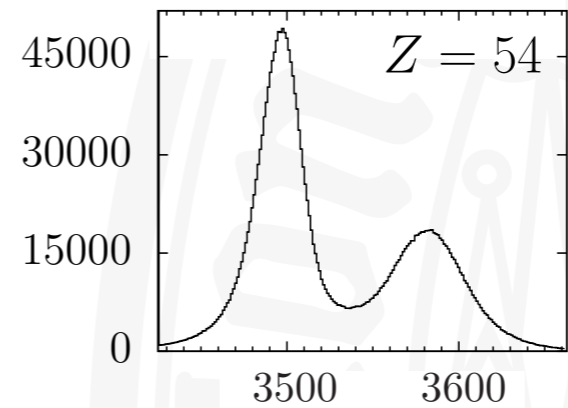




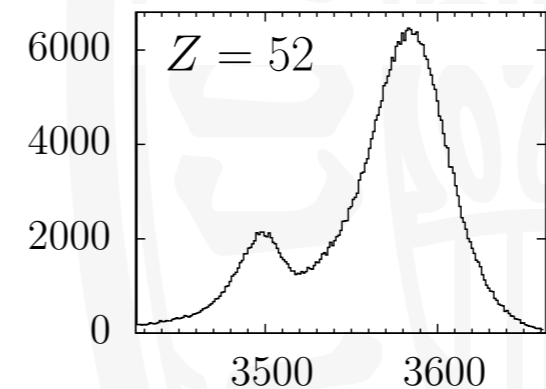
# Discriminating Fission & Transfer



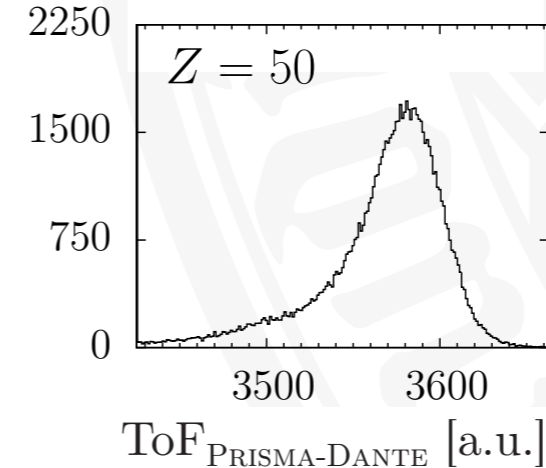
↔ Thorium



↔ Uranium

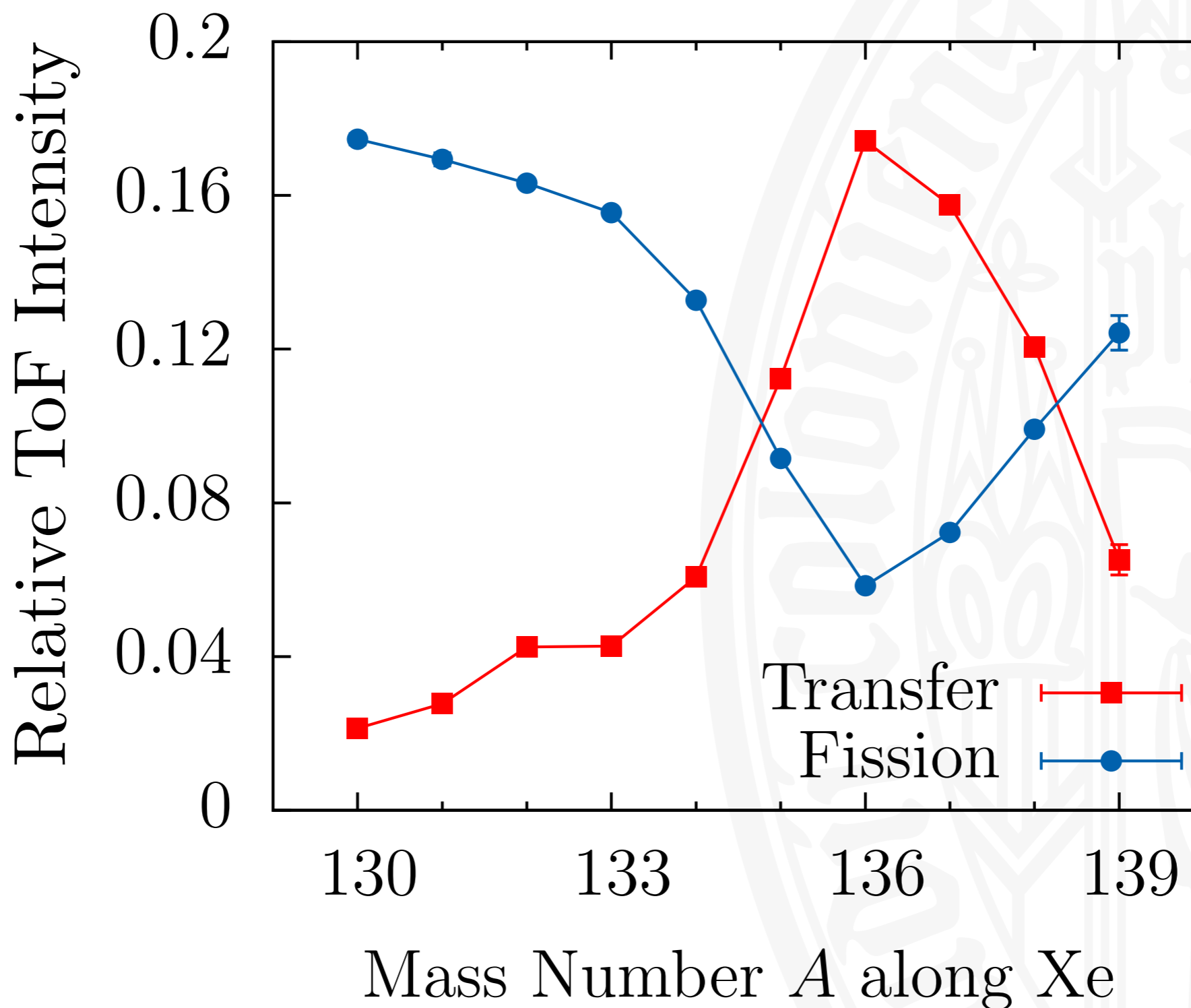


↔ Plutonium

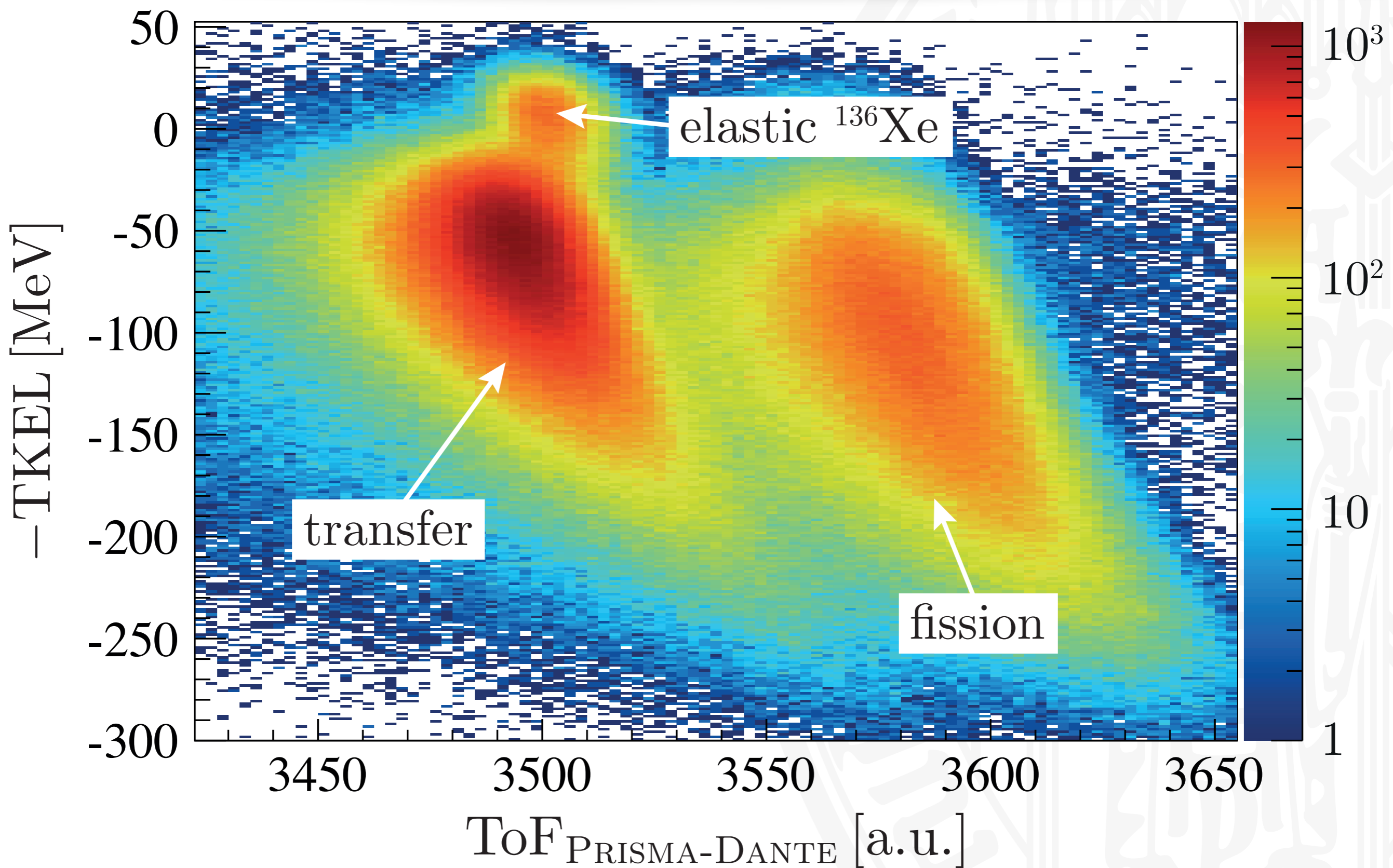


↔ Curium

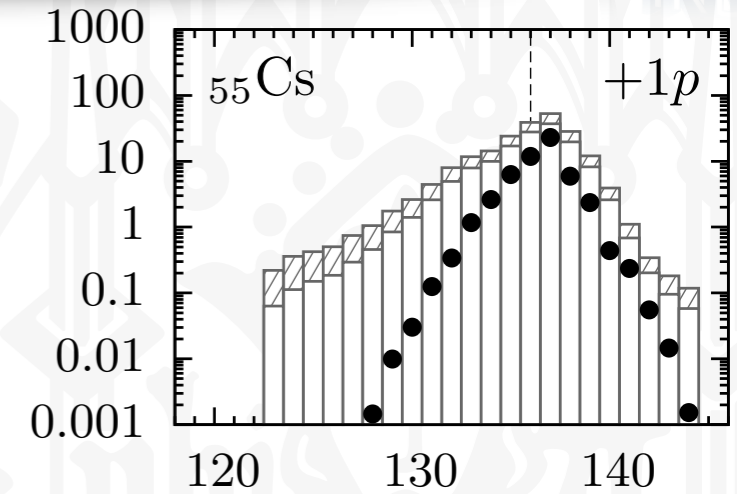
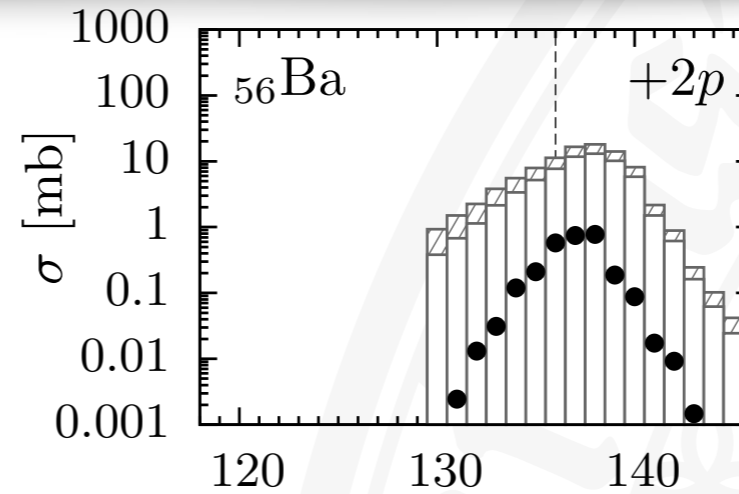
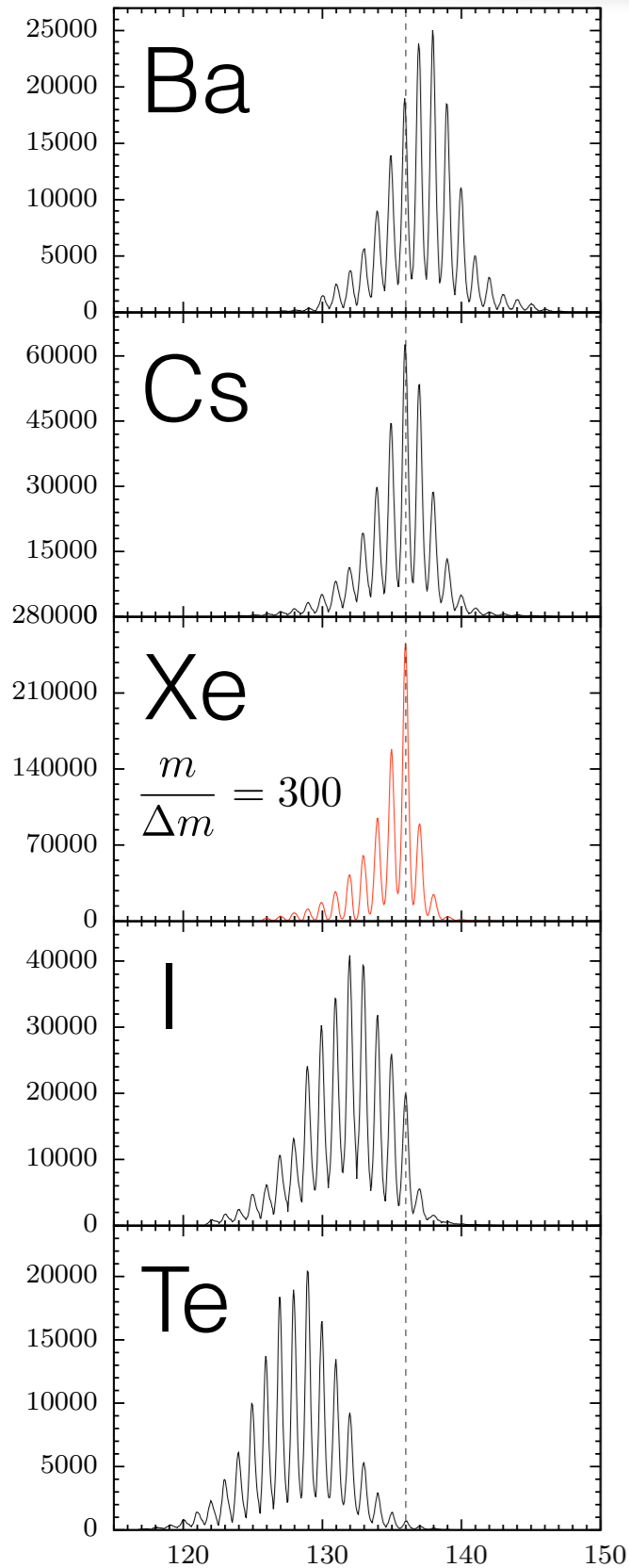
# Discriminating Fission & Transfer



# Selecting Transfer Events






# GRAZING Cross Sections

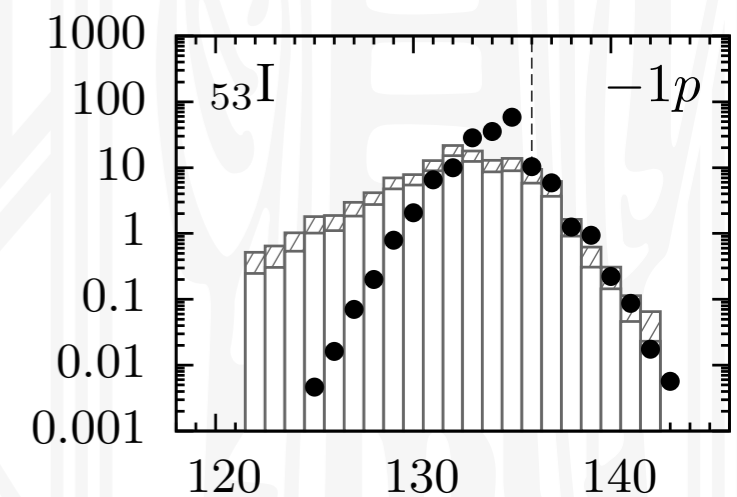
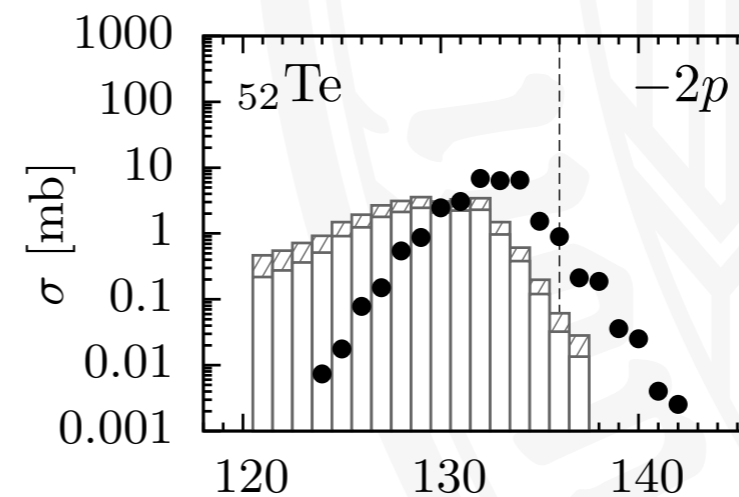
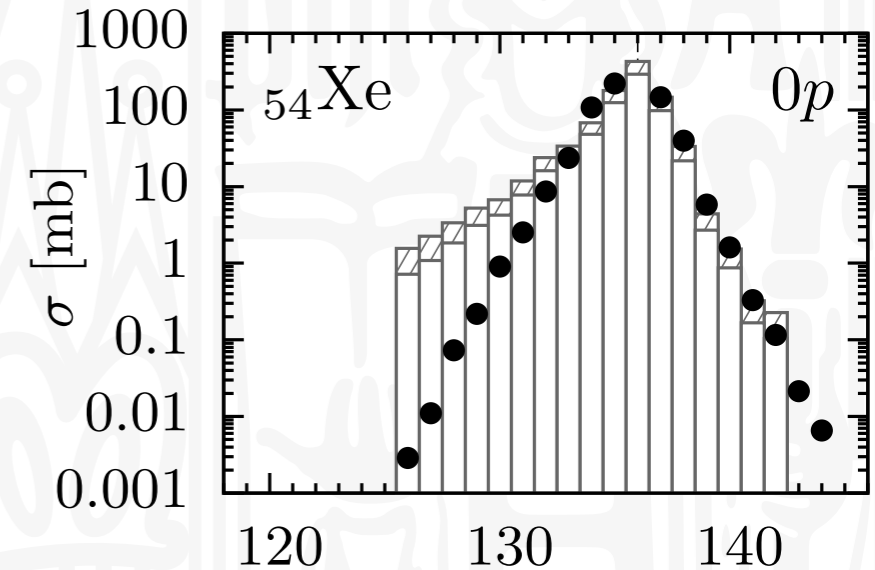


Corrected data normalized  
to +1n channel calculated  
by GRAZING model

A. Winther, Nucl. Phys. A 572, 191 (1994)

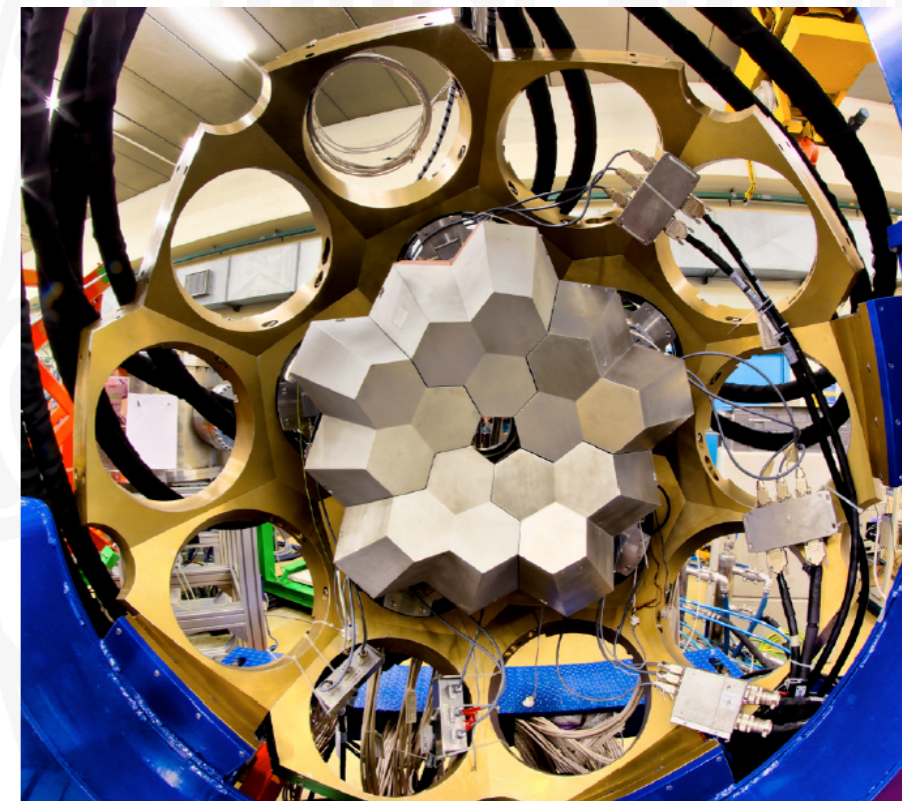
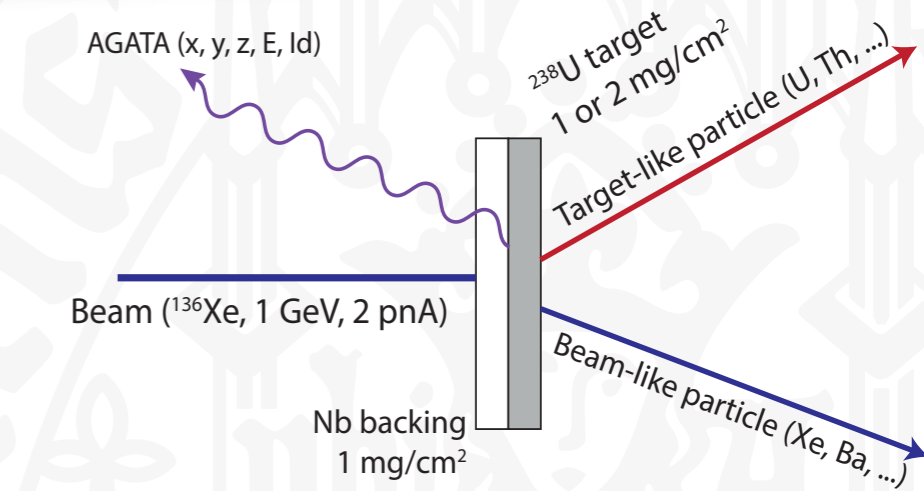
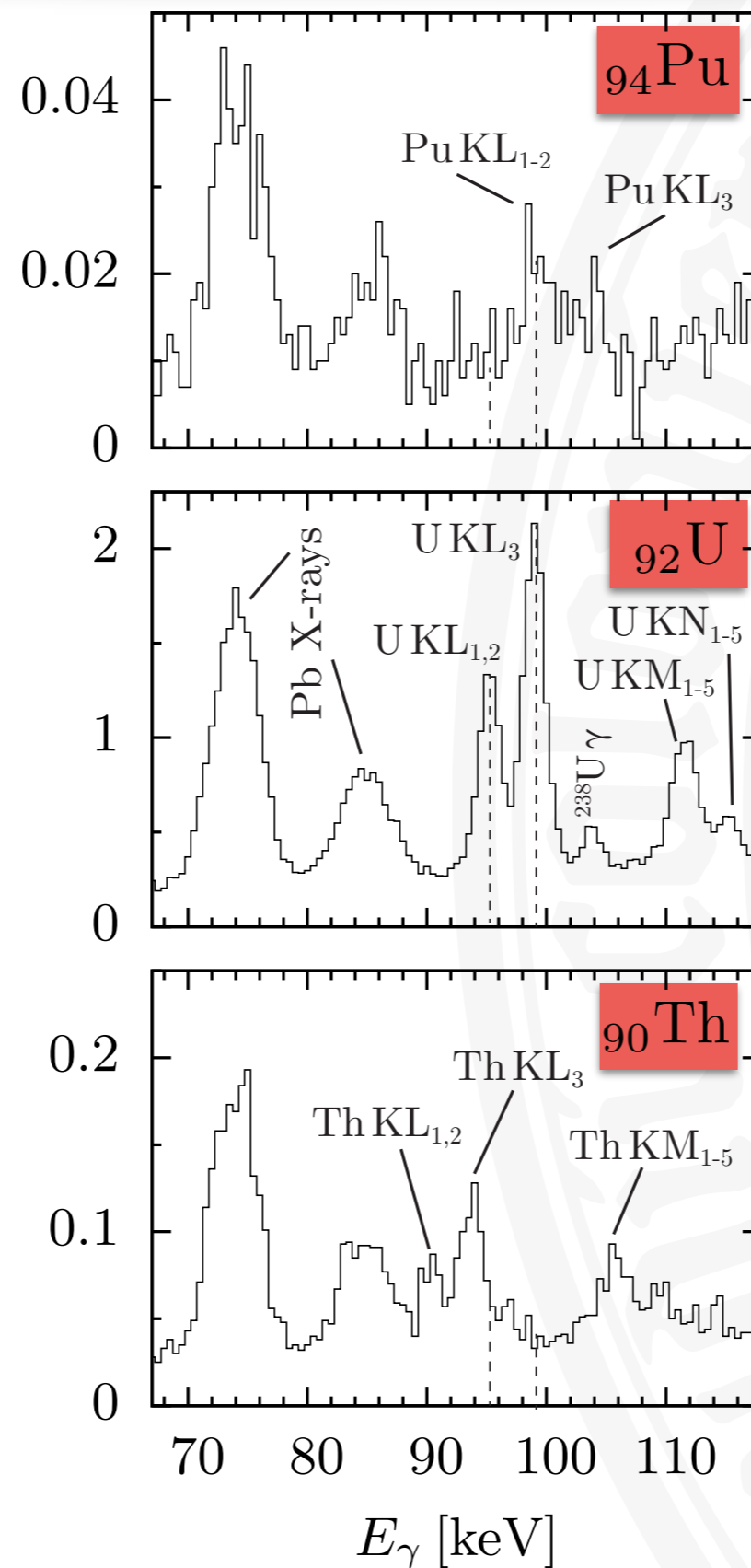
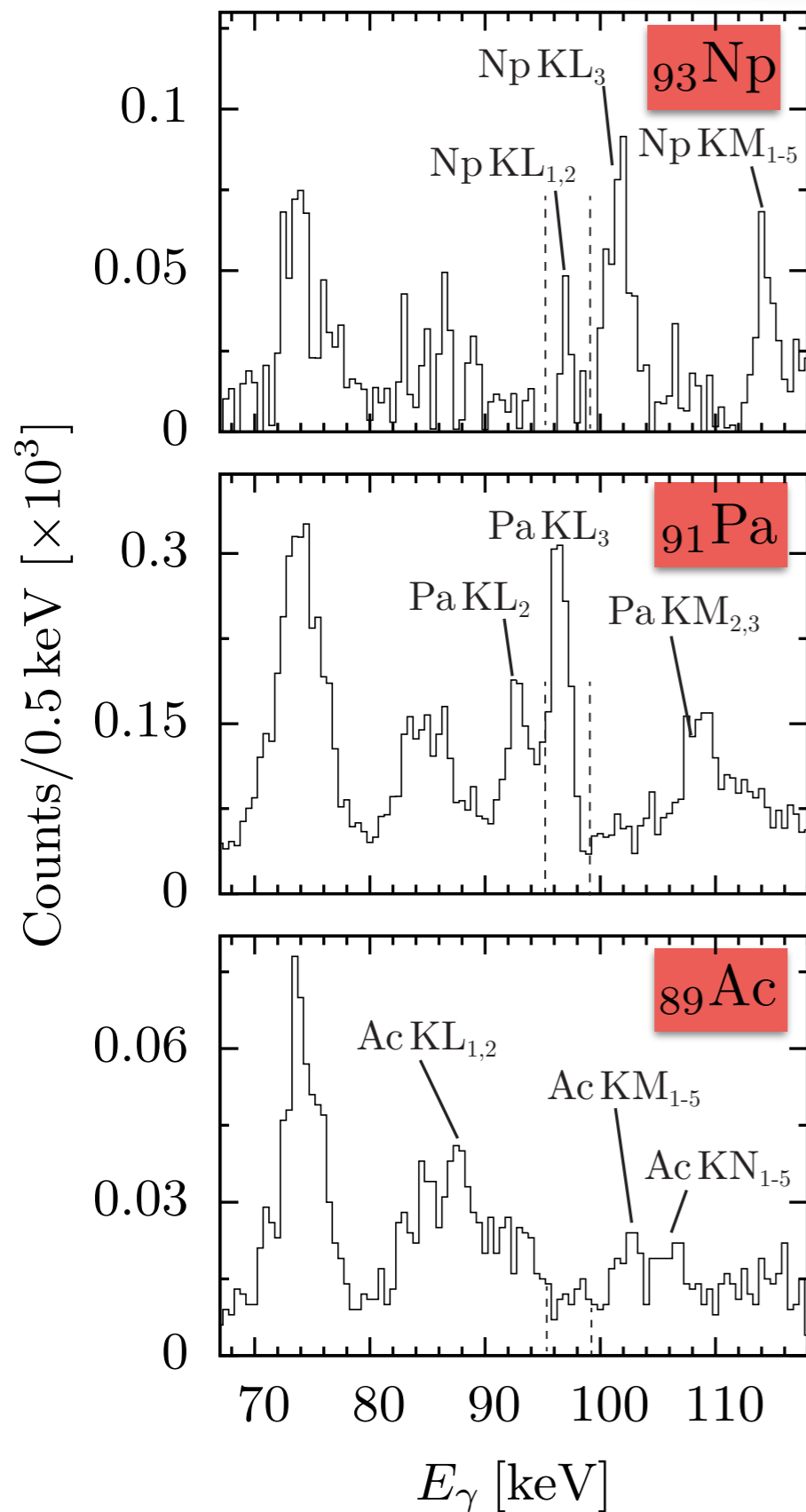


Response corrected mass yields   
Original mass yields   
GRAZING calculation 910 MeV 



**Future:** GRAZING-F model: R. Yanez, W. Loveland. arXiv:1501.01568 [nucl-ex]

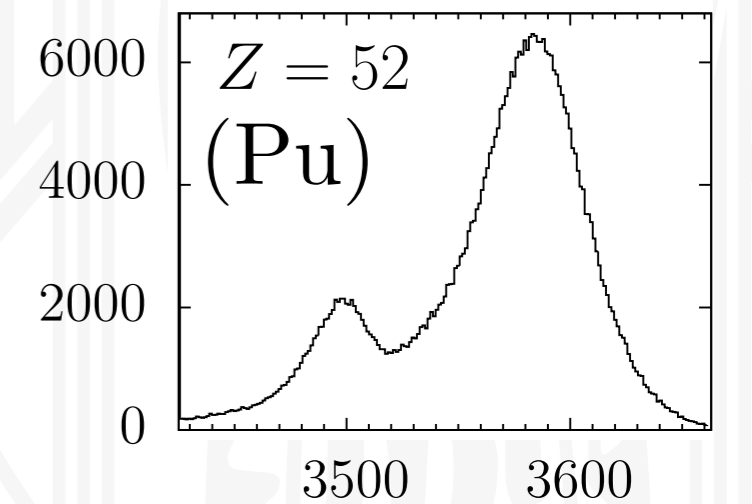
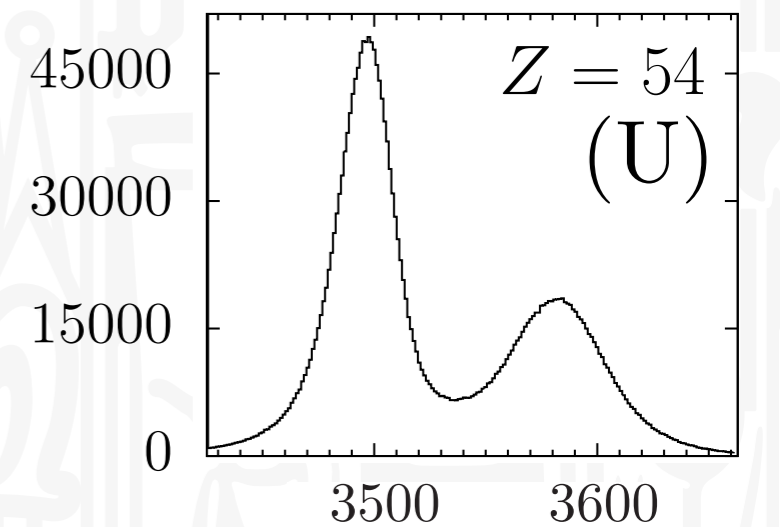
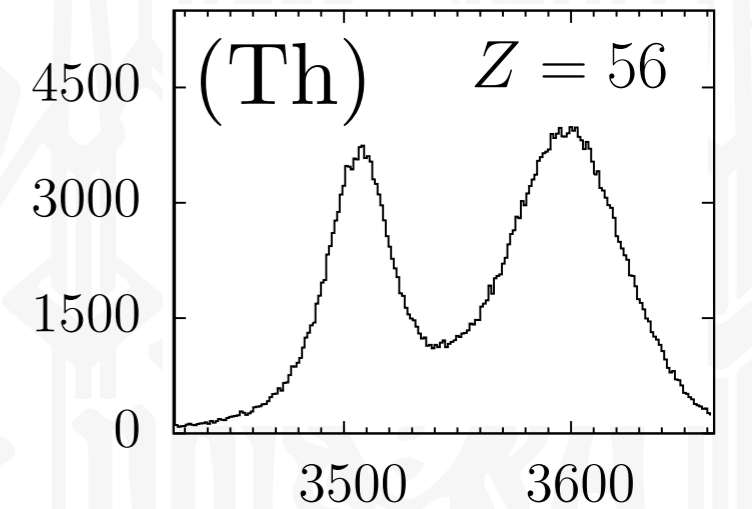
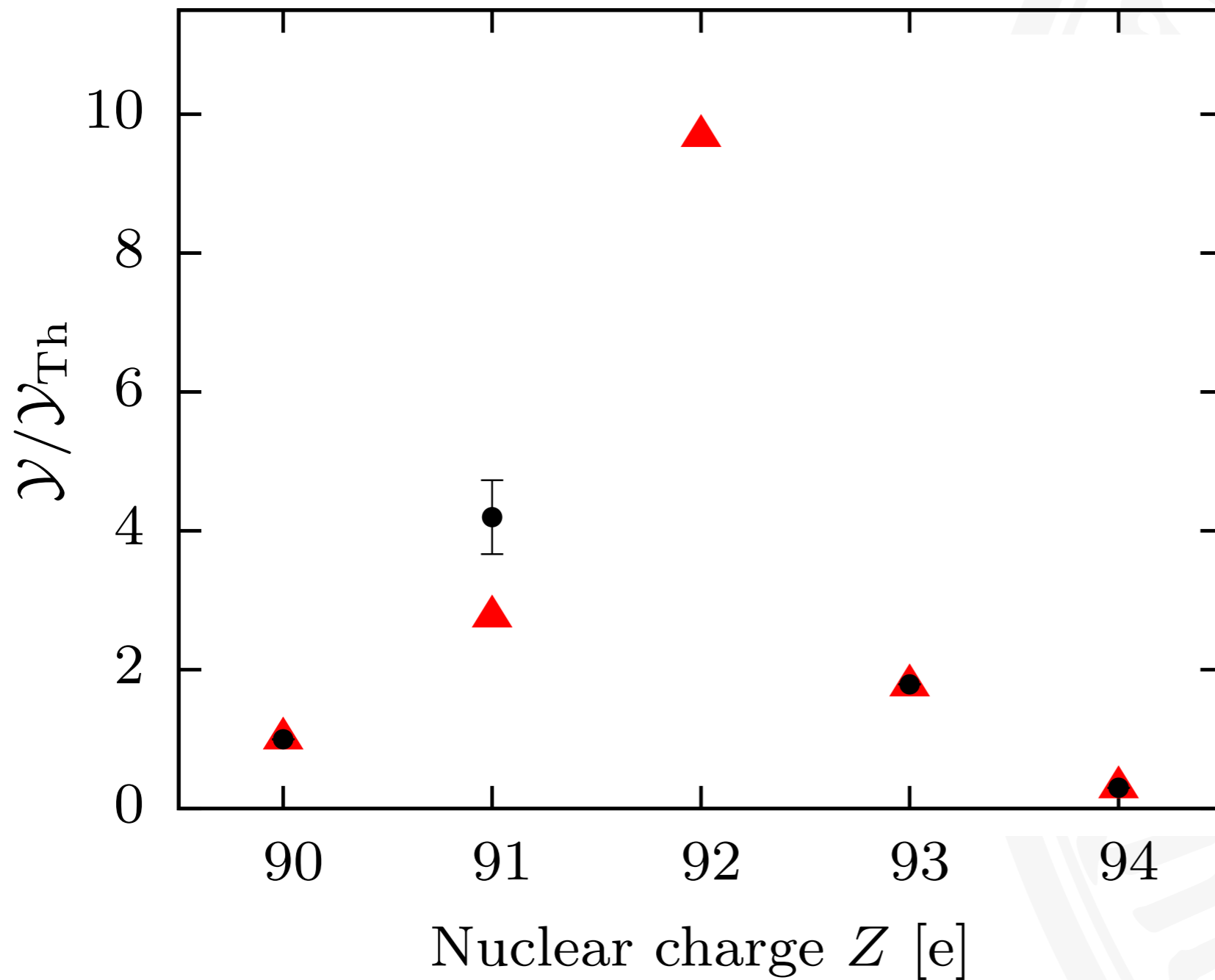
# Actinide Yields via X-ray Spectra



# Actinide Yields via X-rays and TAC

ToF PRISMA-DANTE ▲  
X-rays ●

normalized to Th

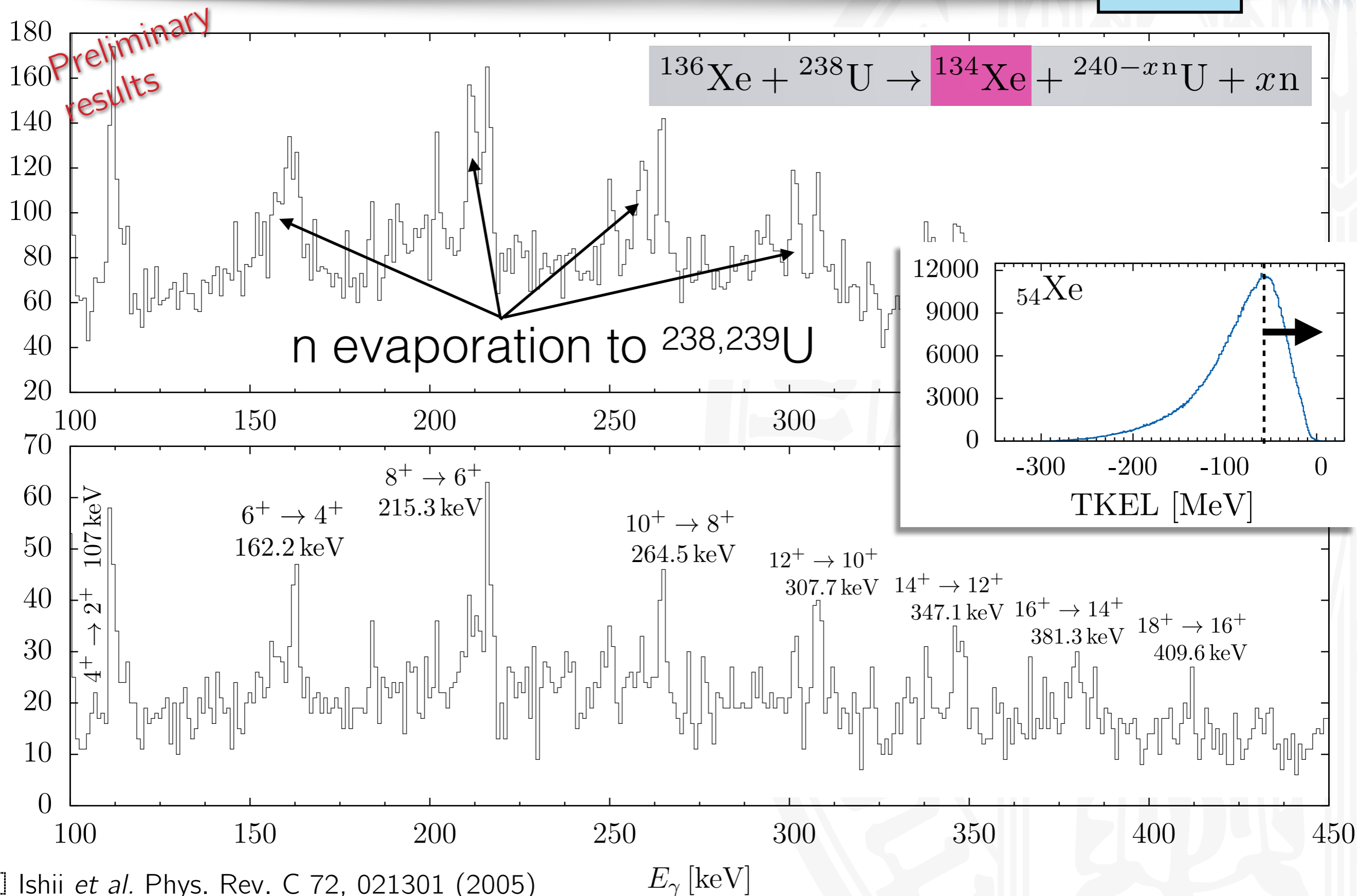


ToF<sub>PRISMA-DANTE</sub> [a.u.]

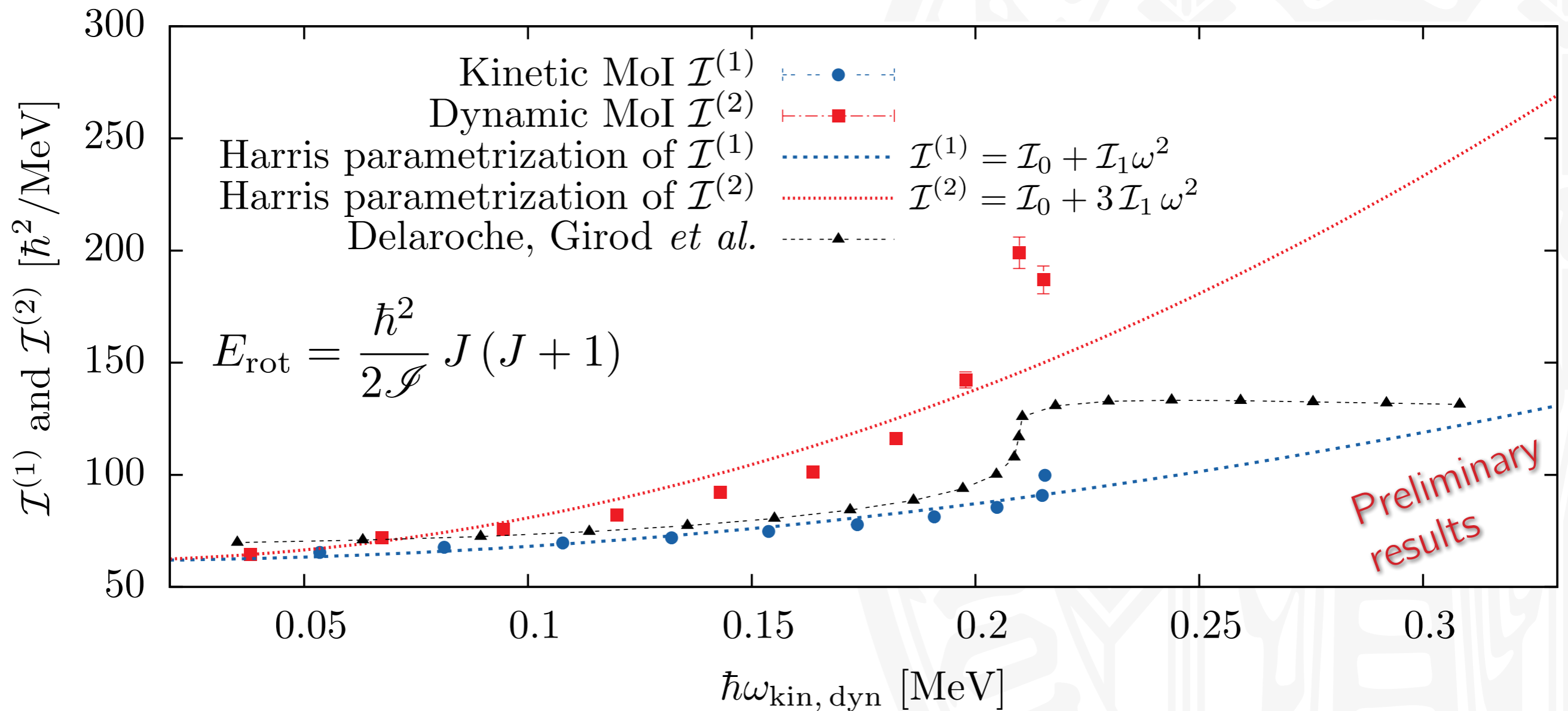
# Neutron-rich actinides: $^{240}\text{U}$

**U 240**

14.1h



## Kinetic and dynamic moments of inertia $\mathcal{I}^{(1)}$ and $\mathcal{I}^{(2)}$ for $^{240}\text{U}$ ground-state band candidates





- Study of multinucleon transfer reaction  $^{136}\text{Xe} + ^{238}\text{U}$
- Discrimination of fission and transfer
- Actinide survivability against fission
- In-beam  $\gamma$ -ray spectroscopy of neutron-rich actinides

A. Vogt,<sup>1, a</sup> B. Birkenbach,<sup>1</sup> P. Reiter,<sup>1</sup> L. Corradi,<sup>2</sup> D. Montanari,<sup>3, b</sup> S. Szilner,<sup>4</sup> T. Mijatović,<sup>4</sup> D. Bazzacco,<sup>3</sup> M. Bowry,<sup>5</sup> A. Bracco,<sup>6</sup> B. Bruyneel,<sup>7</sup> F. Crespi,<sup>6</sup> E. Farnea,<sup>3, c</sup> K. Geibel,<sup>1</sup> A. Giaz,<sup>6</sup> A. Gottardo,<sup>2</sup> H. Hess,<sup>1</sup> P. John,<sup>3</sup> S. Lenzi,<sup>3</sup> S. Leoni,<sup>6</sup> C. Michelagnoli,<sup>3, d</sup> D. Napoli,<sup>2</sup> L. Pellegri,<sup>6</sup> F. Radeck,<sup>1</sup> F. Recchia,<sup>3</sup> E. Şahin,<sup>2, e</sup> M. Seidlitz,<sup>1</sup> D. Schneiders,<sup>1</sup> P. Söderström,<sup>8, f</sup> T. Steinbach,<sup>1</sup> B. Szpak,<sup>9</sup> C. Ur,<sup>3</sup> J. Valiente-Dobón,<sup>2</sup> V. Vandone,<sup>6</sup> and A. Wiens<sup>1</sup>

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<sup>4</sup>*Ruder Bošković Institute, HR-10 002 Zagreb, Croatia*

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<sup>7</sup>*CEA Saclay, Service de Physique Nucleaire, F-91191 Gif-sur-Yvette, France*

<sup>8</sup>*Department of Physics and Astronomy, Uppsala University, SE-75121 Uppsala, Sweden*

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of Physics and Astronomy



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