Spectroscopy of heavy nuclei after multinucleon-transfer reactions

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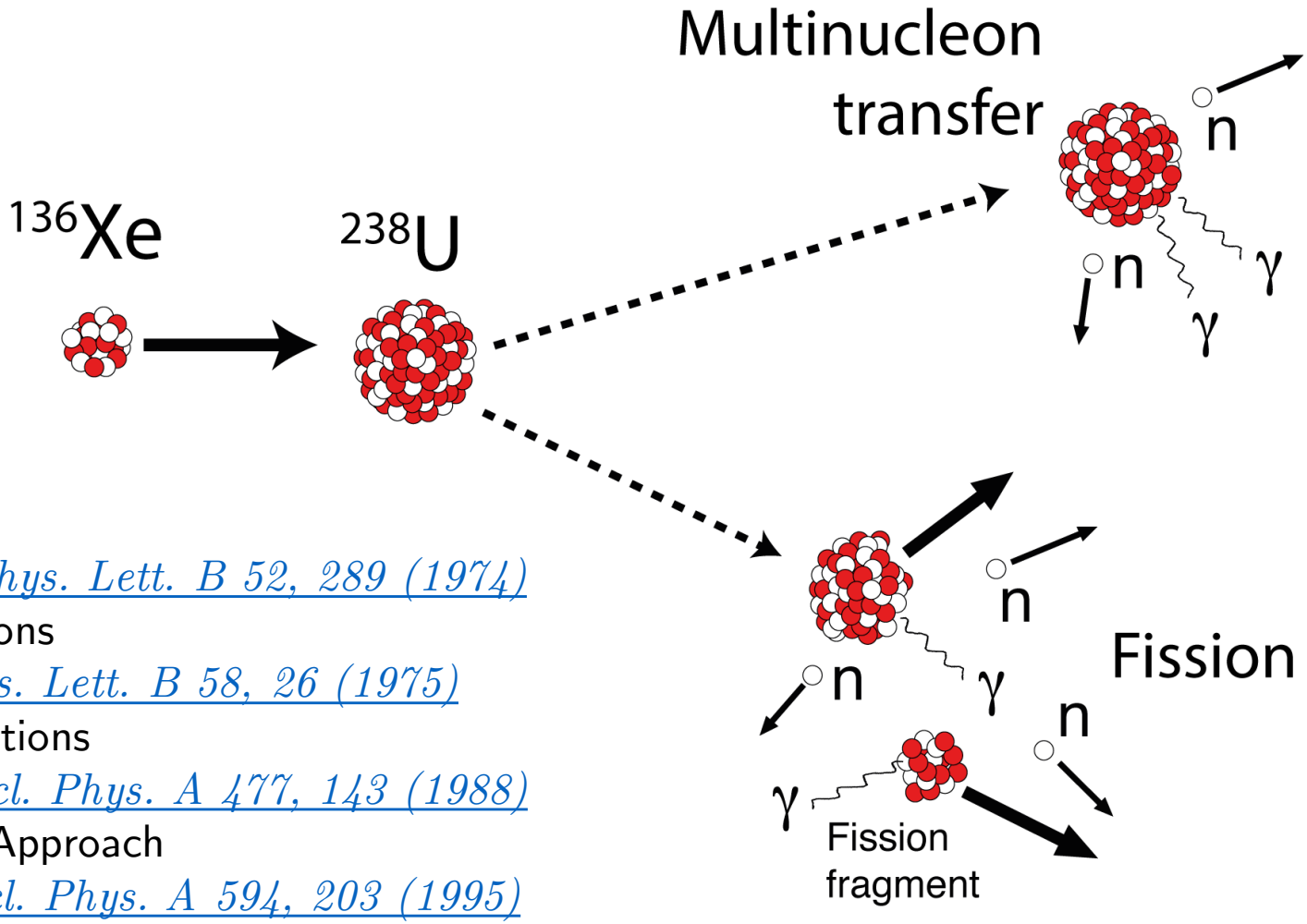
IKP Cologne

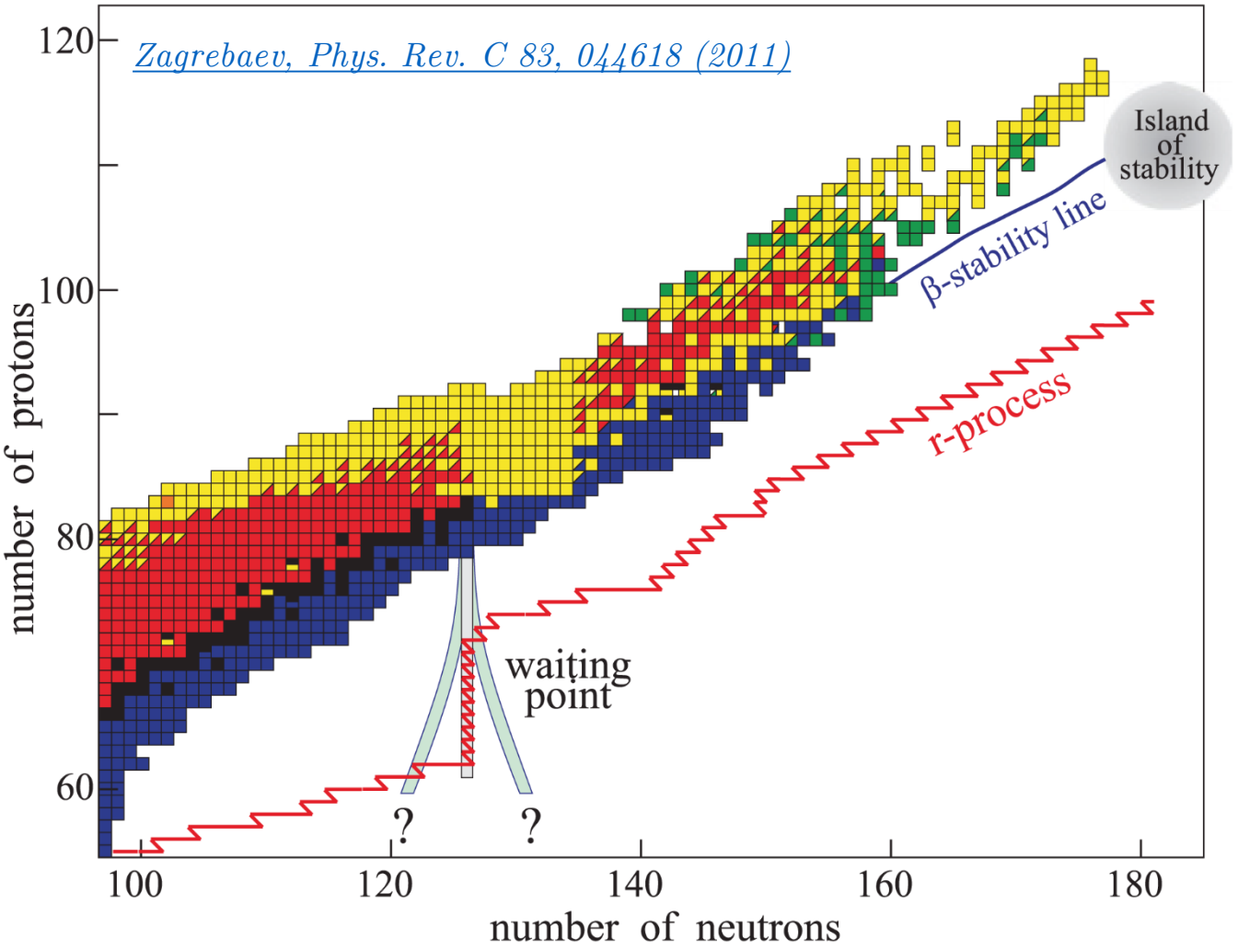
Advances in experimental and theoretical studies of heavy, very heavy and super-heavy nuclei – CEA Saclay Nov. 2015

Multinucleon-Transfer Reactions

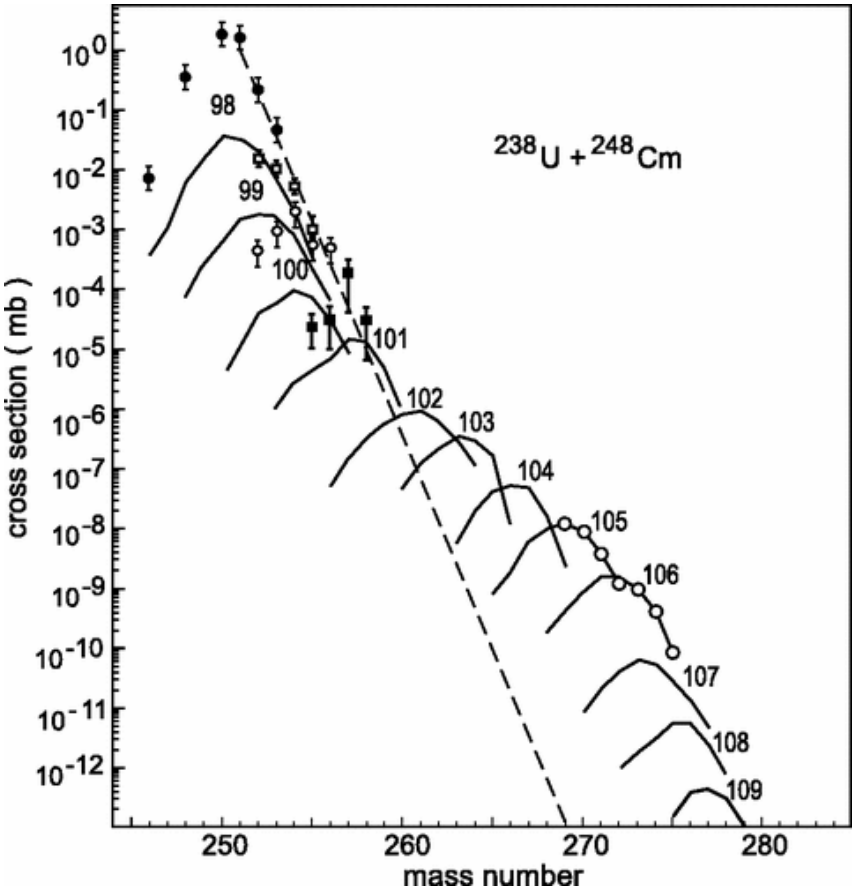


Focker-Planck
Nörenberg, Phys. Lett. B 52, 289 (1974)
Master equations
Moretto, Phys. Lett. B 58, 26 (1975)
Langevin equations
Fröbrich, Nucl. Phys. A 477, 143 (1988)
Semiclassical Approach
Winther, Nucl. Phys. A 594, 203 (1995)

Neutron rich heavy nuclei



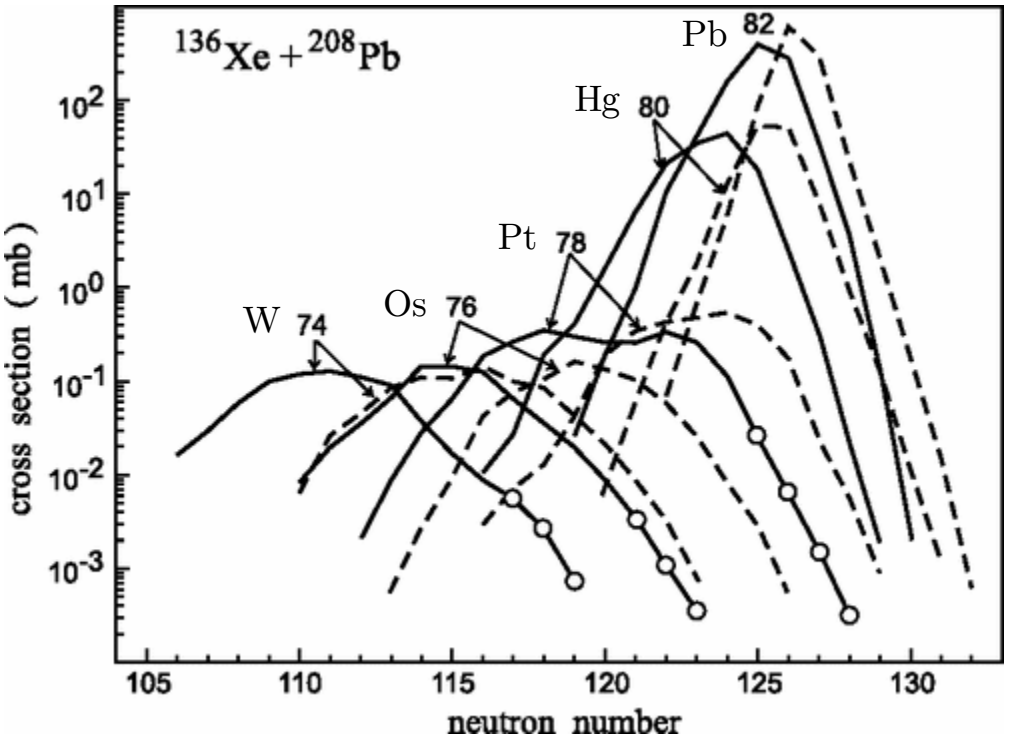
Neutron rich heavy nuclei



[Zagrebaev, Phys. Rev. C 78, 034610 (2008)]

[Kratz, Phys. Rev. C 88, 054615 (2013)]

---- Expected yield without shell effects



[Zagrebaev, Phys. Rev. Lett. 101, 122701 (2008)]

---- Primary yield

—— Surviving nuclei

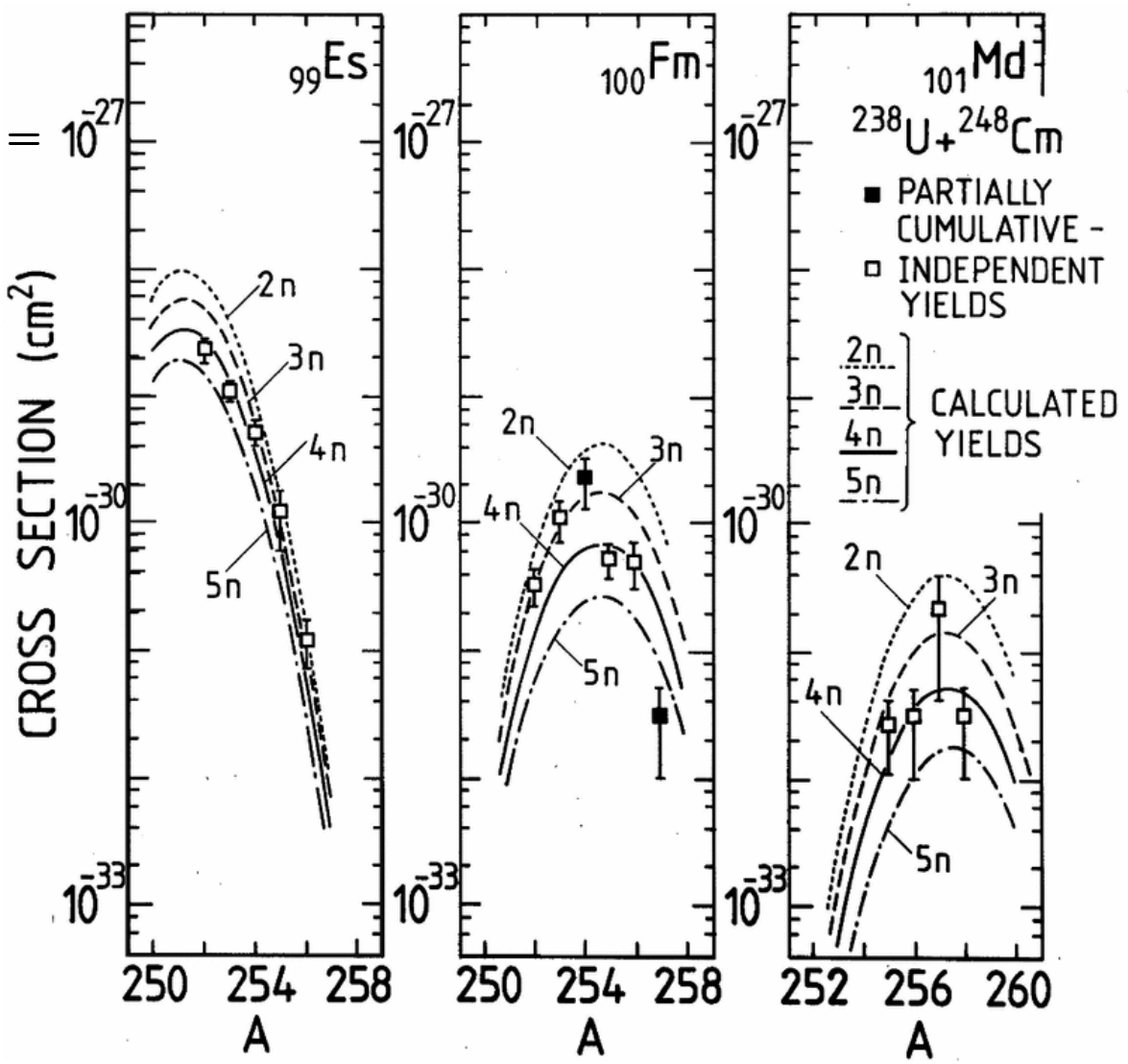
○ Unknown isotopes

Experimental data from chemical separation

1 mb = 10^{-27}

$^{238}U + ^{248}Cm$

Beam:
^{238}U
10 MeV/u

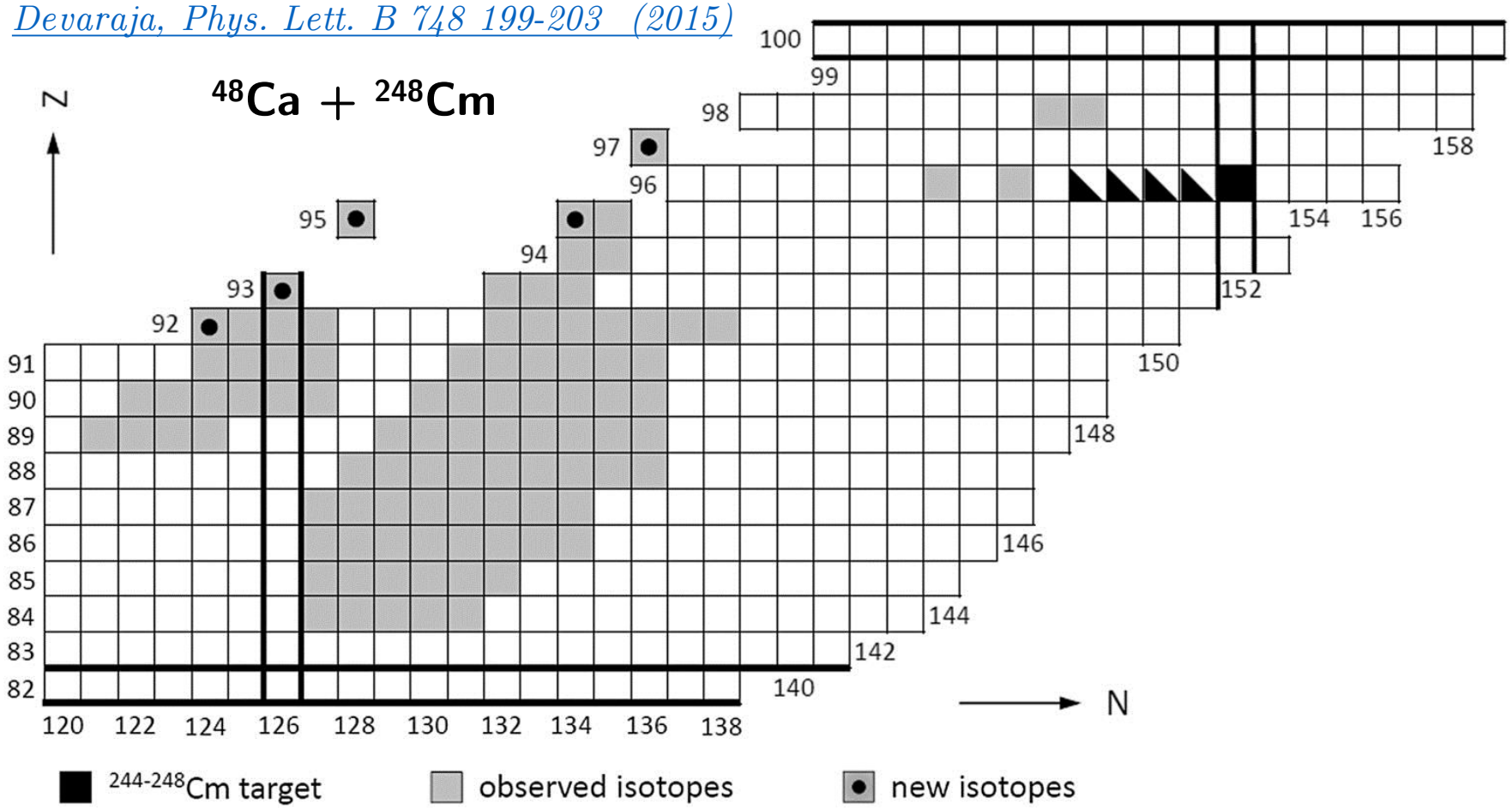


Kratz, Phys. Rev. C 88, 054615 (2013)

Schädel, Phys. Rev. Lett. 48, 852 (1982)

SHIP @ GSI

Devaraja, Phys. Lett. B 748 199-203 (2015)



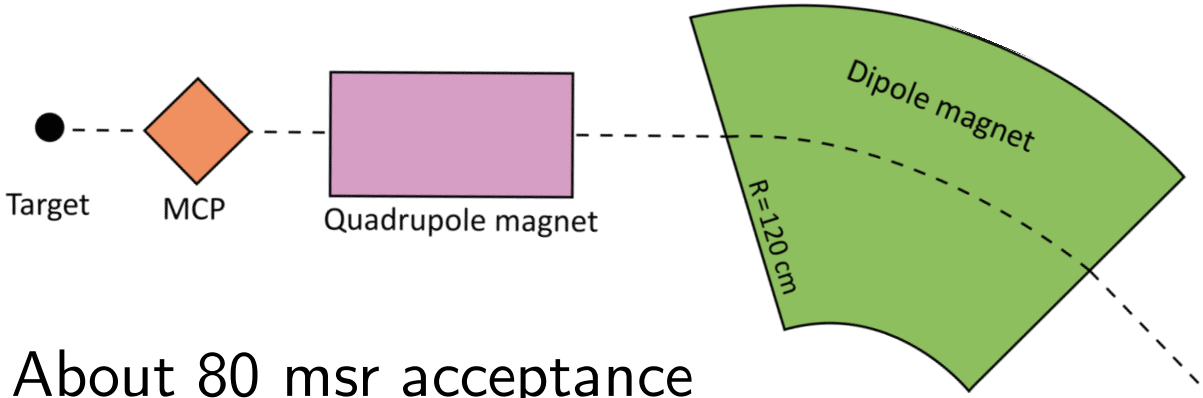
58,64Ni + 207Pb *Comas, Eur. Phys. J. A 49 112 (2013)*

Beliuskina , Eur. Phys. J. A, 50 10 (2014)

Large acceptance magnetic spectrometers

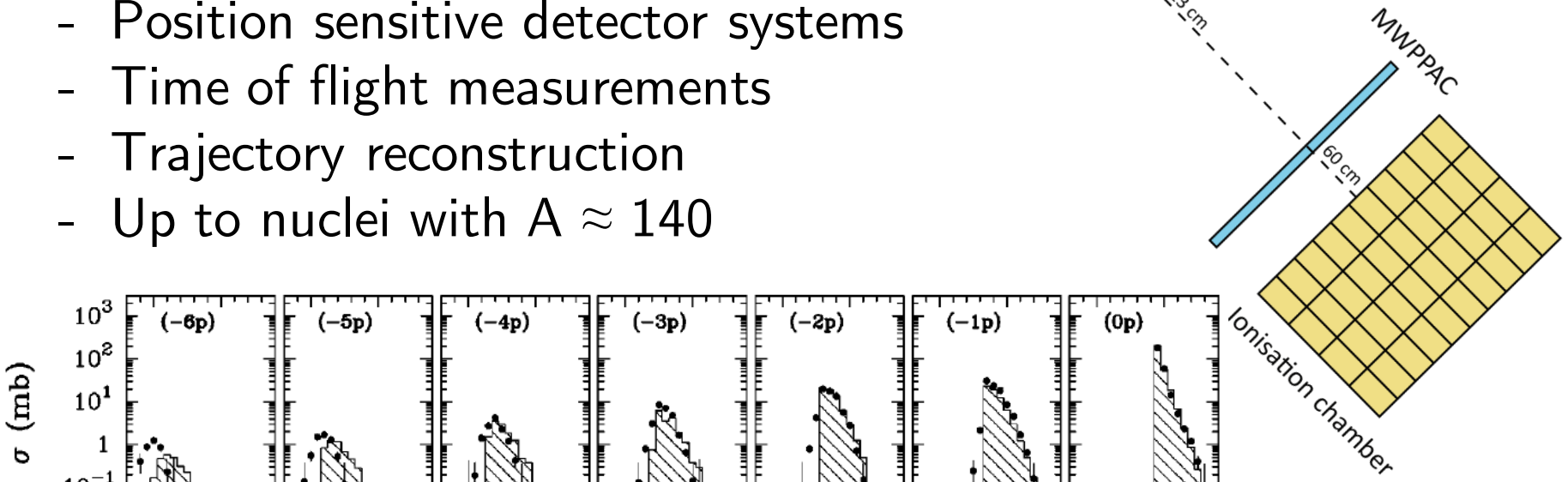
- VAMOS – GANIL, Caen (France)
- PRISMA – INFN, Legnaro (Italy)
- MAGNEX – INFN, Catania (Italy)

PRISMA @ INFN Legnaro



INFN
Istituto Nazionale
di Fisica Nucleare

- About 80 msr acceptance
- Position sensitive detector systems
- Time of flight measurements
- Trajectory reconstruction
- Up to nuclei with A ≈ 140



$^{58}Ni + {}^{208}Pb$

Corradi, Phys. Rev. C 66, 024606 (2002)

Grazing

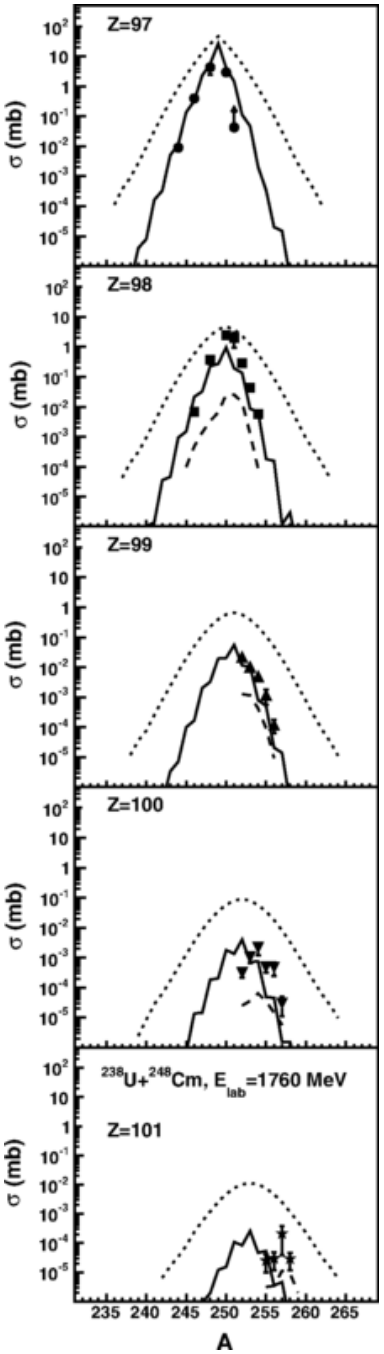
Interactive Fortran code evaluating collisions between heavy nuclei at moderate bombarding energies

- Cross section
  - Mass distribution
  - Charge distribution
  - Kinetic Energies
  - Excitation Energy

*Winther, Nucl. Phys. A **572**, 191 (1994)*
Winther, Nucl. Phys. A 594, 203 (1995)

http://personalpages.to.infn.it/~nanni/grazing/

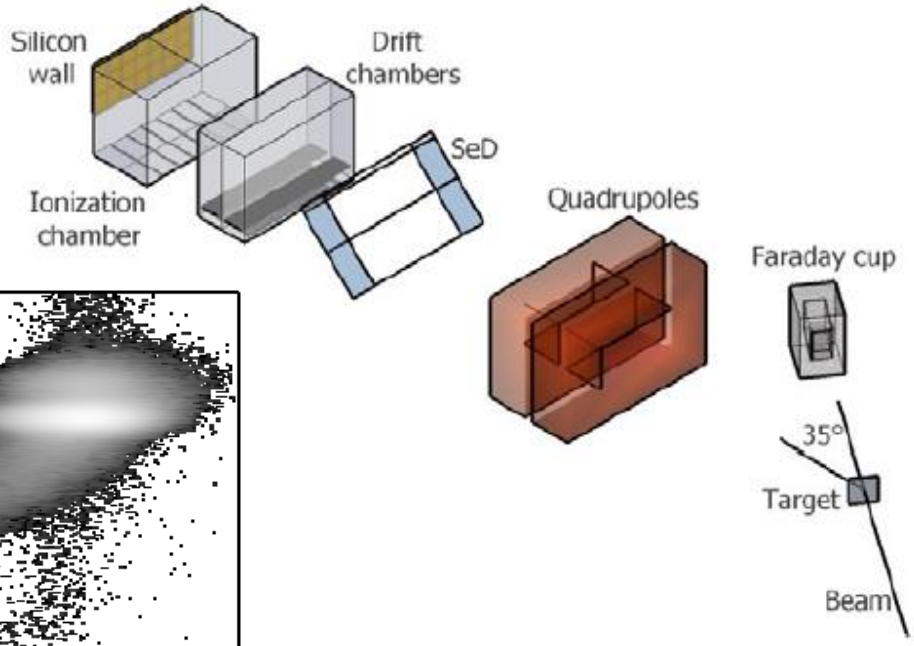
Fission competition included

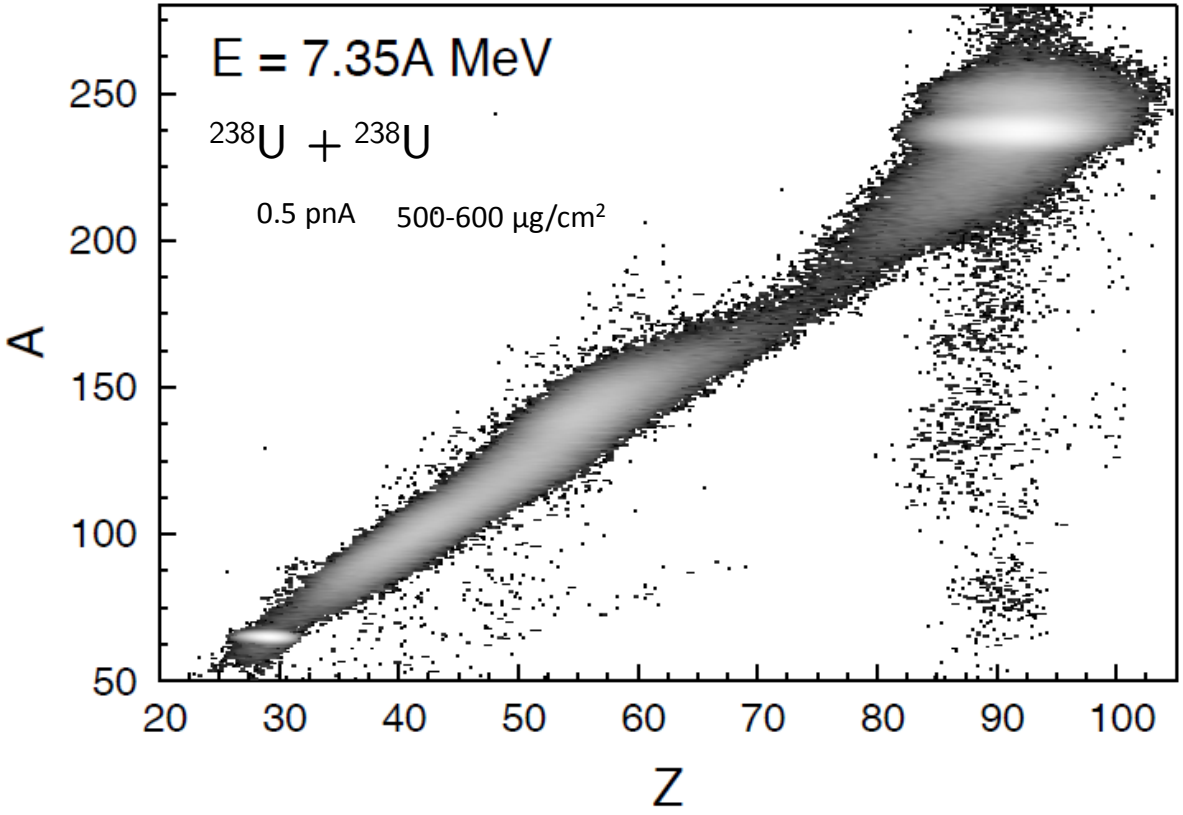


Yanez, Phys. Rev. C 91, 044608 (2015)

VAMOS @ GANIL

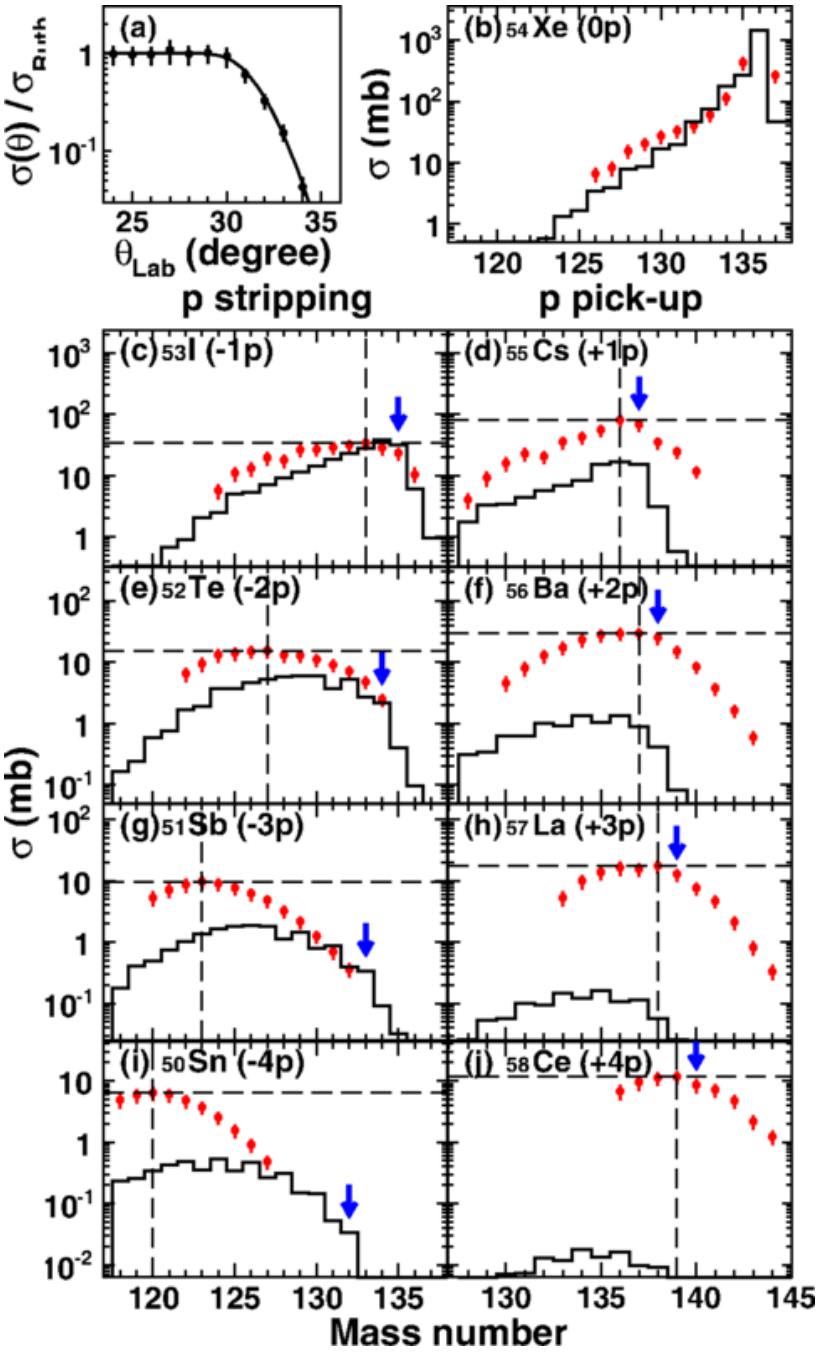
Pure quadrupole mode





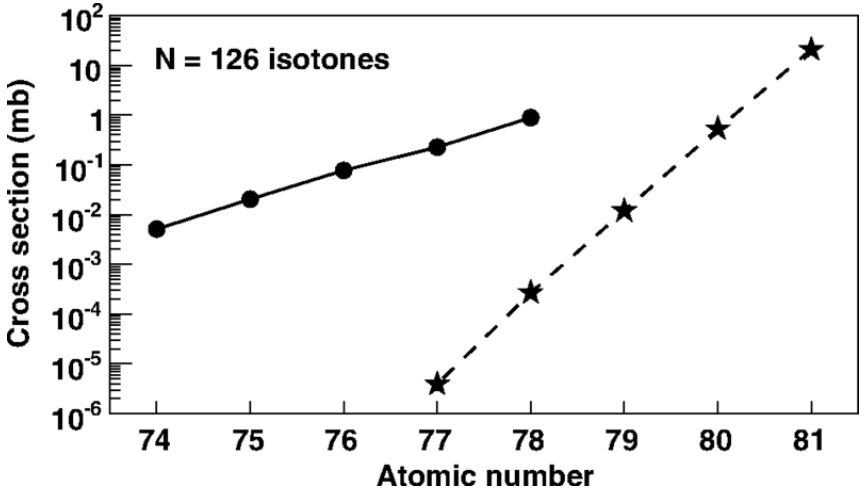
[Golabek, Eur. Phys. J. A 43, 251–259 (2010)]

N = 126 with VAMOS



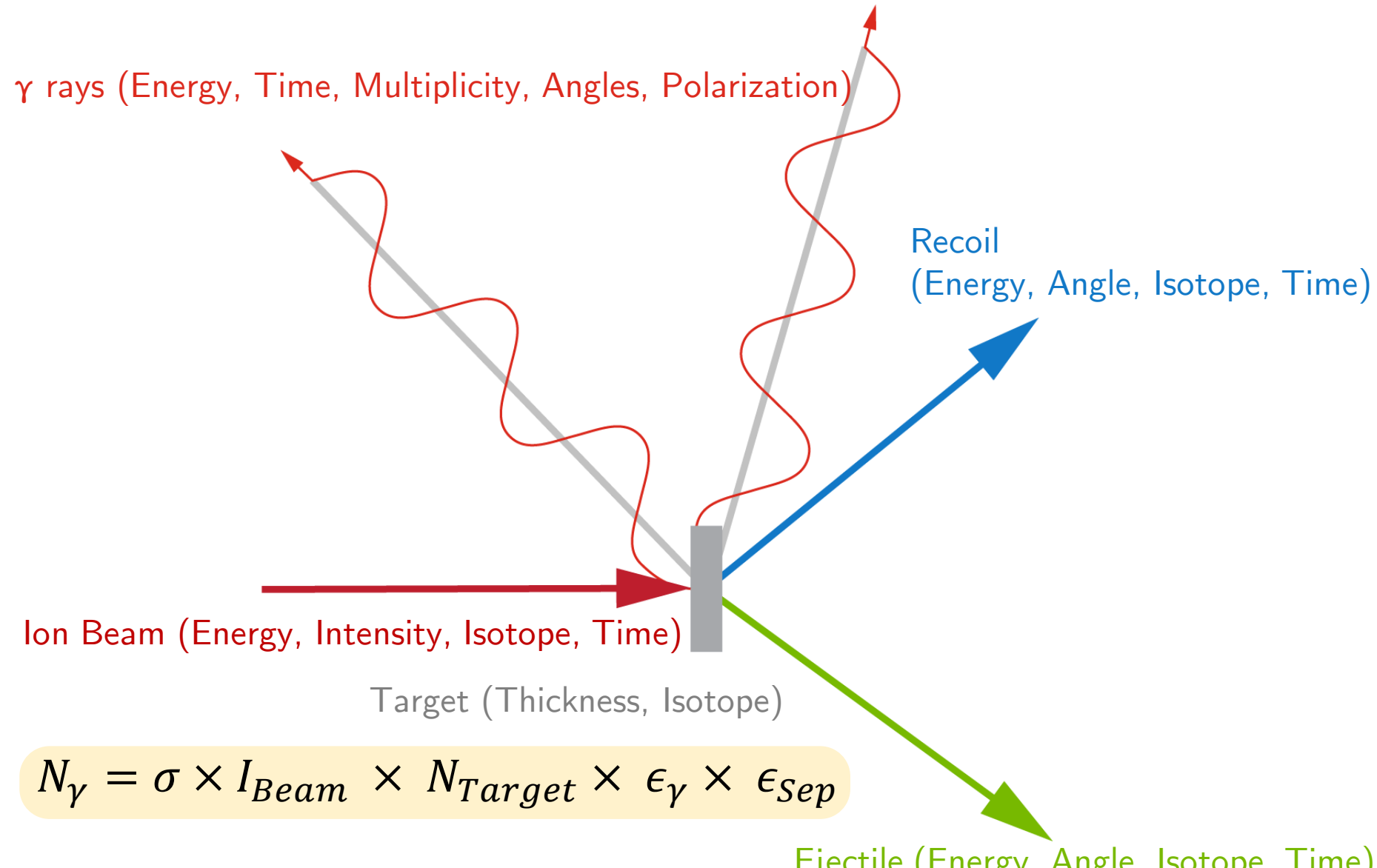
[*Watanabe, Phys. Rev. Lett. 115, 172503 (2015)*]

136Xe + 198Pt
8MeV / u



Prompt γ-ray spectroscopy

Prompt γ-ray spectroscopy

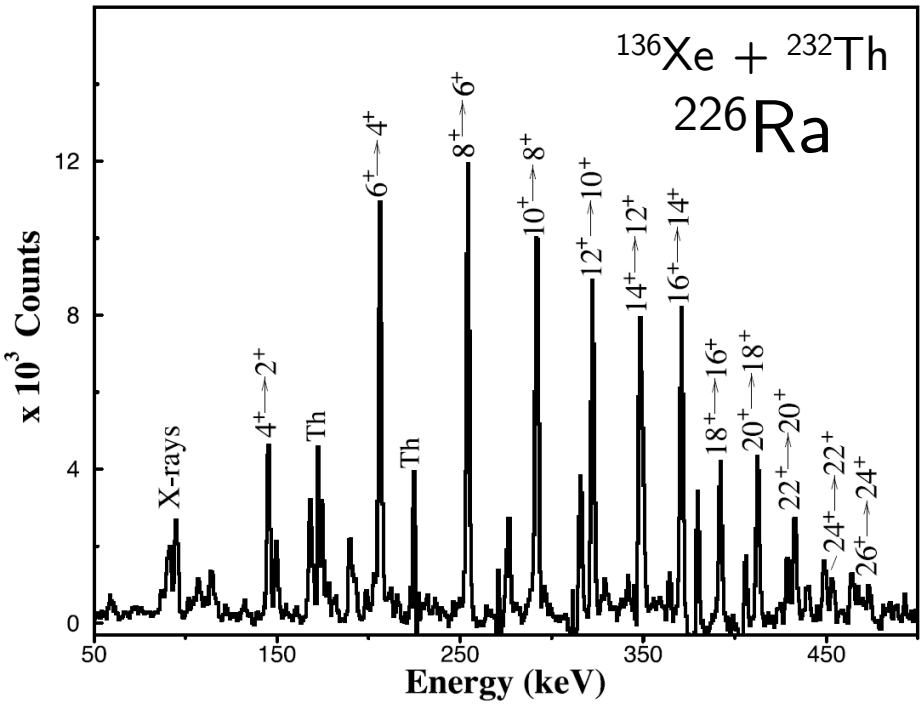


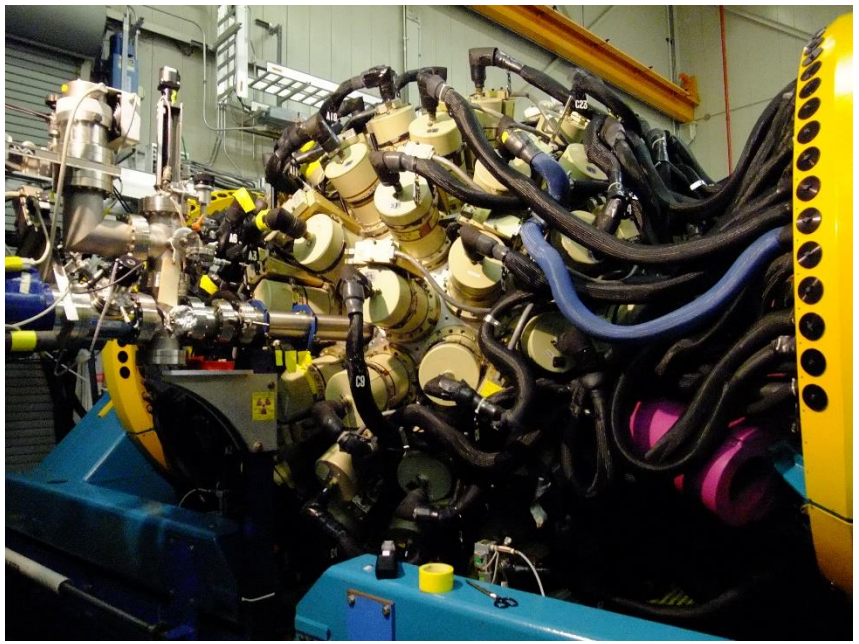
$$N_\gamma = \sigma \times I_{Beam} \times N_{Target} \times \epsilon_\gamma \times \epsilon_{Sep}$$

Thick target $\gamma\gamma(\gamma)$ experiments

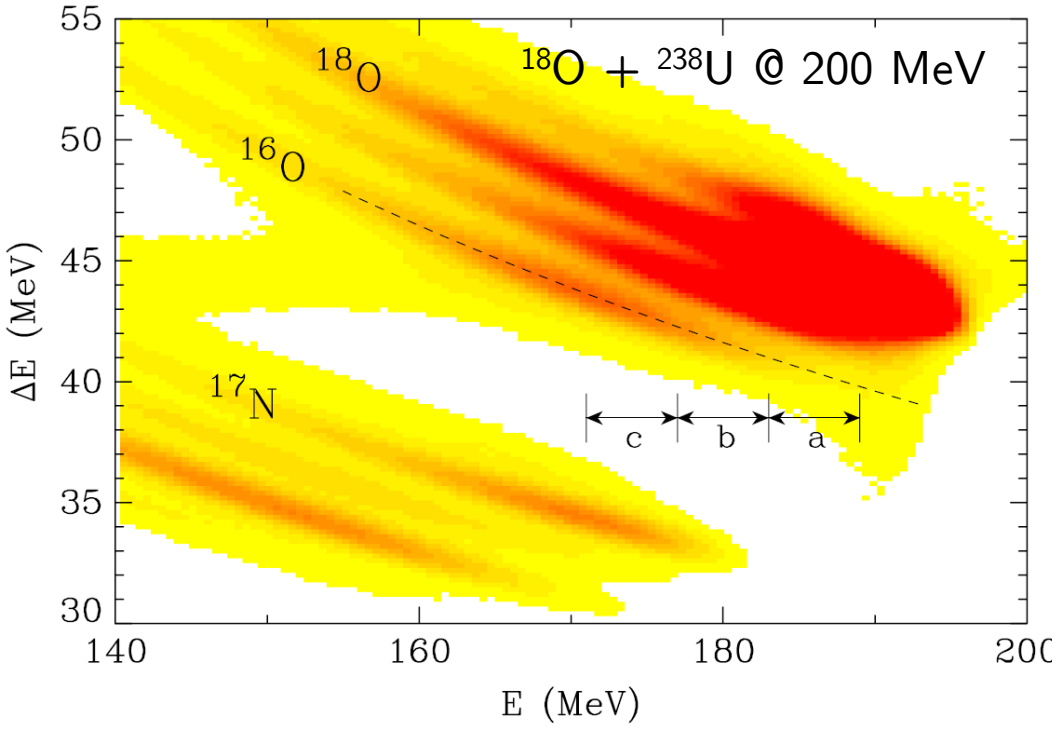
Abstract. Multi-nucleon transfer reactions have been shown to be an important tool for high-spin spectroscopic studies of Rn, Ra and Th nuclei with $N \simeq 134$. These nuclei have been populated using the heavy-ion collisions of ^{56}Fe + ^{232}Th, ^{86}Kr + ^{232}Th and ^{136}Xe + ^{232}Th at beam energies 15–20% above the Coulomb barrier. Excited states with spins as high as $28\hbar$ have been observed using the latter reaction. Yield distributions of binary-reaction products stopped in thick targets have been derived from the analysis of γ–γ and γ–γ–γ coincidence events. These yields indicate that there is significant fission of the target-like reaction products. Intensities deduced for products resulting from neutron transfer or proton transfer appear to be Q-value dependent, while processes involving transfers of several protons and neutrons are governed by mass and charge equilibration.

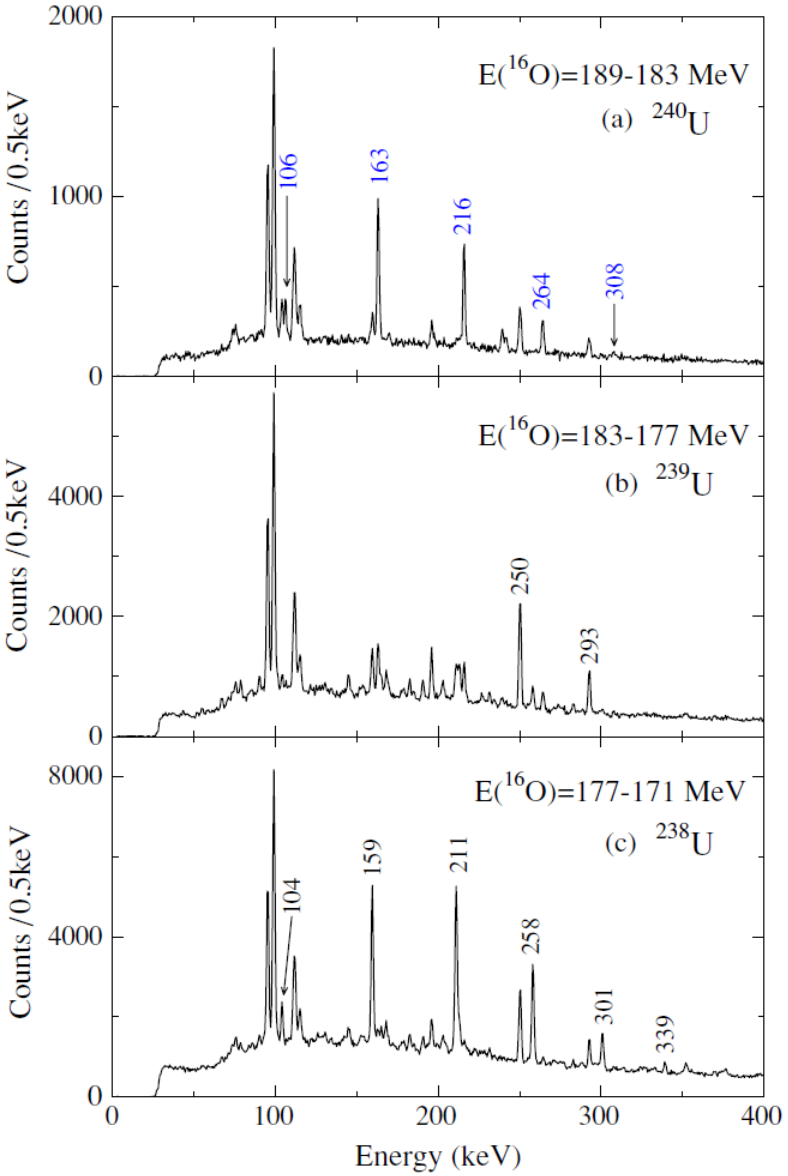
Cocks, J. Phys. G: Nucl. Part. Phys. 26 (2000)





Lighter Ions identified in ΔE - E





Ishii, Phys. Rev. C 72, 021301(R) (2005)

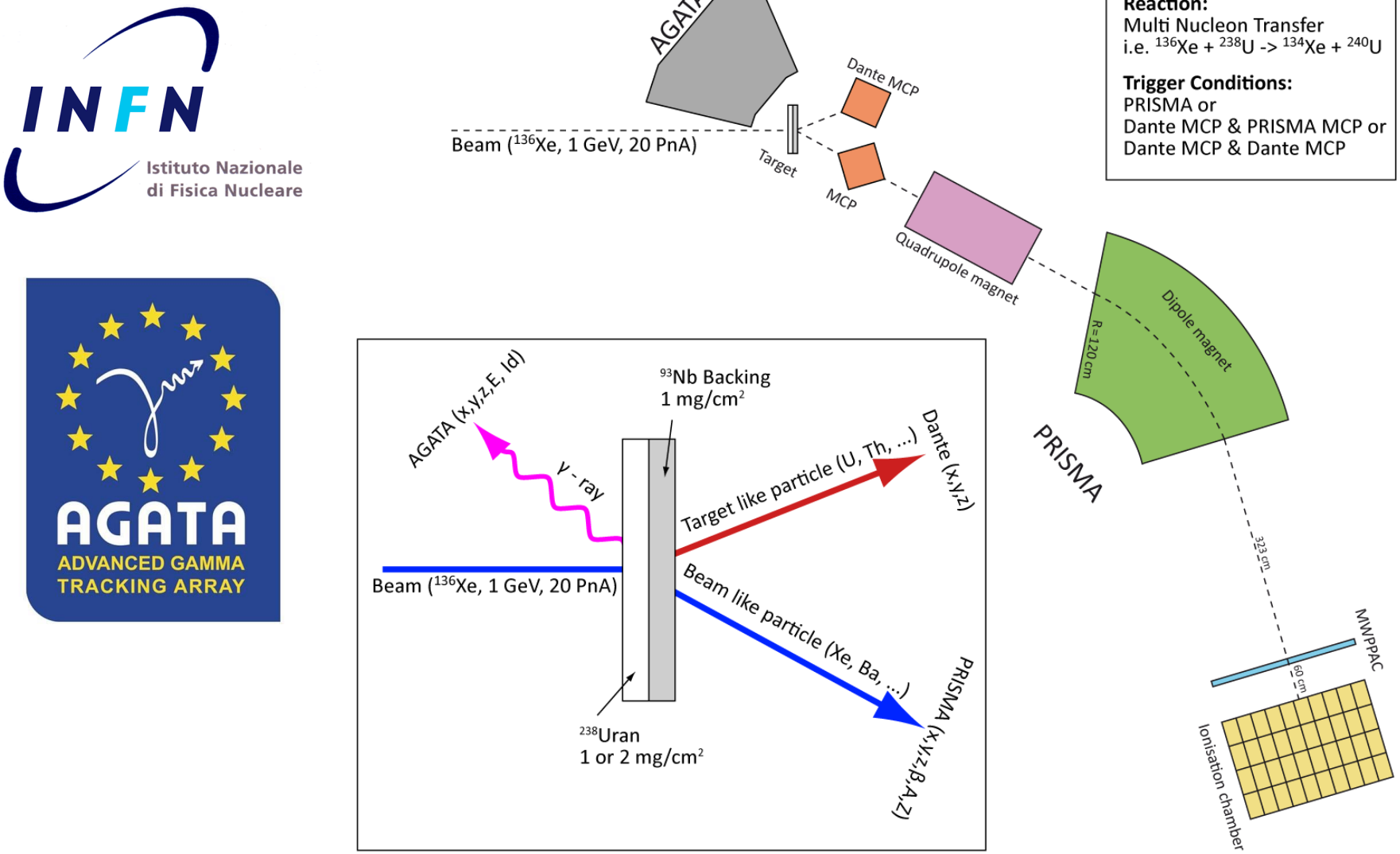
^{242}U and ^{236}Th, ^{249}Cm, $^{248, 250, 252}$Cf

Ishii, Phys. Rev. C 76, 011303(R) (2007)

Ishii, Phys. Rev. C 78, 054309 (2008)

Takahashi, Phys. Rev. C 81, 057303(R) (2010)

Heavy Ions with thin targets and particle identification

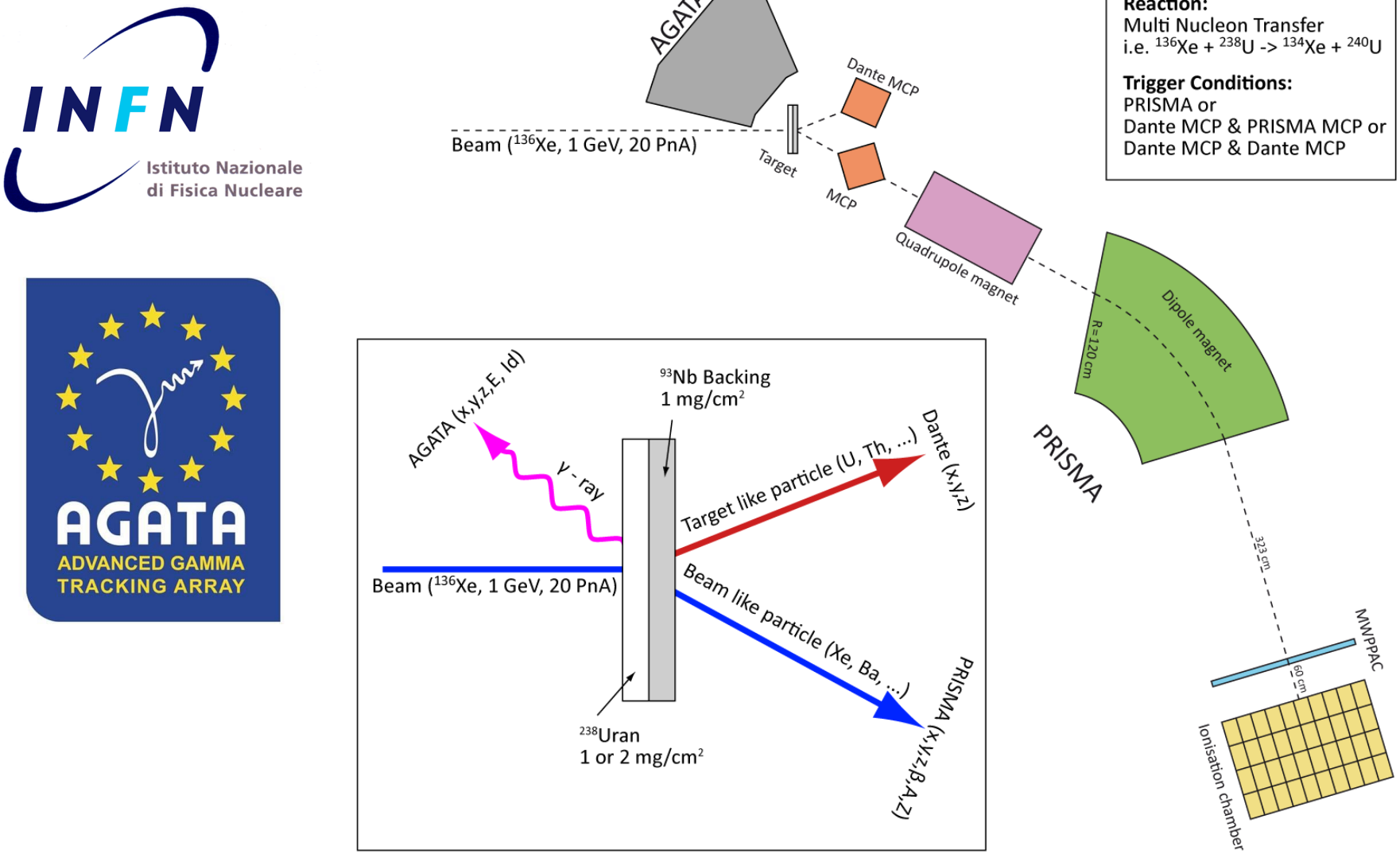


AGATA

- Advanced Gamma Tracking Array
  Bazzacco, Nucl. Phys. A 746 (2004) 248-254
  Akkoyun, Nucl. Instrum. Meth. A 668 (2012) 26
- 8 Triple cryostats / 24 capsules
  Wiens, Nucl. Instrum. Meth. A 618 (2010) 99
- Full digital electronics
- Online PSA and Tracking
- High resolution position sensitive γ ray spectroscopy
- High count rate capabilities

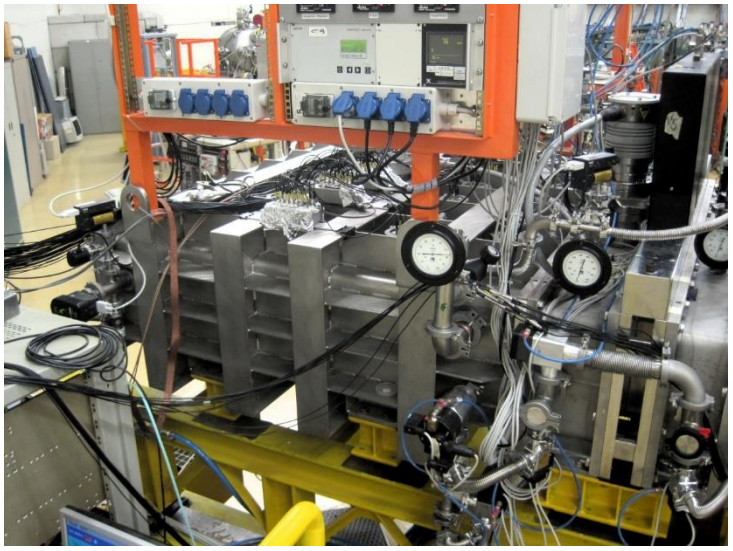
GANIL
laboratoire commun CEA/DSM spiral2 CNRS/IN2P3

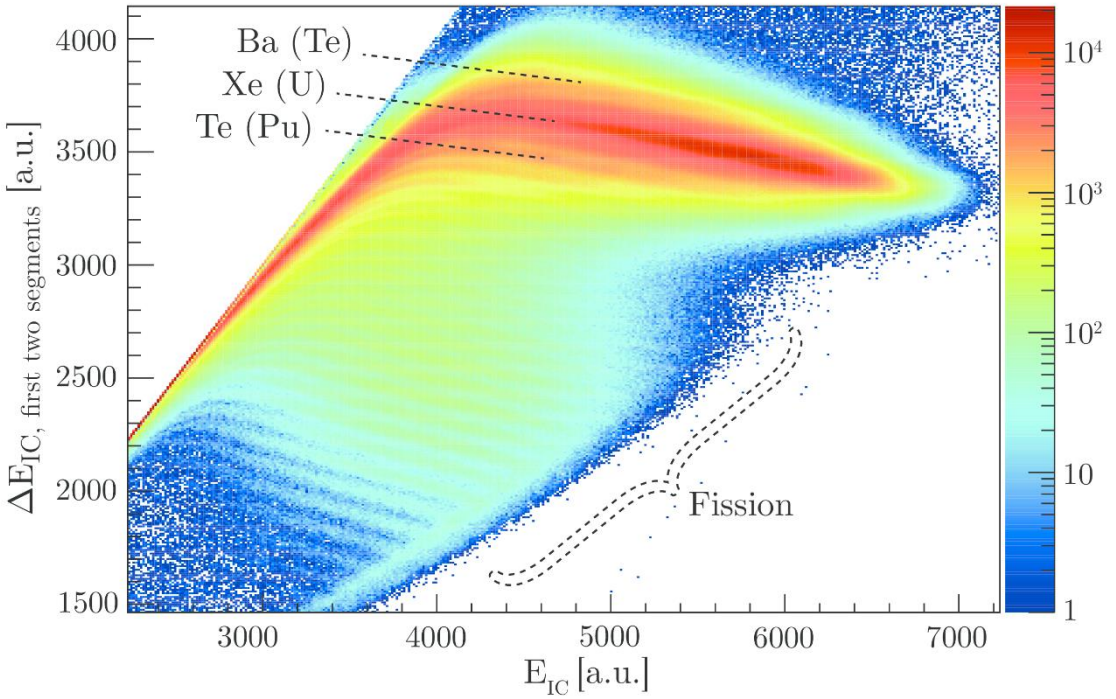
Heavy Ions with thin targets and particle identification

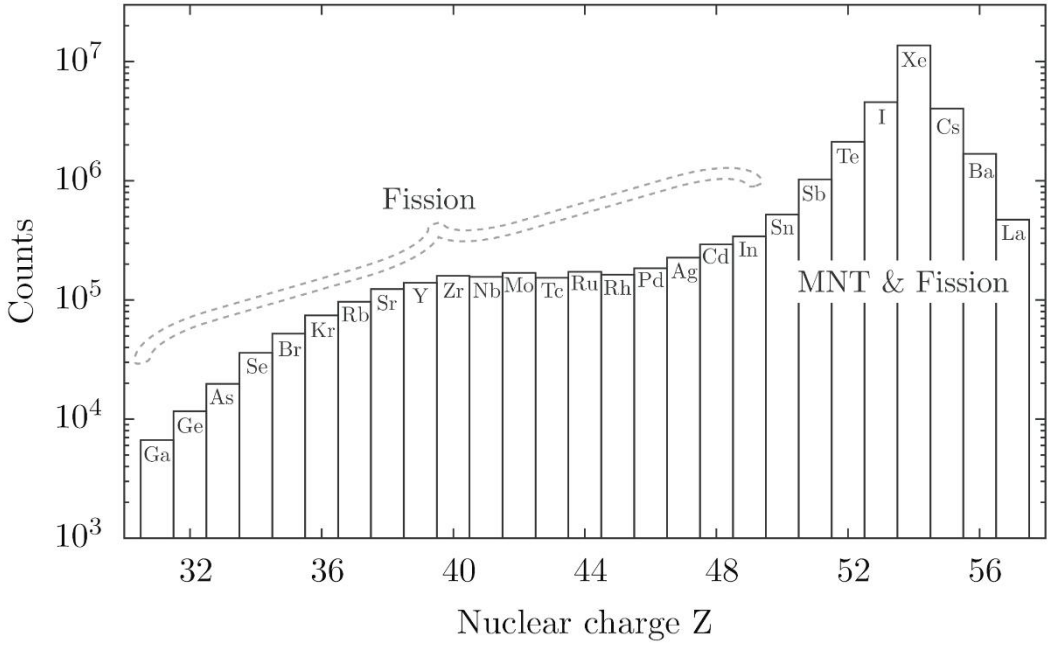


Identifcation of nuclear charge Z

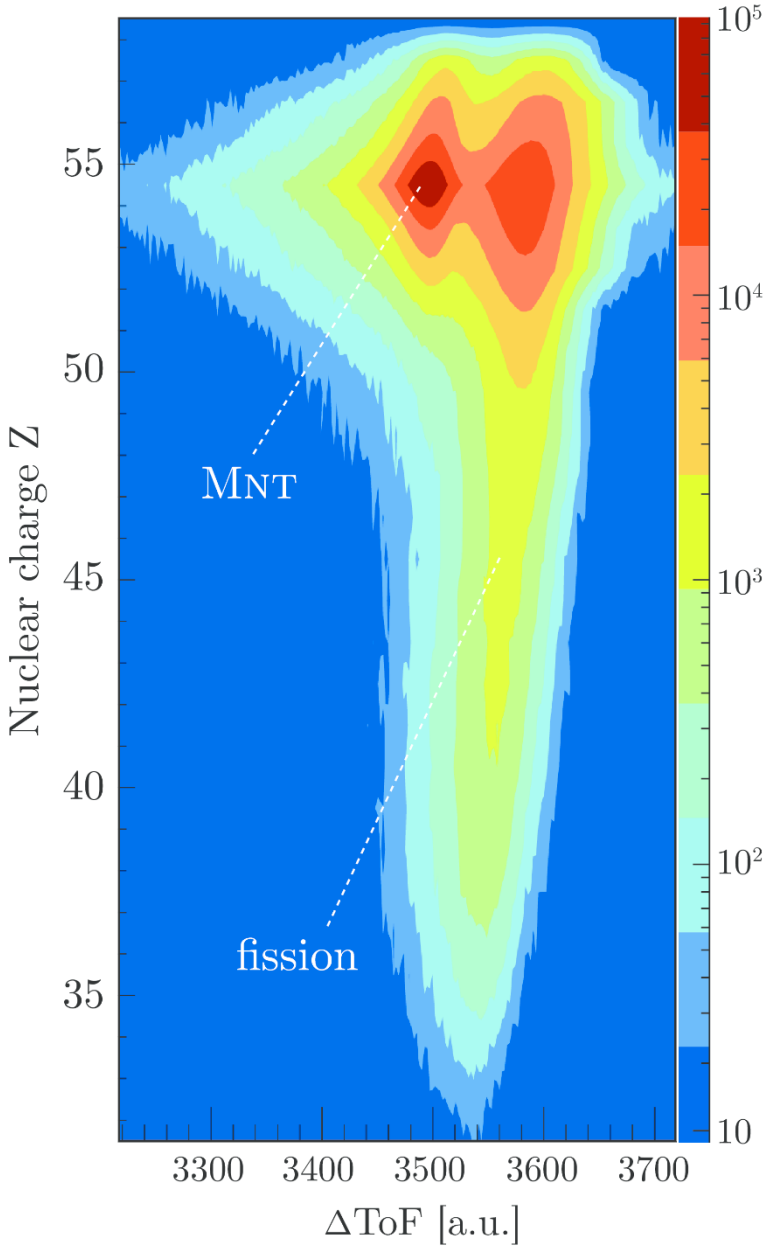
- ΔE – E from the segmented IC (two sets of ΔE were used)
- Lighter / beam-like particles
- Fission and MNT are registered
- Resolution $Z/\Delta Z = 52.7(1)$ (huge yield of Xe isotopes)

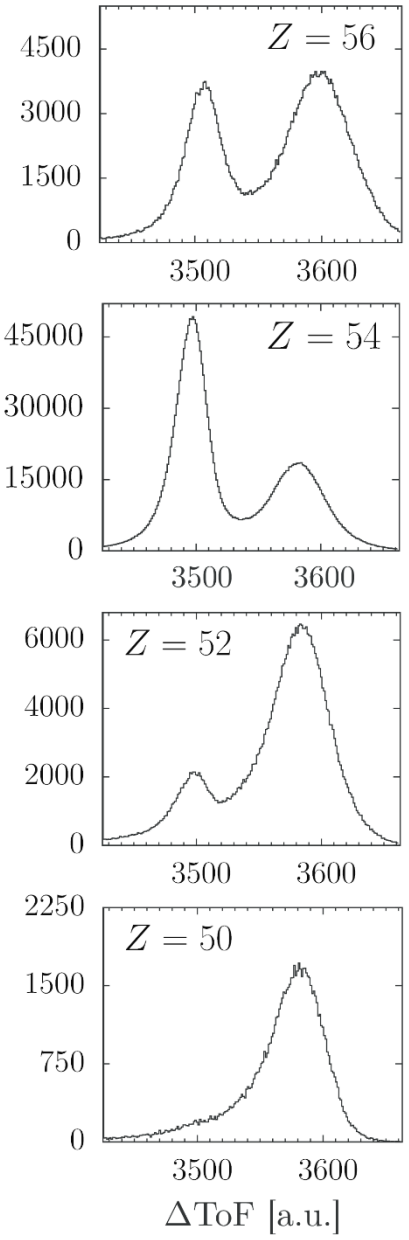


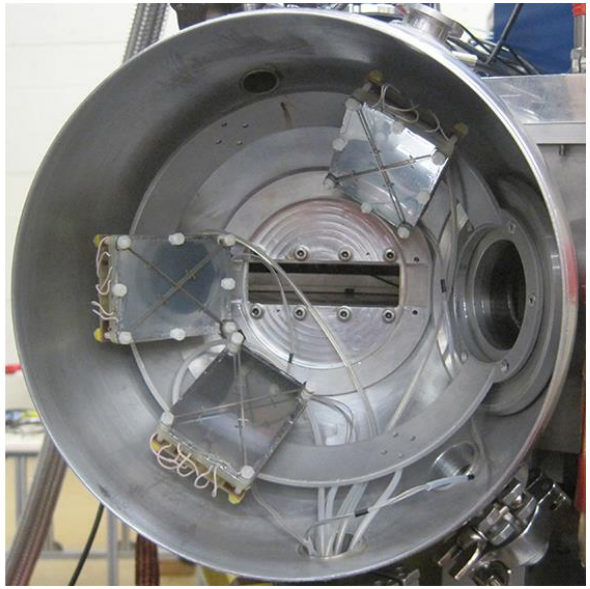


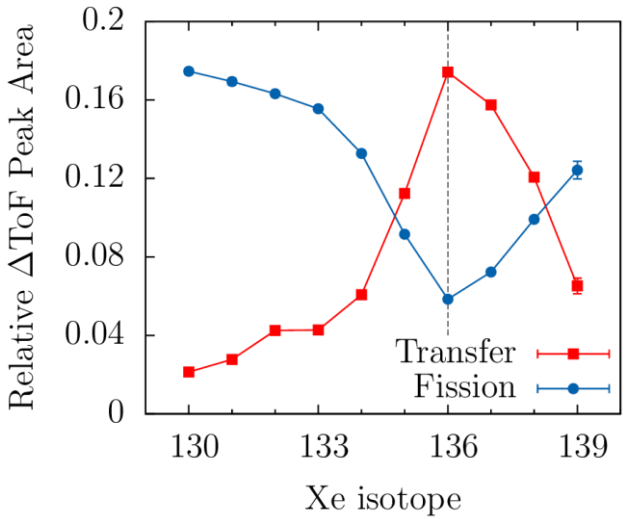


Discriminate between fission and MNT

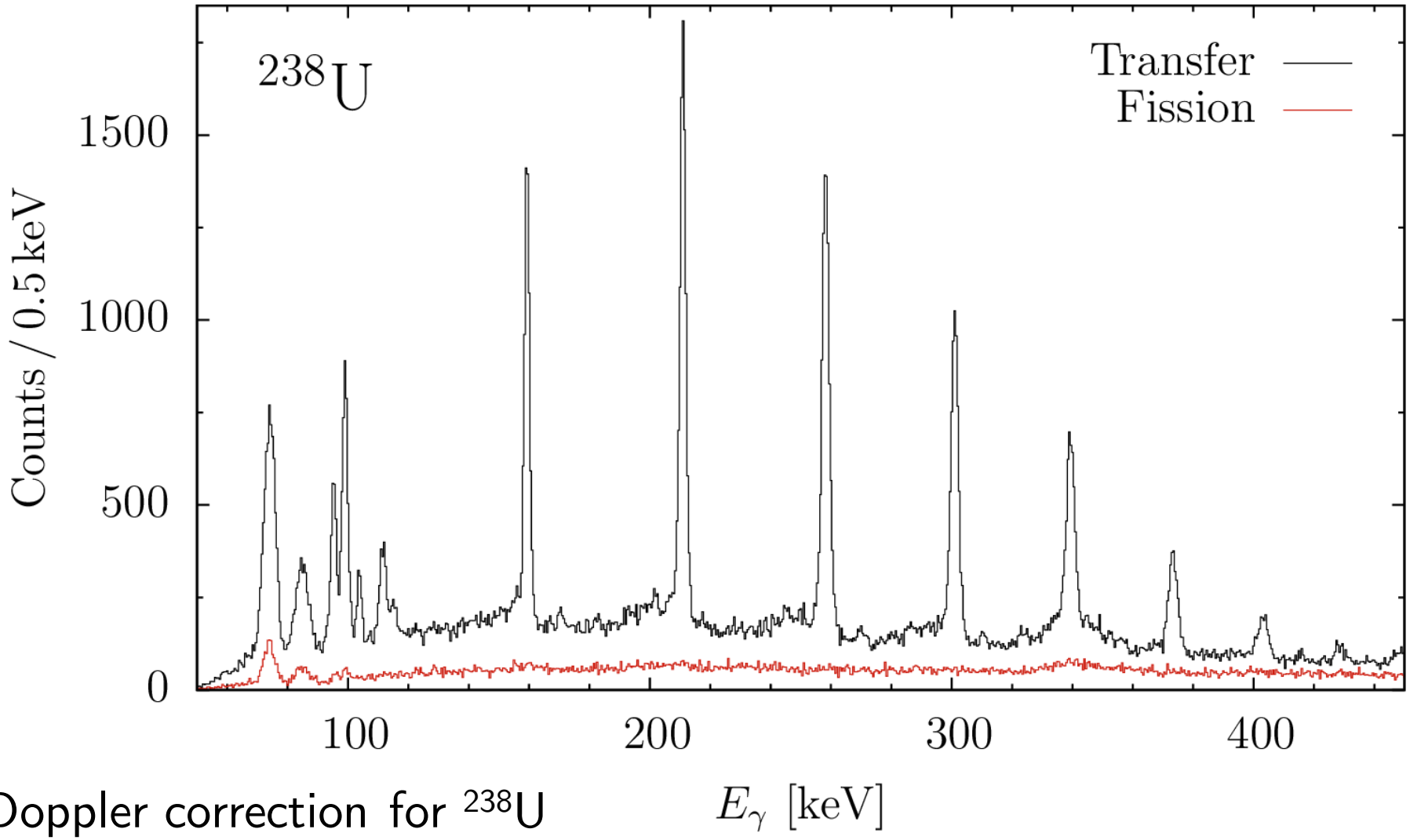








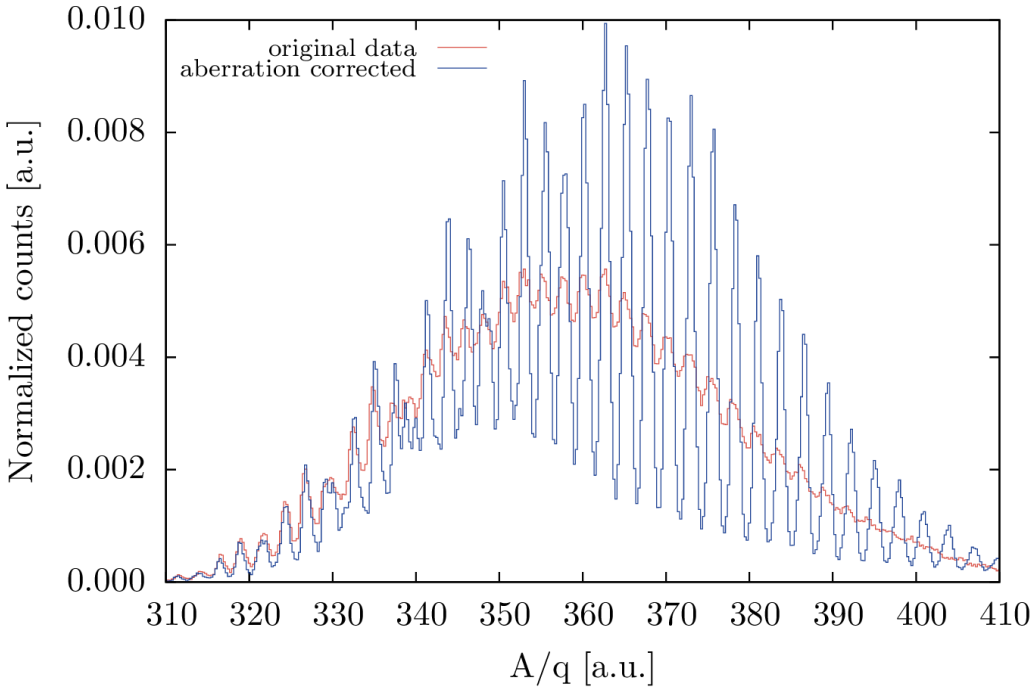
Discriminate between fission and MNT



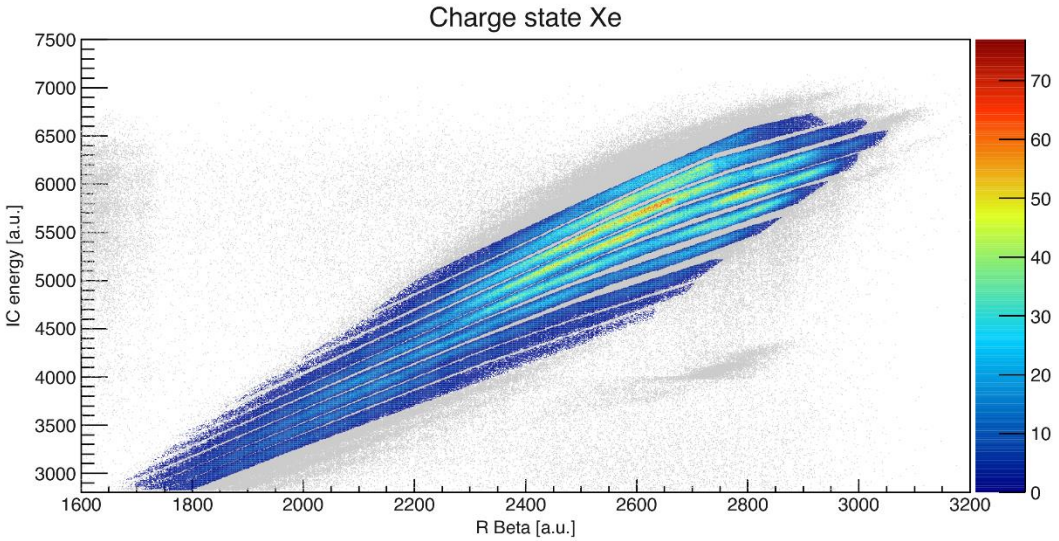
Doppler correction for ^{238}U

Particle gate on ^{136}Xe

Mass identification

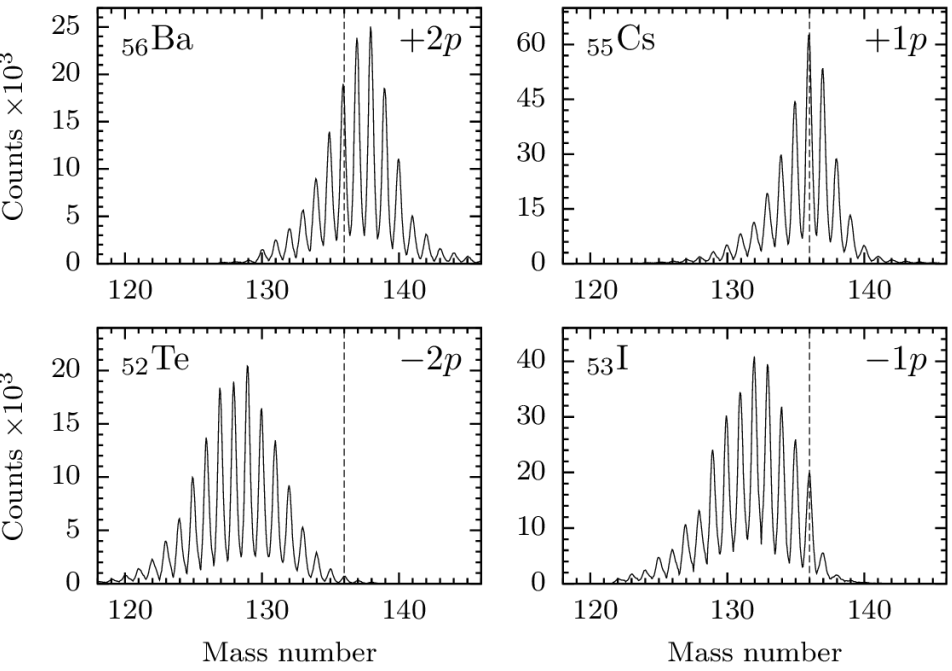


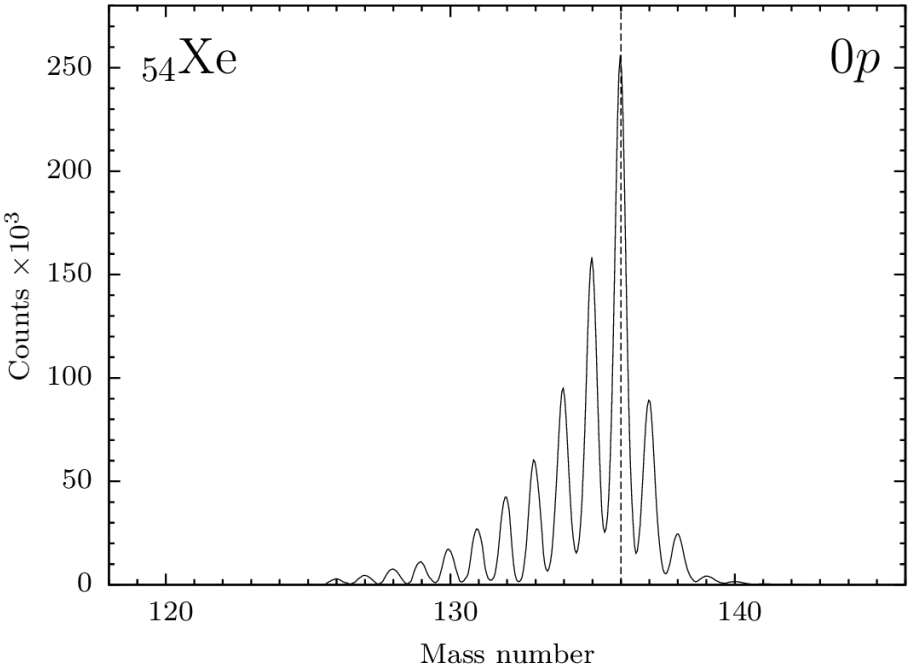
$$A/q = B \times R \frac{t}{l}$$

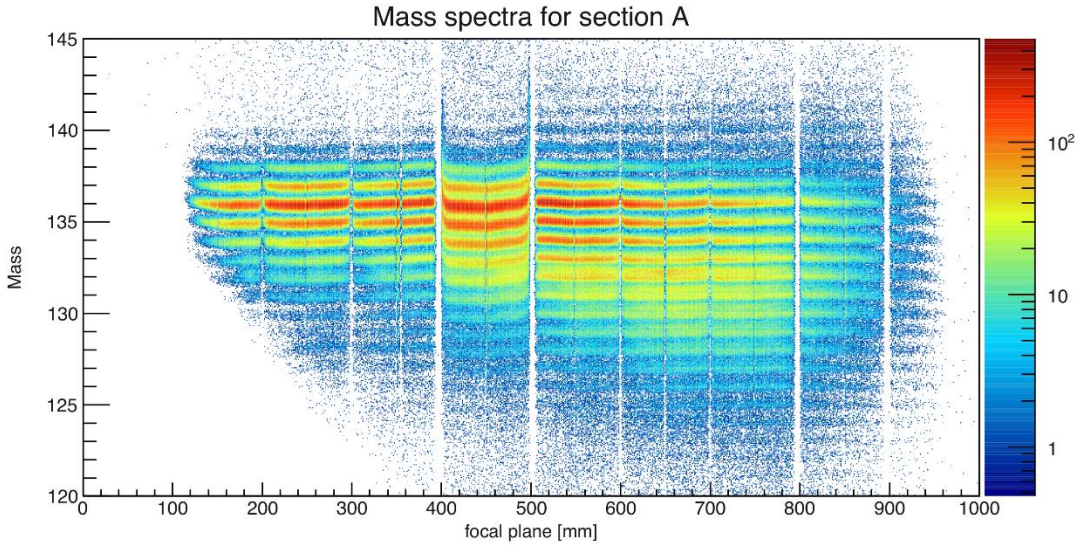


$$E/R\beta \sim q$$

Mass identification

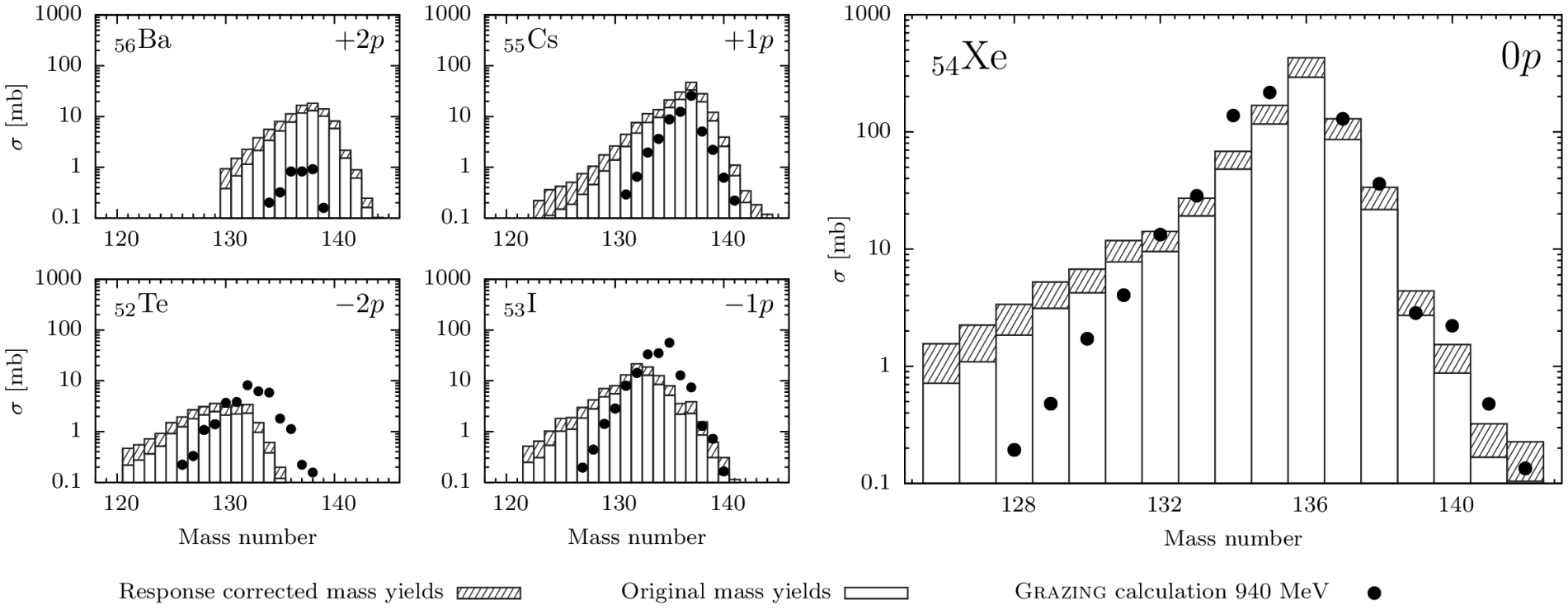




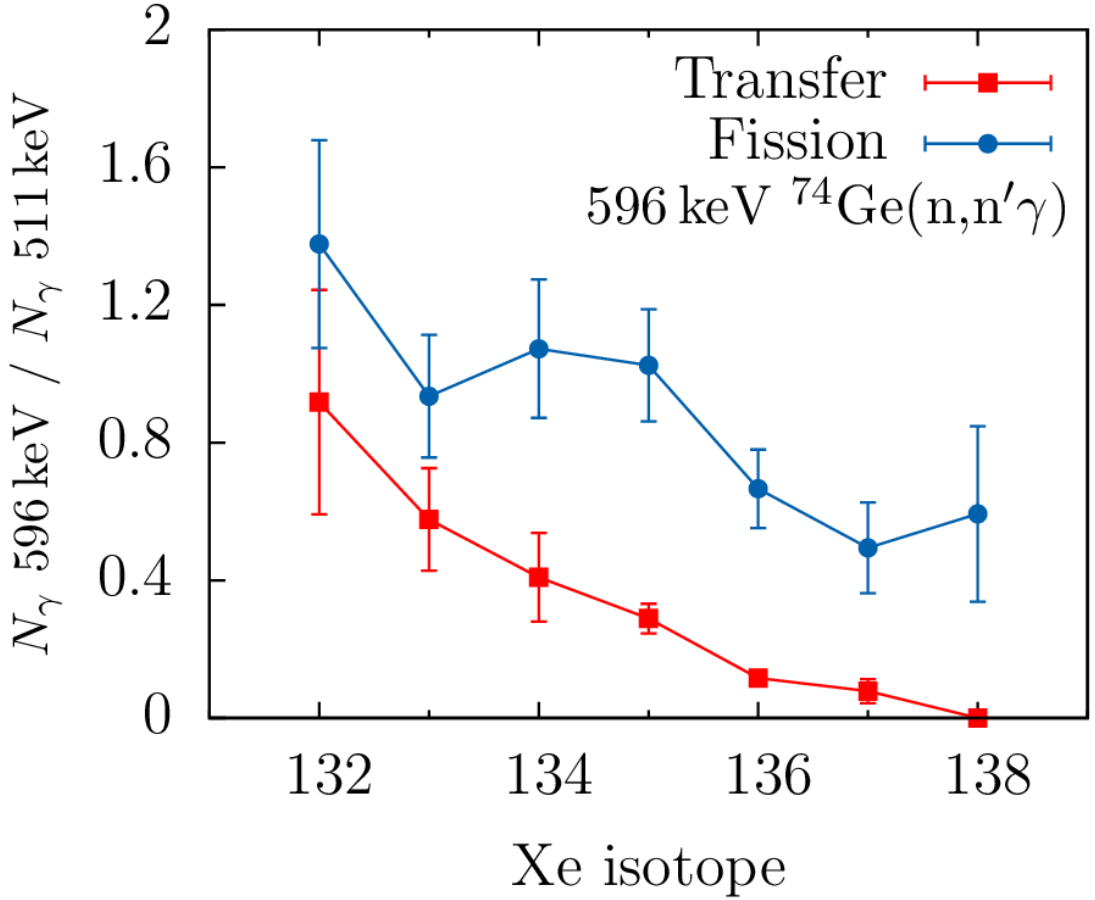


$$A/\Delta A \cong 300$$

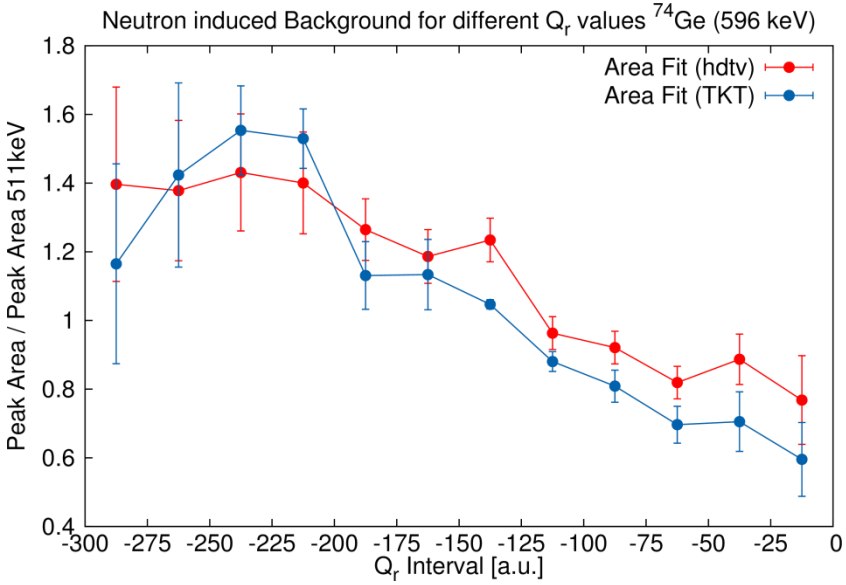
Compare results with calculations

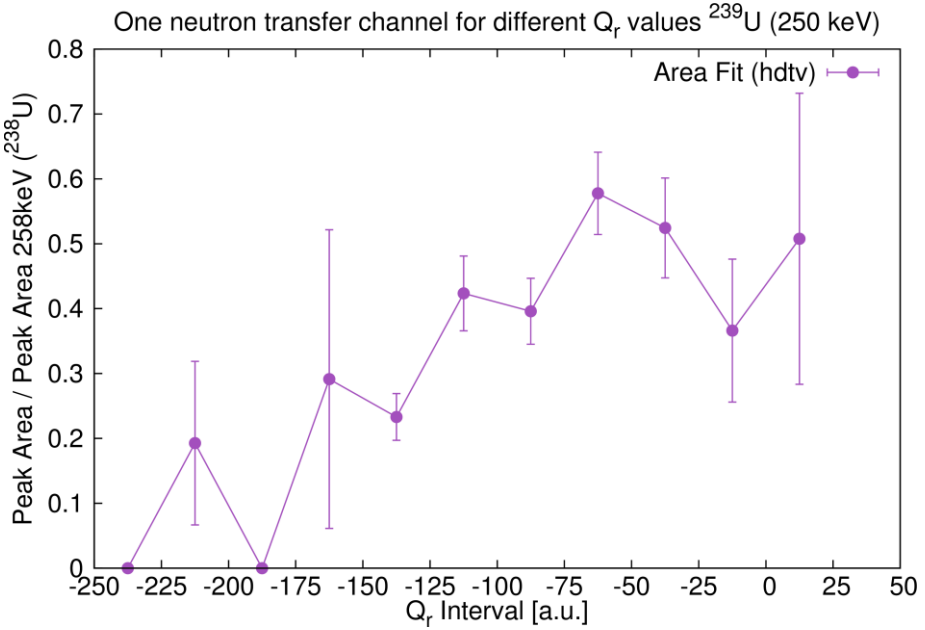


Neutron evaporation

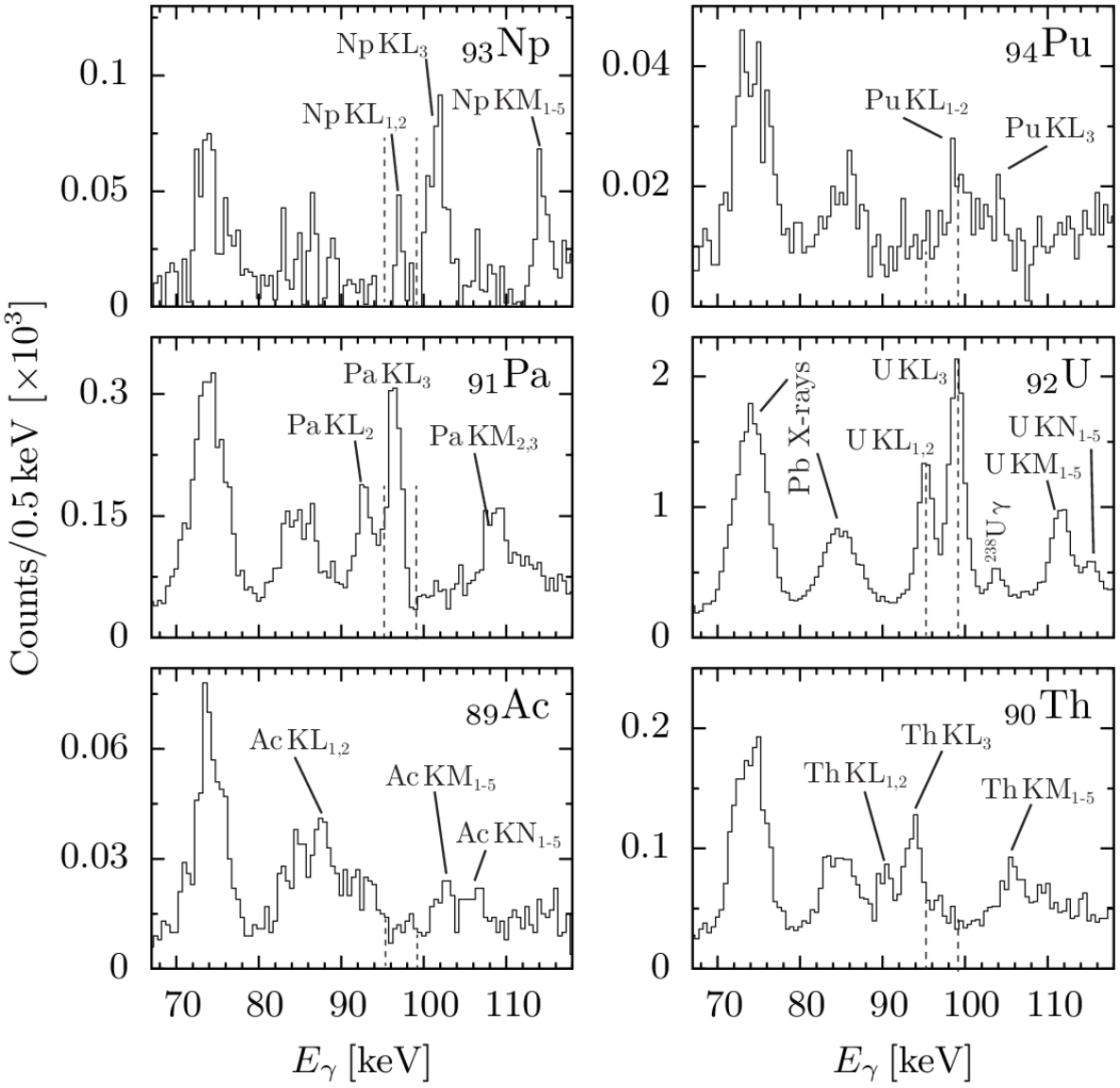


Suppression of Neutron evaporation

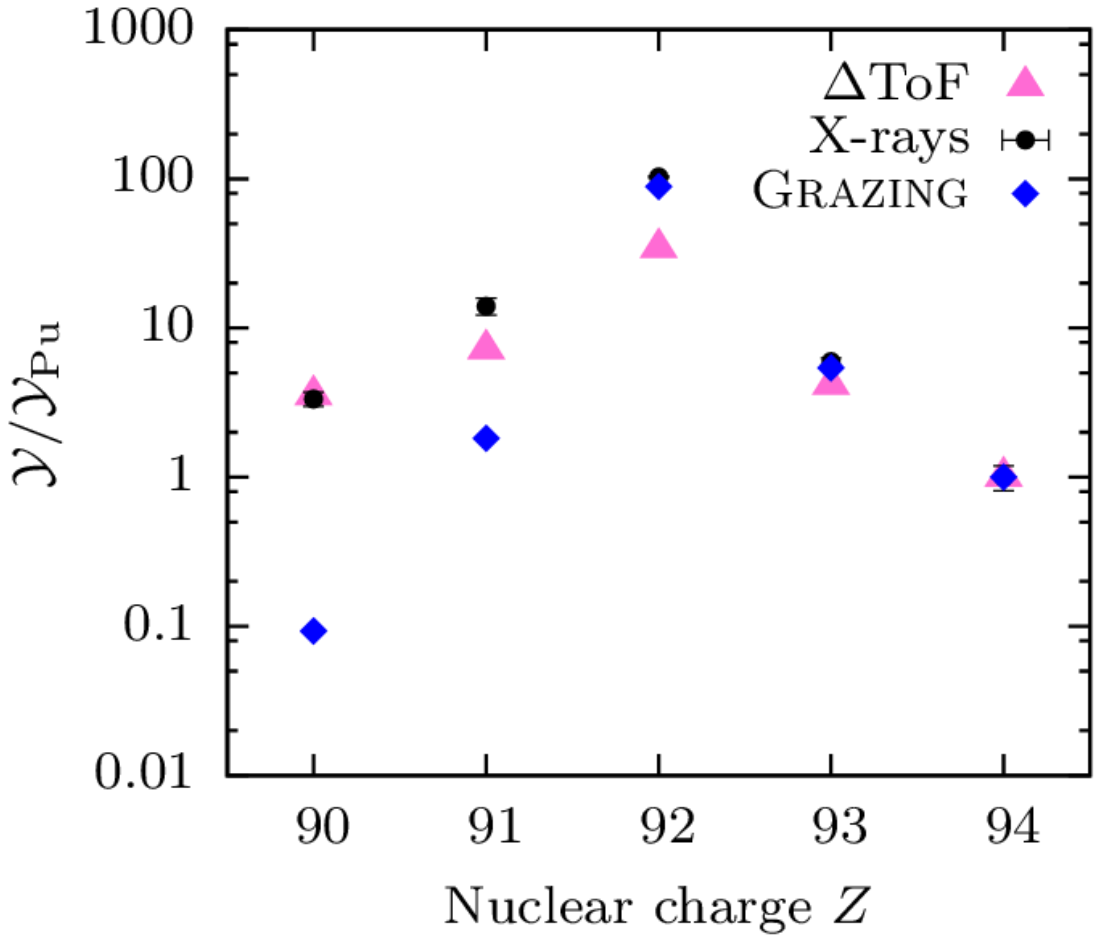




X ray spectroscopy

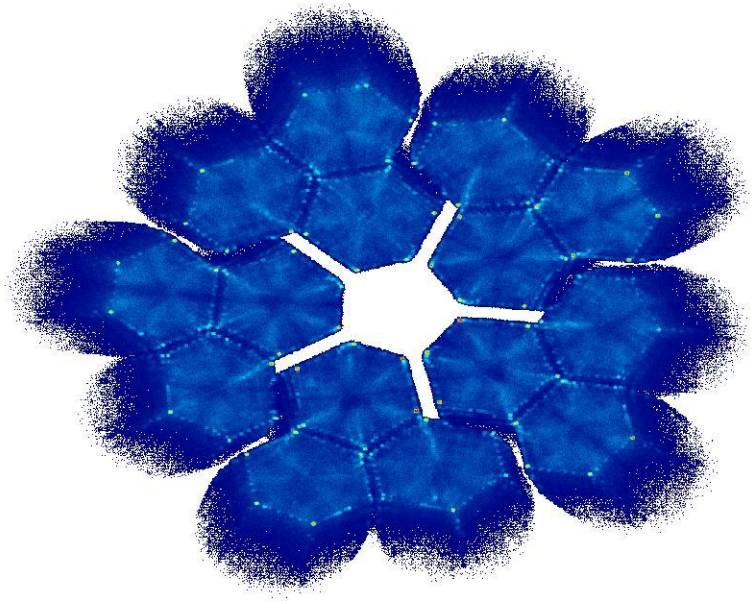


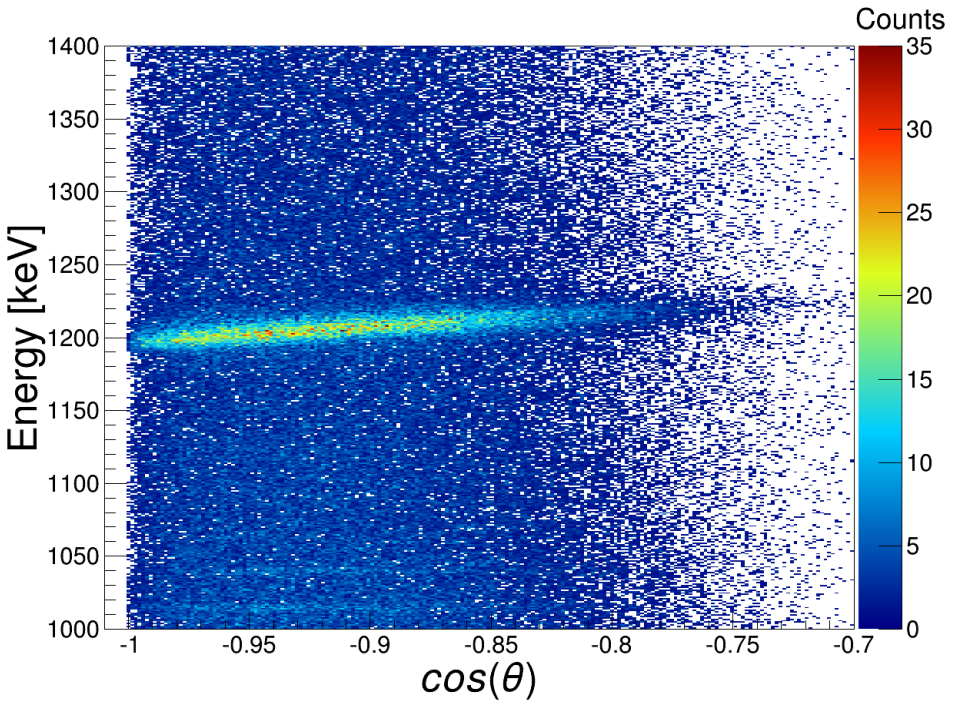
Comparison

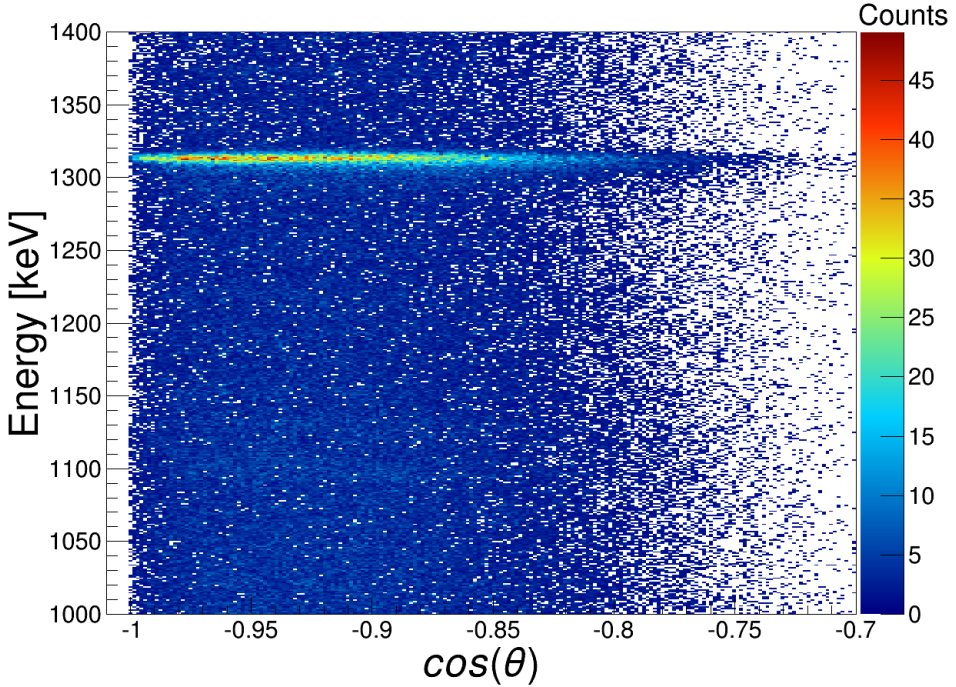

1000
100
10
1
0.1
0.01
90
91
92
93
94
$\mathcal{Y}/\mathcal{Y}_{\mathrm{Pu}}$
Nuclear charge Z
ΔToF
X-rays
GRAZING

Gamma Ray Spectra

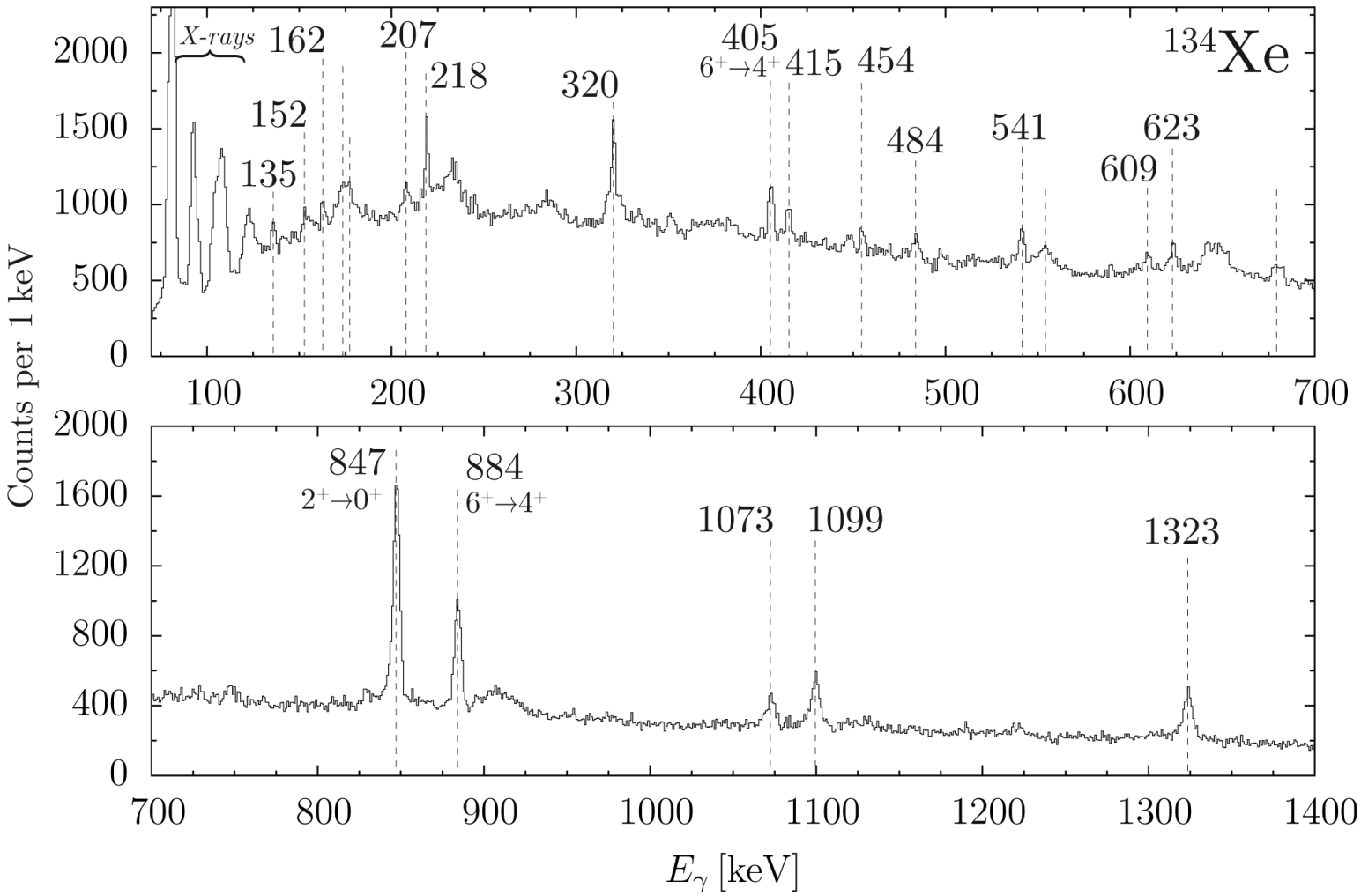
- Doppler Correction needed (β ~ 9%)
- Ejectile velocity given by PRISMA
- Recoil velocity calculated
- Gamma direction by AGATA



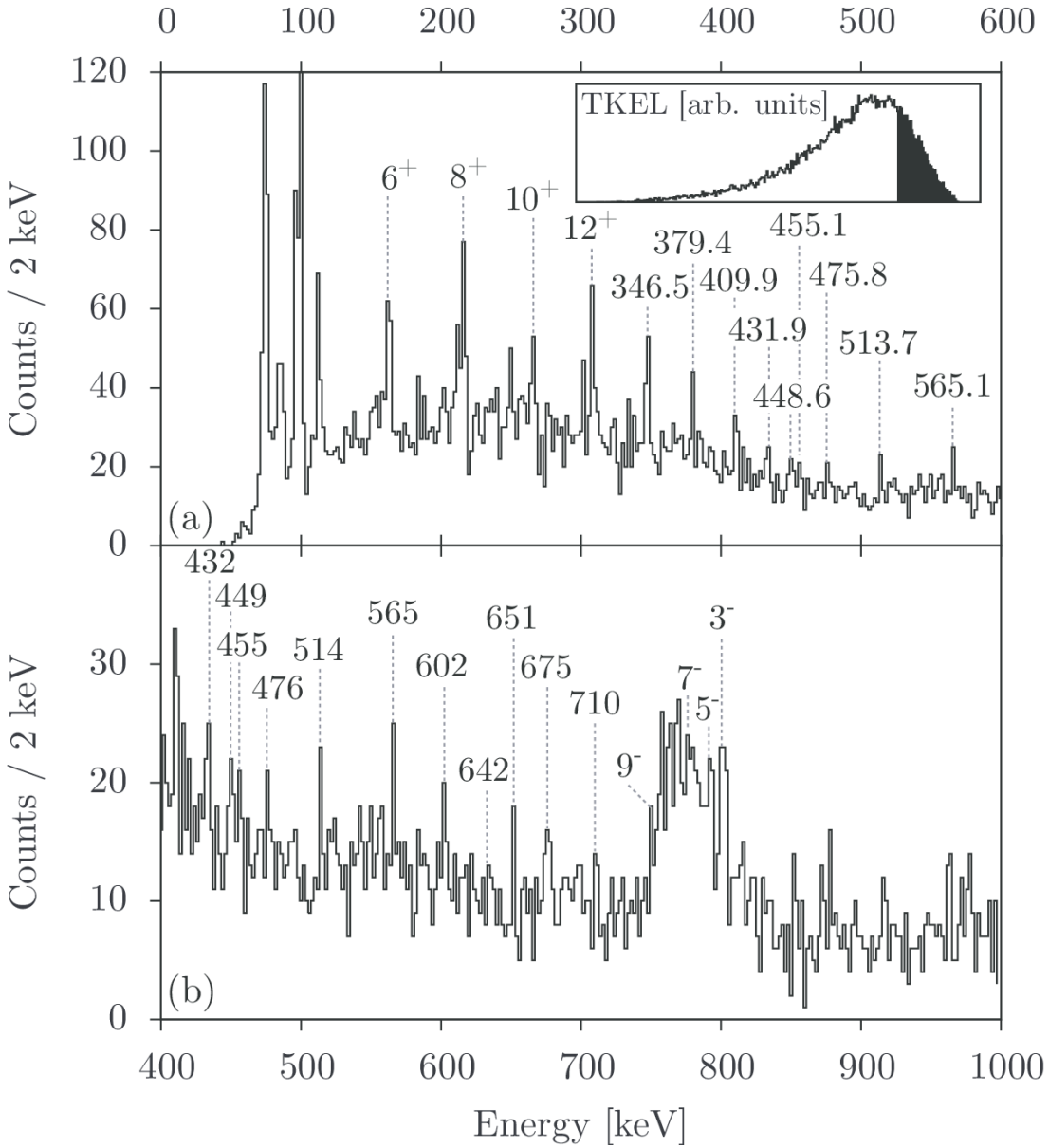


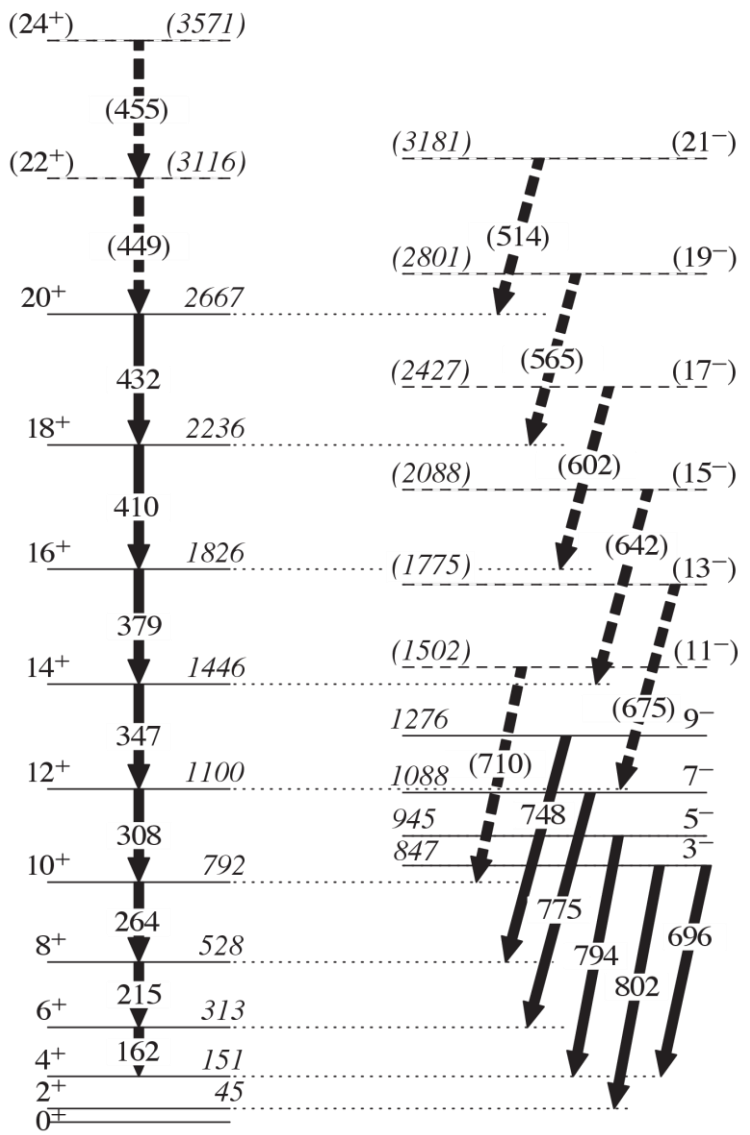


Spectrum of ^{134}Xe

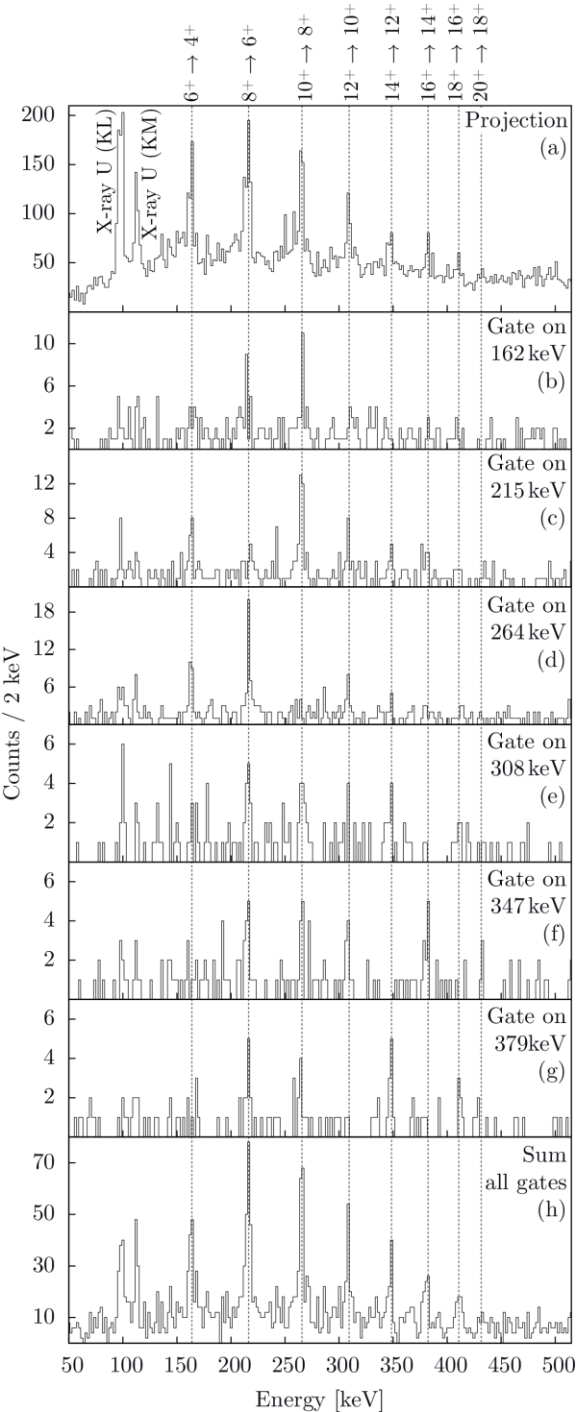


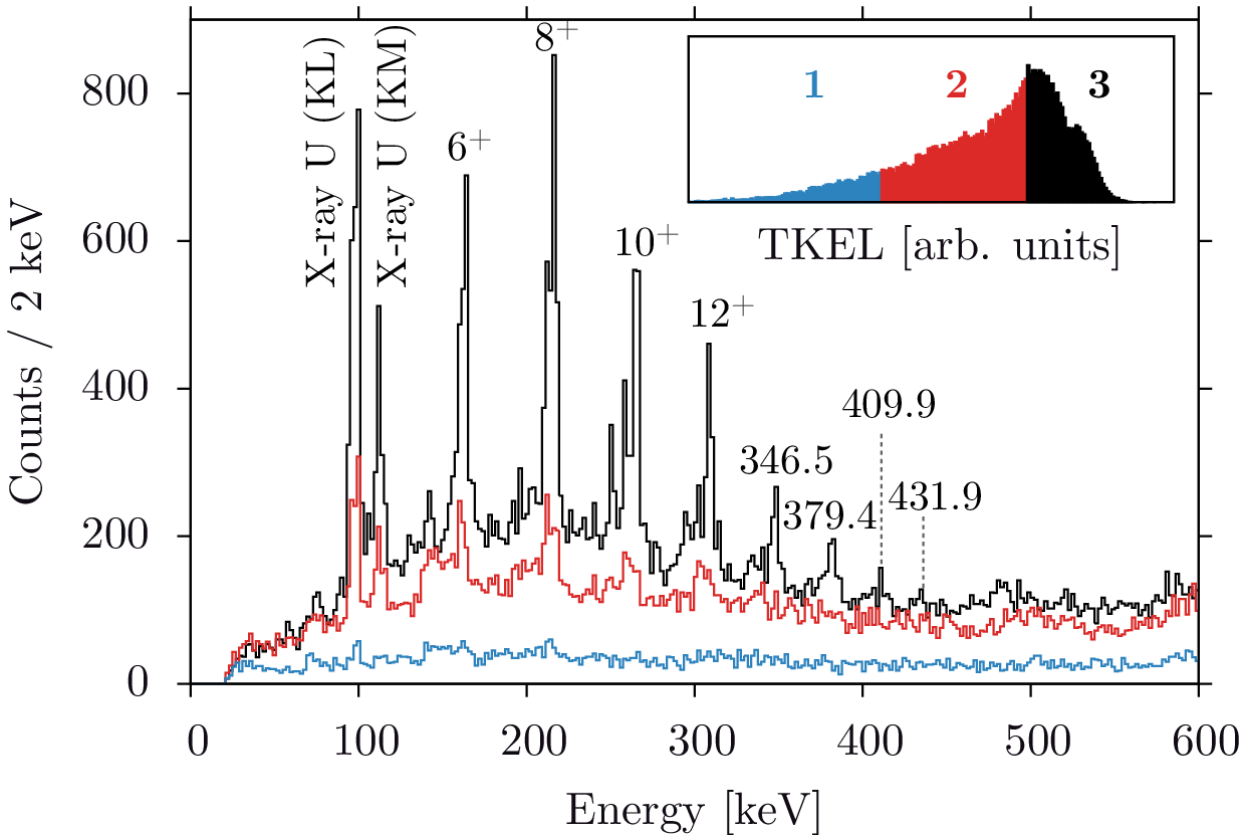
Spectrum of ^{240}U



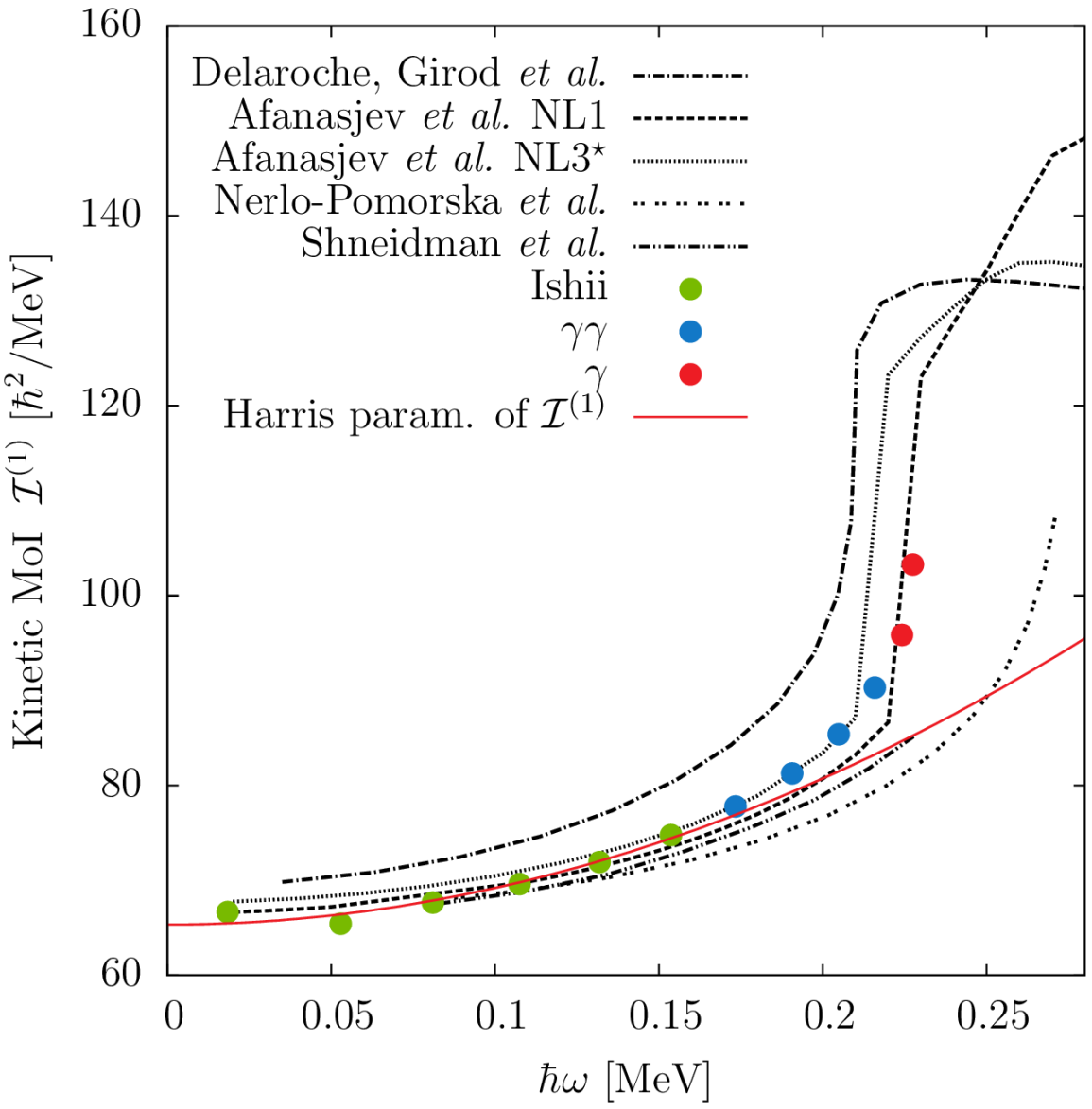


Spectra of ^{240}U

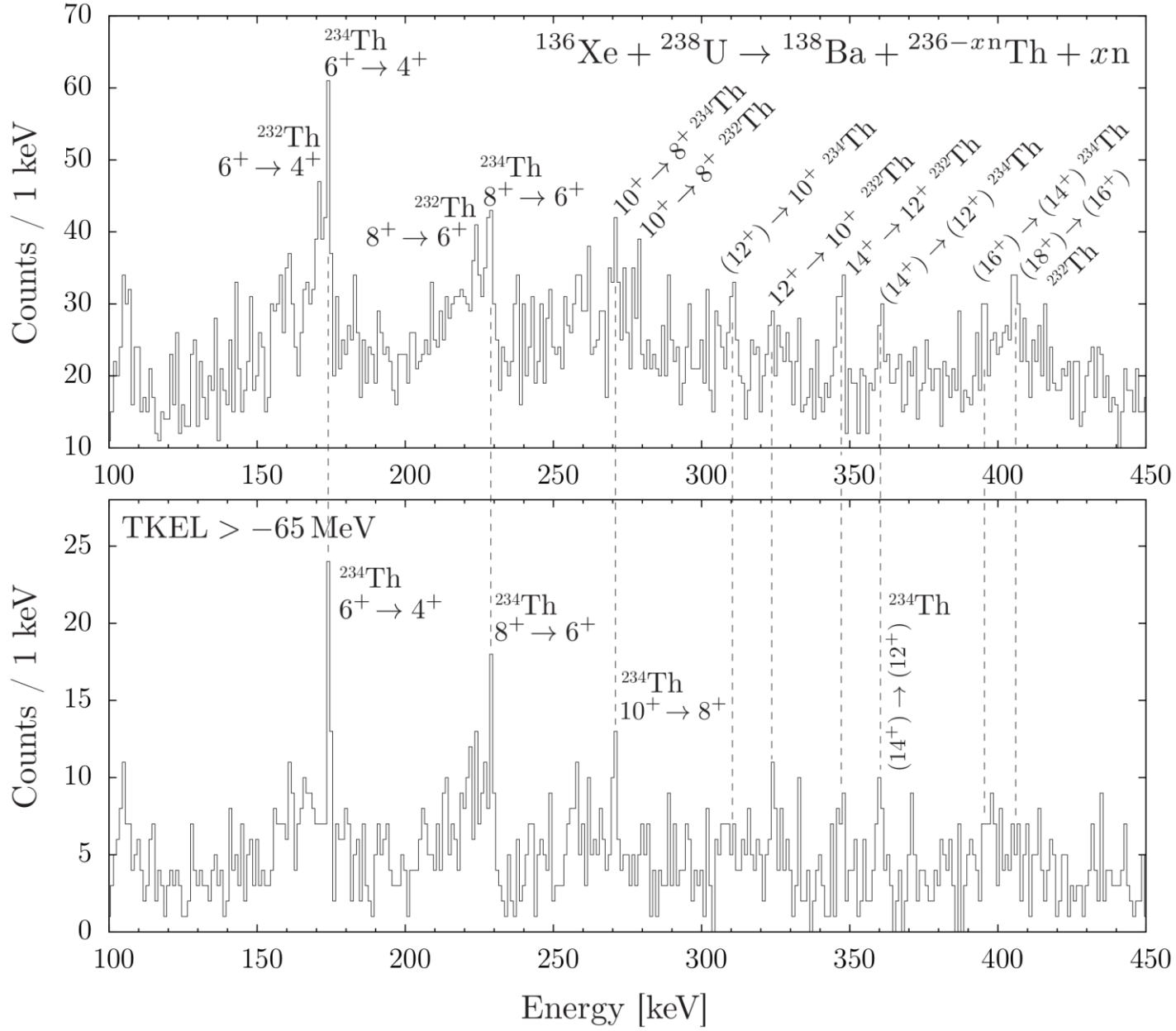




Moment of inertia ^{240}U



Spectrum of Th



More information...

Birkenbach, Phys. Rev. C 92 044319 (2015)

Vogt, Phys. Rev. C 92 024619 (2015)

Vogt, In-Beam Gamma-Ray Spectroscopy of Neutron-Rich Actinides after Multi-Nucleon Transfer Reactions, Master thesis, University Cologne (2014)

Birkenbach, Gamma ray tracking with the AGATA demonstrator – A novel Approach for in-beam spectroscopy, PhD thesis, University Cologne (2014)

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Outlook

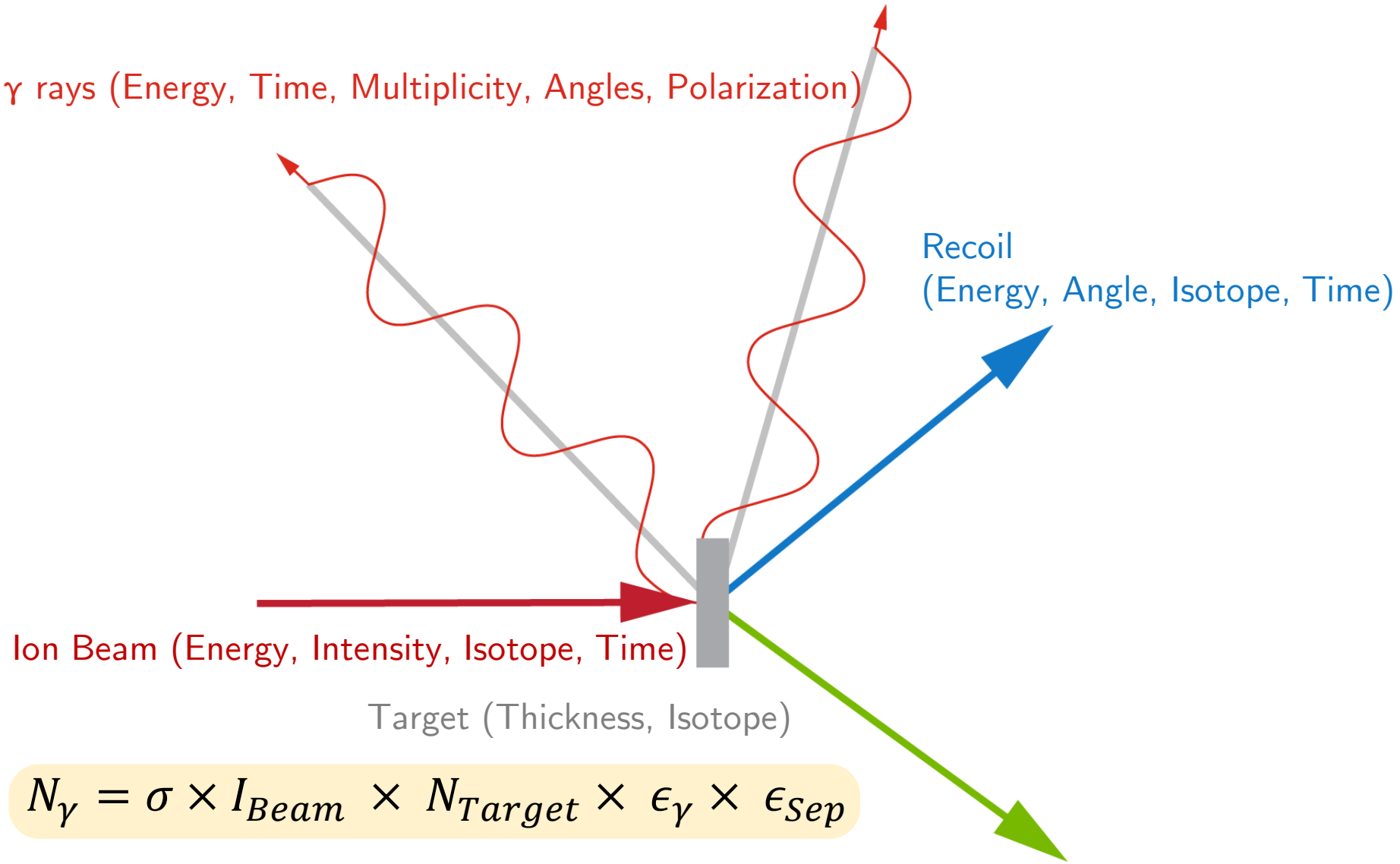
$$N_\gamma = \sigma \times I_{Beam} \times N_{Target} \times \epsilon_\gamma \times \epsilon_{Sep}$$

AGATA @ GANIL

24 Capsules 2015 Campaign

32 Capsules 2016 Campaign

Outlook



$$N_\gamma = \sigma \times I_{Beam} \times N_{Target} \times \epsilon_\gamma \times \epsilon_{Sep}$$

Thank you

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