DE LA RECHERCHE À L'INDUSTRIE

MNT @ ARGONNE

11 MAY 2022

Barbara Sulignano

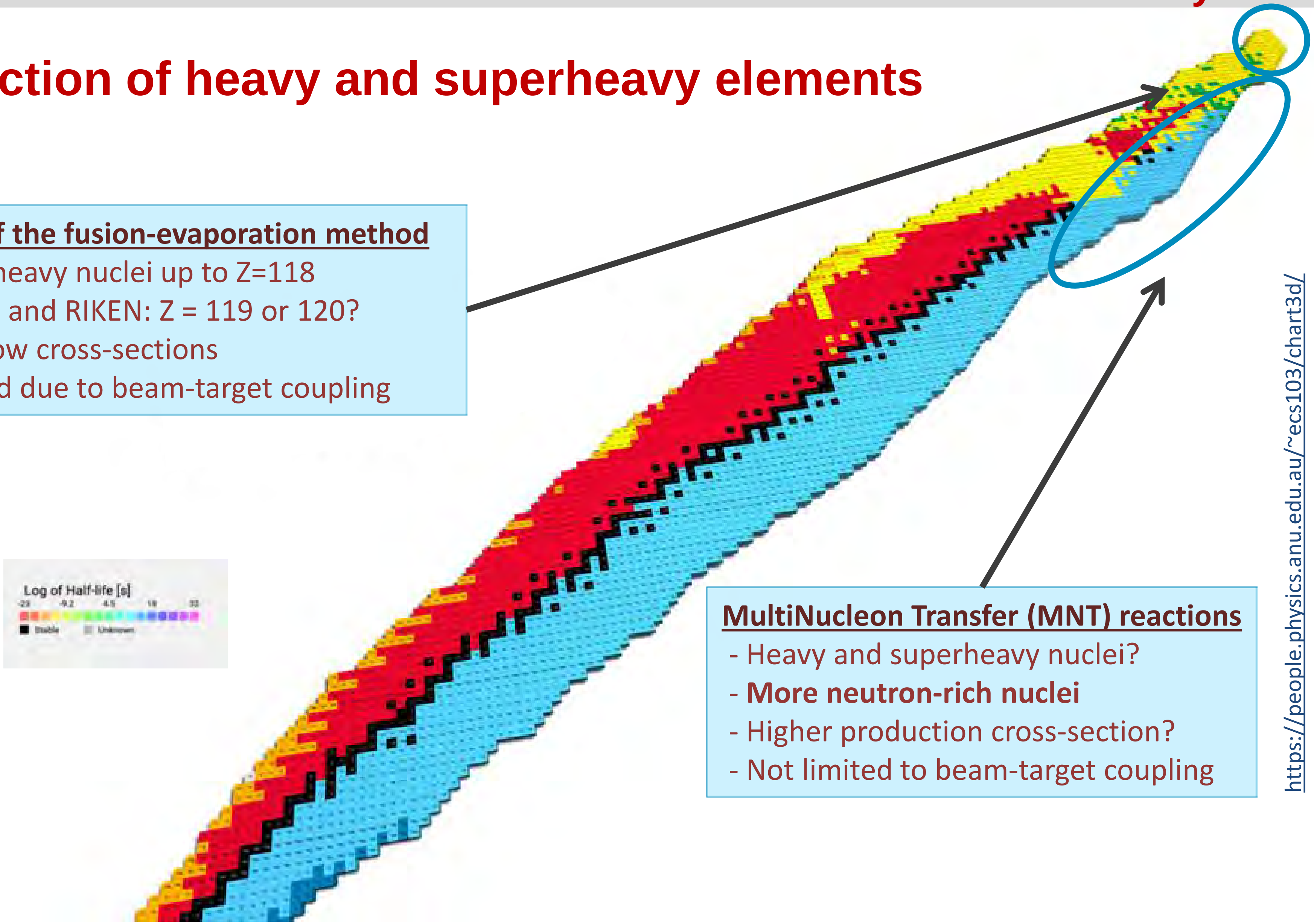
Towards heavy elements via MNT reaction

- **Physics motivations**
- **TEST experiment at Argonne: ^{136}Xe+^{238}U at 0°**
- **First results**
- **Limits, perspectives and outlooks**

PHYSICS MOTIVATION

Superheavy nuclei?
Island of stability?

Production of heavy and superheavy elements



Limits of the fusion-evaporation method

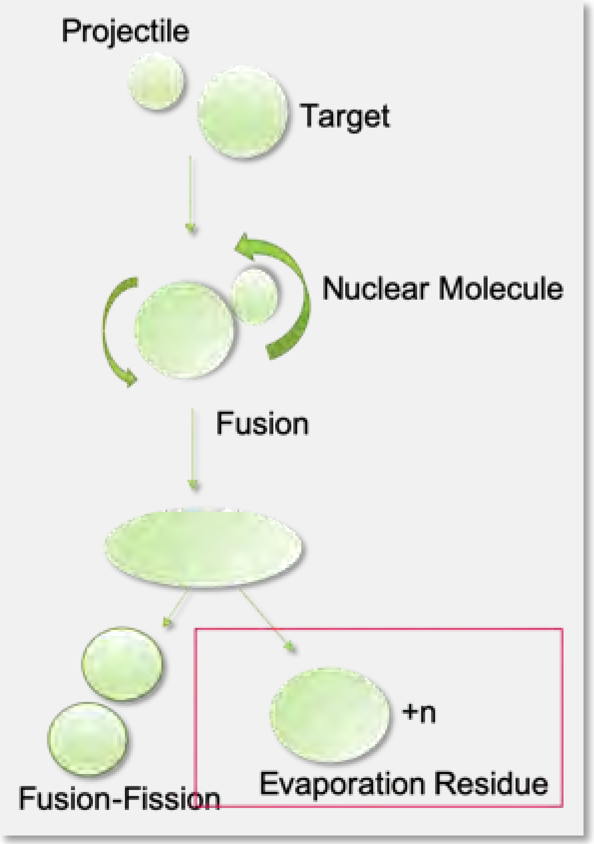
- Superheavy nuclei up to Z=118
- Dubna and RIKEN: Z = 119 or 120?
- Very low cross-sections
- Limited due to beam-target coupling

MultiNucleon Transfer (MNT) reactions

- Heavy and superheavy nuclei?
- **More neutron-rich nuclei**
- Higher production cross-section?
- Not limited to beam-target coupling

https://people.physics.anu.edu.au/~ecs103/chart3d/

Fusion-evaporation limits



Projectile

Target

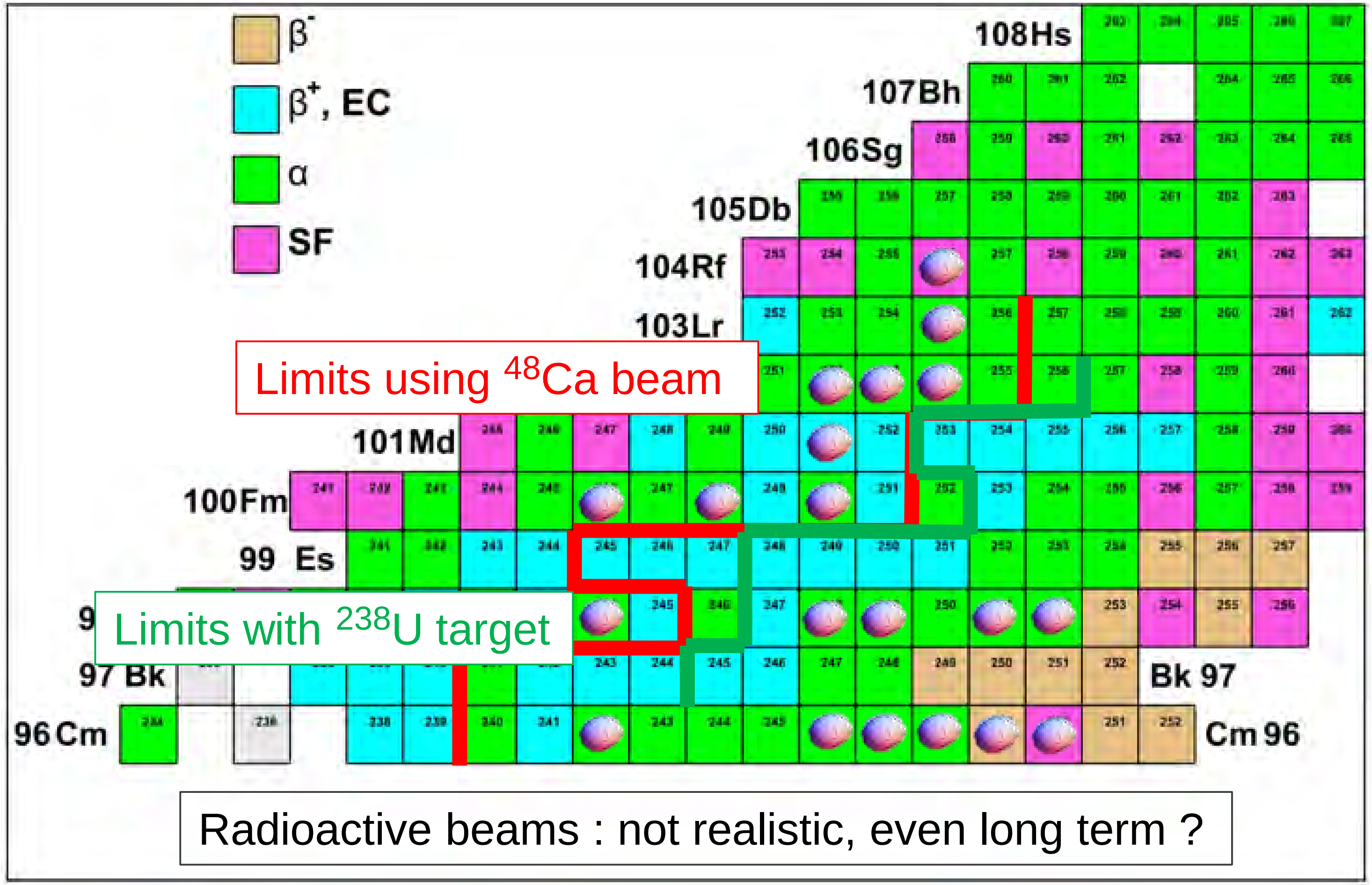
Nuclear Molecule

Fusion

Fusion-Fission

+n

Evaporation Residue



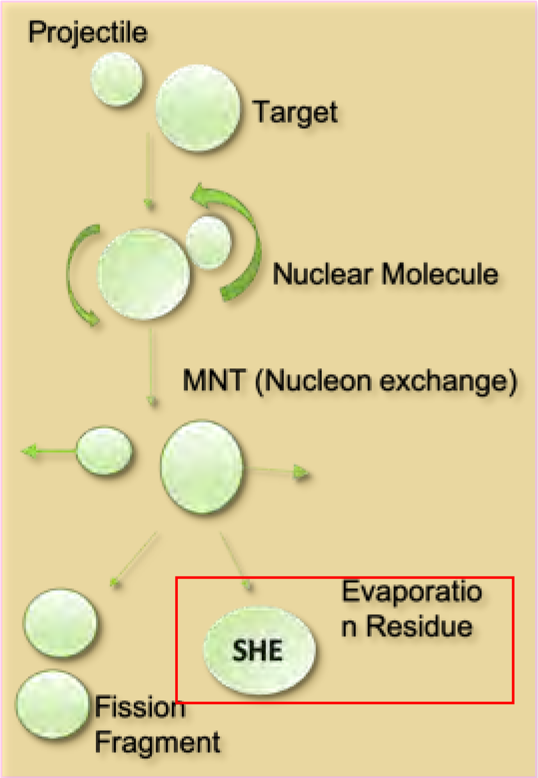
Limits using ^{48}Ca beam

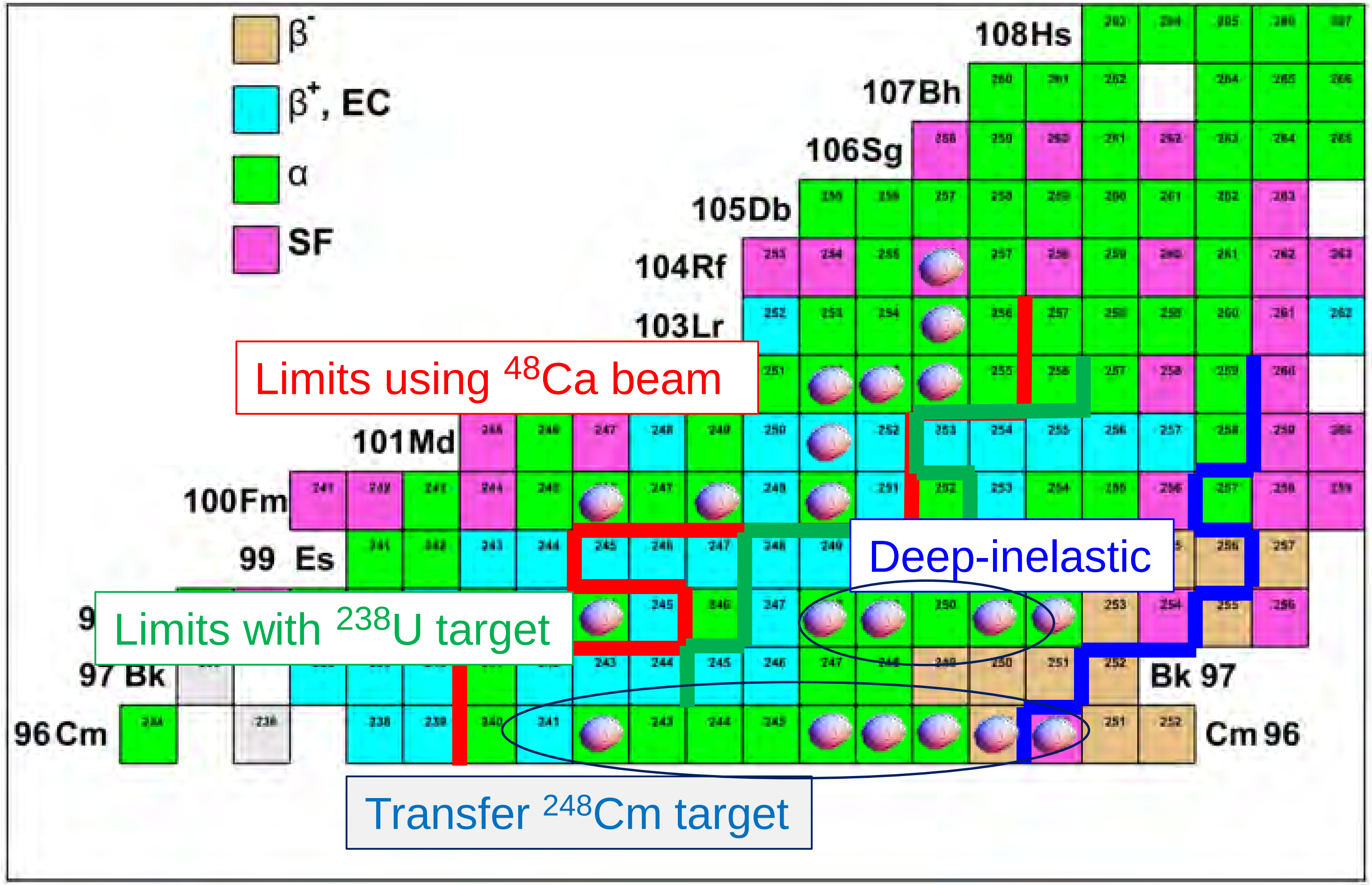
Limits with ^{238}U target

Radioactive beams : not realistic, even long term ?

- ➢ Up to now, the information on the heaviest elements has been obtained via fusion-evaporation reactions.
- ➢ The nuclei, which can be reached are neutron deficient

Deep-inelastic reactions





Limits using ^{48}Ca beam

Deep-inelastic

Limits with ^{238}U target

Transfer ^{248}Cm target

Transfer reactions :
No separation techniques

Inelastic excitation

^{207}Pb + ^{249}Cf

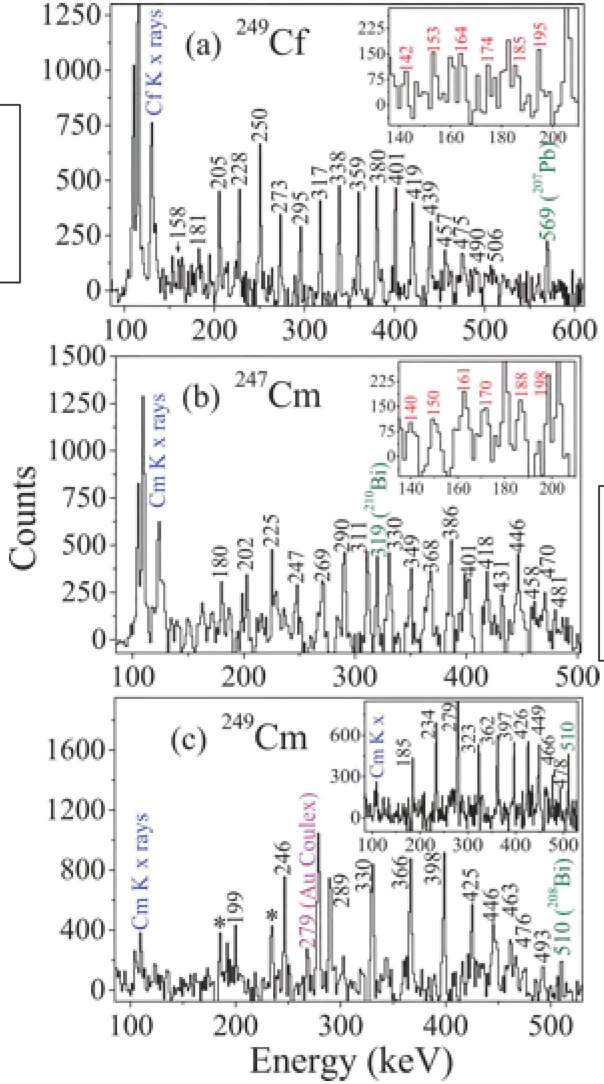
Transfer

^{209}Bi + ^{248}Cm

No Ion detection -

γ^n only

Thick target



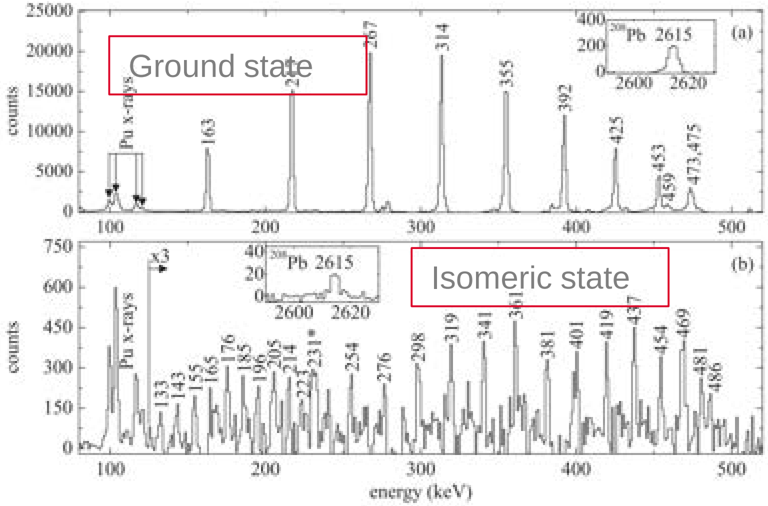
S.K. Tandel et al. PRC 82 (2010) 041301(R)

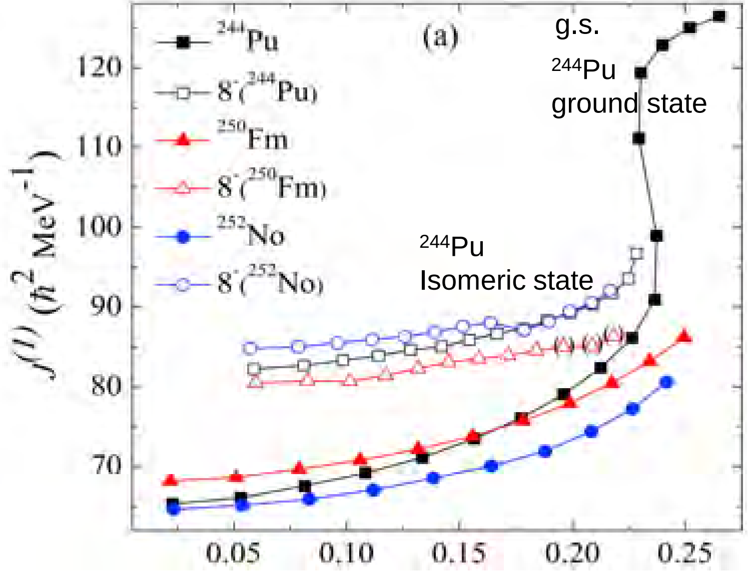
Inelastic excitation

^{47}Ti+ ^{244}Pu

^{208}Pb+ ^{244}Pu

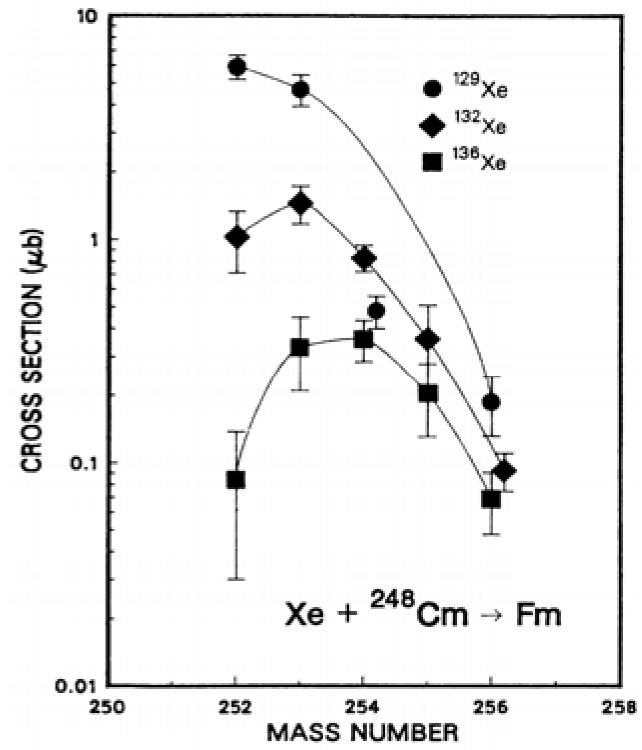
^{244}Pu





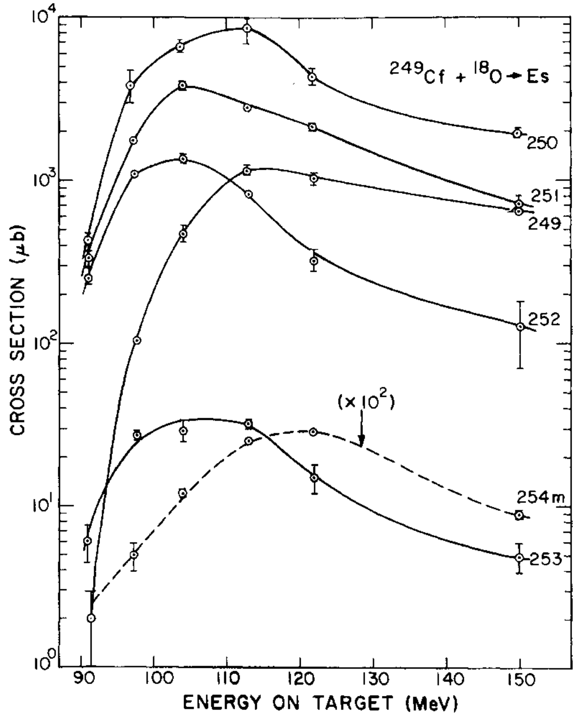
S.S. Hota, S. Tandel et al. Phys. Rev. C **94,**021303 (2016)

Deep-inelastic reactions: Radiochemistry



B. Welch et al. Phys. Rev. C Vol 35 (1987)

→Chemical separation methods
→isotope identification via radioactive decay
→timescale of the fastest radiochemical separation techniques long lived isotope ≈ 10 s
→Nuclei produced: Z=101, N=157

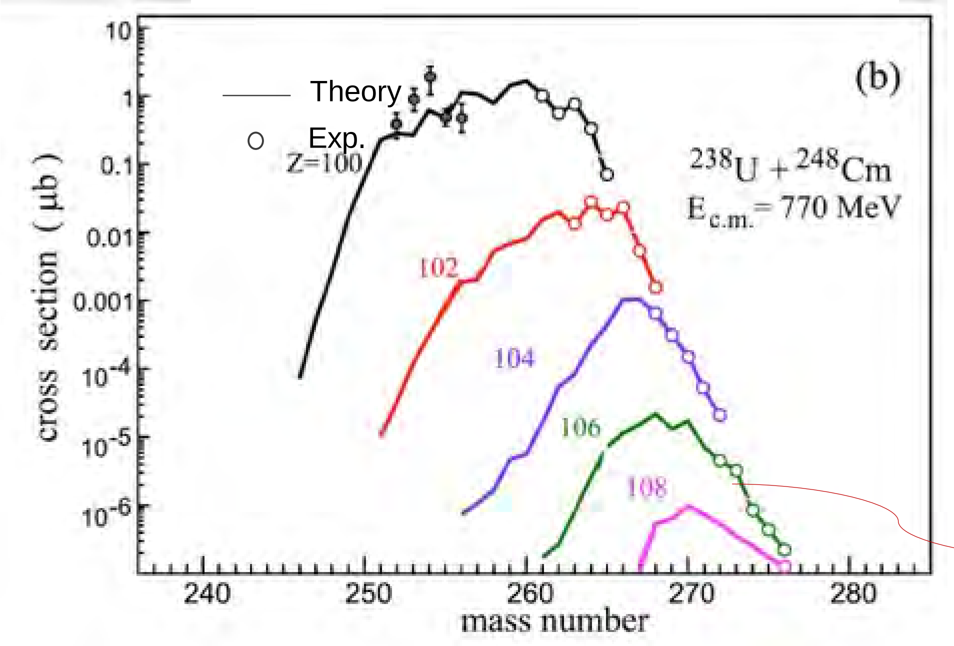


D. Lee et al. PRC 25 (1982) 286 : ^{16}O, ^{18}O, ^{20}Ne, ^{22}Ne + ^{248}Cm
D. Lee et al. PRC 27 (1983) 2656 : ^{18}O + ^{248}Cm, ^{249}Cf
K.J. Moody et al. PRC 33 (1986) 1315 : ^{18}O, ^{86}Kr, ^{136}Xe + ^{248}Cm
M. Schädel et al. Phys. Rev. Lett. 48, 852 (1982): ^{238}U+ ^{248}Cm
A. Türler et al. PRC 46 (1992) 1364 :^{40,44,48}Ca + ^{248}Cm
...

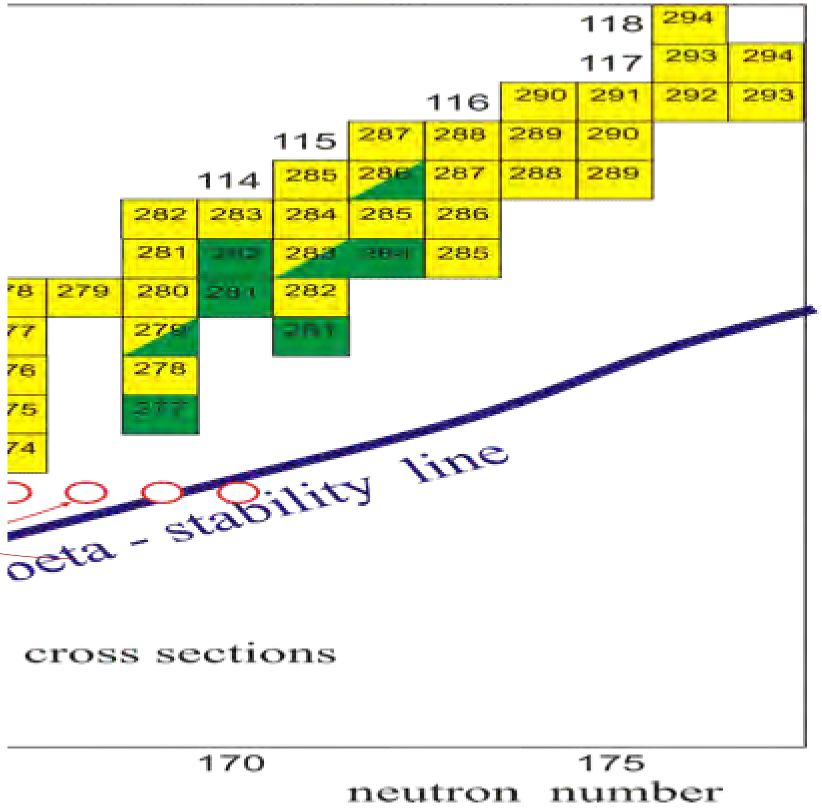
Rebirth of deep-inelastic reactions

A revival of the topics initiated 15 years ago

Cross sections for transfer reaction



V. Zagrebaev,W. Greiner, Nulc. Phys. A 944 (2015)



- ➢ Uncertainty in parameters used to describe the low-energy nuclear dynamics →nucleon transfer rate, nuclear viscosity, and fission barriers

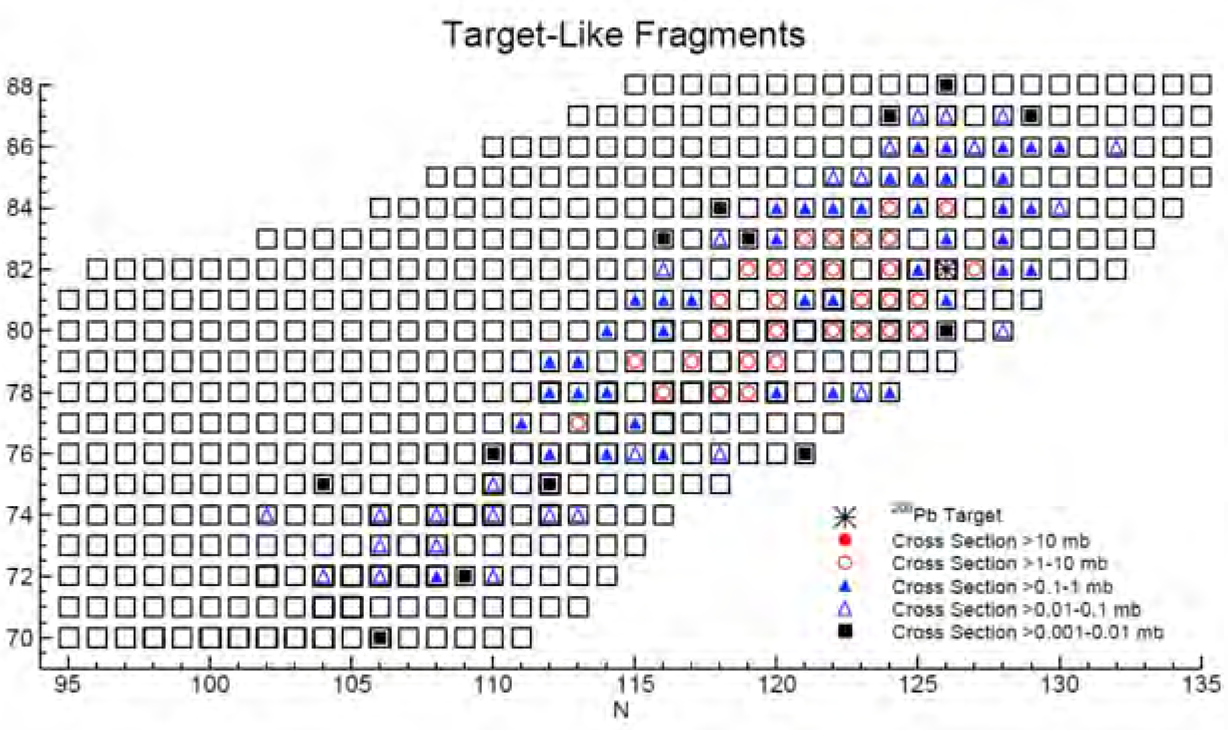
New experimental data on the production of heavy nuclei in low-energy multinucleon transfer reactions becomes crucial

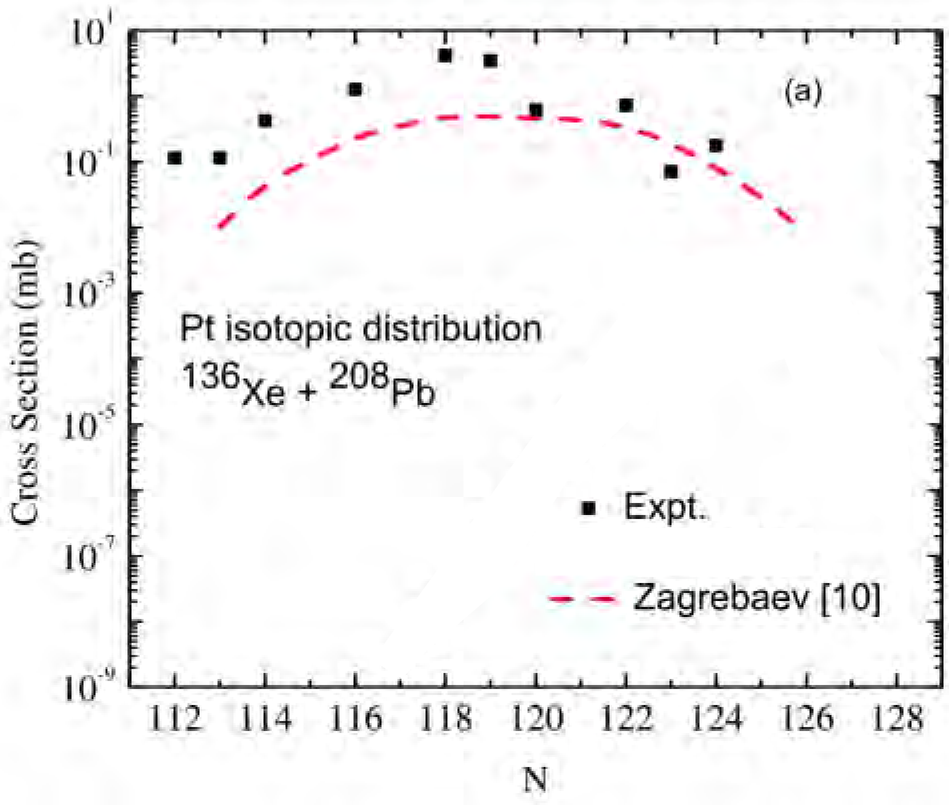
- ➢ Zagrebaev and Greiner theorized that if MNT reactions were run near the barrier [~1.1Vb] shell effects would be preserved and large transfers would occur.
- ➢ **The methods utilise multidimentional langevin equations to describe the dynamics of the heavy ion low energy dissipative collision**

Test of models of multinucleon transfer reaction: ^{136}Xe+^{208}Pb

^{136}Xe+^{208}Pb (E_{beam}= 785 meV) @ Gammasphere: the beam was stopped in the tick target;

J.S. Barrett et al. Phys. Rev. C 91, 064615 (2015)





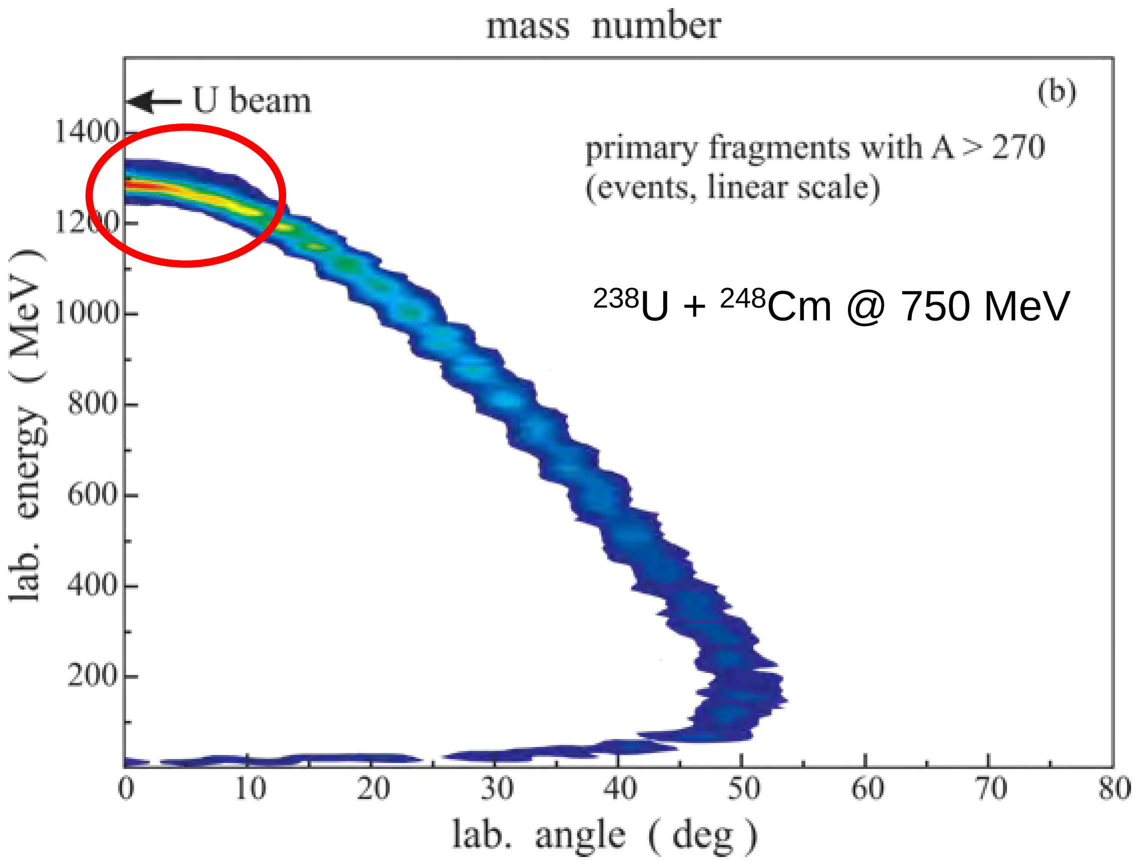
117 target like produced from Yb (Z=70) to Ra (Z=88).

The cross section follow the trend predicted by Zagrebaev for the target like products

V. Zagrebaev, and W. Greiner, Physical Review C 83, 044618 (2011).

At Which angles for deep-inelastic of SHN?

V.I. Zagrebaev and W. Greiner, PRC 83 (2011) 044618



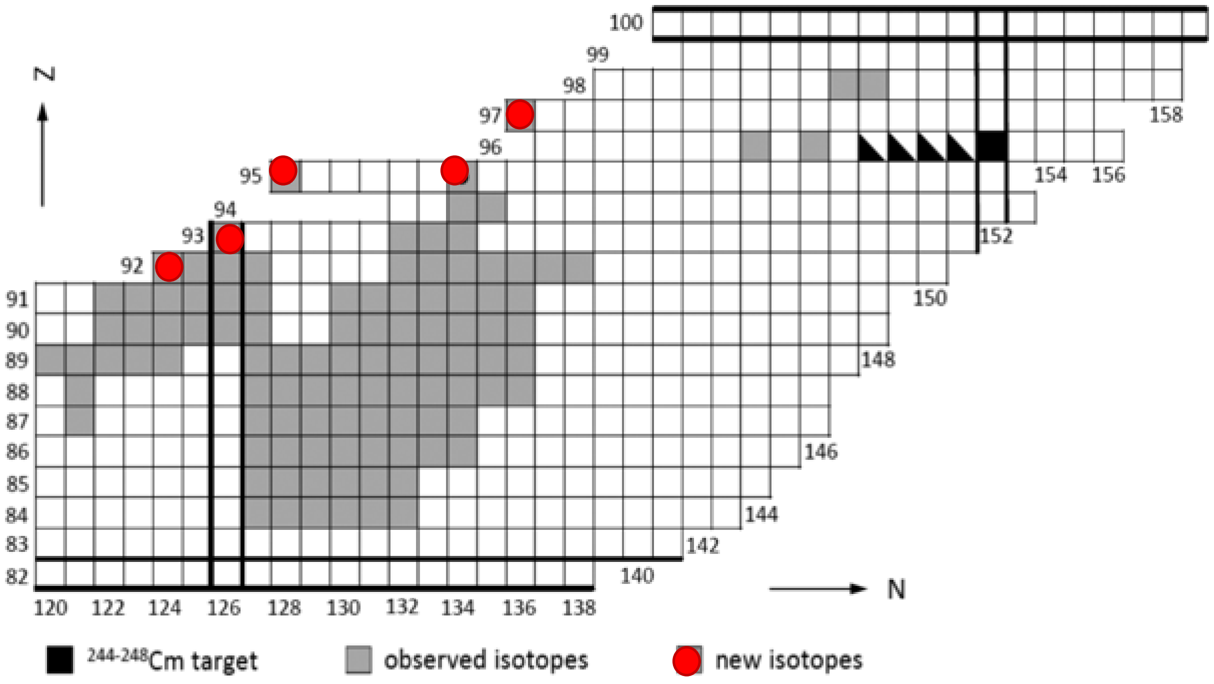
^{238}U + ^{248}Cm @ 750 MeV

The angular distribution of the superheavy nuclei does not reveal any grazing feature, it is forward directed.

- The optimal beam energy is 20-30 MeV higher than corresponding coulomb barrier in the entrance channel
- Heavy target like reaction products are ejected in the forward direction. Grazing angle is @ 0°

Example of successful experiment of transfer reaction for heavy element @ 0°

48Ca+248Cm @ (5.3 MeV/n) At SHIP (GSI)



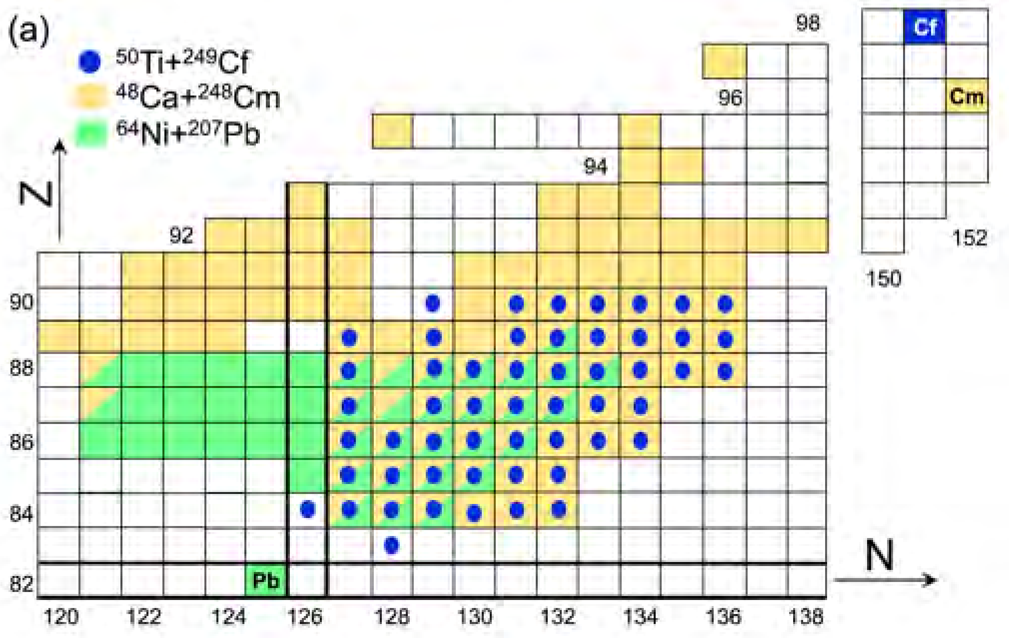
S. Heinz, et al. Eur. Phys. J. A (2016) 52: 278

SHIP

- Mass identification via alpha decay correlation
- Max corr. Time 1s; Small angular acceptance 0.3%

→only central collision with small angular momenta

^{50}Ti+^{249}Cf @ (6.1 MeV/n) At TASCA (GSI)



[1]A. Di Nitto, et al. PLB 784 (2018)199–205

TASCA

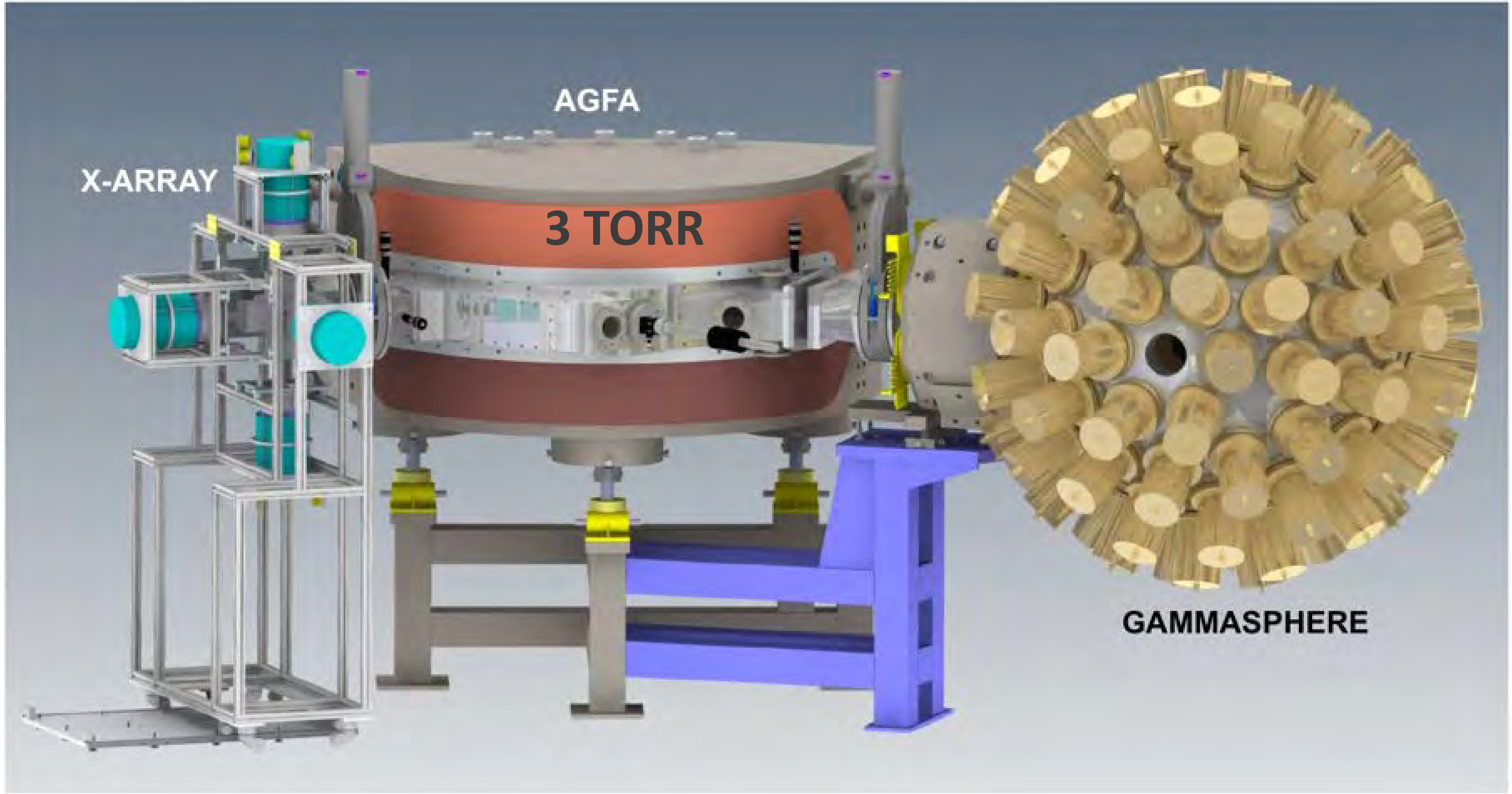
- Gas-filled separator – short lenght
- Mass identification via alpha decay correlations.

Towards heavy elements via MNT reaction

- Physics motivations
- **TEST experiment at Argonne: ^{136}Xe+^{238}U at 0°**
  - Theoretical computations
  - Simulations
  - Experimental set-up
- First results
- Limits, perspectives and outlooks

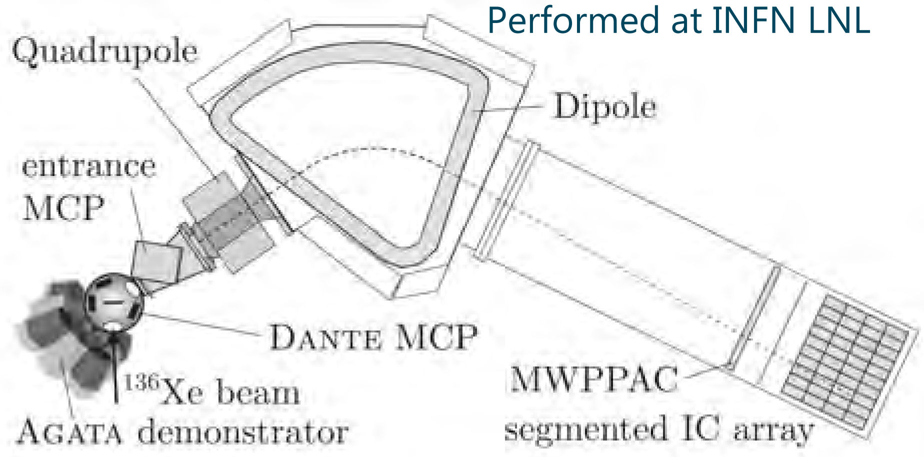
MNT Experiment performed at ARGONNE

^{136}Xe + ^{238}U @ 4.4 and 5.9 MeV/n at 0°

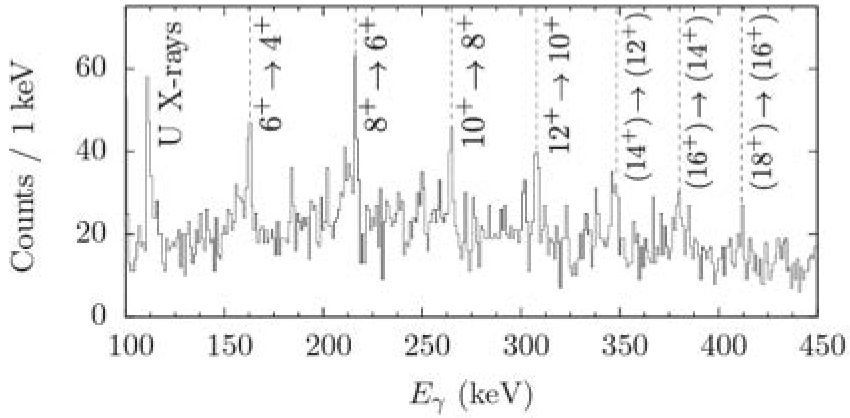


MNT ^{136}Xe+^{238}U at 1GeV and θlab~50°

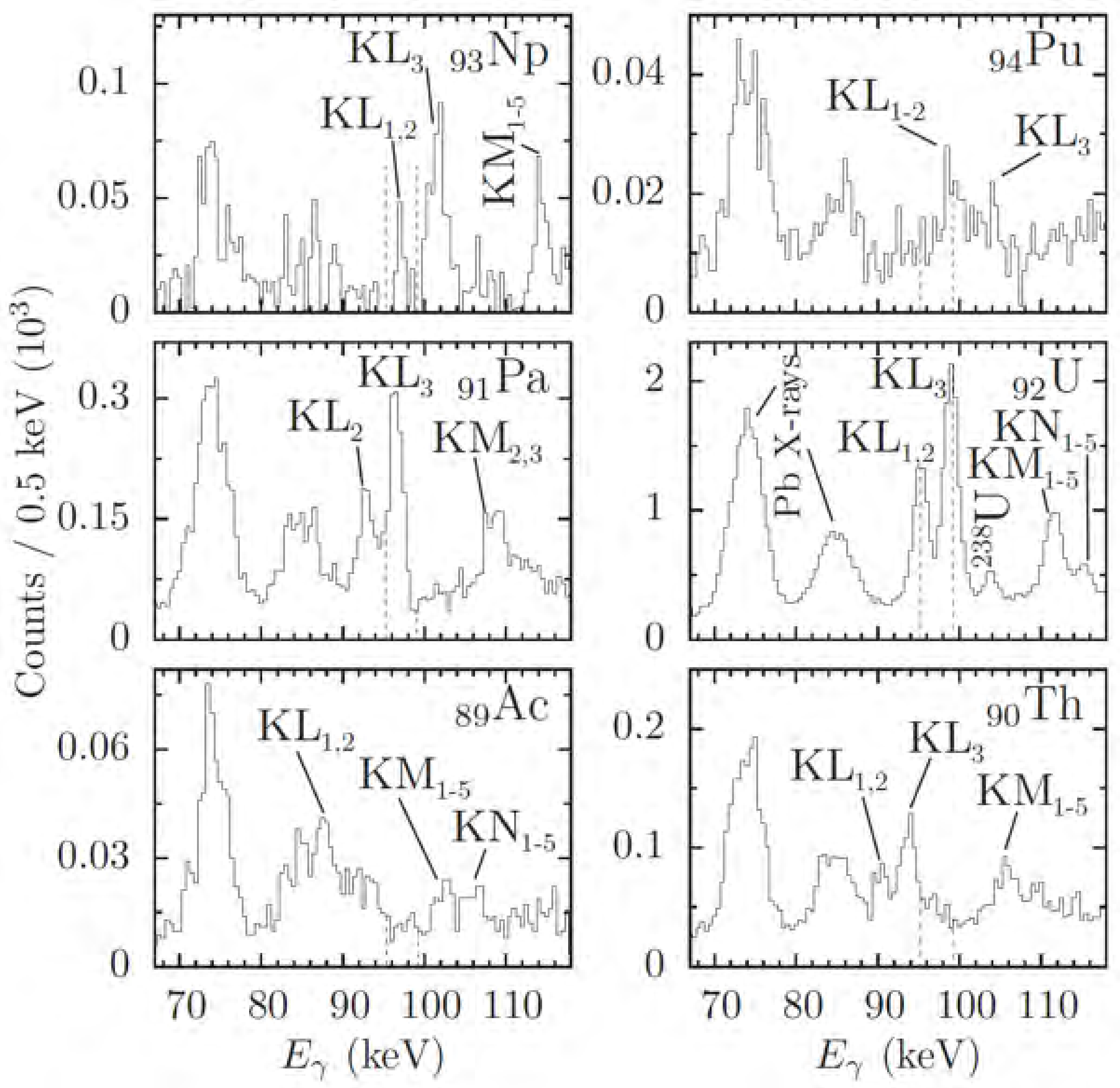
Performed at INFN LNL



Gamma rays of ^{240}U



A. Vogt, et al. PRC 92, 024619 (2015)

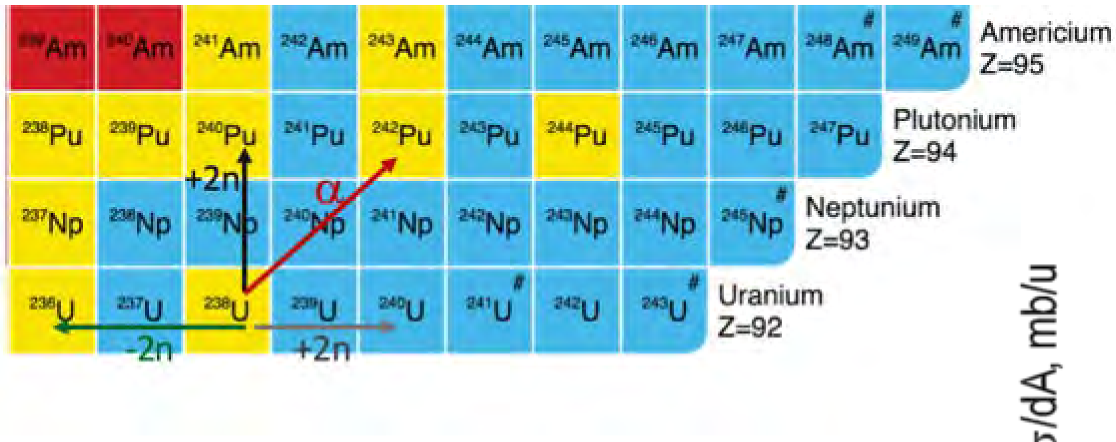


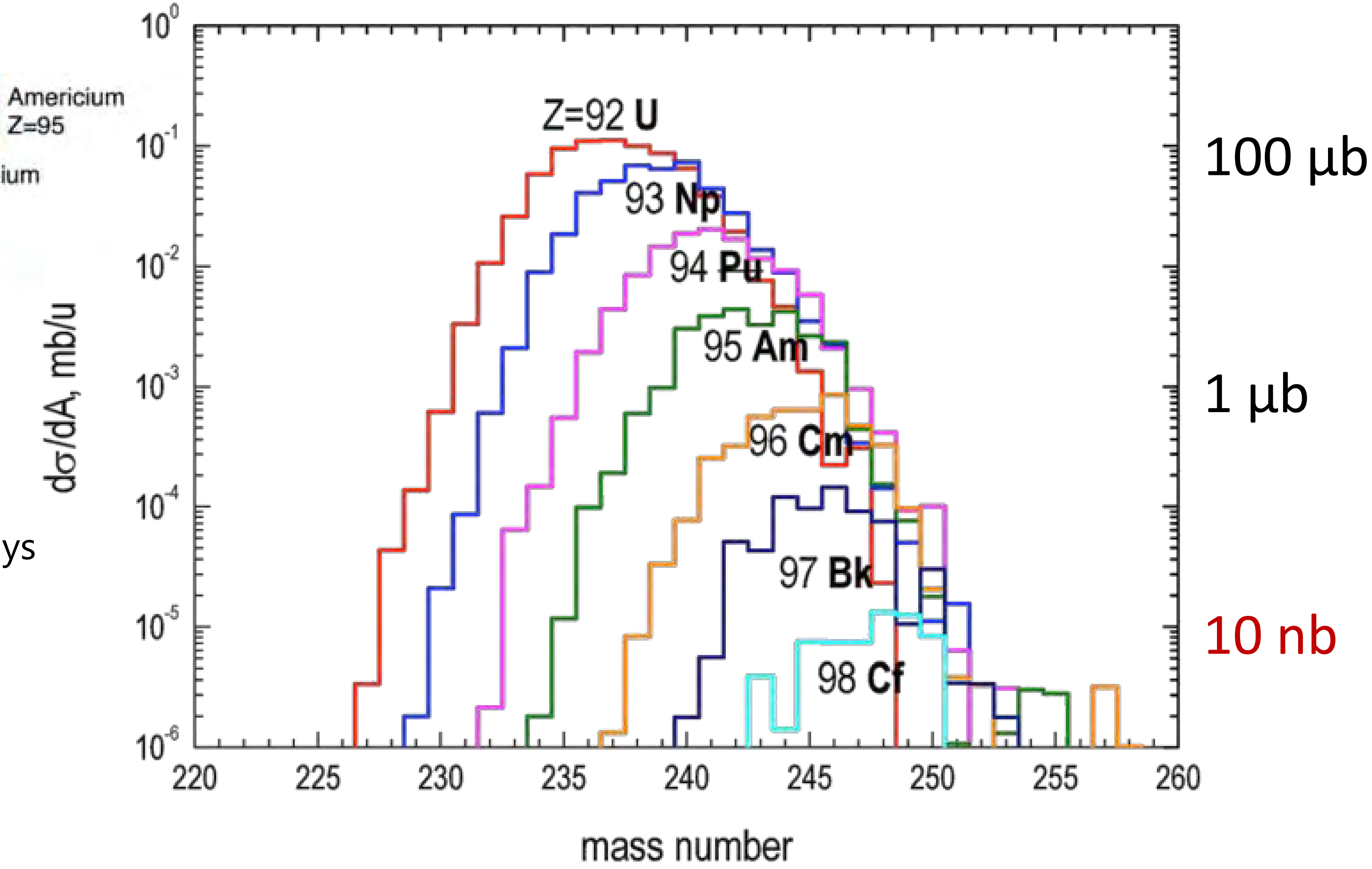
- in coincidence with a time of flight arm, allows identification of the A, Z, and velocity of the PLFs and TLFs.

Theoretical calculations: ^{136}Xe+^{238}U

A. Karpov and V.V. Saiko, Phys. Rev. C 96, 024618 (2017): LANGEVIN MODEL SIMULATION

136Xe + 238U @ E_{cm}~490 MeV ~5.9 MeV/n around 0°





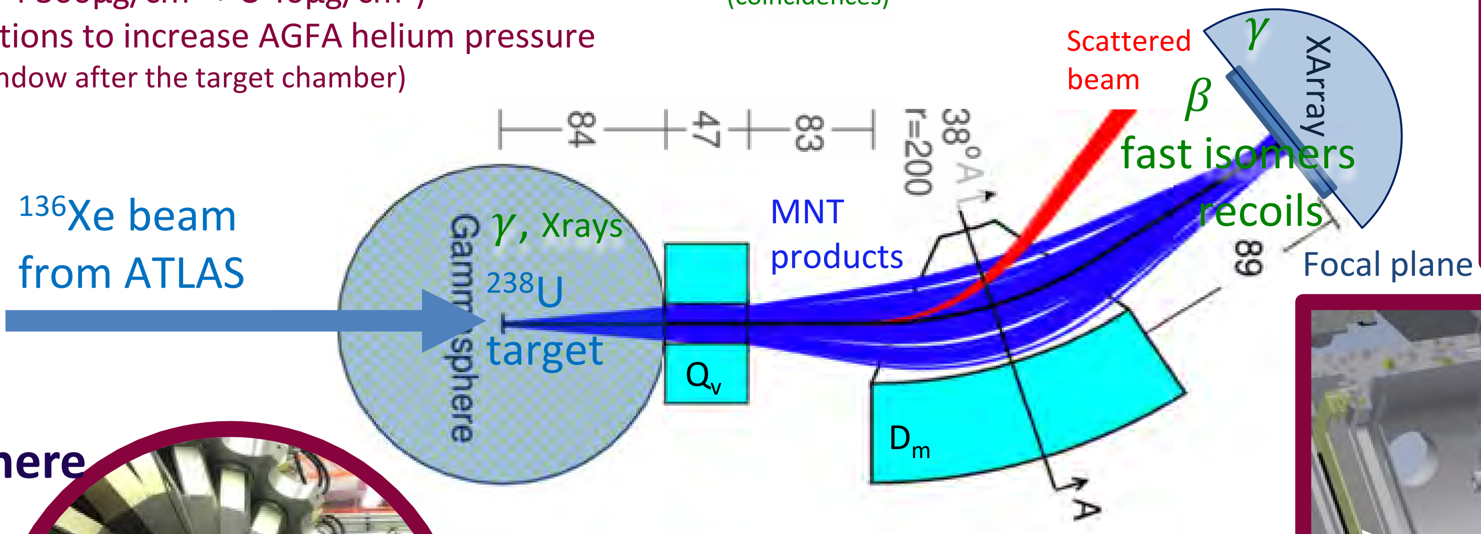
- Identification could be performed via known γ-rays
- Z identification via X-rays
- New neutron rich isotopes could be measured

Multinucleon transfer reactions (MNT) at Argonne

- **Proof-of-principle experiment to study neutron-rich heavy nuclei using MNT reactions**
- 1st MNT reaction using AGFA @ANL to produce heavy nuclei
- **Beam**: ^{136}**Xe** @605, 705 and 809MeV
- **Target**: ^{238}**U** (UF4 300µg/cm^2 + C 40µg/cm^2)
- Innovative solutions to increase AGFA helium pressure up to 3Torr (Ti window after the target chamber)

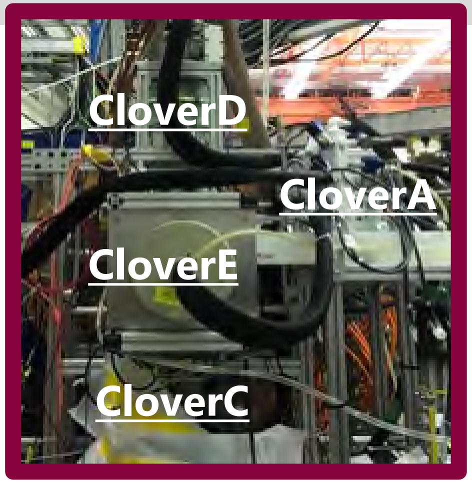
Target-like products identification

(coincidences)



Gammasphere

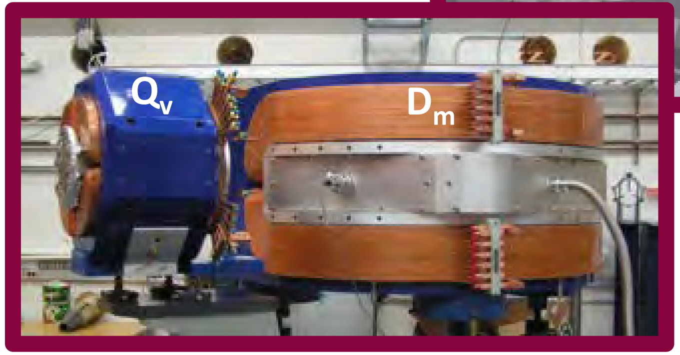
Prompt spectroscopy



Decay spectroscopy

Xarray

Focal plane

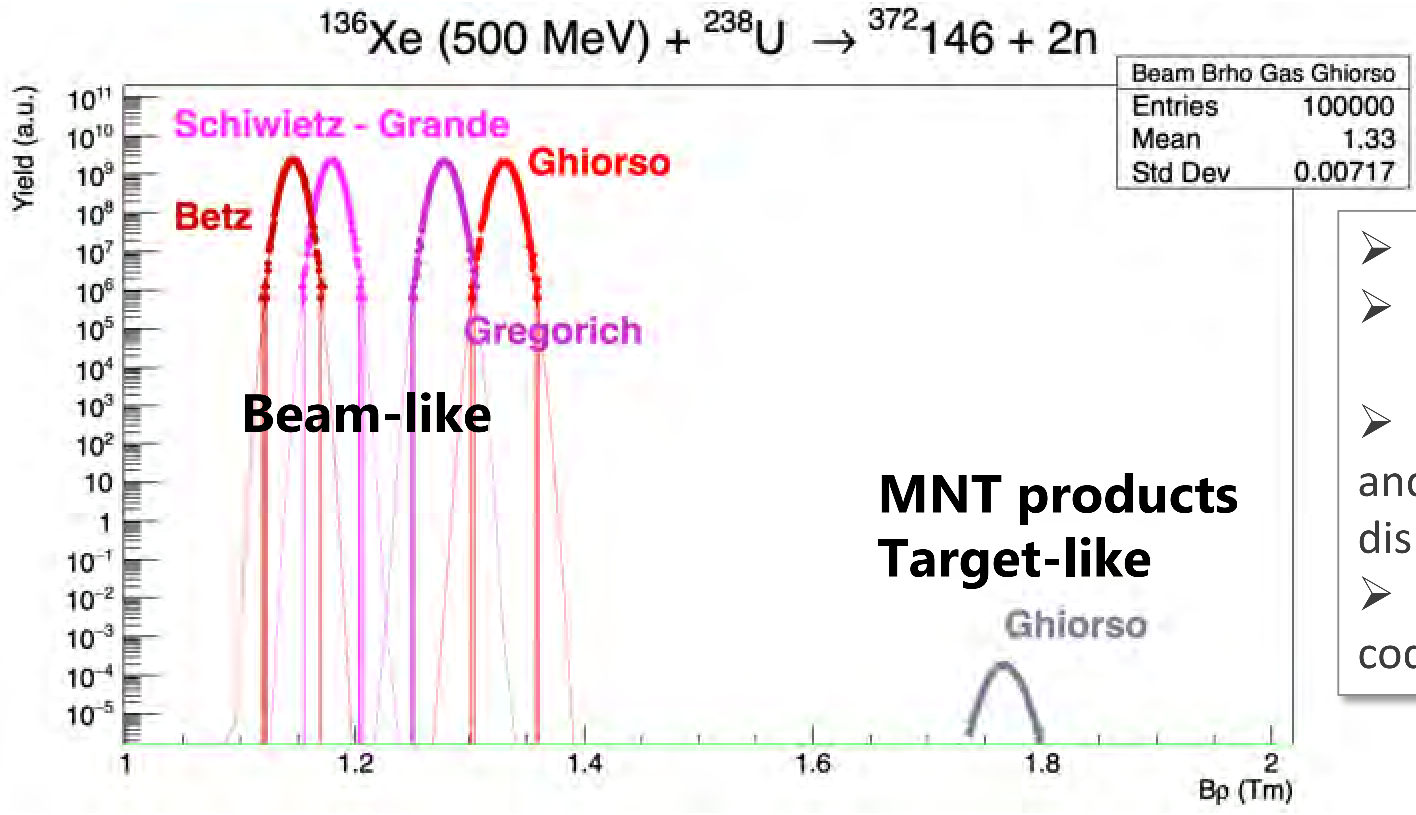


AGFA gas-filled recoil separator

Beam intensity: 20 pnA
GS efficiency: 15% at 200 keV
AGFA efficiency: 50%
DSSD efficiency: 50% (α).

Kinematic simulations

136Xe + 238U @3.7MeV/n around 0°



Beam-like

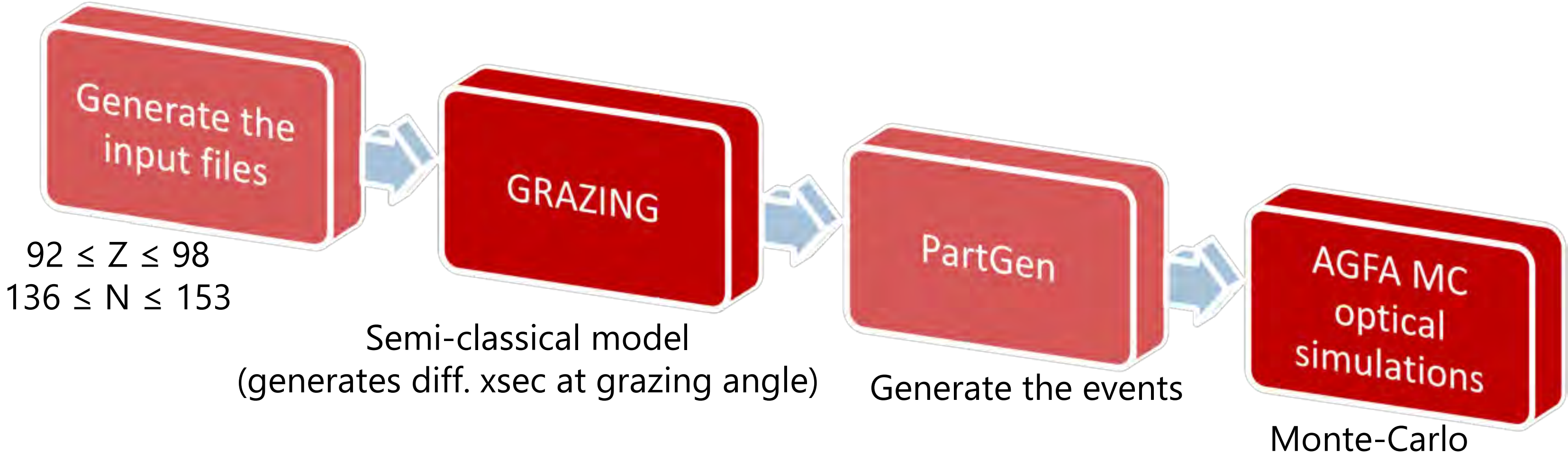
MNT products
Target-like

Bρ distribution of the beam and of the produced target like nuclei.

- The code computes the angular straggling in the gas
- Looks at the influence of the charge exchange on Bρ dispersion
- influence of small angular scattering on Bρ dispersion and the influence of the initial velocity dispersion on Bρ dispersion.
- Provides the final dispersions of the BLFs and TLFs. code.

(Using Vamos gas-filled code by Ch. Theisen)

Optical simulations



Generate the input files

$92 \leq Z \leq 98$
$136 \leq N \leq 153$

GRAZING

Semi-classical model
(generates diff. xsec at grazing angle)

PartGen

Generate the events

AGFA MC optical simulations

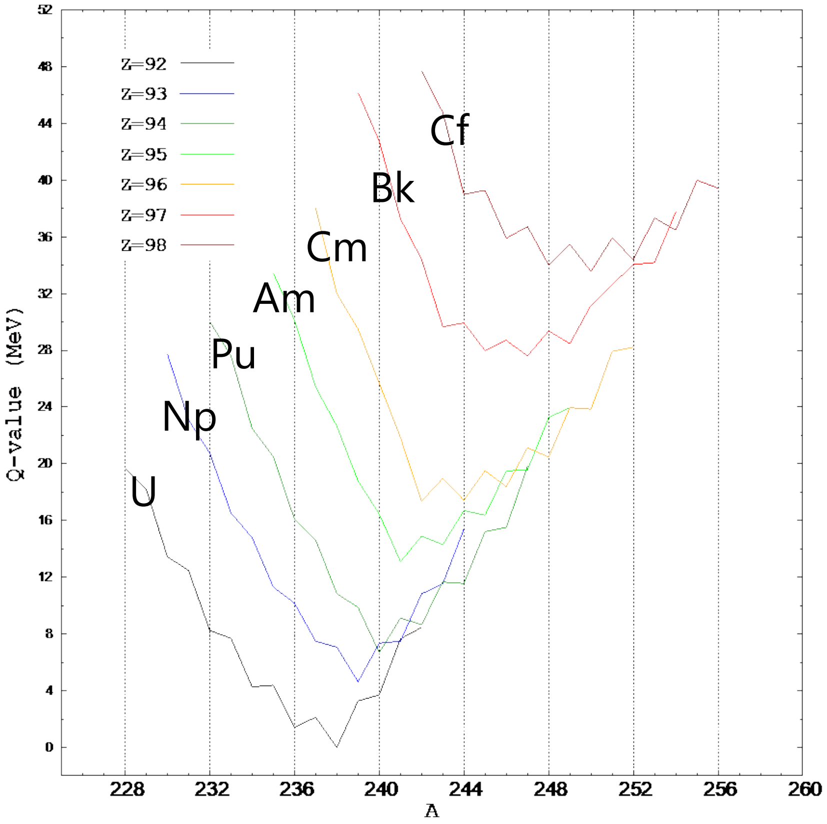
Monte-Carlo

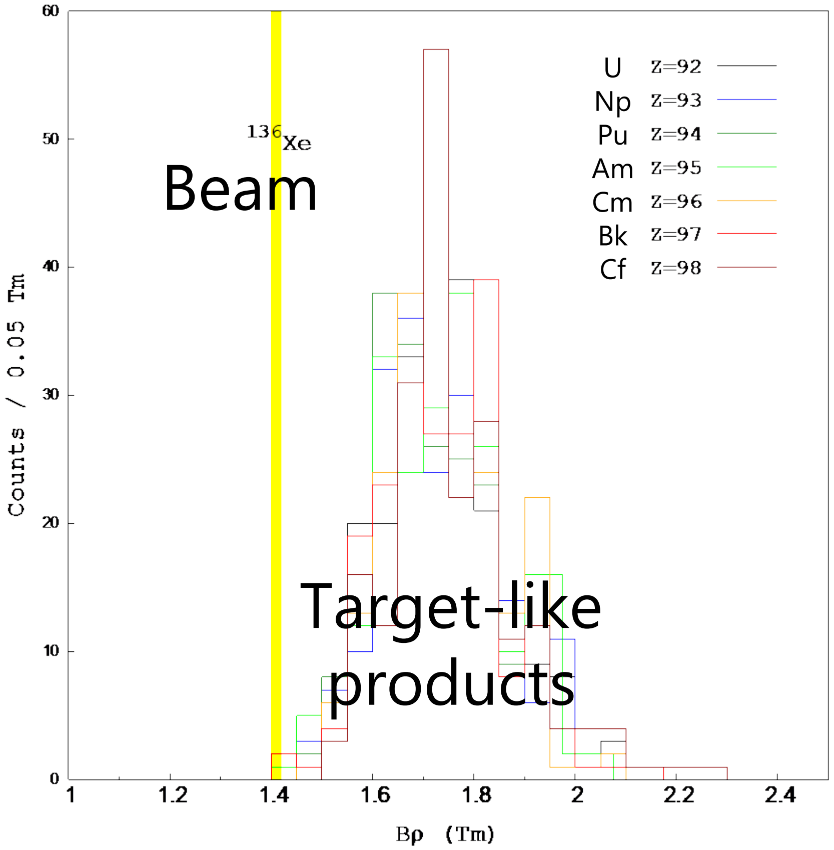
- **GRAZING Code:** **(greetings to M. Siciliano)**
  - **Aim: to produce an event generator to feed the AGFA MC simulation**
  - Estimates the Q-value (with ame2012.cal)
  - Generate the output files of the event generator

$$\mathbf{Z} \quad \boldsymbol{A} \quad \boldsymbol{Q} \quad \overline{\boldsymbol{Q}} \quad \mathbf{E} \quad \vec{\boldsymbol{x}} \quad \frac{\vec{\boldsymbol{p}}}{\|\vec{\boldsymbol{p}}\|} \quad \mathbf{B}\boldsymbol{\rho}$$

- **AGFA Monte-Carlo simulation:** **(greetings to D.H. Potterveld)**
  - Charge state model of Ghioso (A. Ghioro et al. NIM in PRA 269 (1988) 192-201)
  - Optical simulations of AGFA

GRAZING Code



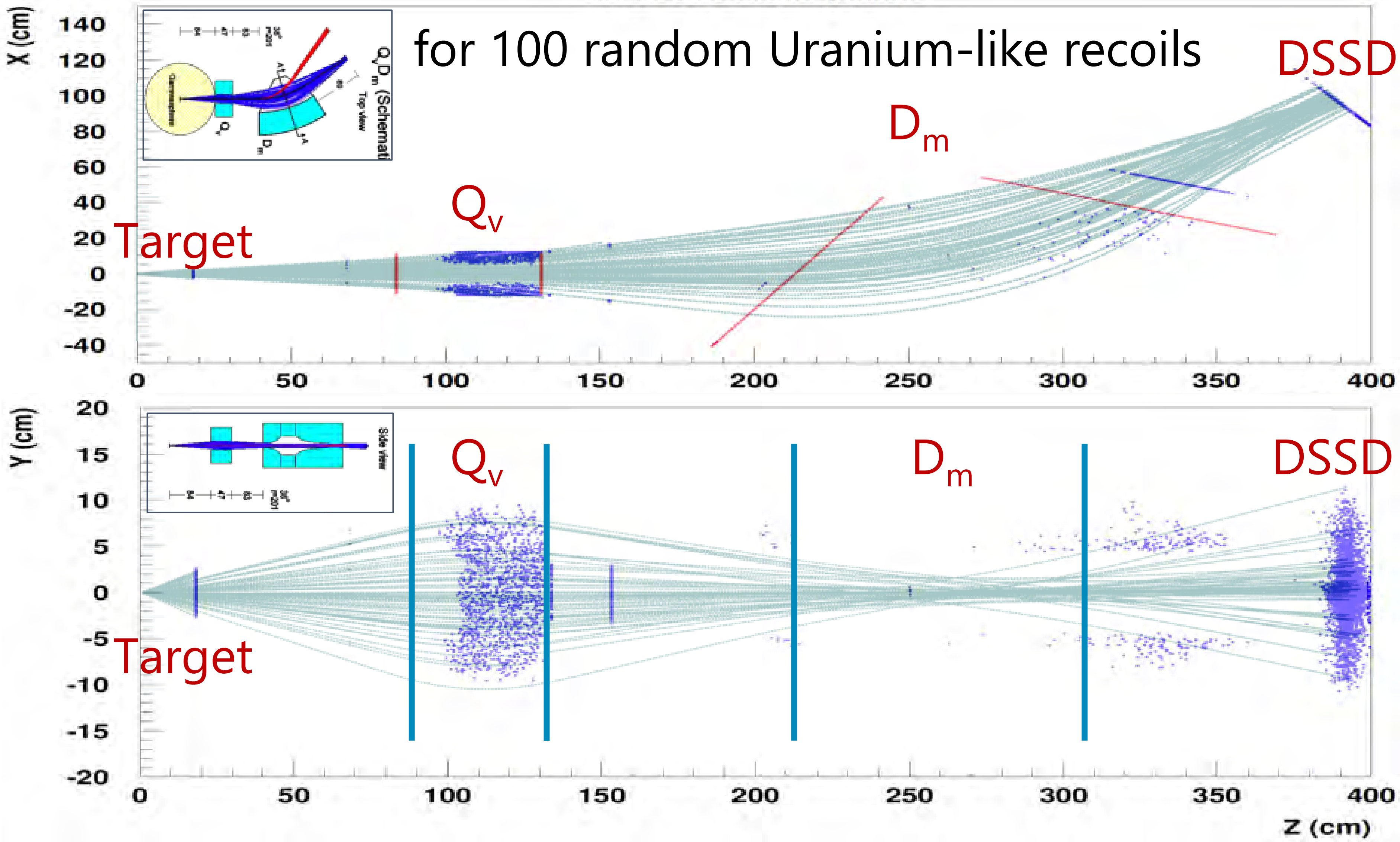


Q-value with respect to the atomic mass

Bρ distribution

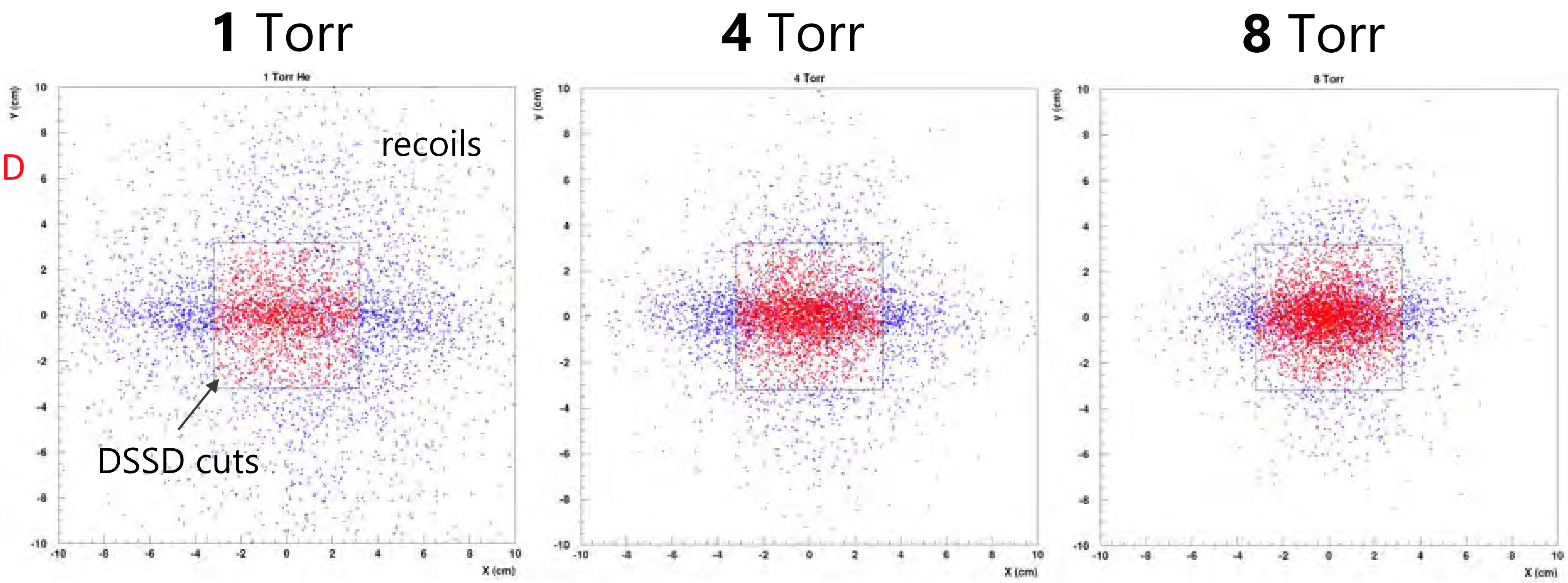
AGFA Monte-Carlo simulations

General overview of the transport of the MNT products from the target to the focal plane

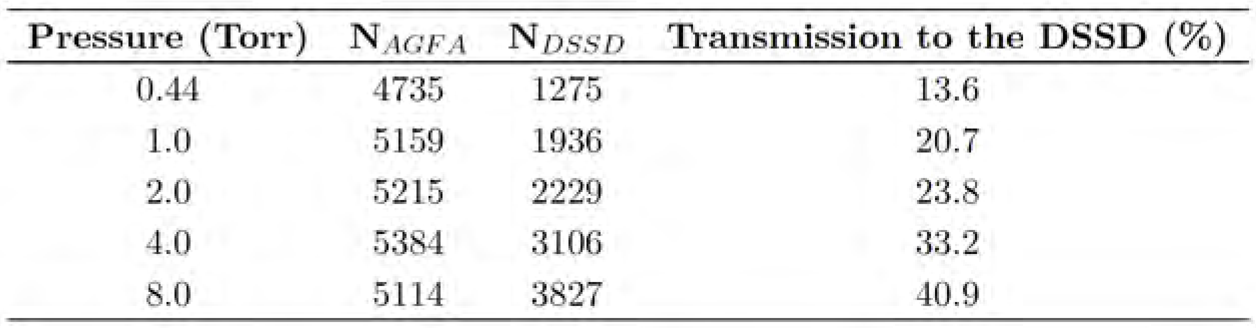


AGFA Monte-Carlo simulations

- All recoils
- Recoils inside the DSSD



X vs Y position of the Uranium-like recoils at the plane of the DSSD (4.6 cm^2).

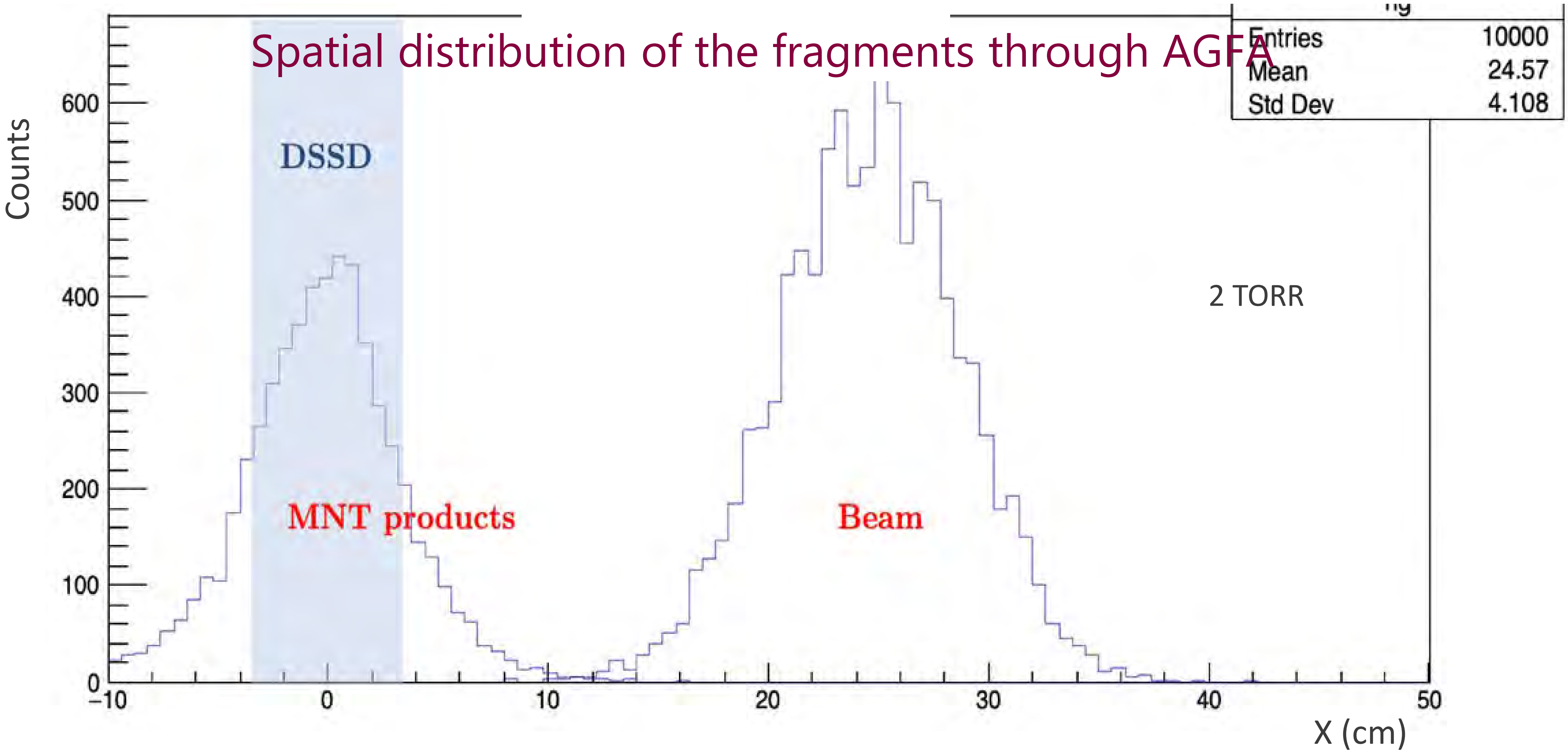


Pressure (Torr)	N_{AGFA}	N_{DSSD}	Transmission to the DSSD (%)
0.44	4735	1275	13.6
1.0	5159	1936	20.7
2.0	5215	2229	23.8
4.0	5384	3106	33.2
8.0	5114	3827	40.9

Efficiency simulated

~28% at 3 Torr

AGFA Monte-Carlo simulations


Spatial distribution of the fragments through AGFA

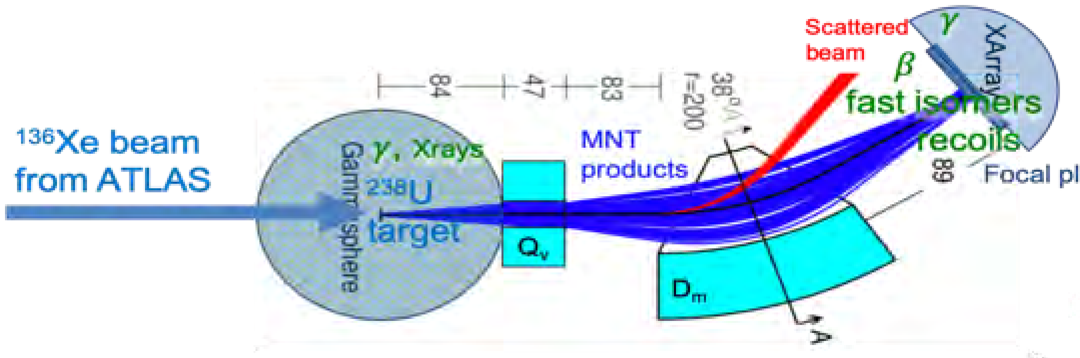
2 TORR

- ➢ Separation power of AGFA is well adapted for MNT reaction products

Towards heavy elements via MNT reaction

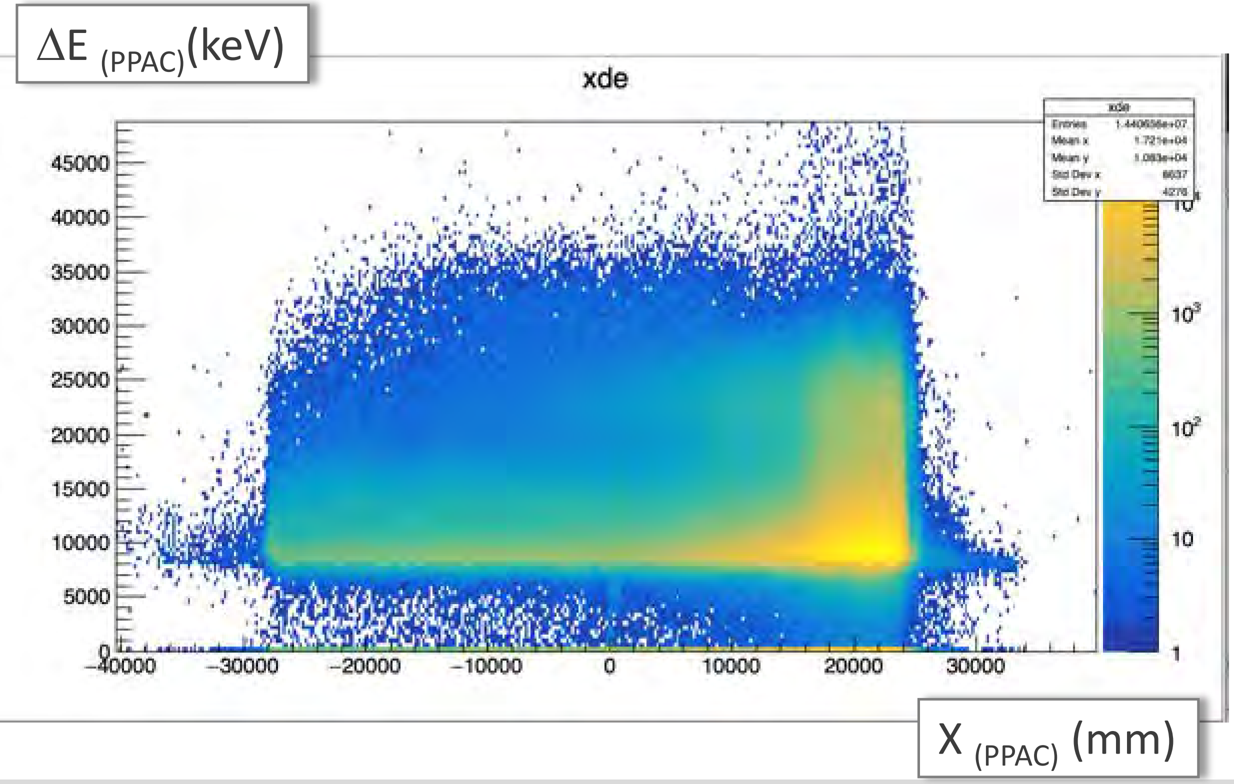
- Physics motivations
- TEST experiment at Argonne: $^{136}Xe+^{238}U$ at 0°
- **First results (PRELIMINARY)**
- Limits, perspectives and outlooks

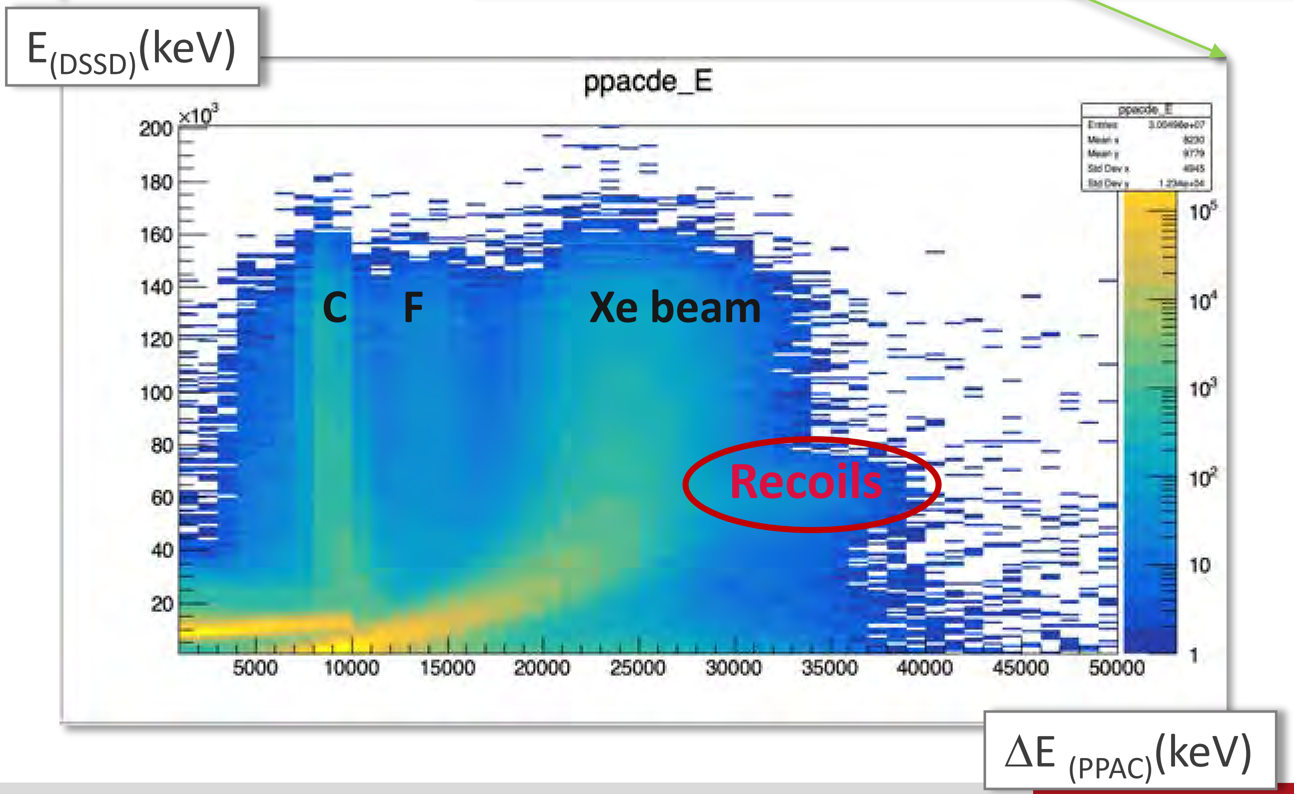
Identification of neutron-rich nuclei (recoils)



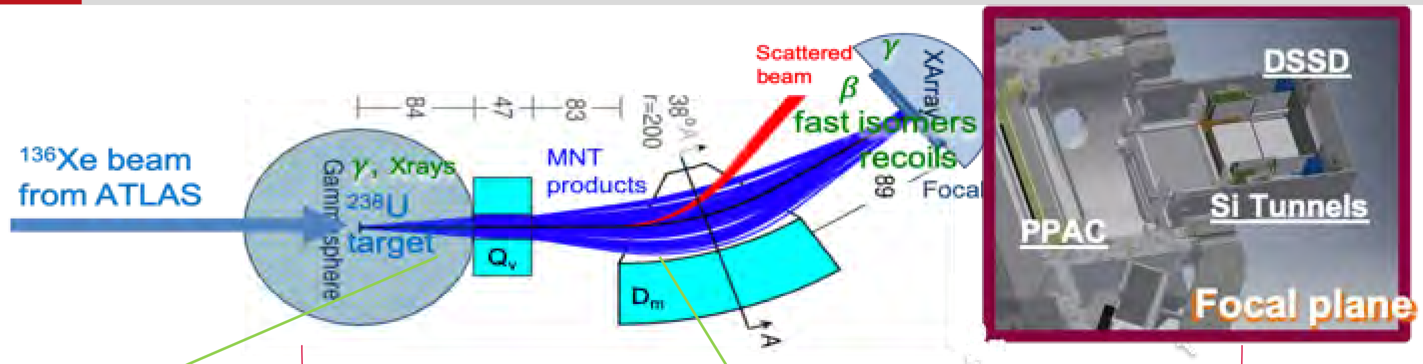
Method:

- The implantation energy in the DSSD
- The energy loss in the PPAC (PPACDE or EPPAC);
- The X dispersion in the horizontal direction at the focal plane, measured by the PPAC;





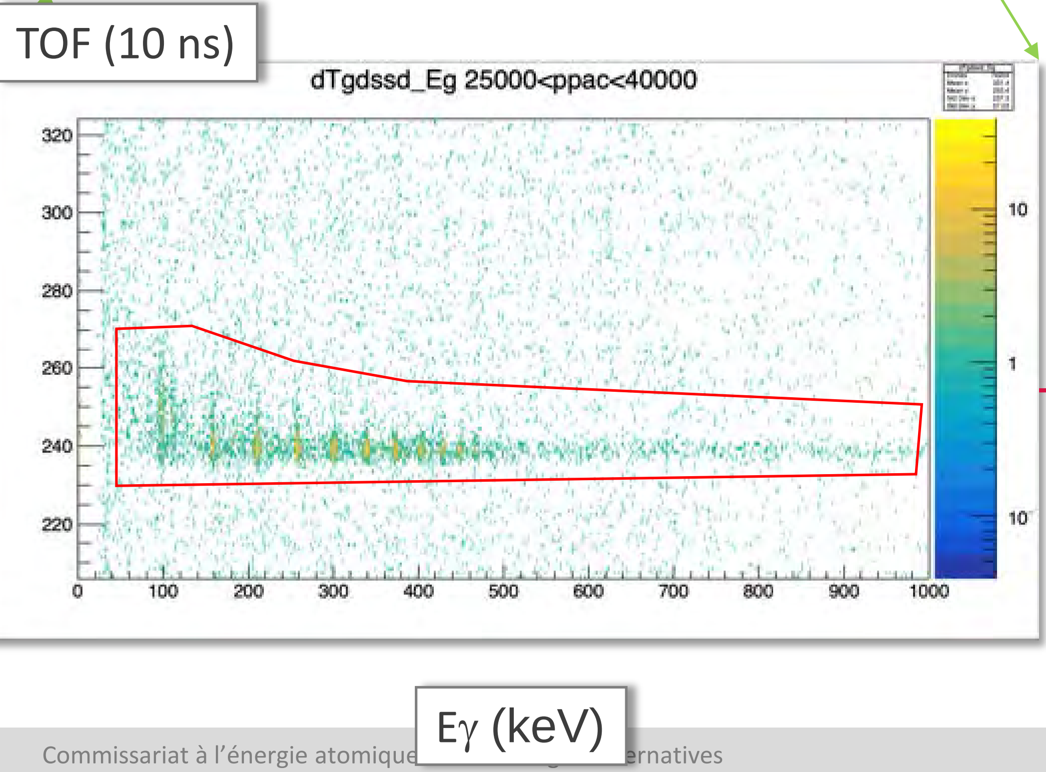
Identification of neutron-rich nuclei (recoils)- PRELIMINARY



Time Of Flight measurement
(GS-PPAC)

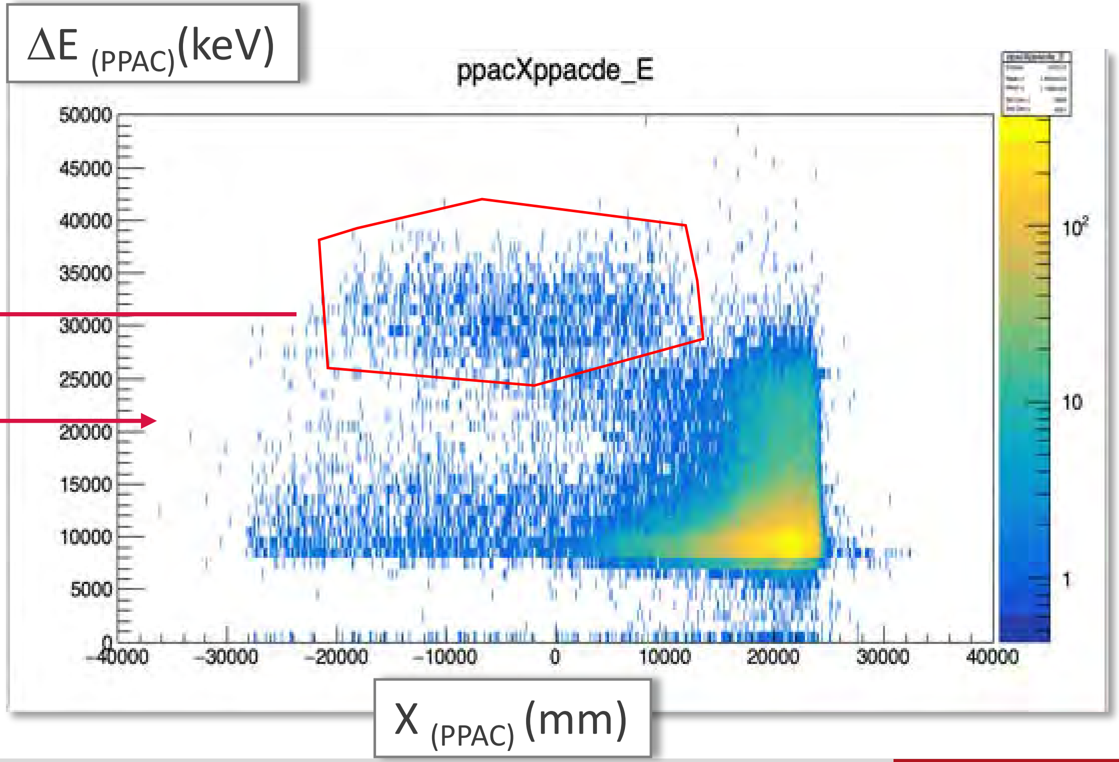
Method:

- The X dispersion in the horizontal direction at the focal plane, measured by the PPAC;
- The energy loss in the PPAC;
- The time of flight (TOF), between Gammasphere and the focal plane PPAC.



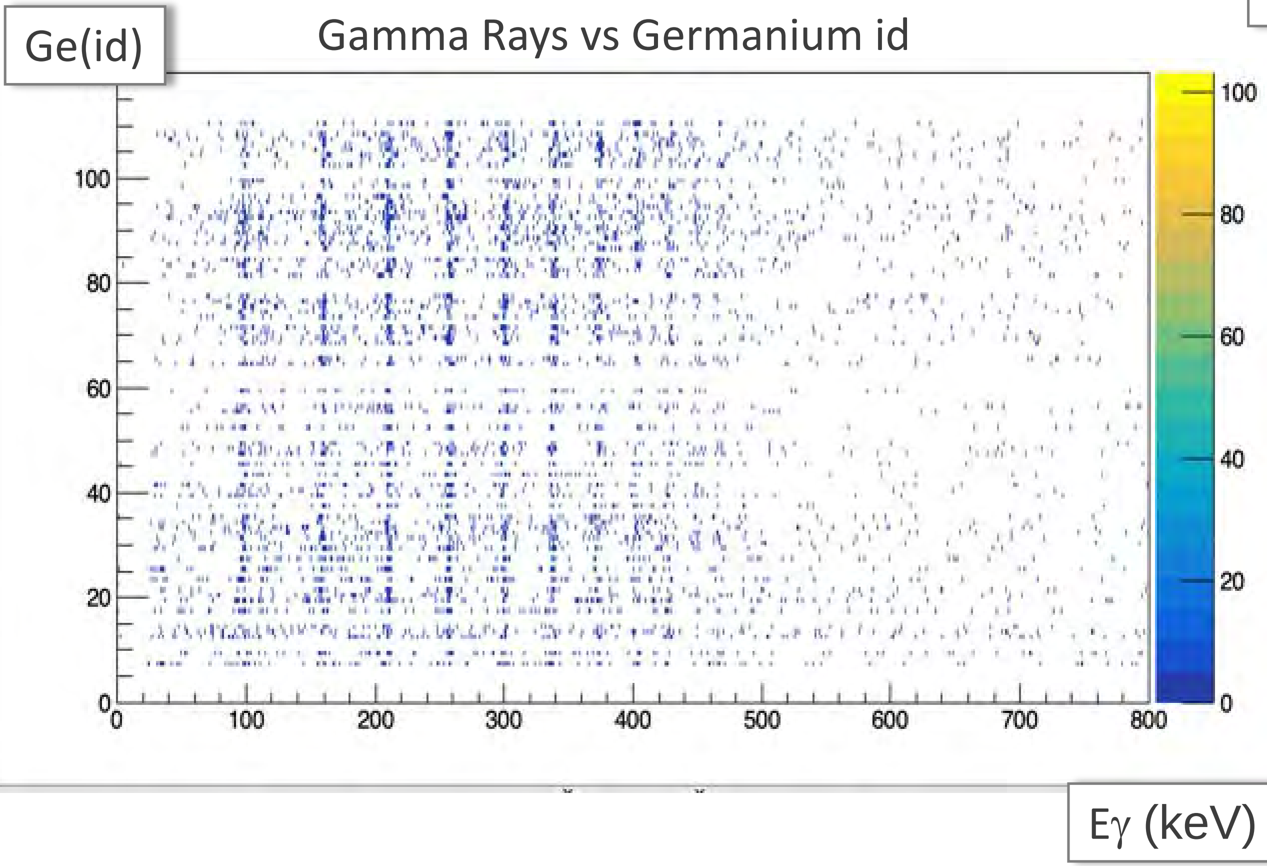
ΔE condition

TOF condition

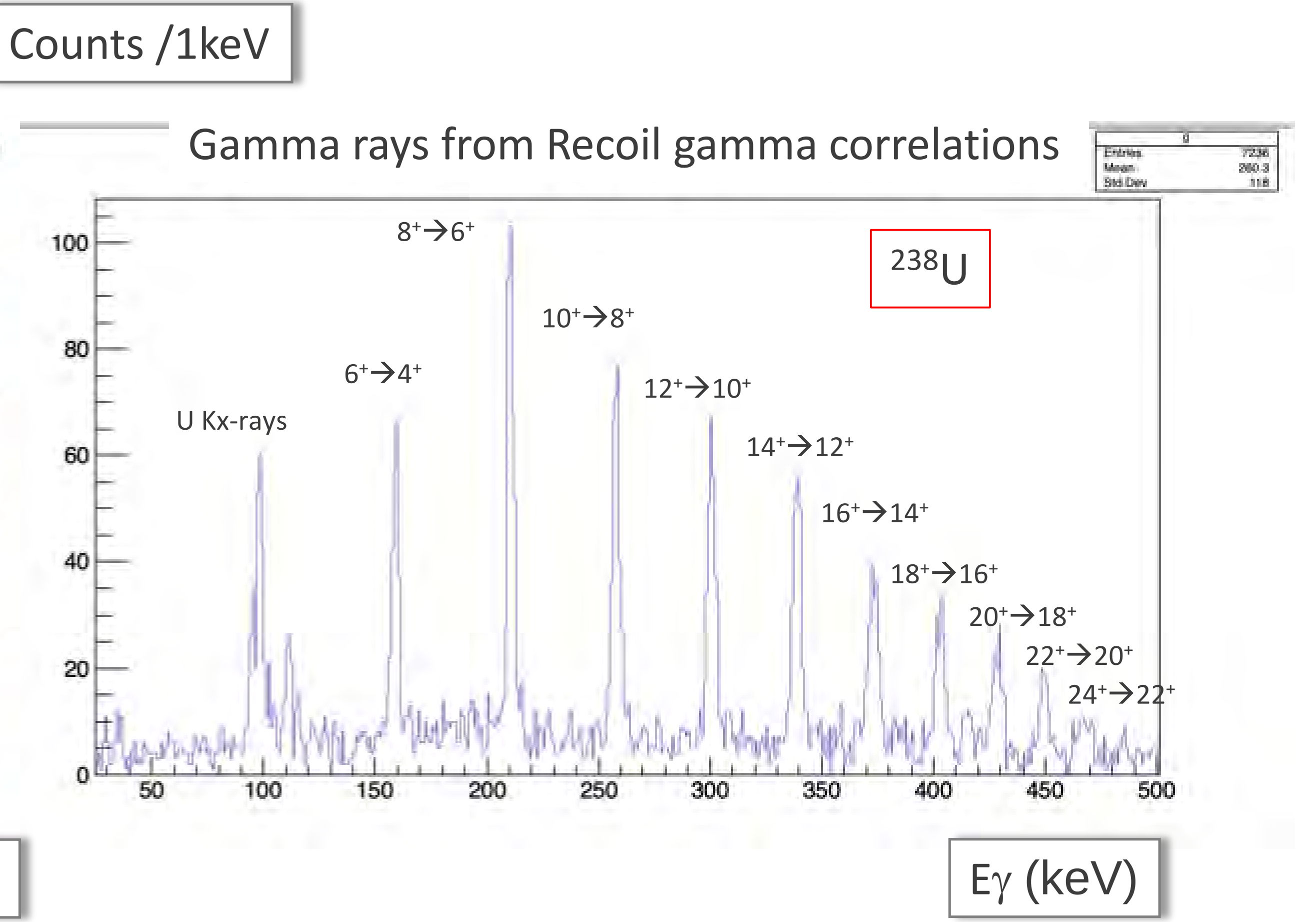


Identification of neutron-rich nuclei (recoils)

Recoil Gamma correlation – prompt gamma



Gamma Rays vs Germanium id

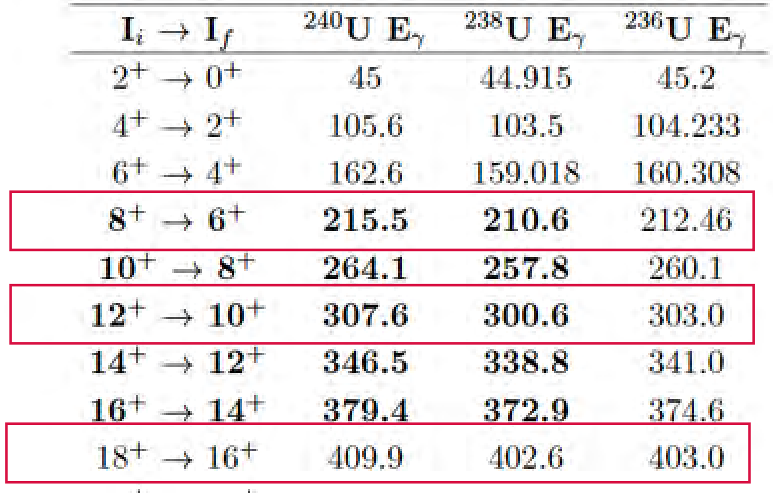


Gamma rays from Recoil gamma correlations

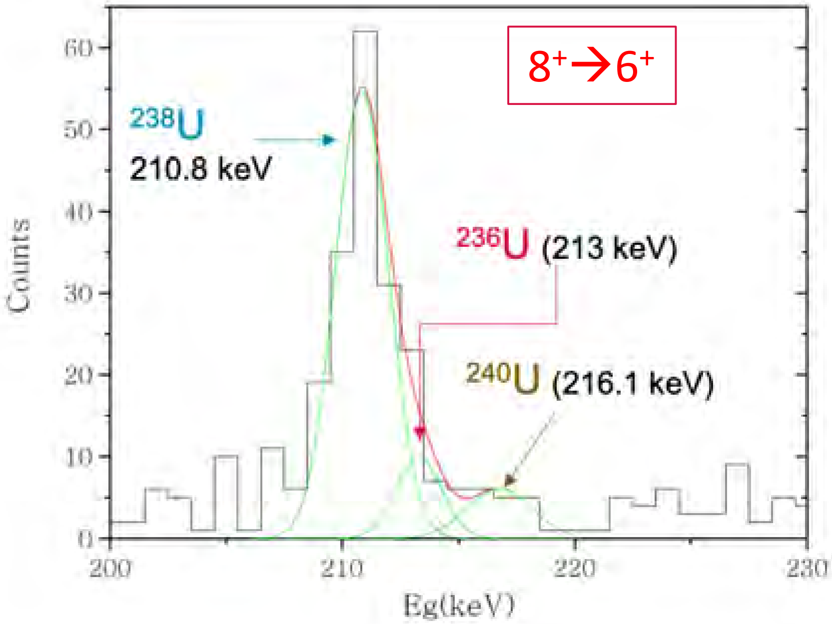
Recoil gamma correlations

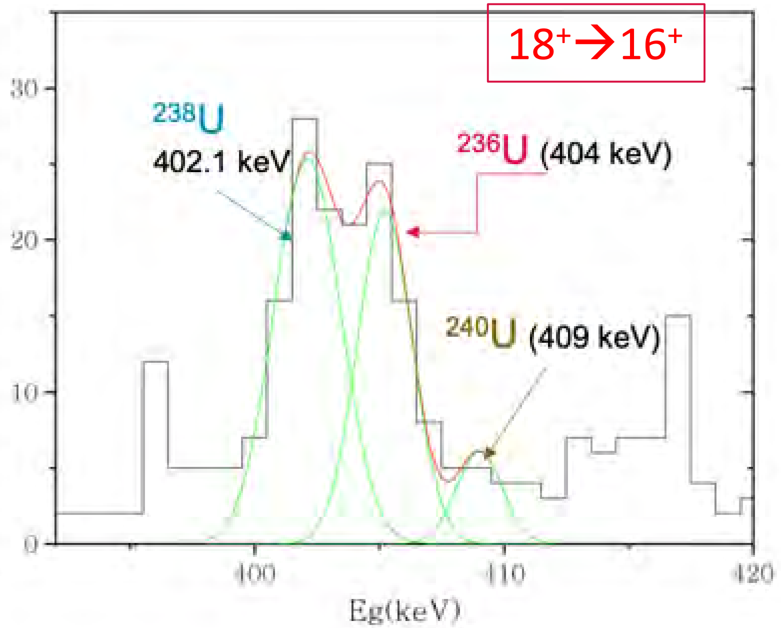
- Selecting the Recoils of interest (cuts: ΔE-E; TOF;ΔE-PPACX)
- Doppler correction
- Energy calibrated

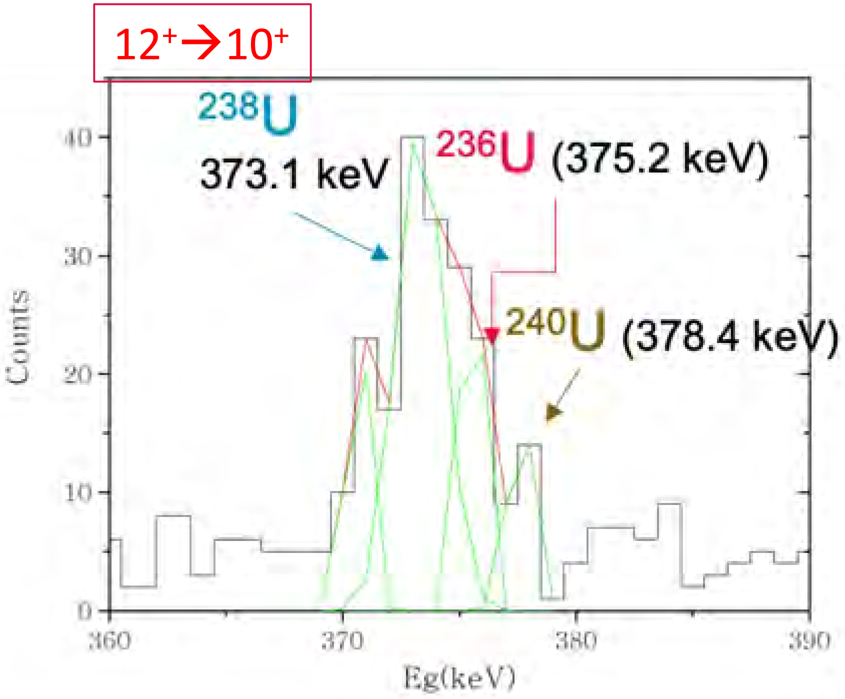
Difficulties in the analysis



$I_i \to I_f$	^{240}U E_γ	^{238}U E_γ	^{236}U E_γ
$2^+ \to 0^+$	45	44.915	45.2
$4^+ \to 2^+$	105.6	103.5	104.233
$6^+ \to 4^+$	162.6	159.018	160.308
$8^+ \to 6^+$	215.5	210.6	212.46
$10^+ \to 8^+$	264.1	257.8	260.1
$12^+ \to 10^+$	307.6	300.6	303.0
$14^+ \to 12^+$	346.5	338.8	341.0
$16^+ \to 14^+$	379.4	372.9	374.6
$18^+ \to 16^+$	409.9	402.6	403.0



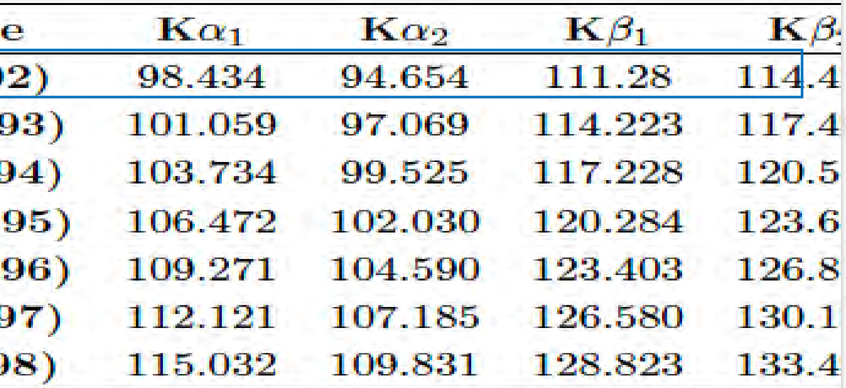




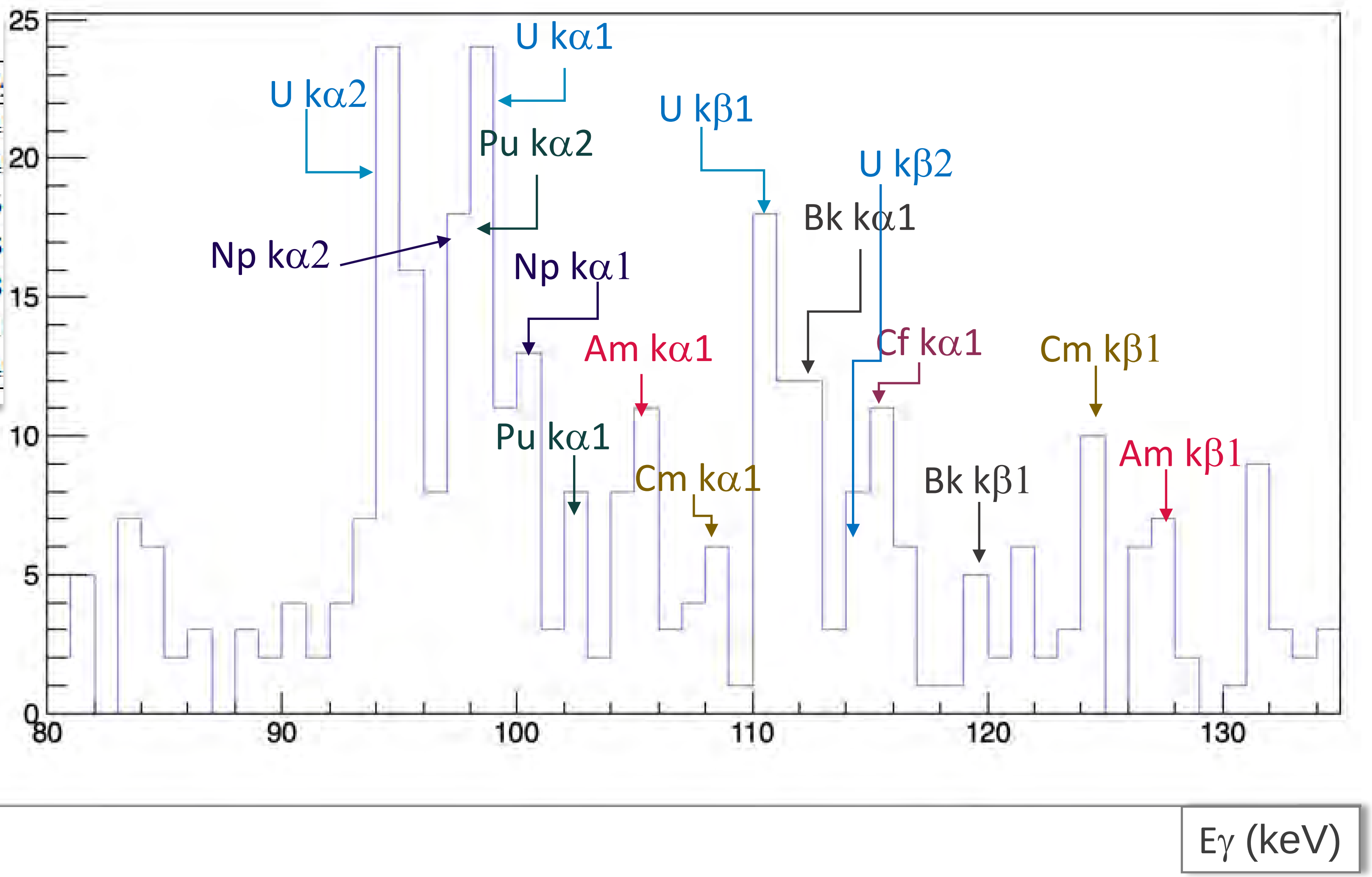
The gamma-ray energies of these uranium isotopes are very close to each other.

Need extremely good energy resolution of GAMMASPERE!

Identification of neutron-rich nuclei (recoils)
Zoom on K X-rays

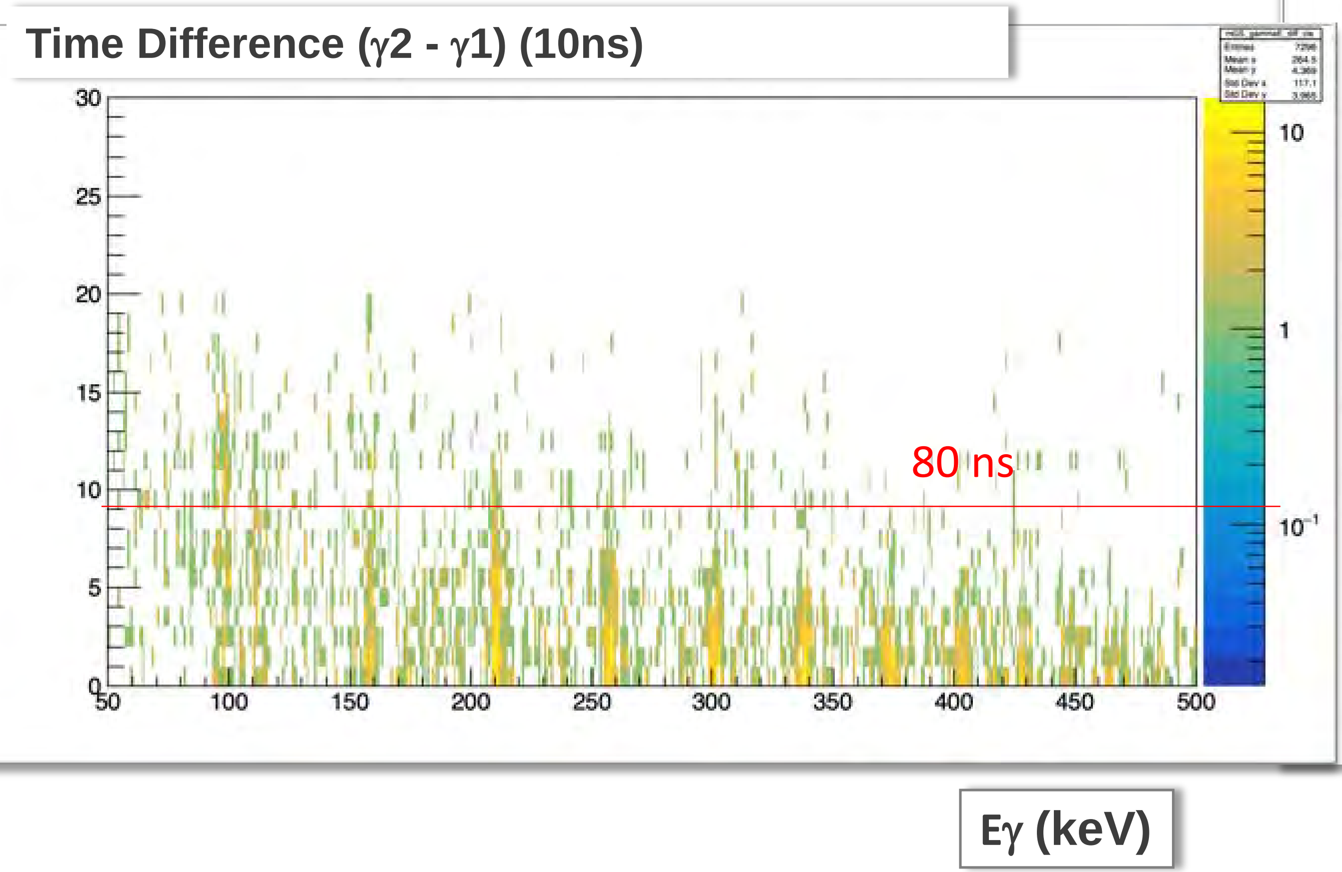


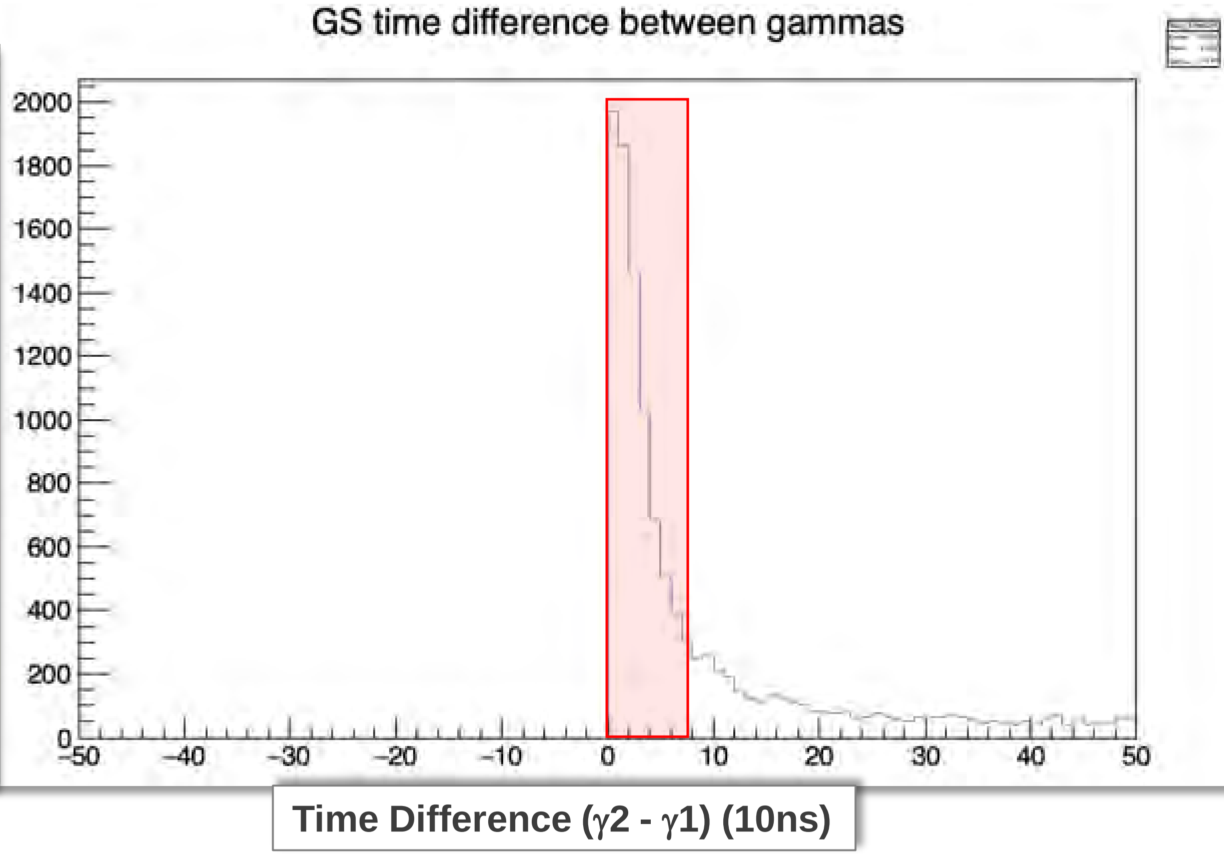
e	$K\alpha_1$	$K\alpha_2$	$K\beta_1$	$K\beta$
2)	98.434	94.654	111.28	114.4
93)	101.059	97.069	114.223	117.4
94)	103.734	99.525	117.228	120.5
95)	106.472	102.030	120.284	123.6
96)	109.271	104.590	123.403	126.8
97)	112.121	107.185	126.580	130.1
98)	115.032	109.831	128.823	133.4



Identification of neutron-rich nuclei (recoils)

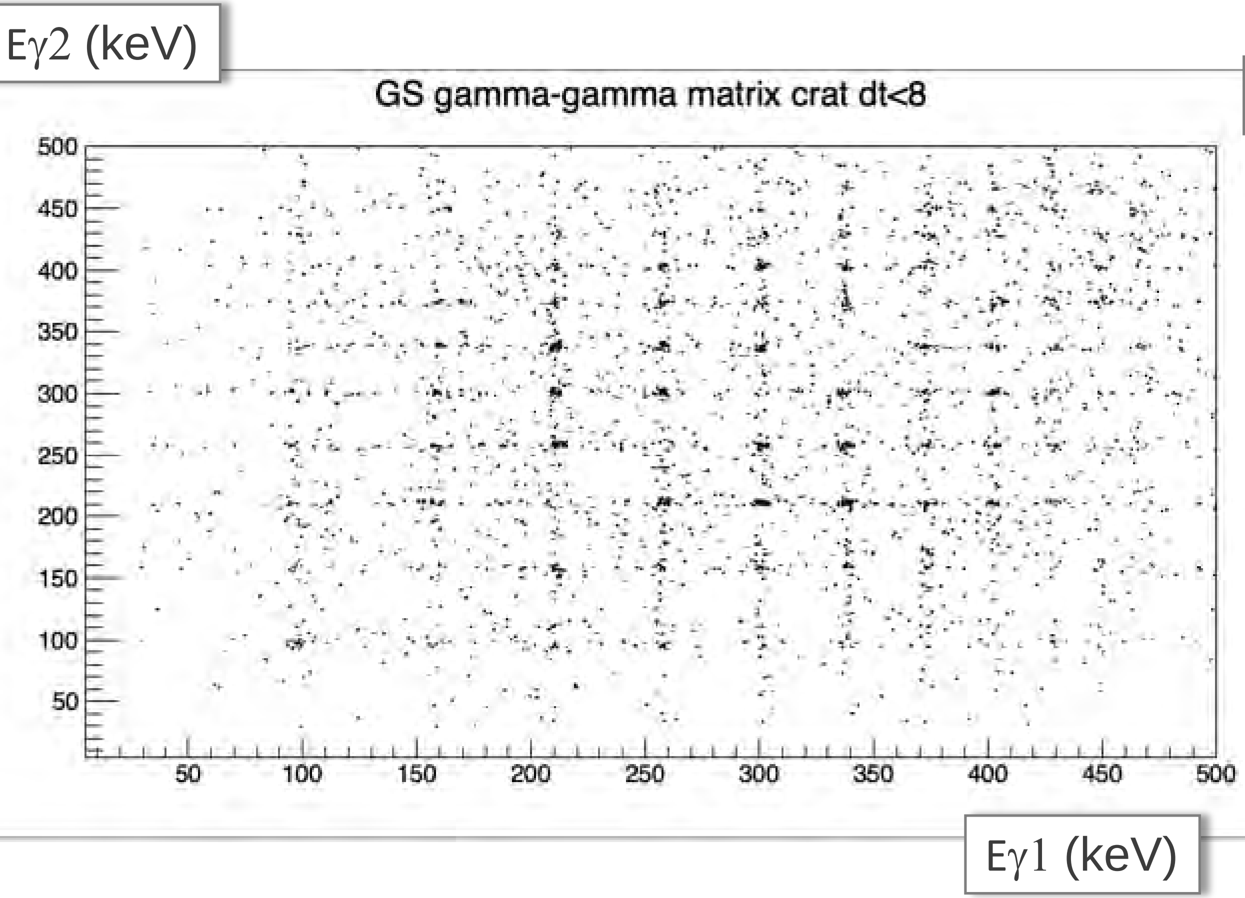
Recoil Gamma – Gamma correlation



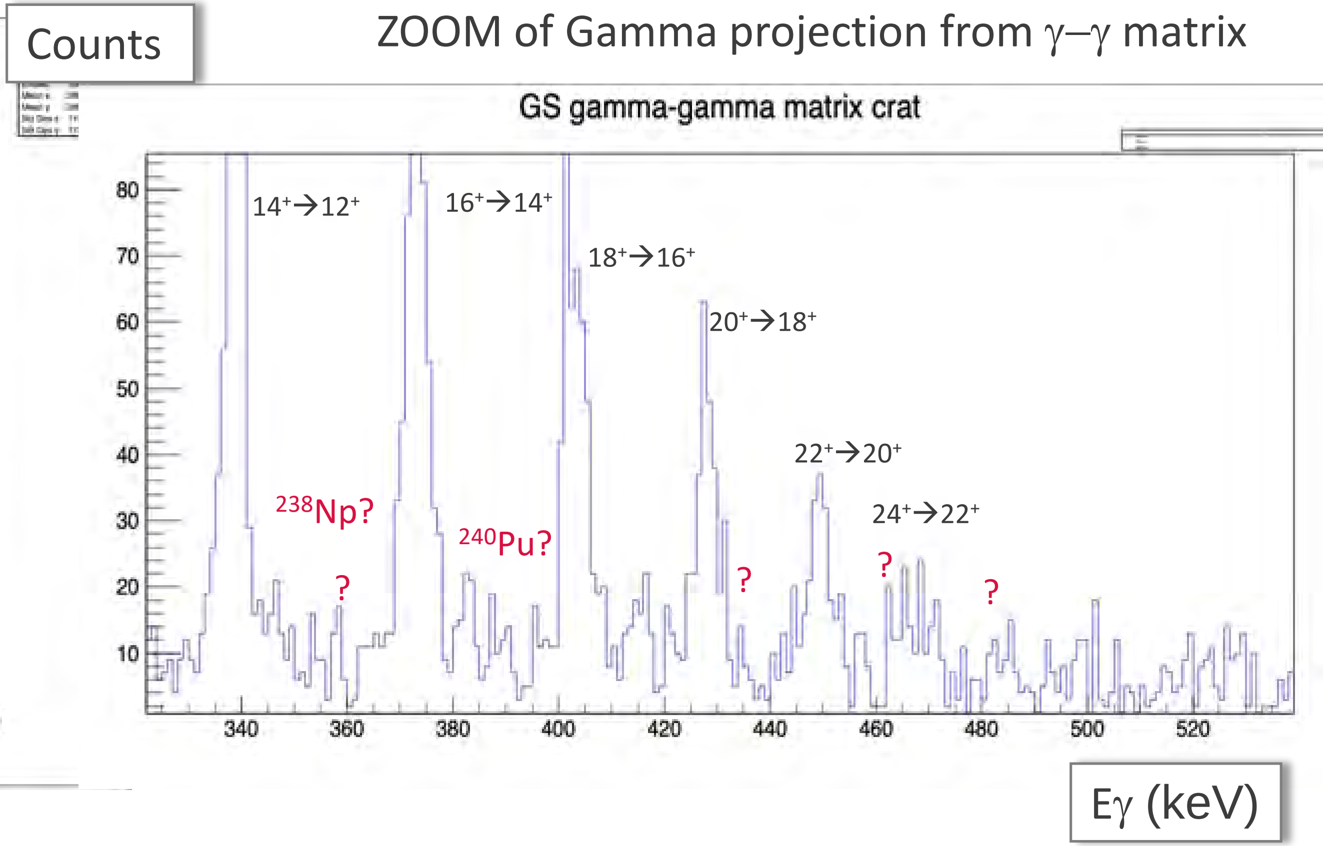


Condition for the two consecutive gamma rays to be considered in coincidences → 80 ns

Identification of neutron-rich nuclei (recoils)
Recoil Gamma – Gamma correlation

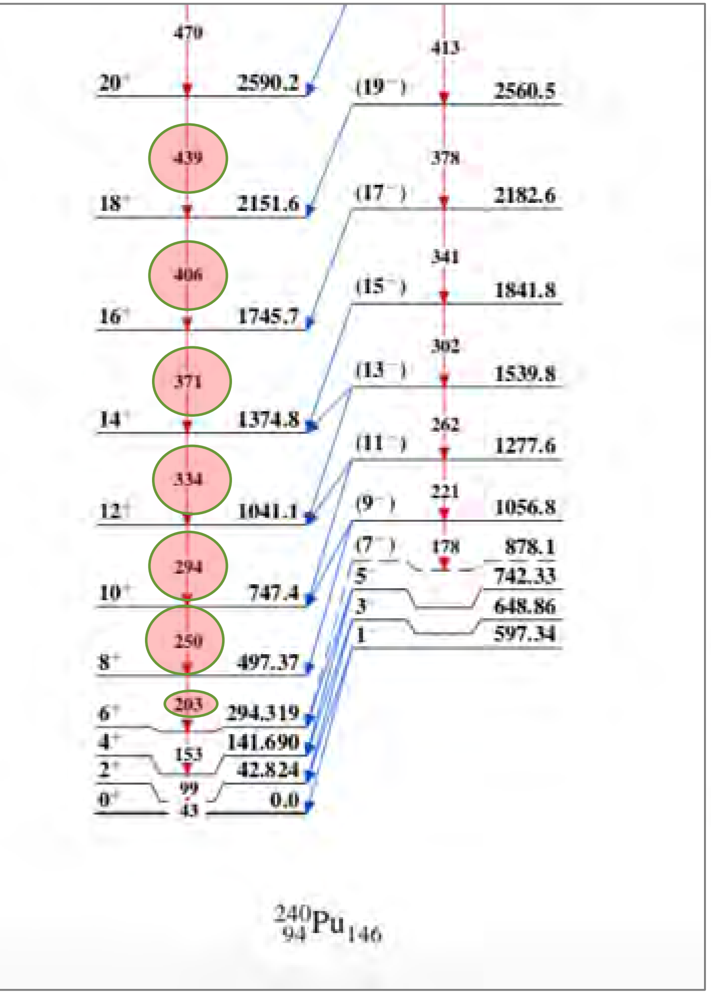


ZOOM of Gamma projection from γ–γ matrix

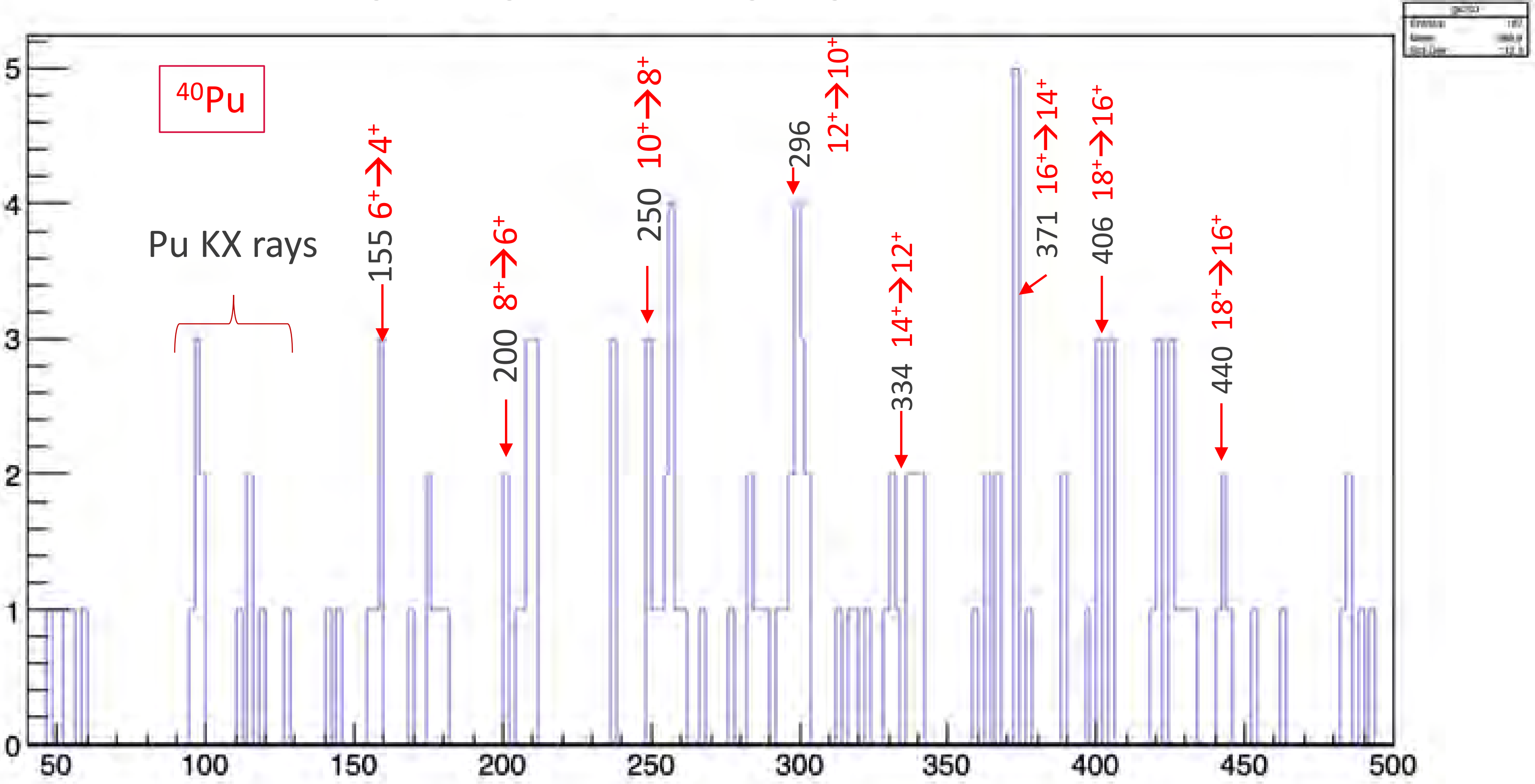


- ➢ The gamma matrix is built selecting the gammas in coincidence inside Gammasphere, i.e. if two gammas that are emitted in less than 80 ns then we select these events and fill the symmetrical matrix.

Example of level of statistics



Recoil gamma gamma-^{240}Pu- gating on 203 & 250 & 294 keV

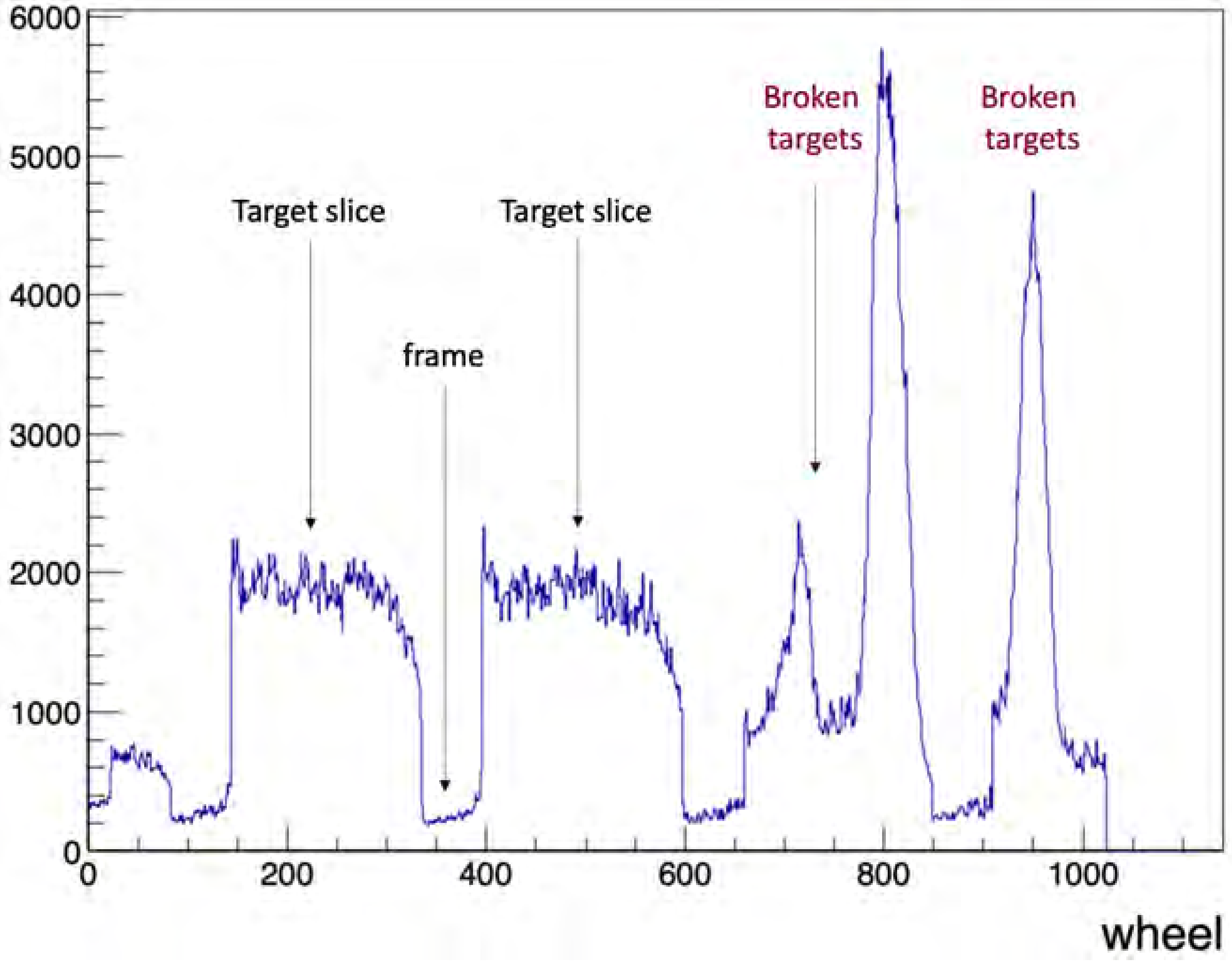


Run only 38 h at 2 pnA →Need more statistics

Towards heavy elements via MNT reaction

- **Physics motivations**
- **TEST experiment at Argonne: $^{136}Xe+^{238}U$ at 0°**
  - Theoretical computations
  - Simulations
  - Experimental set-up
- **First results**
- **Limits, perspectives and outlooks**

Main limits in the test experiment



Lack of statistics

Shift lost due to:

- DAQ issues (reboot IOTs)
- broken targets (mechanical constraints)

had to vent, open the target chamber…

Limitations :

- UF_4 targets, old and fragile (20pnA→2pnA)
- Frequency in the GS crystals (fissions)
- 70/110 working detectors of GS
- bad resolution of the GS crystals
- can not rely on alphas
- no mass identification

New experiment accepted in 2021

Conclusion & outlook

- **In the test experiment we ran at 605 MeV (1.15 VC), at 705 MeV (1.35 VC) and at 809 MeV (1.55 VC) to perform an energy scan.**
- **The best experimental conditions were set for the second energy and we ran for 38 hours at beam energy 705 MeV and beam intensity 2.25 pnA in average at 3 torr:**
  - We collected 10000 recoils-gamma, within 38h at 2.25pnA
  - We observed several X rays from different heavy nuclei
  - Hint for the decay of ^{240}Pu;

- **New experiment accepted in 2021 – Planned in summer 2022 :**

  New metallic targets manufactured at GSI (thanks to B. Lomel, B. Kindler, and their team)
  Annealing of some GS detectors: 70 → 110
  More beam intensity (from 2.25 to 20pnA)
  More gas pressure from 3 to 5 Torr in AGFA

- **Next step towards heavier nuclei using Cm targets**

- **Reflection on installing at AGFA a MR-TOF spectrometer for mass identification**

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Merci de votre attention

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