New paths for the study of heavy nuclei

Jonathan Bequet

New paths for the study of heavy nuclei

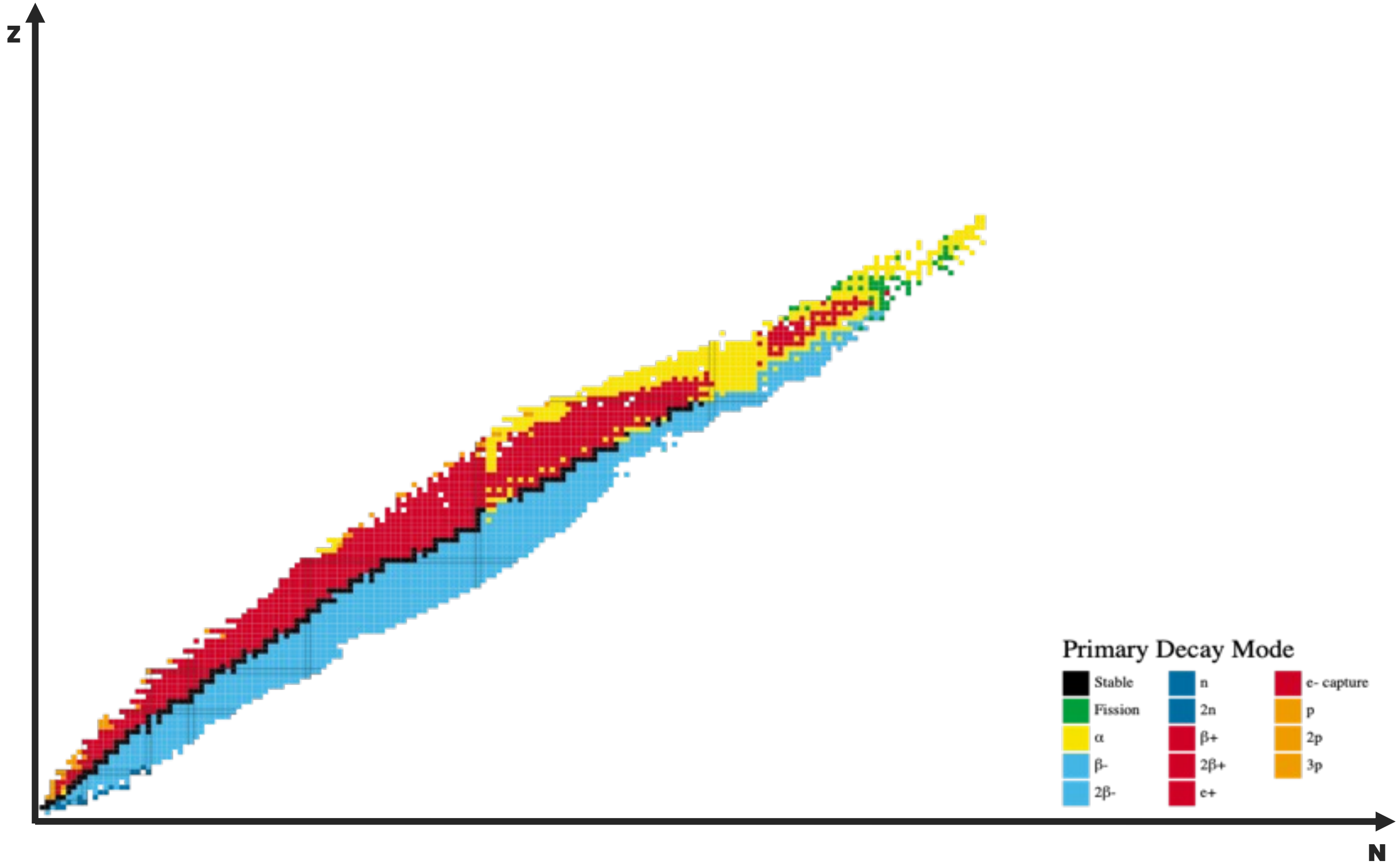
1. **Introduction to Multi-Nucleon Transfer (MNT) and motivations**

2. **The ^{136}Xe+^{238}U MNT experiment @ANL**

3. **Conclusion and outlooks**

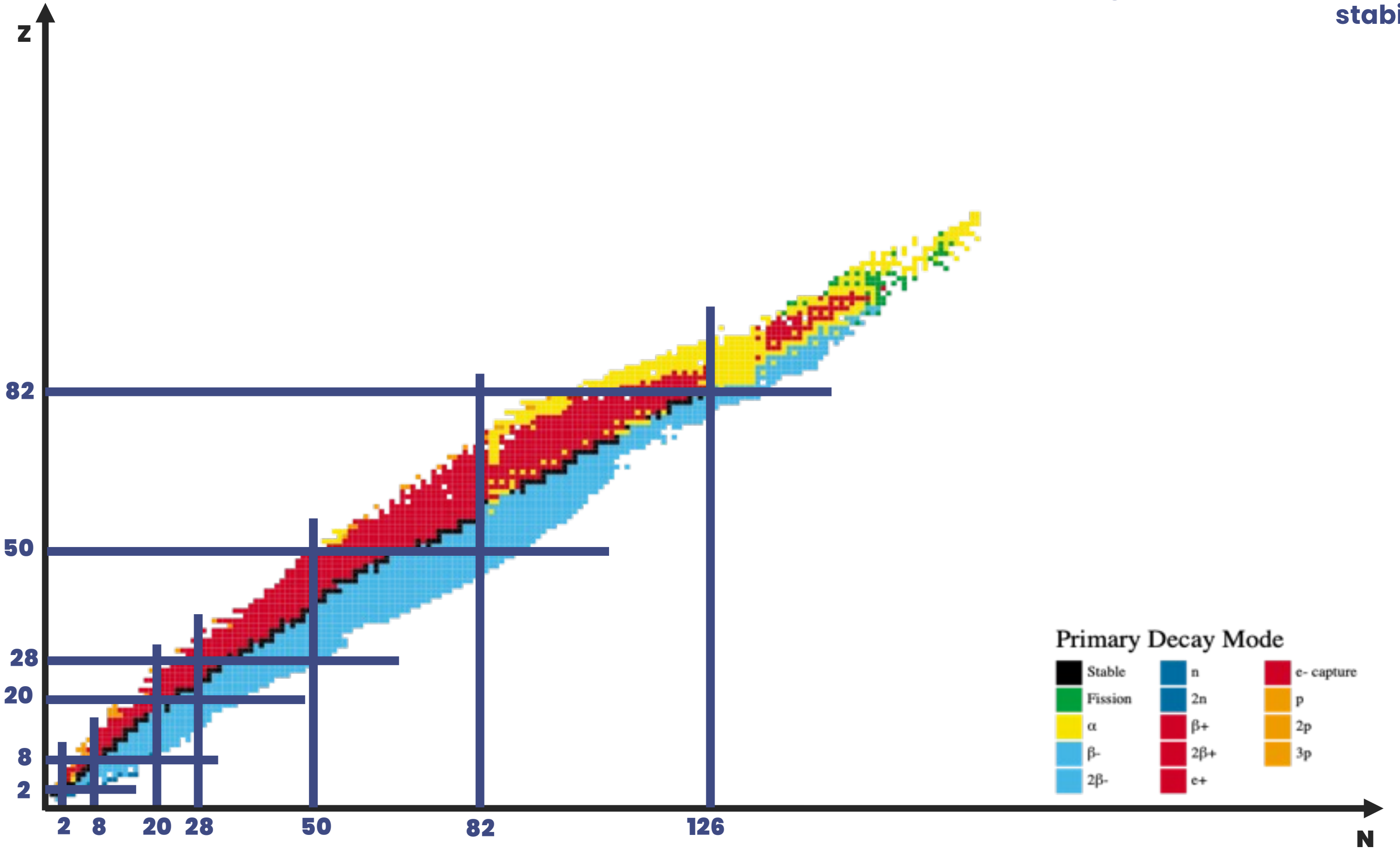
1. Introduction to MNT and motivations

Physics motivation for the study of MNT: The island of stability



Physics motivation for the study of MNT: The island of stability

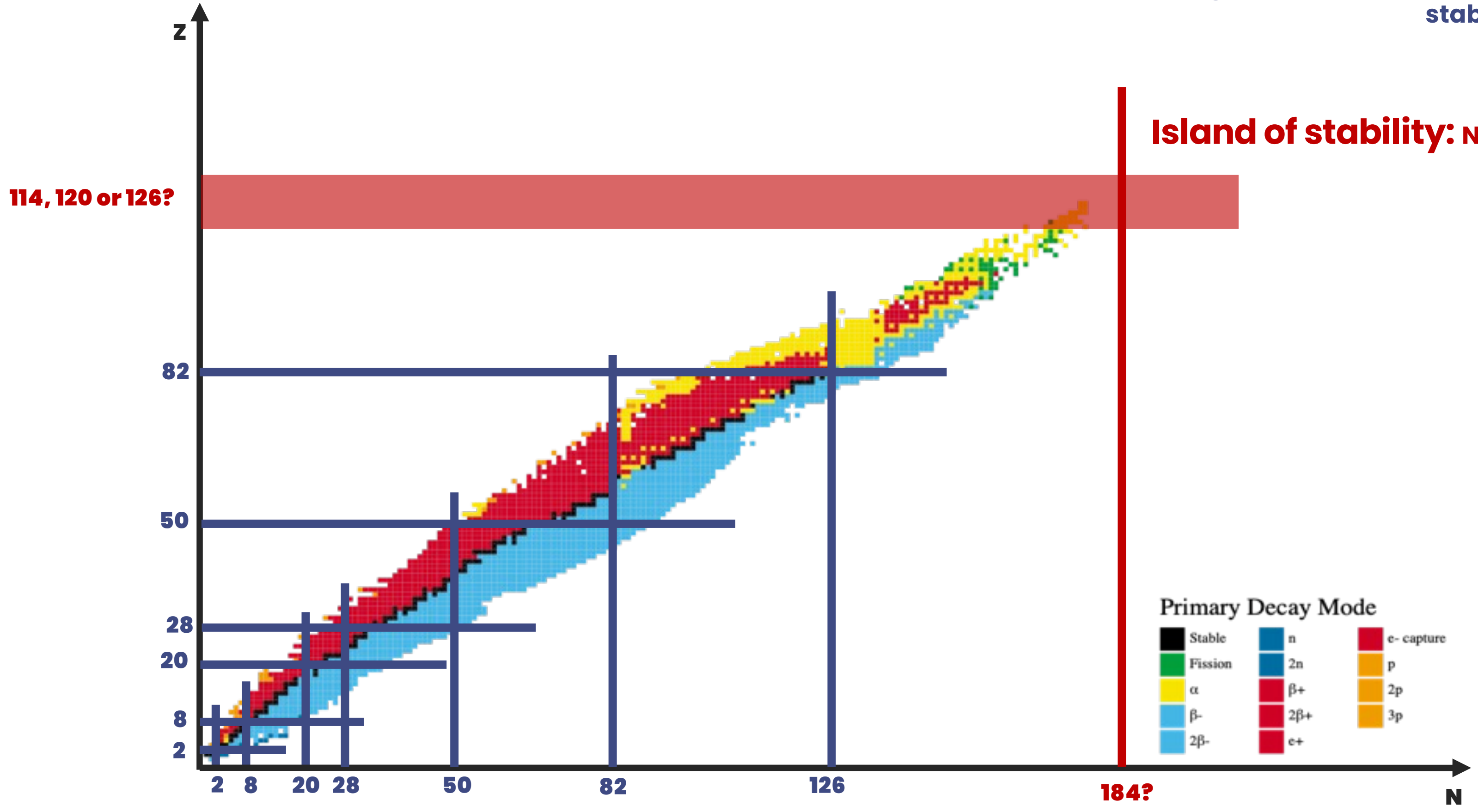
Magic number: the nucleus has an enhanced stability compared to its close neighbours



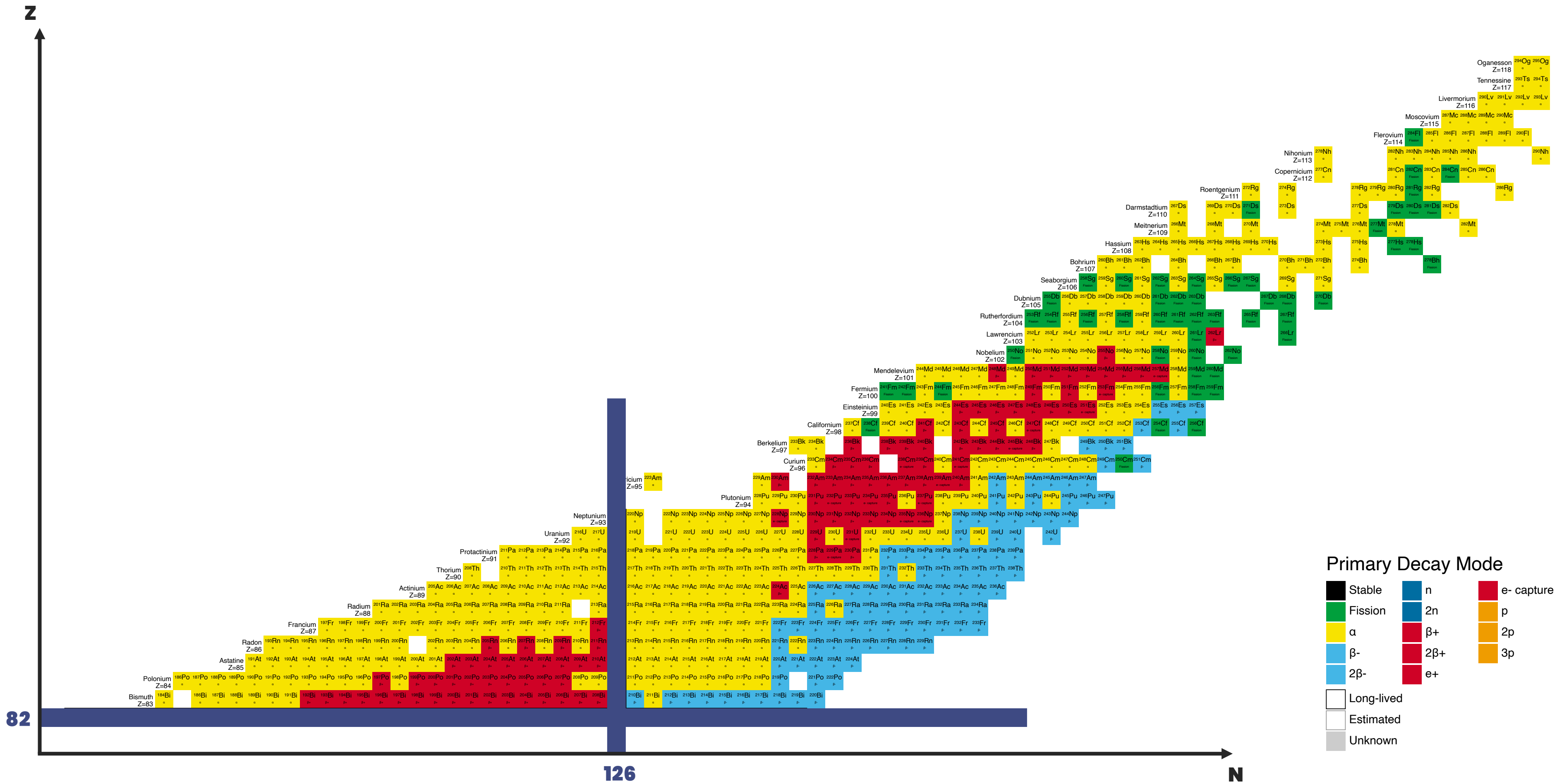
Physics motivation for the study of MNT: The island of stability

Magic number: the nucleus has an enhanced stability compared to its close neighbours

Island of stability: Next magic numbers according to theoretical predictions



Towards heavier nuclei : fusion-evaporation



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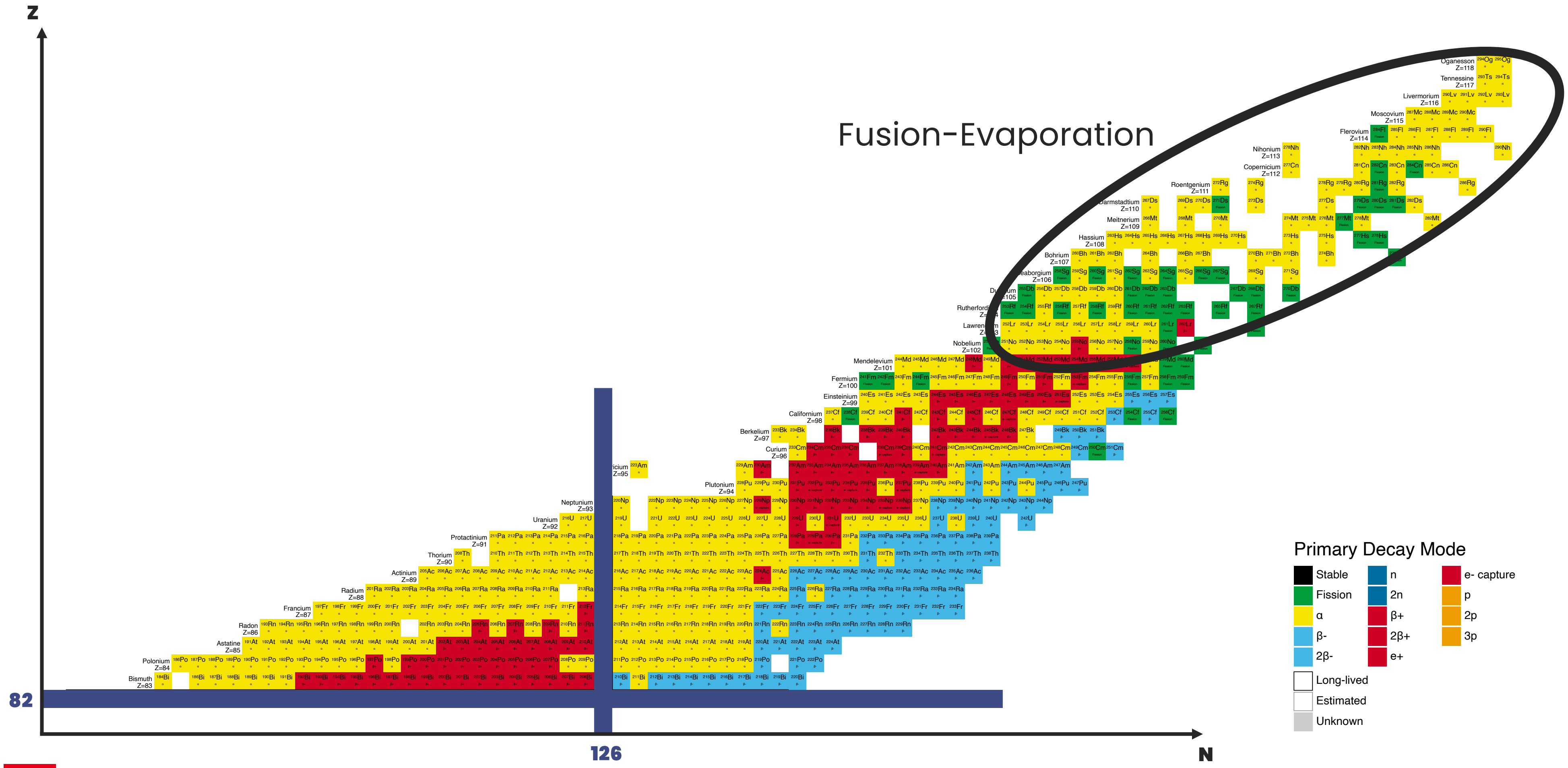

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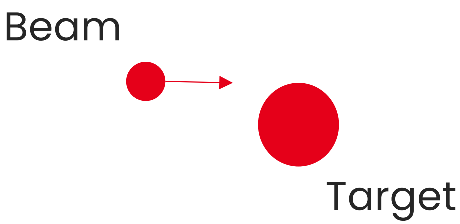

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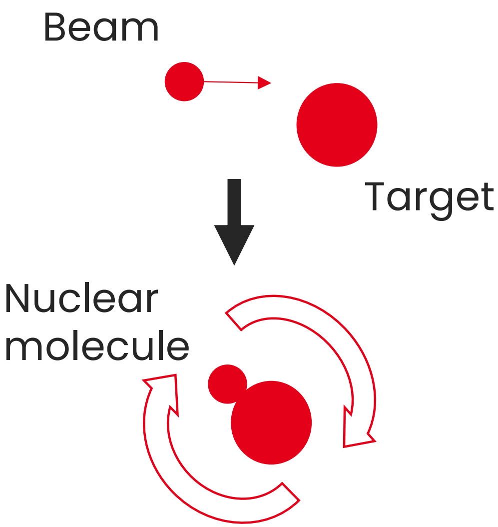

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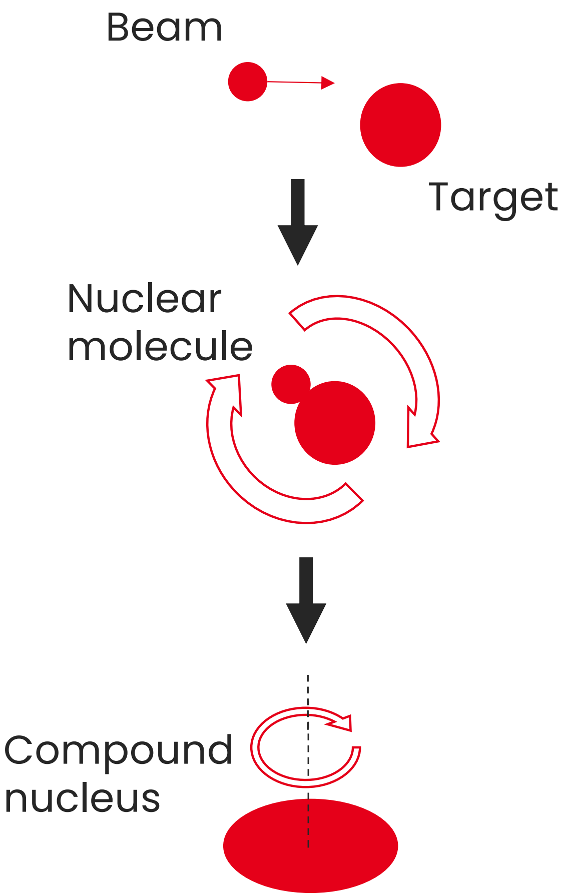

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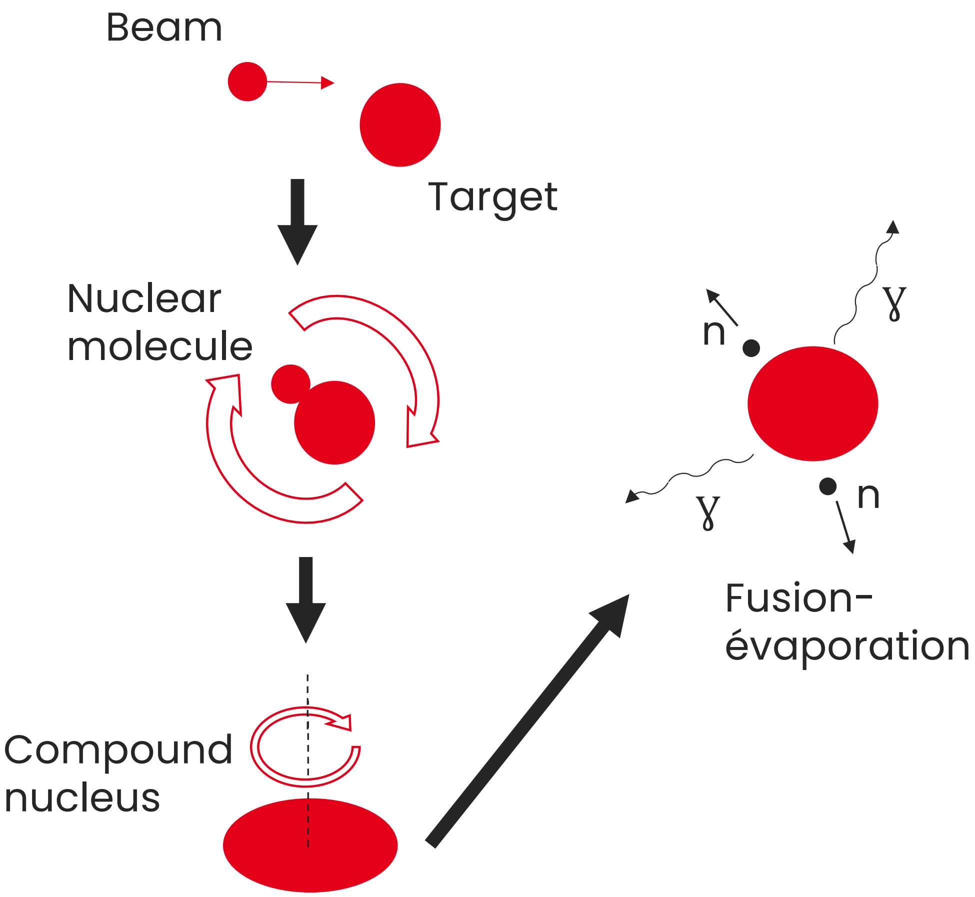
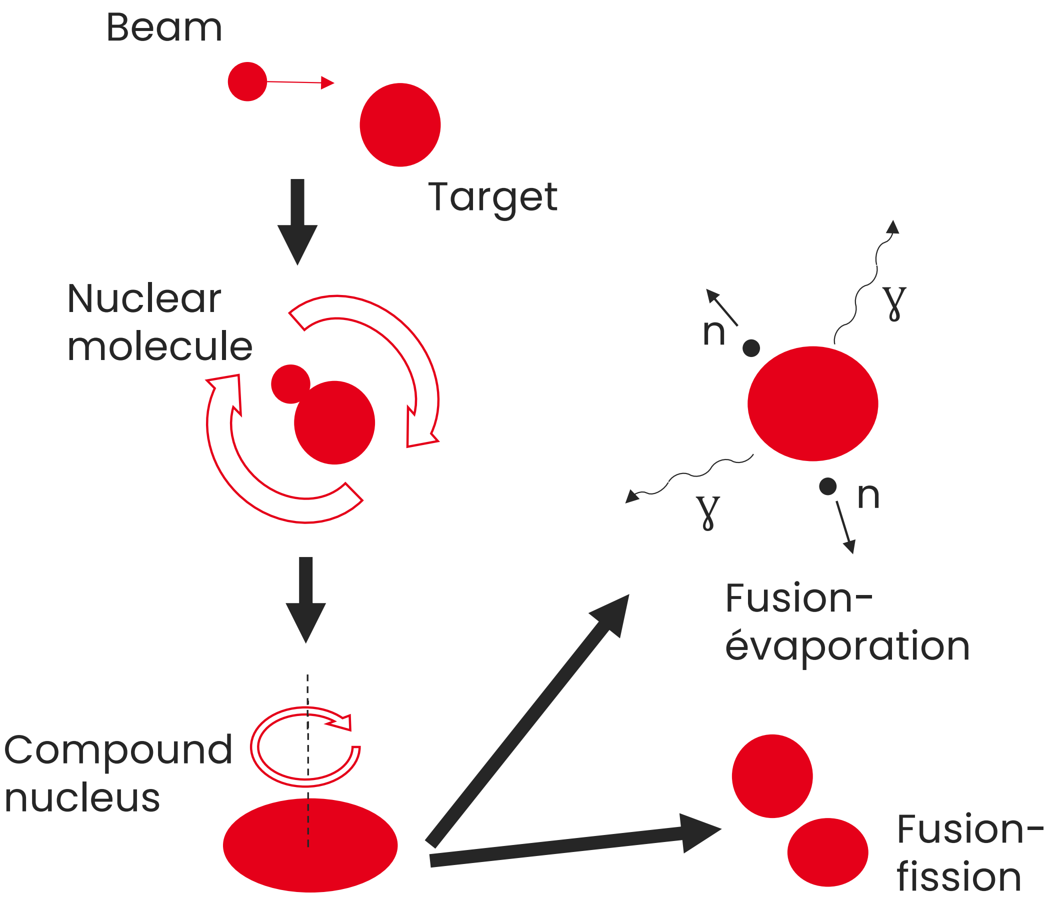
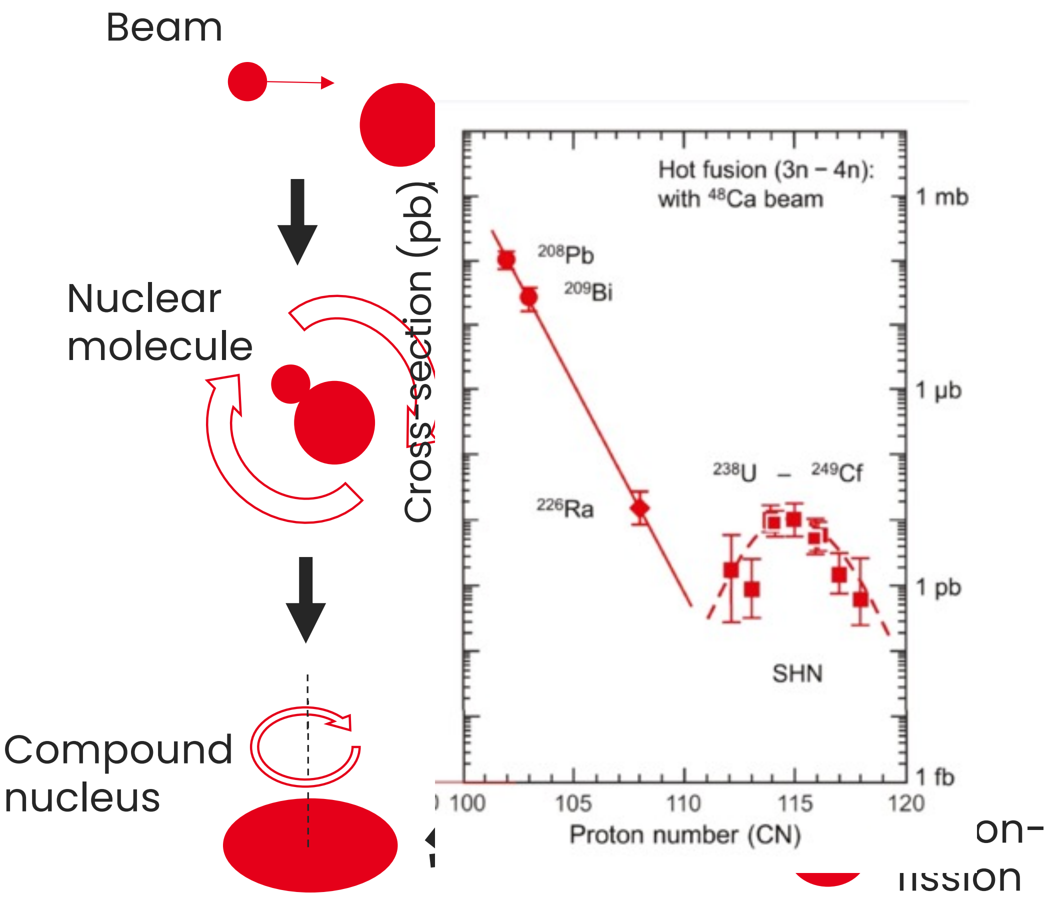


Towards heavier nuclei : fusion-evaporation

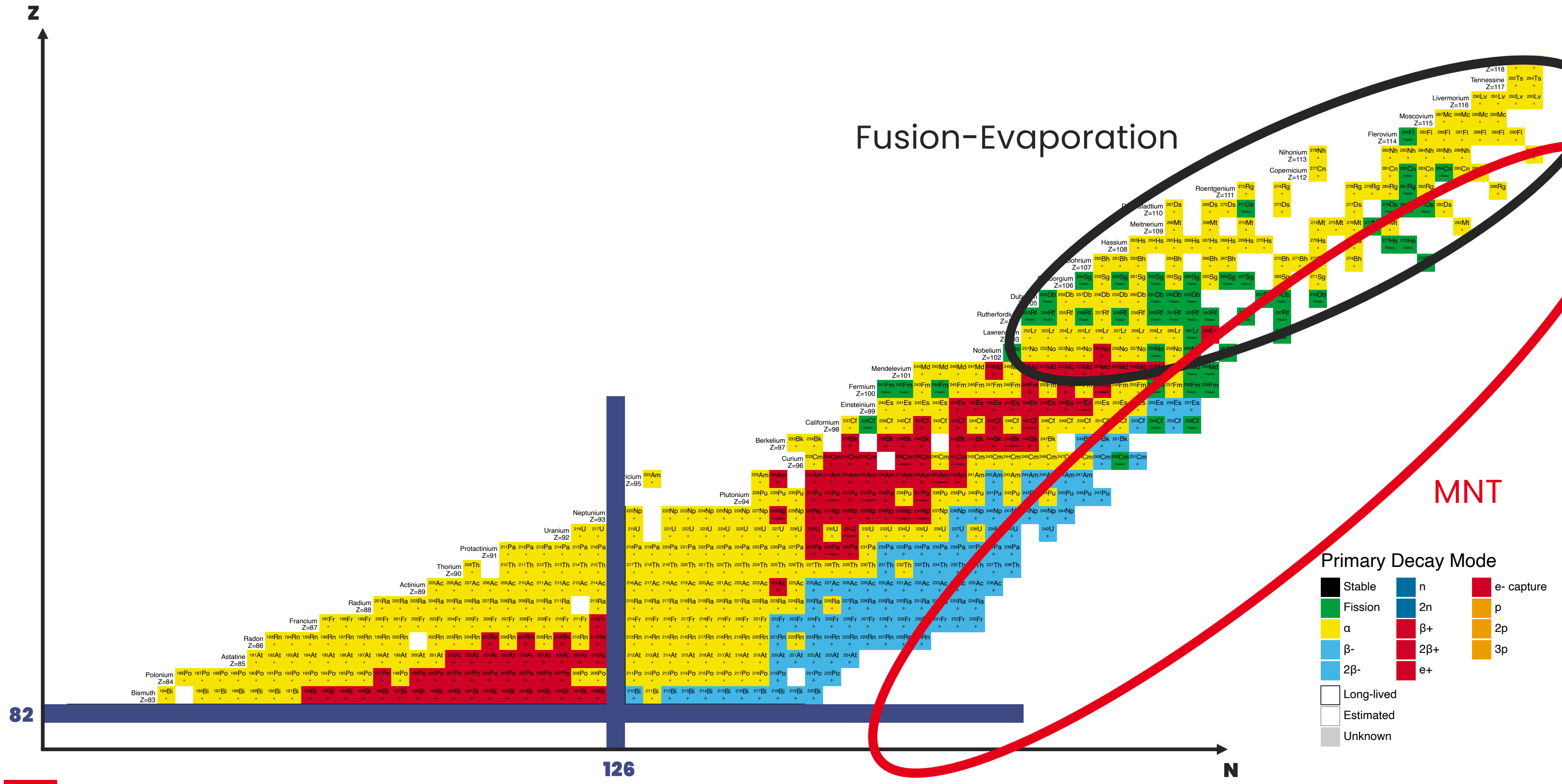


Towards heavier nuclei : fusion-evaporation

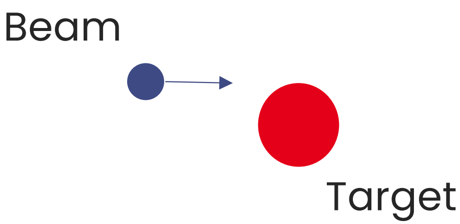


- The Beam/Target combinations are limited due to experimental constraints
- Low cross-sections for the heaviest produced nuclei
- **Problem: Produced nuclei are only neutron deficient**

MNT: a complementary mechanism



MNT: a complementary mechanism



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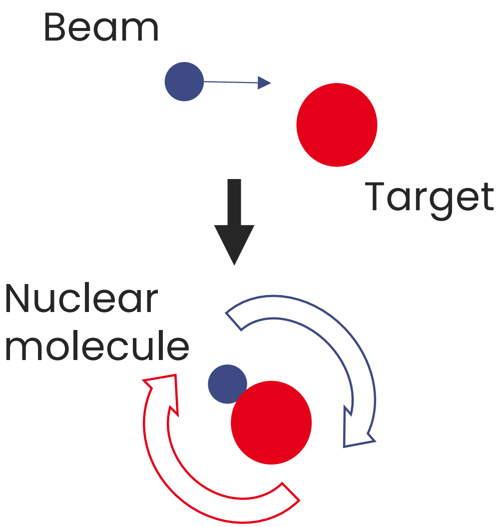

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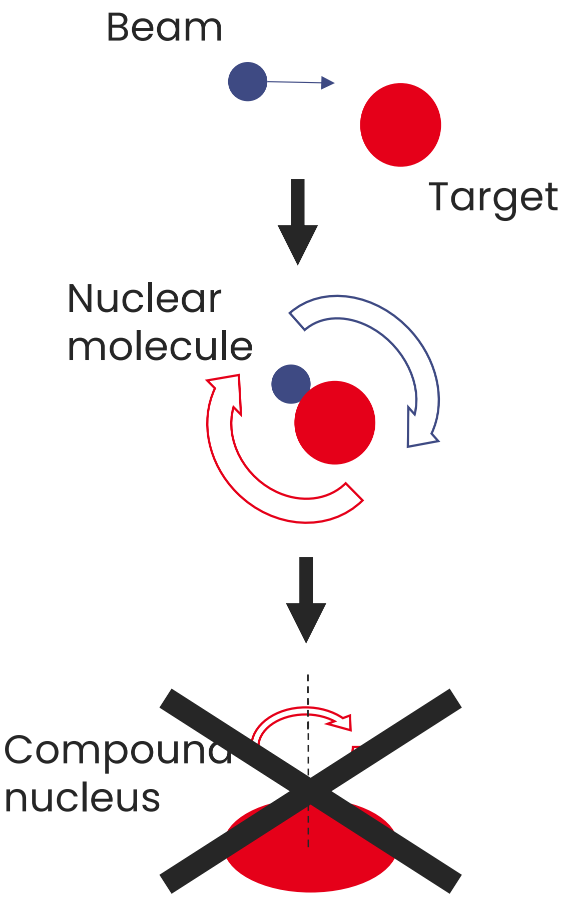

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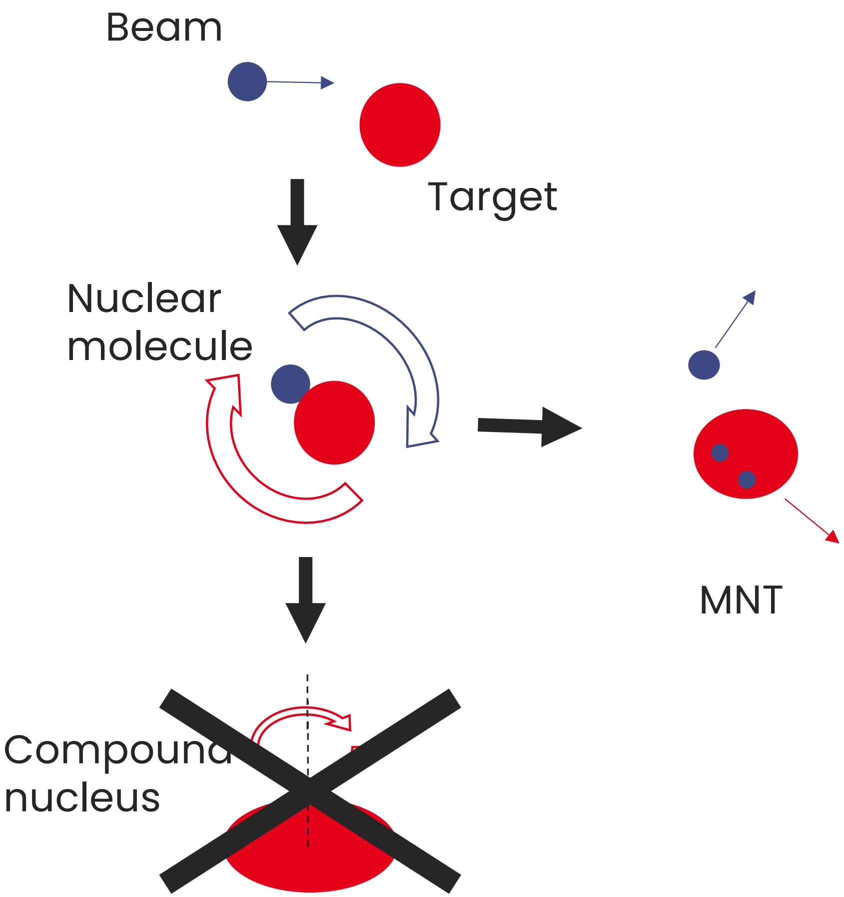

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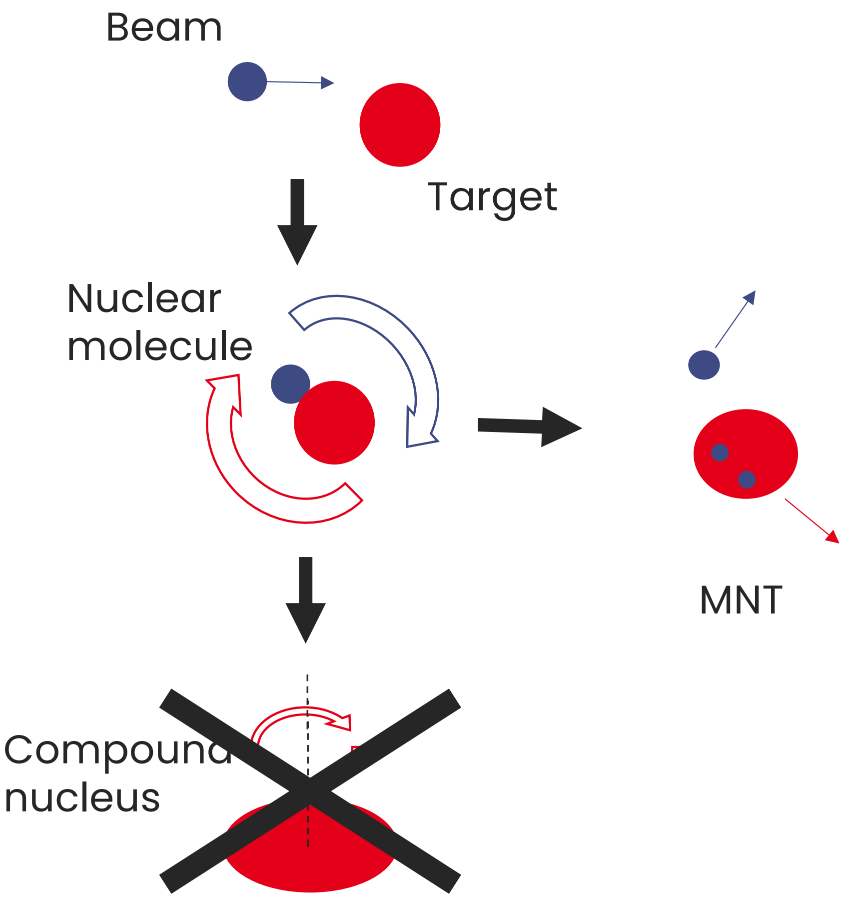
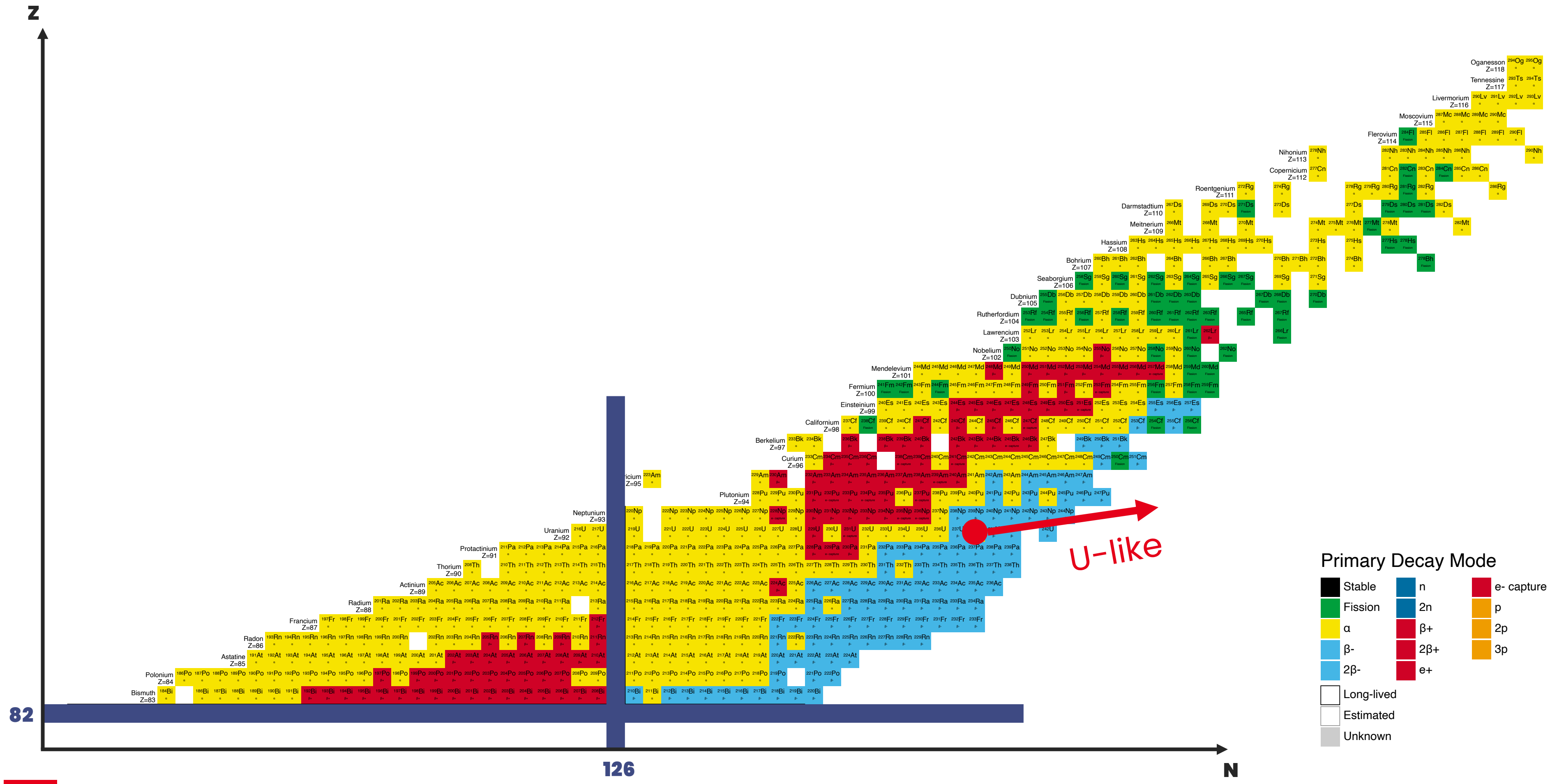


- Complementary to fusion-evaporation regarding the produced nuclei
- **Neutron rich nuclei are accessible**

2. The ^{136}Xe+^{238}U MNT experiment @ANL

MNT using ^{238}U



The experimental setup: $^{136}Xe+^{238}U$

- **Beam**: ^{136}**Xe** at 700 and 800 MeV

^{136}Xe beam
produced by ATLAS

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^{136}Xe beam
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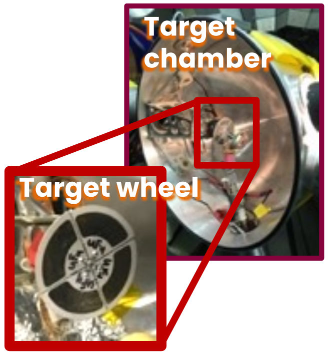
^{238}U
Target



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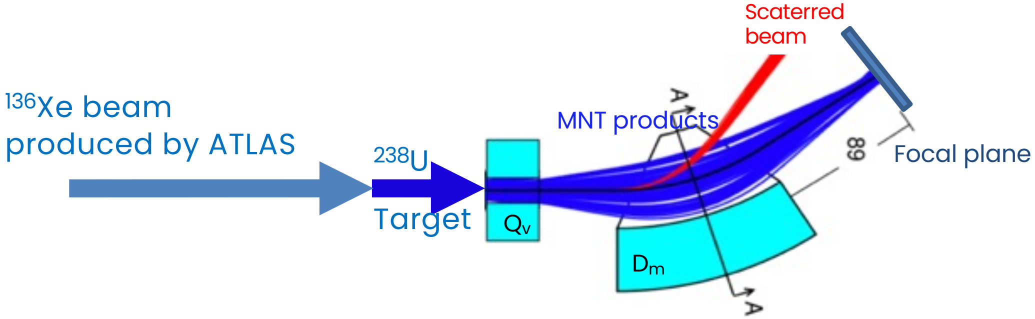

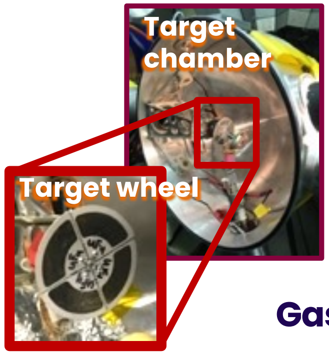

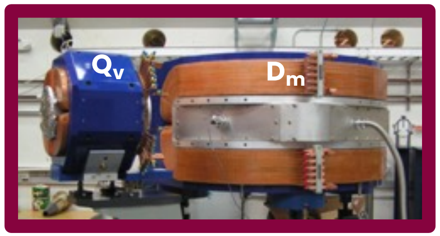

Gas-filled separator AGFA

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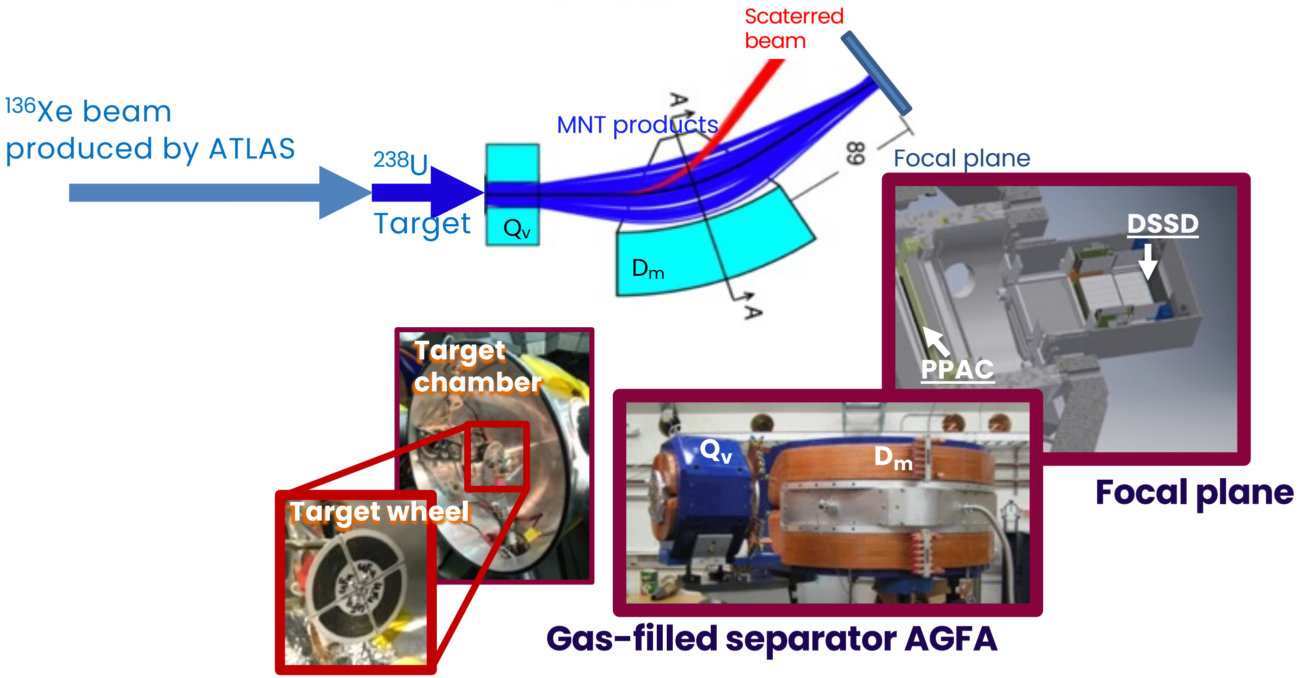
Quasi-target indentification
(coïncidences)



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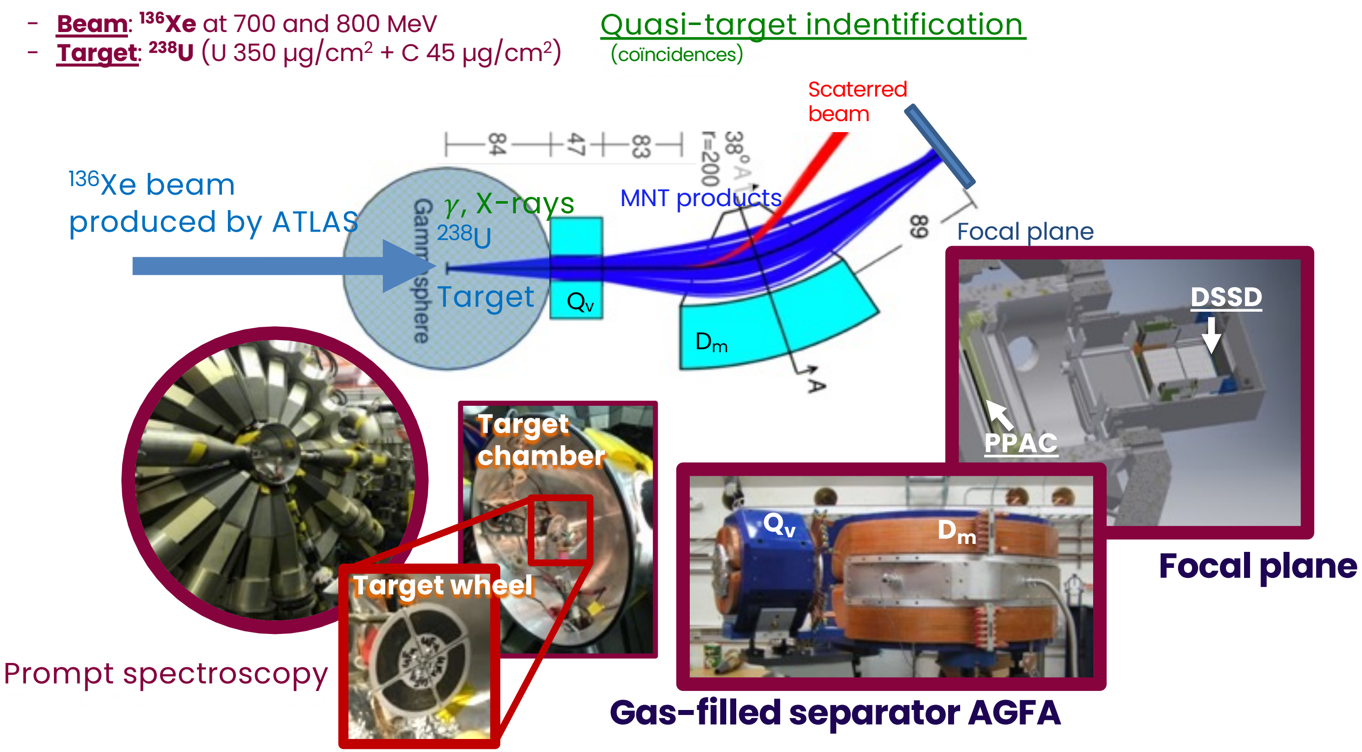

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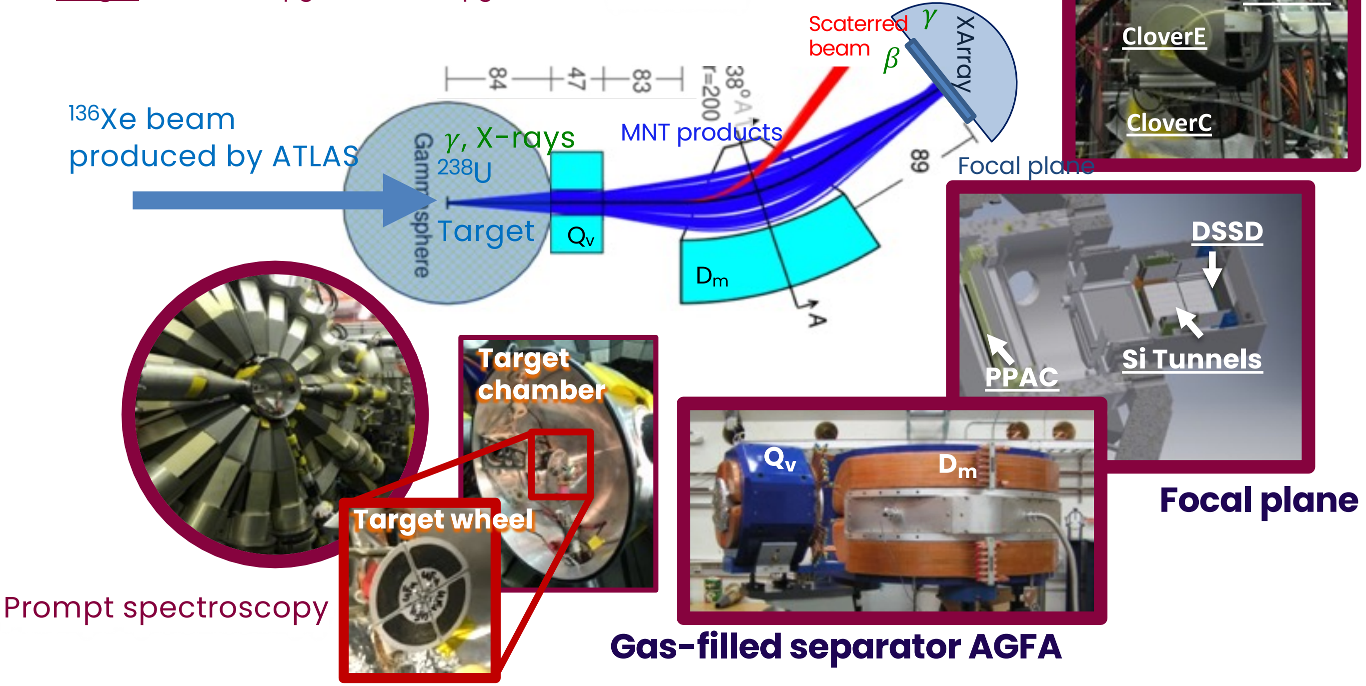
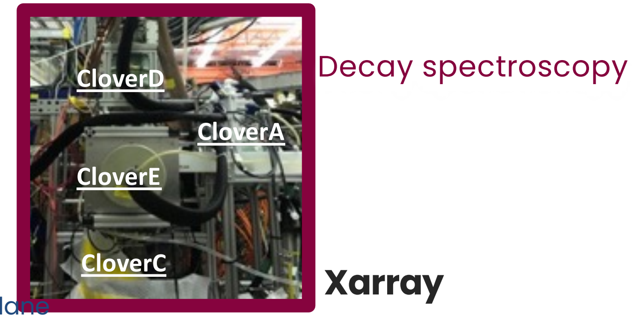
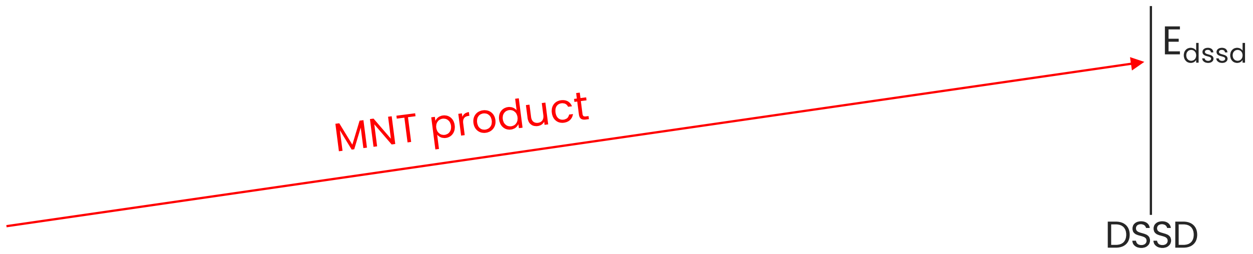




Observables for the analysis

6 chosen Observables for this study:

- Implantation energy in the DSSD



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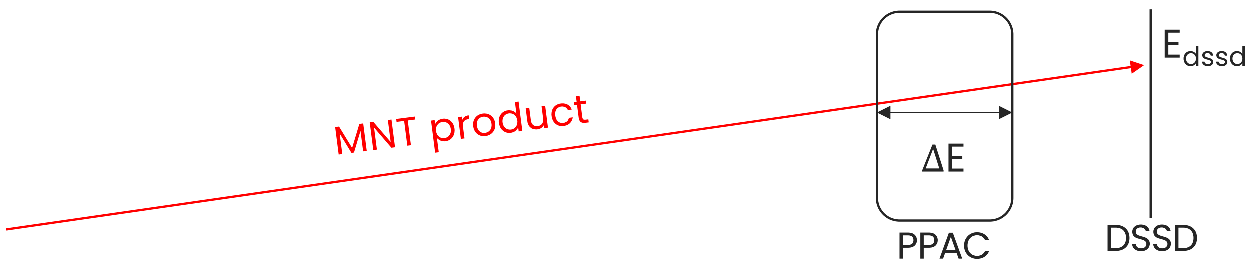

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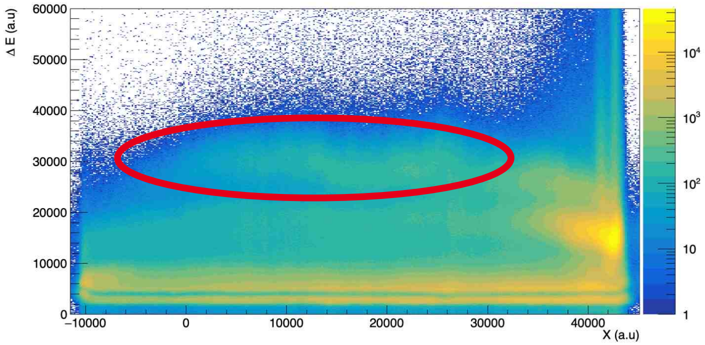
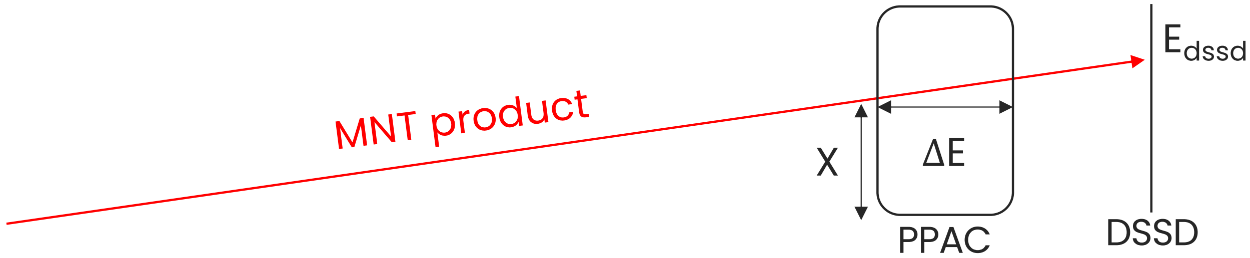
- Position of nuclei in the PPAC

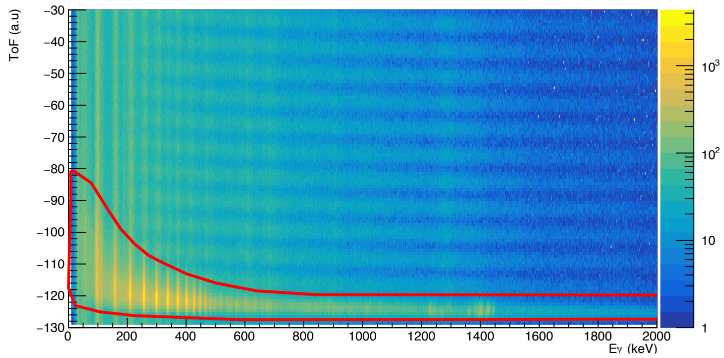


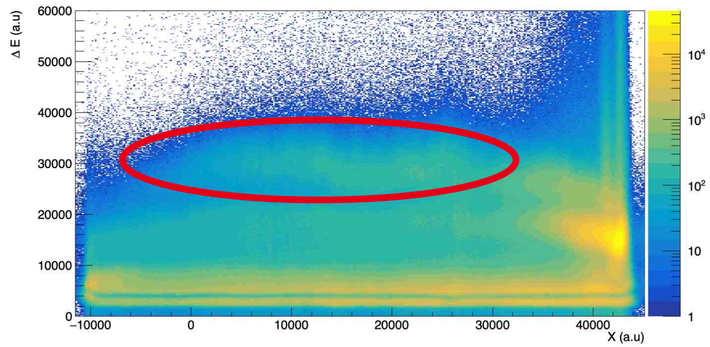


Observables for the analysis

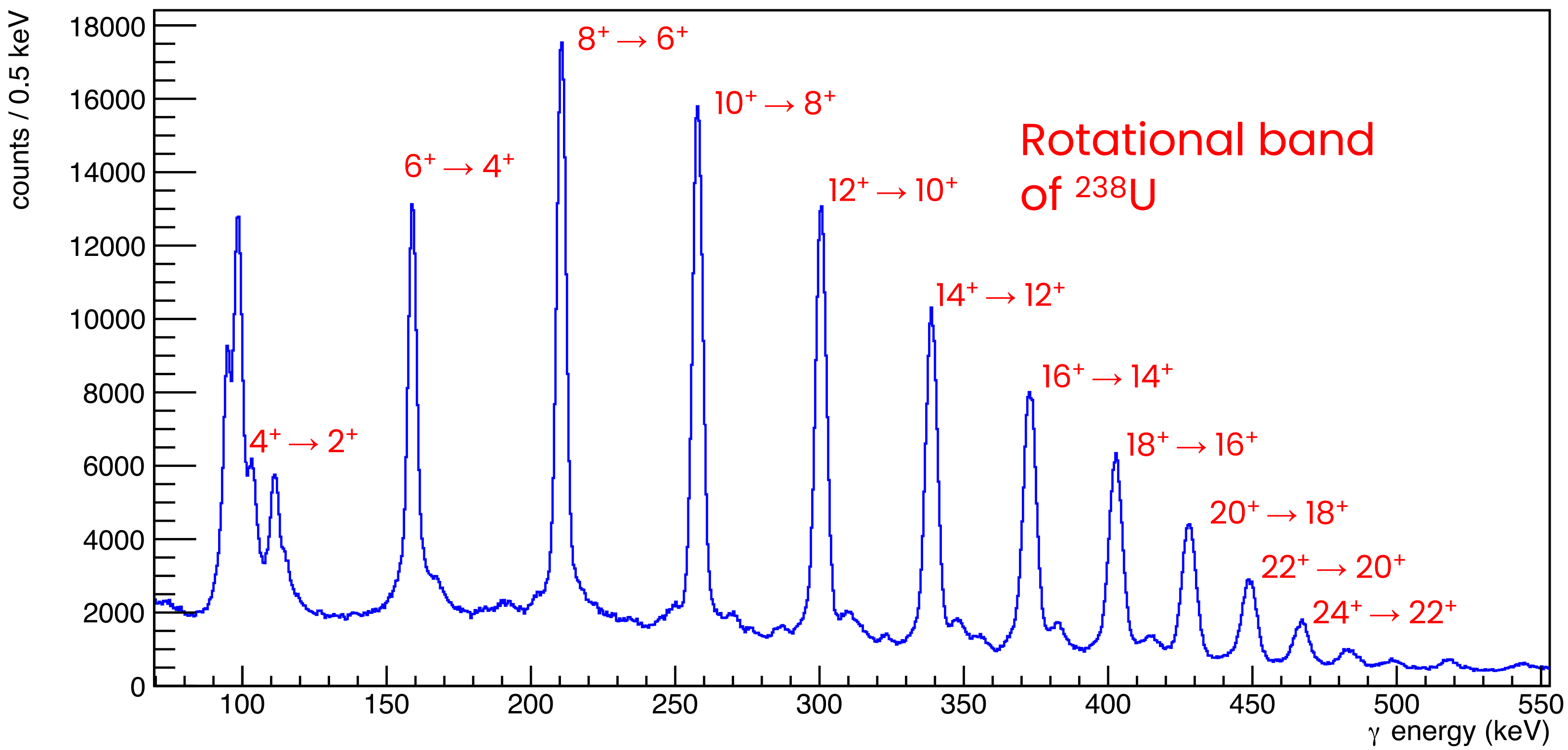
<u>6 chosen observables for this study:</u>

- Implantation energy in the DSSD
- Energy loss in the PPAC
- Position of nuclei in the PPAC
- Time of flight (ToF) between nuclei entering the PPAC and the ɣ they emitted in Gammasphere
- ɣ energies in Gammasphere





Recoil correlated spectrum

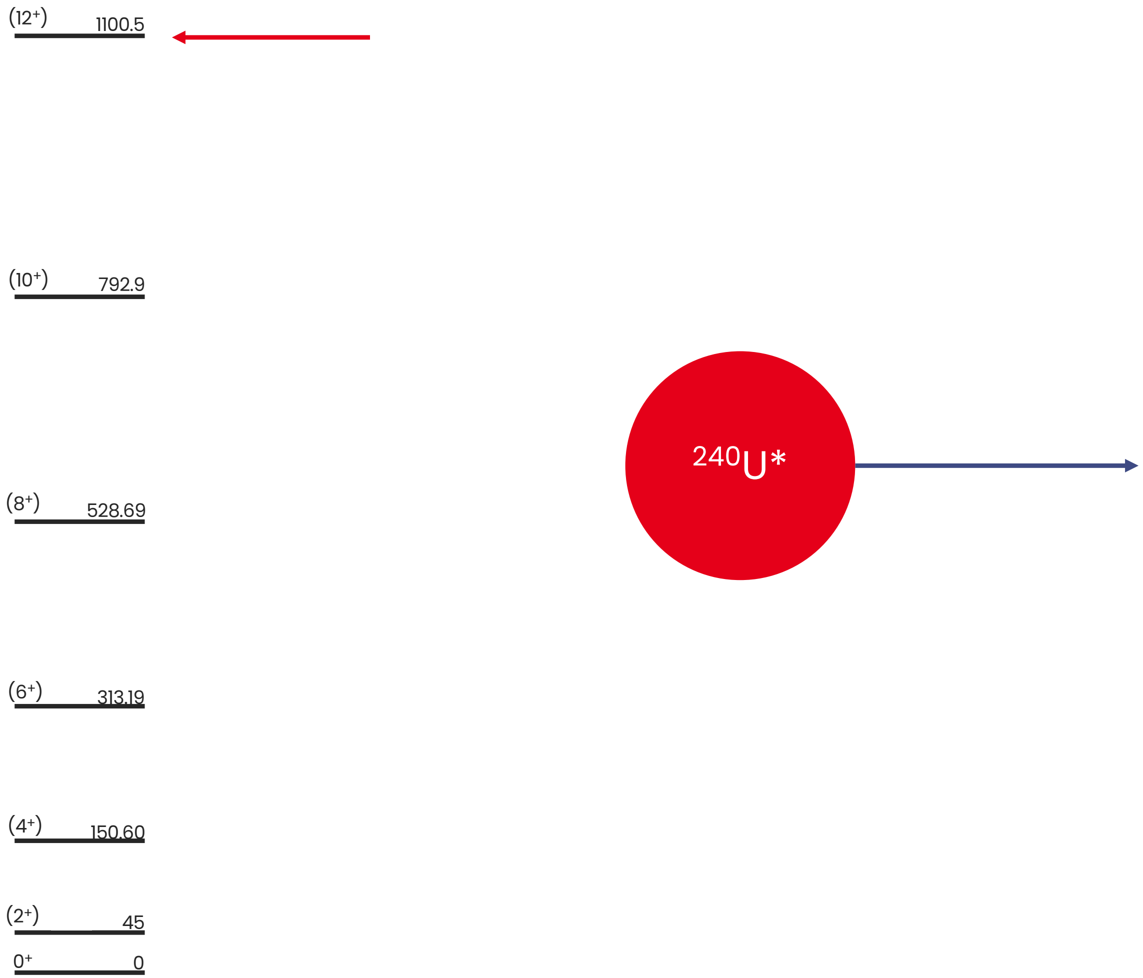


The most intense peaks come from Coulex

→ Background to be supressed

→ ɣ-ɣ correlations

γ-γ Correlations



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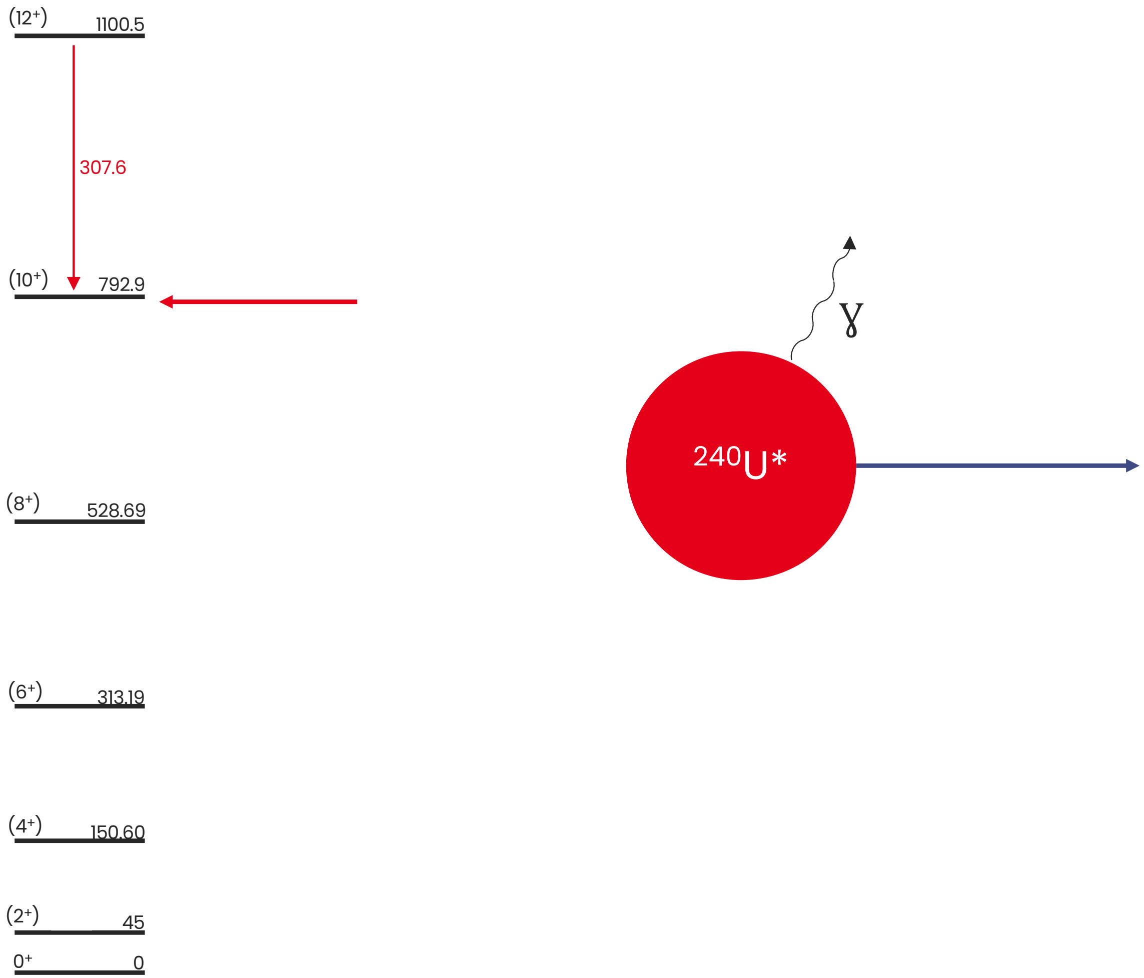

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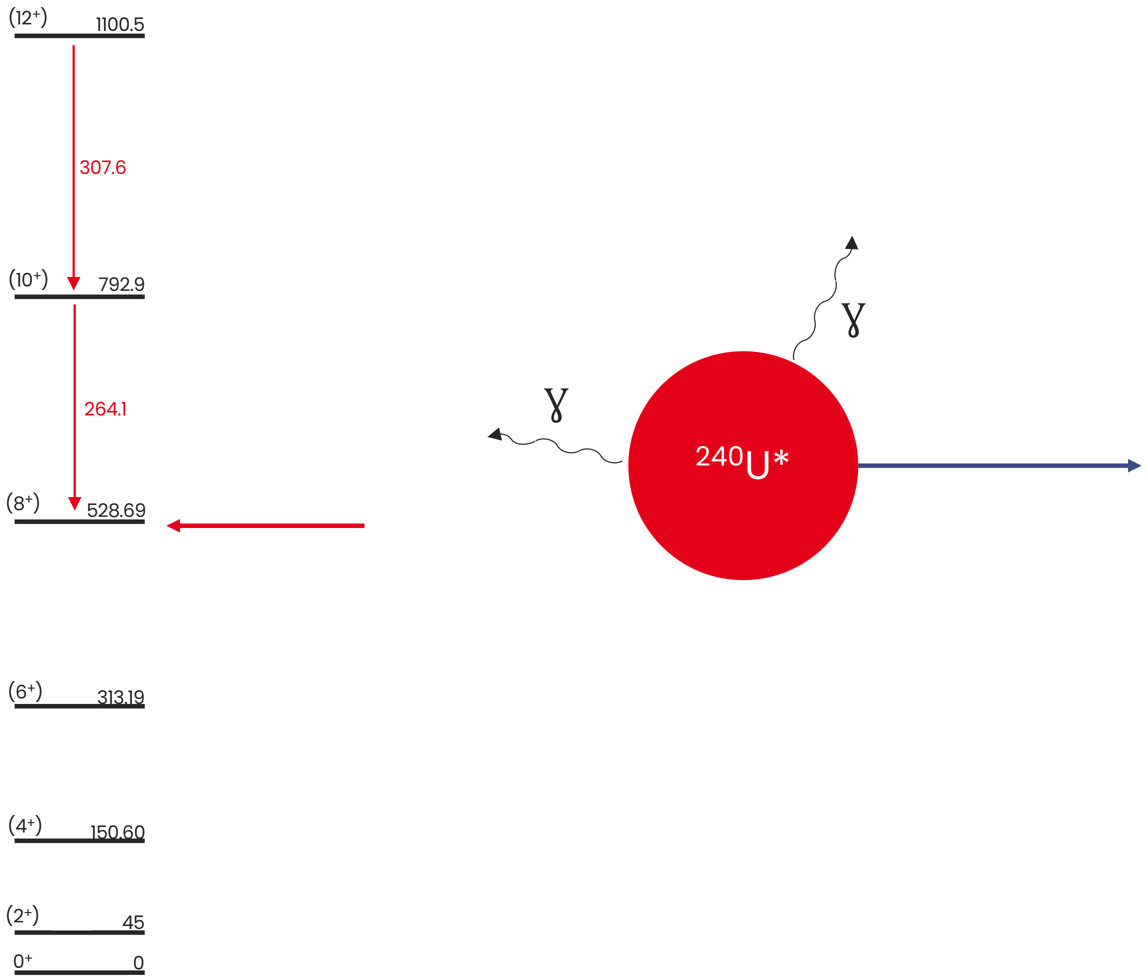

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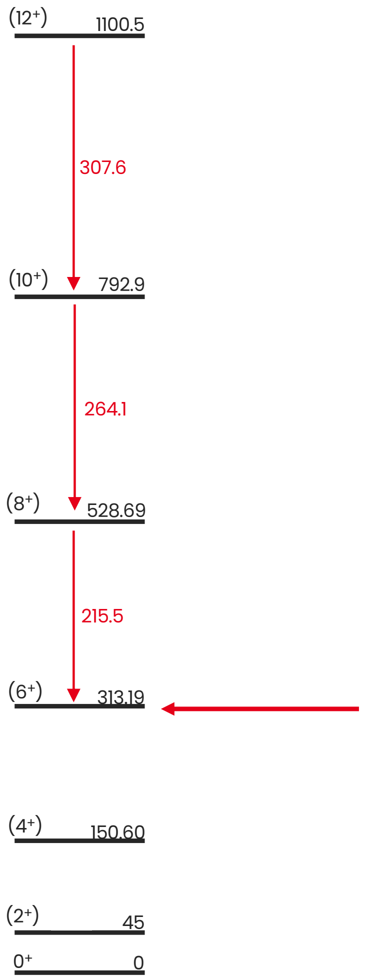

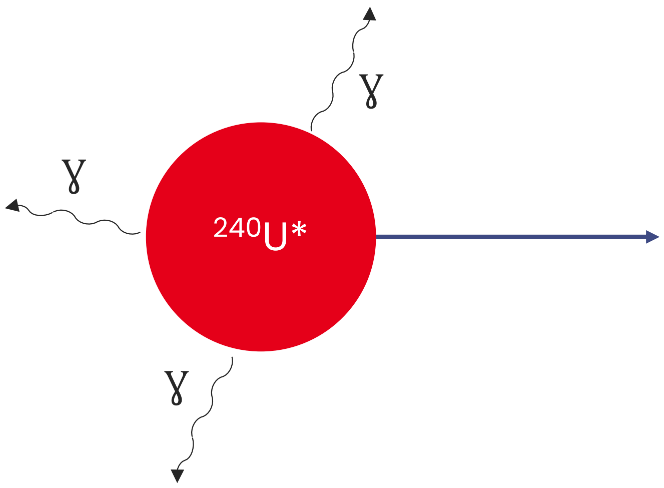

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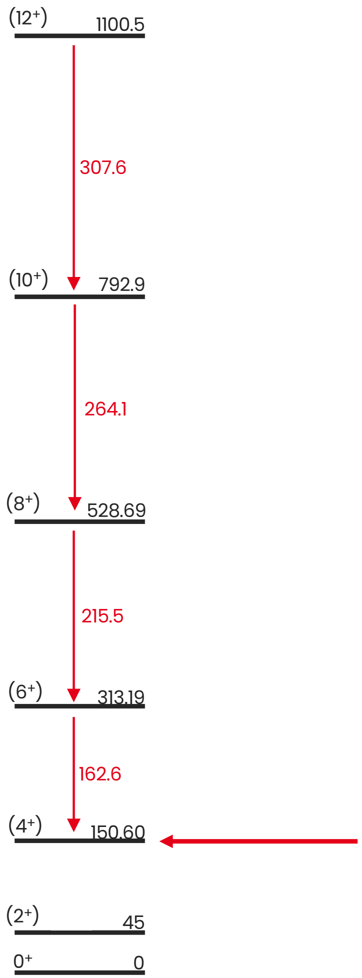

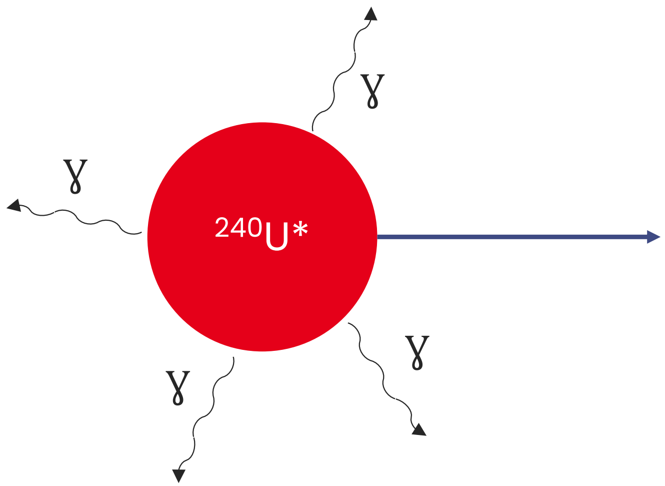

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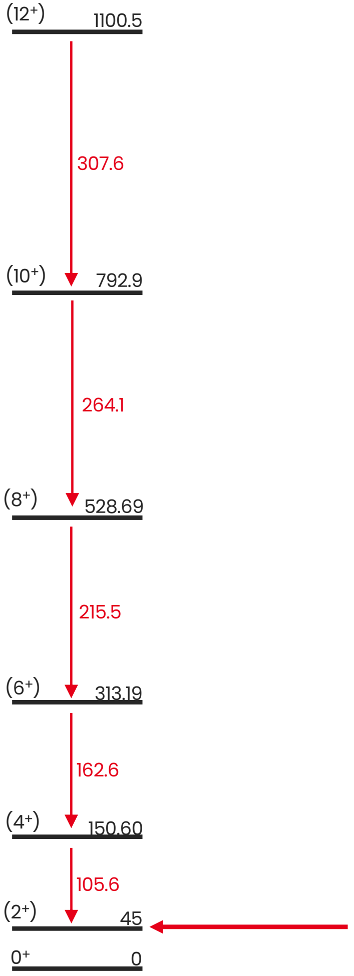

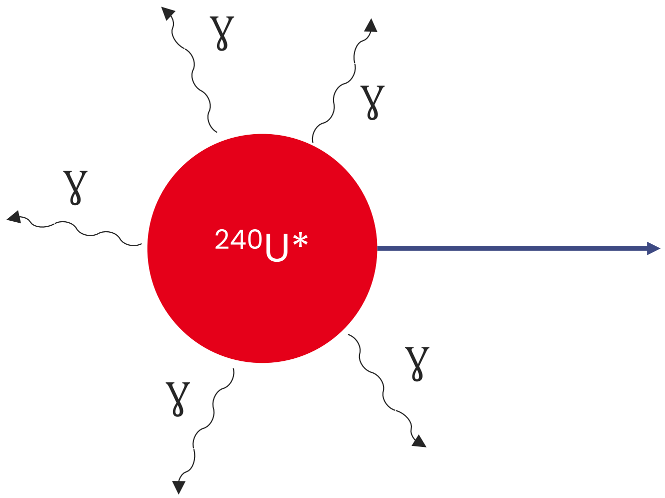

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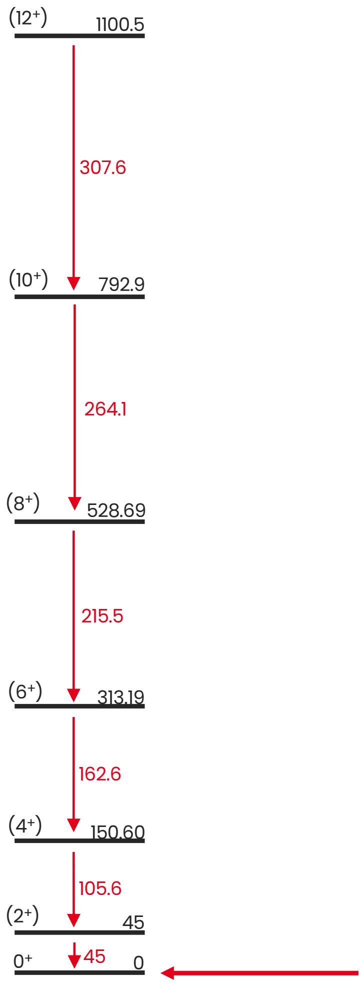
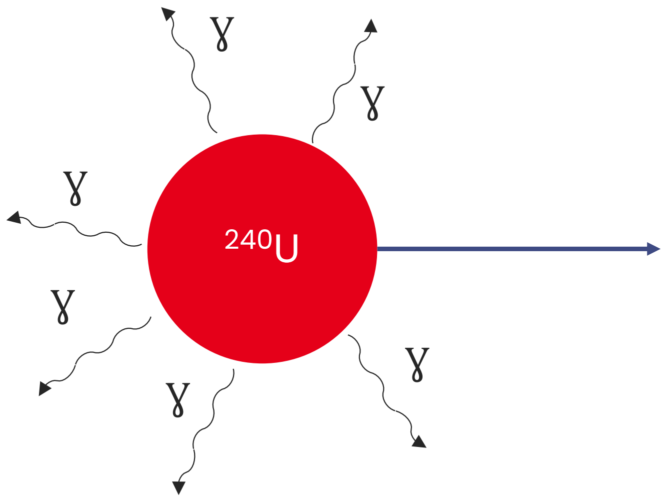


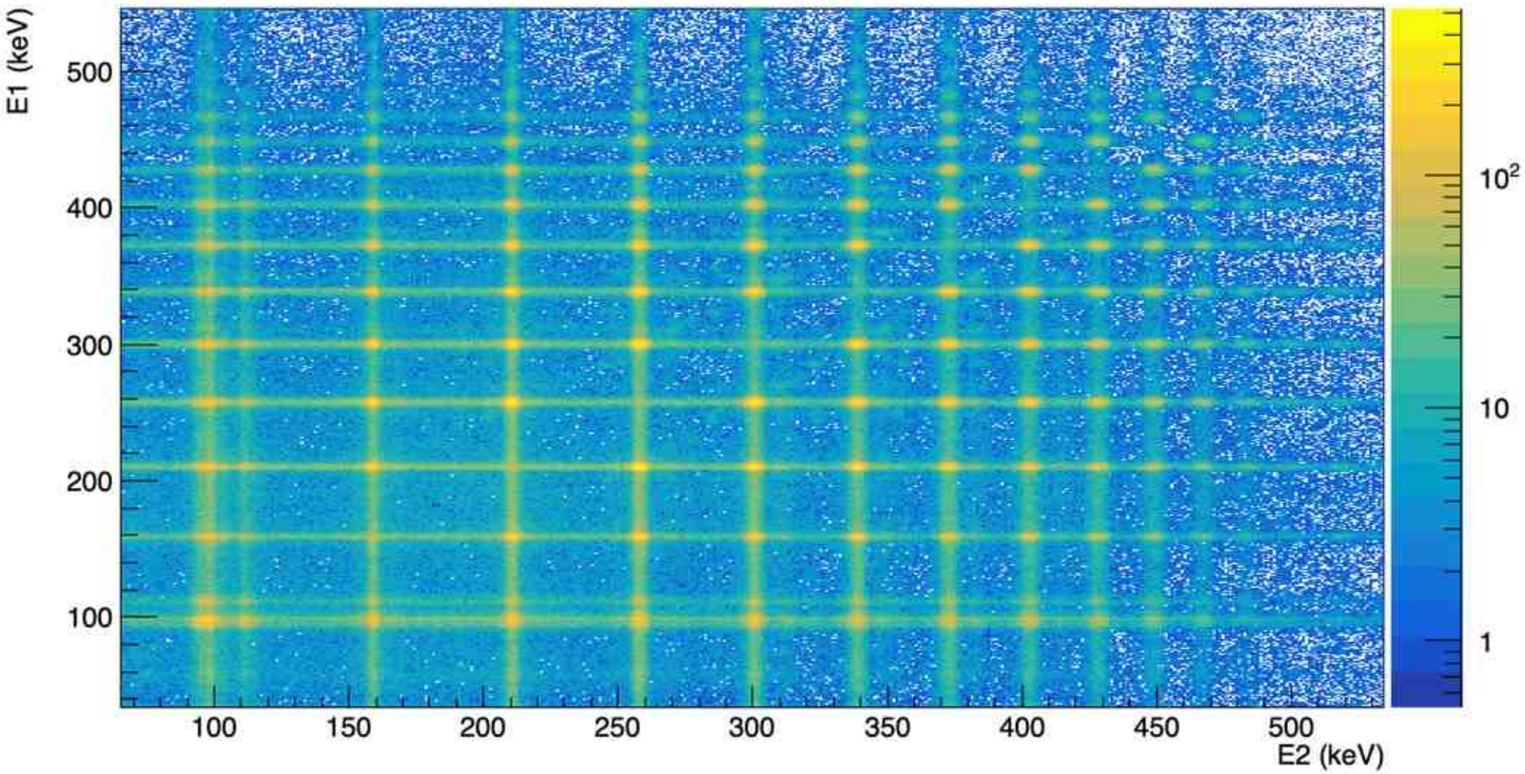


All these γ are emitted at a sub-nanosecond scale

→ They are detected ~ at the same time

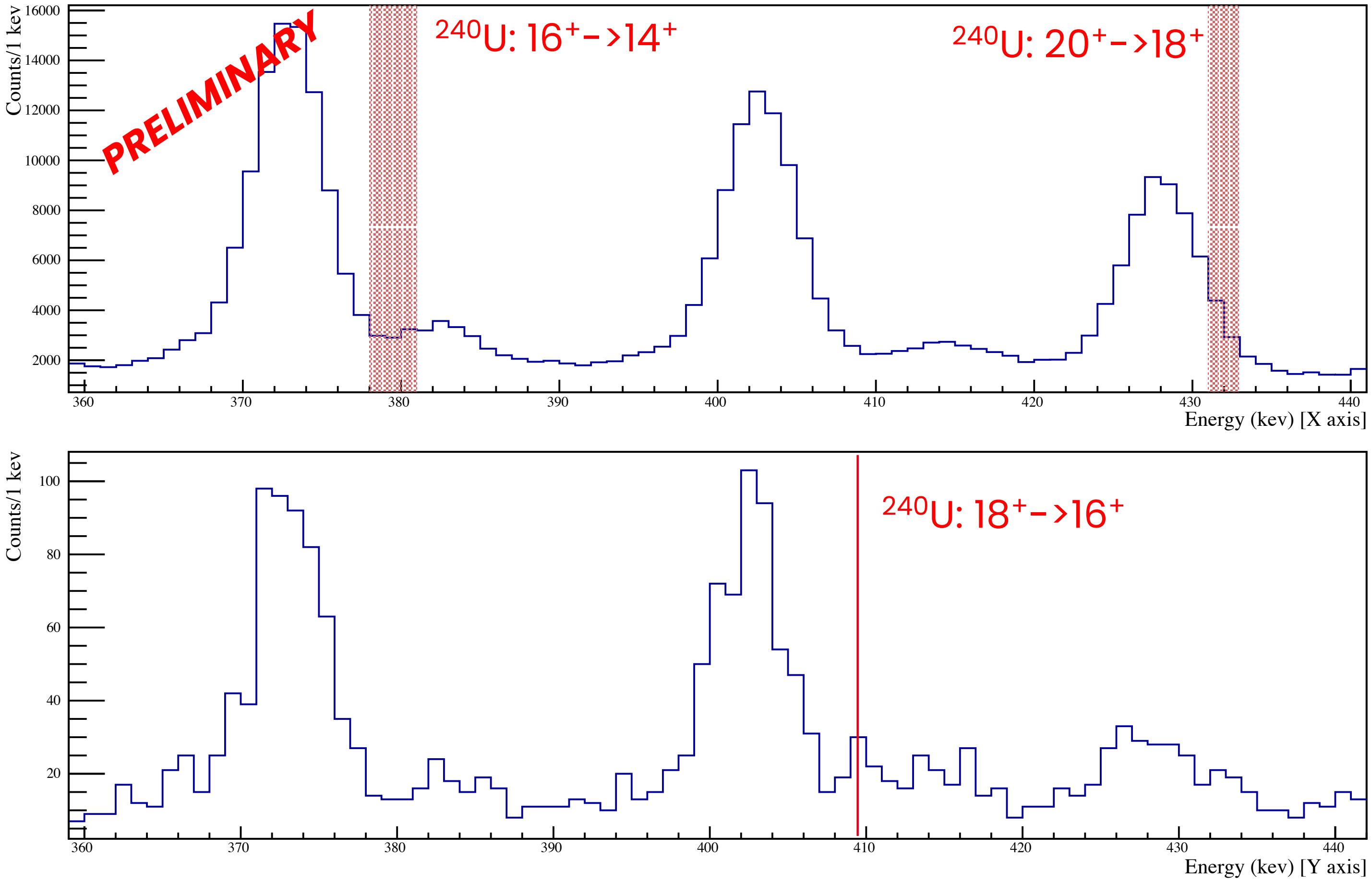
→ Correlate them and look at the pairs (E_1, E_2) we created

γ-γ Matrix



Select MNT by gating on E1 to look at E2

^{240}U identification



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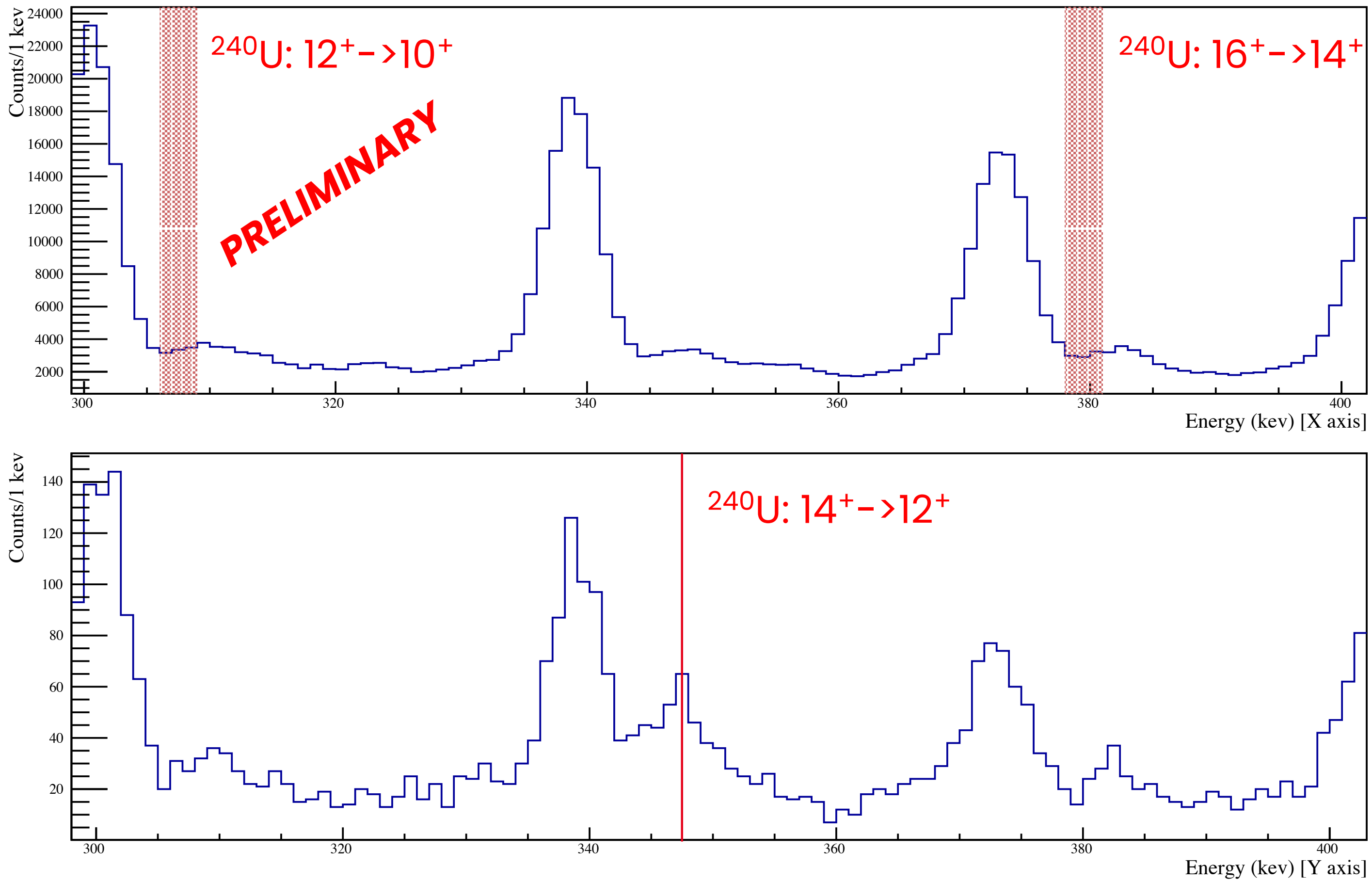

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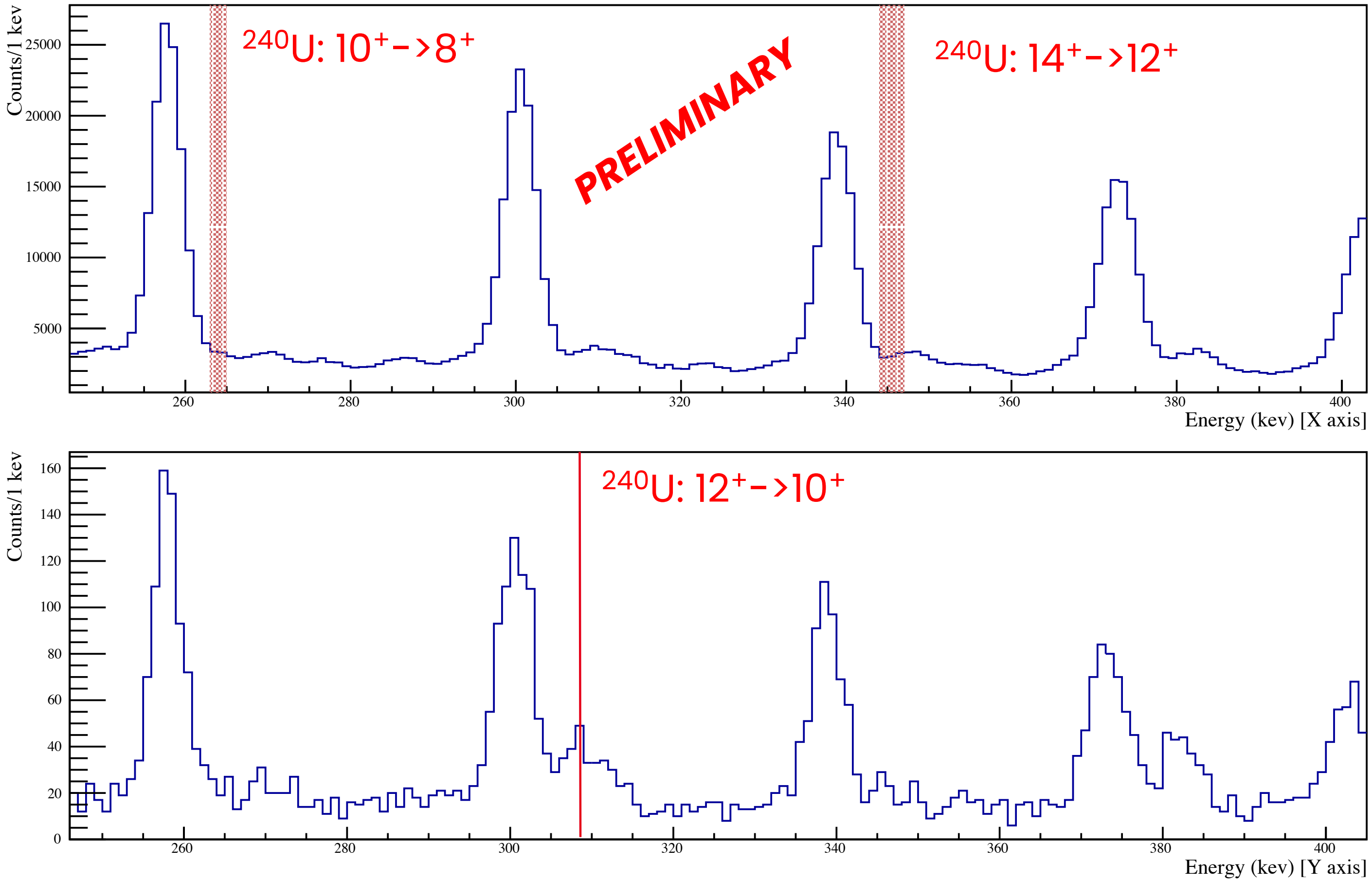

3. Conclusion and outlooks

Conclusion and outlooks

- MNT reactions imply transfer of nucleons between reaction partners.
- It could be a complementary mechanism to fusion-evaporation to produce new neutron-rich heavy and superheavy nuclei.
- An experiment was performed last October to study MNT products from the $^{136}Xe+^{238}U$ reaction.
- First preliminary result: hints for the production of ^{240}U with this reaction.
- This reaction was a first step towards the production of heavier neutron-rich isotopes using different beam/target combinations.

Thank you for your attention

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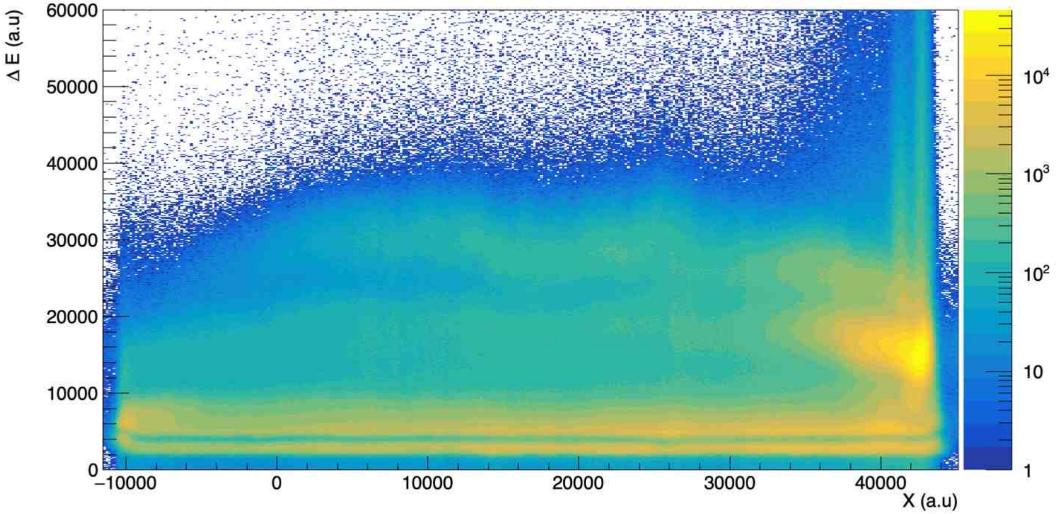
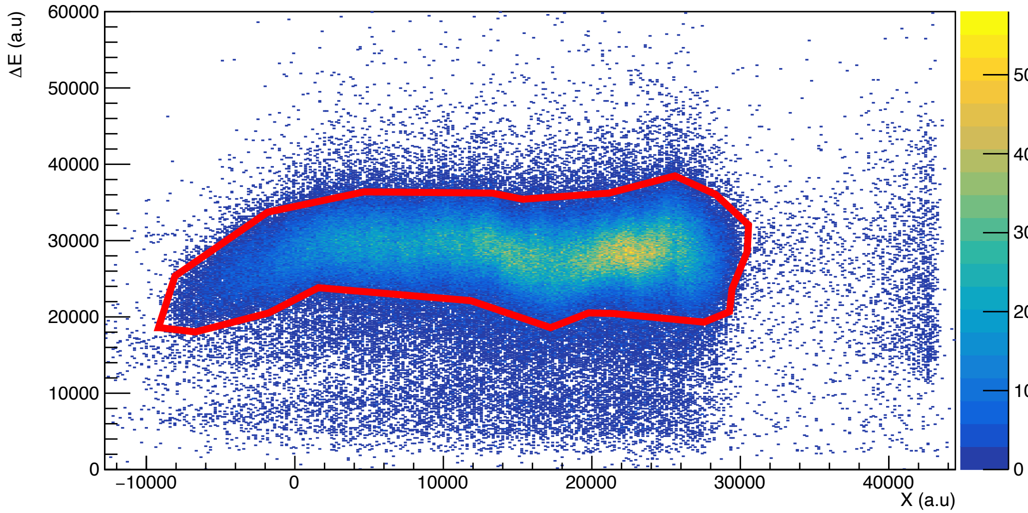
4. Backup

Selecting relevant events

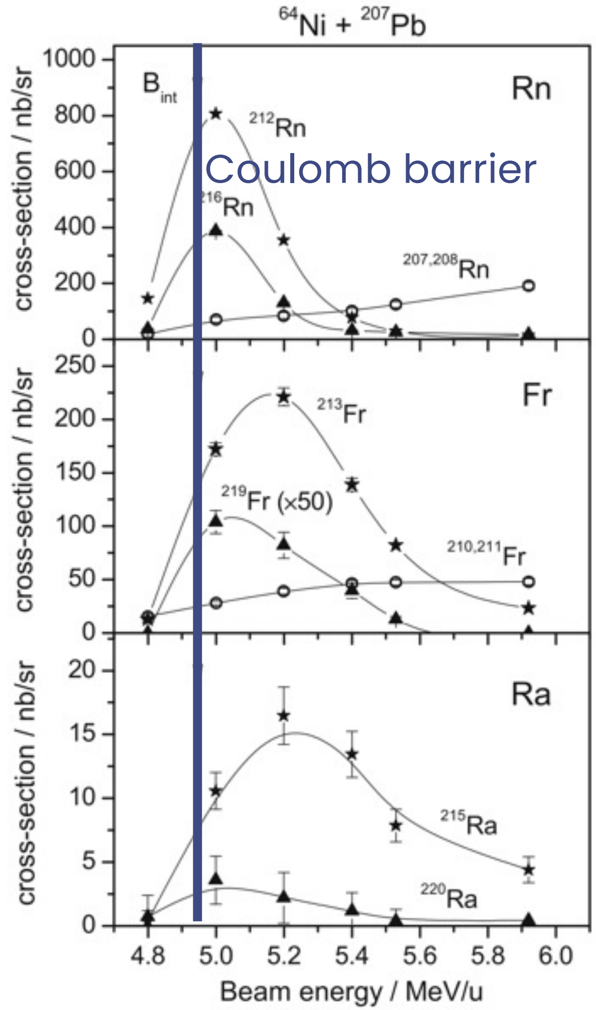




E_{dssd} > 110 MeV
-128 < ToF < -116

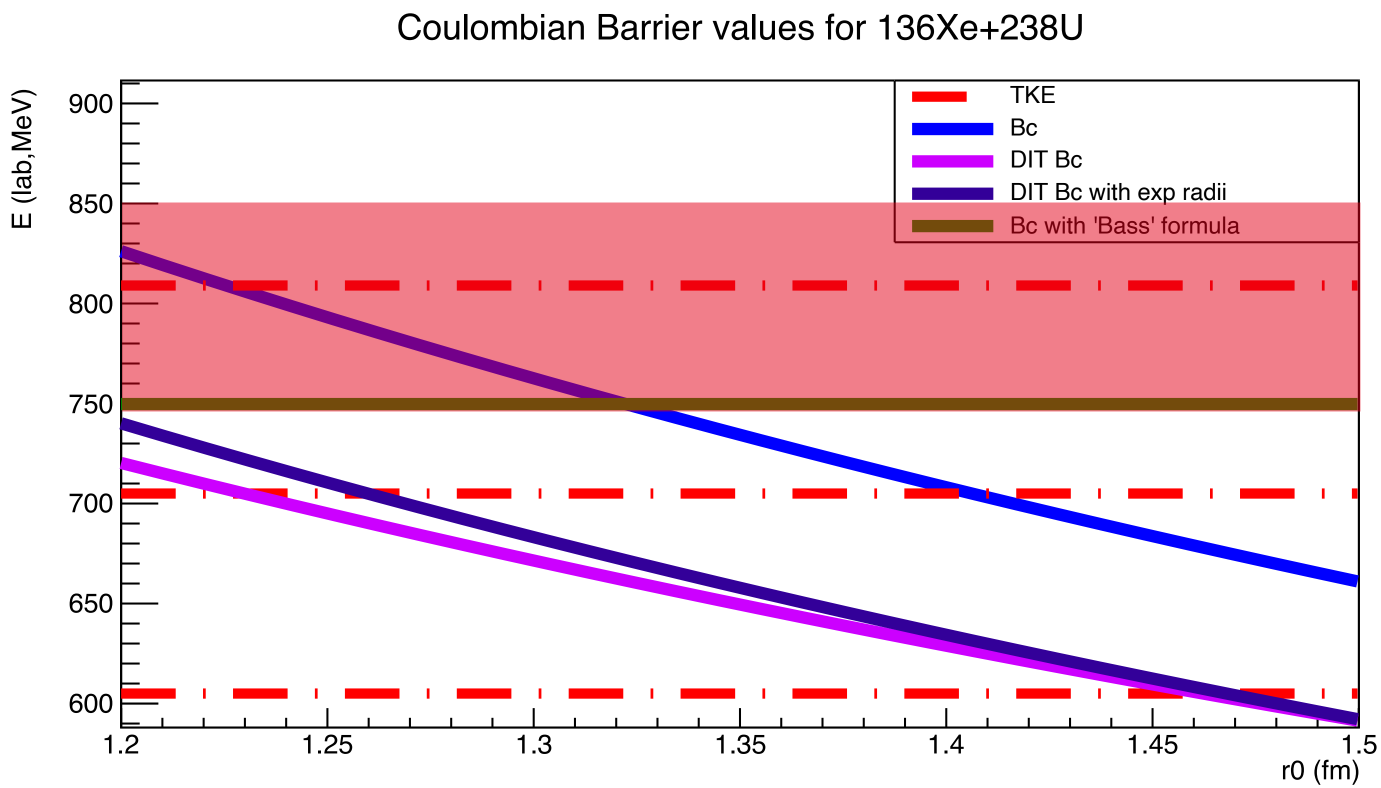
Best energy for MNT reactions

- MNT experiments using SHIP@GSI
- Many beam energies tested near the Coulomb barrier
- Seems to confirm the cross-section enhancement near 1.1 Vc
- Necessity to be very carrefull when choosing the beam energy



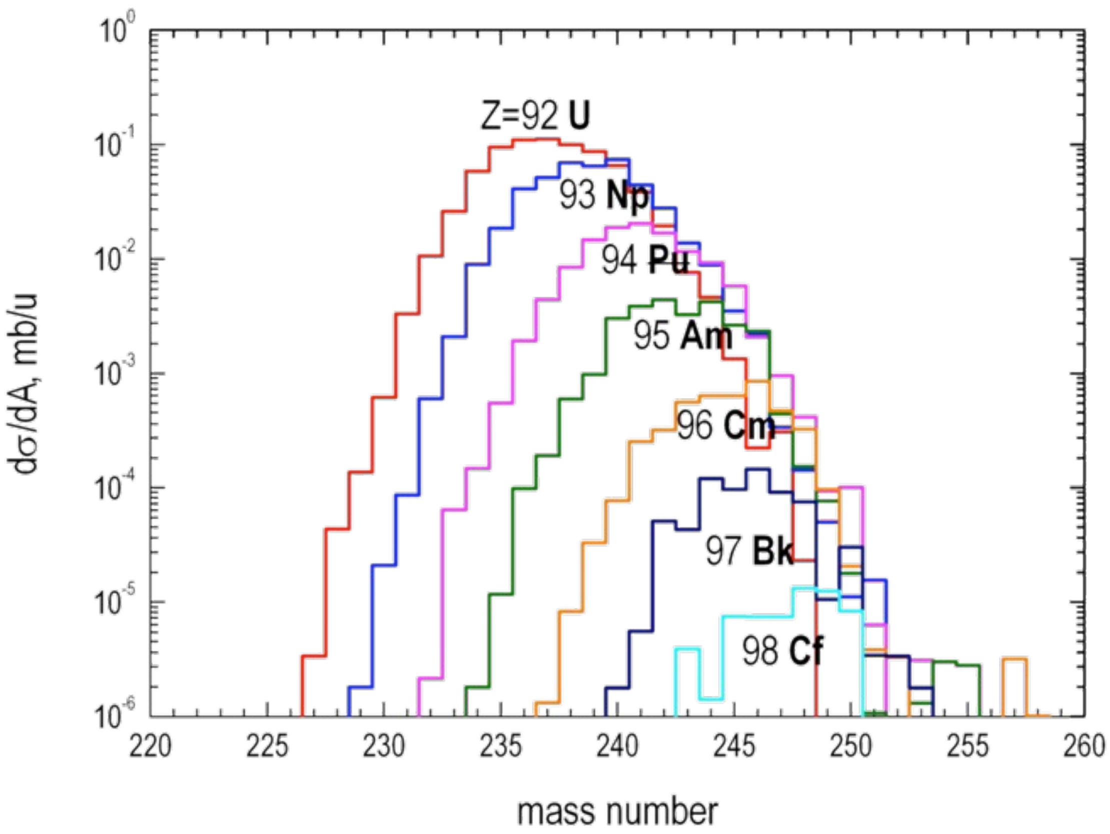
V. F. Comas, S. Heinz; EPJA i2013-13112-x (2013)

Coulombian barrier of the $^{136}Xe + ^{238}U$ reaction



- Coulombian Barrier computed with different formulas
- Should use the Bass one according to literature
- **With E_{beam} = 750 MeV (or more) we should find better cross-sections**

Cross-sections for $^{136}Xe+^{238}U$ at forward angles



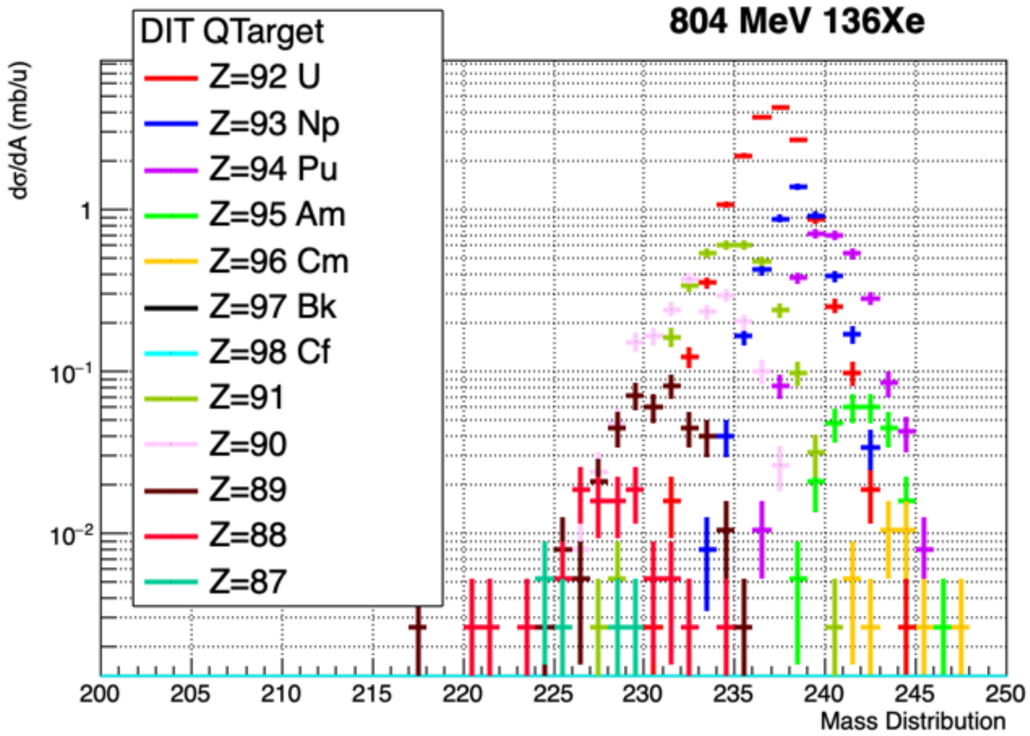
Theoretical predictions (Karpov, private communication)

- Cross sections distribution at forward angles for Quasi-Target products using $^{136}Xe+^{238}U$ with E_{beam} ≈ 800 MeV
- Calculations are done using the Langevin's model first developped by Zagrebaev and Greiner

Cross-sections for ^{136}Xe+^{238}U at forward angles

- Cross sections distribution at forward angles for Quasi-Target products using ^{136}Xe+^{238}U with E_{beam} = 804 MeV

- Calculations are done using the semi-classical simulation code DIT (special thanks to Iulian Stefan from IJCLab)



DIT code (my work)

Cross-sections for $^{136}Xe+^{238}U$ at forward angles

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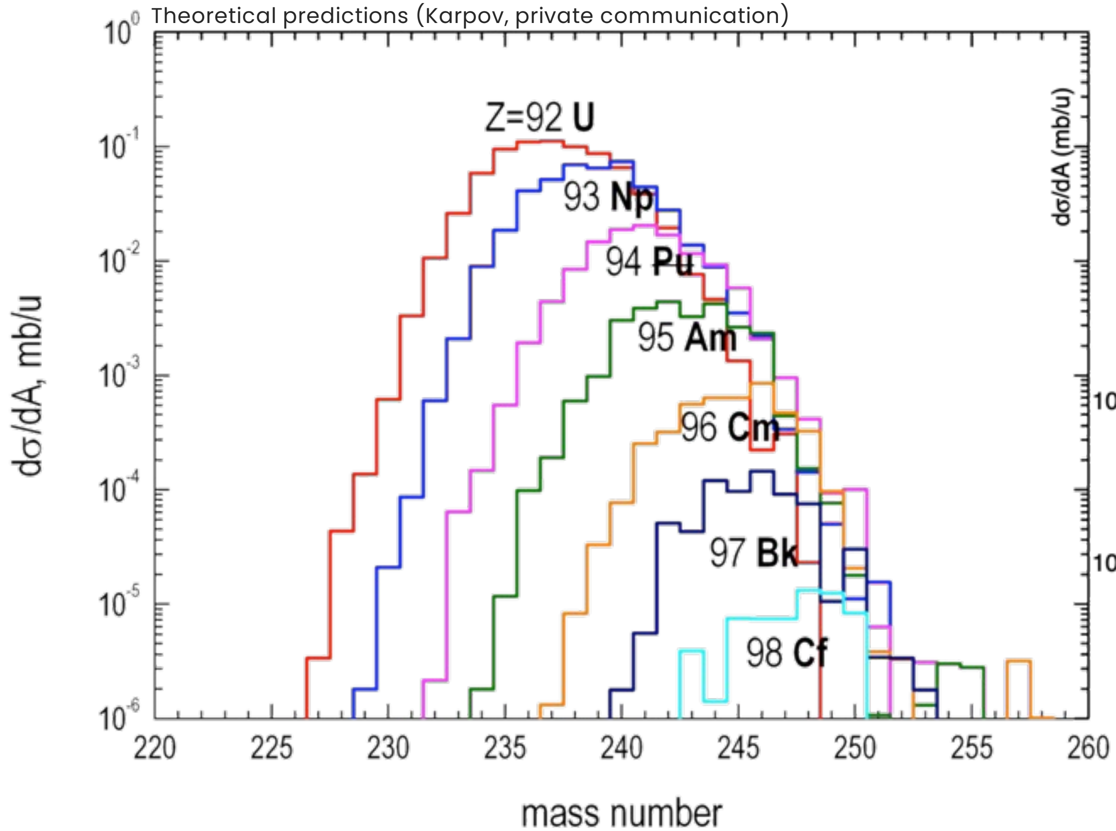

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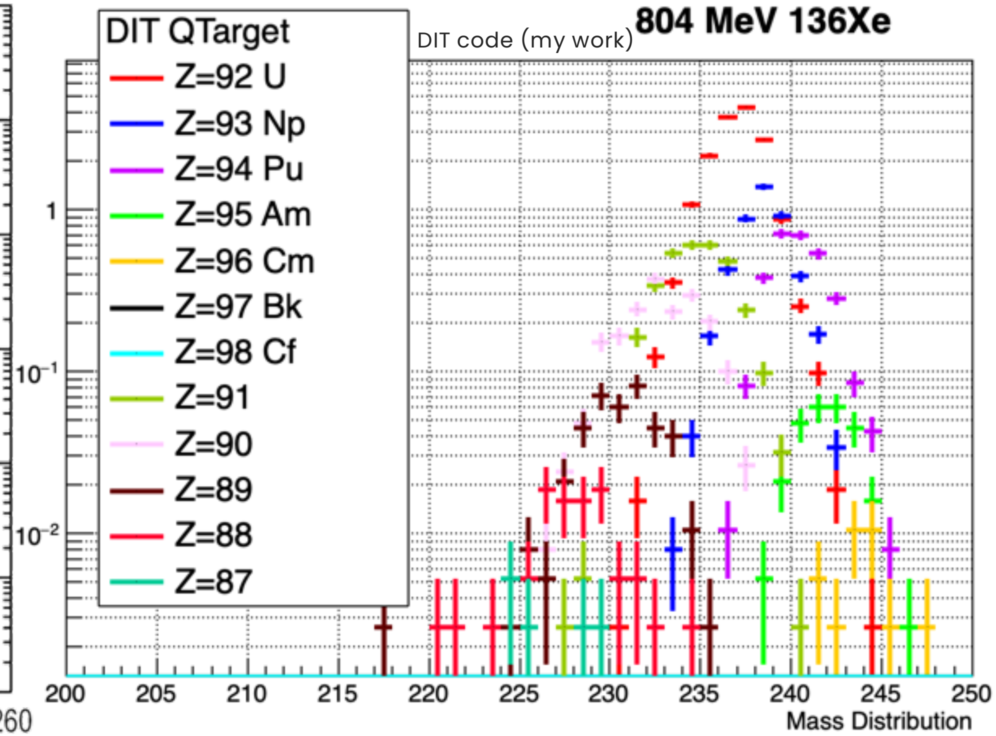
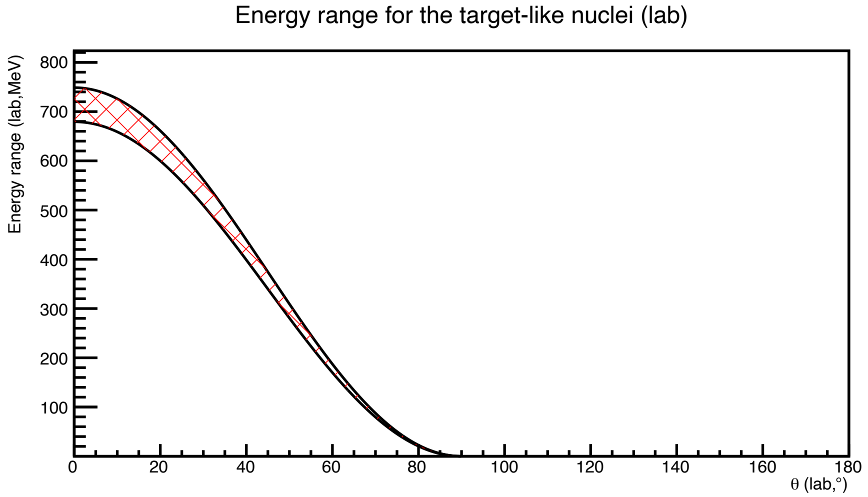
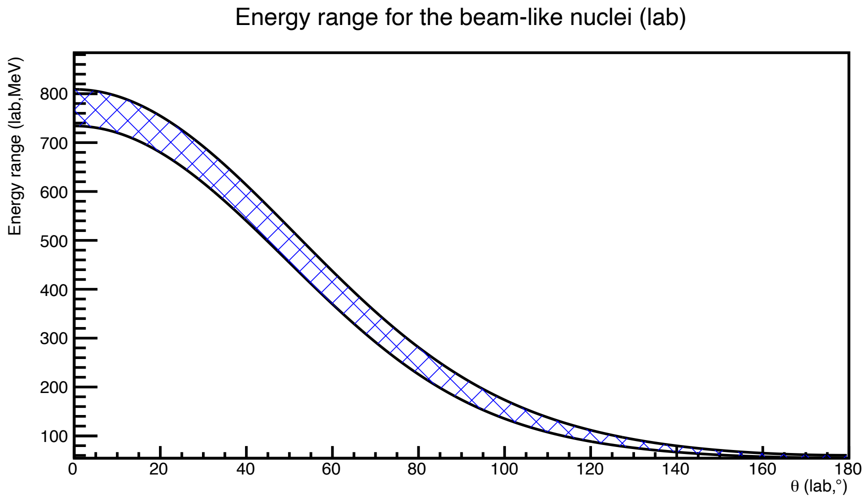


Our semi-classical code is consistent with theoretical predictions: **same trend for the cross-section distribution** with 1 order of magnitude of difference overall

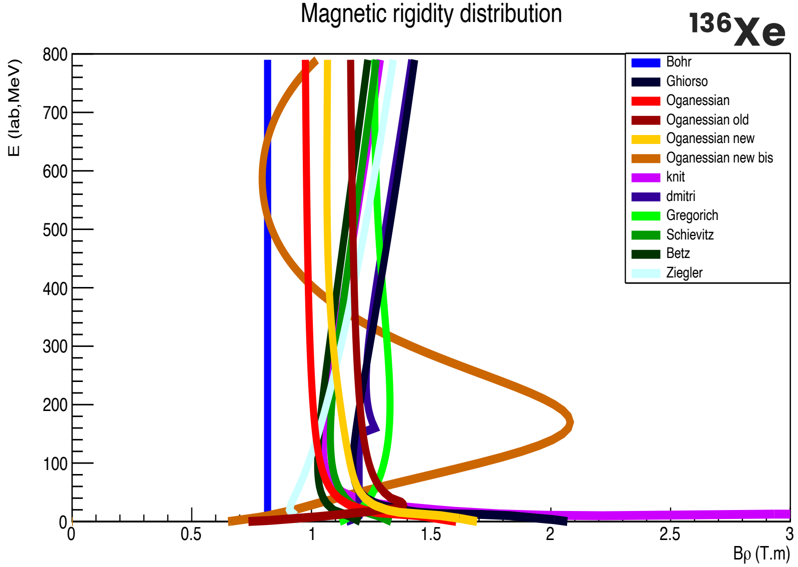
Reaction kinematic

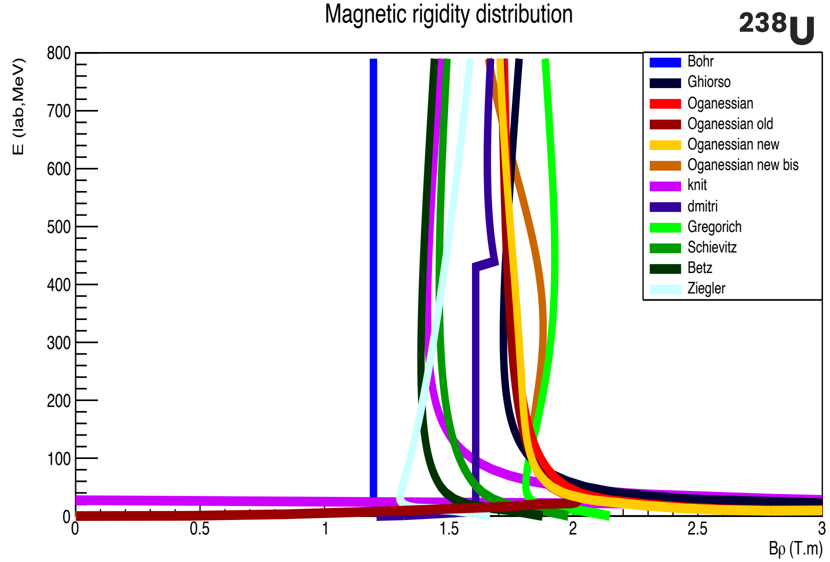
- We can predict the (large) Energy range for both reaction partners
- At a given angle the minimum corresponds to TKE = B_C for the di-nuclear system
- The maximum come from an elastic reaction





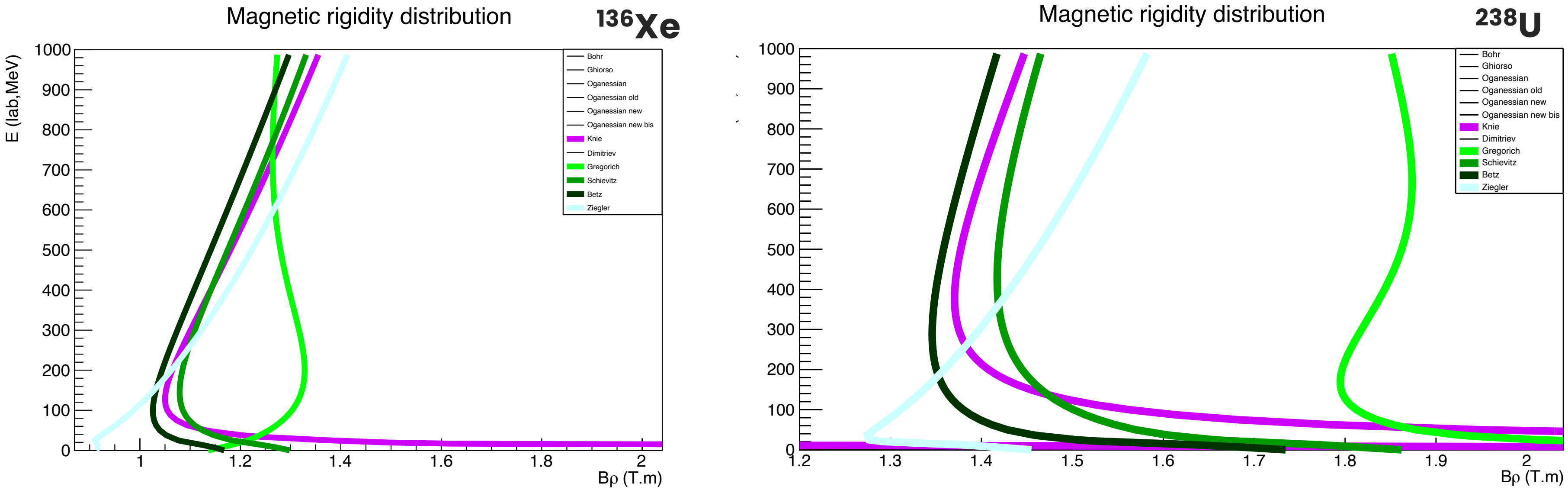
Magnetic rigidity for reaction products and unreacted beam





- Compilation of most of the models available for Bρ in Gas-filled separators
- At our energies, Bρ can be very different depending on the model used
- Most of the experimental data used to fit such models have far lower kinetic energies than for this experiment

Magnetic rigidity for reaction products and unreacted beam

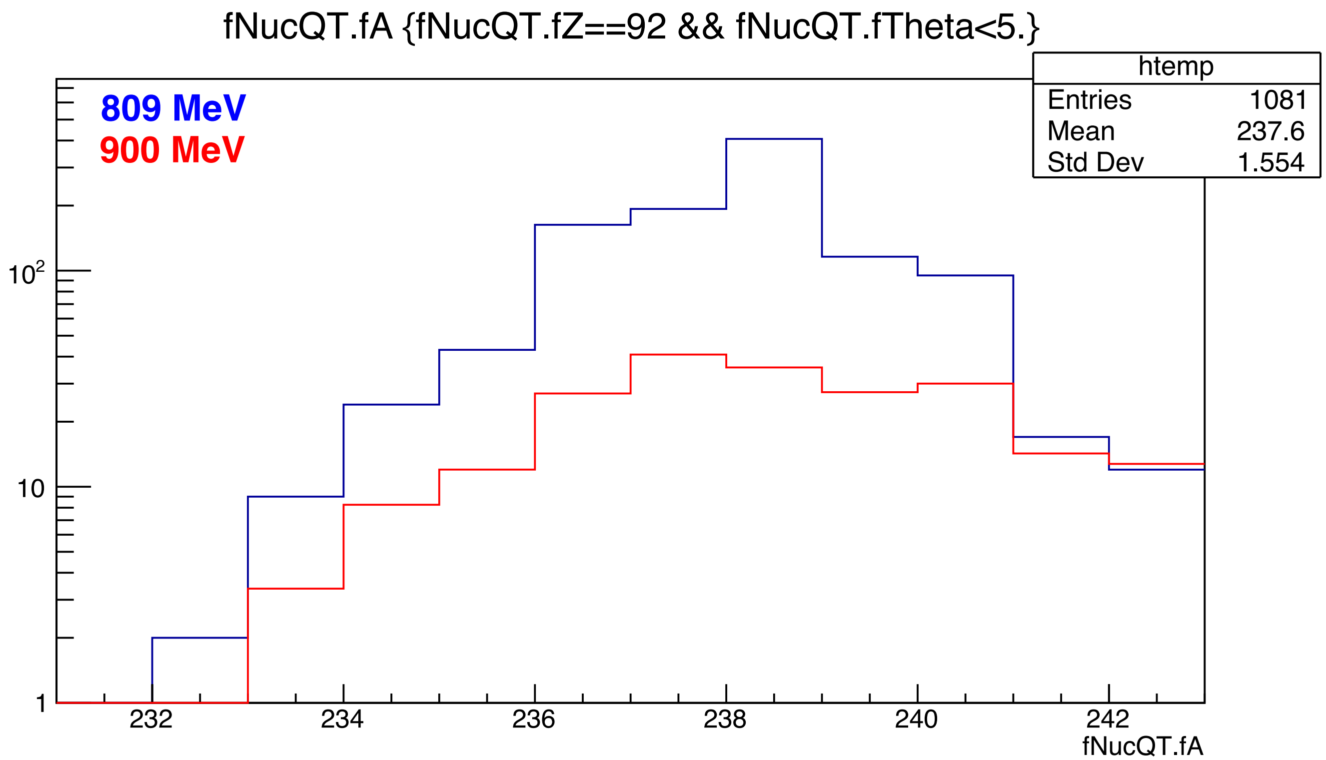


- Here are only selected the models that could be compatible with this experiment

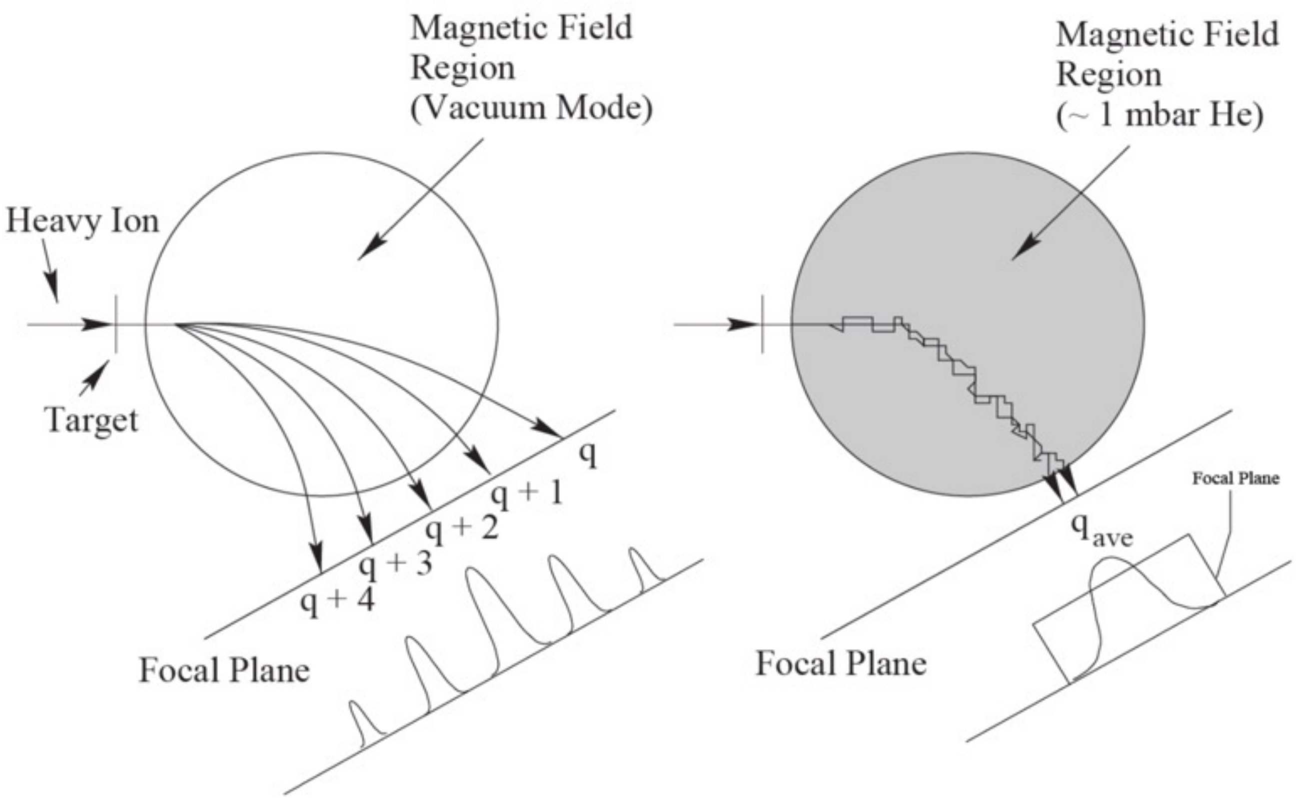
Yields at different energies

- Comparison of the yields for Uranium isotopes from DIT at 800 and 900 MeV

- DIT predicts better yields around 800 MeV which should also be the best one according to Zagrebaev's theory

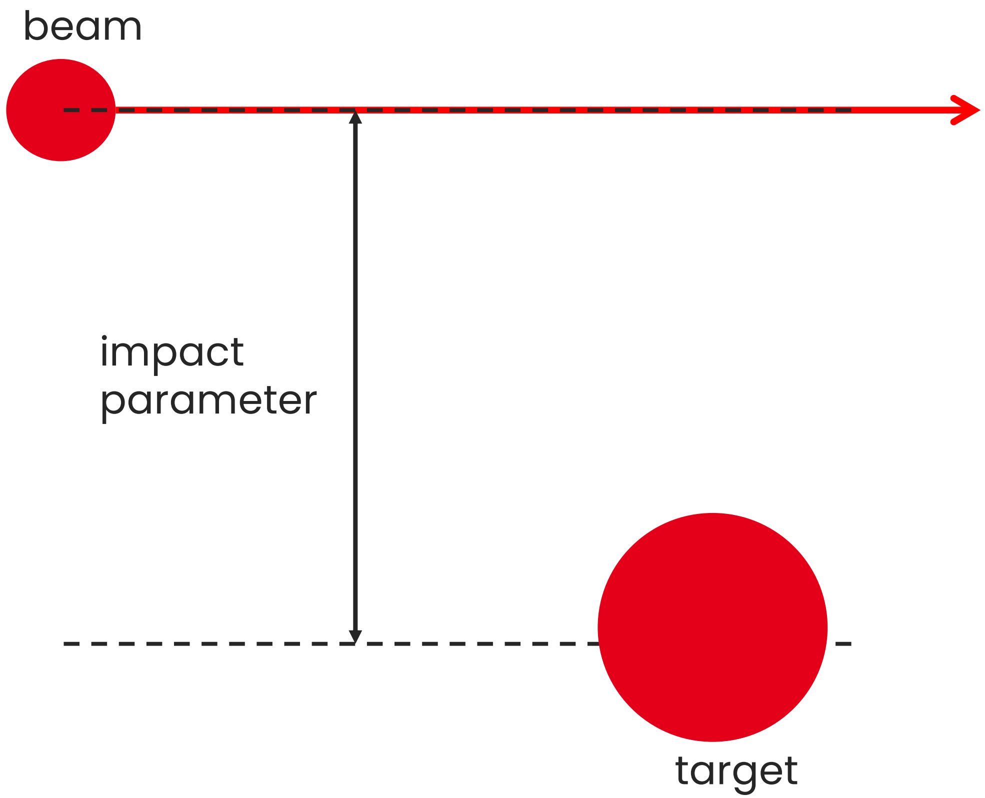


GAS FILLED SEPARATOR



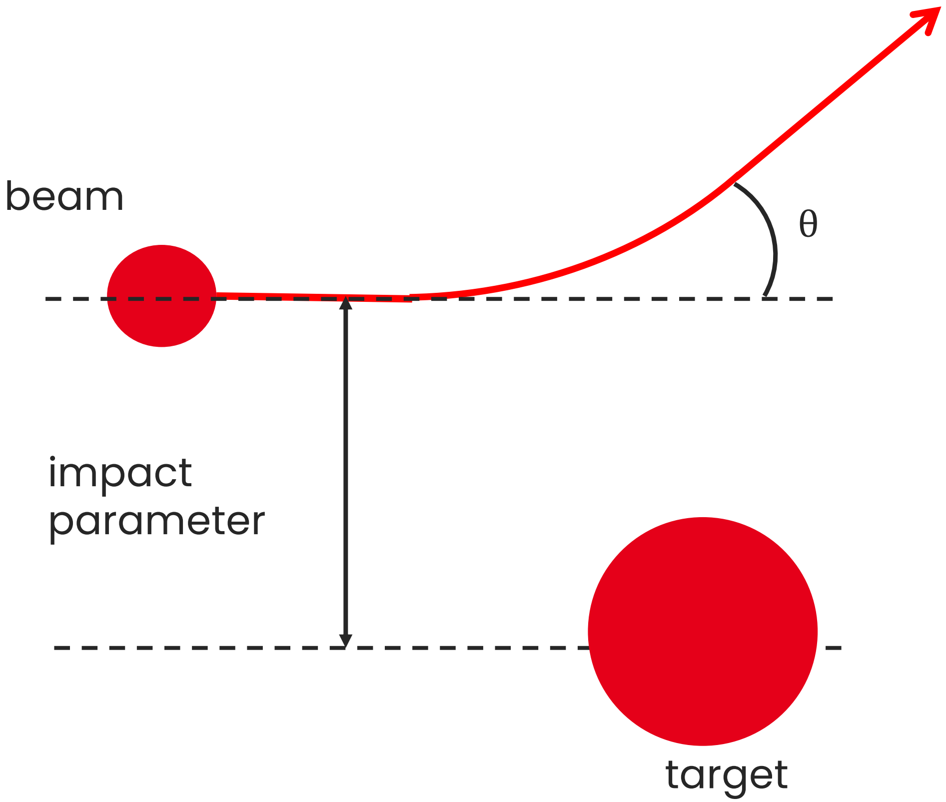
Greenlees, P. *Identication of Excited States and Evidence for Octupole Deformation in* 226*U.* PhD thesis (University of Liverpool, 1999).

GRAZING ANGLE AND ANGULAR DISTRIBUTION



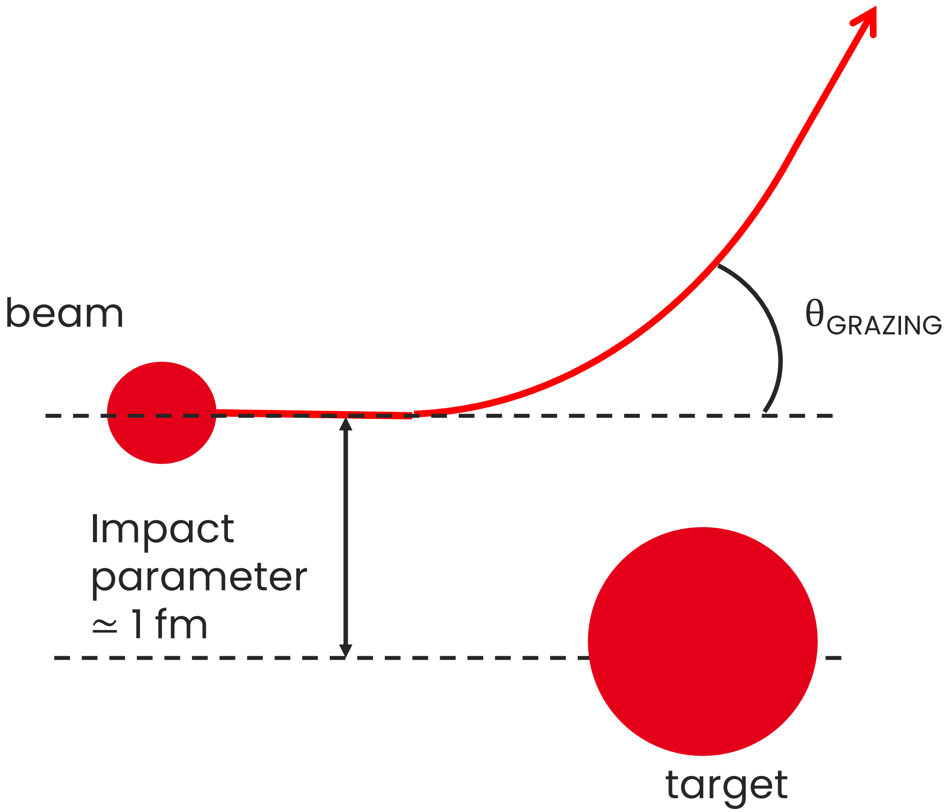
For an high enough impact parameter the nuclei won't be scattered

GRAZING ANGLE AND ANGULAR DISTRIBUTION



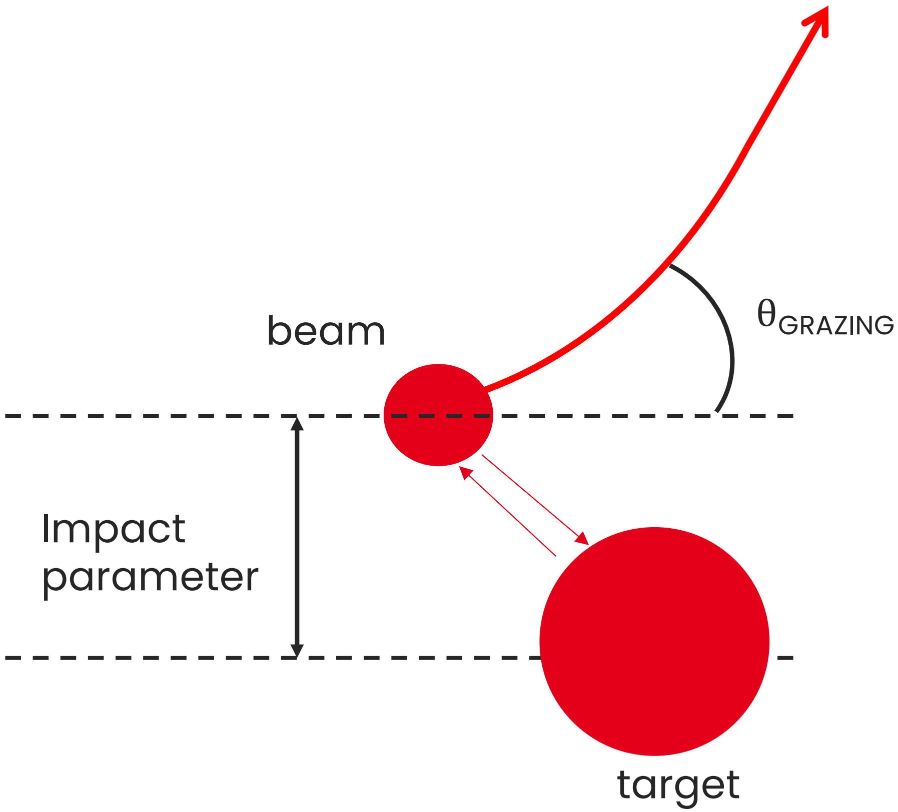
The lower the impact parameter is, the higher the scattering angle will be.

GRAZING ANGLE AND ANGULAR DISTRIBUTION

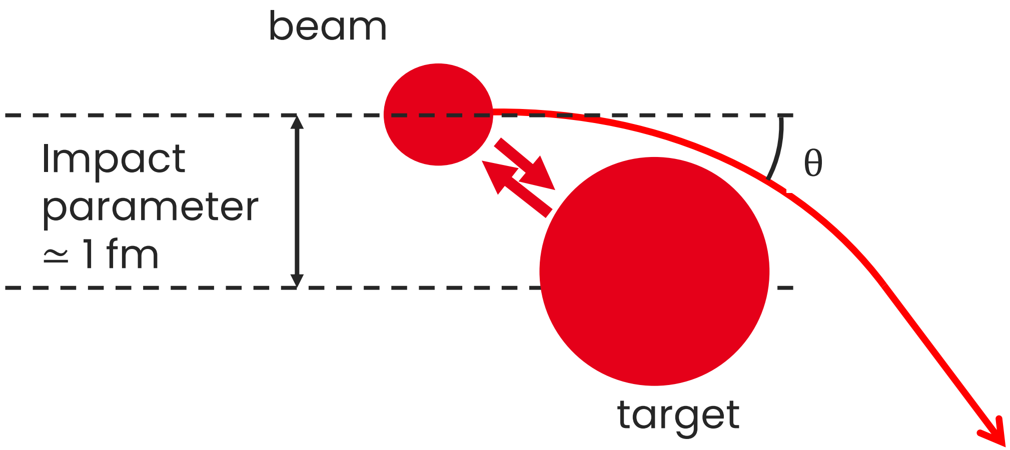


The grazing angle is the value for which the Rutherford scattering cross-section goes down to ¼ of its maximum value

GRAZING ANGLE AND ANGULAR DISTRIBUTION

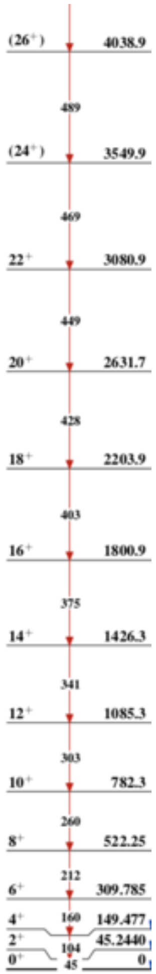


GRAZING ANGLE AND ANGULAR DISTRIBUTION

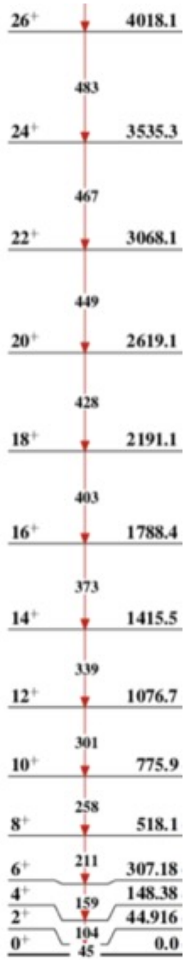


Level schemes

^{236}U



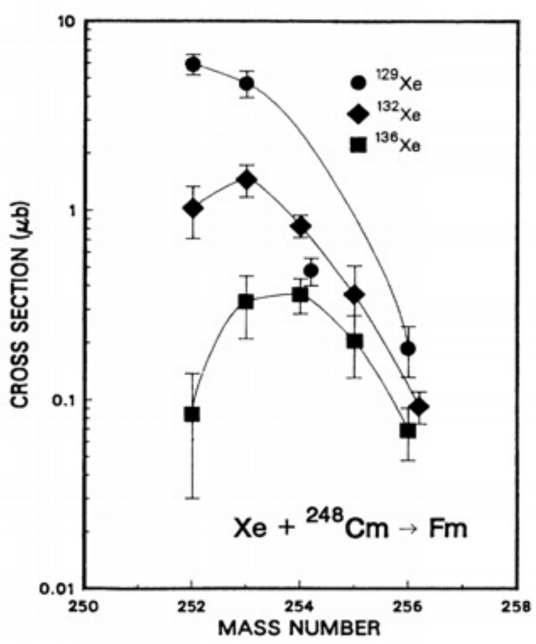
^{238}U



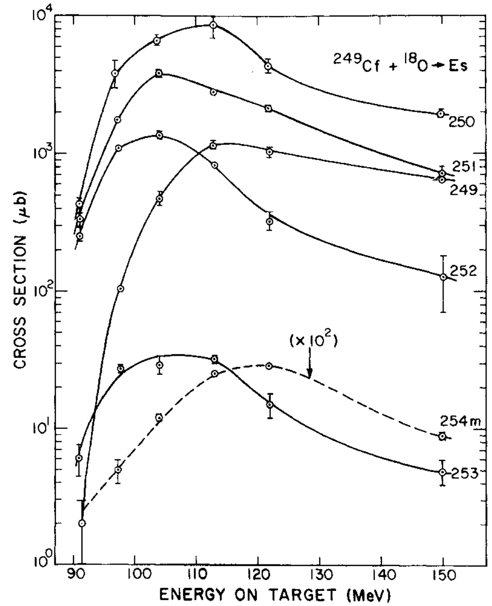
^{240}U

Brief history of MNT: radiochemistry

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



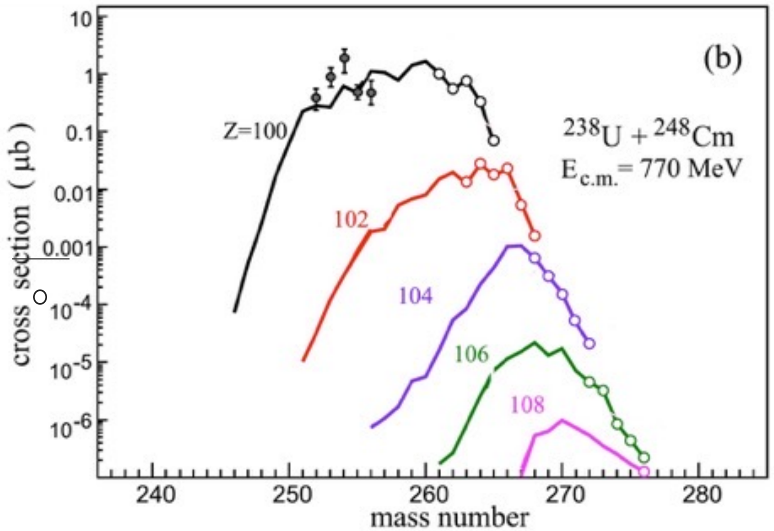
→Chemical separation methods
→isotope identification via radioactive decay
→timescale of the fastest radiochemical separation techniques long lived isotope ≈ 10 s
→Nuclei produced: Z=101, N=157



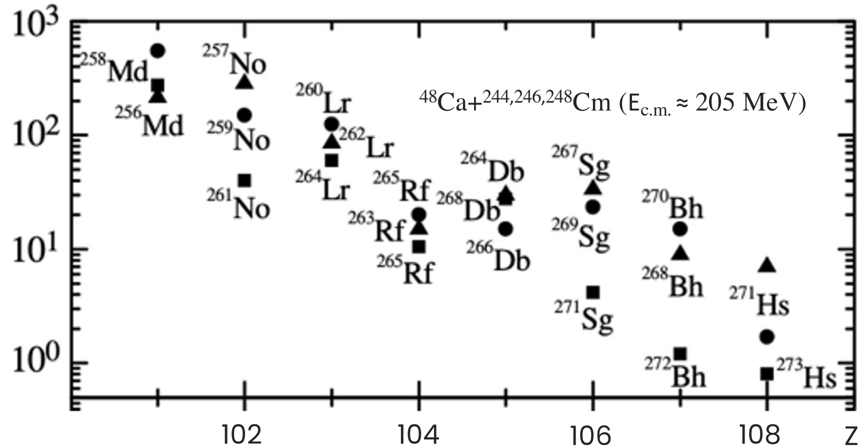
D. Lee et al. PRC 25 (1982) 286 : ^{16}O, ^{18}O, ^{20}Ne, ^{22}Ne + ^{248}Cm
D. Lee et al. PRC 27 (1983) 2656 : ^{18}O + ^{248}Cm, ^{249}Cf
K.J. Moody et al. PRC 33 (1986) 1315 : ^{18}O, ^{86}Kr, ^{136}Xe + ^{248}Cm
M. Schädel et al. Phys. Rev. Lett. 48, 852 (1982): ^{238}U+ ^{248}Cm
A. Türler et al.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

Brief history of MNT: a renewed interest

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



G. G. Adamian , PHYSICAL REVIEW C **71**, 034603 (2005)

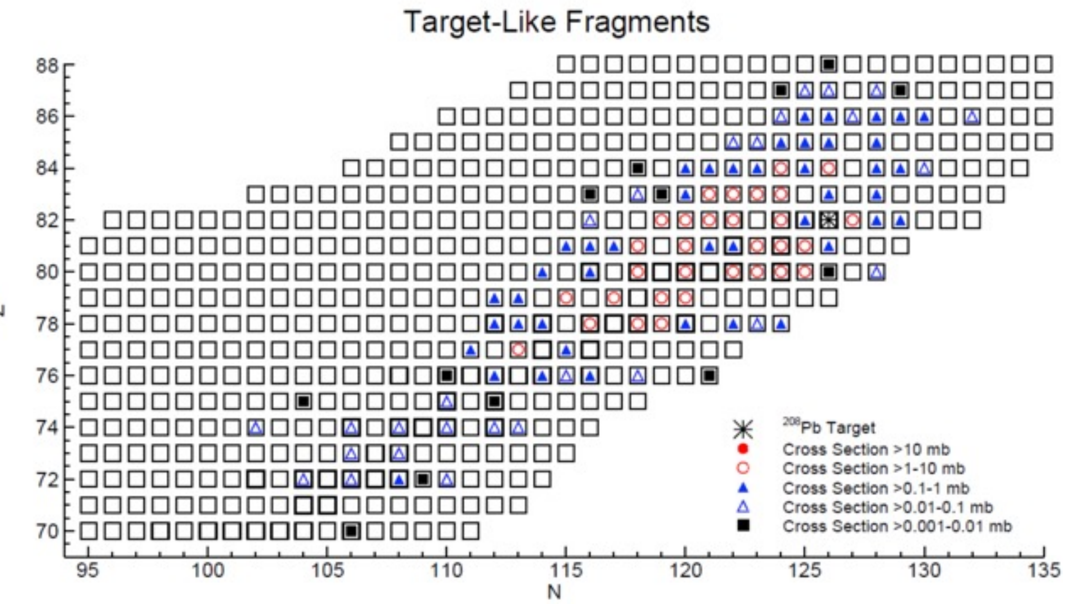


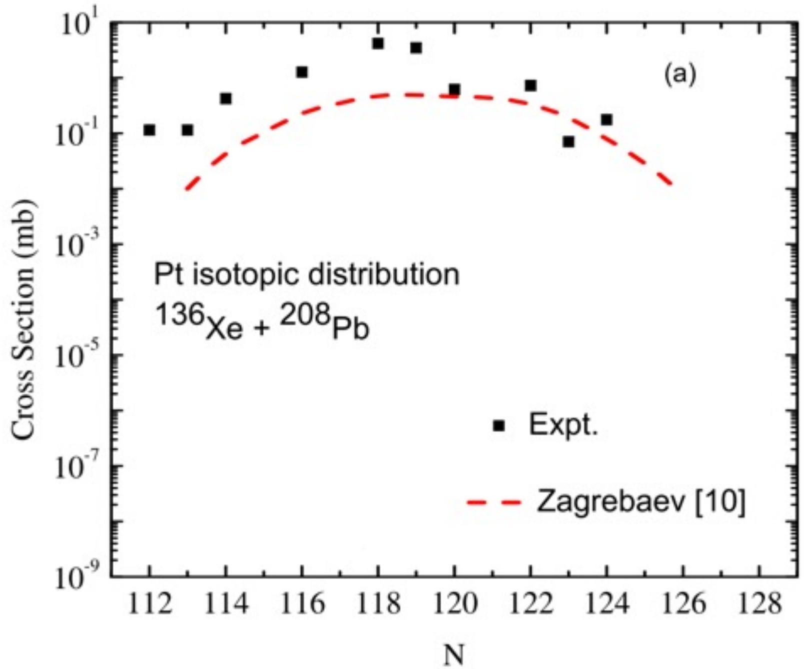
- Zagrebaev and Greiner developed a model using **multidimensional langevin equations** to describe the dynamics of MNT at low energy
- They theorized that if MNT reactions were run near the barrier [~1.1Vb] shell effects would be preserved and large transfers would occur at forward angles.
- Adamian et al. describe such reactions as the evolution of a **dinuclear system**.
- Contrary to Langevin model, lighter beams are favored
- **Different models predict reasonable cross-sections for the production of superheavy nuclei**

Test of models of MNT reaction: $^{136}Xe+^{208}Pb$

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

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



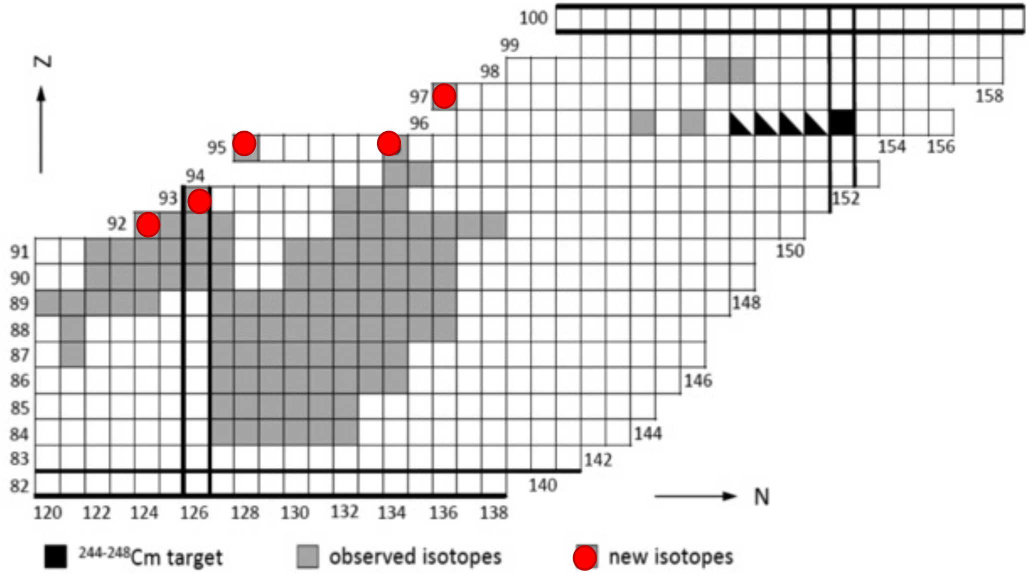


117 target like produced from Yb (Z=70) to Ra (Z=88).
The cross section follow the trend predicted by Zagrebaev for the target like products

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

Examples of successful MNT experiments for heavy elements @ 0°

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



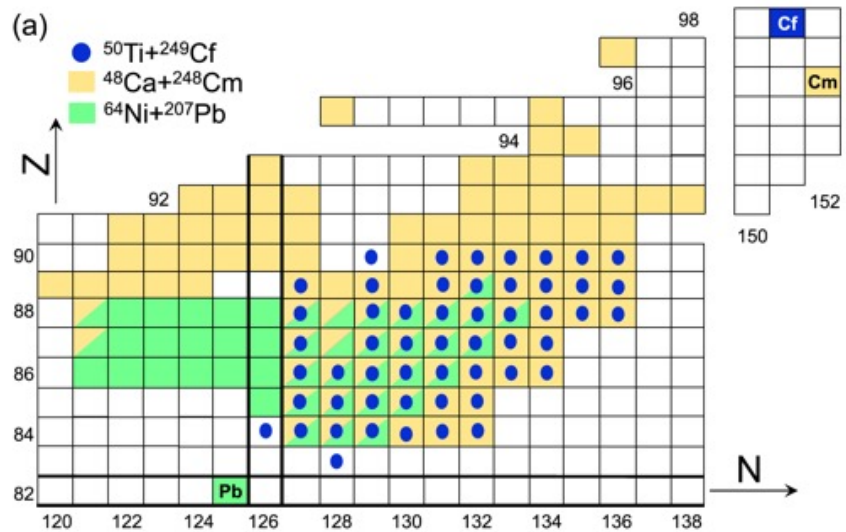
S. Heinz, et al. Eur. Phys. J. A (2016) 52: 278

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.