SYSTEMATIC INVESTIGATION OF THE ENERGY DEPENDENCE IN ^{136}XE ON PROTON SPALLATION REACTIONS

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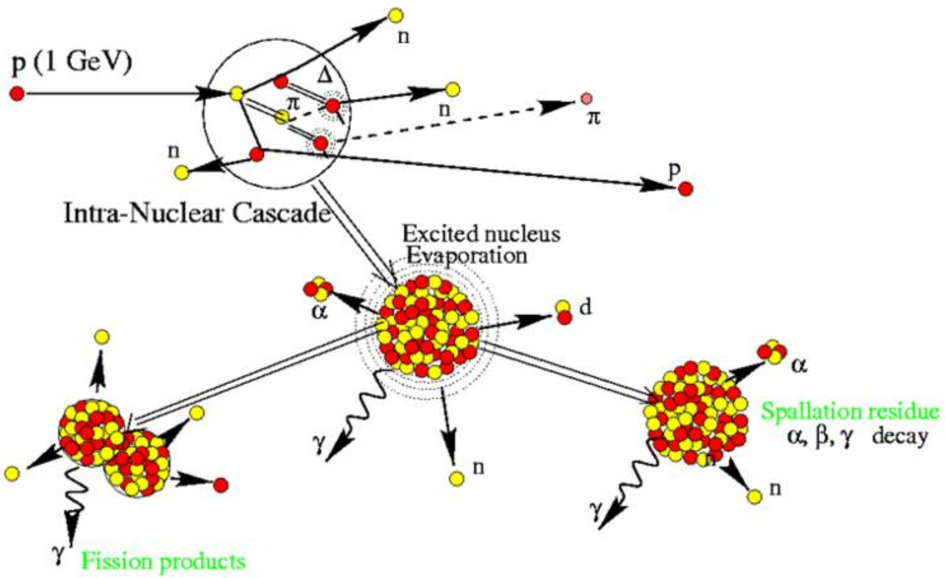
Spallation reactions: Introduction

- Spallation reactions refer to the nuclear interaction between a light relativistic hadron and a heavy nucleus

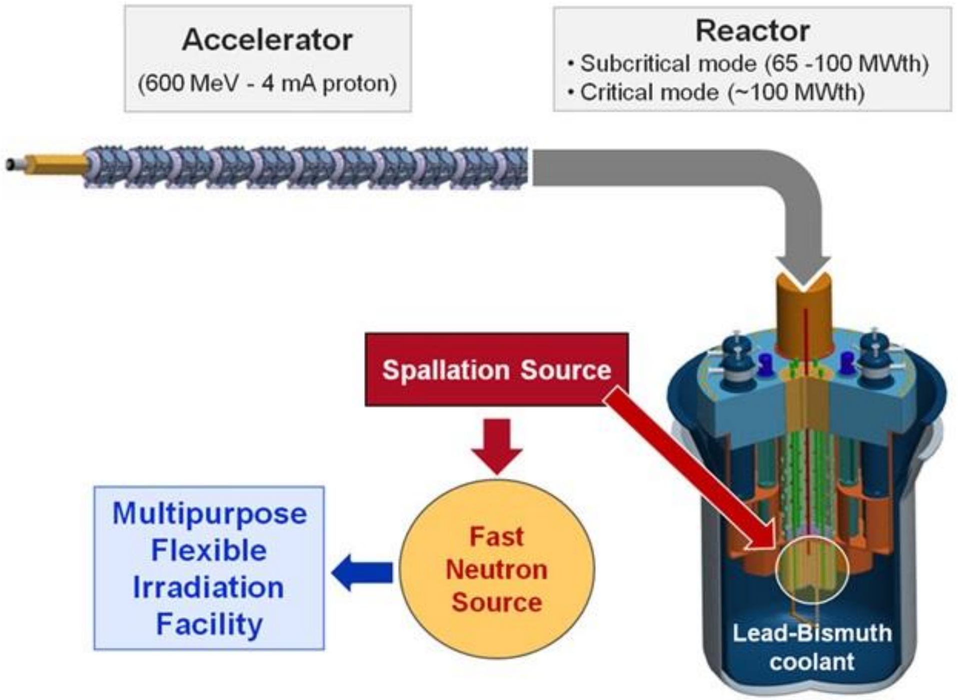
- They cover an energy range from a few hundreds MeV up to several GeV

- They are usually described as two stage process



Spallation reactions: Applications

- Intense neutron sources such as SNS, SINQ, J-PARC or future ESS
- Astrophysics and space science
- Safety and radiation protection
- Nuclear waste transmutation (ADS)



Spallation reactions: Models

- Transport codes as MCNP or GEANT use nuclear models codes when experimental data is missing
- Different models are available such as QMD or intranuclear cascade models (CEM, **INCL**, **ISABEL**...) and de-excitation models (**ABLA**, Gemini...)
- Their predictive potential can be tested in benchmarks for reproducing experimental quantities: systematic experimental data is required (https://www-nds.iaea.org/spallations/)

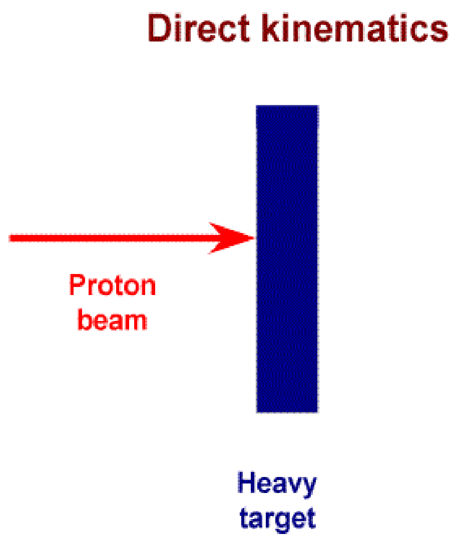
Spallation reactions: Experiments

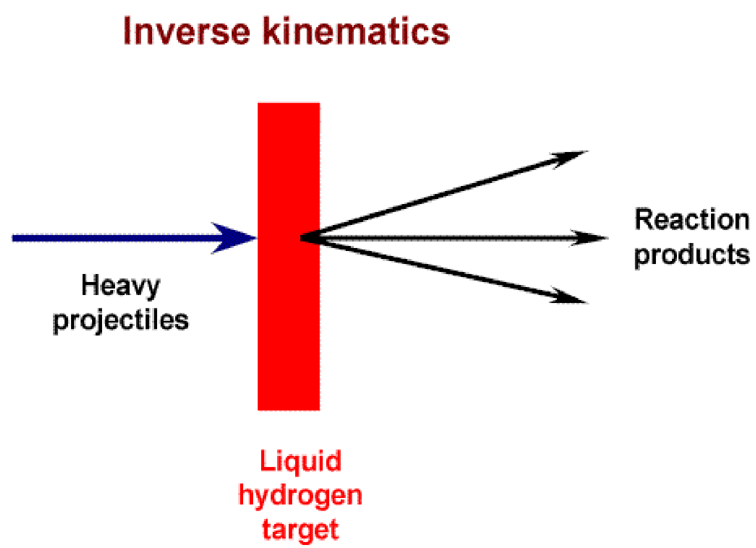
DIRECT KINEMATICS

- Reaction products analysed by using their radioactive decay or by on-line and off-line mass spectrometry (stable products).
- Limited access to short-lived products and to the reaction mechanism

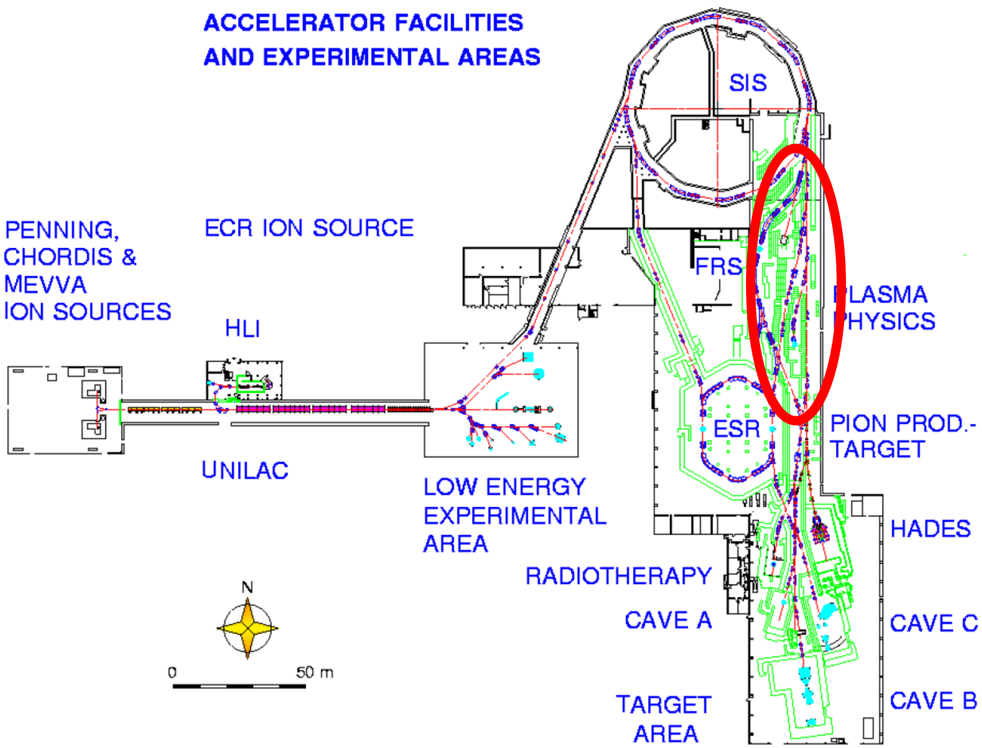
INVERSE KINEMATICS

- In-flight identification of A and Z by a spectrometer
- Access to kinematic properties
- Independent of chemical and decay properties of the products

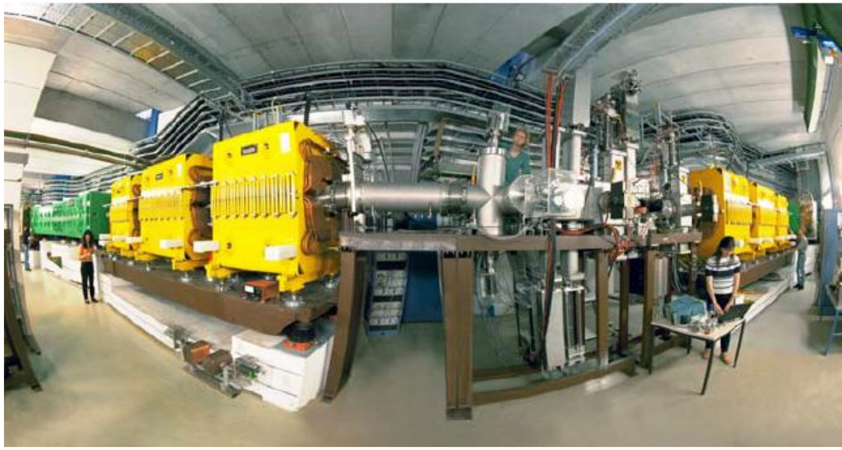




Spallation at GSI-FRS



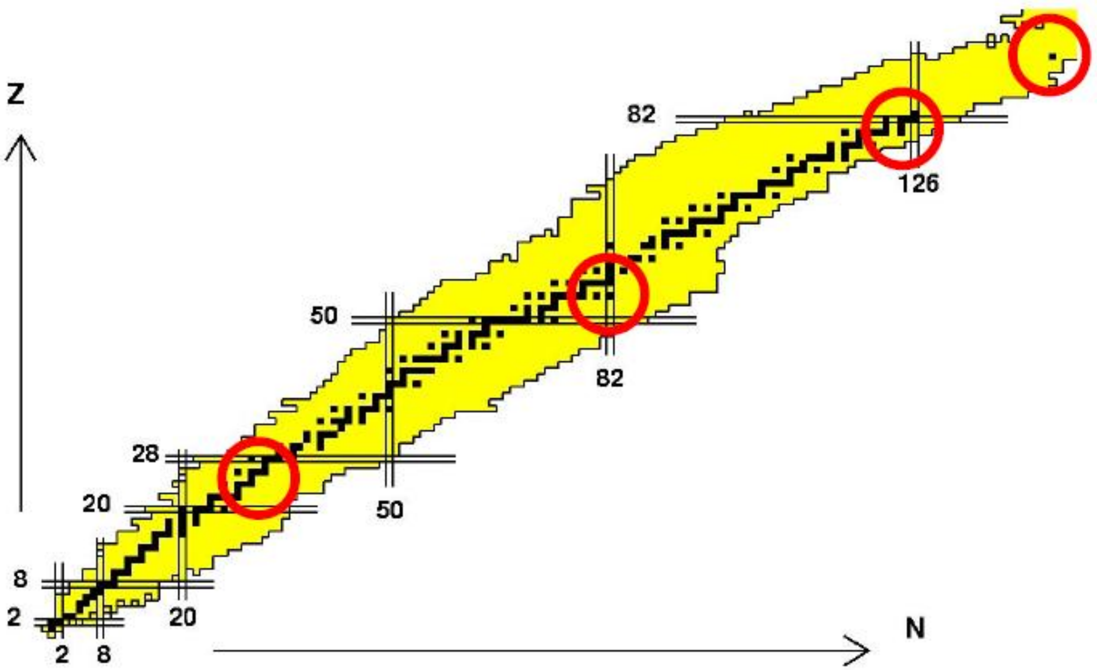
FRagment Separator



Relativistic heavy-ion beams

- pulsed beams (~ 4 s spill, 8 s cycle)
- 200 A MeV – 1000 A MeV

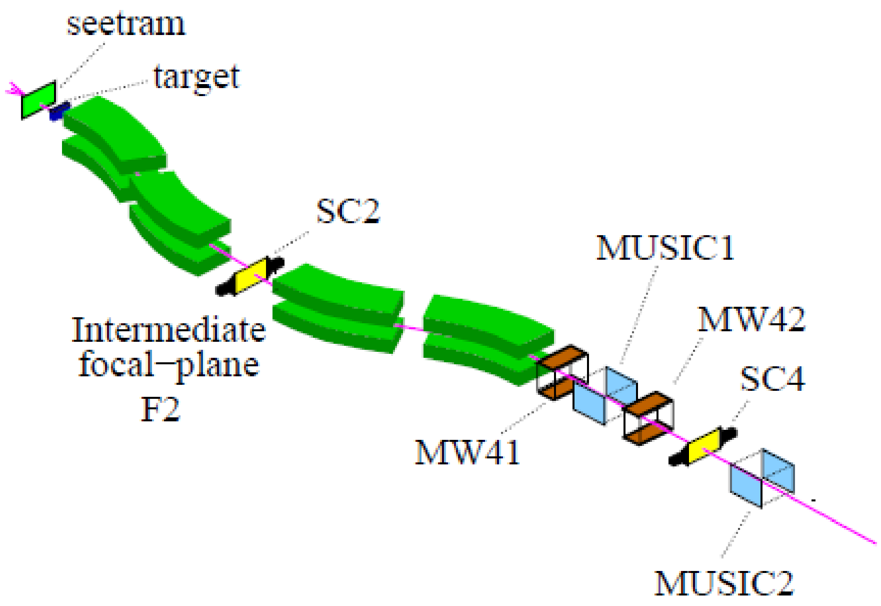
Spallation at GSI-FRS



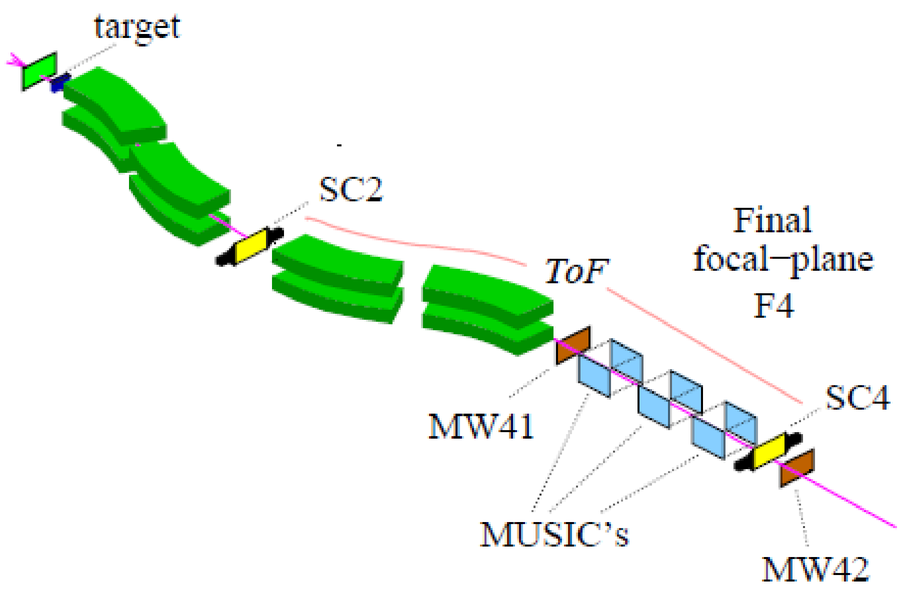
- ✓ ^{238}U (1000 A MeV)+p,d
- ✓ ^{208}Pb(1000, 500 A MeV)+p
- ✓ ^{197}Au(800 A MeV)+p
- ✓ ^{136}Xe (1000, 500, 200 A MeV)+p
- ✓ ^{56}Fe (1000, 500, 300 A MeV)+p

Experimental program developed by a collaboration GSI, IPN-Orsay, SPhN-Saclay, USC and CENBG and partially funded by EU (FP5 HINDAS project)

FRS experimental setup



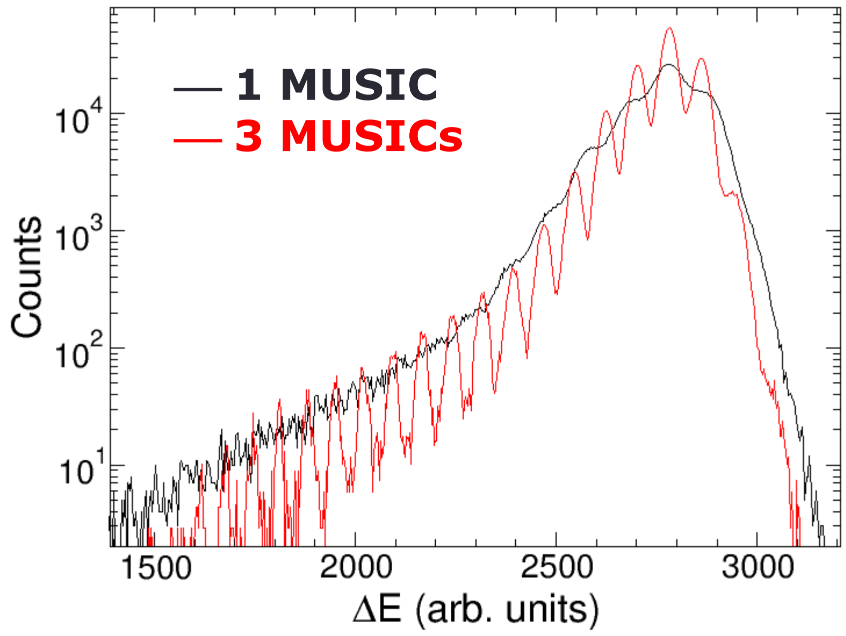
1000 and 500 A MeV setup

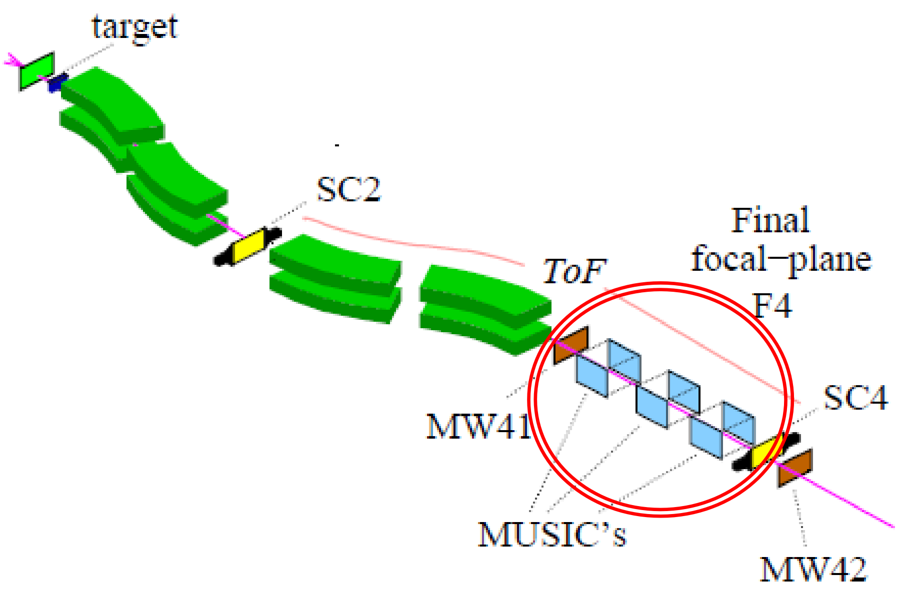


200 A MeV setup

Data Analysis: ^{200}Xe+p case

Identification in Z

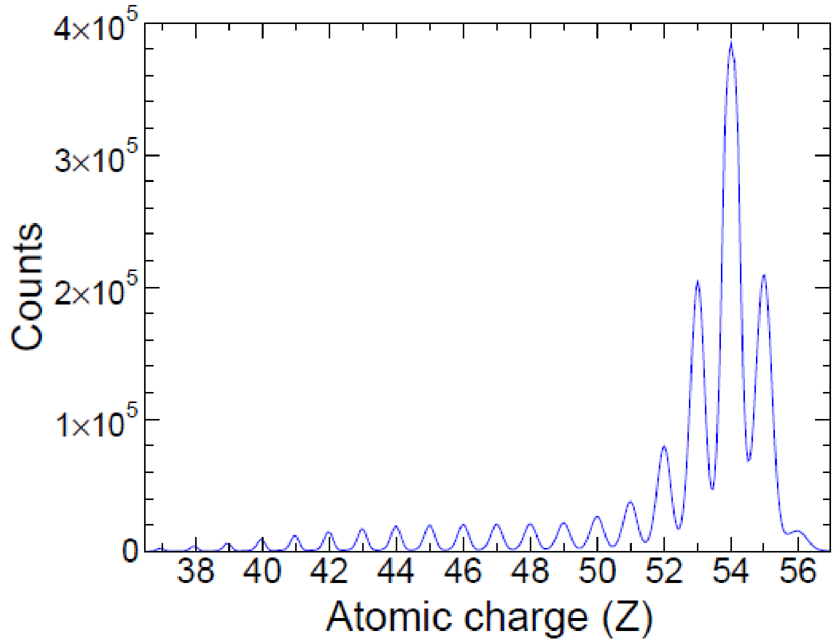




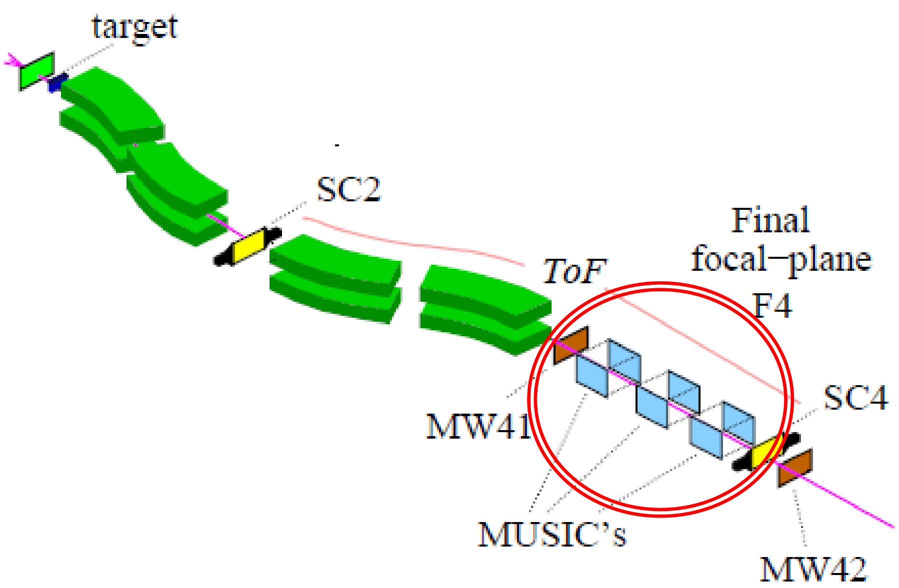
Data Analysis: ^{200}Xe+p case

Identification in Z

$$\Delta E = P(x_4)Q(ToF)R(Z)S(A_{cent}, \Delta E)$$



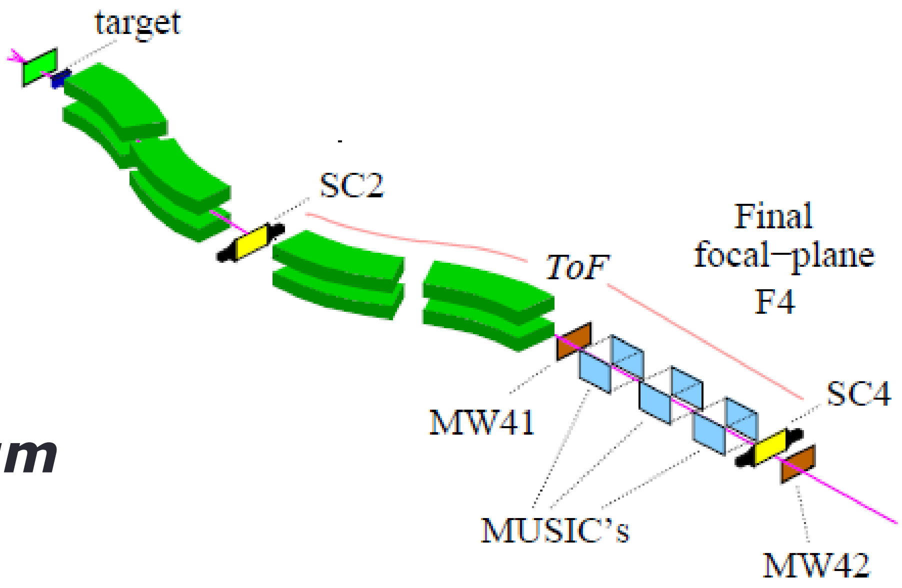
$$\Delta Z/Z = 1 \times 10^{-3}(FWHM)$$



Data Analysis: ^{200}Xe+p case

Identification in A

$$B\rho = \beta\gamma \frac{A}{q} c \frac{m_0}{e}$$



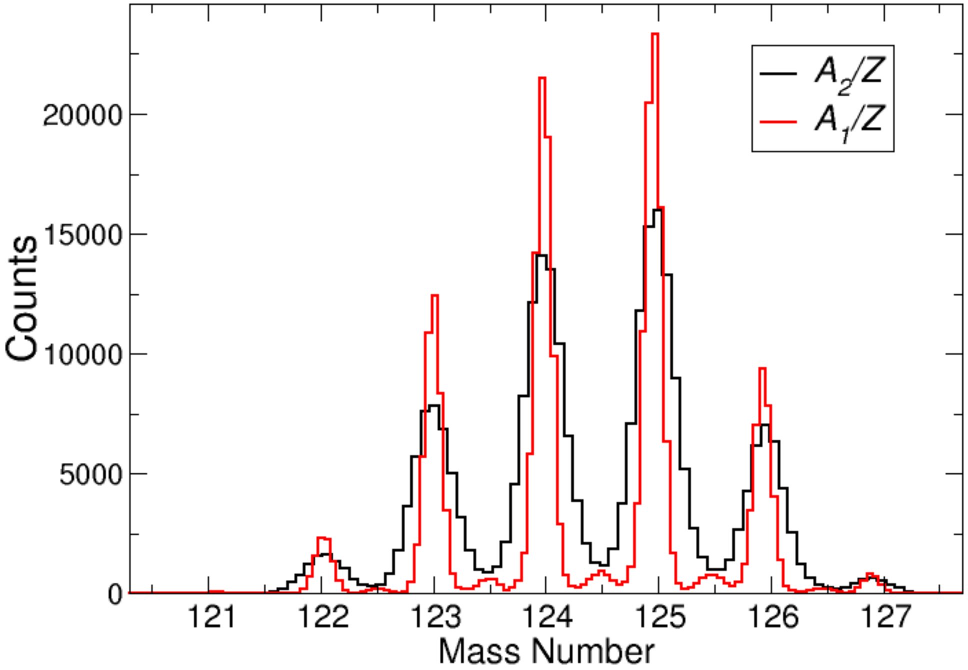
Bρ : magnetic rigidity

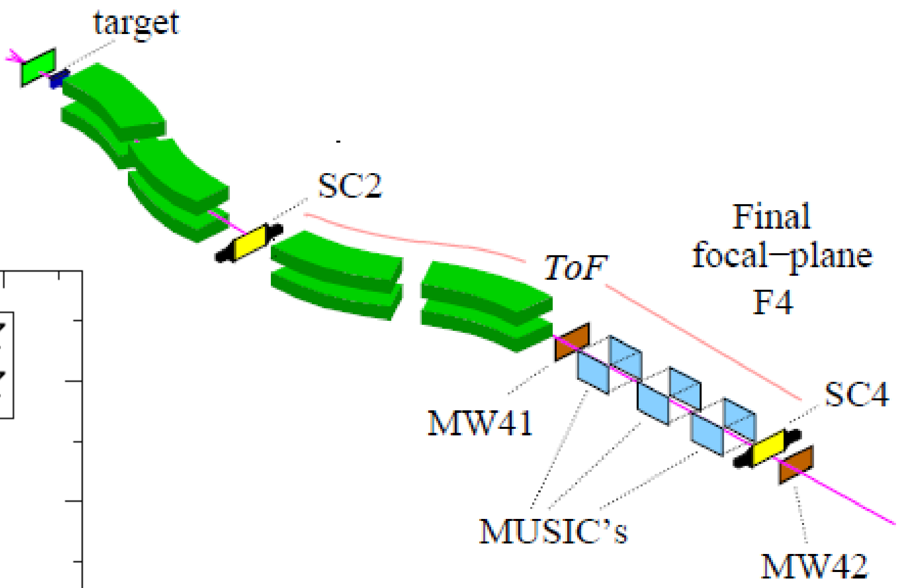
$\beta\gamma$: relativistic momentum

Data Analysis: ^{200}Xe+p case

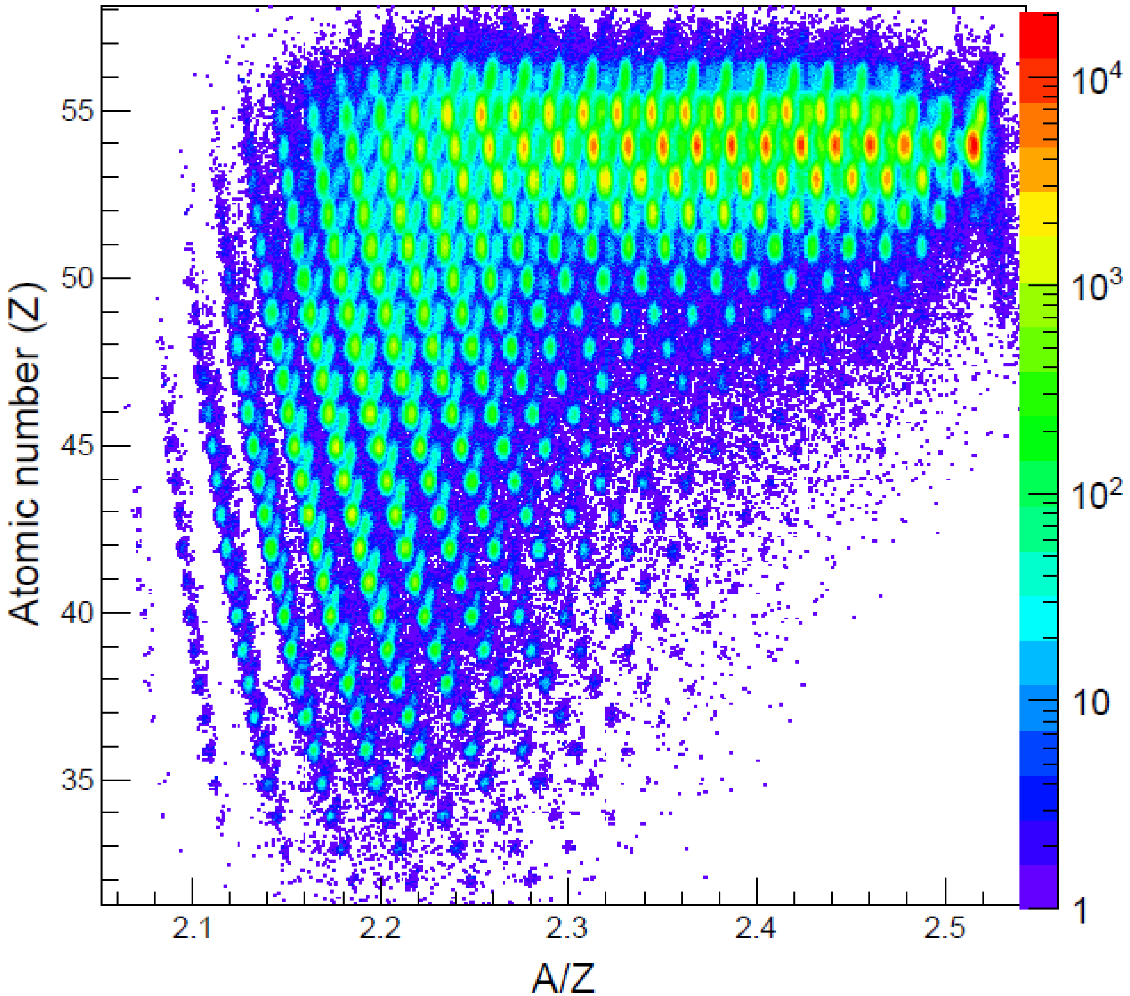
Identification in A

$$B\rho = \beta\gamma \frac{A}{q} c \frac{m_0}{e}$$

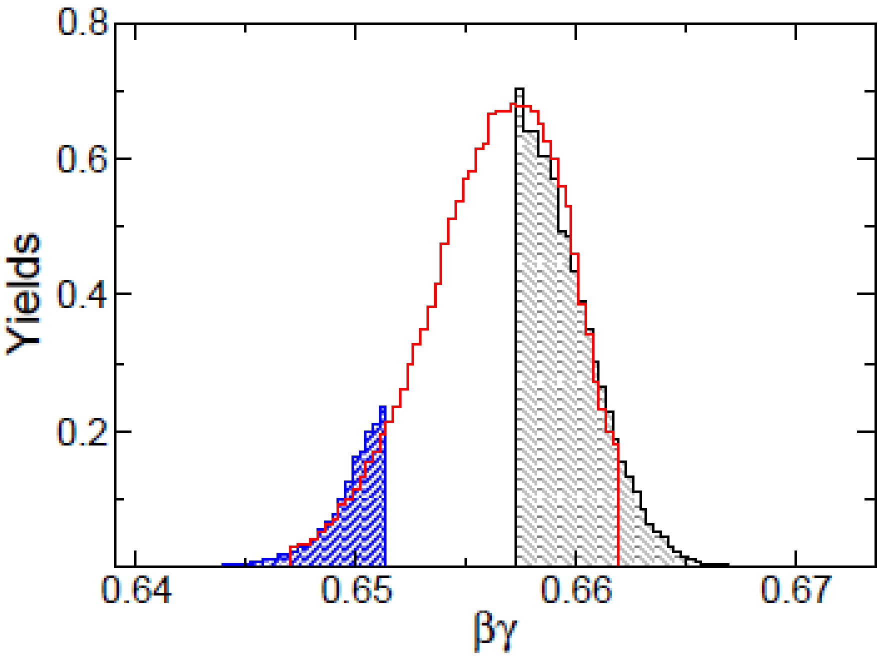




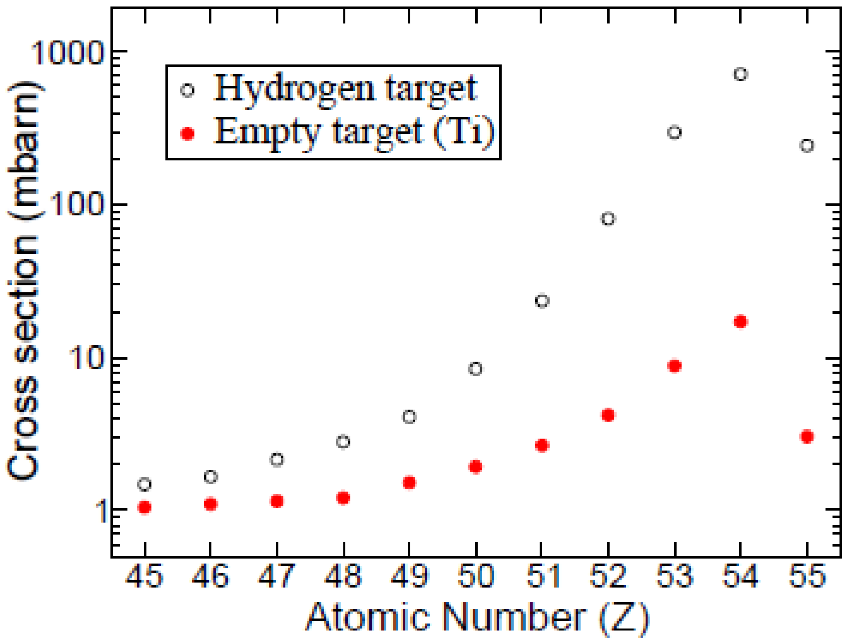
Data Analysis: ^{200}Xe+p case



Data Analysis: $^{200}Xe+p$ case



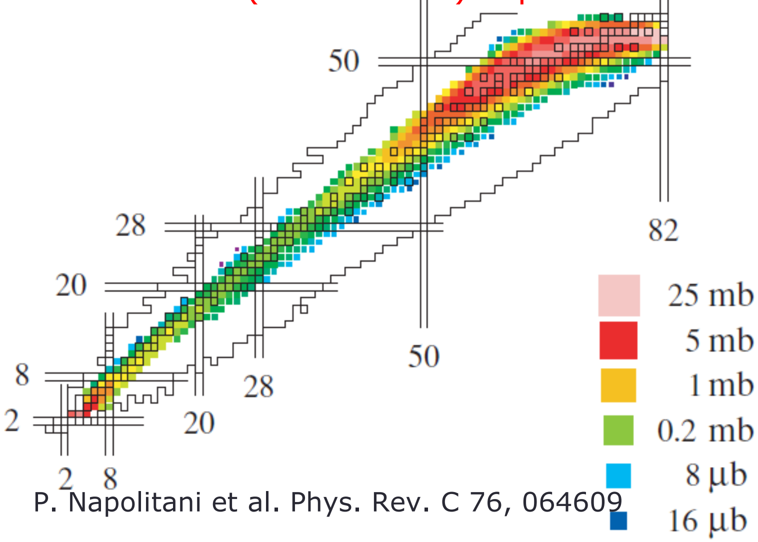
Isotopic yield obtained by integrating the momentum distribution



Sustraction of the titanium container contribution

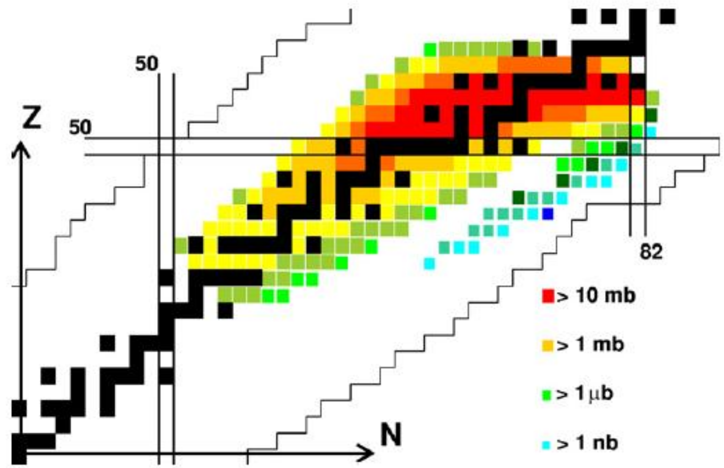
Results

^{136}Xe (1000 A MeV) + p



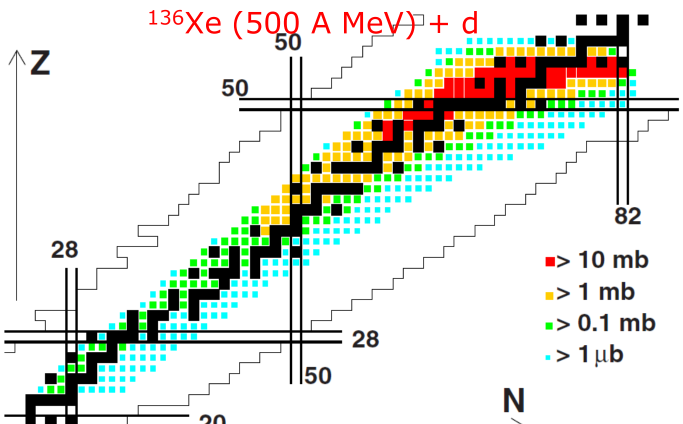
P. Napolitani et al. Phys. Rev. C 76, 064609

^{136}Xe (500 A MeV) + p



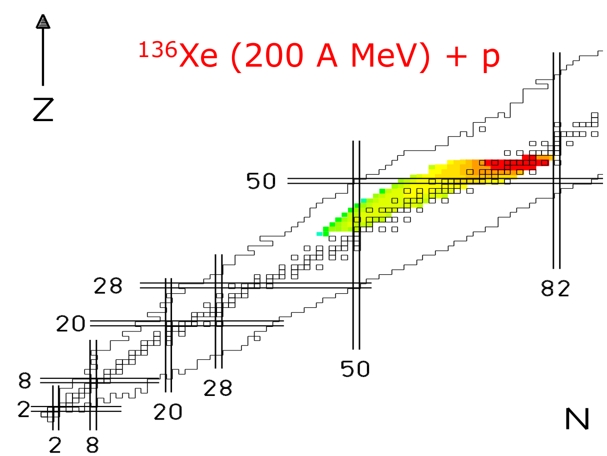
L. Giot et al. Nucl. Phys A 899,116

^{136}Xe (500 A MeV) + d



J. Alcantara et al. Phys. Rev. C 92, 024607

^{136}Xe (200 A MeV) + p

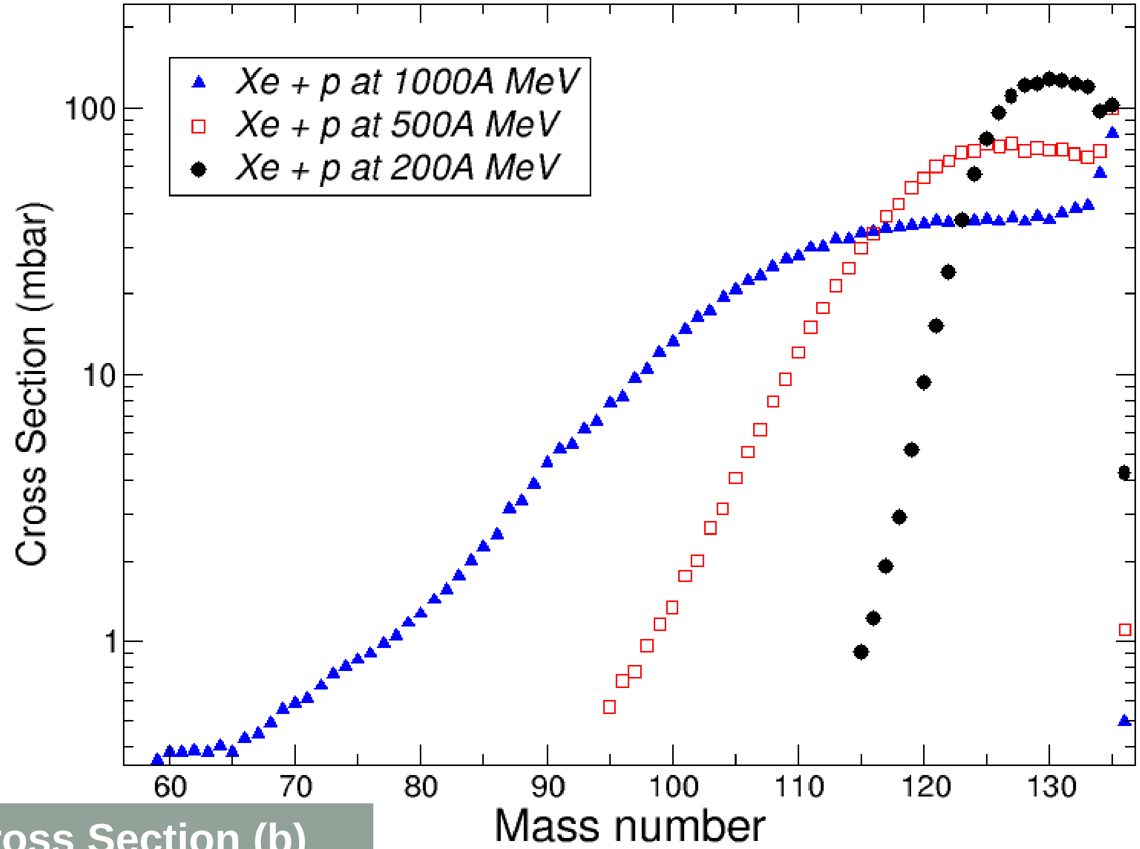


C. Paradela et al. Phys. Rev. C in preparation

Mass distribution of the products

- Higher incident energies, residues with less mass are produced

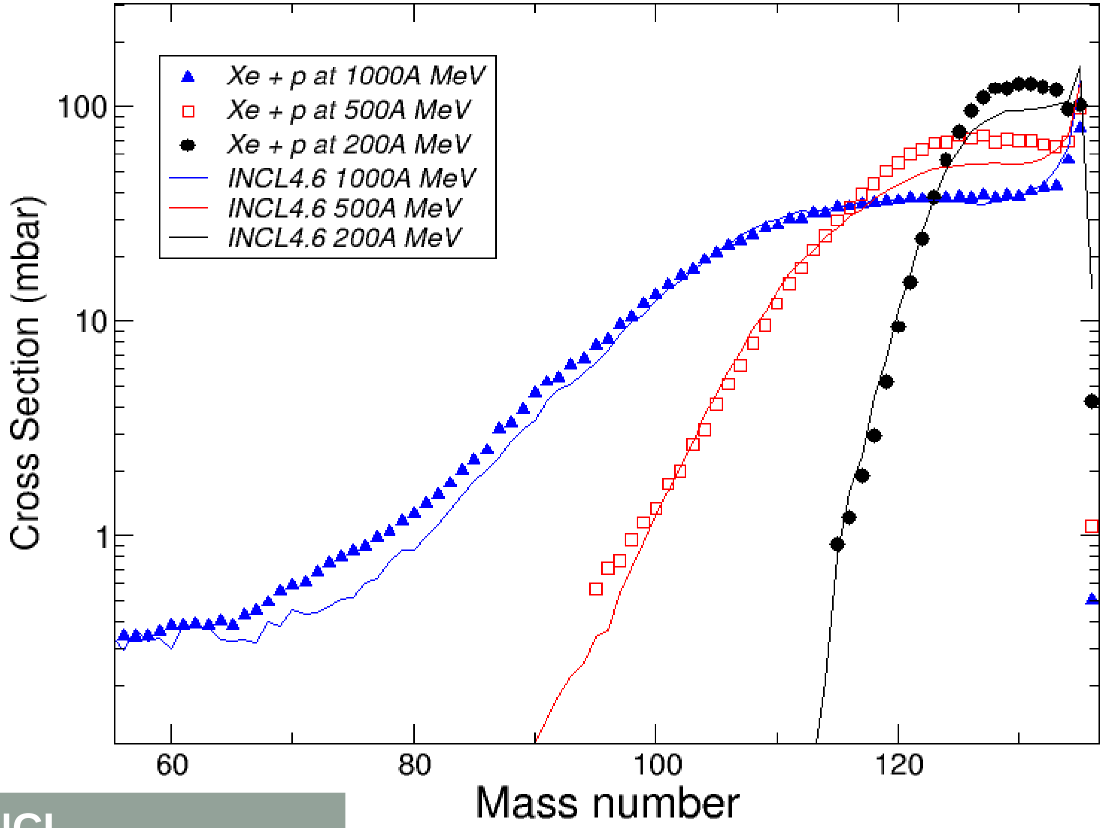
- Similar total cross section independently of the energies



Energy (A MeV)	Exp. Total Cross Section (b)
1000	1393 ± 72
500	1388 ± 97
200	1405 ± 166

Comparison to codes

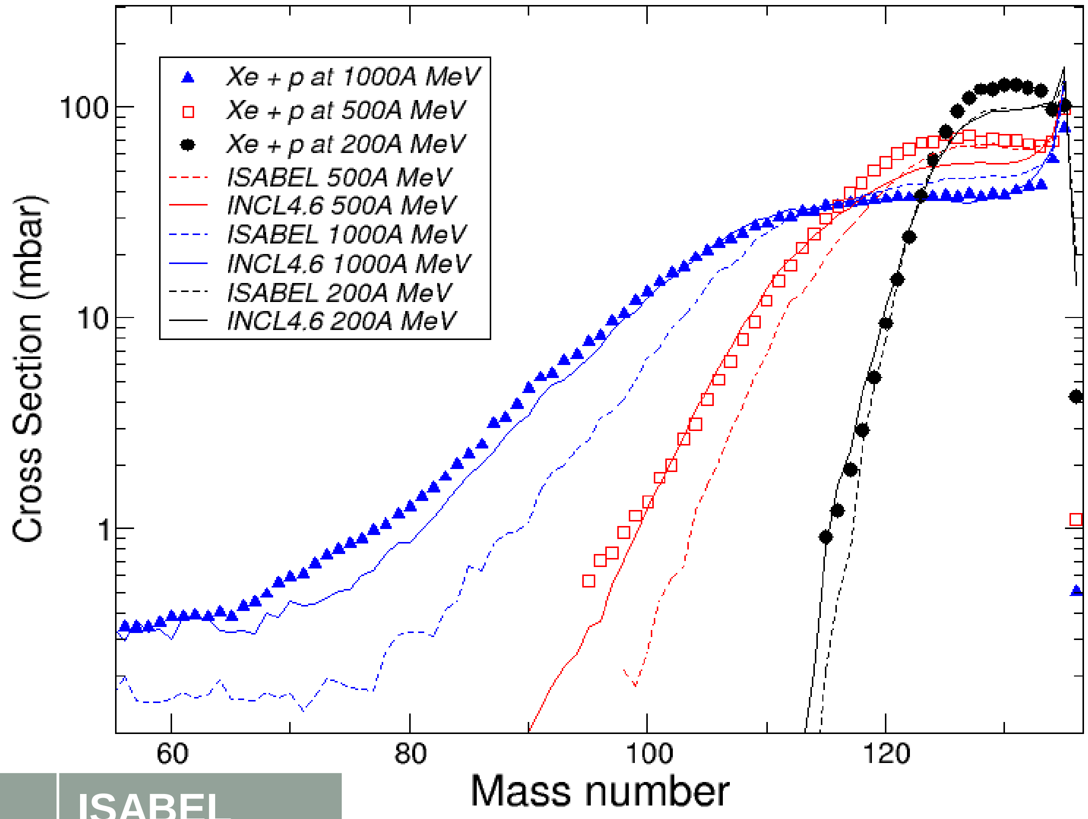
- INCL4.6+ABLA07 reproduce rather well the shape of the isobaric distribution
- Better performance at high incident energies
- Energy dependence in the total cross section



Energy	Experiment	INCL
1000	1393 ± 72	1378
500	1388 ± 97	1265
200	1405 ± 166	1223

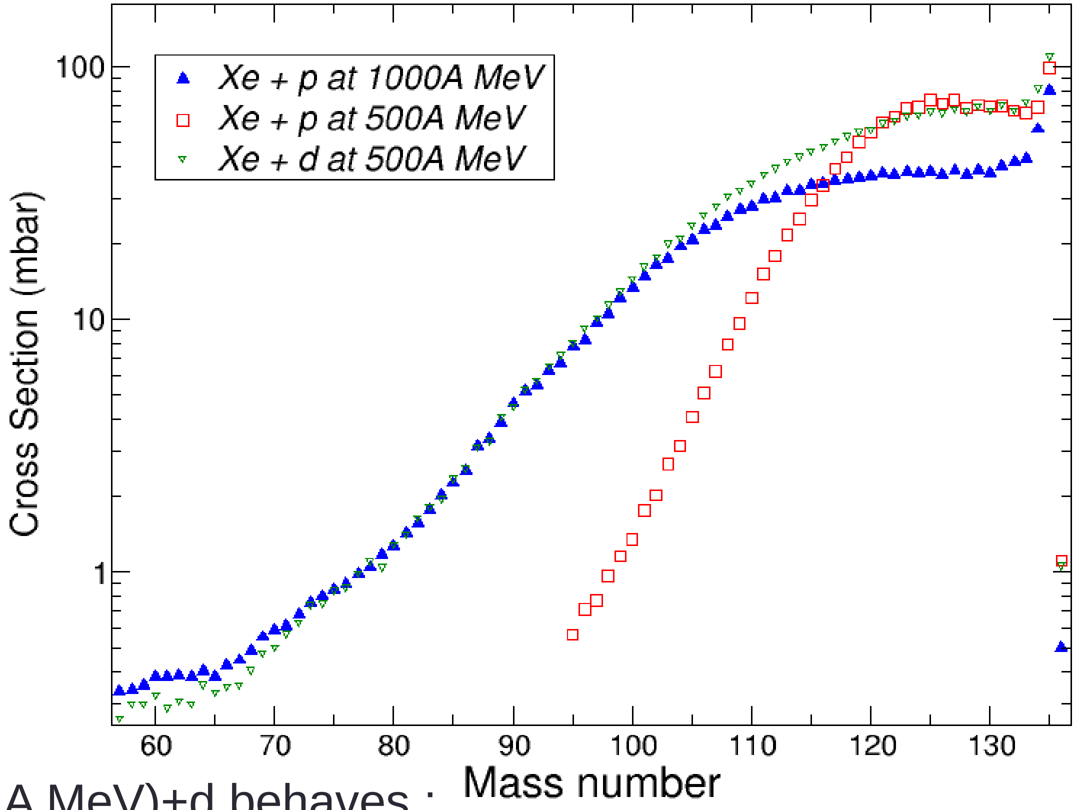
Comparison to codes

- ISABEL+ABLA07 perfoms worse at 1 A GeV
- Problems with the prefragment excitation energy
- Same energy dependence in the total cross section



Energy	Experiment	INCL	ISABEL
1000	1393 ± 72	1378	1335
500	1388 ± 97	1265	1253
200	1405 ± 166	1223	1193

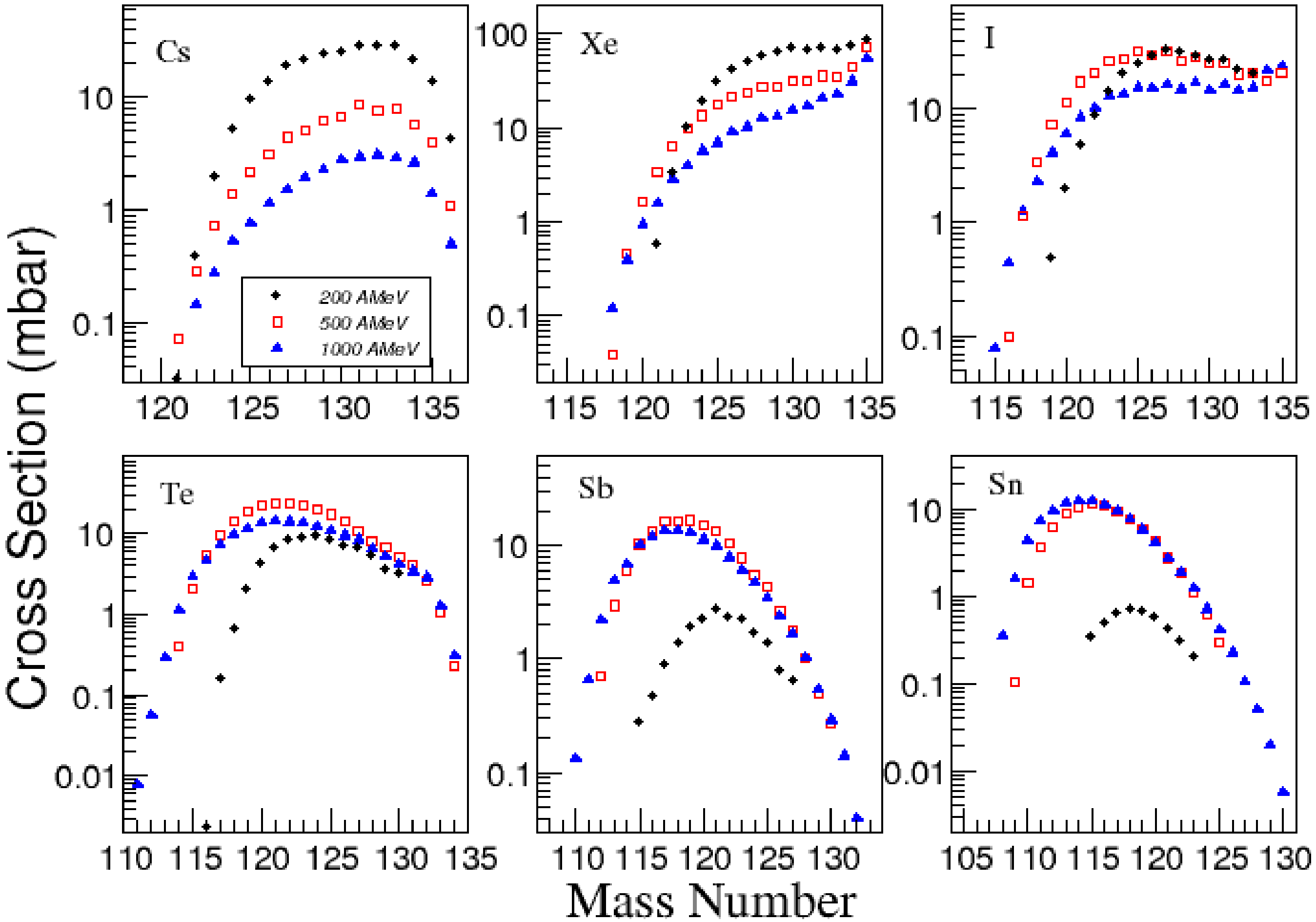
Proton vs Deuterium



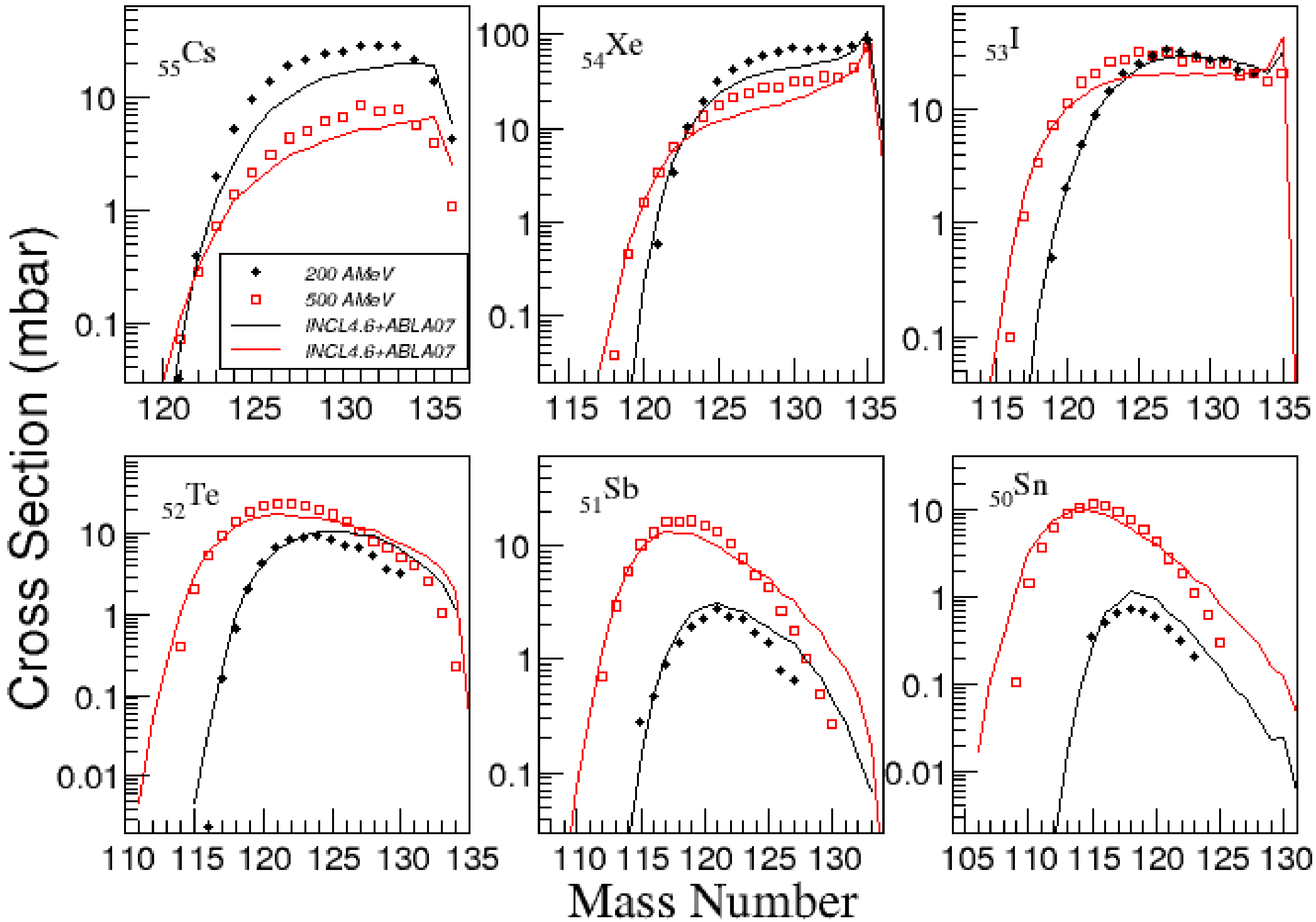
^{136}Xe(500 A MeV)+d behaves :

- Similar to ^{136}Xe(500 A MeV)+p close to the projectile (one nucleon from the target in periferal collisions)
- Similar to ^{136}Xe(500 A MeV)+p far from the projectile (both target nuclei contribute to the prefragment excitation energy)

Isotopic cross section



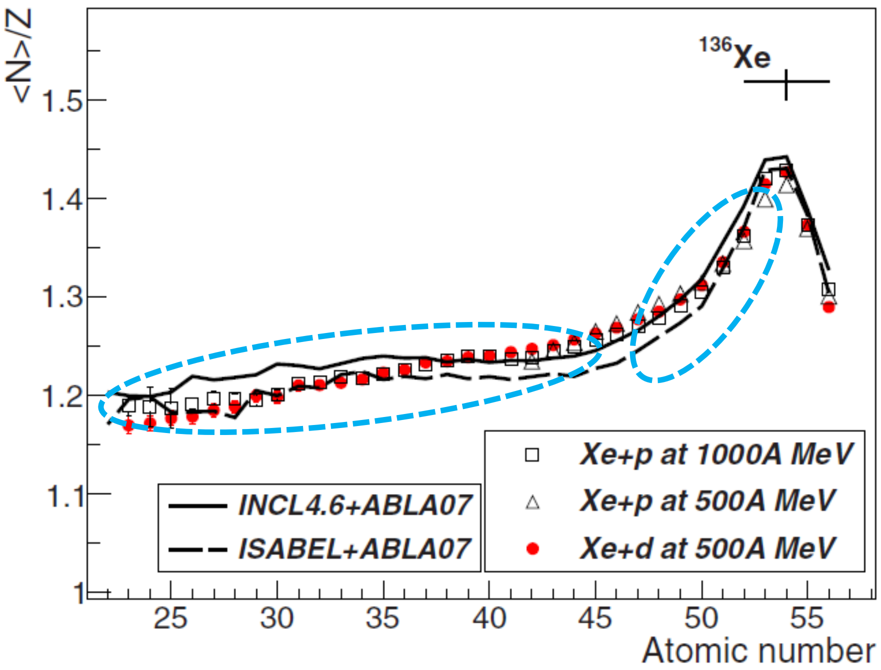
Isotopic cross section



Average neutron excess <N>/Z

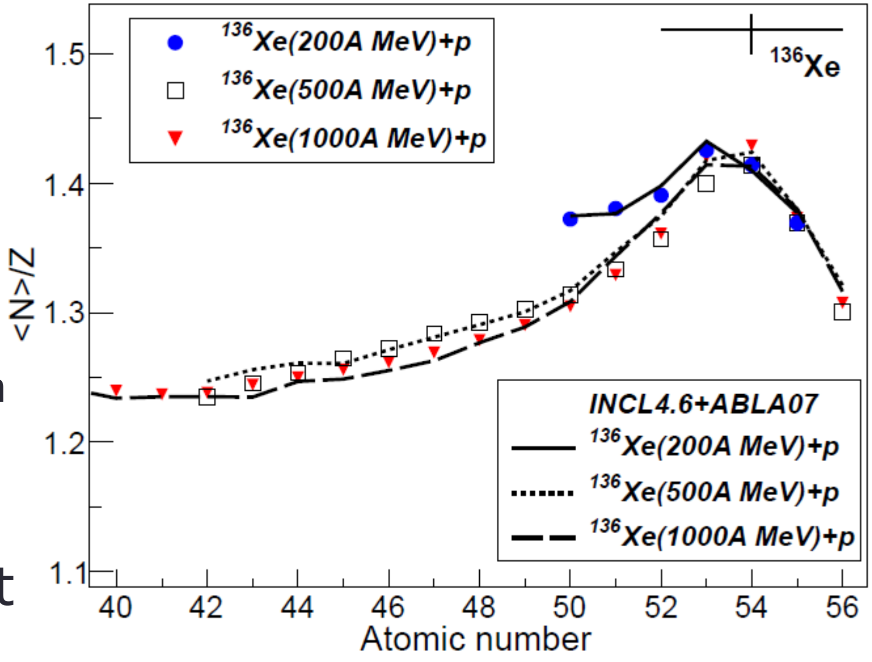
- Evolution of the average neutron excess is not affected by larger excitation energies

- Two different product regions:
  - Close to ^{136}Xe, deexcitation via neutron evaporation
  - Far from ^{136}Xe (residue corridor), competition between neutrons and light charge particles



Average neutron excess <N>/Z

- Evolution of the average neutron excess is not affected by larger excitation energies
- Two different product regions:
  - Close to ^{136}Xe, deexcitation via neutron evaporation
  - Far from ^{136}Xe, competition between neutrons and light charge particles
- At 200 MeV the prefragment excitation energy is too small to evaporate neutrons



Conclusions

- The results on the ^{136}Xe+p reaction concludes the spallation program performed at the FRS-GSI facility
- The 200 MeV data is of special interest for benchmarking the nuclear models in their limit of validity and relevant for thick target simulation
- Overall good performance of the studied nuclear codes even when larger discrepancies for decreasing energies are observed

Data Analysis: ^{200}Xe+p case