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Detailed investigation of Residual Nuclei Produced in Spallation Reactions at GSI

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Detailed Investigation of Residual Nuclei Produced in Spallation Reactions at GSI

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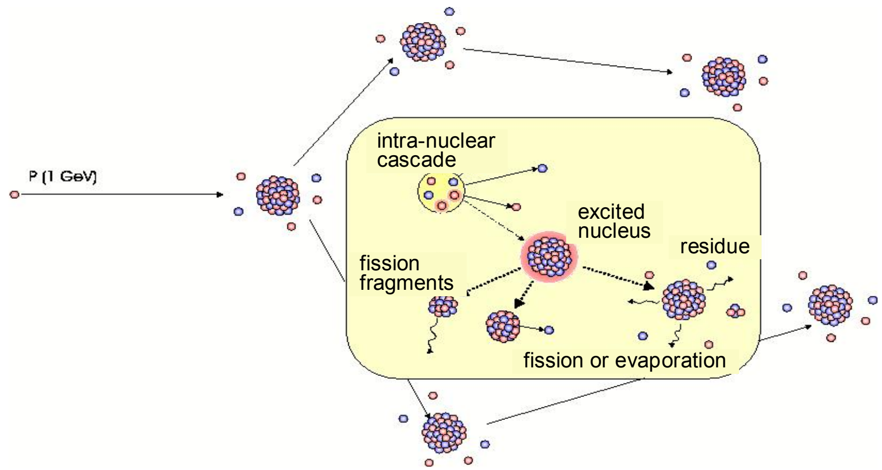
Motivation

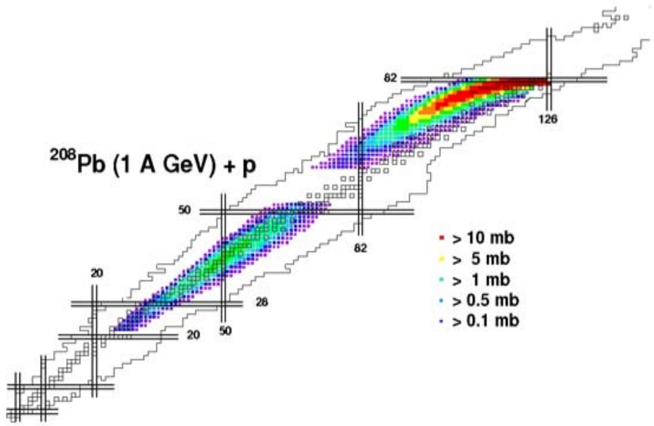
Accurate measurements of isotopic production cross sections of spallation residues



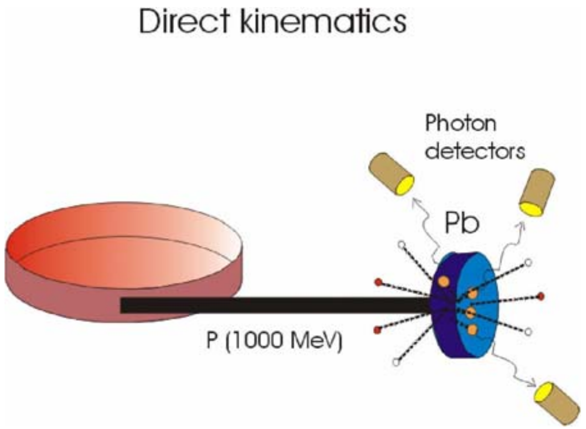
Residual nuclei provide information on both stages of the collision:

- Residues close in neutron and atomic number to the initial nucleus are more sentitive to the first stage of the collision

- Ligther residues are more sensitive to the de-excitation phase (evaporation or fission)

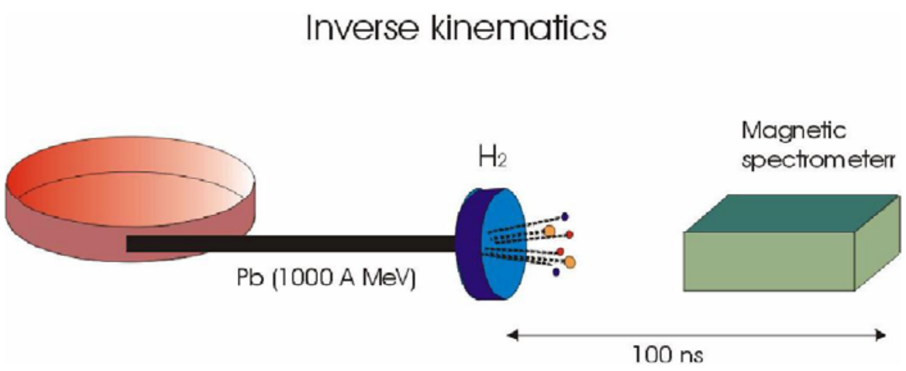


Reaction kinematics



γ-ray spectroscopy or mass spectrometry

- simple experimental set-up
- fast experiments: full excitation functions
- residue identification after β-decay
- mostly isobaric distributions are provided
- no kinematical information



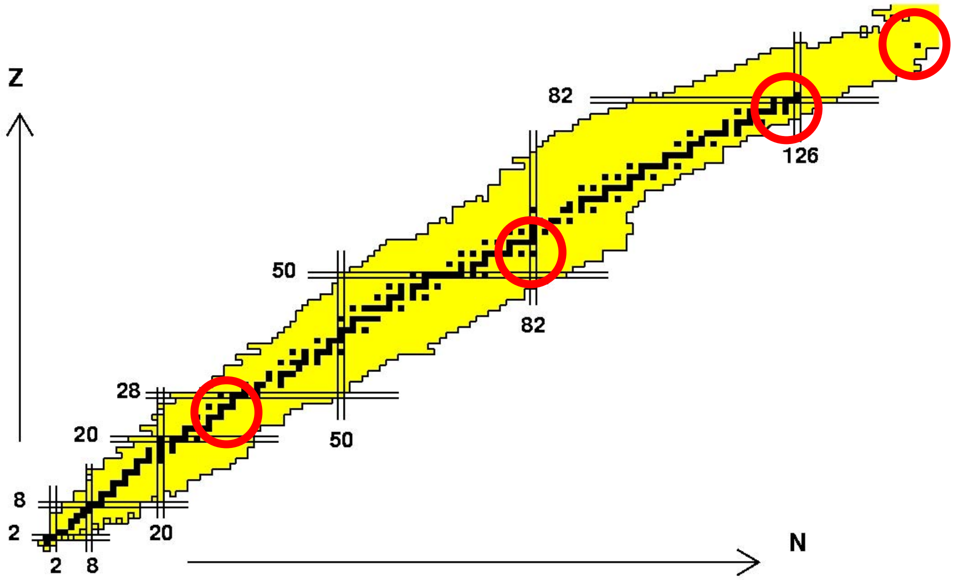
In-flight magnetic identification

- full isotopic identifiction
- mometum measurement
- complicated experimental set-up
- long beam times
- only selected reactions can be investigated

Experimental programme

Experimental programme

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



Collaboration GSI,IPN-Orsay,SPhN-Saclay,USC, CENBG

Partially funded by UE under FP5 HINDAS project

Layout

✓ Experimental technique
- Isotopic identification of spallation residues
- Cross sections determination

✓ Results
- Isotopic production cross sections
- Longitudinal momentum distributions

✓ The first stage of the collision

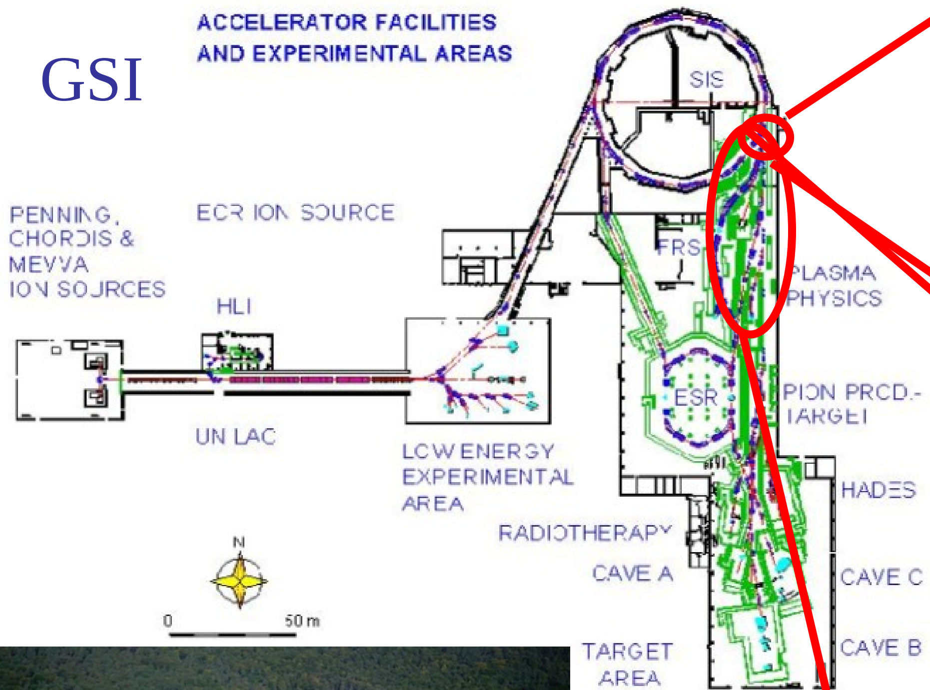
✓ Pre-fragment de-excitation
- Fission
- Statistical evaporation
- Intermediate-mass fragment emission

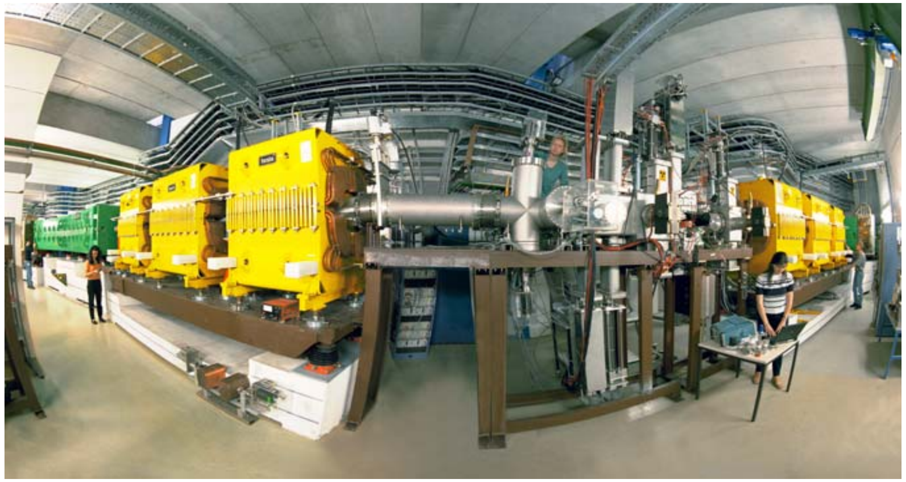
✓ Summary

Experimental technique: setup

Gesellschaft fur Schwerionenforschung (GSI)

GSI





Relativistic heavy-ion beams

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

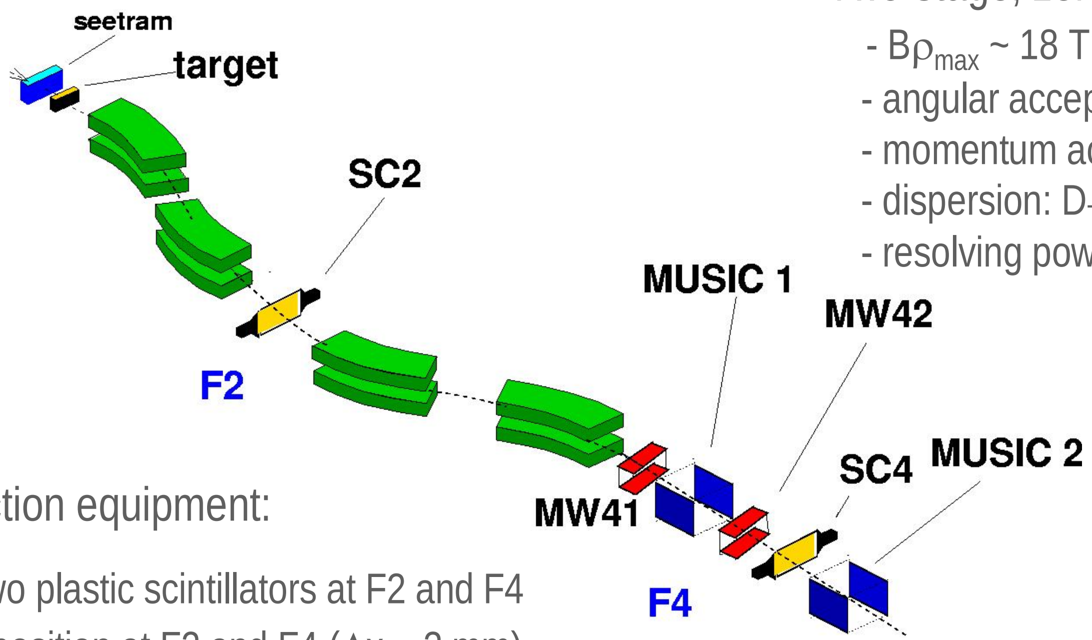
Secondary Electron Monitor (SEETRAM)

Cryogenic target (1 cm thickness)

- 1 cm thick., Ti windows (36 mg/cm2)
- H_2 (87 mg/cm_2), D_2 (201 mg/cm^2)

Experimental technique:setup

FRagment Separator (FRS)



Two-stage, zero degree achromatic spemetrometer:

- $B\rho_{max}$ ~ 18 Tm
- angular acceptance: $\Delta\theta$ ~ 15 mrad
- momentum acceptance: $\Delta p/p$ ~ 3%
- dispersion: D_{TA-F2} ~ 7 cm/% (F2 image plane ~ 20 cm)
- resolving power: $B\rho/\Delta B\rho$ ~ 1500

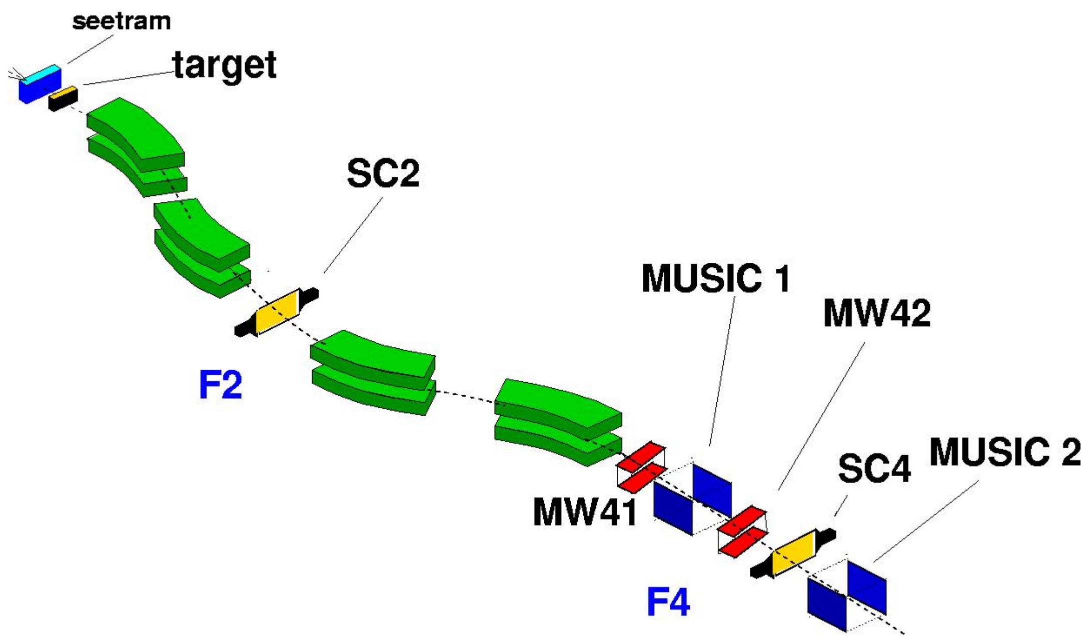
Detection equipment:

- Two plastic scintillators at F2 and F4
  position at F2 and F4 (Δx ~ 3 mm)
  F2-F4 Time of Flight (ΔToF ~ 150 ps)
- Multi-Sampling Ionisation Chamber (MUSIC)
  dE/dx, position and angle
- Multi-wire chambers for position calibrations

$$\frac{A}{Q} \propto \frac{B\rho}{\beta\gamma}$$

Experimental technique:setup

Fragment Separator (FRS)



✓ (A/Z) identification: $\frac{A}{Z} \propto \frac{B\rho}{\beta\gamma}$

$$\begin{cases} B\rho = (B\rho)_0 \cdot \left(1 - \frac{x_2 - M_2 x_4}{D_1}\right) \\ \beta\gamma = \frac{L}{c \cdot ToF} \cdot \left(1 - \frac{L^2}{c^2 \cdot ToF^2}\right)^{-1/2} \end{cases}$$

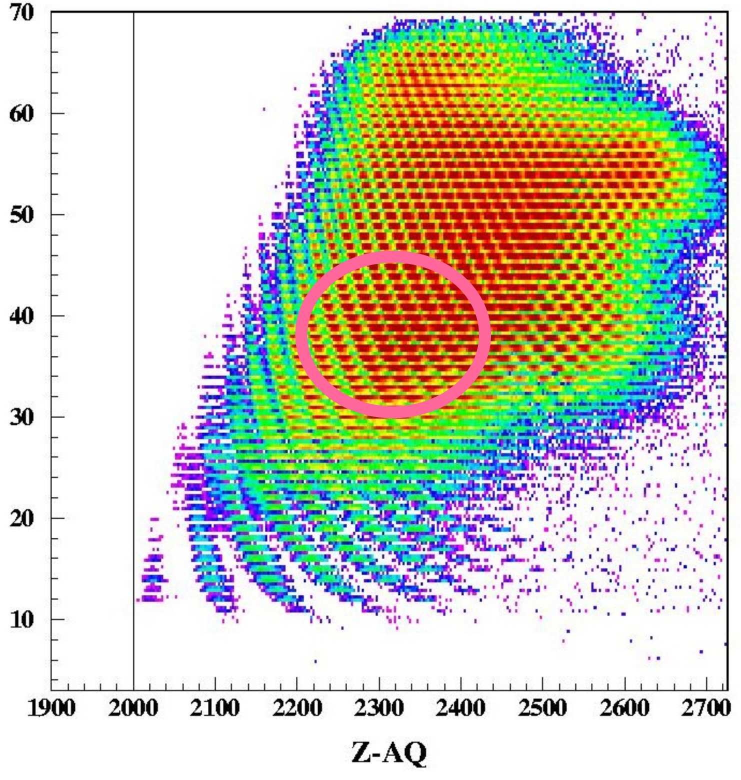
✓ Z identification: $Z \propto \sqrt{dE/dx}$

✓ Longitudinal velocities:

$$v \rightarrow \beta\gamma = \frac{Z}{A} B\rho$$

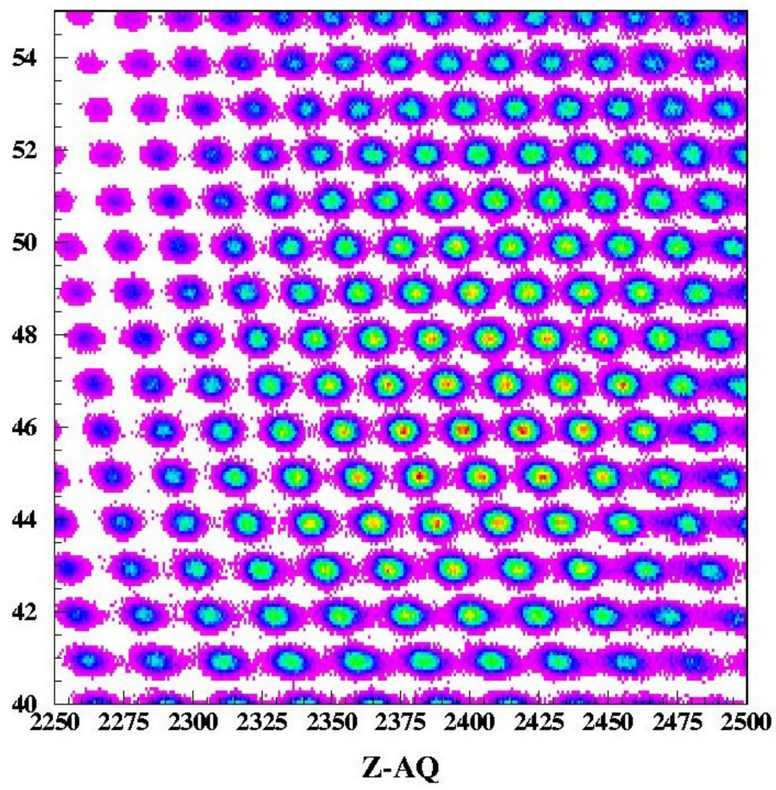
Experimental technique: isotopic identification

Isotopic identification procedure



More than 1000 fission Fragments identified in the reaction ^{238}U(1 A GeV)+d

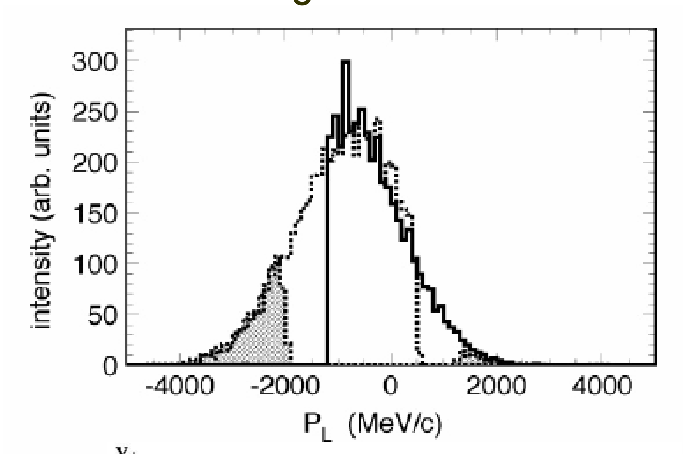
J. Pereira, et al., PRC 75 (2007) 014602

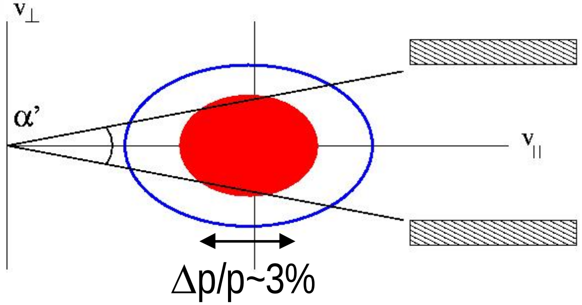


Experimental technique: isotopic production yields

Reconstruction of the longitudinal momentum distribution

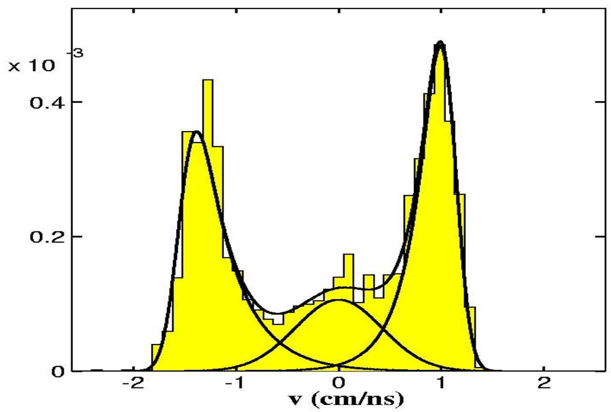
Fragmentation

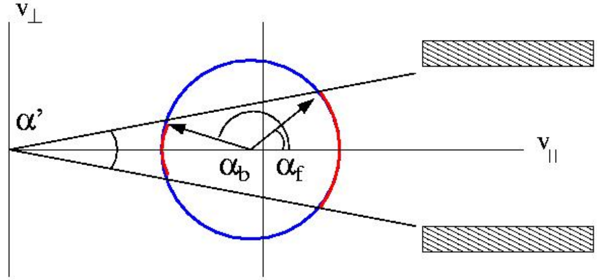




$$T_{fr} = 1 - \exp\left(-\frac{\alpha^2}{2\sigma(\theta)^2}\right)$$

Fission





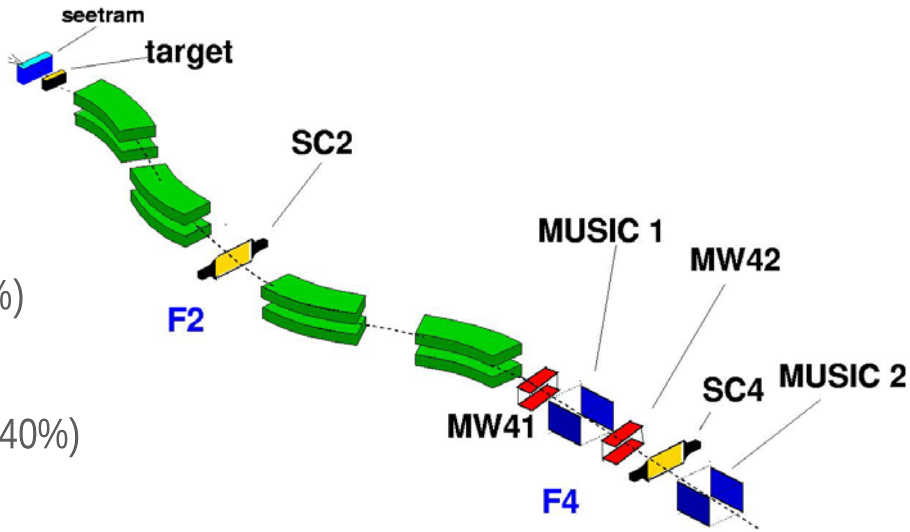
$$T_f = \frac{1 - \cos\alpha_f}{2} \qquad T_b = \frac{1 + \cos\alpha_b}{2}$$

Experimental technique: isotopic production yields

Reconstruction of the isotopic production yields

$$Y(Z,A) = Y^{mes}(Z,A)\cdot f_{sc2}\cdot f_{eff}\cdot f_{chs}\cdot f_{Ti}\cdot f_{mr}\cdot f_{T}\cdot f_{DT}$$

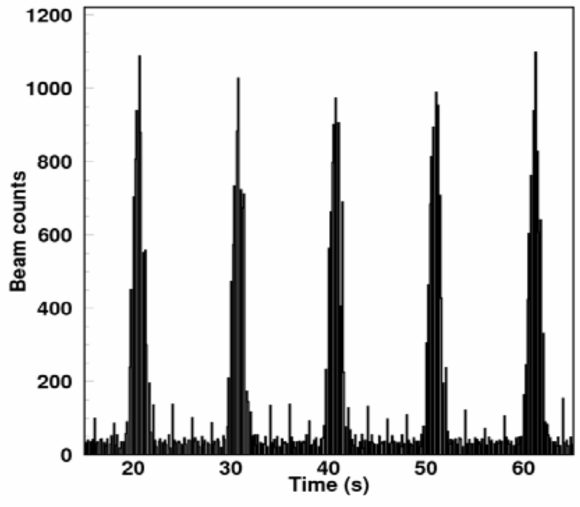
- f_{sc2}: Interactions of nuclei in scintillator SC2 (~5%)
- f_{eff}: Detection efficiencies (~97%)
- f_{chs}: Charge-state contamination (~1-30%)
- f_{Ti}: Nuclear reactions in the Ti target container (~1%)
- f_{mr}: Multiple-reactions in the target (~5-30%)
- f_{T}: Angular transmission (frag. ~85-100%, fission ~10-40%)
- f_{DT}: Acquisition dead time (~20%)



Experimental technique: cross sections

Determination of the isotopic production cross sections

$$\sigma(N,Z) = \frac{Y(N,Z)}{N_{pro} \cdot N_{tar}}$$



Accuracy

- ✓ Beam intensity: ~5-10%
- ✓ Target thickness: ~5%
- ✓ yield statistics: < 1%
- ✓ yield corrections: ~5-30%

final accuracy
- fragmentation ~ 5-15%
- fission ~ 15-30%

Layout

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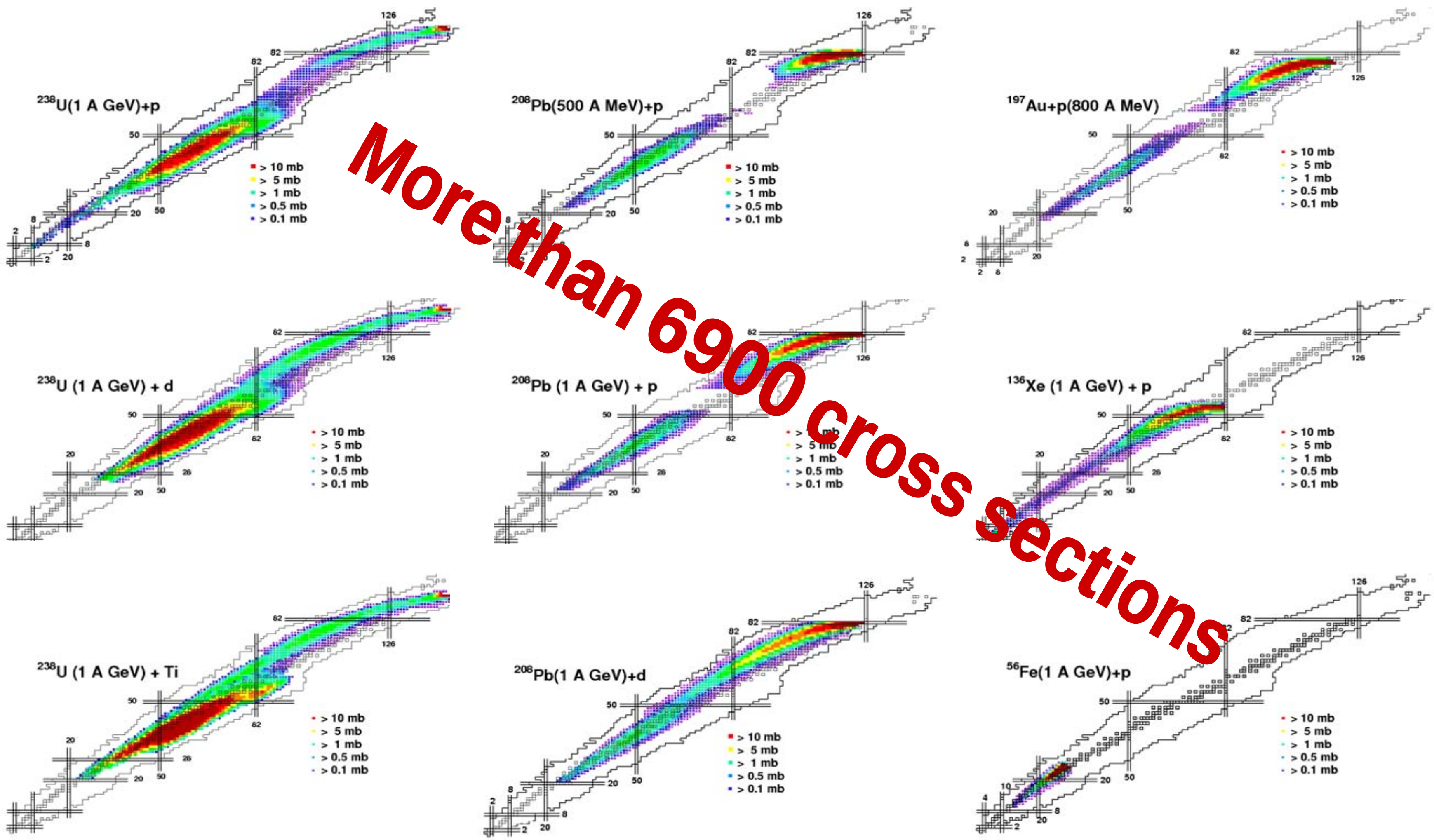
  - Statistical evaporation
  - Intermediate-mass fragment emission
- ✓ Summary

Results: Isotopic Production Cross Sections



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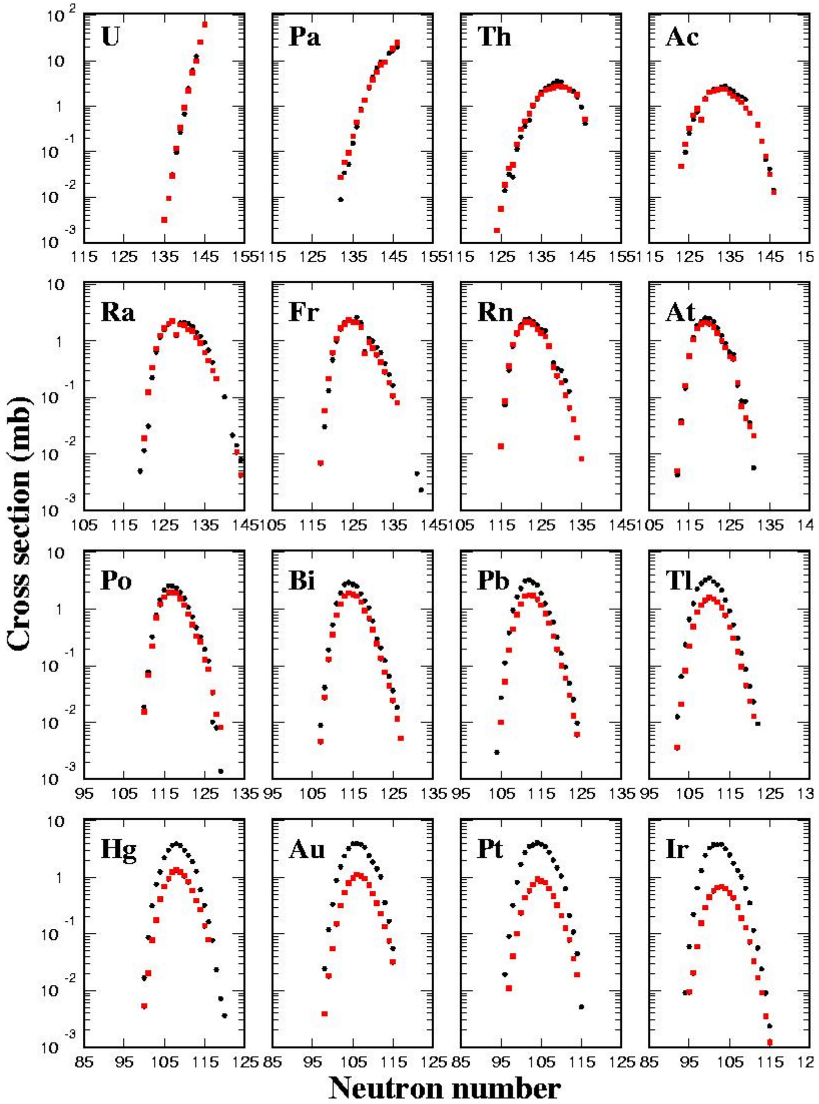
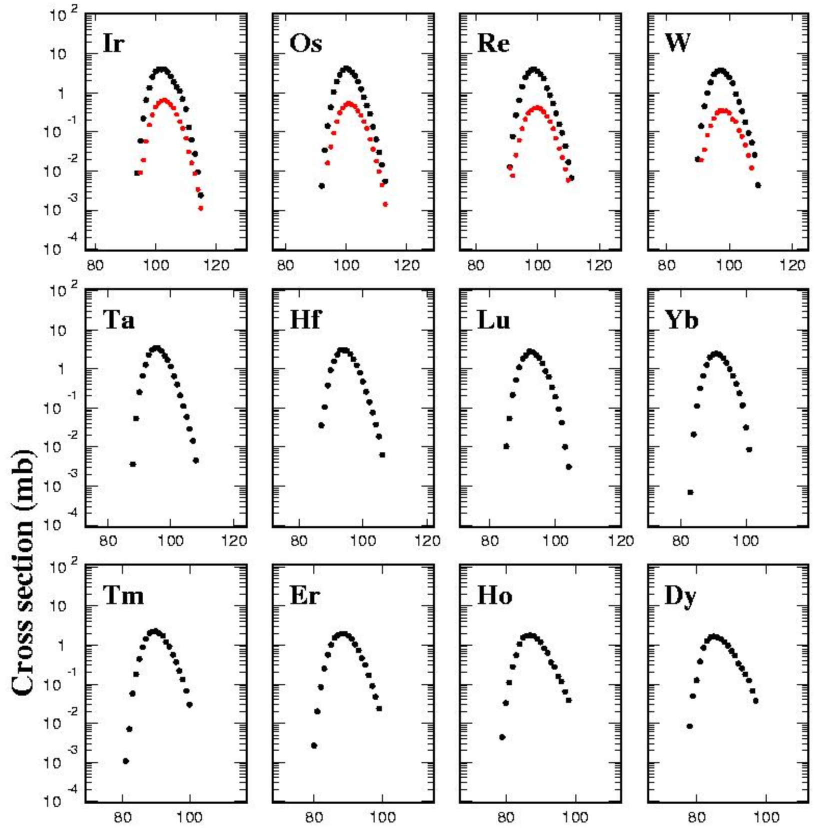
Results: Isotopic Production Cross Sections





^{238}U(1 A GeV) + p

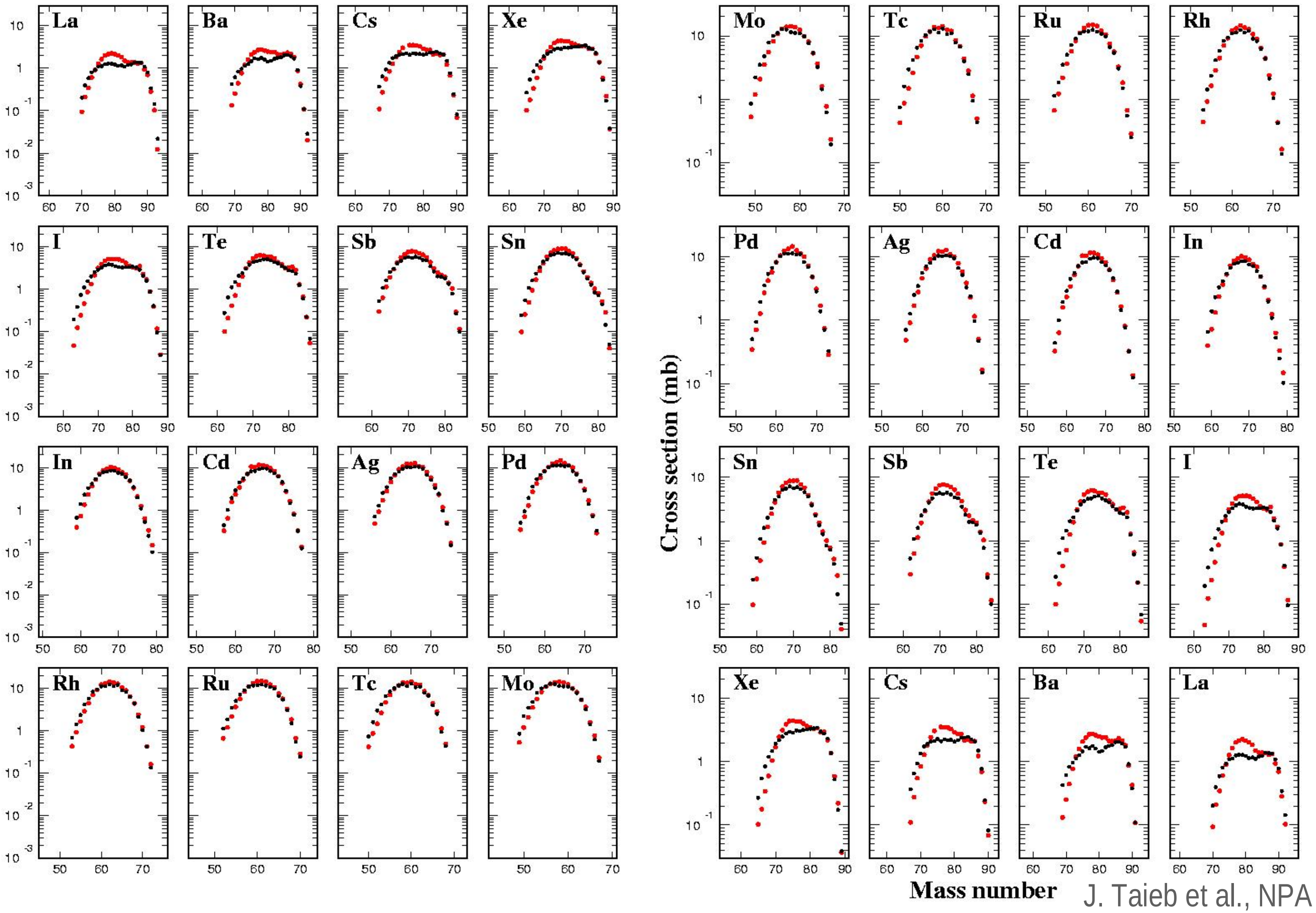
^{238}U(1 A GeV) + d

Evaporation residues

M. Bernas et al., NPA 725 (2003) 213

E. Casarejos et al., PRC 74 (2006) 044612

Results: Isotopic Production Cross Sections



^{238}U(1 A GeV) + p

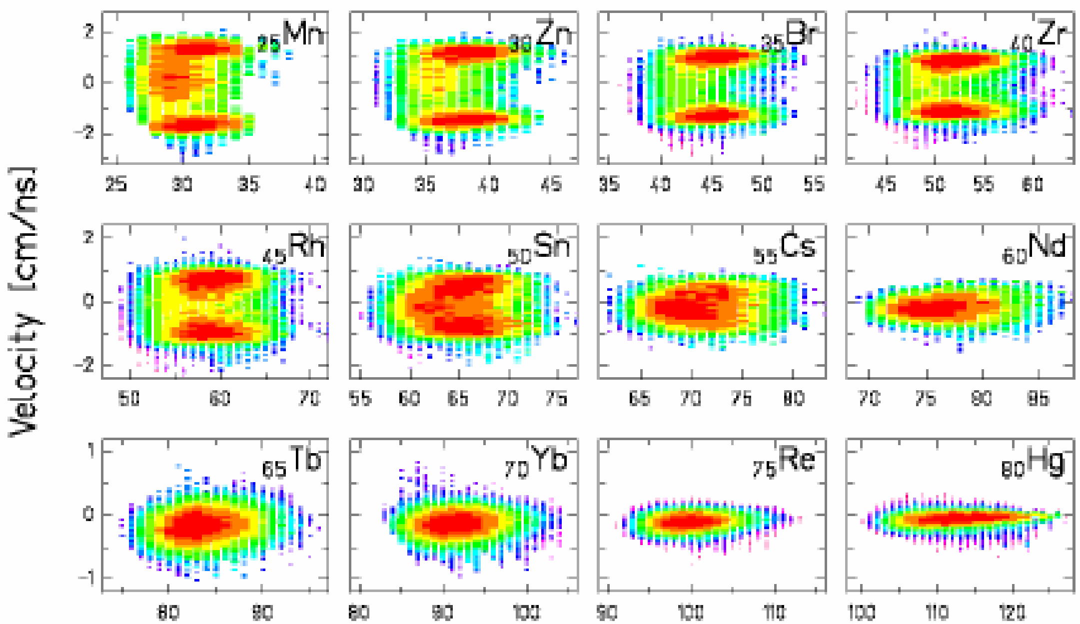
^{238}U(1 A GeV) + d

Fission residues

J. Taieb et al., NPA 724 (2003) 413

J. Pereira et al., PRC 75 (2007) 014602

Results: Velocity distributions

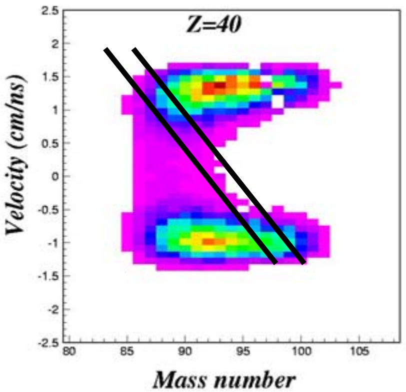


Neutron number

^{208}Pb(1 A GeV) + p

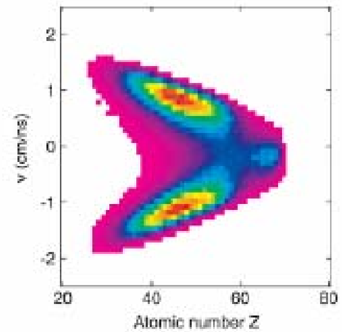
T. Enqvist et al.,
NPA 686 (2001) 481

^{238}U(1 A GeV) + d

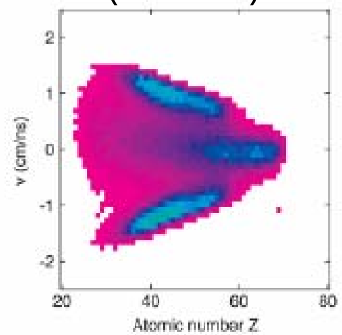


J. Pereira et al.,
PRC 75 (2007) 014602

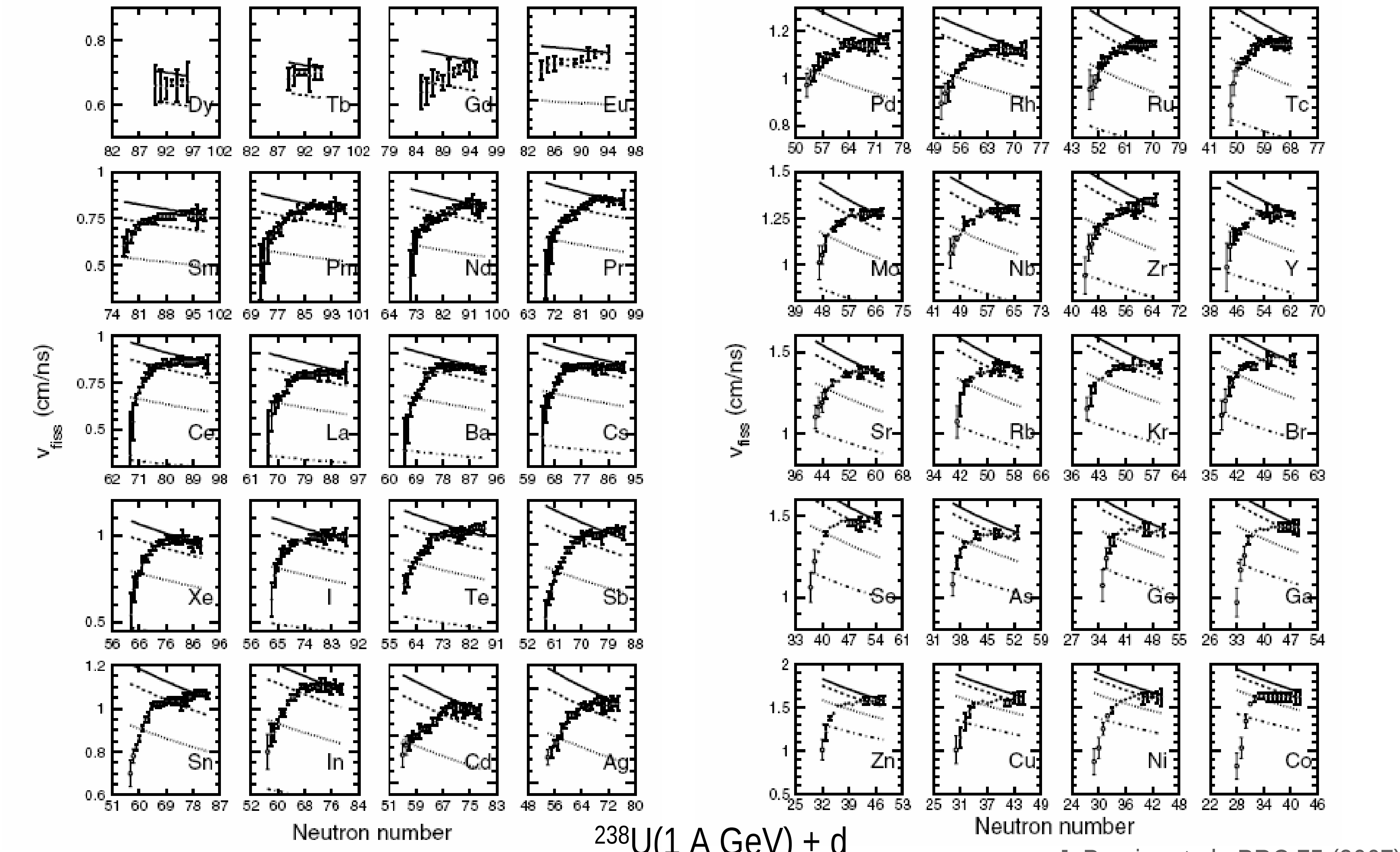
^{238}U(1 A GeV) + d



^{238}U(1 A GeV) + Ti



Results: Velocity distributions



^{238}U(1 A GeV) + d

J. Pereira et al., PRC 75 (2007) 014602

Layout

- ✓ Experimental technique
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- ✓ **The first stage of the collision**
- ✓ Pre-fragment de-excitation
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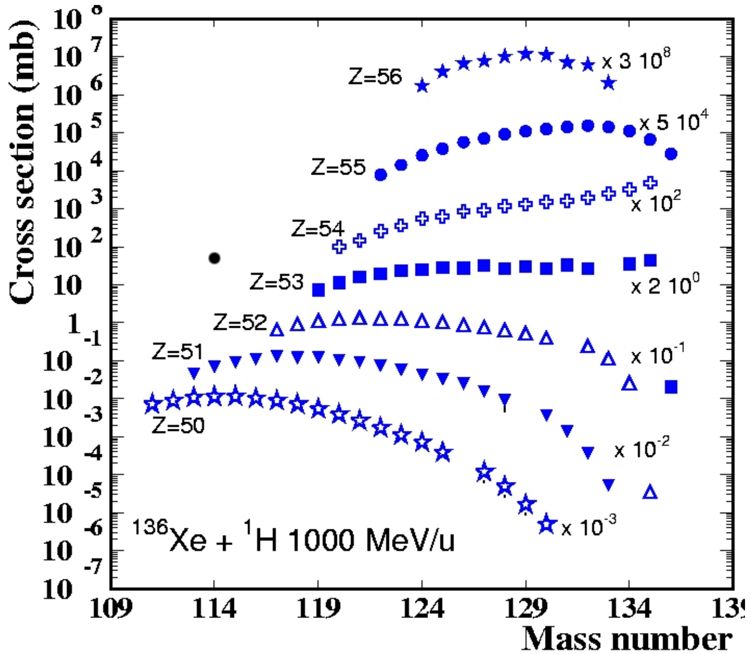
- ✓ Summary

The first stage of the collision

^{136}Xe(1 A GeV) + p



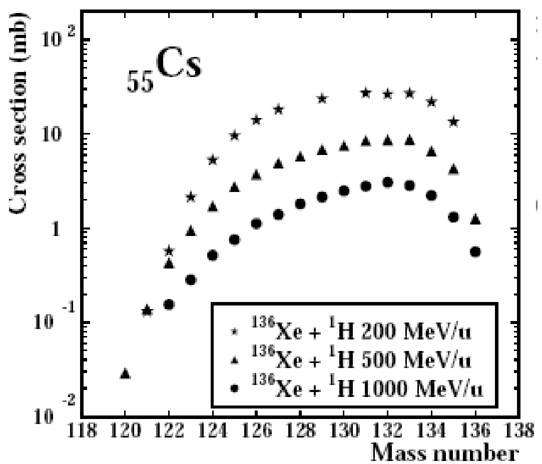
Residual nuclei close in neutron and atomic number to the initial nucleus are more sensitive to the first stage of the collision

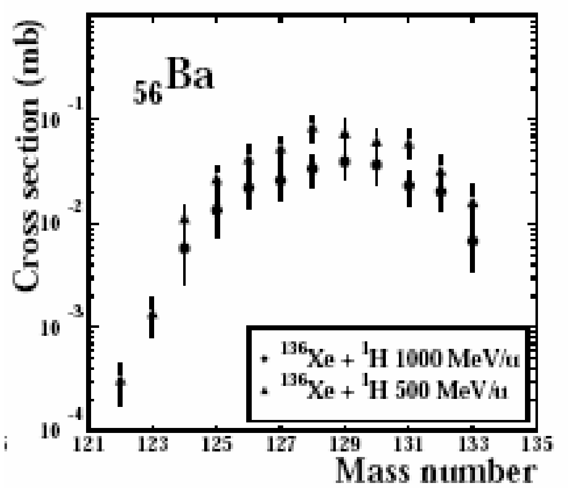
- In particular the charge-exchange channels can provide insight into the NN interaction in the nuclear medium

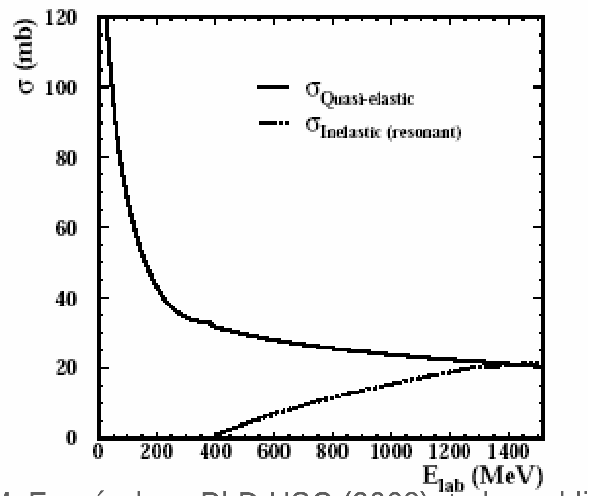
M. Fernández., PhD USC (2008), to be published

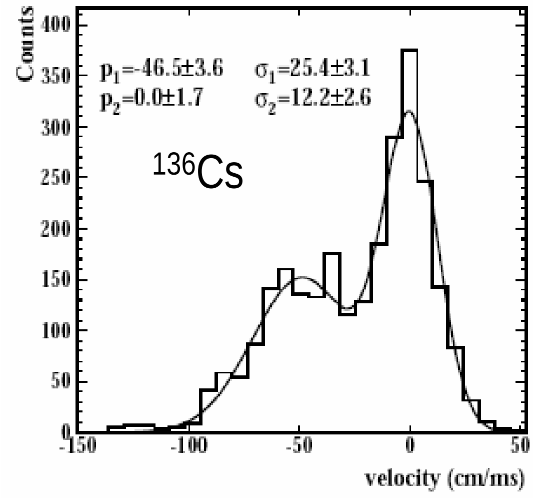
The first stage of the collision

^{136}Xe(1 A GeV) + p





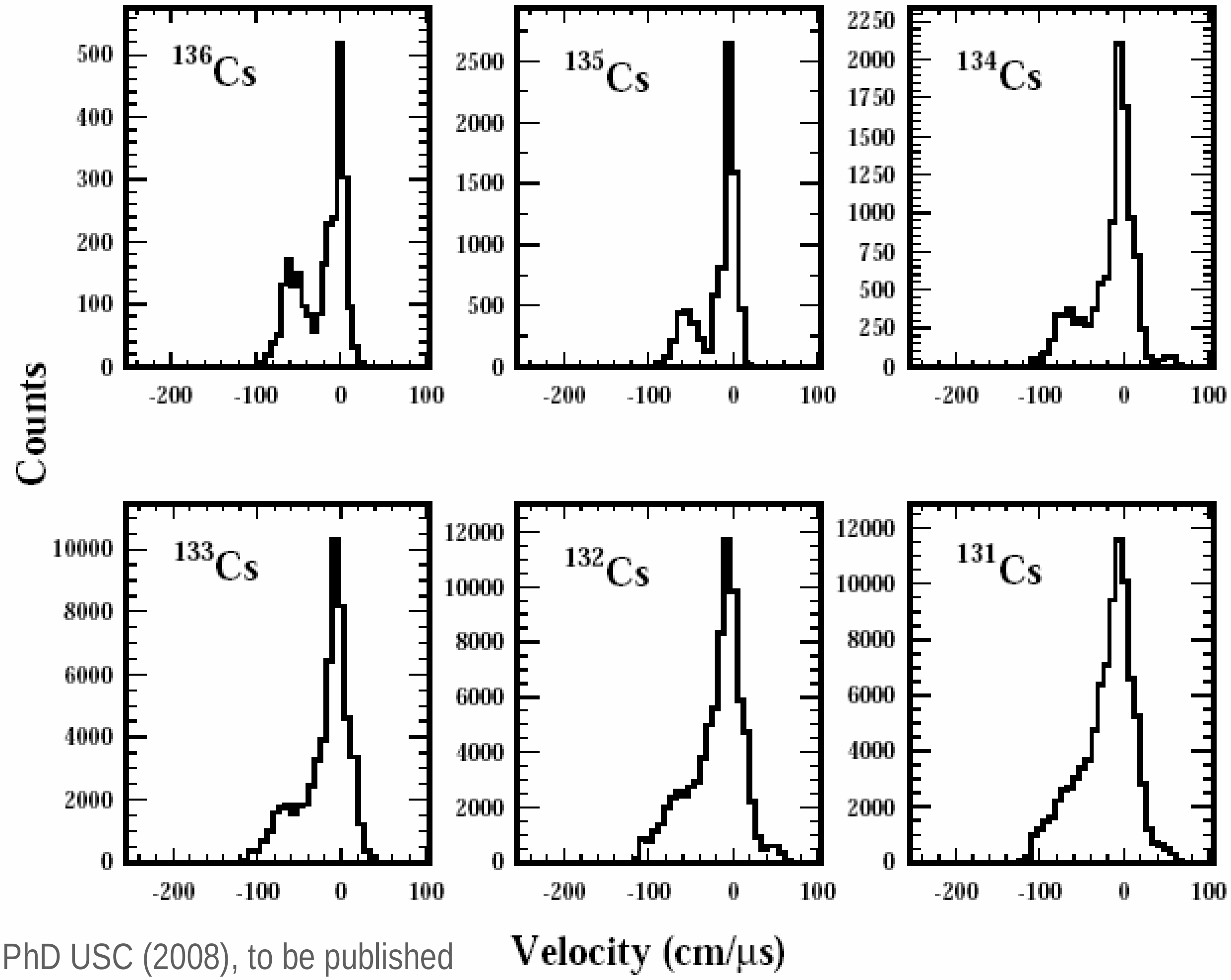




M. Fernández., PhD USC (2008), to be published

The first stage of the collision

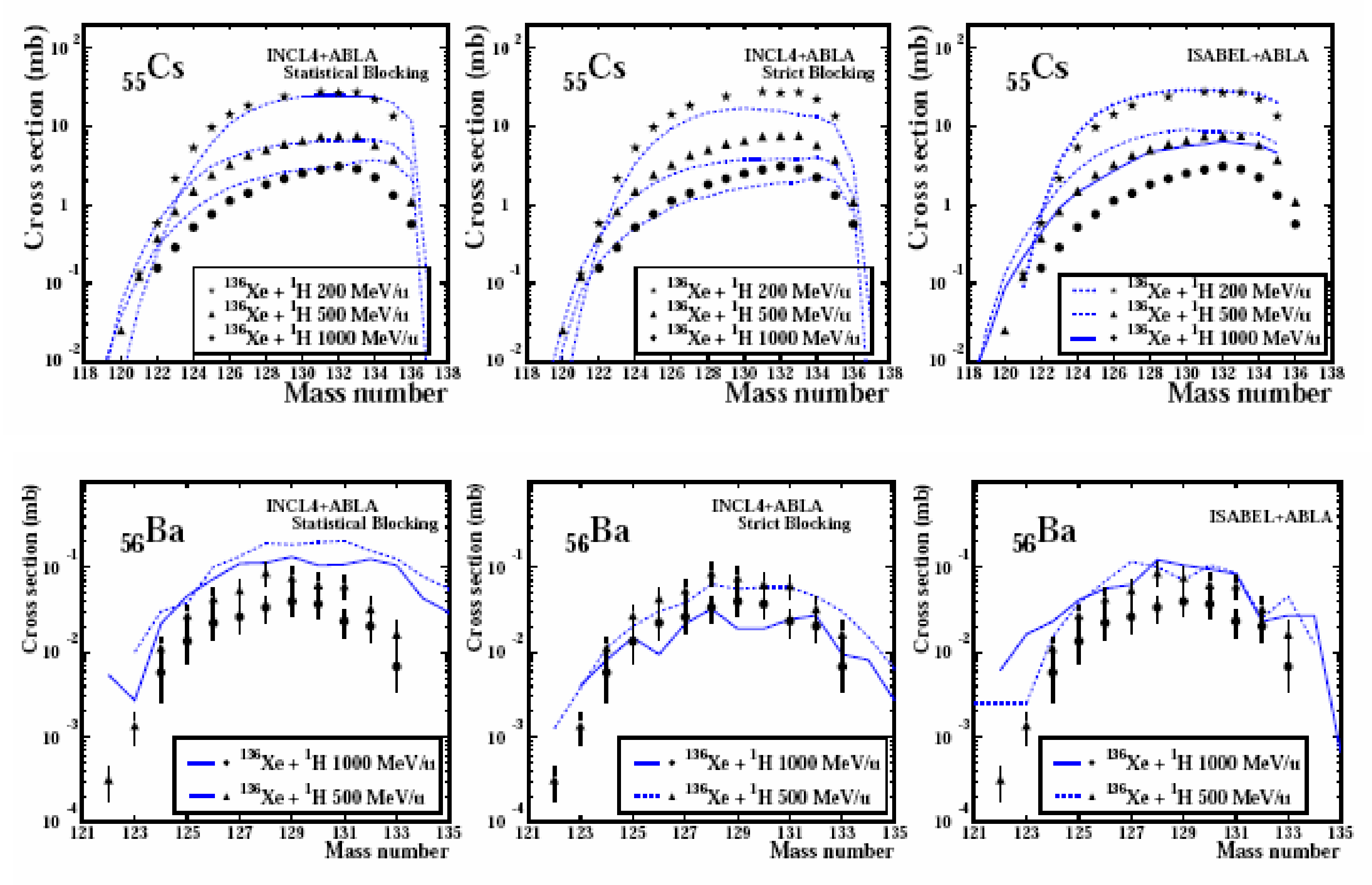
^{136}Xe(1 A GeV) + p



M. Fernández., PhD USC (2008), to be published

The first stage of the collision

^{136}Xe(1 A GeV) + p



M. Fernández., PhD USC (2008), to be published

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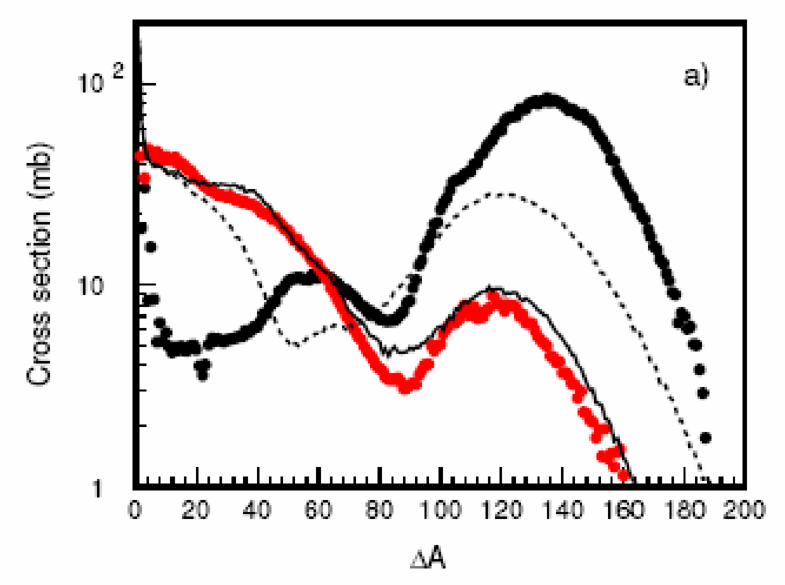
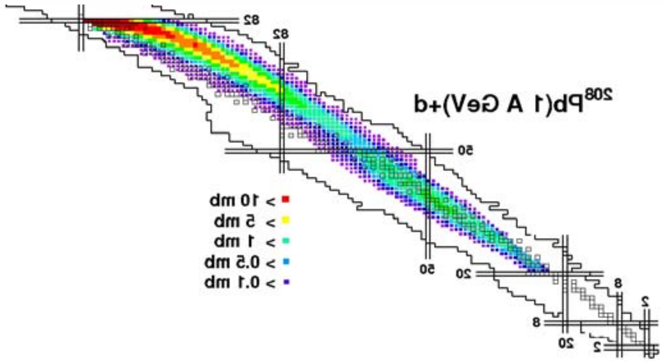
Pre-fragment de-excitation: fission

Fission probability: Γ_f/Γ_n





^{208}Pb(1 A GeV) + d

^{238}U(1 A GeV) + d

Isabel+ABLA (^{208}Pb(1 A GeV)+d)

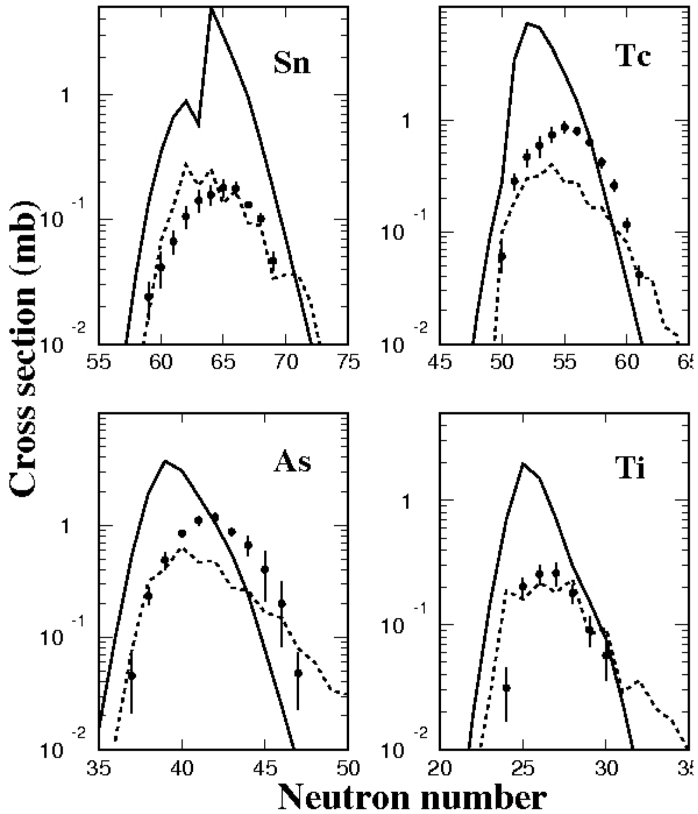
– – – Γ_f: statistical model for fission

——— Γ_f: dynamical model for fission

J. Benlliure et al., PRC 74 (2006) 014609

Pre-fragment de-excitation: fission

Isotopic distribution of fission yields



^{197}Au(800 A MeV)+p

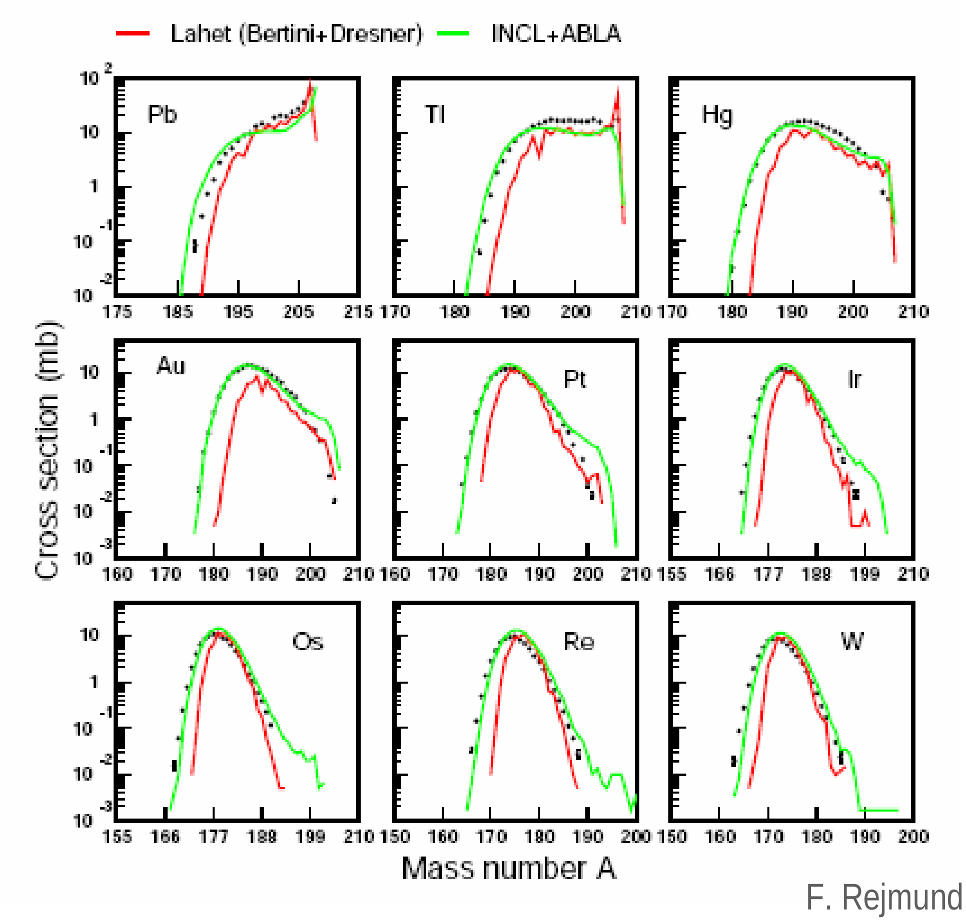
- - - LAHET (Bertini+Dresner)

—— R. Silberberg et al. Astr. Phys. J. 501 (1998) 911

J. Benlliure et al., NPA 683 (2001) 513

Pre-fragment de-excitation: statistical evaporation

Fission probability: Γ_f/Γ_n

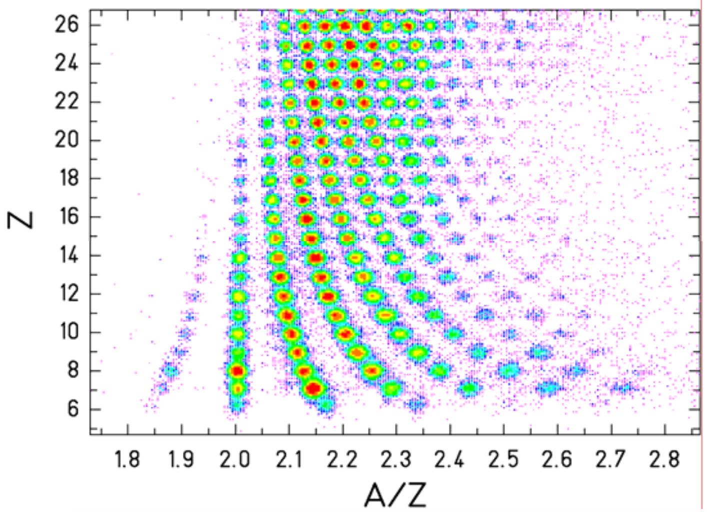


^{197}Au(800 A MeV) + p

F. Rejmund et al., NPA 683 (2001) 540

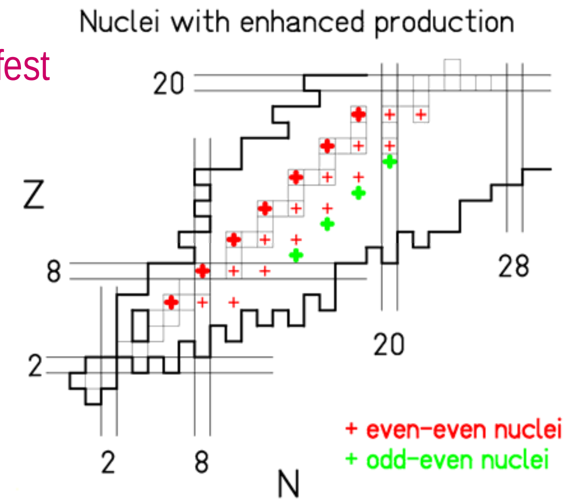
Pre-fragment de-excitation: statistical evaporation

Even-odd stagering

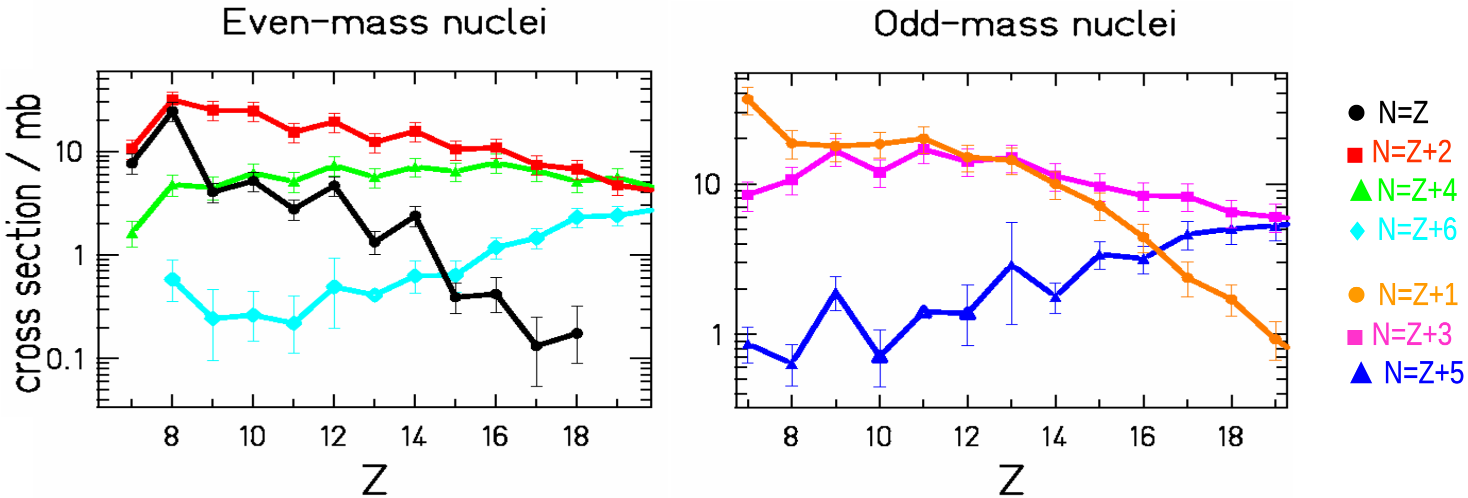


New complex structures manifest in the isotopic distribution of reaction residues

M.V. Ricciardi et al.,
Nucl. Phys. A 733 (2004) 299



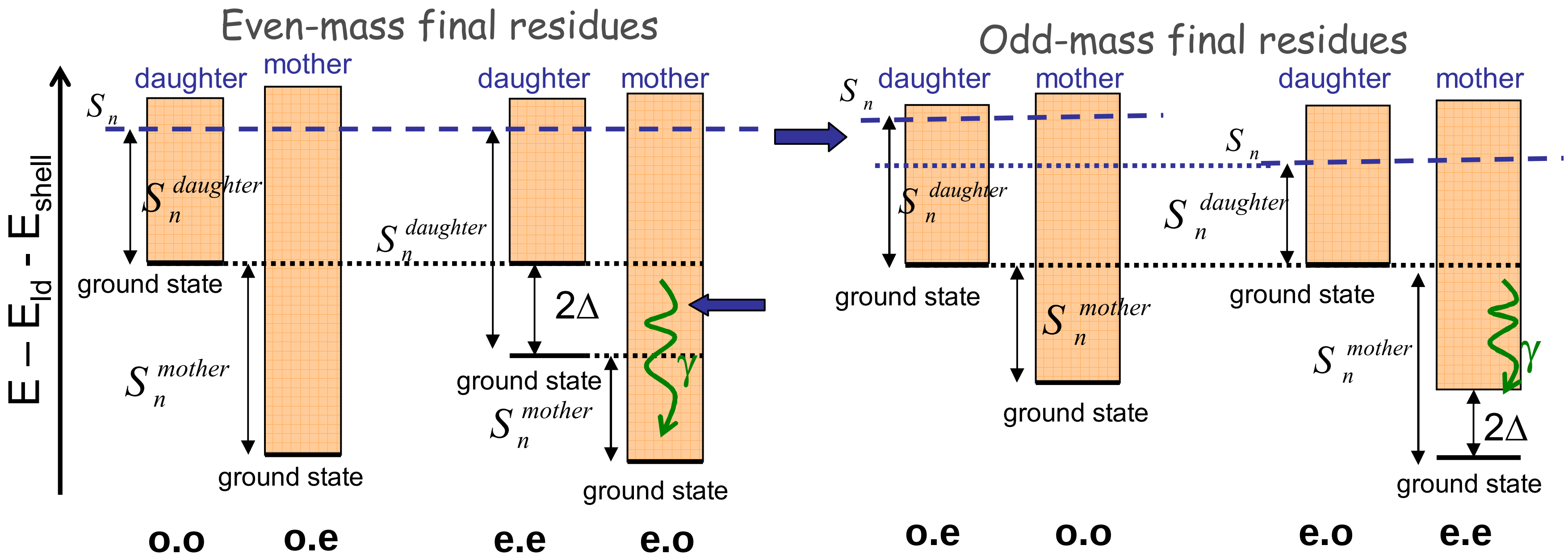
N-Z=constant



Pre-fragment de-excitation: statistical evaporation

Even-odd stagering

The final yields are governed by the number of bound states in both, the daughter and the mother nuclei, which are defined by level densities, ground state masses and separation energies.

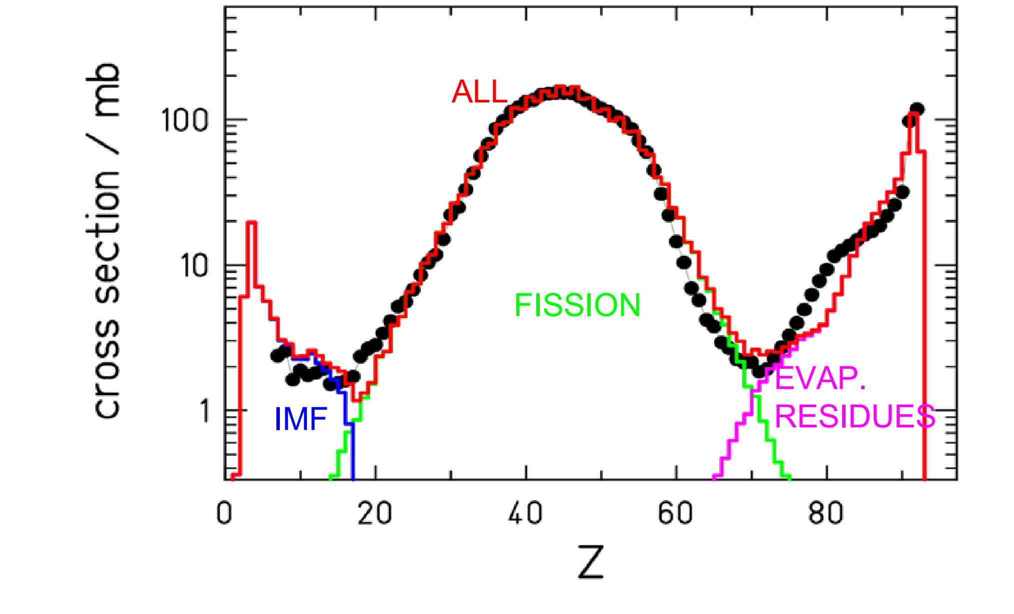


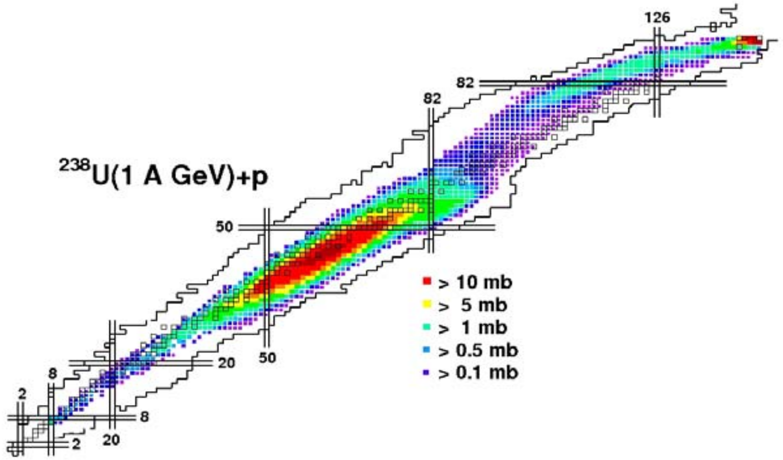
- ✓ Even-mass residues with even-Z are more probable
- ✓ Odd-mass residues with odd-Z are also more probable
- ✓ Even-odd staggering decreases with the mass (g emission)

Pre-fragment de-excitation: intermediate-mass fragments

Fission probability: Γ_f/Γ_n

^{1238}U(1 A GeV) + p





M.V. Ricciardi et al., PRC 73 (2006) 014607

Summary

✓ A large data set on residual nuclei produced in spallation reactions have been obtained at GSI

- 14 reactions have been investigated using five projectiles (^{238}U, ^{208}Pb, ^{197}Au, ^{136}Xe and ^{56}Fe) cryogenic proton and deuterium targets and different projectile energies

- More than 7000 cross sections have been determined with an accuracy between 5 and 30%

✓ The sensitivity of these data to different aspects of the modelization of spallation reactions has been investigated

- Residual nuclei close in neutron and atomic number to the projectile, in particular charge-exchange reactions, probe the intra-nuclear cascade phase

- The comparison between fissile and less fissile systems helps in characterising the neutron/fission competition during the evaporation phase

- The emission of intermediate-mass fragments or the even-odd stagering in the cross provide also information on the evaporation phase

Collaborators

P. Armbruster[a], L. Audouin[b], J. Benlliure[a,c], M. Bernás[b], A. Boudard[d], E. Casarejos[c], S. Czajkowski[e], T. Enqvist[a], B. Fernández[d], M. Fernández[c], L. Giot[a], A. Kelic[a], R. Legrain[d], S. Leray[d], B. Mustapha[b], P. Napolitani[a,b], C. Paradela[b,c], J. Pereira[c], M. Pravikoff[e], F. Rejmund[a,b], K.-H. Schmidt[a], C. Stéphan[b], J. Taieb[a,b], L. Tassan-Got[b], C. Villagrasa[d], C. Volant[d], W. Wlazlo[d]

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e) CENBG, F-33175 Gradignan cedex, France

Publications list

^{238}U(1 A GeV)+p

- J. Taieb et al., Nucl. Phys. A 724 (2003) 413
- M. Bernas et al., Nucl. Phys. A 725 (2003) 213
- M. Bernas et al., Nucl. Phys. A 765 (2006) 197
- M.V. Ricciardi et al., Nucl. Phys. A 701 (2002) 156
- P. Armbruster et al., Phys. Rev. Lett. 93 (2004) 212701

^{238}U(1 A GeV)+d

- J. Benlliure et al., Phys. Rev. C 74 (2006) 014609
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