Investigating the structure and dynamics of the atomic nucleus using relativistic heavy-ion collisions in inverse kinematics

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Curso de física nuclear experimental

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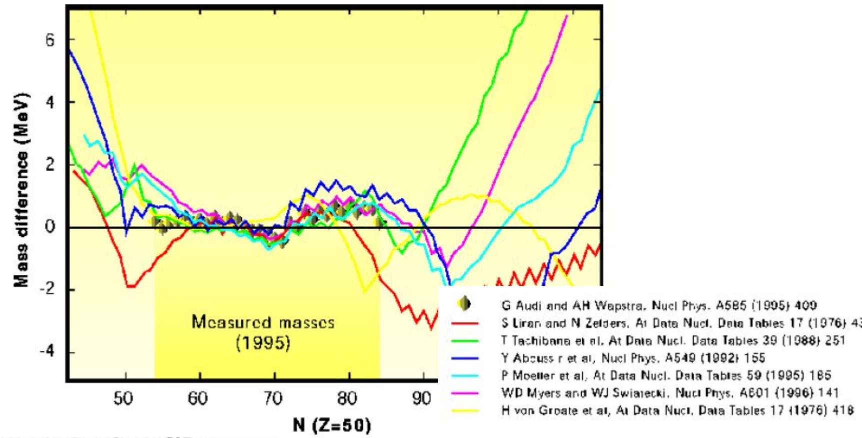
Layout

- ✓ Experimental investigation of the atomic nucleus
- ✓ Why do we use inverse kinematics?
- ✓ Why do we work at relativistic energies?
- ✓ Examples on nuclear structures studies
- ✓ Examples on nuclear dynamics studies

Experimental investigation of the atomic nucleus

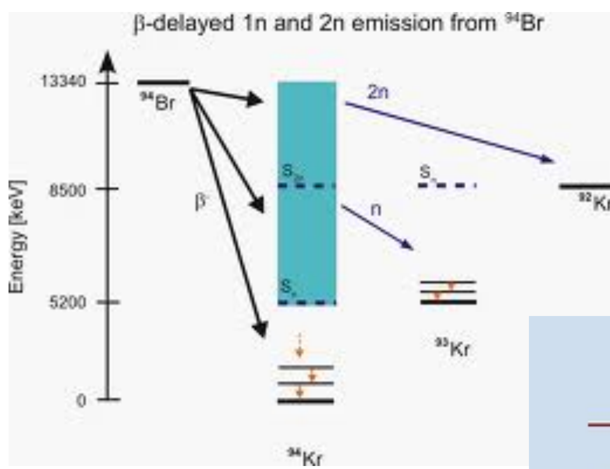
✓ Ground-state properties.

- masses
- size: matter and charge radial distributions, deformation
- electromagnetic moments



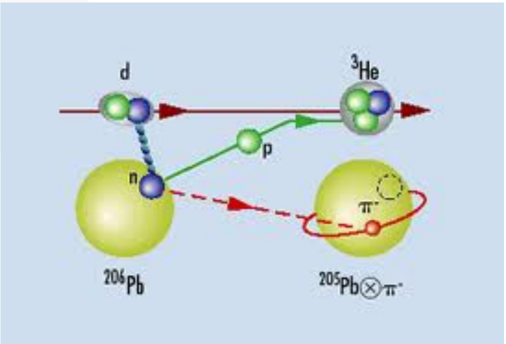
✓ Radioactive decays.

- decay properties
- beta-delayed gamma emission
- beta-delayed particle emission



✓ Nuclear reactions.

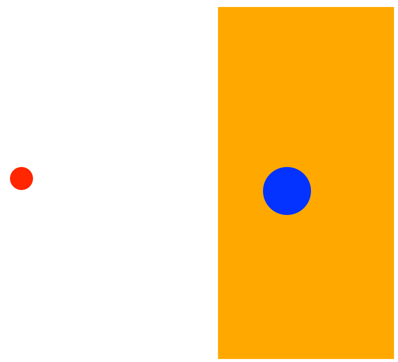
- direct reactions
- compound nucleus reactions



The use of inverse kinematics

Direct kinematics

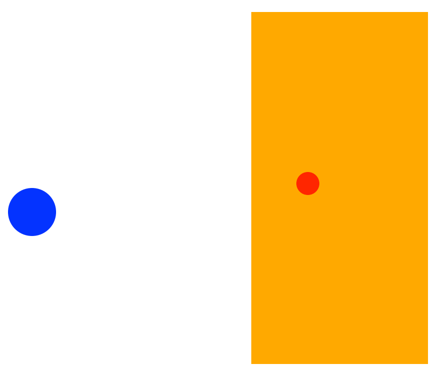
Light projectile impinging into a heavy target nucleus



- light jectiles can be detected
- target residue can only be idenfied using radiative processes

Inverse kinematics

Light projectile impinging into a heavy target nucleus



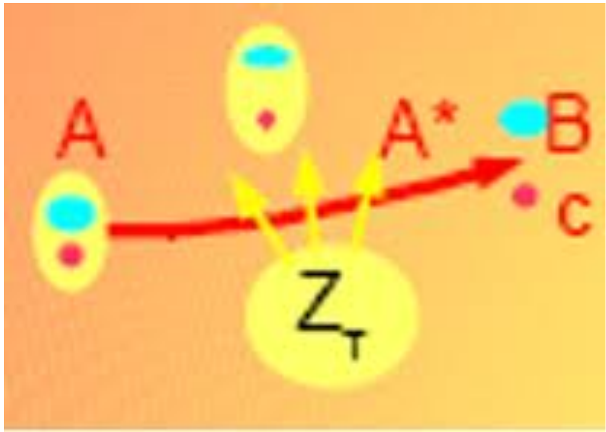
- light and heavy ectiles can be detected

The use of inverse kinematics

Advantages

✓ Reactions induced by exotic projectiles

$$^{8}B(\gamma, p)^{7}Be$$



The use of inverse kinematics

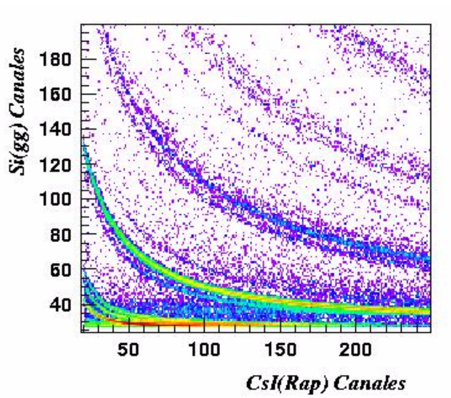
Advantages

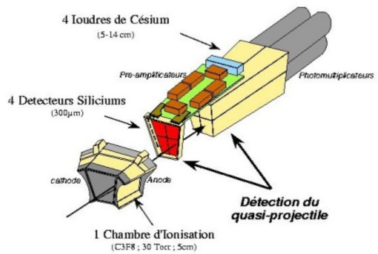
✓ Reactions induced by exotic projectiles

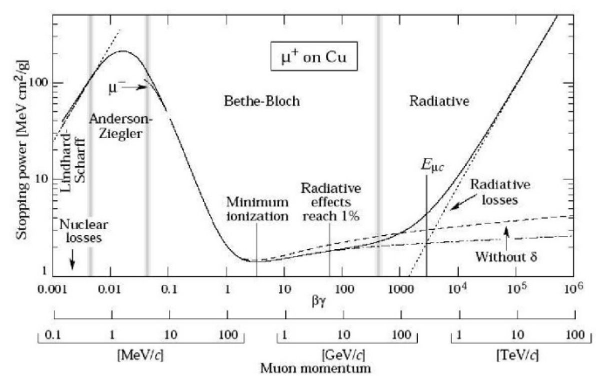
✓ Improved charge identification of reaction ejectiles

$$\frac{dE}{dx} = f(Z^2, A, \beta\gamma)$$

$$R \propto \frac{\sqrt{A \cdot E}}{Z^{2/3}}$$







The energy deposition of ions with Z > 40 and E < 1 A MeV is below the Bragg peak.

The use of inverse kinematics

Advantages

✓ Reactions induced by exotic projectiles

✓ Improved charge identification of reaction ejectiles

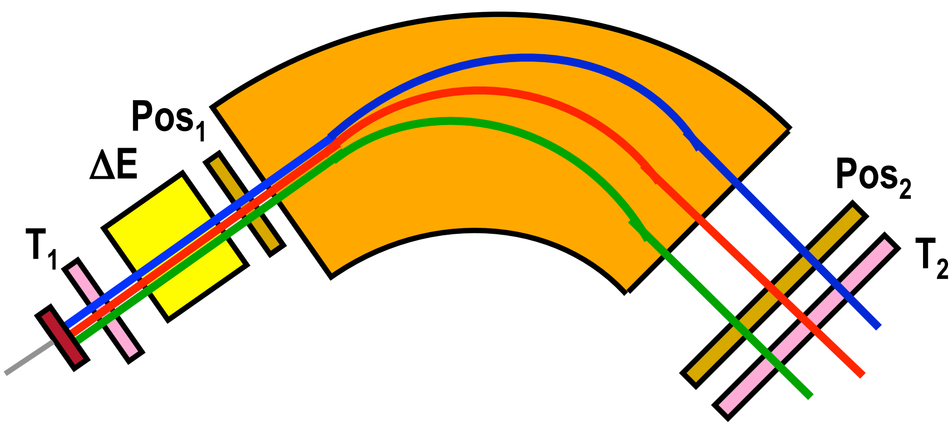
✓ Heavy ejectiles fully identified in Z and A

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

$Pos_1, Pos_2 \rightarrow L_1, L_2, L_3 \rightarrow \rho_1, \rho_2, \rho_3$

$T_1, T_2 \rightarrow L_1, L_2, L_3 \rightarrow \beta\gamma_1, \beta\gamma_2, \beta\gamma_3$ } A_1, A_2, A_3

$\Delta E_1, \Delta E_2, \Delta E_3$ (q=Z) $\rightarrow Z_1, Z_2, Z_3$



The use of inverse kinematics

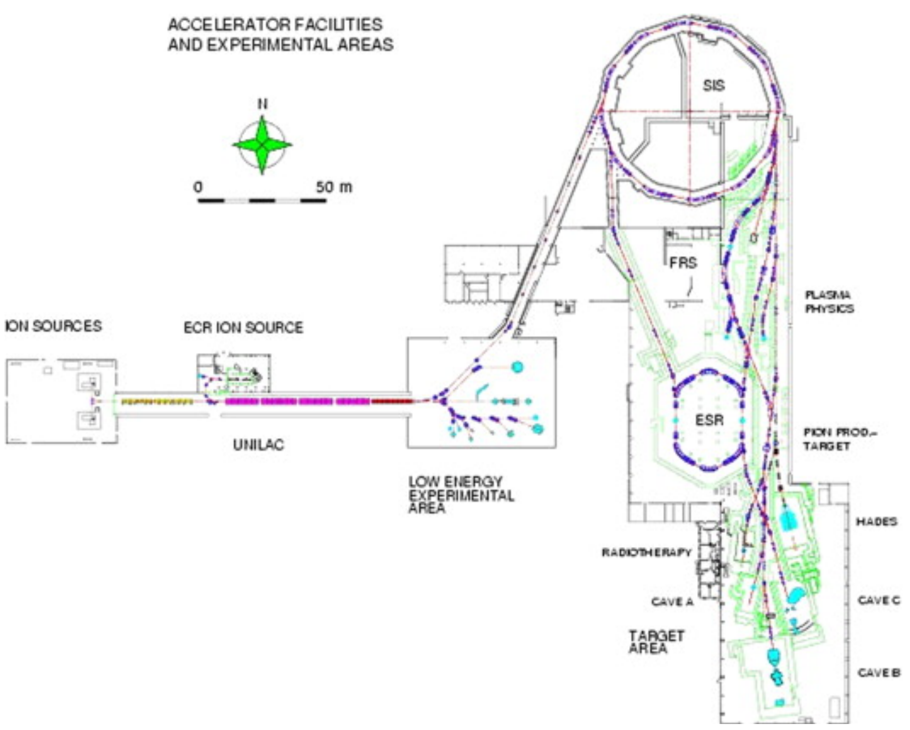
Drawbacks

✓ Complex heavy-ion accelerators with limited beam intensities

Present acceleration technologies:

- proton accelerators ~ 10^{16} p/s

- heavy-ion accelerators ~ 10^{12} ions/s



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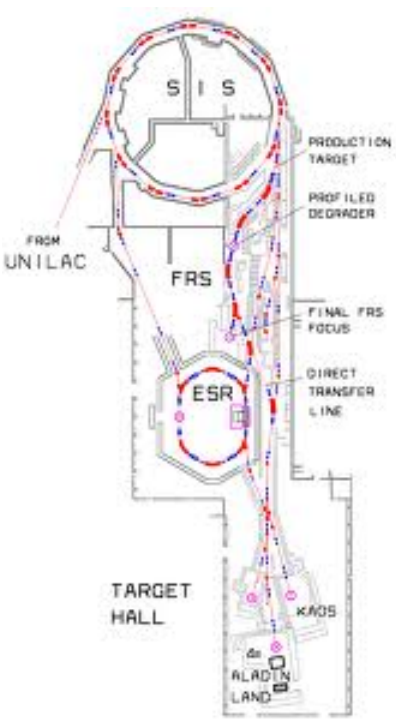
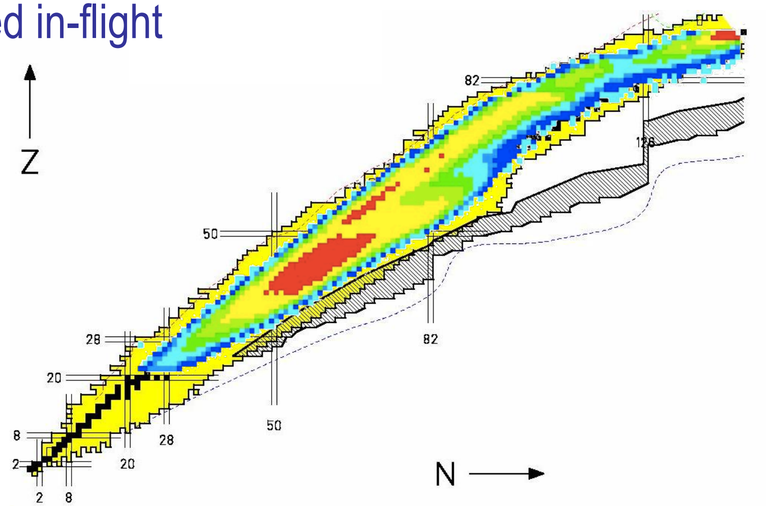
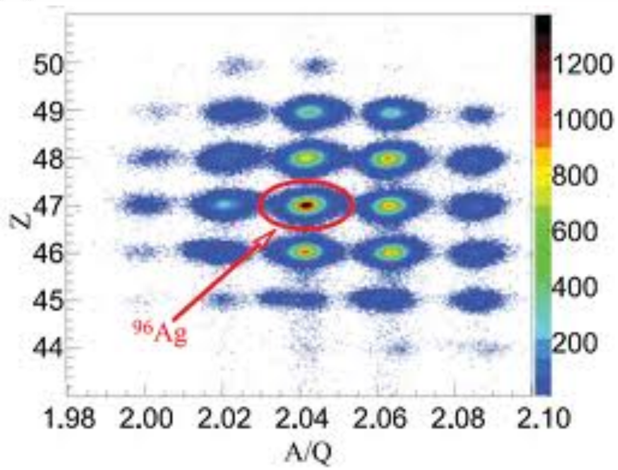
The use of relativistic energies

Advantages

✓ Exotic nuclei can be produced in-flight





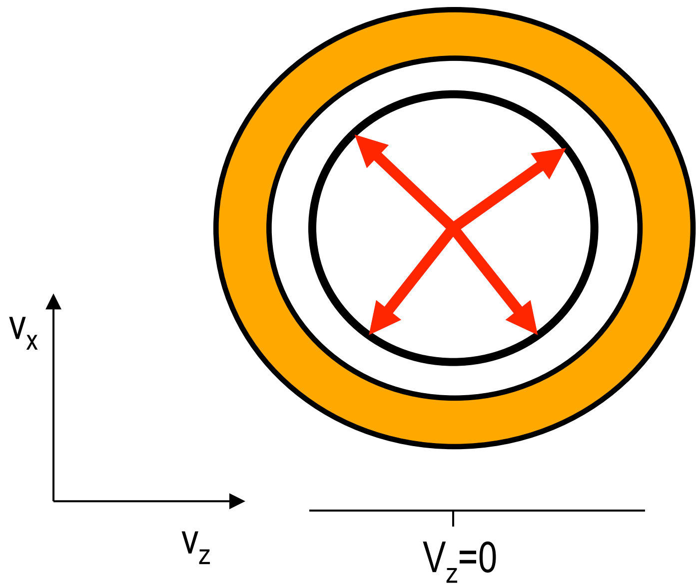


The use of relativistic energies

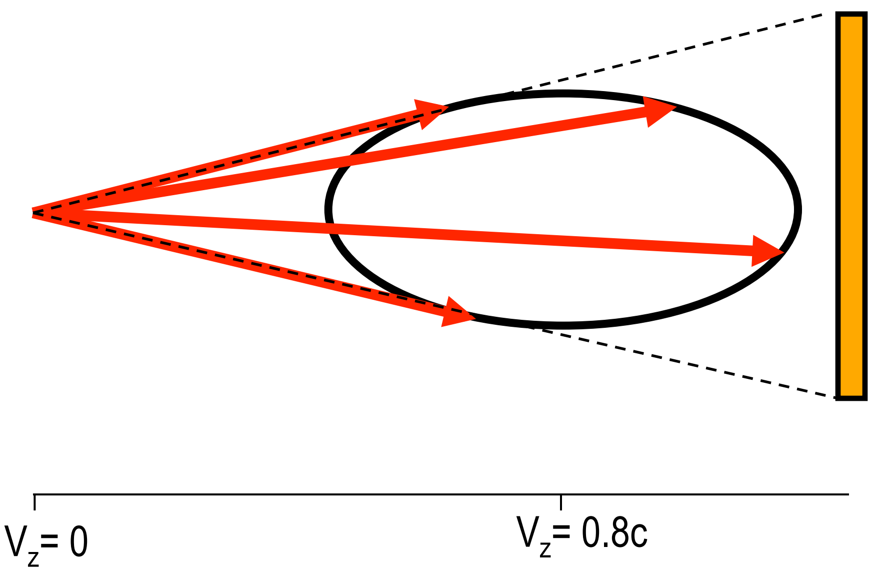
Advantages

- ✓ Exotic nuclei can be produced in-flight
- ✓ Detectors with smaller angular acceptance

Direct kinematics



Inverse kinematics



The use of relativistic energies

Advantages

- ✓ Exotic nuclei can be produced in-flight
- ✓ Detectors with smaller angular acceptance
- ✓ Thicker targets

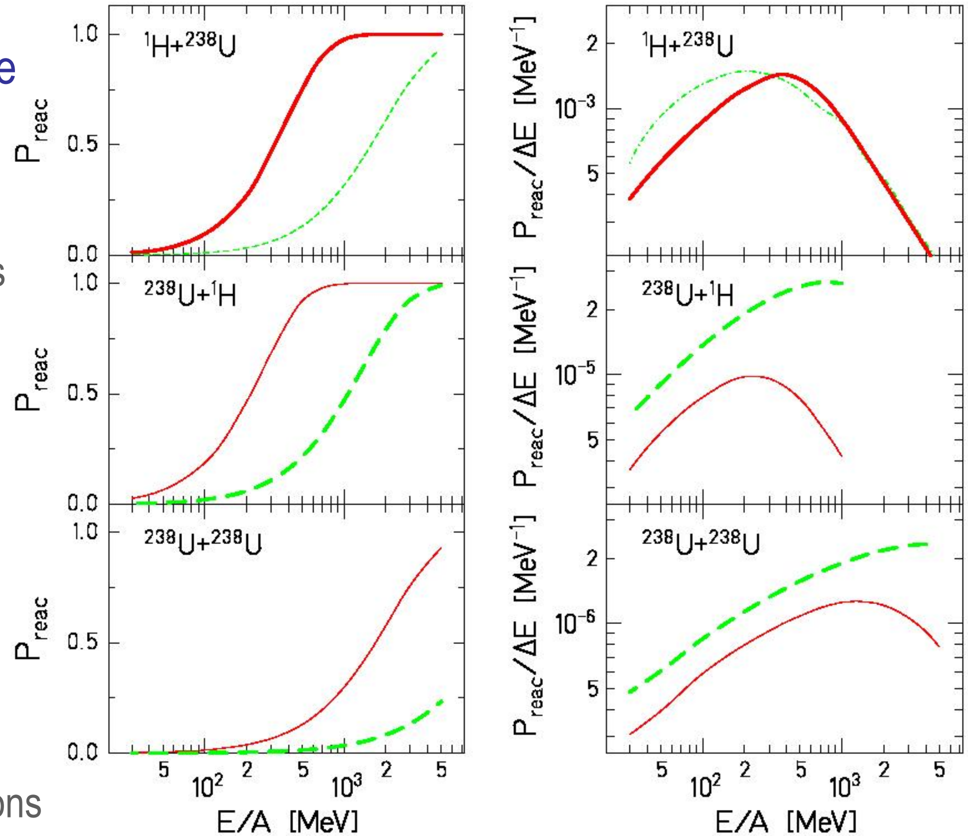
The range (R) of incoming projectiles increases with energy, and then the possible target thickness (~ 10% of R).

$$P_{reaction} = \sigma\, N_{projectiles}\, N_{target}$$

Typical range of projectiles

- $E<E_{fermi}$ 0.1R ~ 100 mg/cm^2
- $E>>E_{fermi}$ 0.1R ~ 1 g/cm^2

The heat induced by electromagnetic interactions may limit the target thickness.



The use of relativistic energies

Advantages

✓ Exotic nuclei can be produced in-flight

✓ Detectors with smaller angular acceptance

✓ Thicker targets

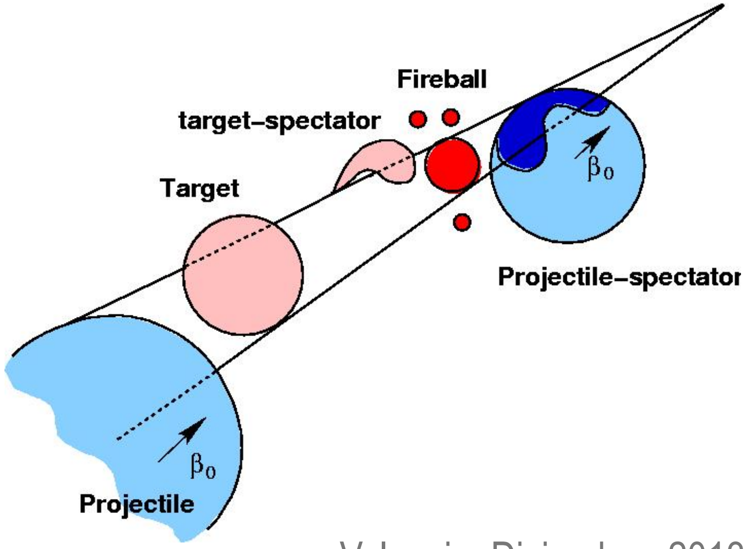
✓ Simpler description of the reaction mechanism

Glauber picture:

- adiabatic approximation

- eikonal approximation (out-going plane wave): direct reactions

- participant-spectator picture: compound nucleus reactions



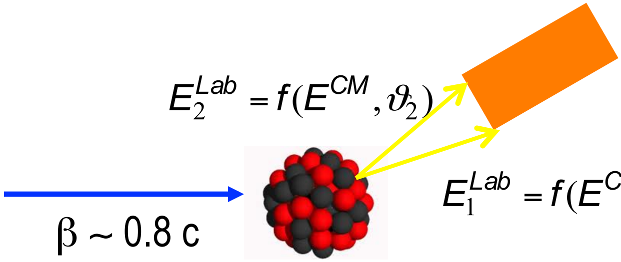
The use of relativistic energies

Drawbacks

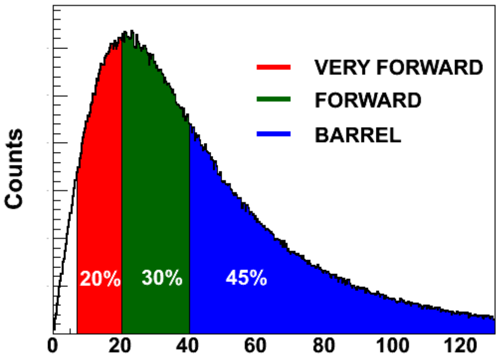
- ✓ Gamma rays are Lorentz boosted

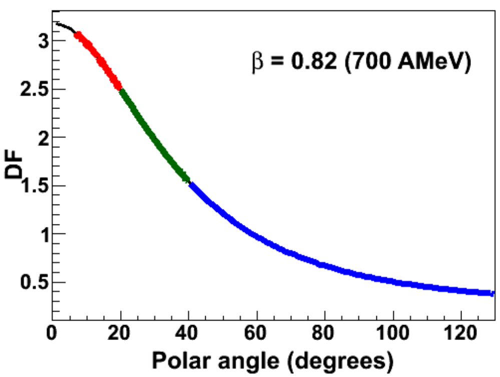
$$DF = \frac{E^{Lab}}{E^{CM}} = \frac{1}{\gamma(1-\beta\cos\vartheta)}$$

$$E_2^{Lab} = f(E^{CM}, \vartheta_2)$$

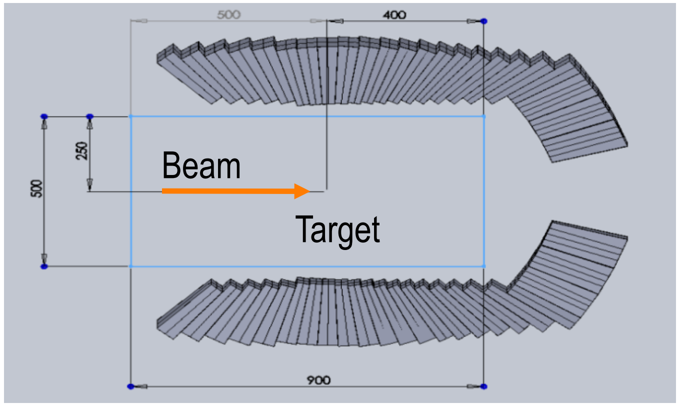


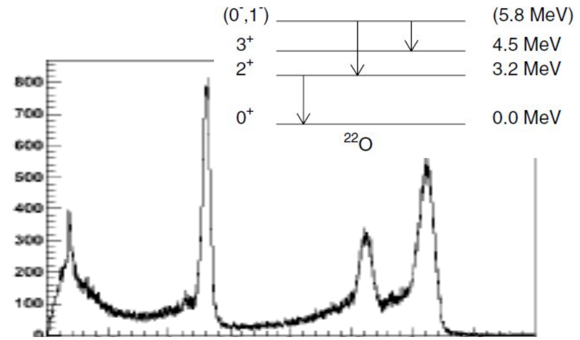
$$E_1^{Lab} = f(E^{CM}, \vartheta_1)$$

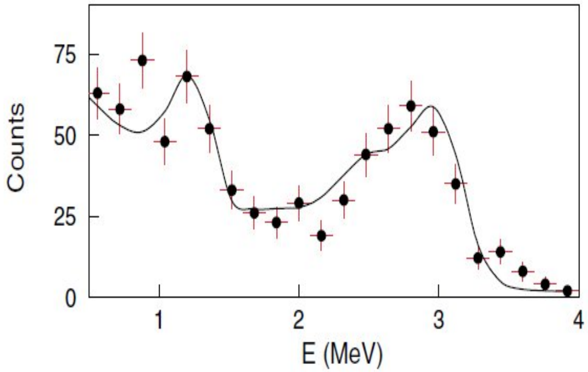




$$\frac{\Delta E^{Lab}}{E^{Lab}} = \frac{\beta\sin}{1-\beta\cos\vartheta}\Delta\vartheta$$





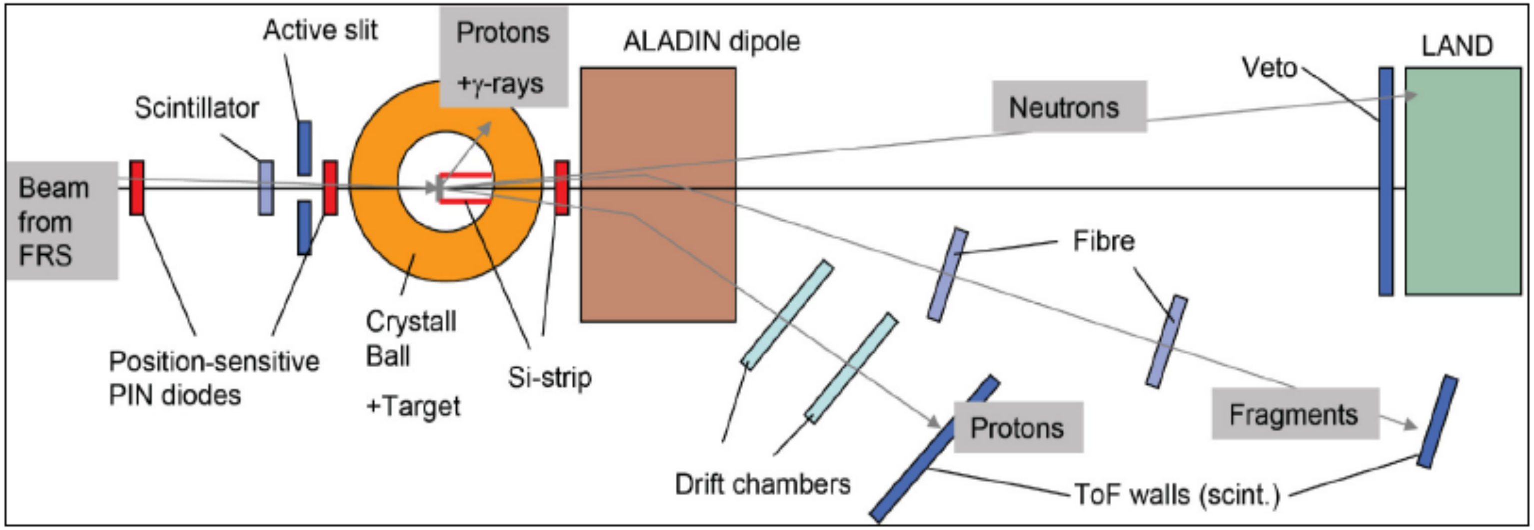


The use of relativistic energies

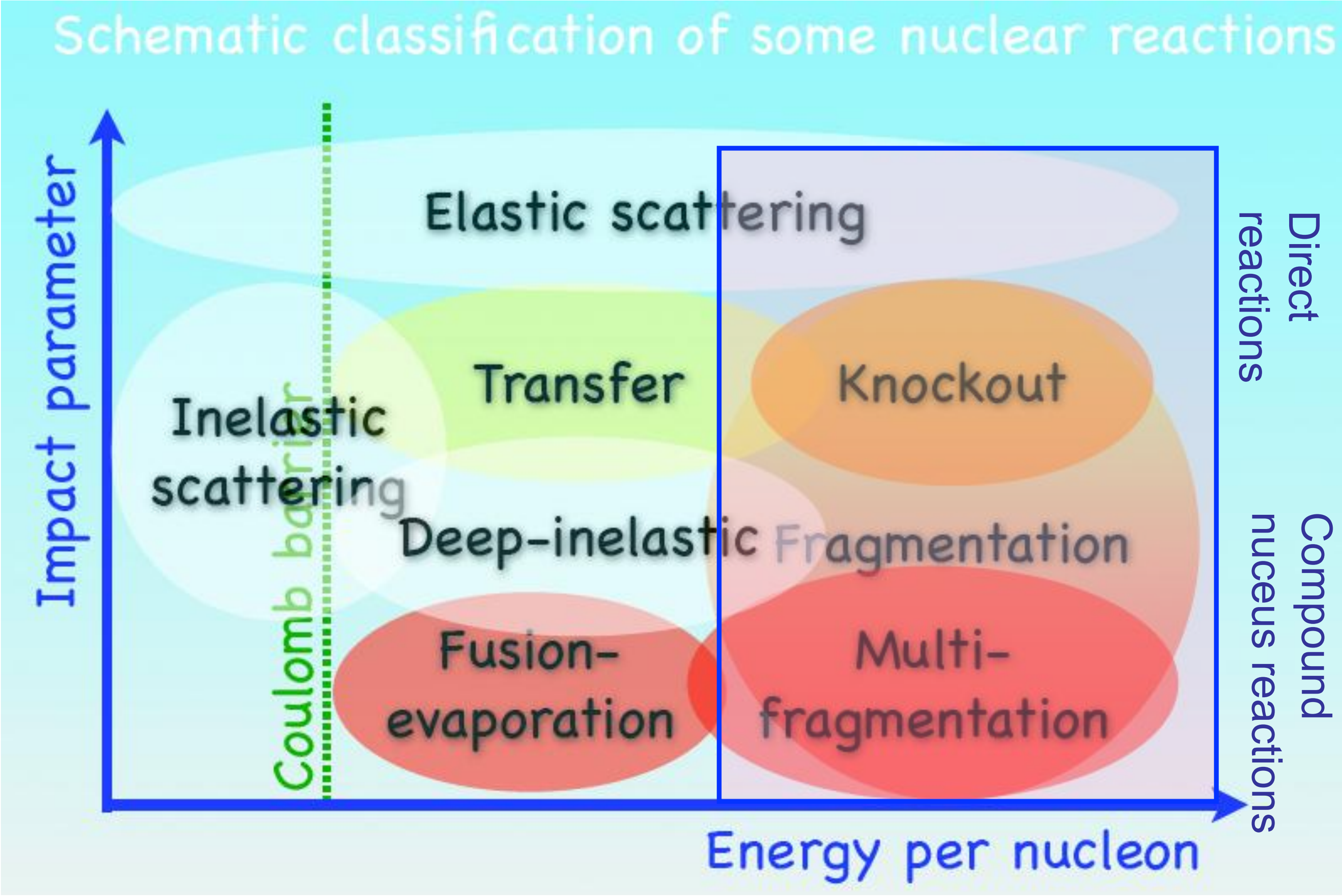
Drawbacks

✓ Gamma rays are Lorentz boosted

✓ Light ejectiles require complex detectors



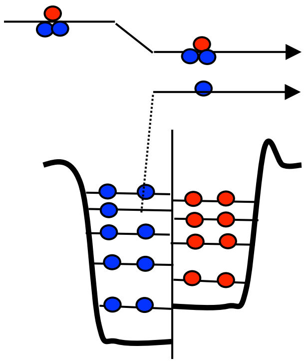
The use of relativistic energies



Nuclear structure investigations

Knock-out reactions as a spectroscopic tool

→ The momentum of the knocked out nucleon or the excitation energy gained by the residual nucleus will characterize the single-particle state occupied by the removed nucleon



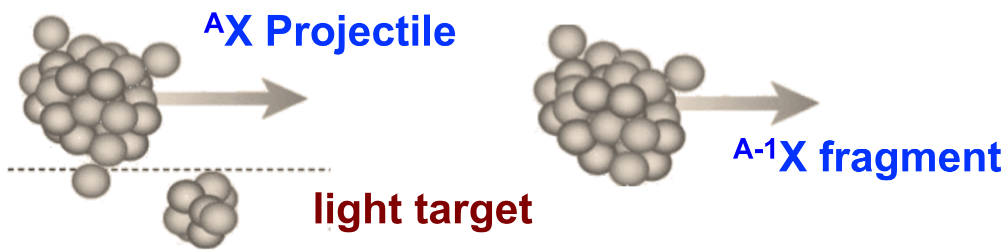
→ In general these are known as "**quasi-free**" scattering processes, although for valence nucleons (elastic channel) the term "**knock-out**" is used.

→ The use of inverse kinematics is mandatory for the complete characterization of the reaction channel and in particular when using non stable nuclei.

Nuclear structure investigations

Knock-out reactions

This is a "quasi-free" scattering on the valence nucleons leading to a bound residual nucleus (A-1) not necessarily on its ground state



The accurate measurement of the longitudinal momentum of the residual nucleus in inverse kinematics, and the possible gamma rays emitted during the knock-out charactarize the ground state of the projectile nucleus.

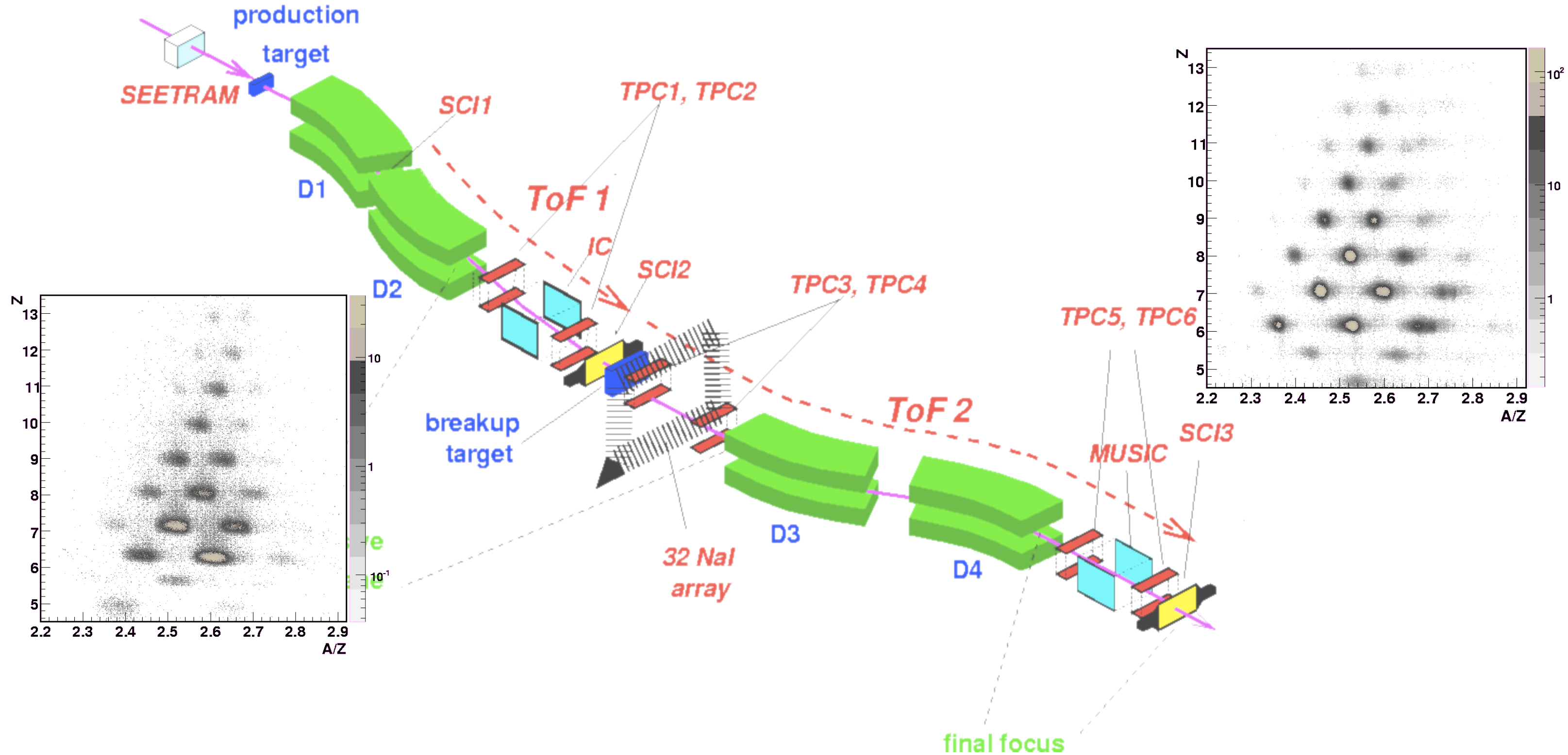
$$| P > = \sum C^2S \left(| C > \otimes | n > \right)$$

- $| P >$: Ground state of the exotic projectile
- C^2S: Spectroscopic factor — Cross-sections
- $| C >$: ^{A-1}X fragment — Gamma ray tagging
- $| n >$: removed neutron — ^{A-1}X fragment momentum distribution

Nuclear structure investigations

Knock-out reactions

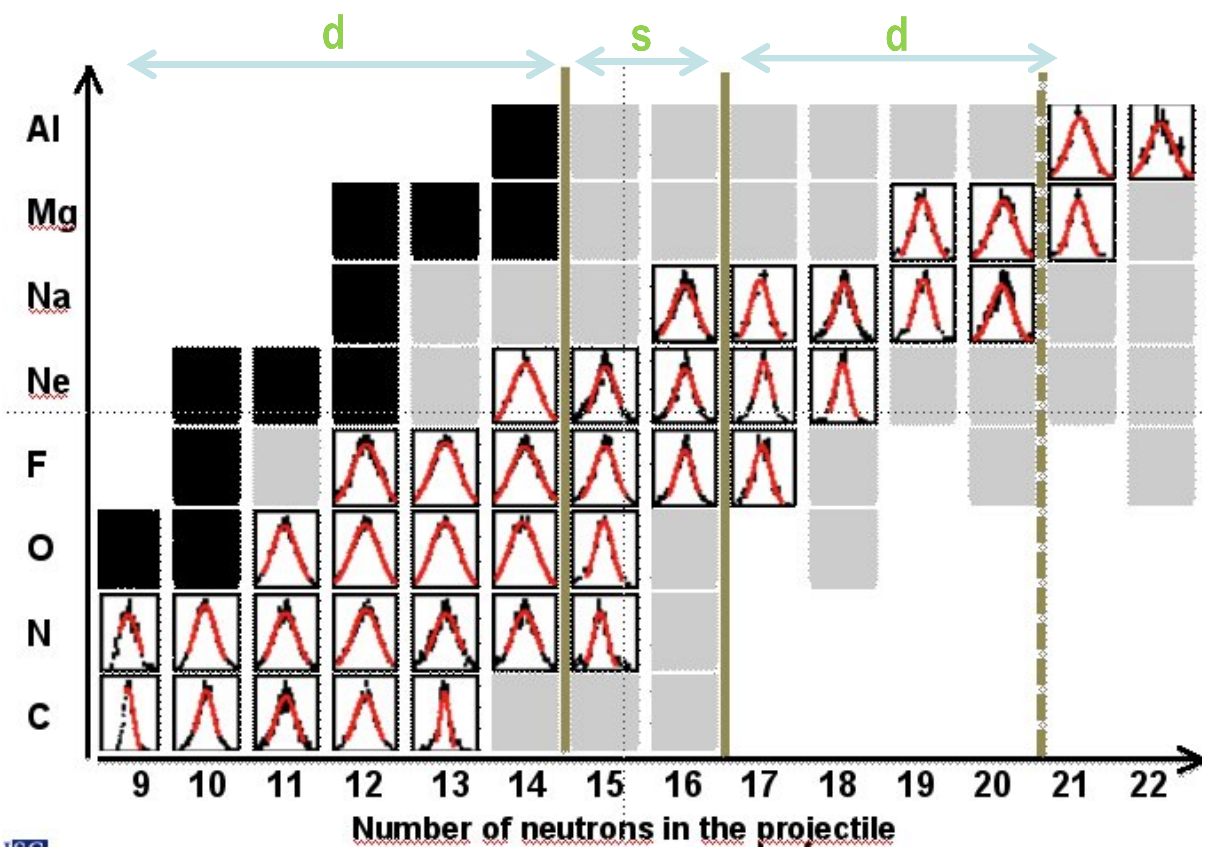
The accuracy in the measurement of the longitudinal mometum of the recoiling projectile residue requires the use of a high-resolving power magnetic spectrometer such as the FRS at GSI.

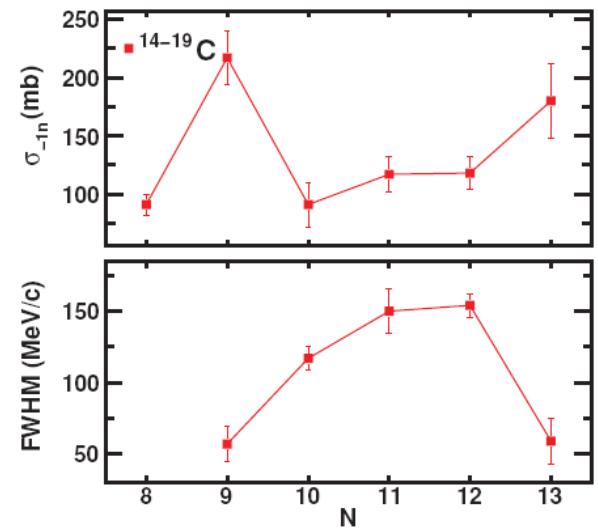


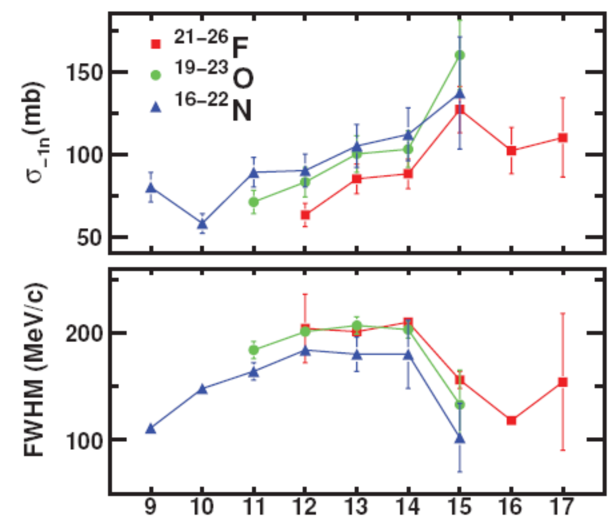
Nuclear structure investigations

Knock-out reactions

1-n knock-out cross section and the width of the momentum distributions reveal halo structures and shell evolution.





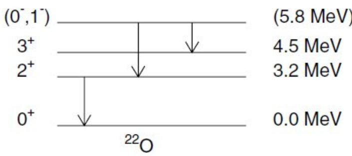


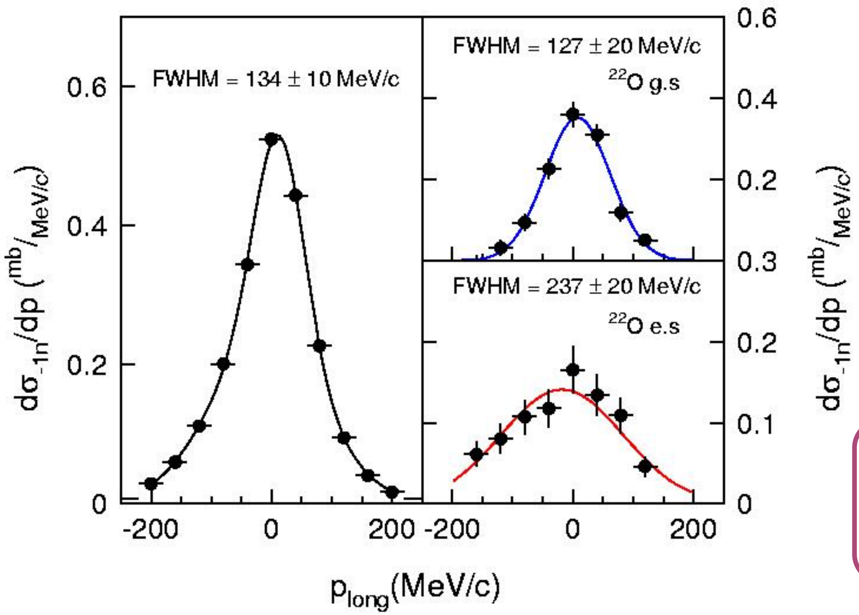
Nuclear structure investigations

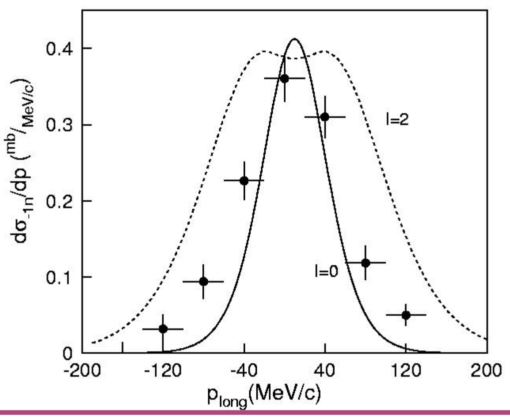
Knock-out reactions

Knock-out with gamma tagging allow for detailed spectroscopic studies.

The case of $^{23}O \rightarrow {}^{22}O+n$





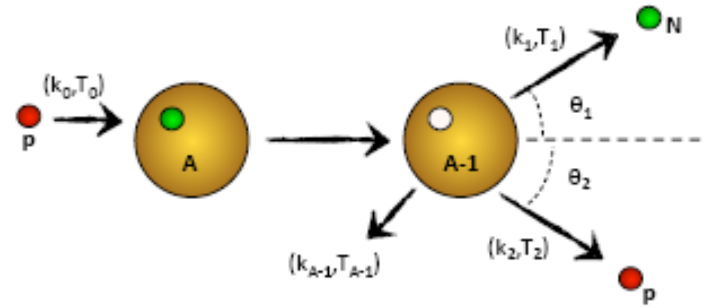


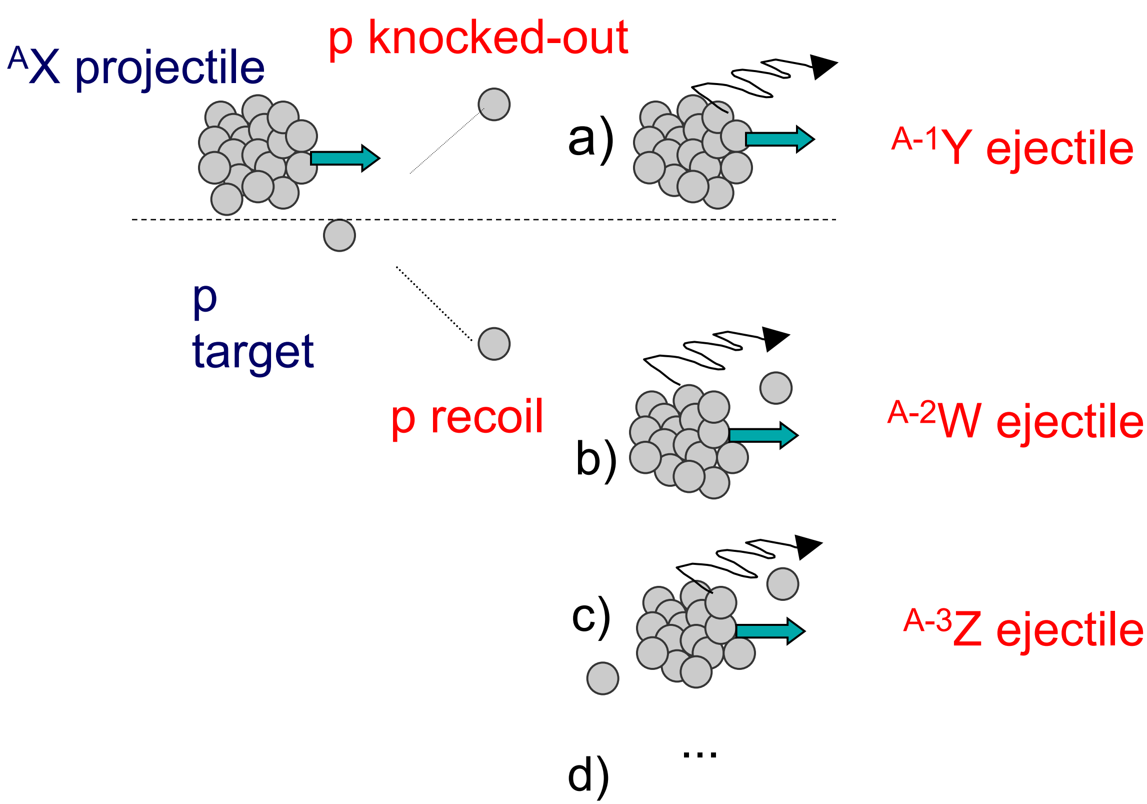
$|1/2^{+}\rangle = a|\, 0^{+} \otimes 2s_{1/2} \rangle + b|\, 2^{+} \otimes 1d_{5/2} \rangle$

Nuclear structure investigations

Quasi-free nucleon scattering

Nucleon-nucleon scattering in presence of nuclera matter.
Strong kinematic correlation between the incident and the knocked-out nucleons (p,2p) and (p,pn).





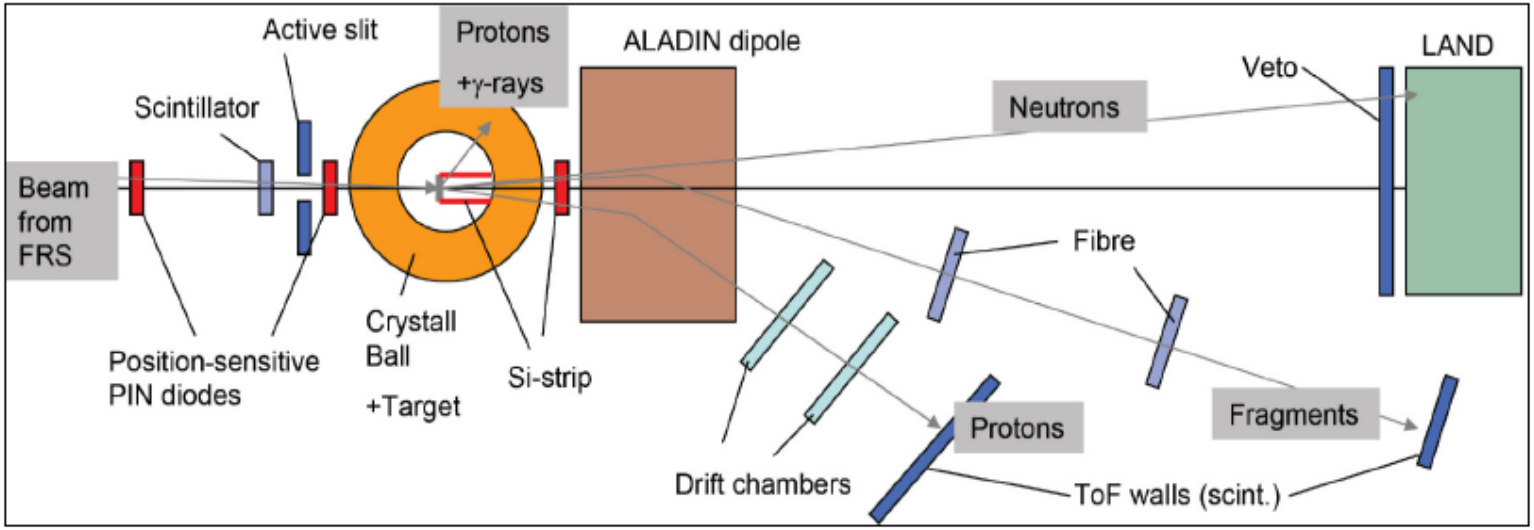
If valence nucleons are knocked out the residual nucleus is bound. In deeply-bound nucleon knock out the residual nucleos is unbound.

Detailed spectroscopic information on deeply unbound single-particle states requires the reconstruction of the invariant mass in complete kinematic measurements.

Nuclear structure investigations

Quasi-free nucleon scattering

Complete kinematic measurements require the identification and momentum determination of all nucleons, residual fragments and gamma rays produced in the reaction..



Excited single-particle states in the final residual fragment are determined as:

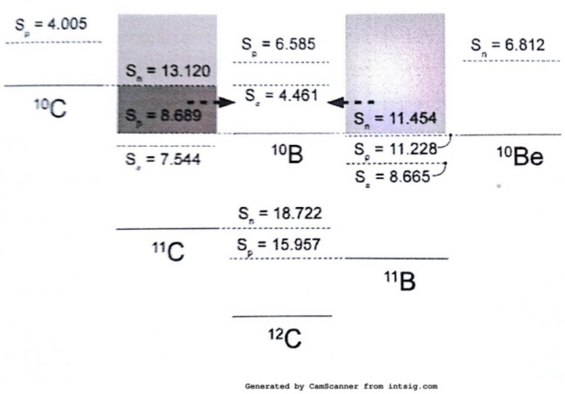
- bound states from gamma tagging
- unbound states from the reconstruction of the invariant mass

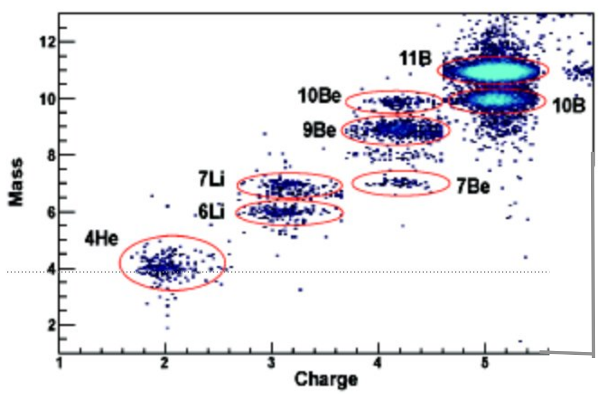
$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j \left(1 - \beta_i \beta_j \cos\vartheta_{ij}\right)} + E_\gamma - m_{res}$$

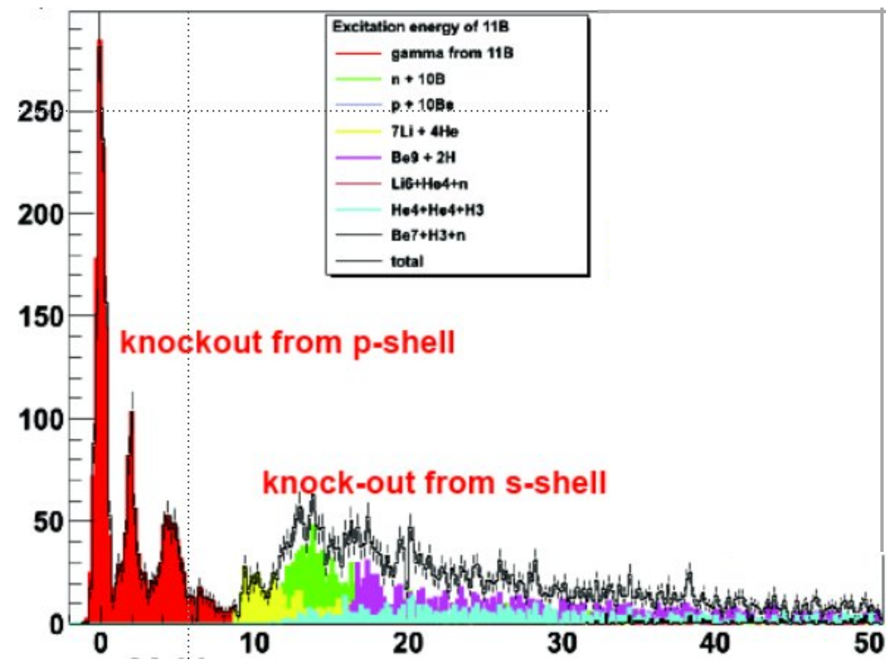
Nuclear structure investigations

Quasi-free nucleon scattering: $^{12}C(p,2p)$

Proof of principle with a stable beam.





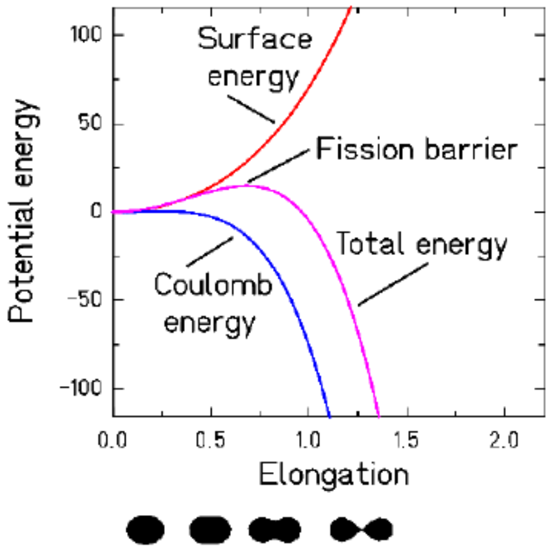


Fission studies

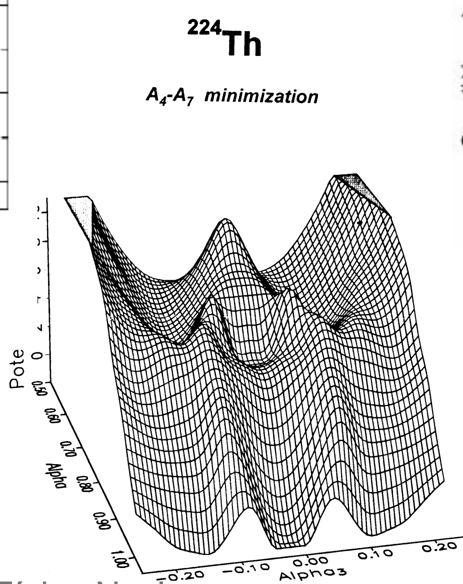
At low energies fission is governed by the potential energy landscape according to two main degrees of freedom:

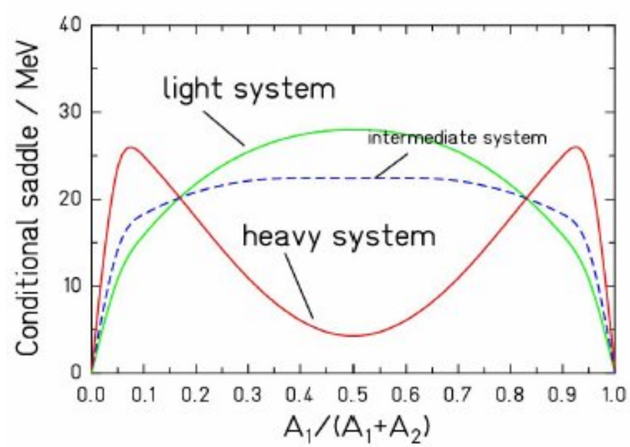
- **deformation**: when fission takes place

- **mass asymmetry**: how fission occurs



- Fission cross sections
- Excitation energy





- Mass and charge distributions of fragments
- Kinetic energies

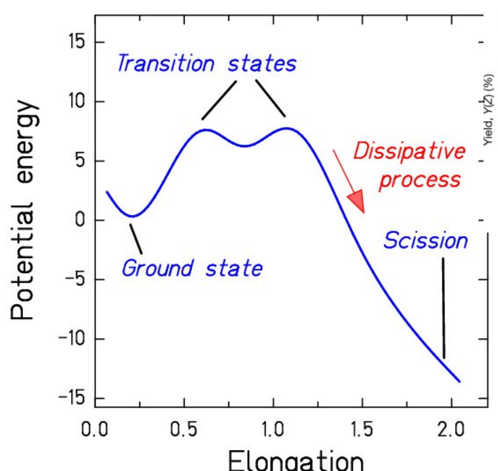
Fission studies

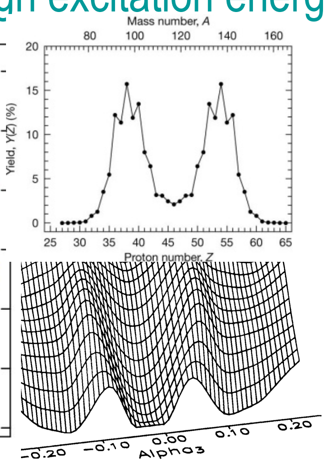
At low energies fission is governed by the potential energy landscape according to two main degrees of freedom:

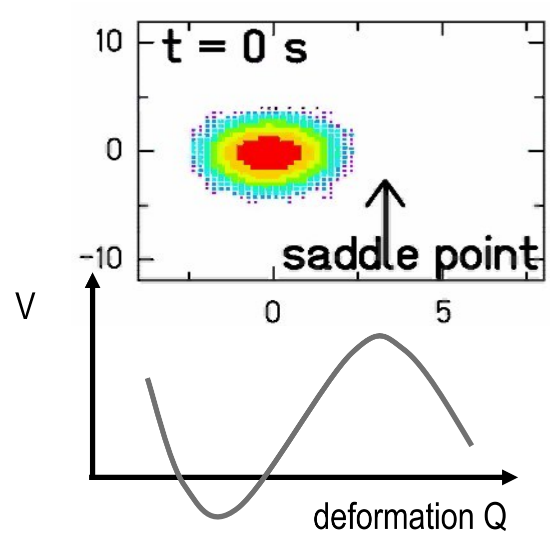
- **deformation**: when fission takes place
- **mass asymmetry**: how fission occurs

Coupling between intrinsic and collective degrees of freedom also manifest as a dissipative process:

- **saddle-to-scission** excitations: pair breaking
- **ground-to-saddle** transient effects at high excitation energy: fission delay







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Fission studies

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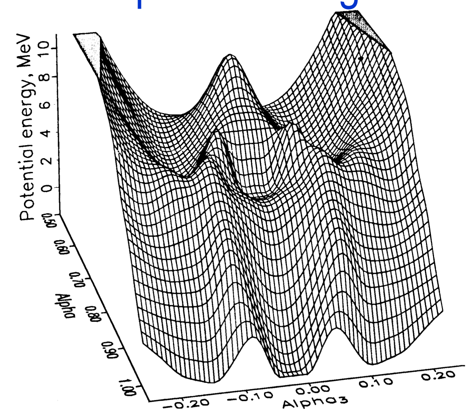

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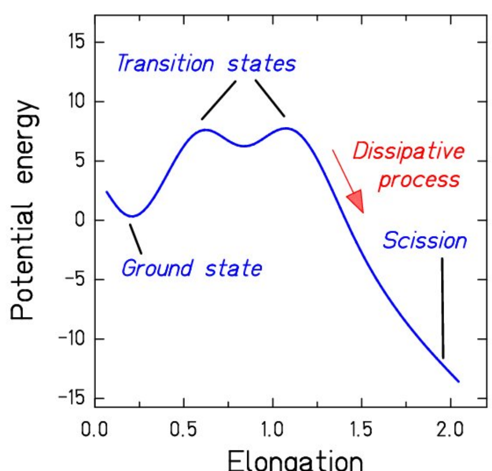
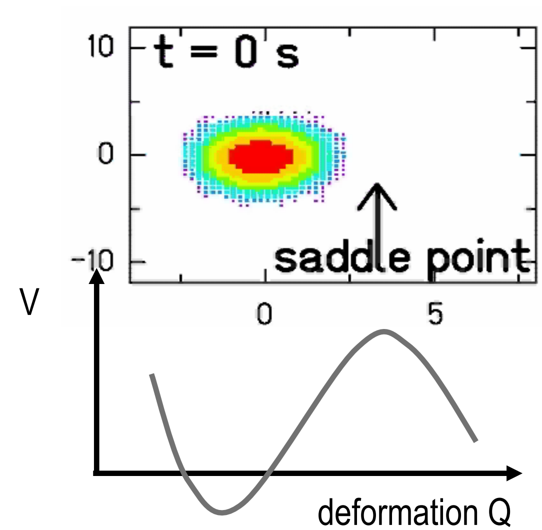
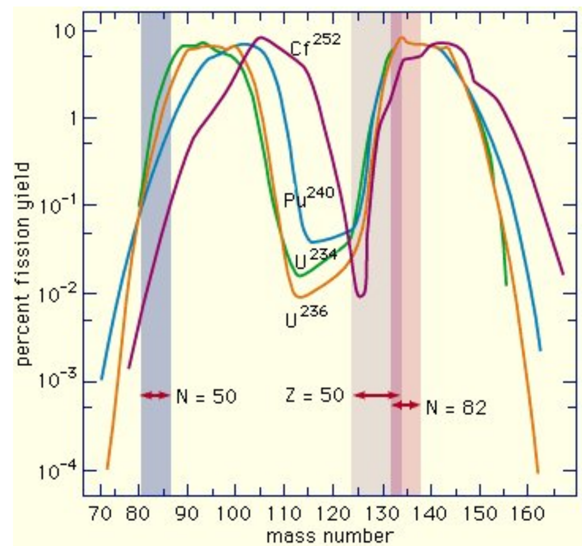


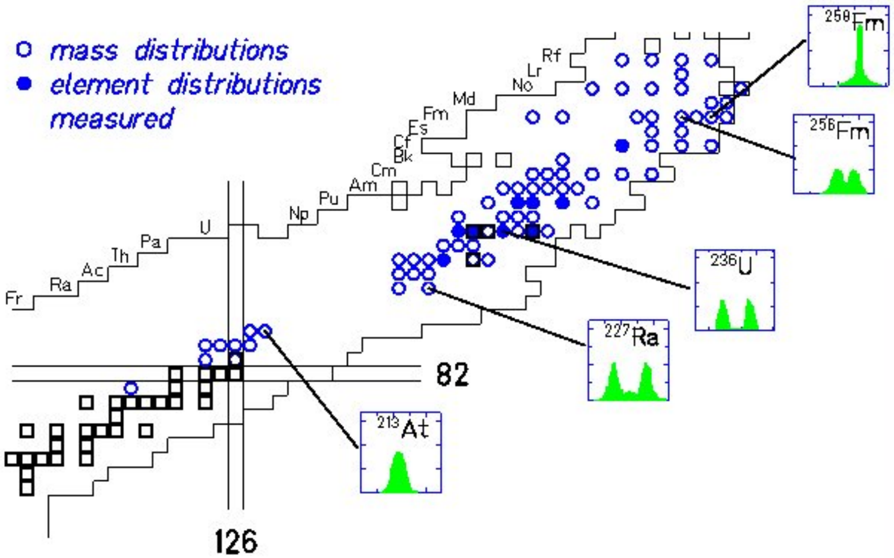


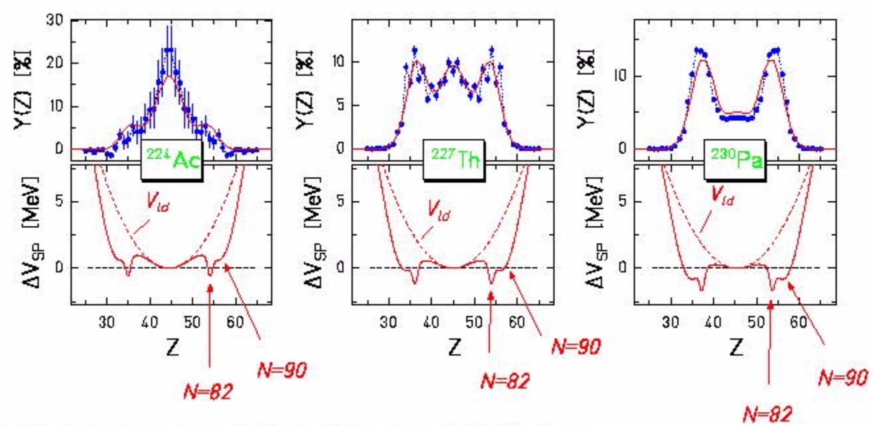
Fission studies

Shell effects manifest in the mass/charge asymmetry degree of freedom:

- Shell closure around Z=50 and N=82,86 was though to explain the mass asymmetry in the actinide region
- The curvature of the liquid-drop potential with mass asymmetry explained the transition to symmetry in pre-actinides





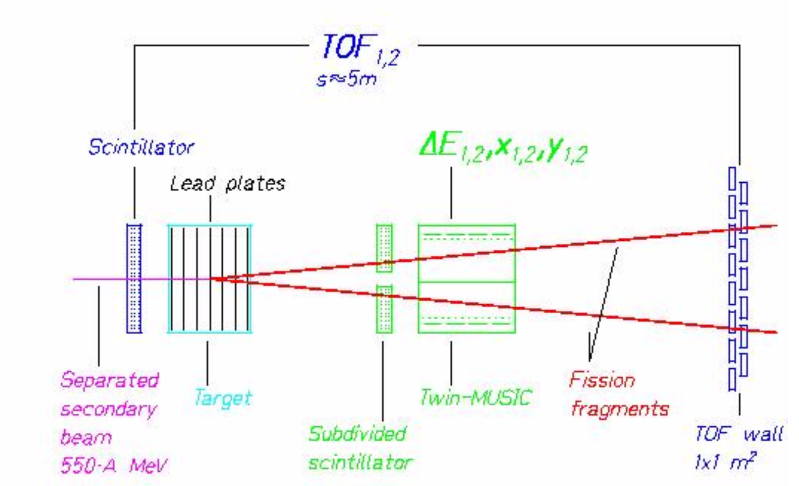


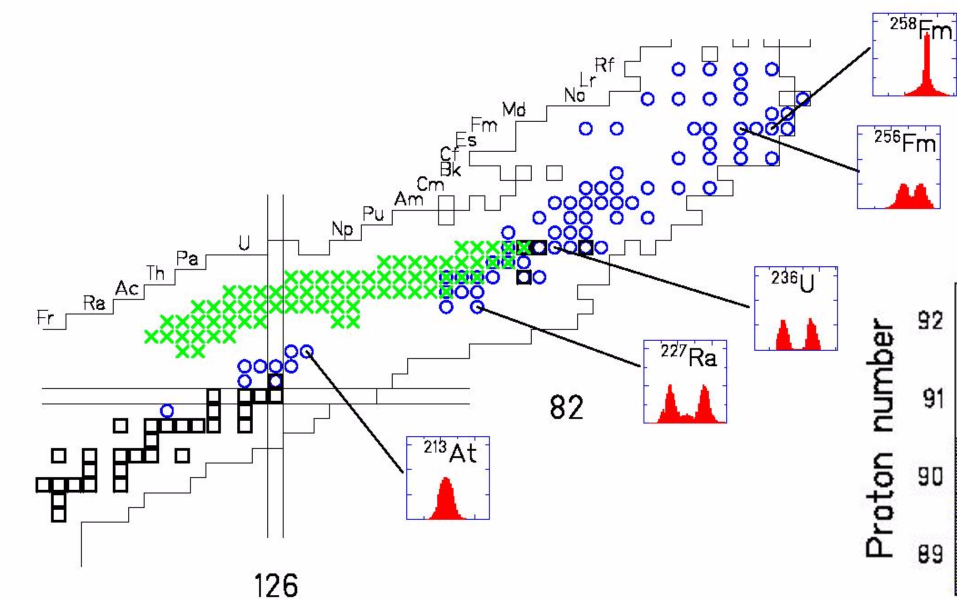
Mostly mass distributions were at reach experimentally

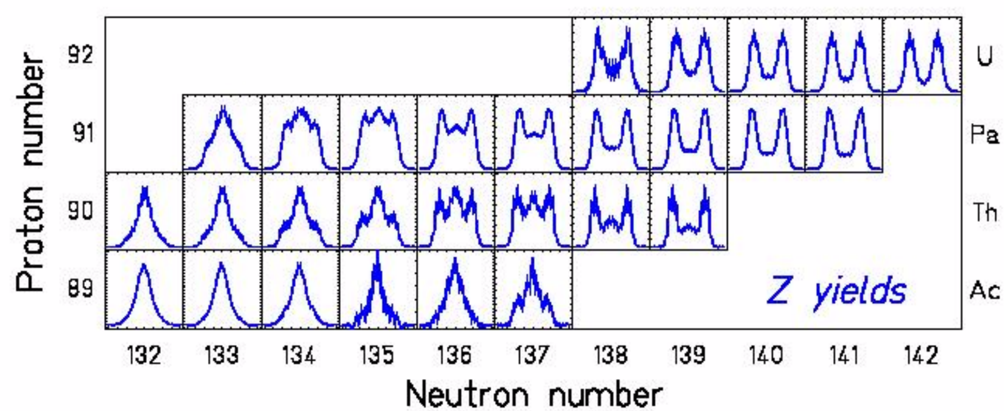
Fission studies

Inverse kinematics gave access to investigate the fission of actinides and pre-actinides produced in the fragmentation of ^{238}U and accurately measure the charge distributions of the fission fragments:

- The transition between asymmetric and symmetric fission was confirmed





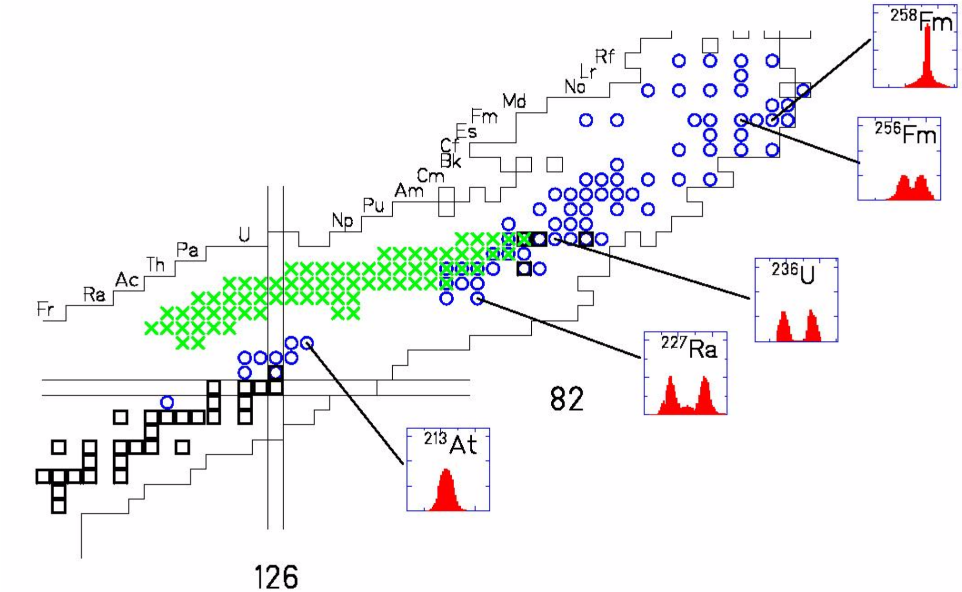


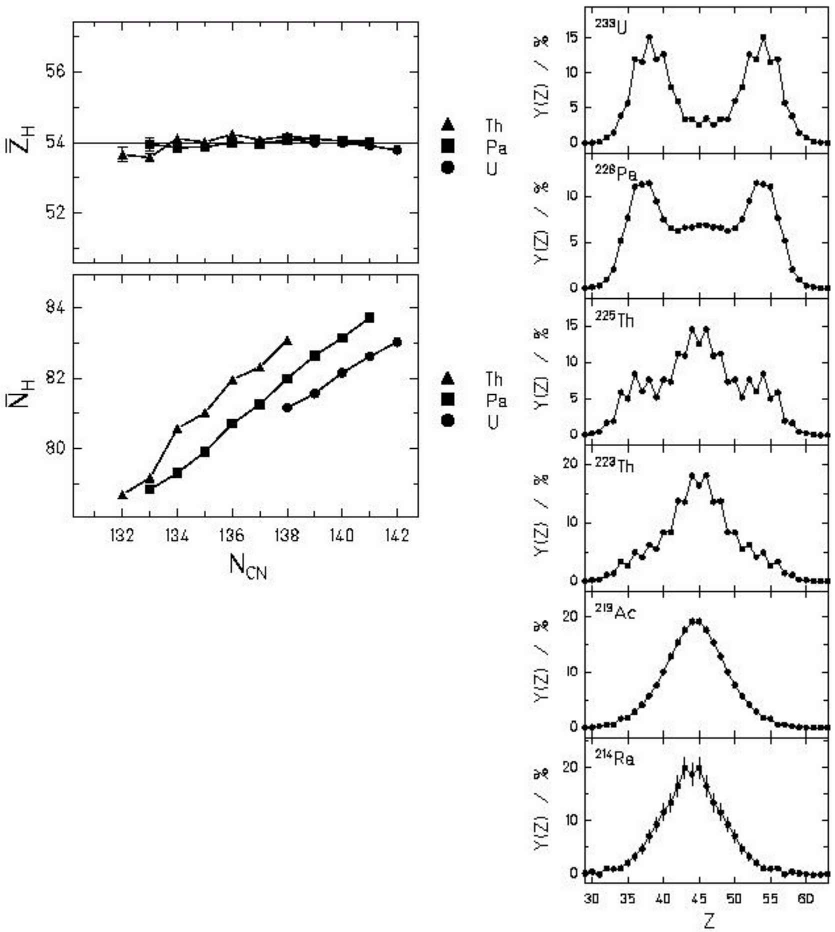
K.-H. Schmidt et al. NPA (2000)

Fission studies

Inverse kinematics gave access to investigate the fission of actinides and pre-actinides produced in the fragmentation of ^{238}U and accurately measure the charge distributions of the fission fragments:

- The transition between asymmetric and symmetric fission was confirmed
- But no real evidences for the shell closure at Z=50 or N=82,86 were observed





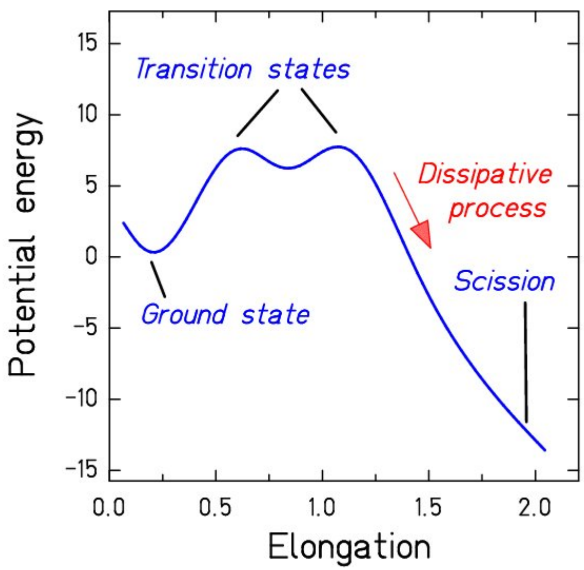
K.-H. Schmidt et al. NPA (2000)

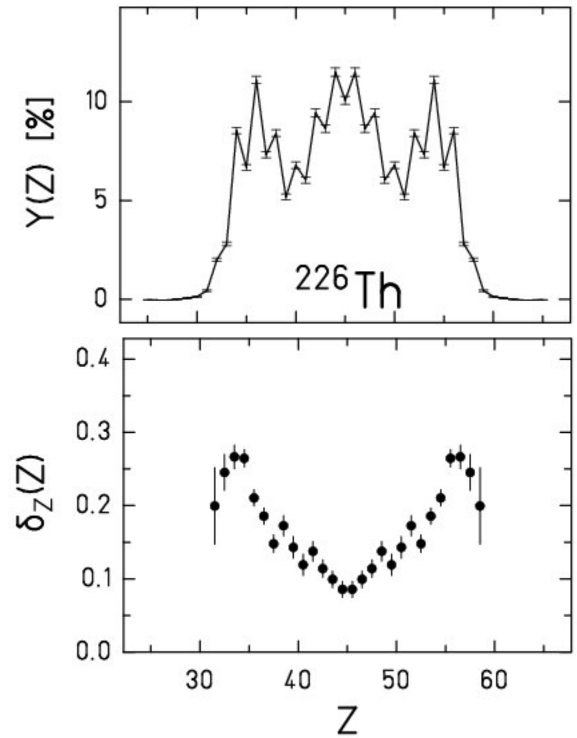
Fission studies

The coupling between intrinsic and collective degrees of freedom is another open question in fission:

- Pair breaking in low-energy even fissioning systems is considered as a prove of energy transfer between potential-deformation energy and intrinsic excitations understood as a dissipative process

- However, the magnitude of the even-odd staggering also depends on the asymmetry of the process





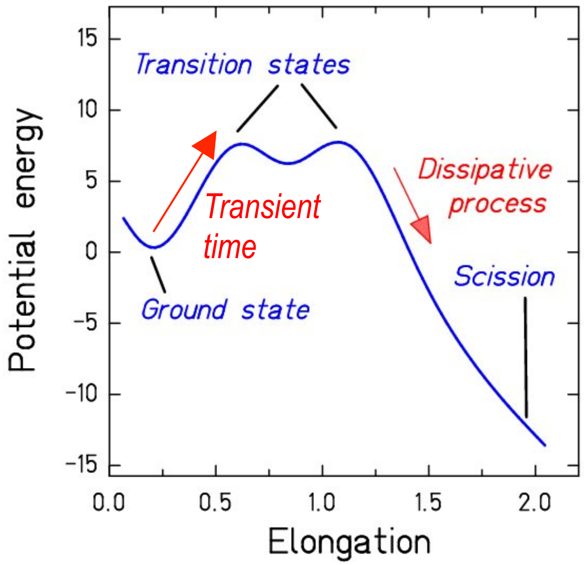
The relation between even-odd staggering in fission fragments and energy dissipation is still under debate

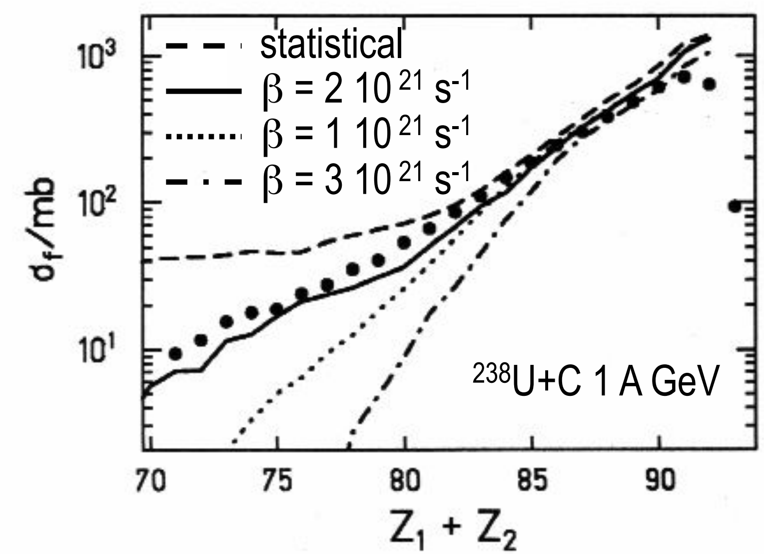
Fission studies

The coupling between intrinsic and collective degrees of freedom also manifest as a transient effect from ground to saddle at high excitation energies:

- Transient effects from ground to saddle will delay fission with respect to competing de-excitation channels reducing its probability

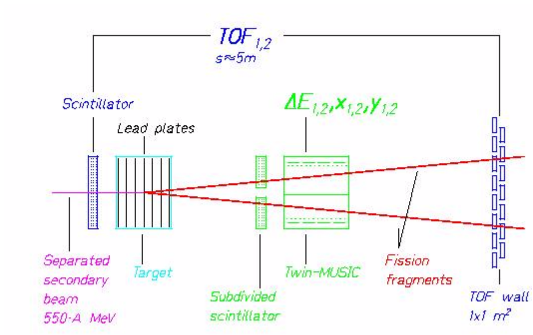
- Pre-scission neutron and gamma emission and fission probabilities evidence this effect

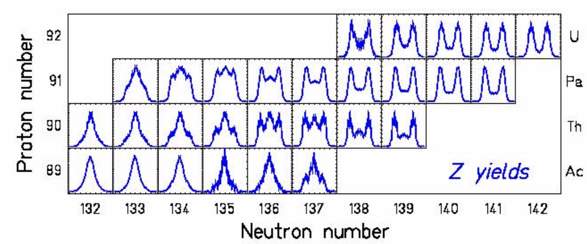




The magnitude of the viscosity parameter producing transient effects and its possible dependence with temperature and deformation are not yet known.

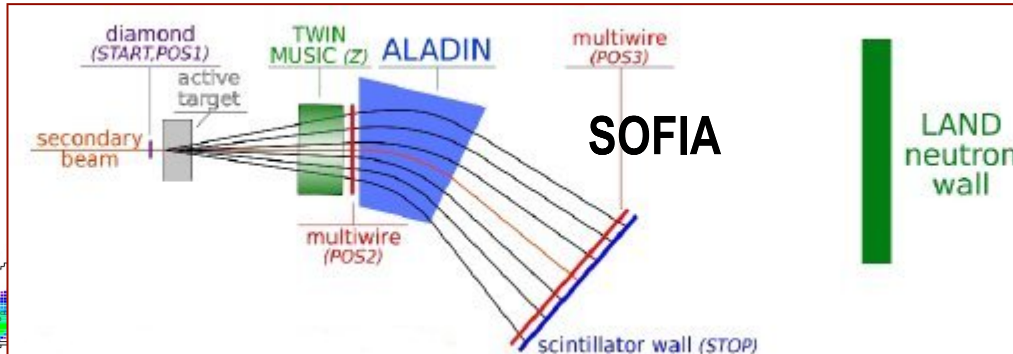
Fission studies



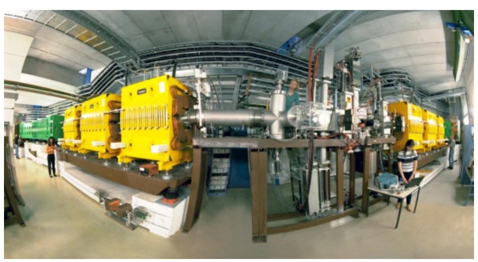


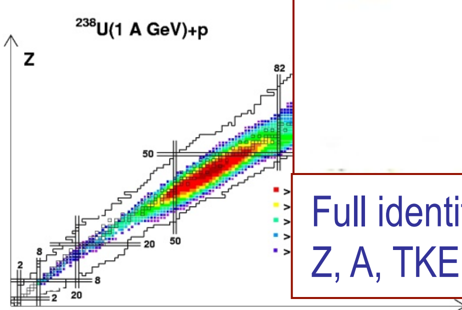
- structural effects in fission

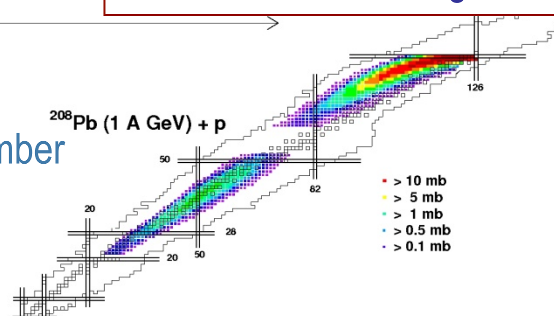
- detection of both fission fragments
- but only the atomic number is determined



Full identification of both fission fragments
Z, A, TKE, neutrons, gammas, light-charged particles







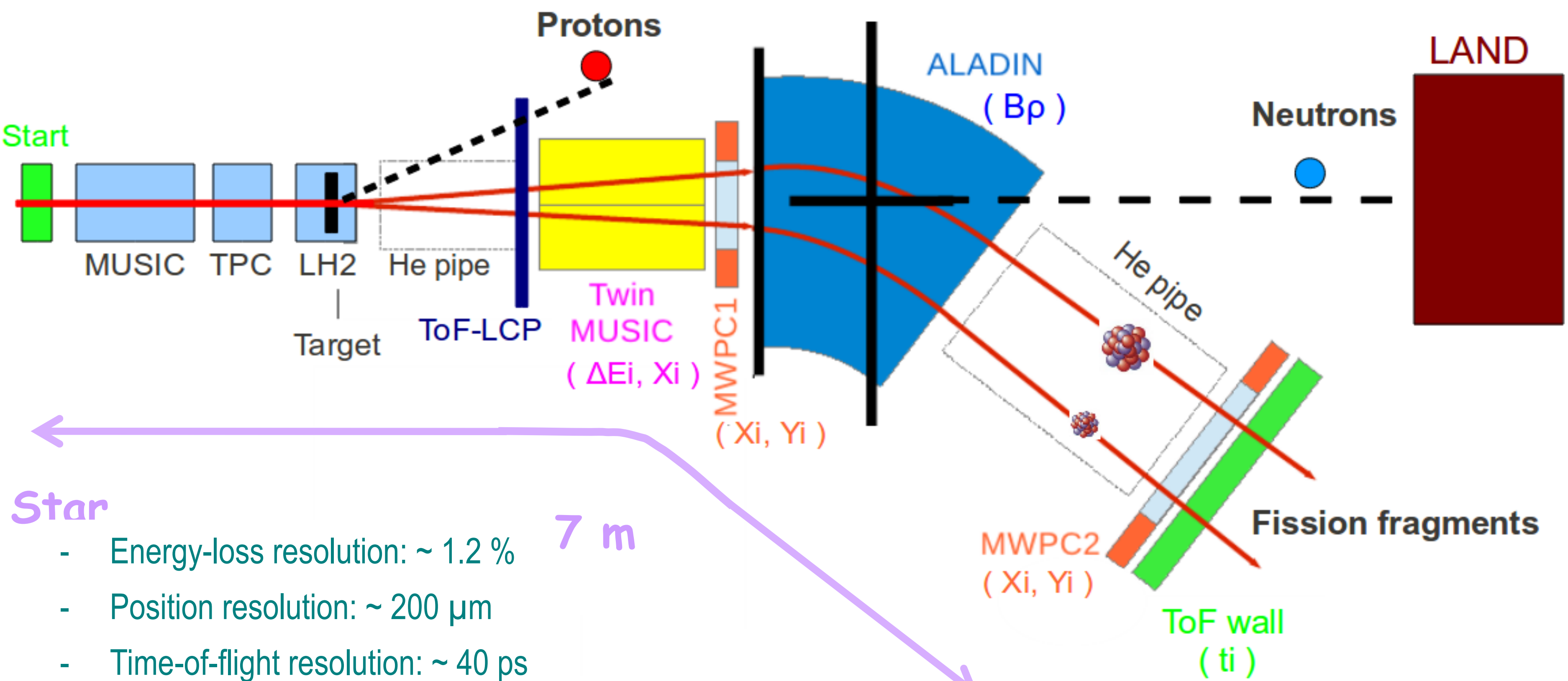
- full identification in mass and atomic number
- but only one fragment is measured

- dynamics of fission at high excitation energy

Proposed experiment

Experimental setup

Full identification in A, Z of both fission fragments together with light-charged particles and neutrons

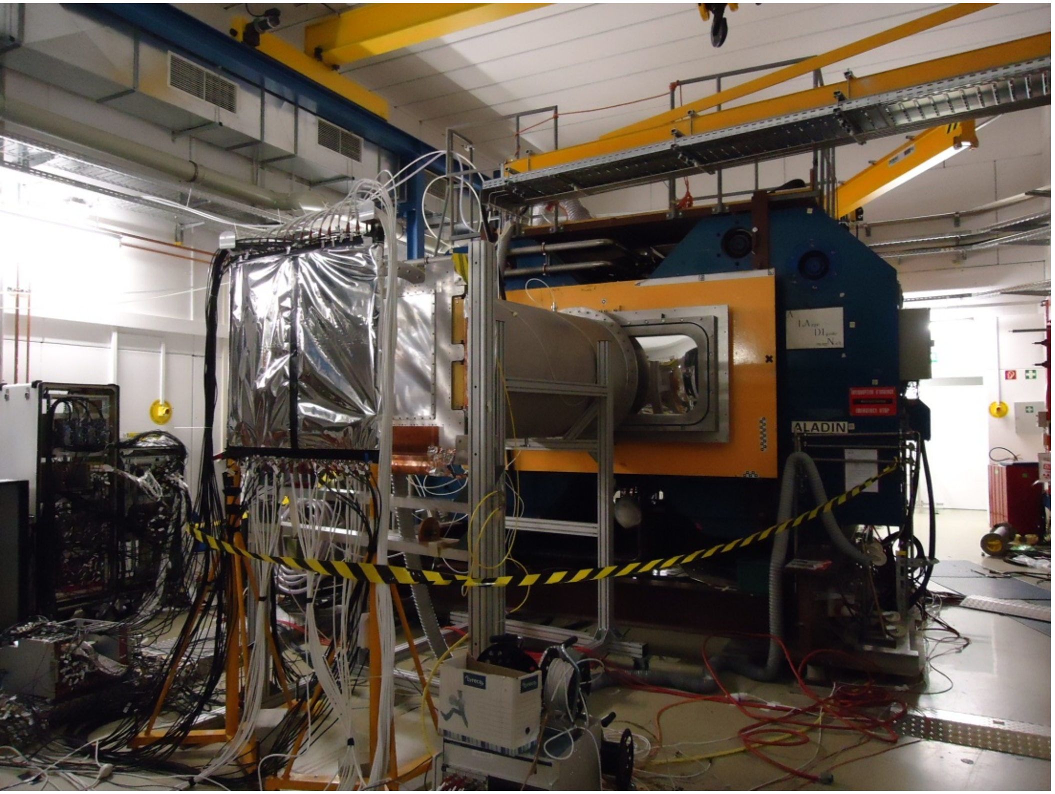


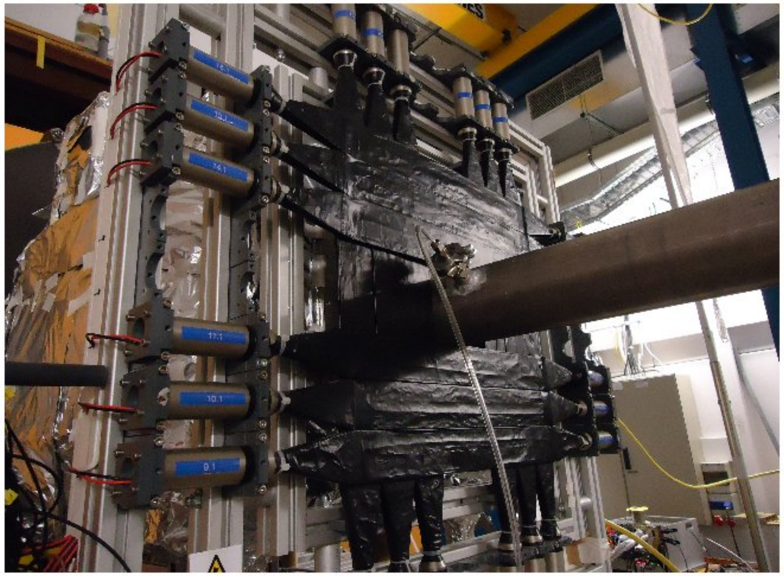
- Energy-loss resolution: ~ 1.2 %
- Position resolution: ~ 200 μm
- Time-of-flight resolution: ~ 40 ps
- Limited straggling (helium pipes)

Proposed experiment

Experimental setup

Full identification in A, Z of both fission fragments together with TKE and neutrons





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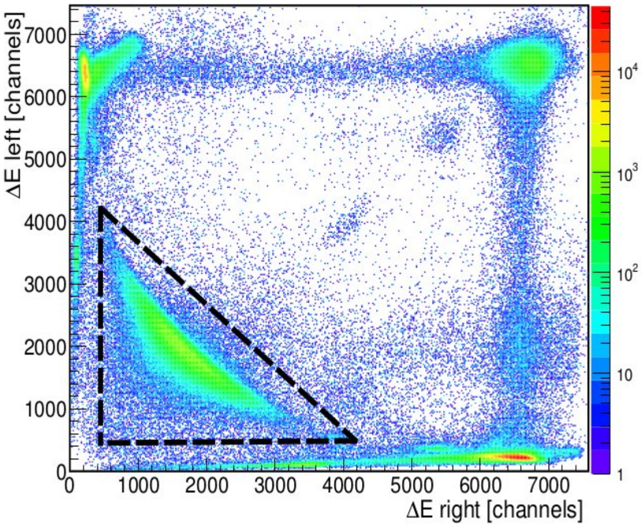
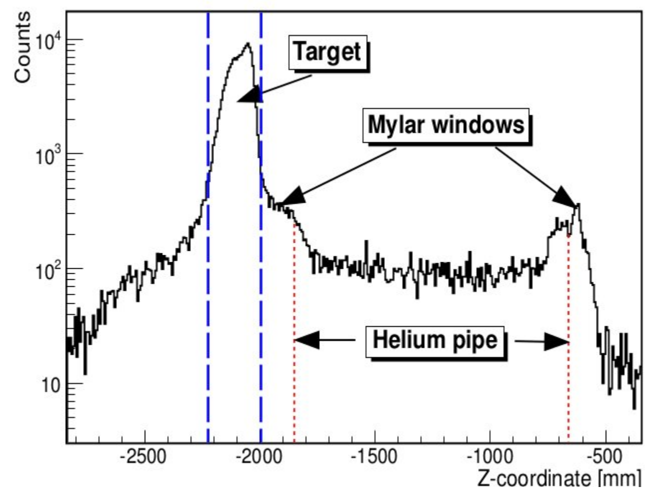
Results

Total fission cross sections

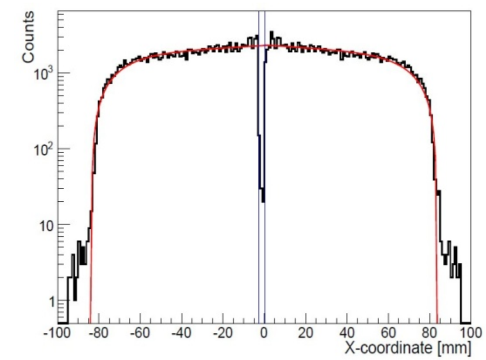
Identification of fission reactions

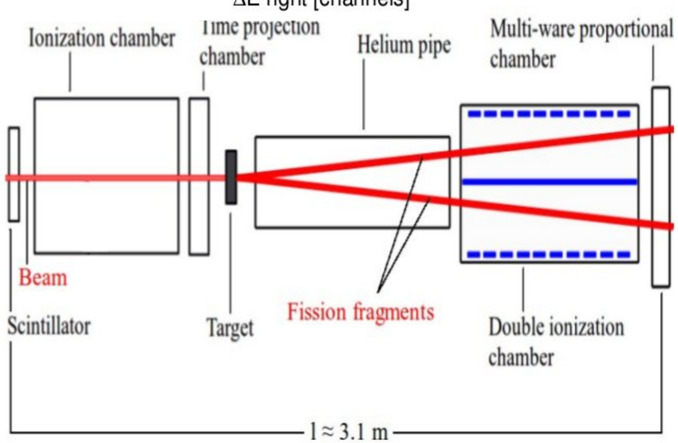


Identification of fissions in the H_2 target

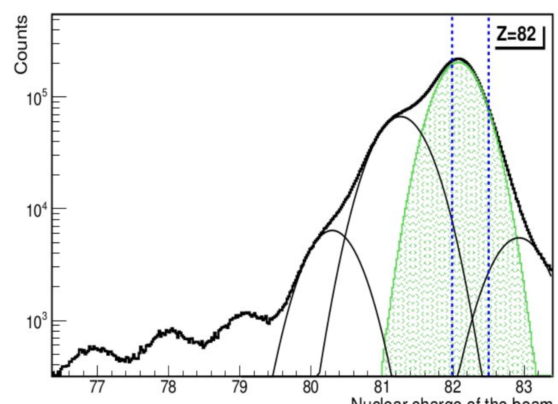


Detection efficiency



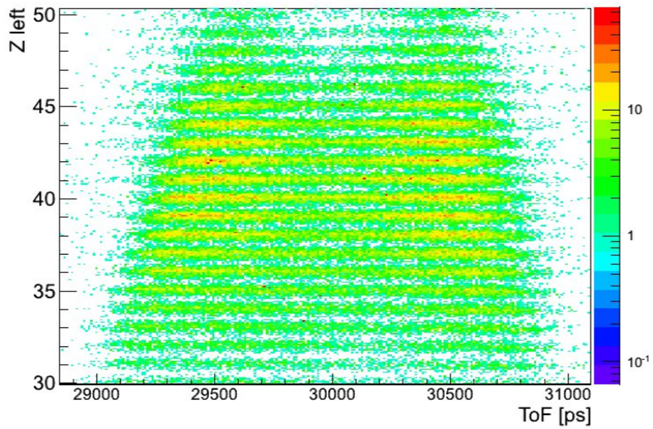


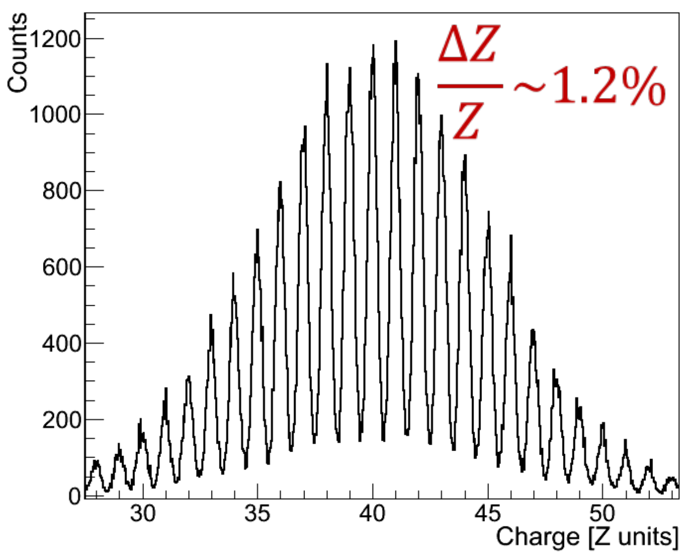
Identification of projectile nuclei

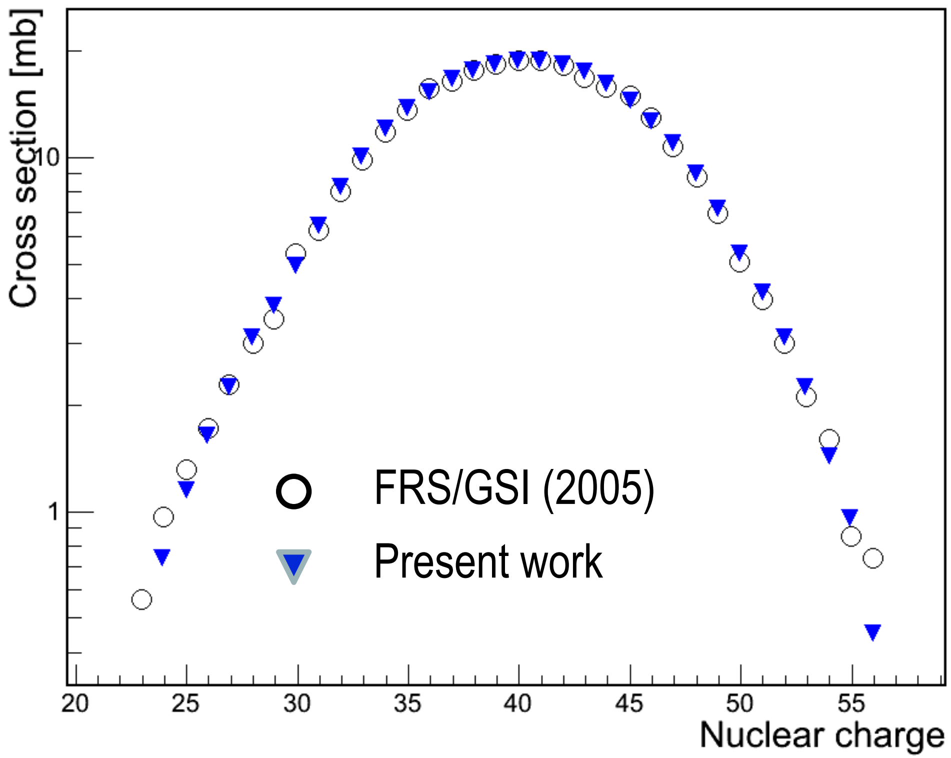


Results

Fission yields: charge distributions



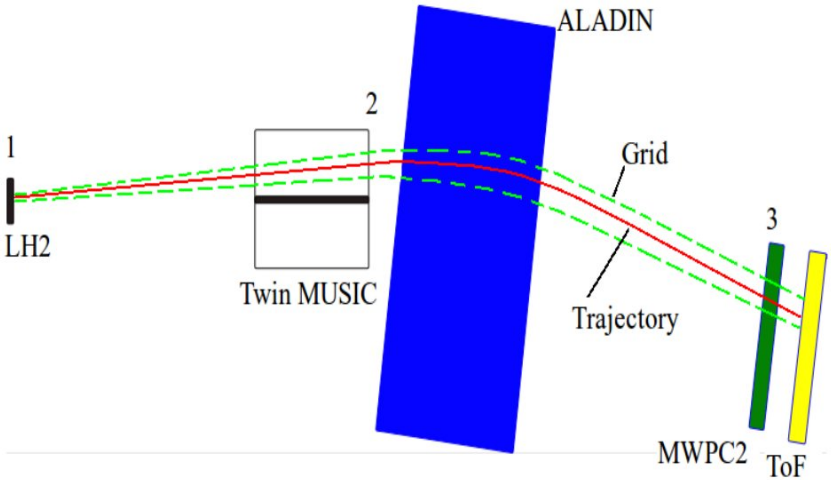




The problem with the 2005 GSI data was in the absolute normalization but not on the relative isotopic distributions.

Results

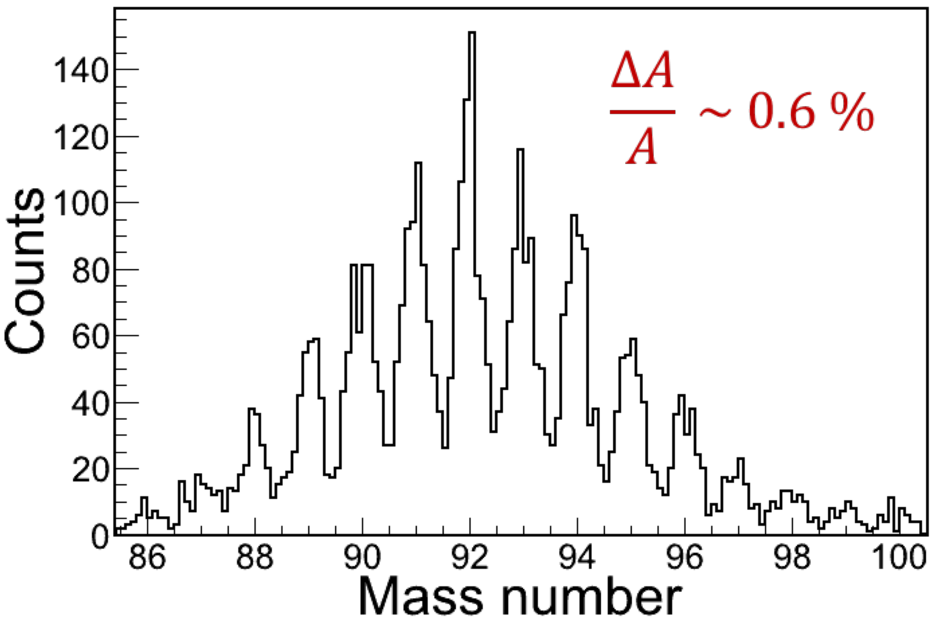
Fission yields: isotopic distributions



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

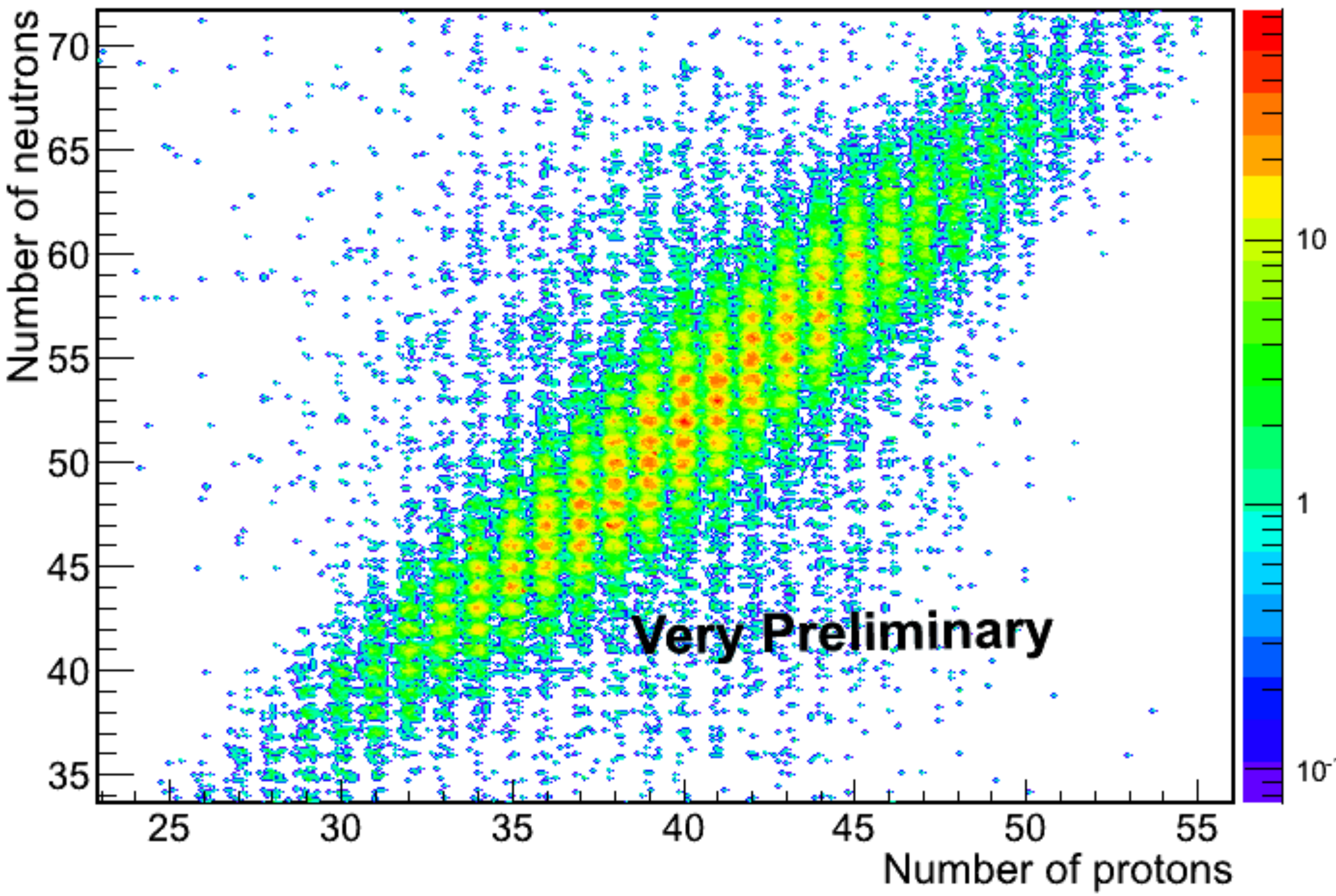
ρ → tracking (twin-MUSIC + MWPC)

$\beta\gamma$ → time of fligth (scintillators)



Results

Fission yields: isotopic distributions



Conclusions

✓ The use of inverse kinematics makes possible to investigate reactions induced by exotic nuclei but also to improve the identification of the reaction products, in particular heavy residues.

✓ At relativistic energies we increase the geometrical acceptance of the detectors and the target thicknesses but we also simplify the description of the reaction mecachanism.

✓ Knock-out and quasi-free scattering constitute and important spectroscopic tool for investigating the structure of nuclei far from stability.

✓ Heavy-ion reactions at relativistic energies using inverse kinematics are also an important tool for the investigation of the dynamics of nuclear matter, as for example fission