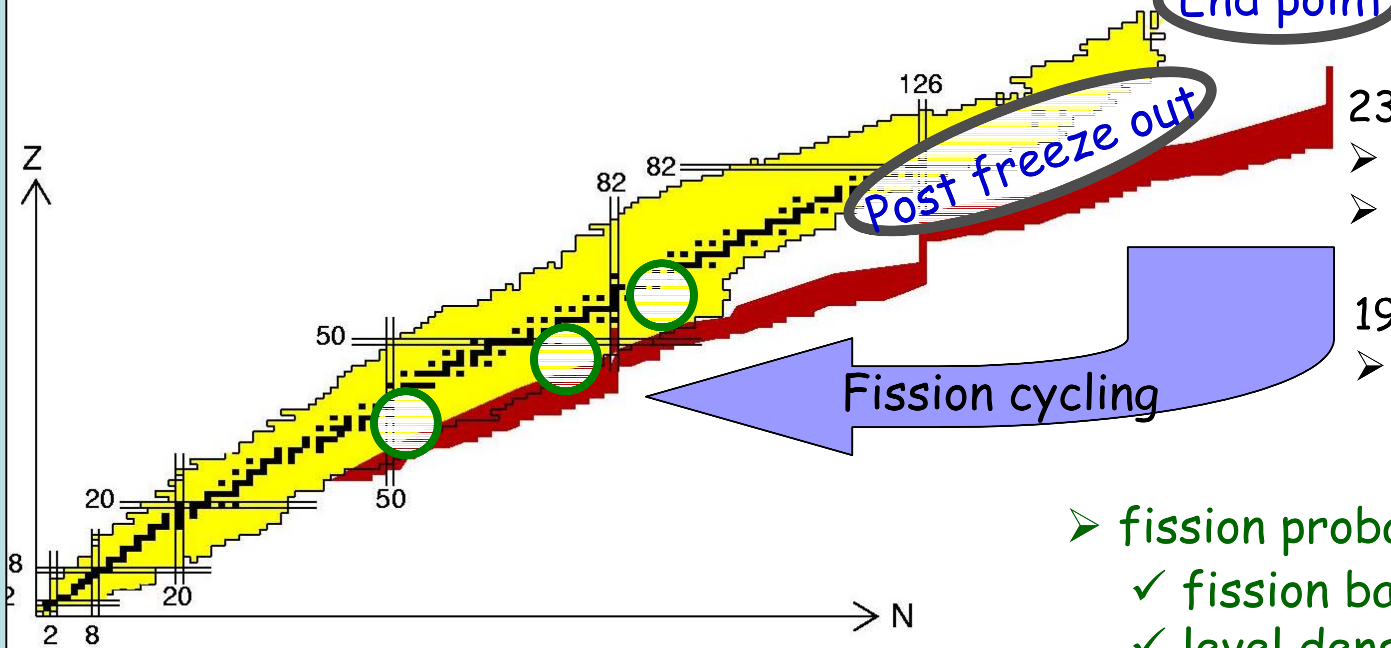
Fission and the r-process: experimental achievements and future possibilities

J. Benlliure

Universidad de Santiago de Compostela, Spain

RIA workshop

The role of fission



260 < A < 320
- spontaneous fission
- n-induced fission

230 < A < 260
- spontaneous fission
- β-delayed fission

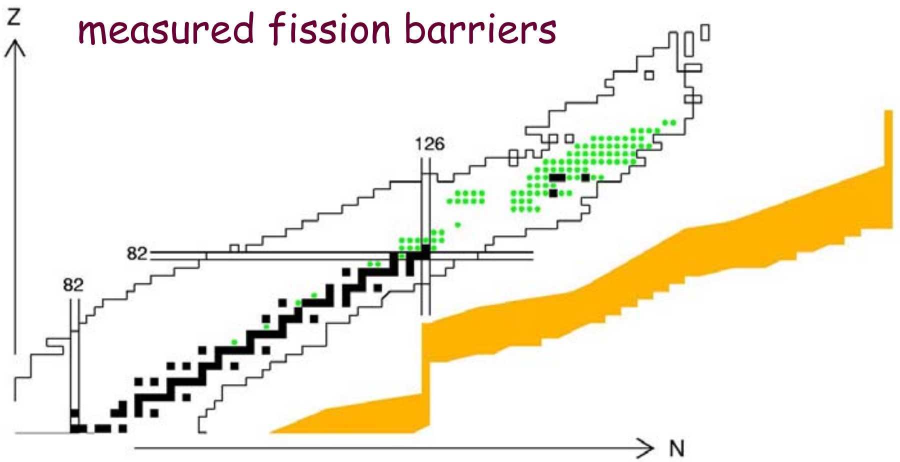
190 < A < 230
- ν-induced fission

- fission probabilities
  - ✓ fission barriers
  - ✓ level densities
  - ✓ masses
- fission fragment distributions

Present knowledge

The exact end point of the r-process and the impact of fission in the observed abundances is unknown because:

- site conditions not well known
- fission barriers still uncertain
  - ✓ limited experimental information
  - ✓ progress in calculations with n-rich nuclei (A. Mamdouh et al. NPA 679 (2001) 337)

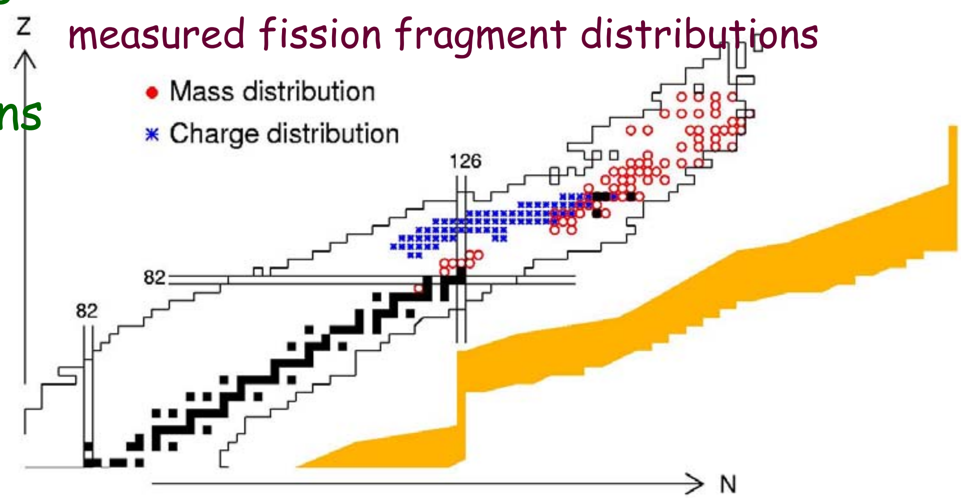


Present knowledge

The exact end point of the r-process and the impact of fission in the observed abundances is unknown because:

- site conditions not known
- fission barriers highly uncertain
  - ✓ limited experimental information
  - ✓ progress in calculations with n-rich nuclei (A. Mamdouh et al. NPA 679 (2001) 337)
- poor information on fission fragment distributions
  - ✓ recent progress on both measurements and calculations (K.-H. Schmidt and collaborators)

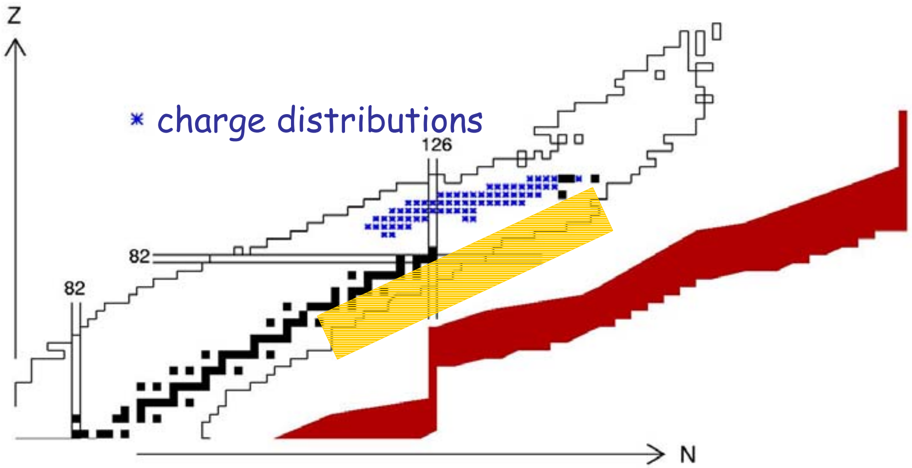
measured fission fragment distributions



Investigations at GSI

Fission of heavy-exotic nuclei:

- ➢ charge distributions
  - ✓ measurements
  - ✓ fission model

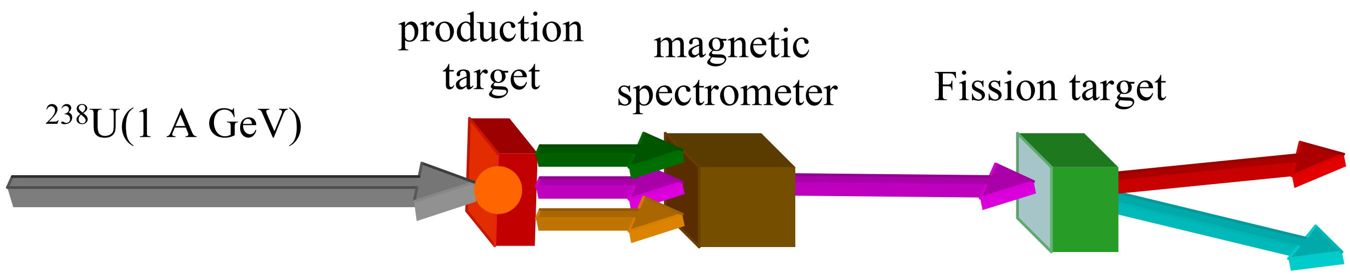


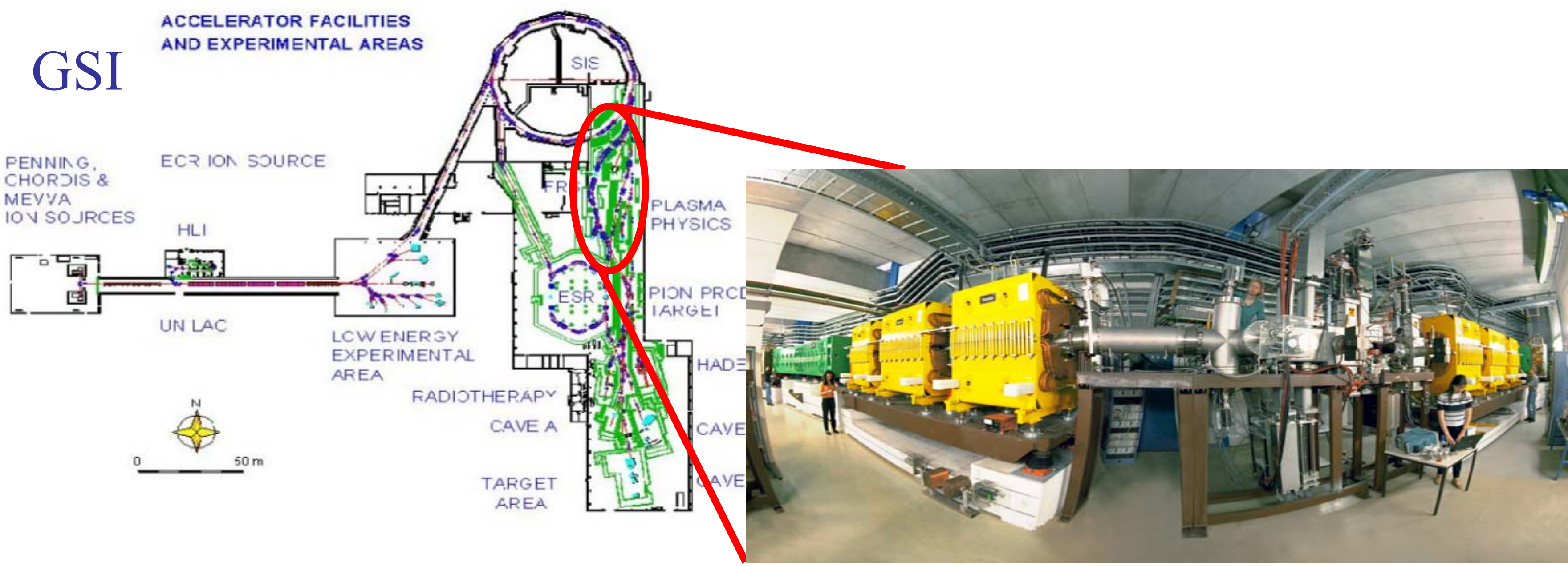
- ➢ fission probability around closed shells

- ➢ production of heavy neutron-rich isotopes in projectile fragmentation

- ➢ future projects

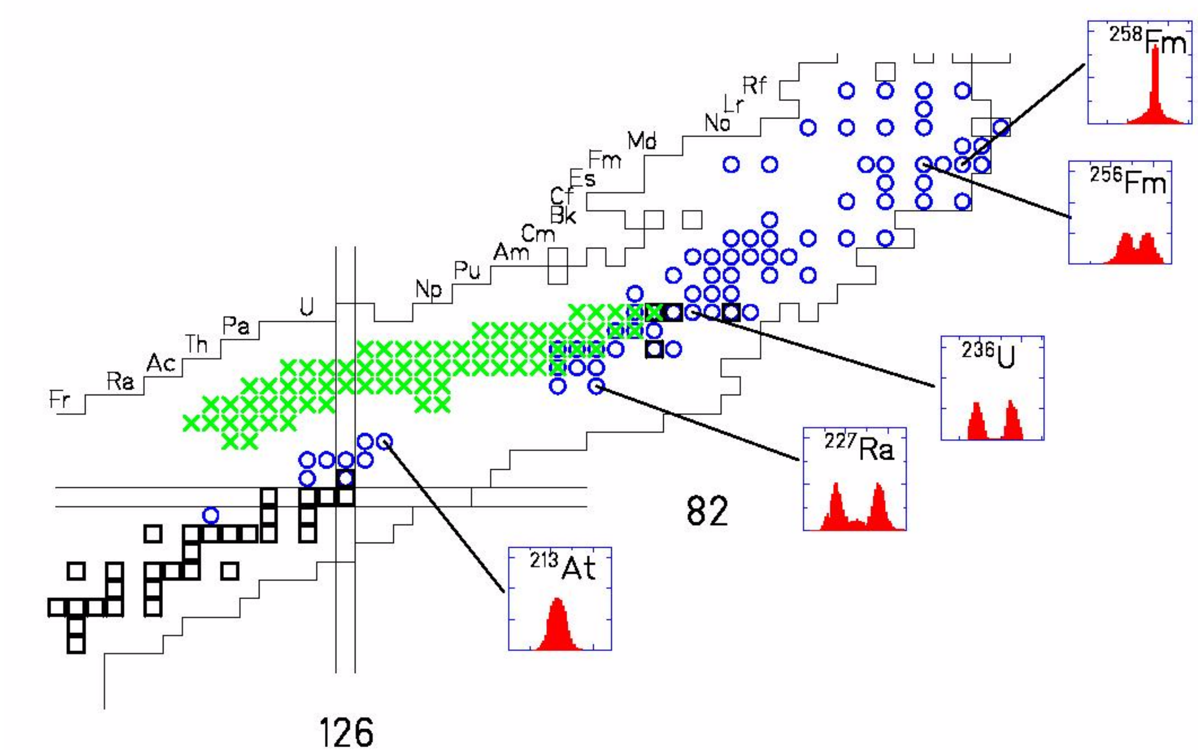
Fission experiments with RNB





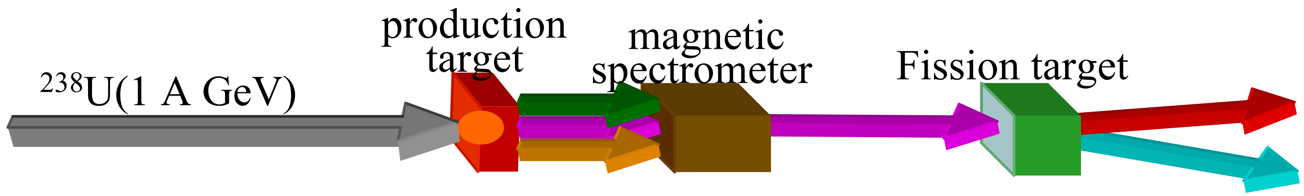
Fission experiments with RNB

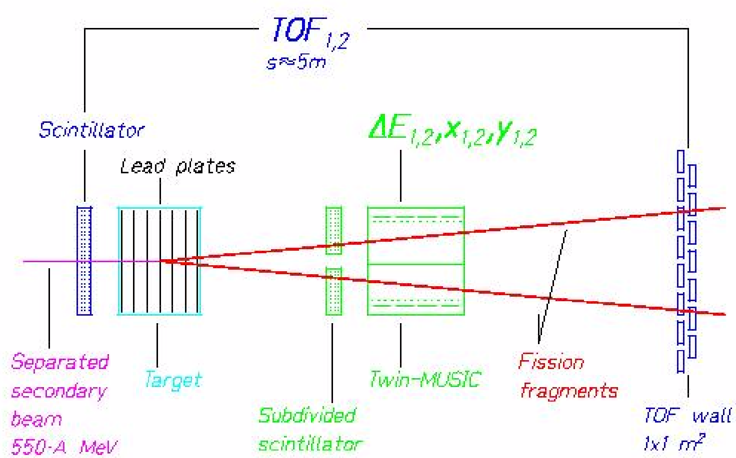
Investigated nuclei



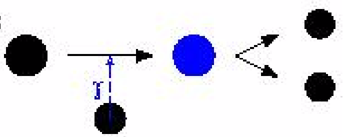
- Fissioning nuclei along large chains in N and Z
- The transition from asymmetric to symmetric fission is covered

Fission experiments with RNB





- *electromagnetic interaction*
  - *Excitation of the giant resonances (dipole-, quadrupole-)*



- *11 MeV mean excitation energy (FWHM ≈ 7 MeV)*
- *≈ 3.9 barn excitation cross section*

Features:

full detection of both fission fragments

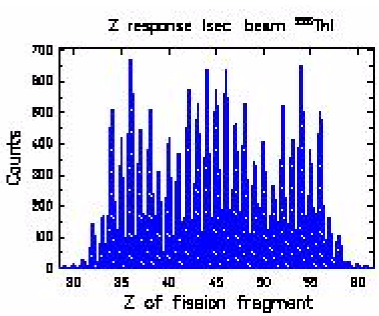
excellent Z resolution

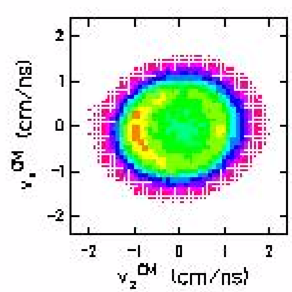
kinematic analysis

Results:

Z yields

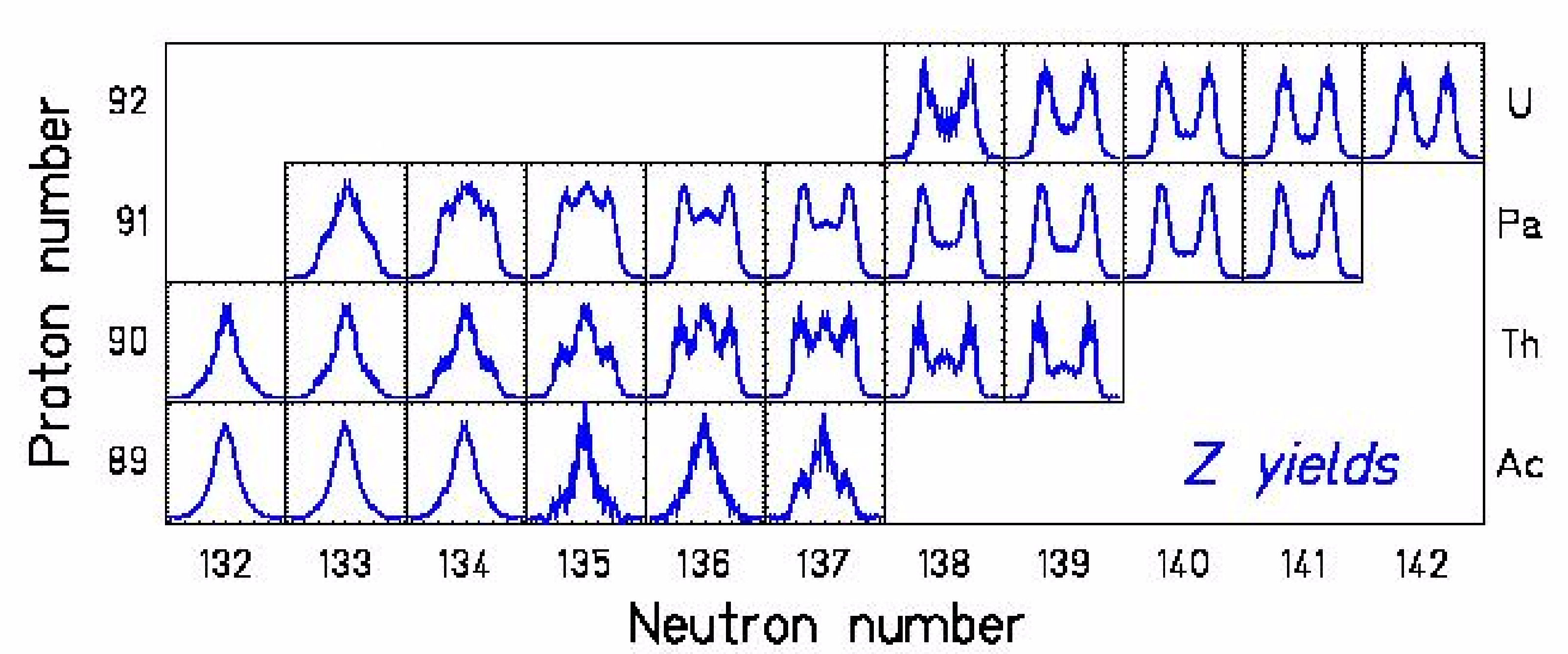
total kinetic energies





Fission experiments with RNB

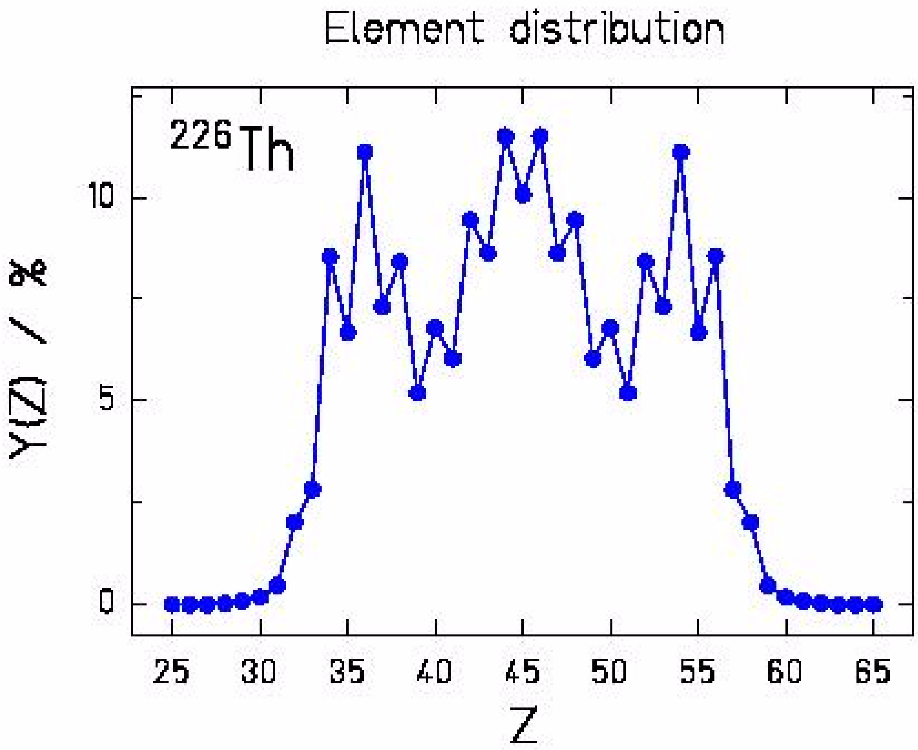
Measured charge distributions



- Fission-fragment charge-distributions of 70 preactinides were measured
- The transition from asymmetric to symmetric fission is covered

K.-H.Schmidt et al., NPA 665 (2000) 221

Fission experiments with RNB

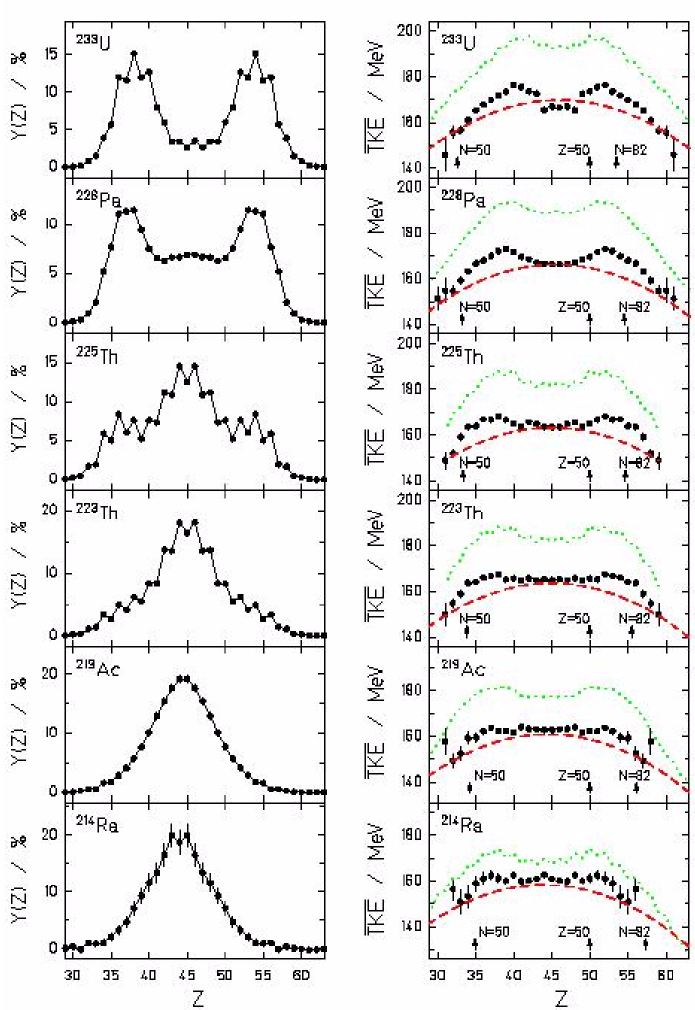


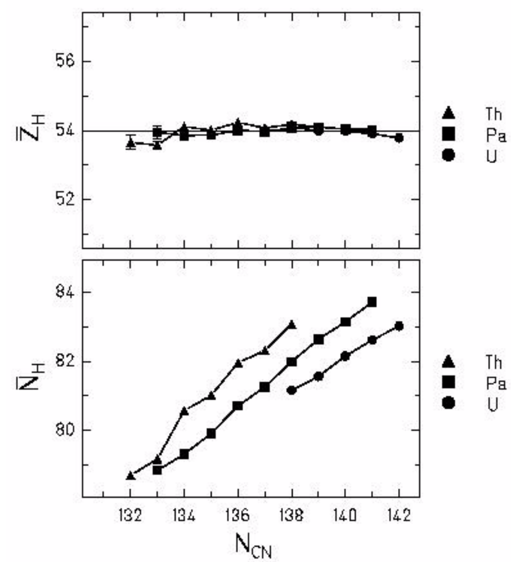
Gross structure ➔ shell effects

Fine structure ➔ pairing correlations

Fission experiments with RNB

Shell effects at large deformation



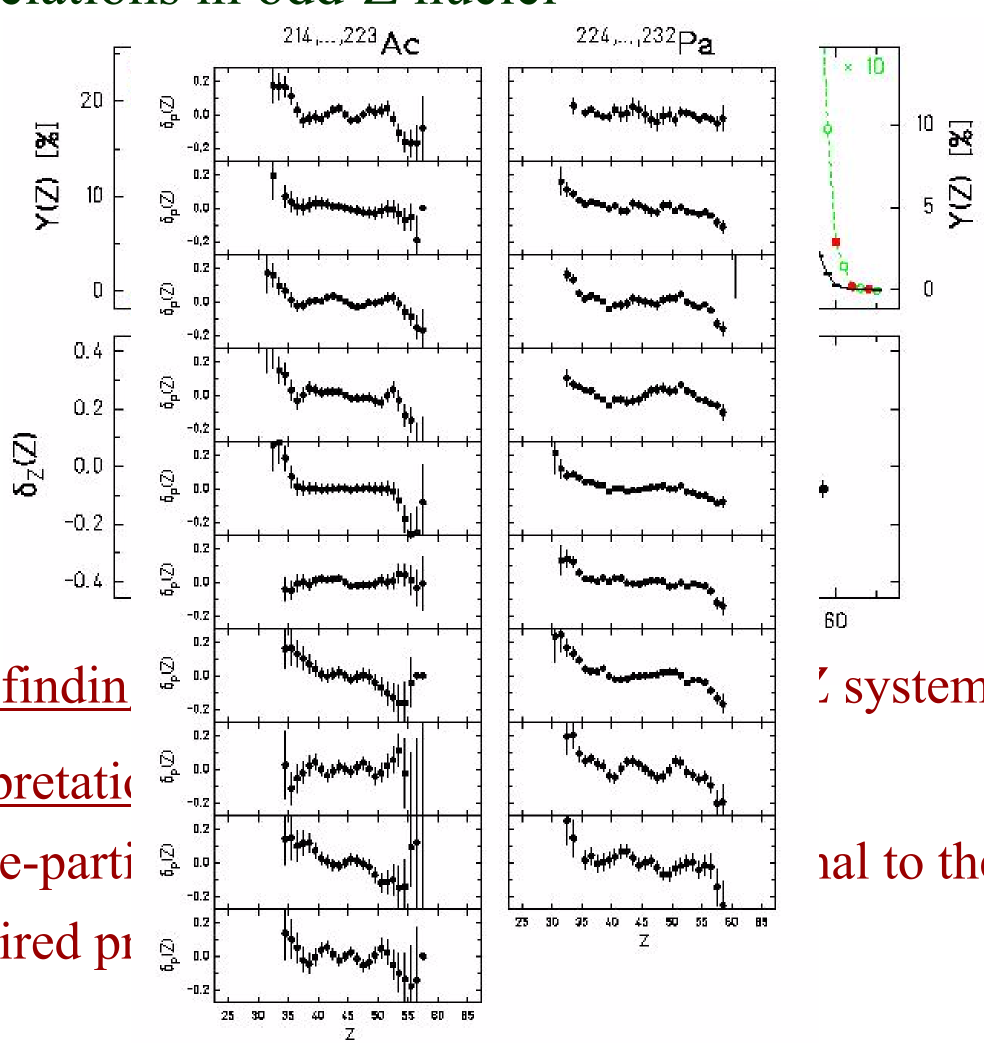


- New data: fixed mean charge of the heavy residue Z_H=54
- Previous knowledge: fixed mean mass of the heavy residue A_H=140 (N_H=82)

Measurements of the mass and charge distributions in coincidence are required

Fission experiments with RNB

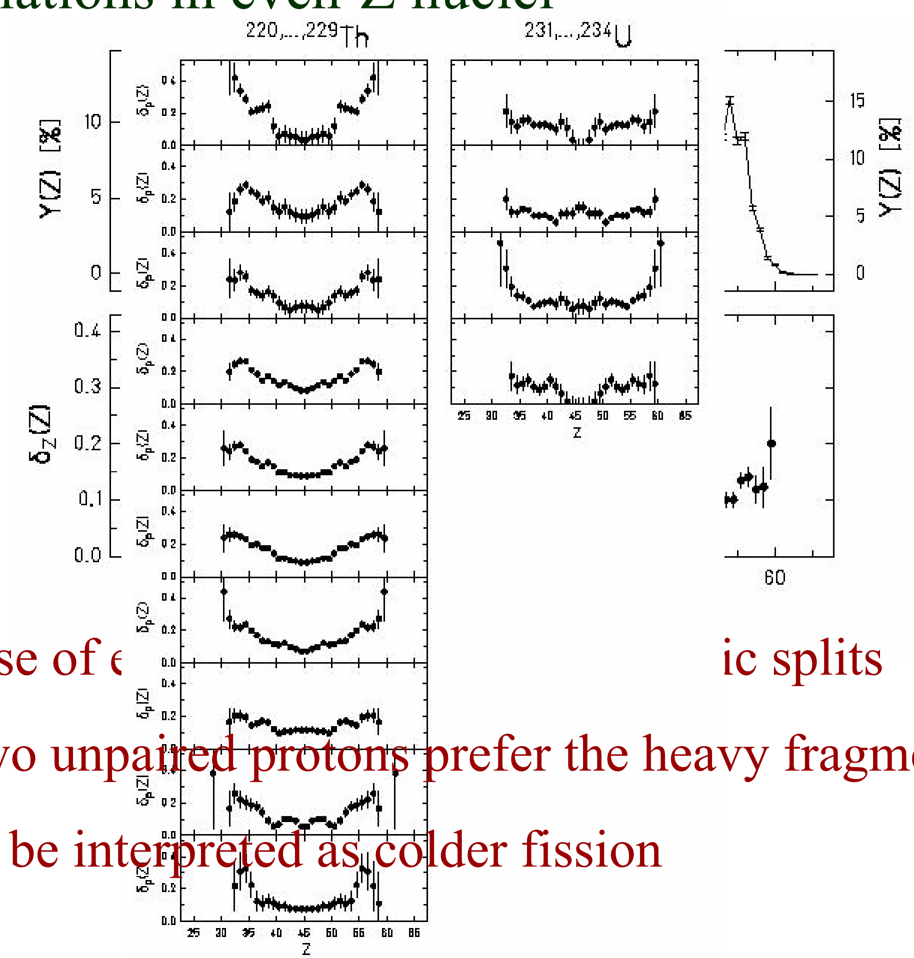
Pairing correlations in odd-Z nuclei



- New findin … systems
- Interpretati …
  single-parti … al to the volume
  unpaired pı …

Fission experiments with RNB

Pairing correlations in even-Z nuclei



- Increase of e … ic splits
- The two unpaired protons prefer the heavy fragment
- Not to be interpreted as colder fission

Fission model

Description of the mass and charge distribution of fission residues

$$Y(\eta) \propto \exp\left\{2\sqrt{a\left[E^* - U(\eta)\right]}\right\} \longrightarrow \rho(E^*)\exp\left\{-\frac{(\eta-\eta_{cn}/2)^2}{2\sigma_\eta^2}\right\}$$

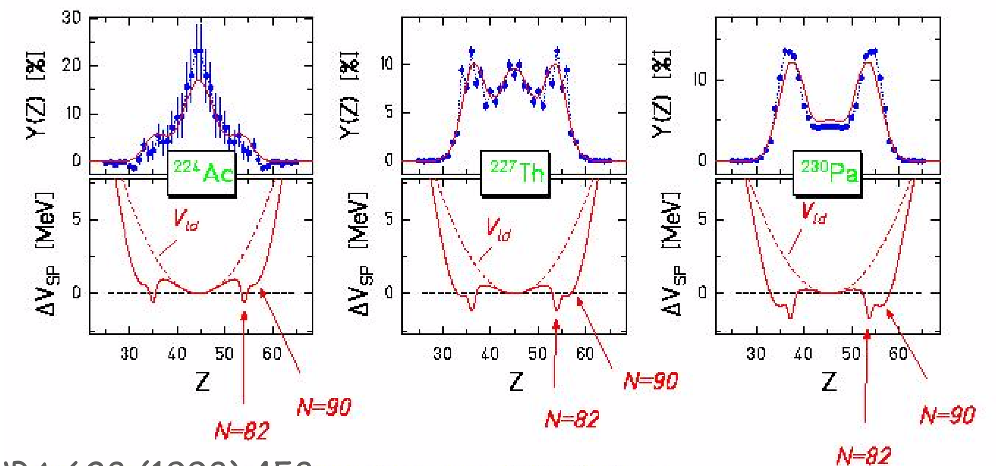
$$2\sigma_\eta^2 = \frac{T}{C_\eta}$$

$$\begin{aligned} U(\eta) &= U_{mac}(\eta) \\ &+U_{sh,1}(\eta) + U_{sh,1}(\eta_{cn}-\eta) \\ &+U_{sh,2}(\eta) + U_{sh,2}(\eta_{cn}-\eta) \end{aligned}$$

η = A (mass split) or N/Z

C_η = stiffness of the potential

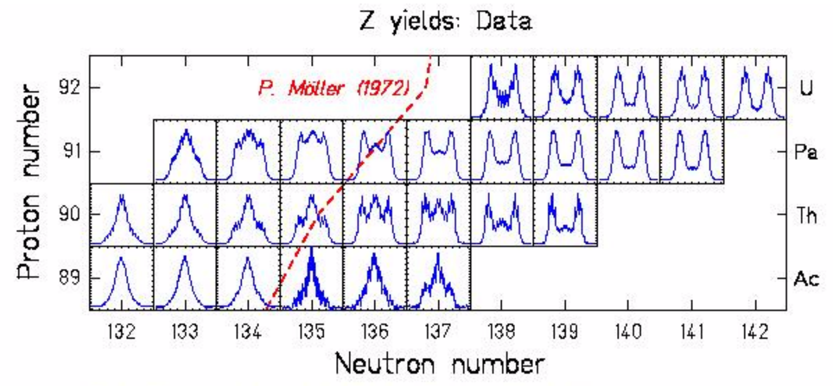
$$U_{mac}(\eta) = C_\eta(\eta - \eta_{cn}/2)^2$$

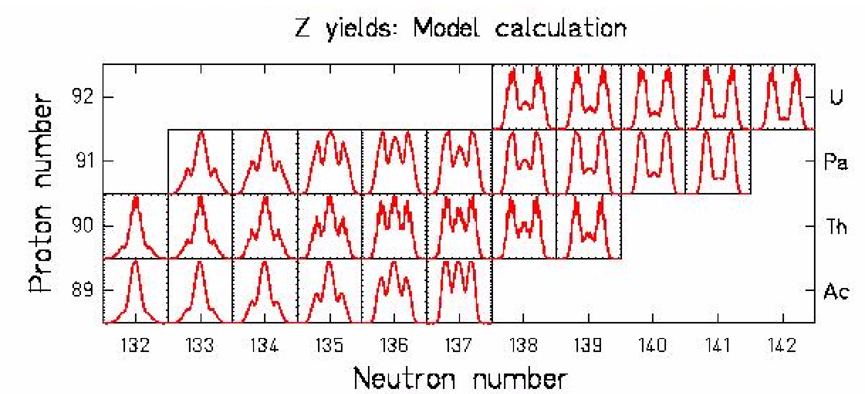


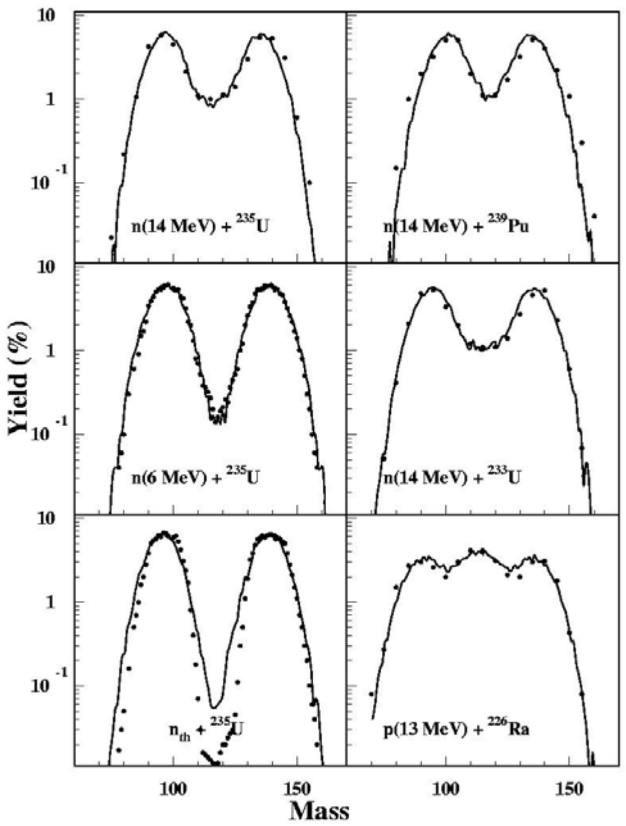
J. Benlliure et al., NPA 628 (1998) 458

Fission model

Benchmark of model calculations







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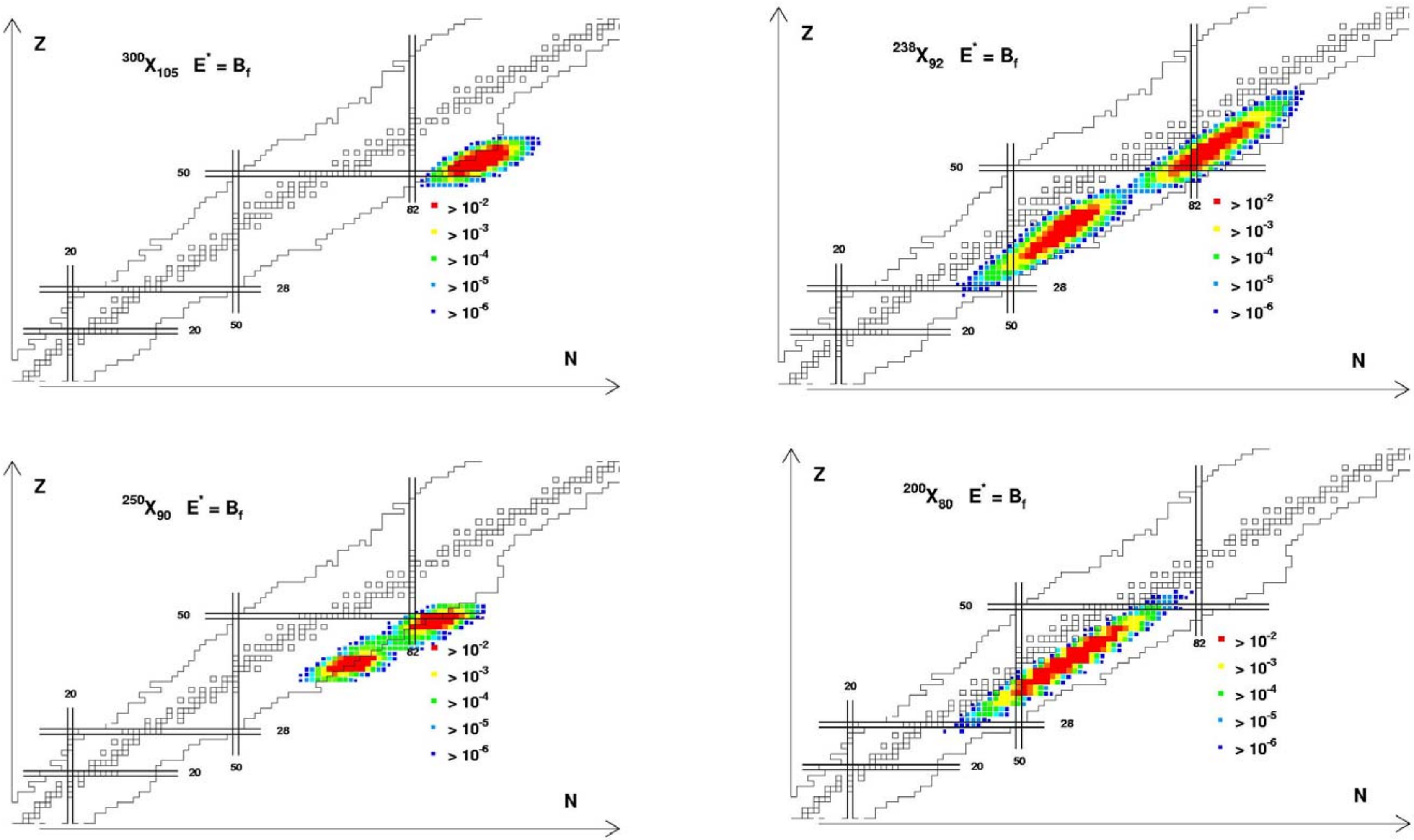
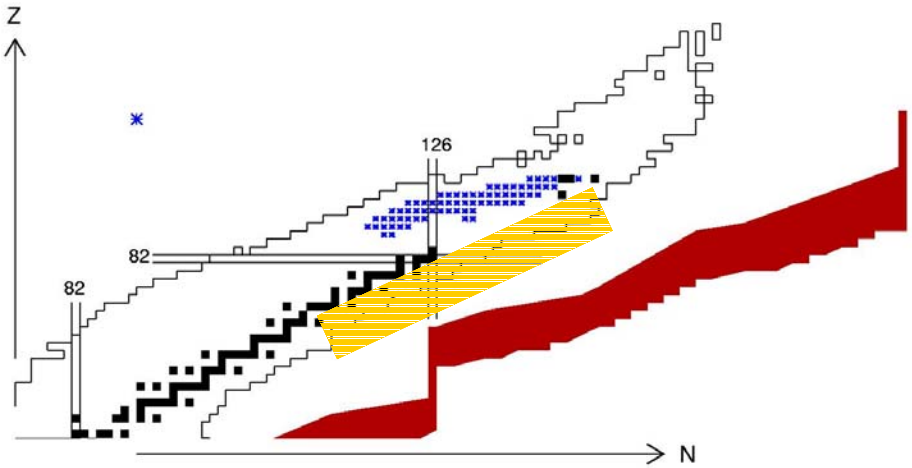
Fission model



Investigations at GSI

Fission of heavy-exotic nuclei:

- charge distributions
  - ✓ measurements
  - ✓ fission model



- fission probability around closed shells

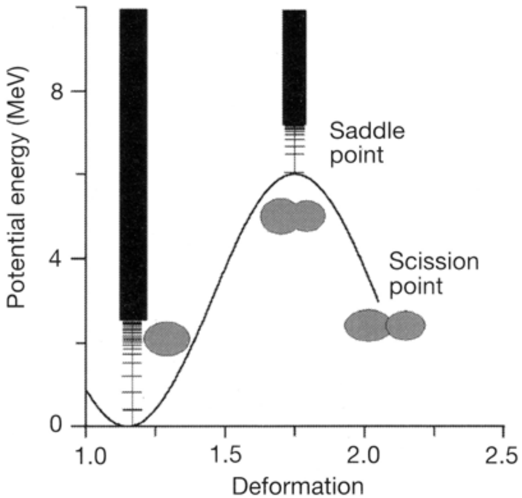
- production of heavy neutron-rich isotopes in projectile fragmentation

- future projects

Fission probability

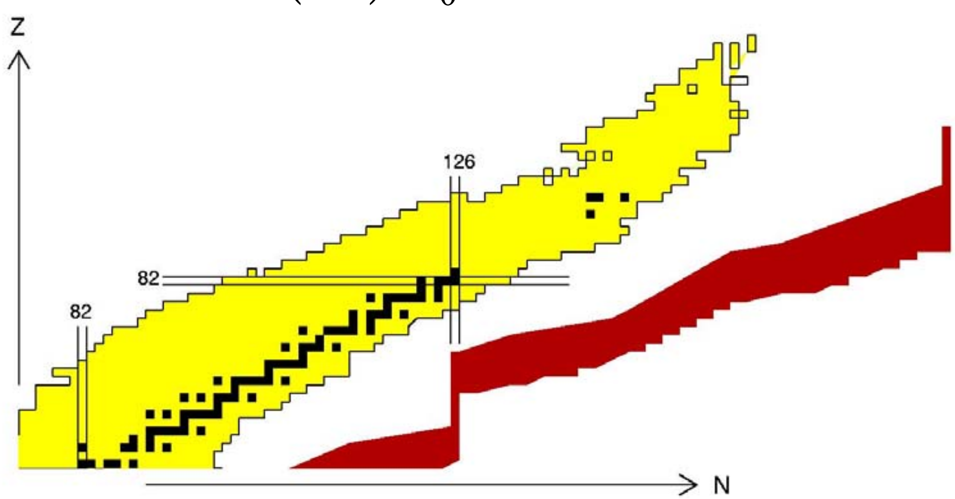
The fission probability is governed by the number of states above the fission barrier:

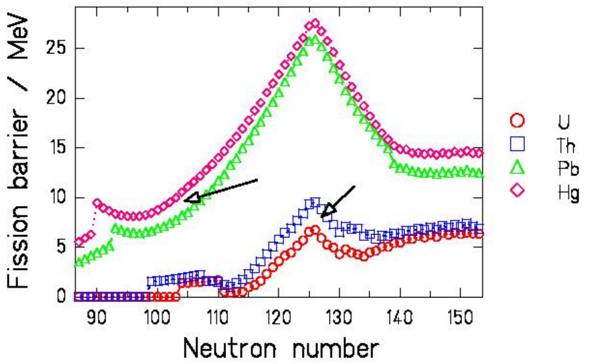
- ✓ fission barriers
- ✓ intrinsic excitations
- ✓ collective excitations
- ✓ shell effects and pairing corrections



$$\Gamma_f = \frac{1}{2\pi\rho\left(E^*\right)} \int_0^{E^*-B_f} \rho_{saddle}(E)\mathrm{d}E$$

Stalibilization against fission due to shell closure around N=126 and Z=82





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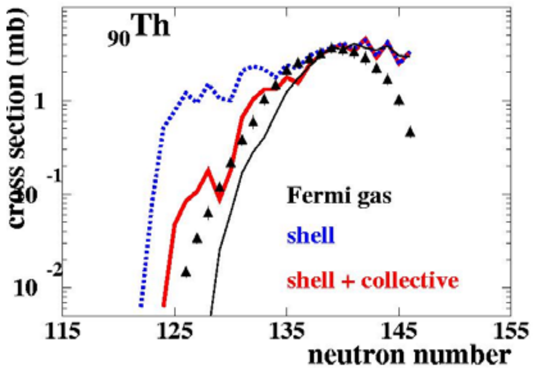
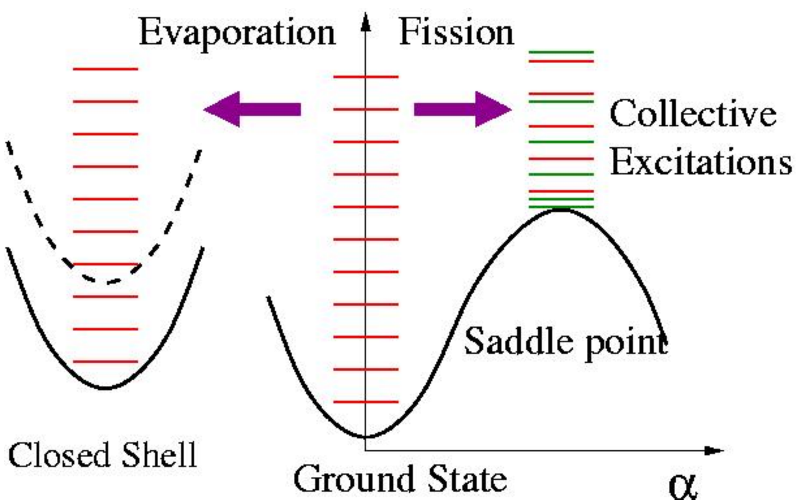
Fission probability

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



Measured isotopic distributions of heavy neutron-deficient isotopes do not show any enhanced production around N=126



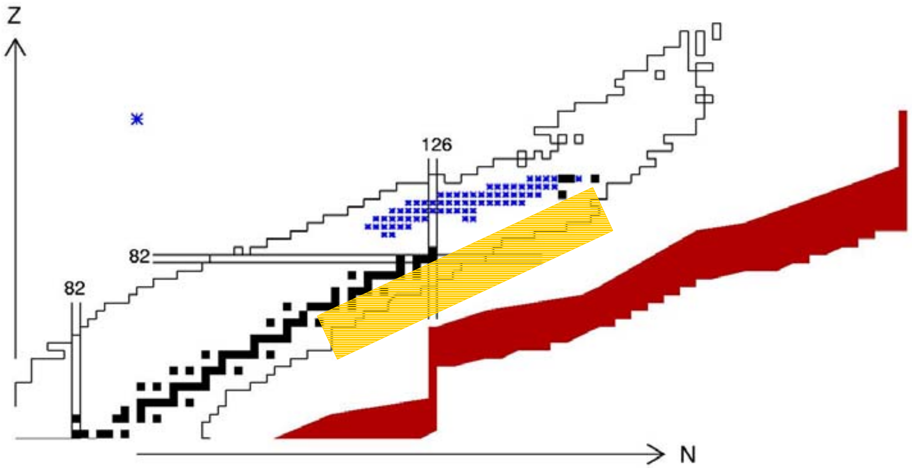
Shell effects are compensated by collective excitations

A.R Junghans et al., NPA 629 (1998) 635

Investigations at GSI

Fission of heavy-exotic nuclei:

- charge distributions
  - ✓ measurements
  - ✓ fission model
- fission probability around closed shells



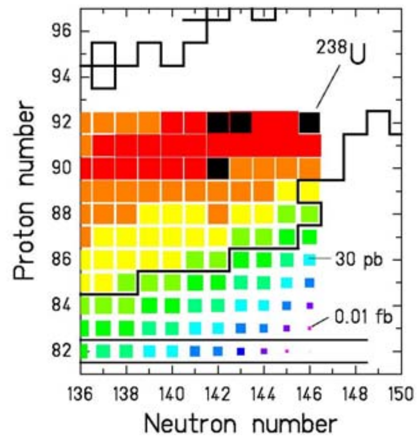
- production of heavy neutron-rich isotopes in projectile fragmentation
- future projects

Production of heavy neutron-rich isotopes

Cold-fragmentation reactions

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

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

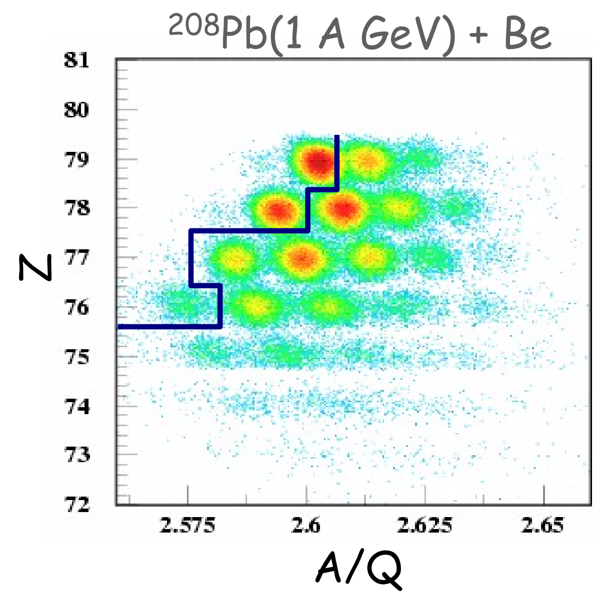


Peripheral heavy-ion reactions at relativistic energies:

✓ large fluctuations in N/Z and excitation energy

Proton-removal channel:

✓ only protons are abraded and the induced excitation energy remains below the particle emission threshold



More than 15 new neutron-rich isotopes in the A=200 region

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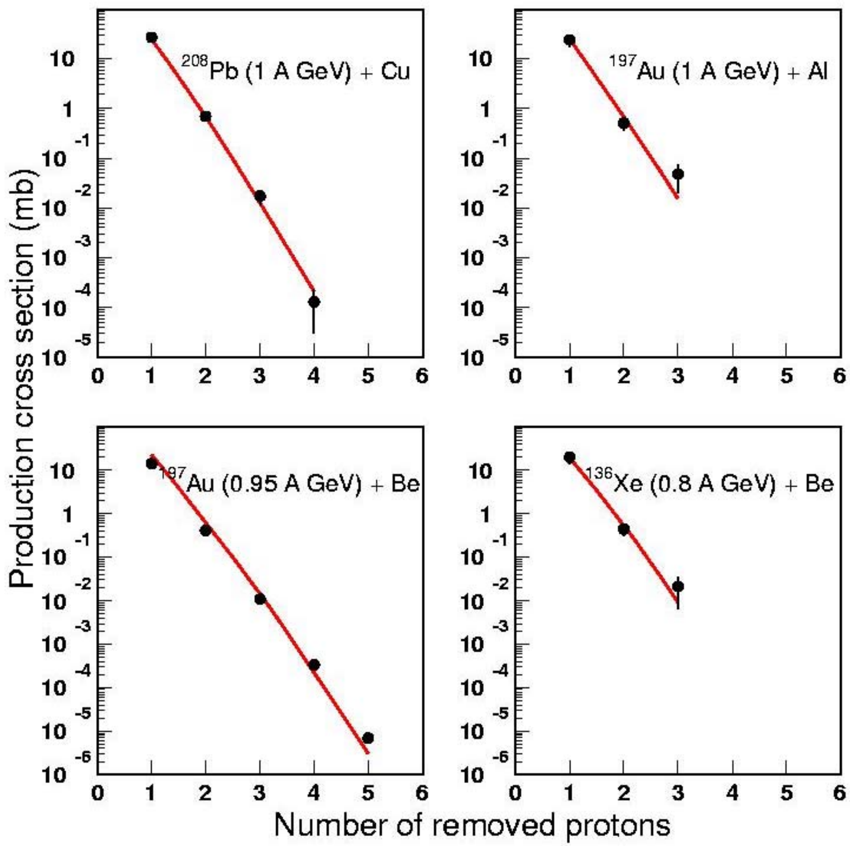
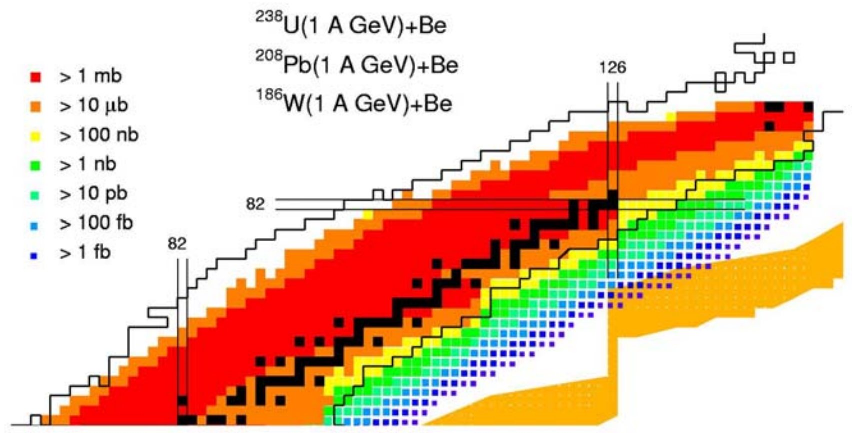
Production of neutron-rich isotopes

Benchmark of model calculations



Estimated production of heavy neutron-rich isotopes in cold-fragmentation reactions



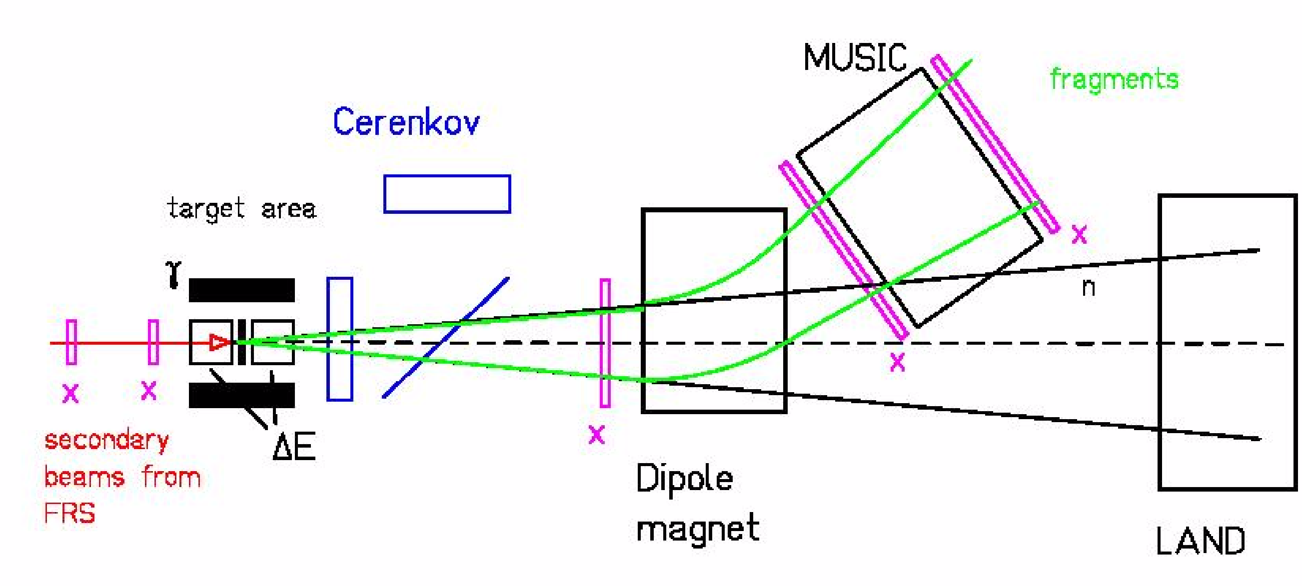
J. Benlliure et al., Nucl. Phys. A660 (1999) 87

Future experiments

Future GSI facility + SuperFRS + advanced experimental setup for fission studies with relativistic RNB

charge + mass + neutrons

Music + dipole + Cerenkov + Land



Conclusions

A full description of the observed r-process abundances requires an improved understanding of fission. However, important progress has been done recently in both, experiments and model calculations.

- Experiments with exotic fissile nuclei allowed to measure the charge distributions of fission residues covering the transition between asymmetric and symmetric fission

- Semi-empirical model calculations providing a reliable description of mass and charge distributions of fission residues have been developed

- Experimental data proved the role of collective excitations in the fission probability

- Dedicated experiments have shown the important progress that can be made with future RNB facilities in the production of heavy neutron-rich nuclei approaching the r-process path in the mass region $150<A<240$

The new facilities and experimental setups will offer new opportunities to investigate fission of neutron-rich isotopes. In particular fusion reactions induced by neutron-rich projectiles will allow to approach the r-process end point.

Collaborators

K.-H. Schmidt, A. Heinz, A. R. Junghans, P. Armbruster, C. Böckstiegel, H.-G. Clerc, A. Grewe, A. Heinz, M. de Jong, J. Müller, M. Pfützner, S. Steinhäuser, B. Voss,

Gesellschaft fur Schwerionenforschung, Darmstadt, Germany

Institut fur Kernphysik, Technische Hochschule, Darmstadt, Germany

Universidad de Santiago de Compostela, Spain