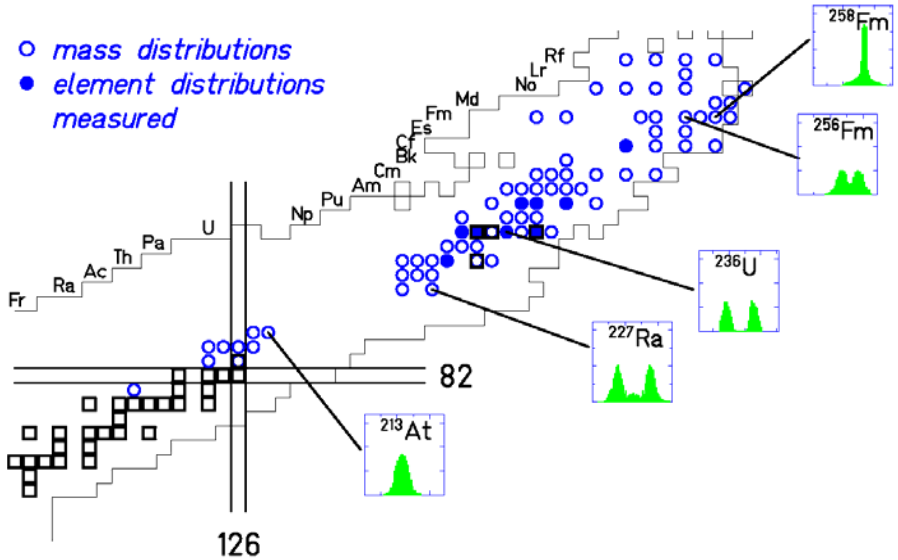
# Research on fission at GSI with applications to nuclear technology and astrophysics

*Karl-Heinz Schmidt, GSI Darmstadt*

# Previous experimental knowledge

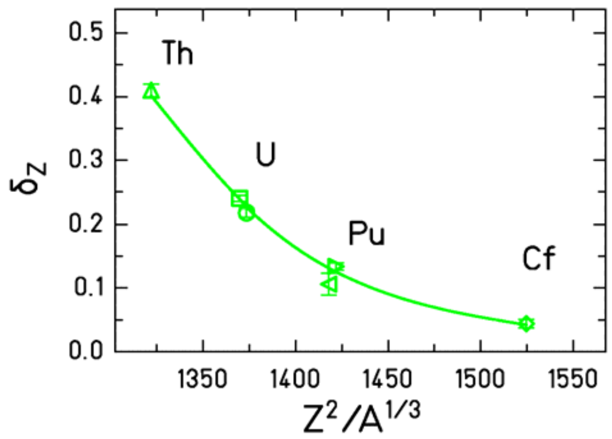
**Fission channels**

- variation with *E**
- variation with *A* and *Z* of the fissioning system



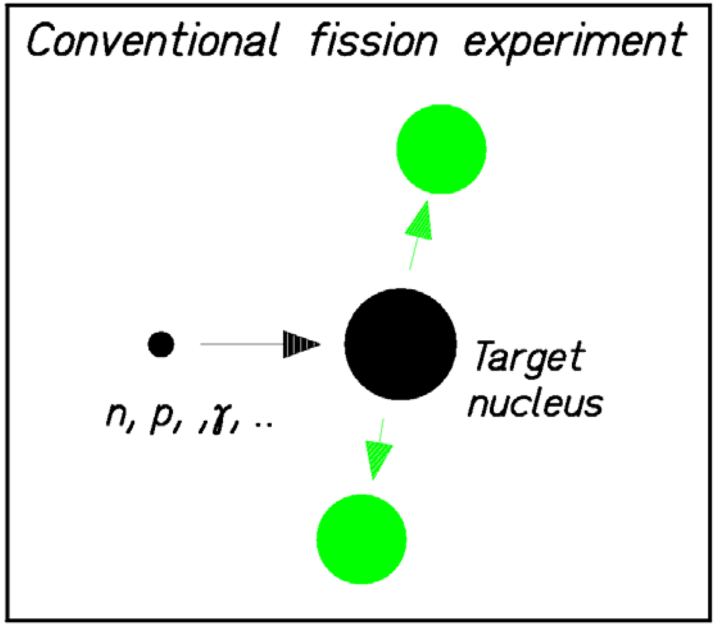

**Even-odd effect in the Z yields**

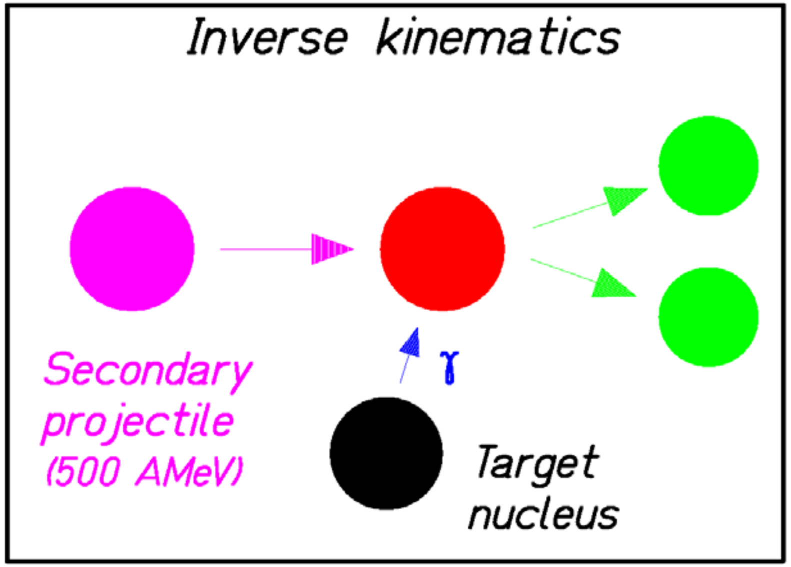
- variation with *E**
- variation with $Z^2/A^{1/3}$




**Neutron yields,**
**Kinetic energy,**

…




**Fission of target nuclei**

**Fission of projectile nuclei**

1. **Better means for detection by the high velocity of the products!**
2. **Short-lived nuclei accessible!**

## Experimental progress
## (overview on the different approaches)

# Methods for the detection of fission fragments

- discovery of fission (1939) ► *chemical identification in Z*
- kinetic energy of the fragments ► *ionisation chamber*
- cumulative yields (after ß decay) ► *gamma spectroscopy*
- ≈ $A_1$ and $A_2$ ► *double E, double ToF*
- elements *Z* ► *X rays*
- *A* and *Z* of the light fragments ► *Spectrographe (Lohengrin) + energy loss* (limited to target material with long half-lives and thermal neutrons)
- ***A* and *Z* ► in-flight identification *in inverse kinematics***
- **$Z_1$ and $Z_2$ ► in-flight identification *in inverse kinematics***
- ***A* and *Z* ► high-resolution mass measurement (*traps*), normalisation?**

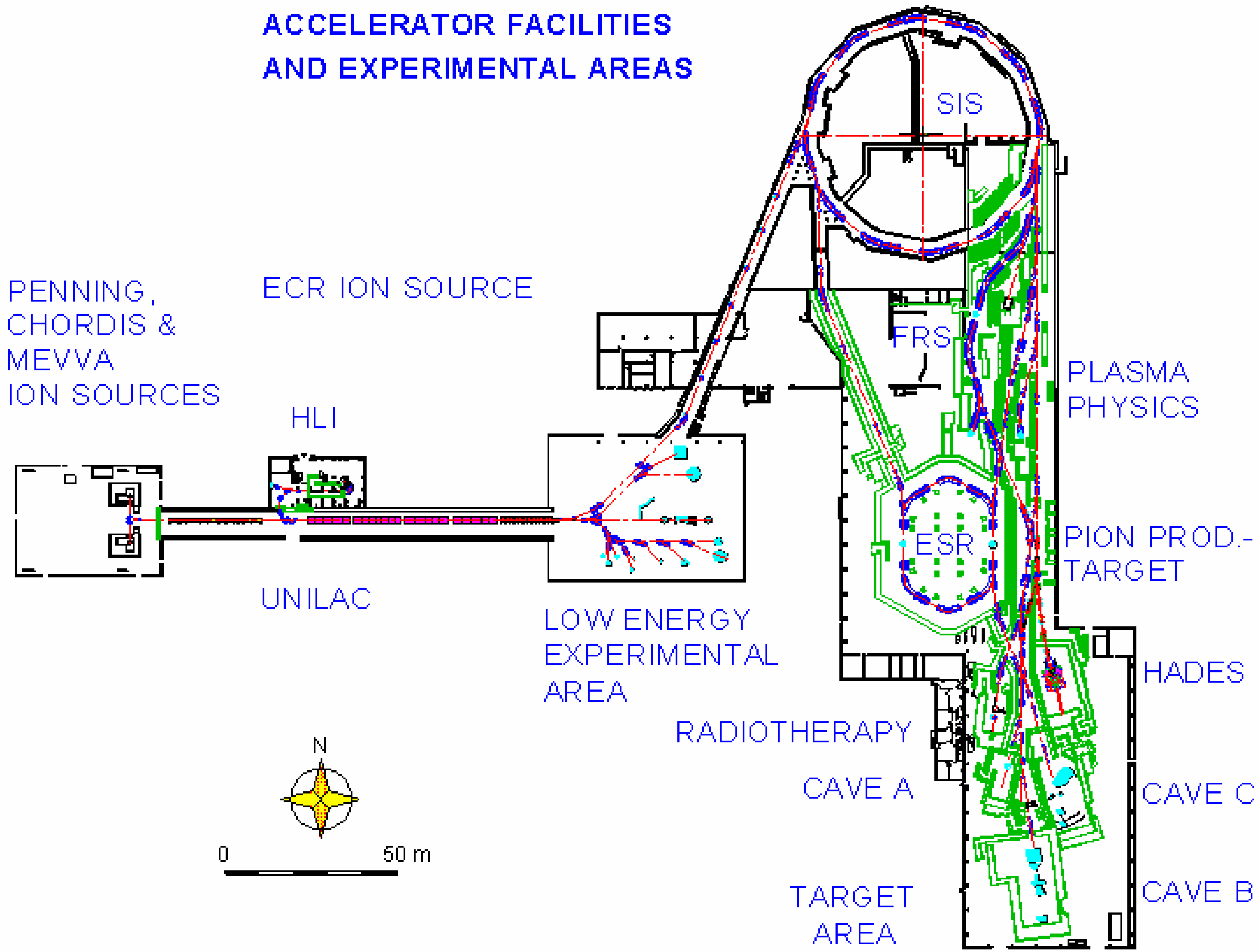
# Choice of the fissionning system

- Primordial nuclides ($^{238}U$, $^{235}U$, $^{232}Th$) ► *target*
- Fission reactors (neutron capture - ß) ► *target* (long-lived nuclides)
- Nuclear explosions (neutrons capture – ß) ► *target* (long-lived nuclides)
- Products of direct reactions ► *target* (long-lived nuclides)
- **Projectile fragmentation (*A* < 238) ► *beam* (half-life > 100 ns)**

# Excitation mechanisms:

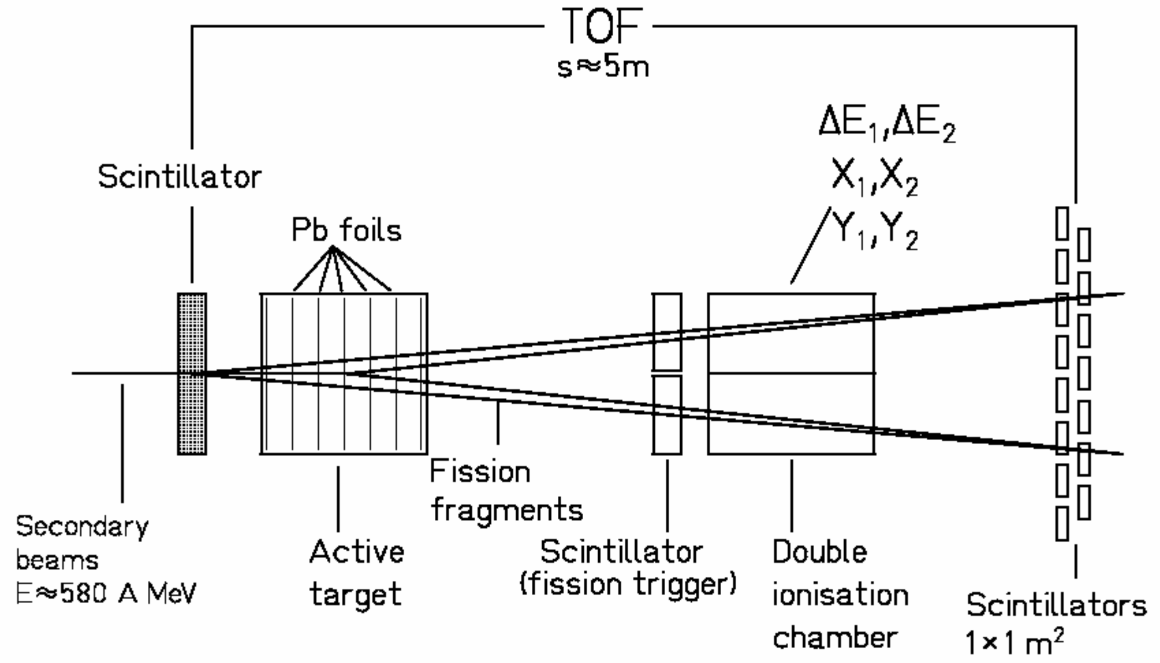
- neutrons (thermal, fast, mono energetic)
- electrons
- photons (bremsstrahlung, mono energetic)
- protons and other charged particles (fusion, direct reactions)
- spontaneous fission
- **electromagnetic and nuclear interaction *in inverse kinematics***
    - nuclear target (GSI) -> distribution in $E^*$ (≈ RGD in e.m. and $E^* \uparrow$ in nucl.)
    - electron collider – ions (FAIR) -> well-defined $E^*$

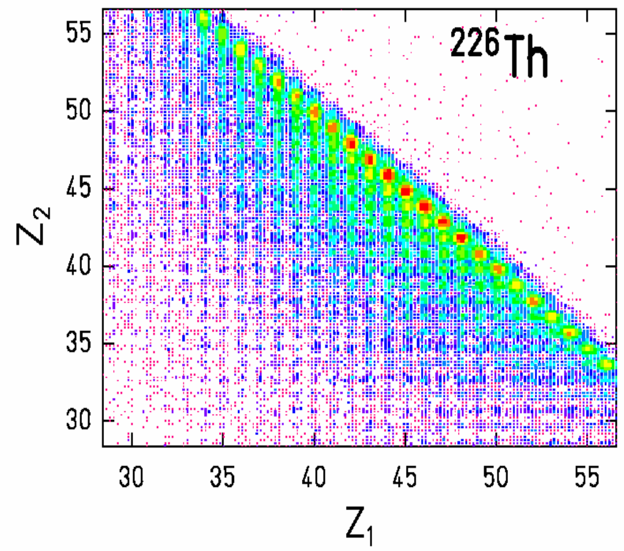
# The installations of GSI actually used for fission studies


ACCELERATOR FACILITIES
AND EXPERIMENTAL AREAS
SIS
PENNING,
CHORDIS &
MEVVA
ION SOURCES
ECR ION SOURCE
HLI
FRS
PLASMA
PHYSICS
ESR
PION PROD.-
TARGET
UNILAC
LOW ENERGY
EXPERIMENTAL
AREA
HADES
RADIOTHERAPY
CAVE A
CAVE C
N
0
50 m
TARGET
AREA
CAVE B

## 1. Z identification of <u>both</u> fission fragments
## (Applicable to short-lived radioactive fissile systems)

# Double ionisation chamber – time-of-flight wall

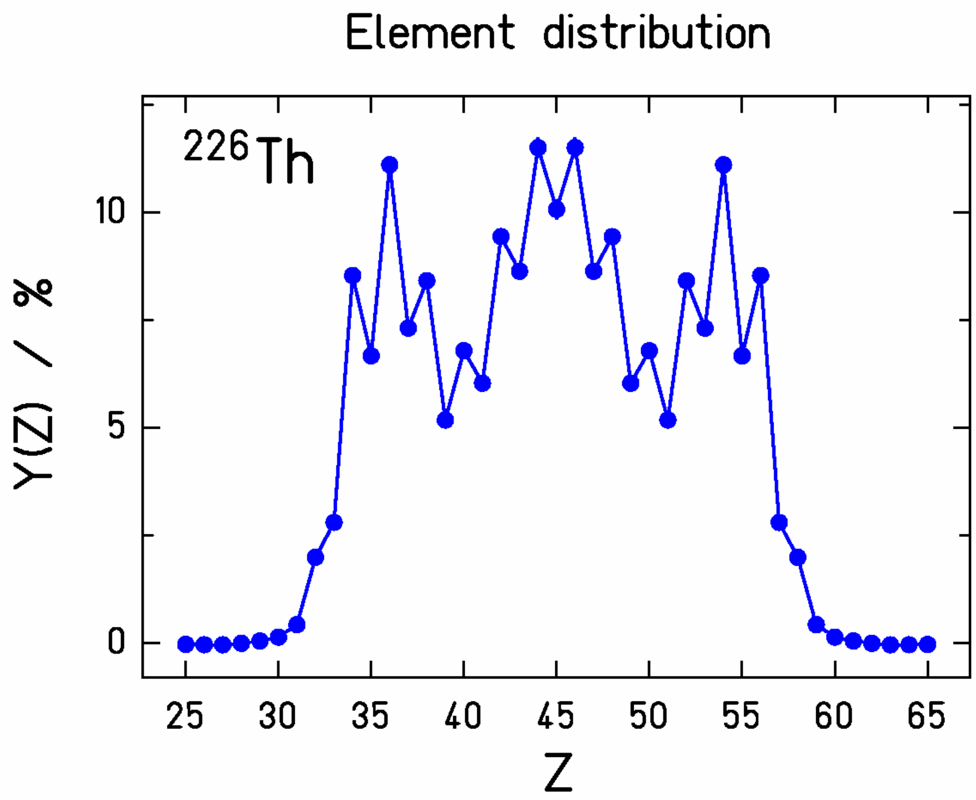



**The detectors**

**Identification of both fragments in Z**

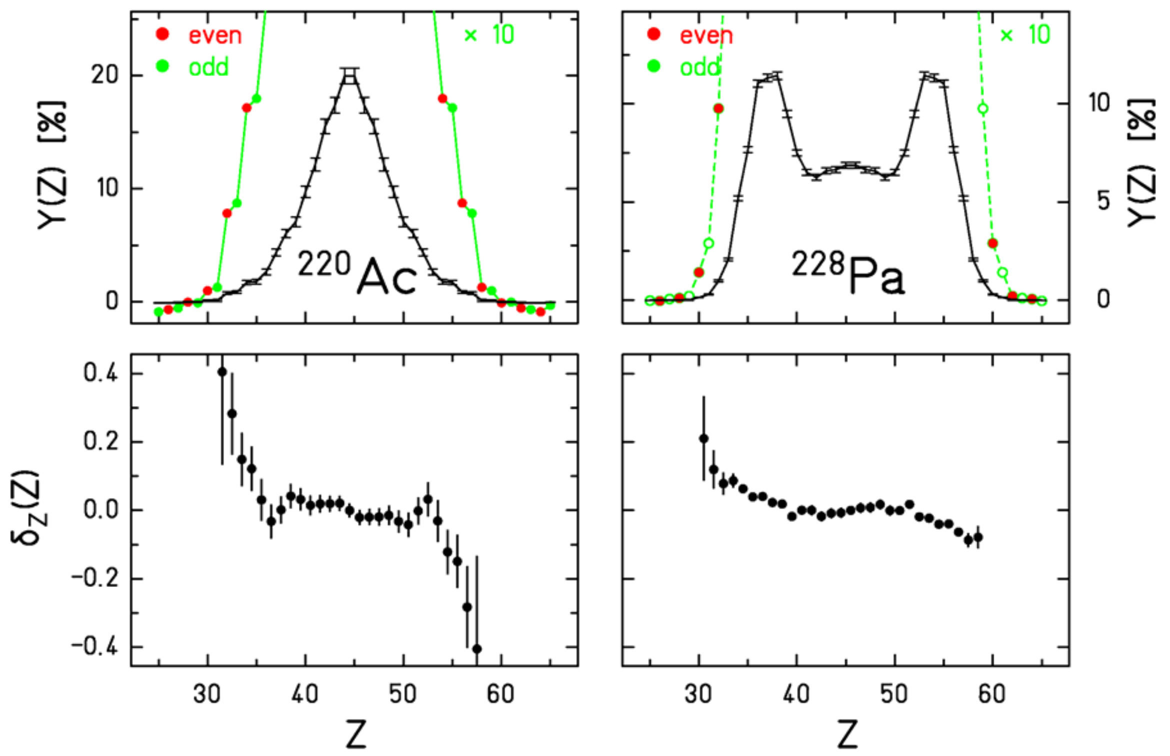
# Z distributions




**Fission after excitation of the giant dipole resonance.**

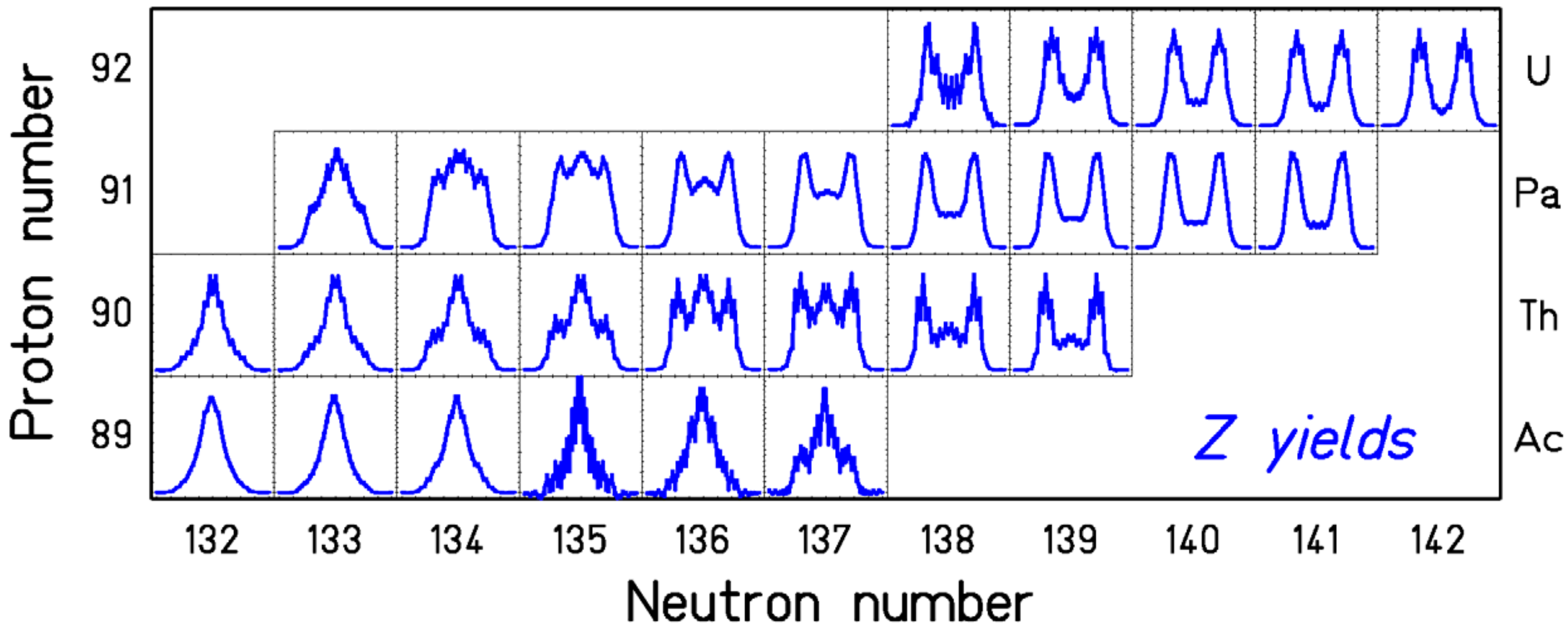
**($t_{1/2}$ of $^{226}$Th = 31 minutes !)**

# Appearance of an even-odd effect for odd-*Z* fissioning nuclei




**Statistical explication by the phase space available for one individual proton in the two fragments at scission (*g* ~ *A*).**

# Bimodal fission of the neutron-deficient actinides

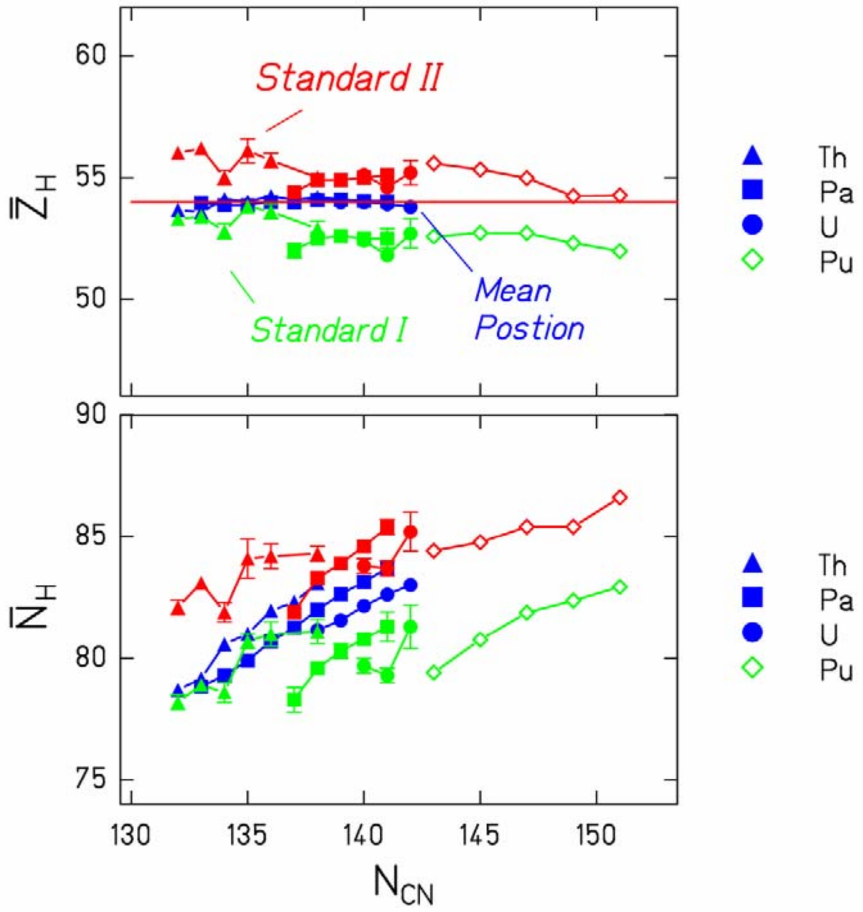



**$Z$ distributions after excitation of the GDR ($E^*$ ≈ 11 MeV)**

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

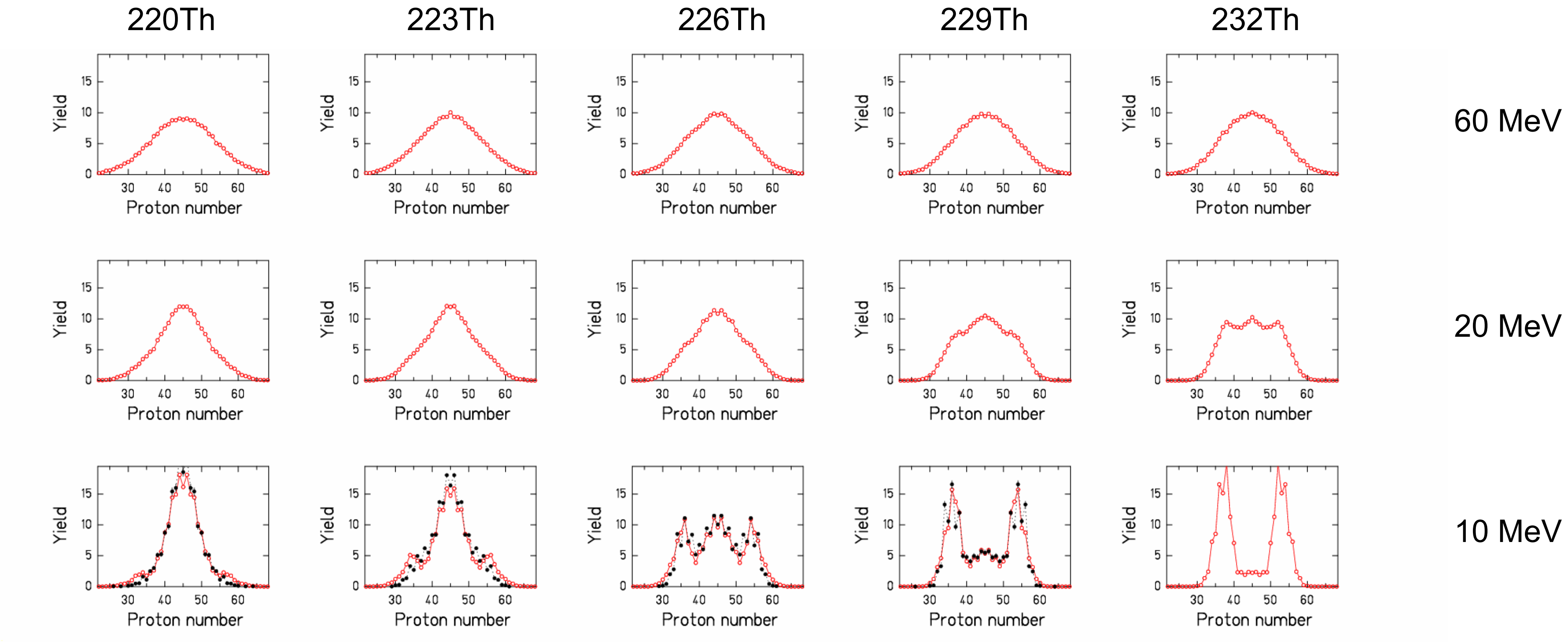
**General view on the experimental results on fission of light actinides by use of secondary beams of radioactive nuclides.**

# Stability of the position of the heavy group at $Z = 54$




**Surprising, since neutron shells are believed to be decisive.**

# Evolution of the fission *Z* distribution as a function of *A* and *E**




**red**: PROFI calculations, **black:** experimental data (K.-H. Schmidt et al., NPA 665 (2000) 221)

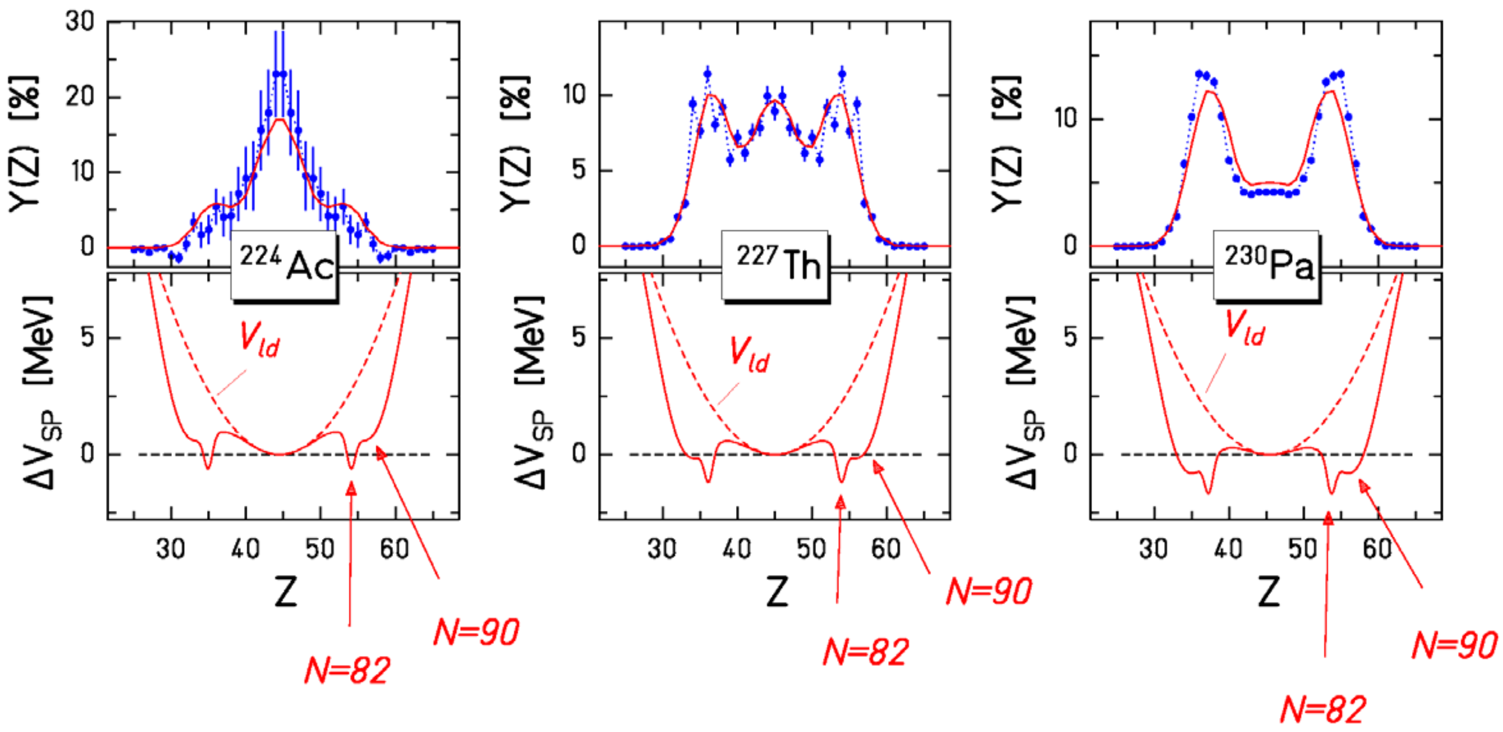
Ingredients of the fission model: Level densities, assumptions on dynamic, adjusted potential.

Macroscopic potential: property of the compound nucleus, favours symmetric fission.

Shells: properties of the fragments (2-center shell model), favour fission channels; disappear with *E**.

**Nuclide distribution: superposition of fission from different nuclei at different *E**.**

# Variation of potential at outer saddle



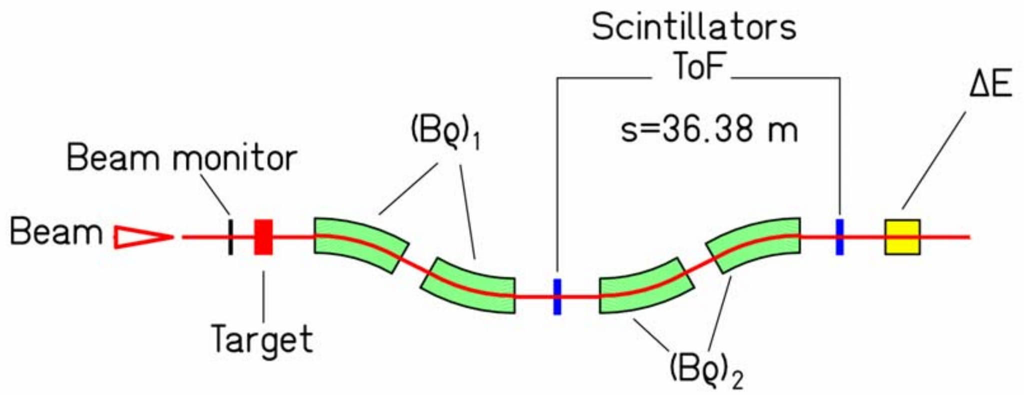

**Transition from single-humped to double-humped distributions investigated experimentally** (K.-H. Schmidt et al., NPA 665 (2000) 221) **and explained by macroscopic (CN) and microscopic (nascent fragments) properties of the potential-energy landscape near saddle**

**Essential ingredient: Vanishing of shell effects with increasing excitation energy.**

(J. Benlliure et al., Nucl. Phys. A 628 (1998) 458)**.**

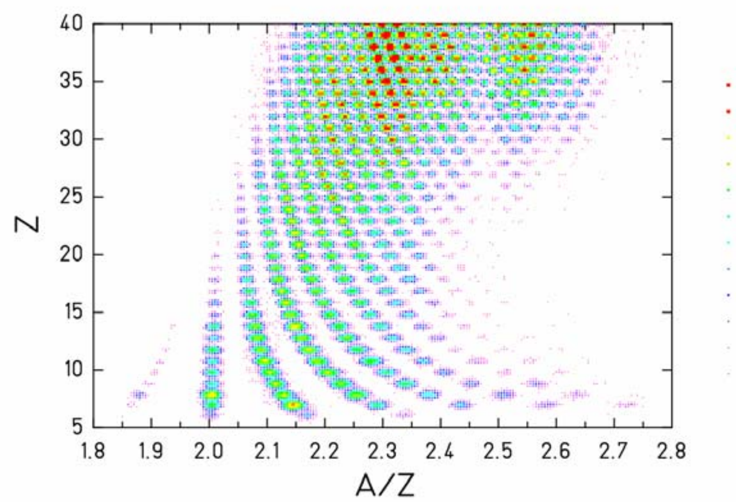
# 2. Full identification of <u>one</u> fission fragments in *Z* <u>and</u> *A*

# The fragment separator as a magnetic spectrometer




**Spectrometer**

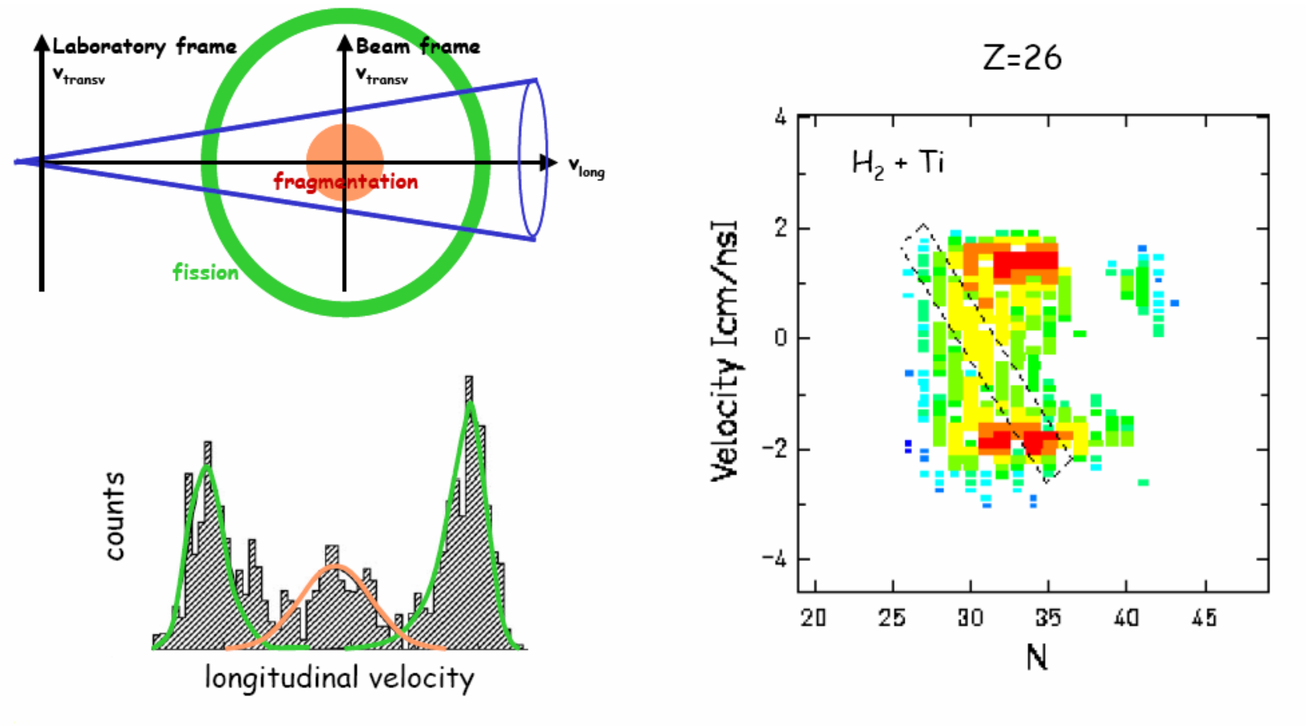
$^{238}U$ (1A GeV) + $^{1}H$




**Nuclide identification**
(M. V. Ricciardi)

Resolution $p/\Delta p \approx 2000$.
Acceptance $\Delta B\rho / B\rho = 3\%$ and $\Theta_{max}$=15 mr.
Identification in $Z$ and $A$ by magnetic deflection, tracking, *ToF* et $\Delta E$.
Basic equations: $B\rho = m_0 \boldsymbol{A} c \beta \gamma / (e \boldsymbol{Z})$ et $\Delta E \propto \boldsymbol{Z}^2 / v^2$

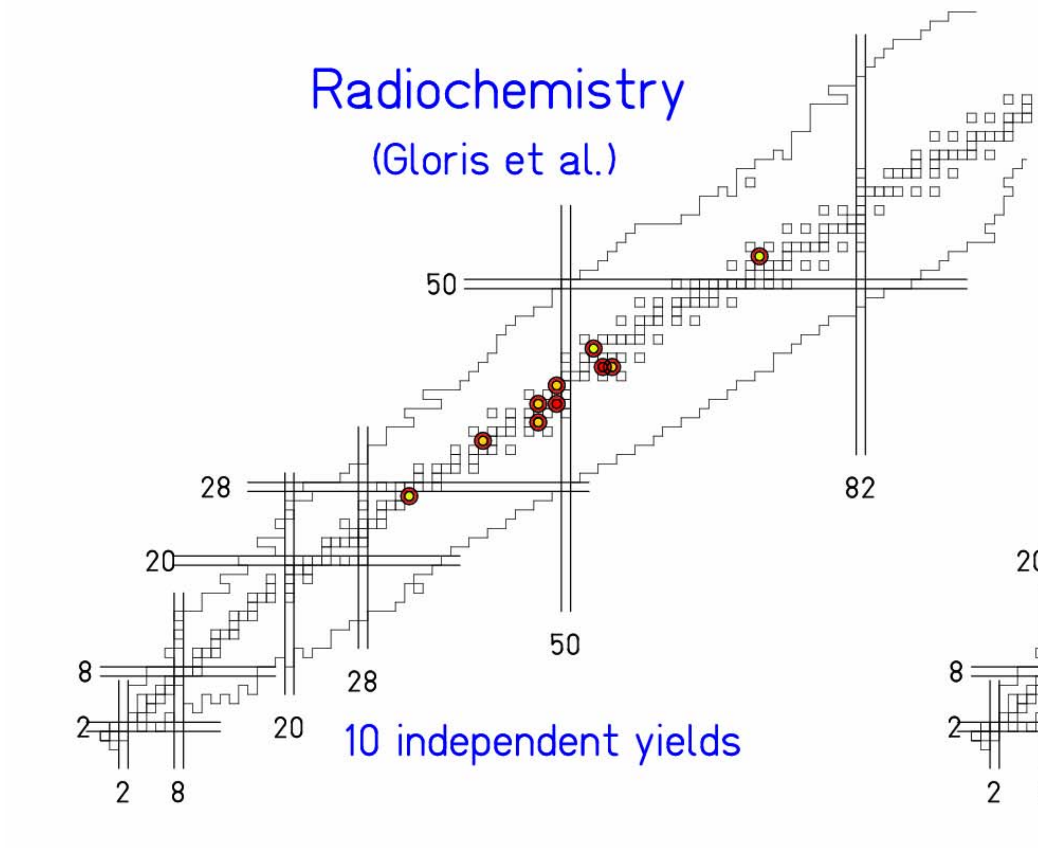
# Kinematical signature of fission

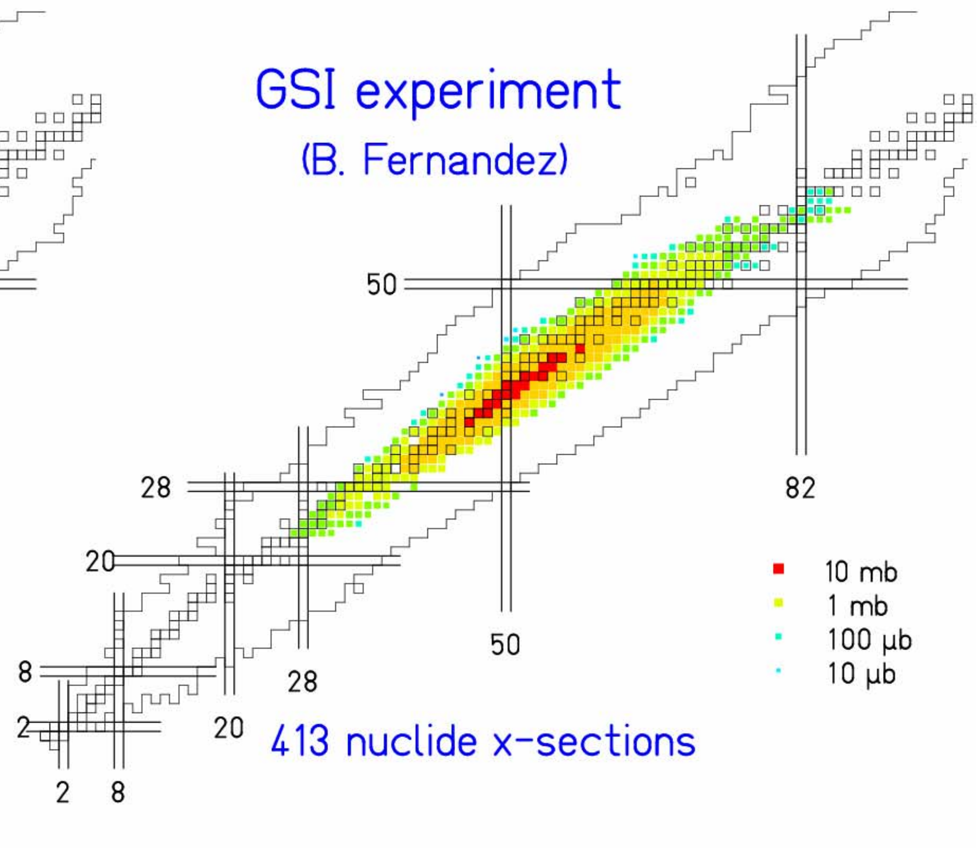



The Coulomb repulsion of the fission fragments causes a double-humped profile in the measured velocity distribution.

# Experimental progress by inverse-kinematics method

**Example: Fission of lead induced by ≈ 500 MeV protons**

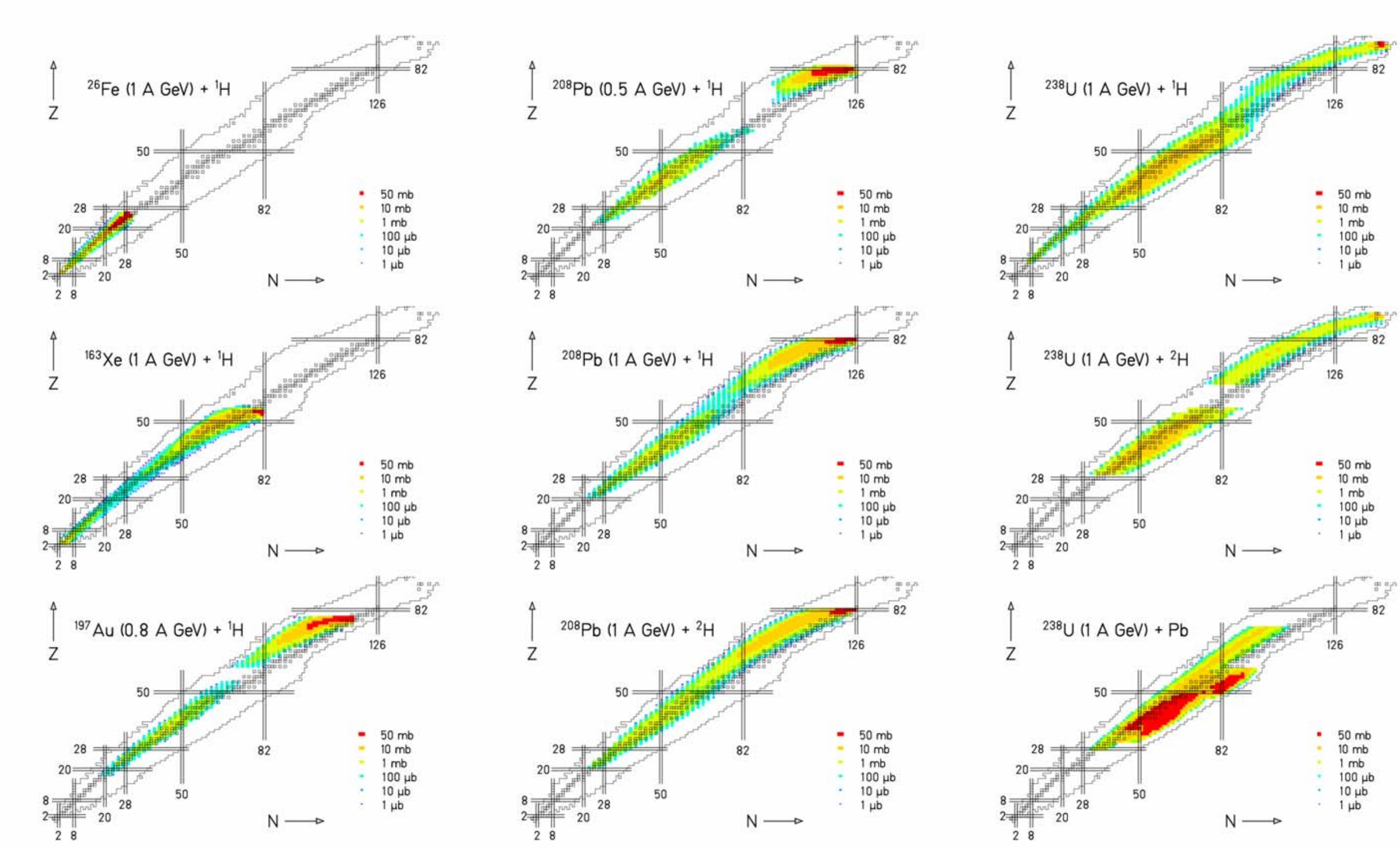



**protons (553 MeV) on lead**

**$^{208}$Pb (500 A MeV) on hydrogen**

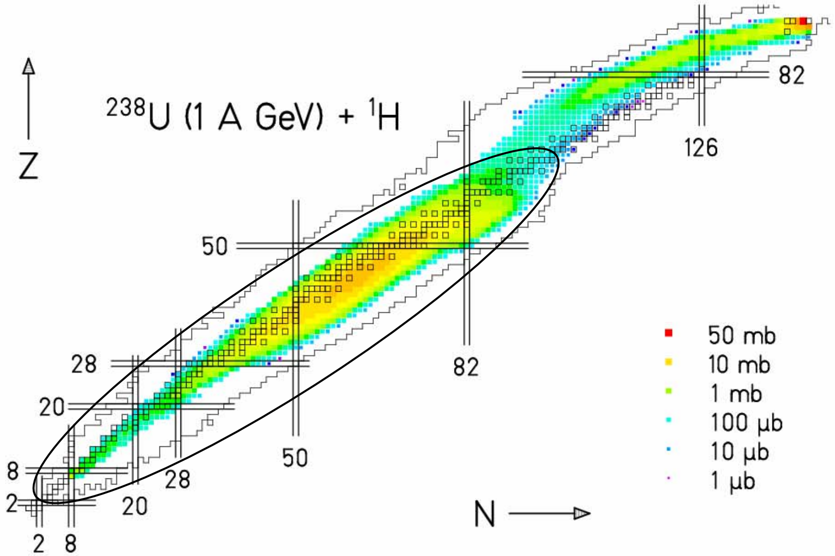
# Some systems investigated (7732 data points)

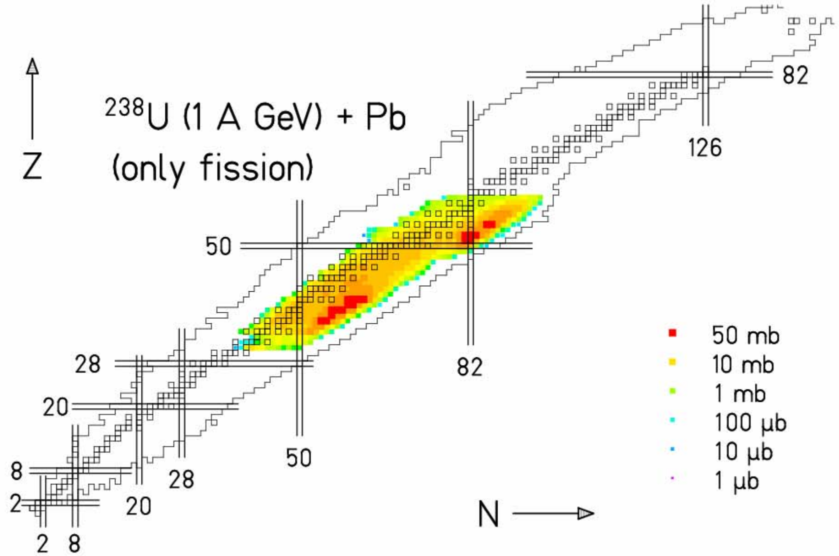


# List of systems investigated

| | |
|---|---|
| $^{56}$Fe (0.3 to 1.5 *A* GeV) + $^{1}$H | C. Villagrasa, PhD thesis<br>P. Napolitani et al., PRC 70 (2004) 054607 |
| $^{136}$Xe(0.2 to 1 *A* GeV) + $^{1,2}$H | P. Napolitani, PhD thesis<br>L. Giot, in preparation<br>M. Fernandez, in preparation |
| $^{197}$Au (0.8 *A* GeV) + $^{1}$H | F. Rejmund et al., NPA 683 (2001) 540<br>J. Benlliure et al., NPA 683 (2001) 513 |
| $^{208}$Pb (1 *A* GeV) + $^{1,2}$H | T. Enqvist et al., NPA 686 (2001) 481<br>T. Enqvist et al., NPA 703 (2002) 435<br>A. Kelić et al., PRC 70 (2004) 064608 |
| $^{208}$Pb (0.5 *A* GeV) + $^{1}$H | B. Fernandez et al., NPA 747 (2005) 227<br>L. Audouin et al., arXiv-nucl-ex/0503021 |
| $^{238}$U (1 *A* GeV) + $^{1,2}$H | M. V. Ricciardi et al., arXiv-nucl-ex/0508027<br>M. Bernas et al., NPA 725 (2003) 213<br>M. Bernas et al., submitted<br>J. Taieb et al., NPA 724 (2003) 413<br>J. Pereira, PhD thesis<br>E. Casarejos, PhD thesis<br>P. Armbruster et al., PRL 93 (2004) 212701 |
| $^{238}$U (1 *A* GeV) + Pb | T. Enqvist et al., NPA 658 (1999) 47 |

# Comparison of two systems

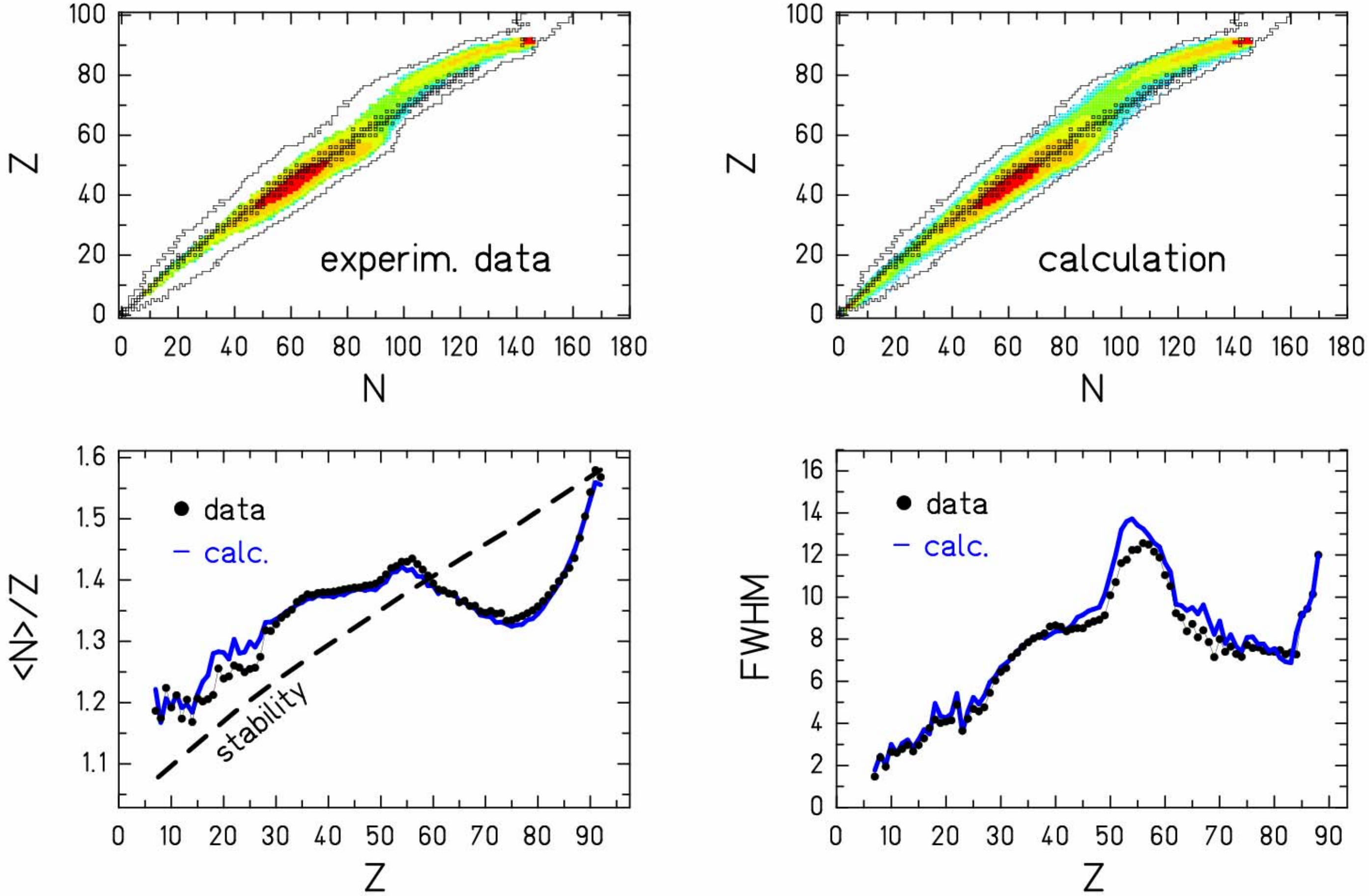


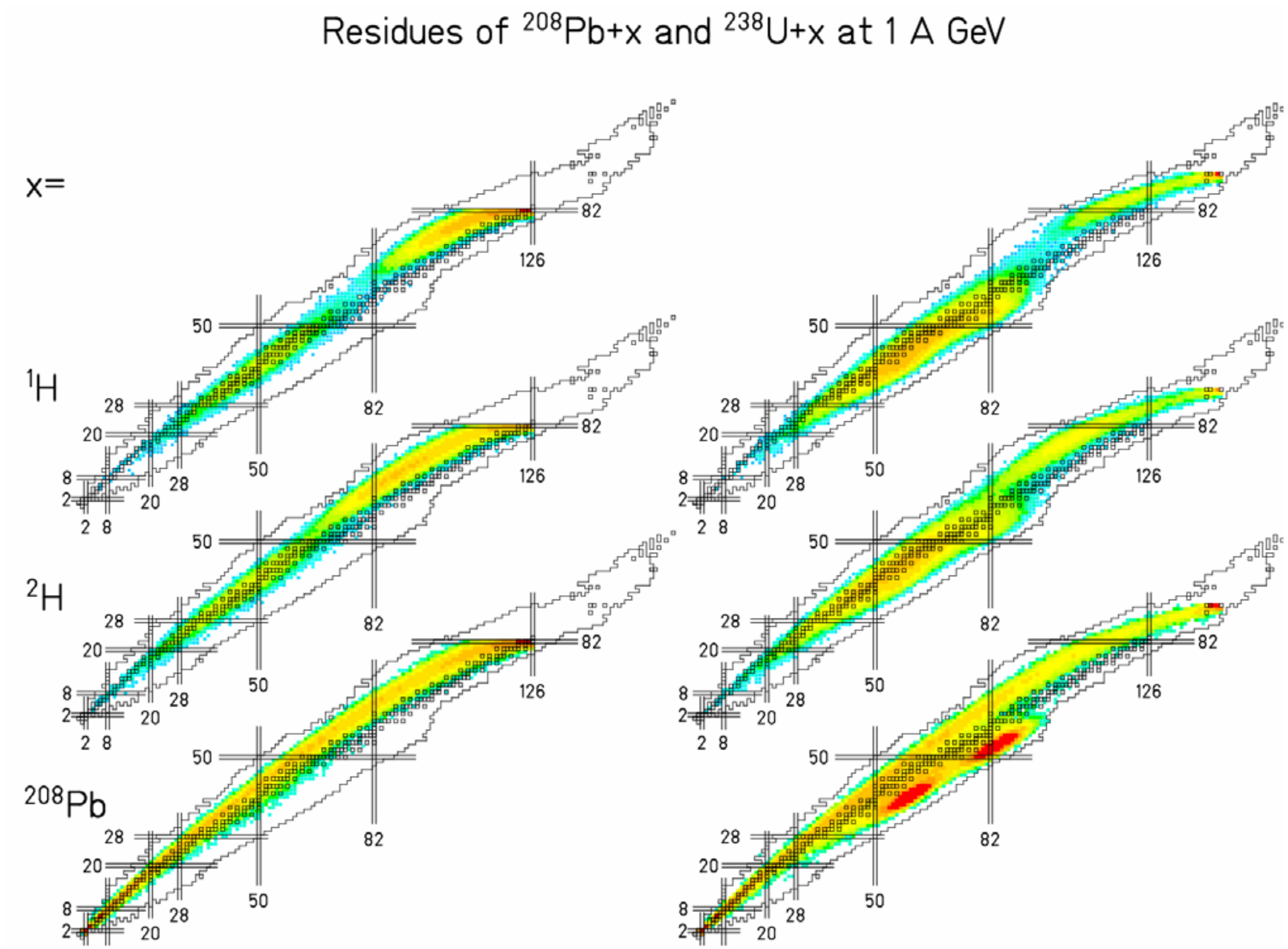

**Fission of $^{238}$U induced in a hydrogen and a lead target:**

**Very different nuclide distributions.**

# Reproduction of $^{238}$U (1 *A* GeV) + $^{1}$H



# Systematics of model calculations

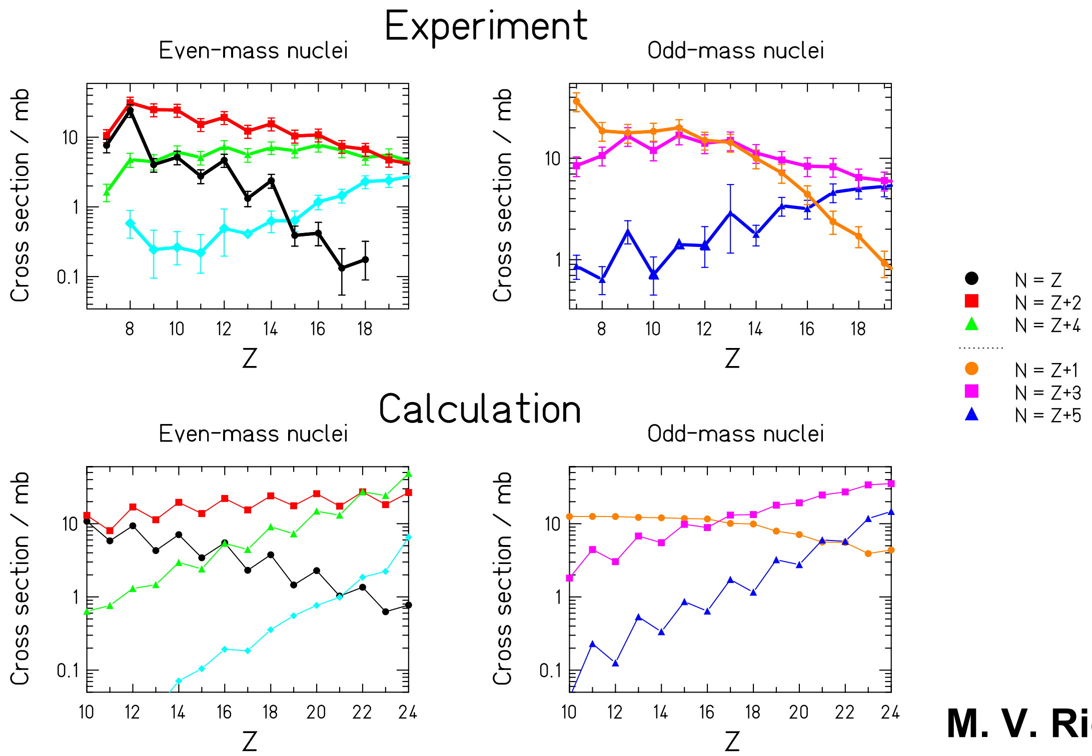



**Very different isotopic distributions for different projectile-target combinations!**

**Experimental data are well reproduced.**

# Even-odd effect of very light fragments

**Observation in high-energy reactions** (*systematically studied at GSI*) linked to the phase transition liquid – super fluid in the evaporation process.



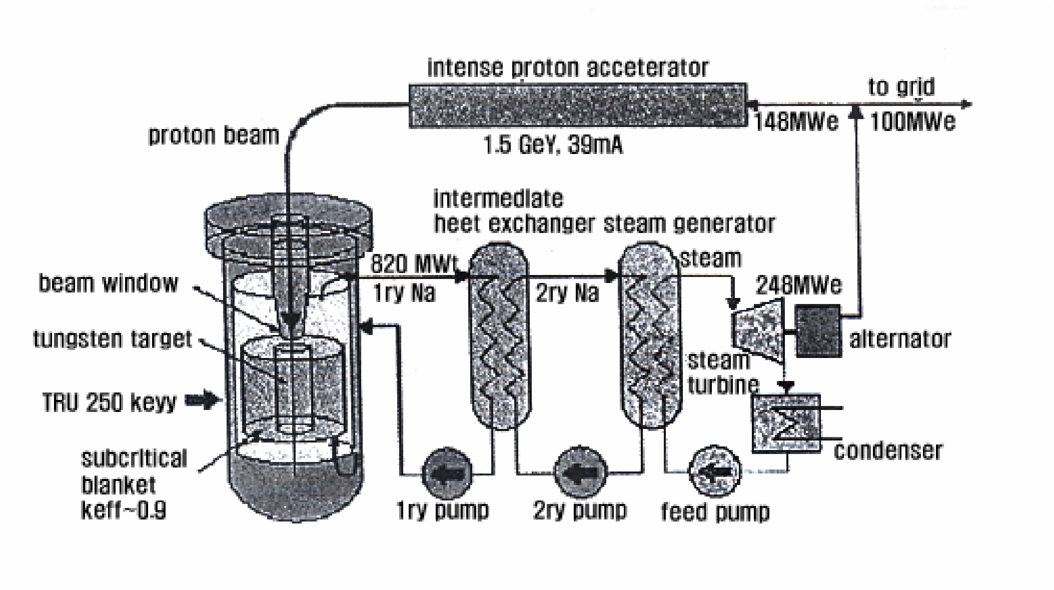

Even-odd effect in the production of light fragments in $^{238}$U (1 *A* GeV) + Ti.
(Complex features!)

Reproduction of the main characteristics by statistical model.
Importance of γ competition!

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

# Applications

***Nuclear data for spallation neutron sources (in particular ADS),***



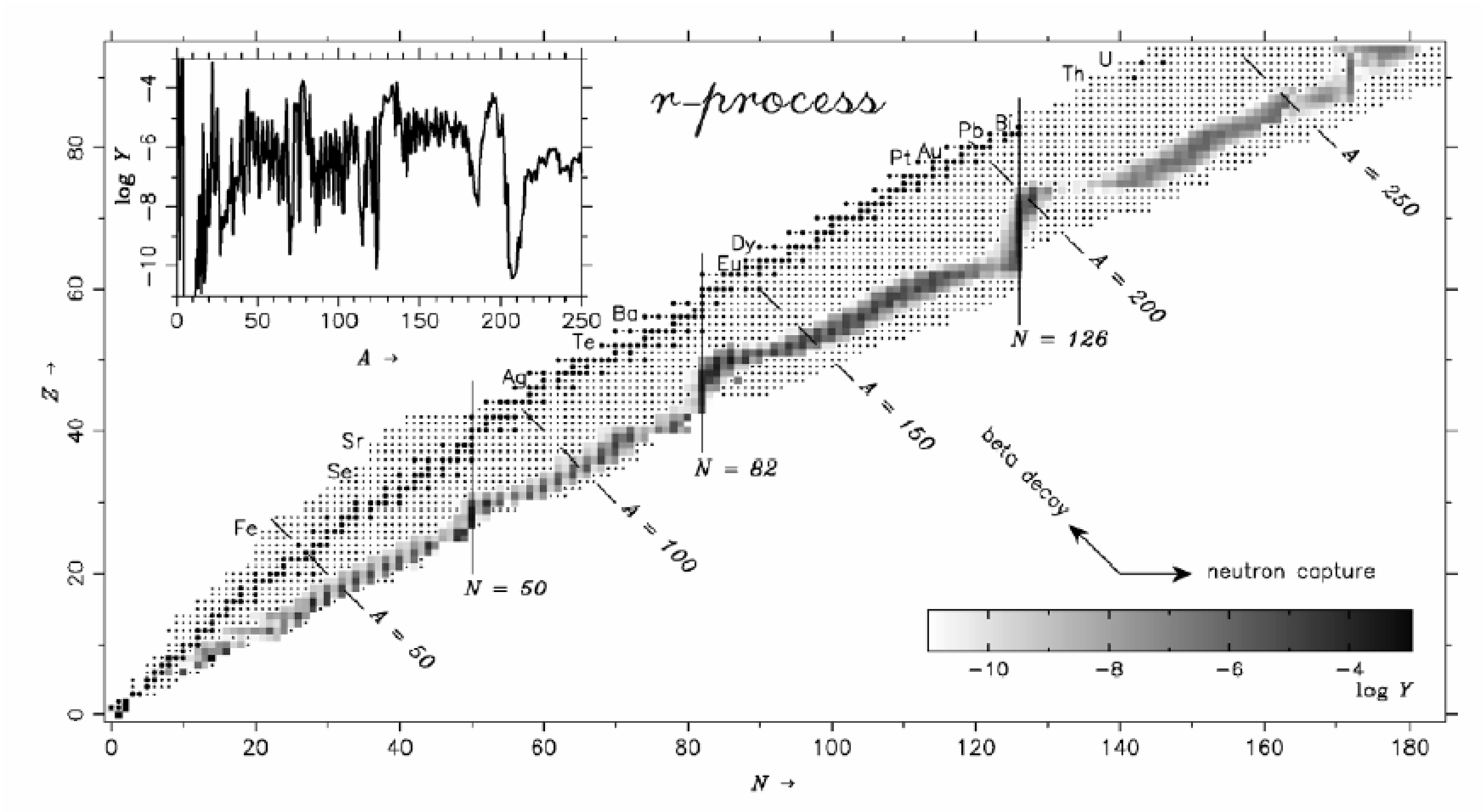

***Astrophysics (reactions of cosmic rays in the interstellar medium),***

***Nuclear safety (shielding and radioactive inventory),***

***Medicine (cancer therapy with heavy-ion irradiation)***

***→ Need for good knowledge on nuclear reactions up to E/A ≈ 1 GeV including heavy residues.***

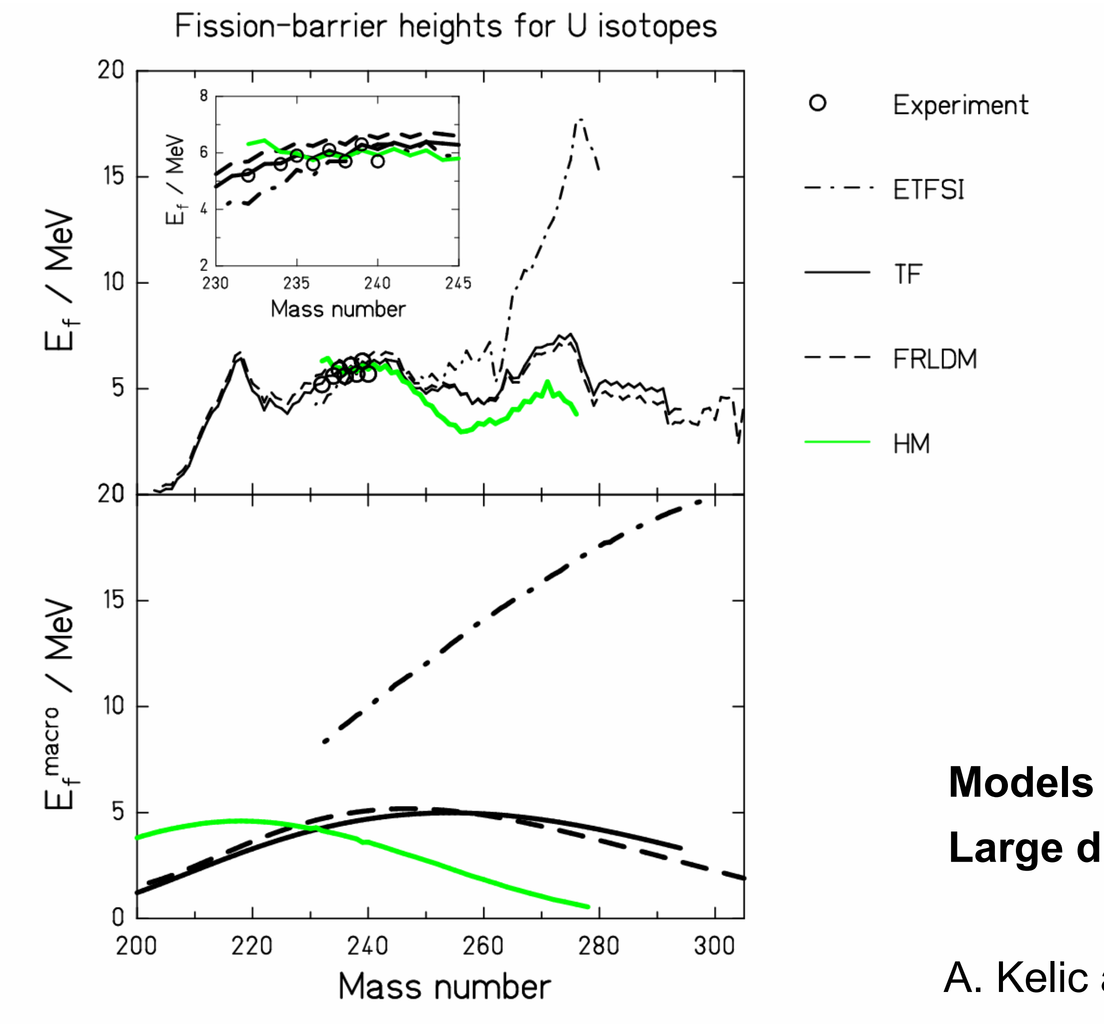
# Role of fission in the r process




**Fission terminates the r process -> Fission barrier heights**

**Fission produces nuclei in the fission-fragment region -> Nuclide distributions**

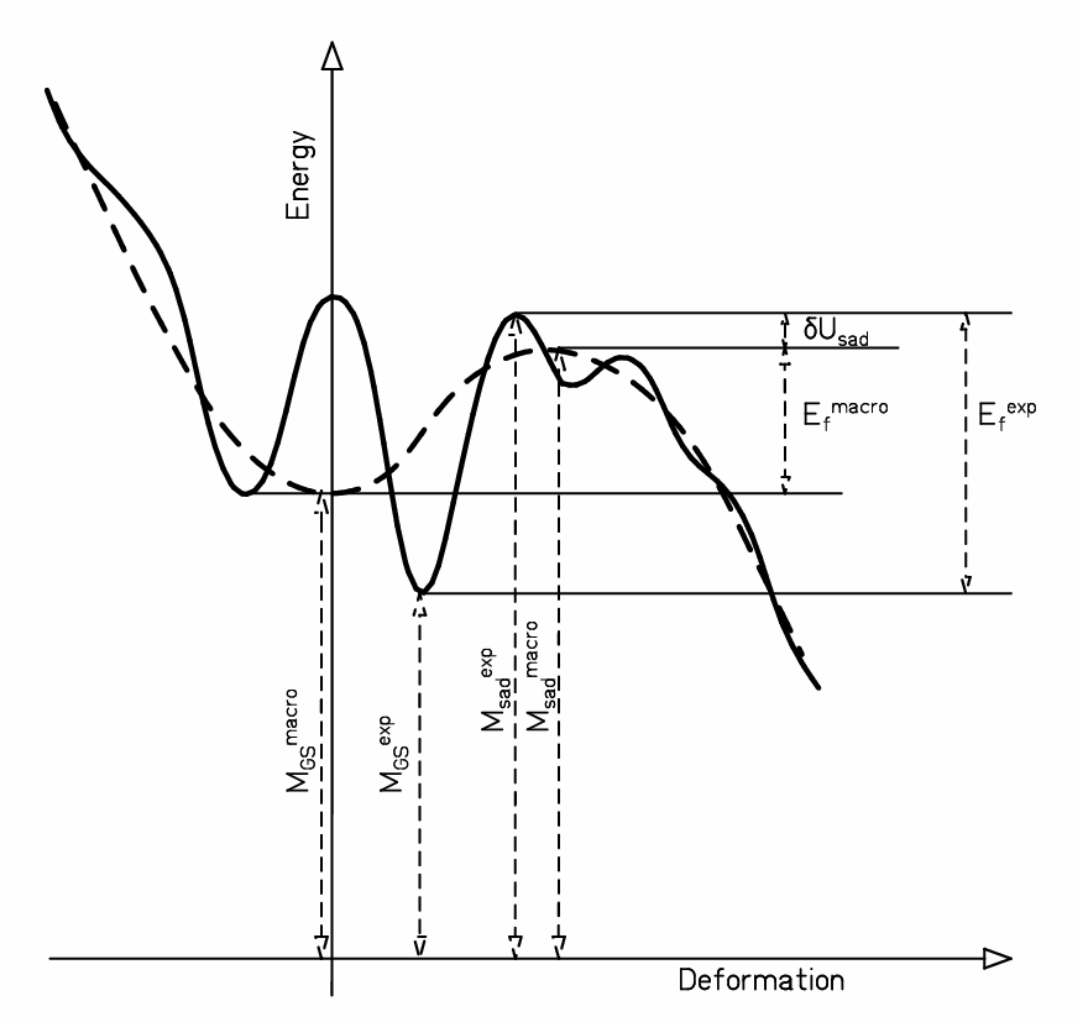
# Fission-barrier heights




**Models reproduce well the measured barriers.**
**Large discrepancies for r-process nuclei!**

A. Kelic and K.-H. Schmidt, Phys. Lett. B

# The topographic theorem



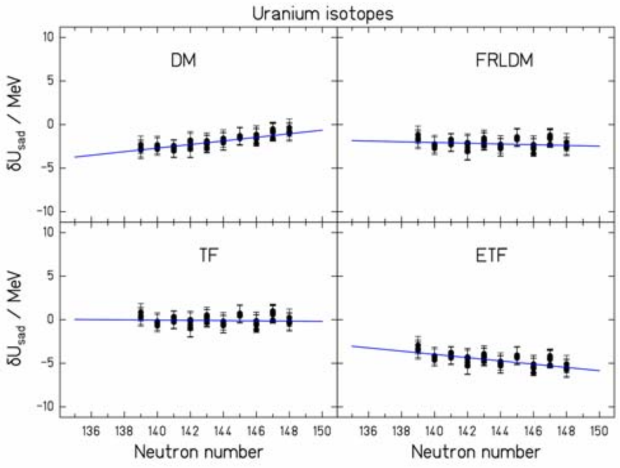

**B. Myers and W. Swiatecki (Nucl. Phys. A 601 (1996) 141):**

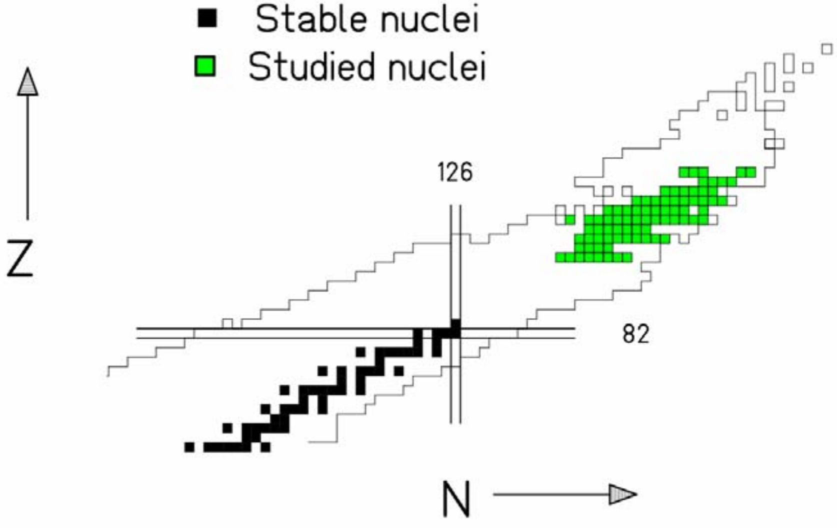
**Energy of highest saddle close to energy at liquid-drop barrier**

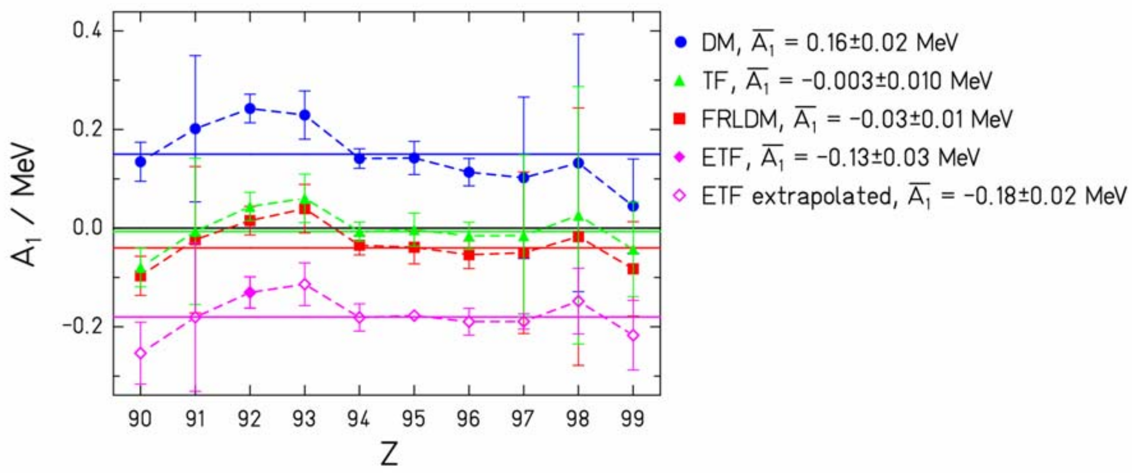
**or**

**shell effects at the barrier are small.**

# Analysis of $B_{exp} - B_{mac}$



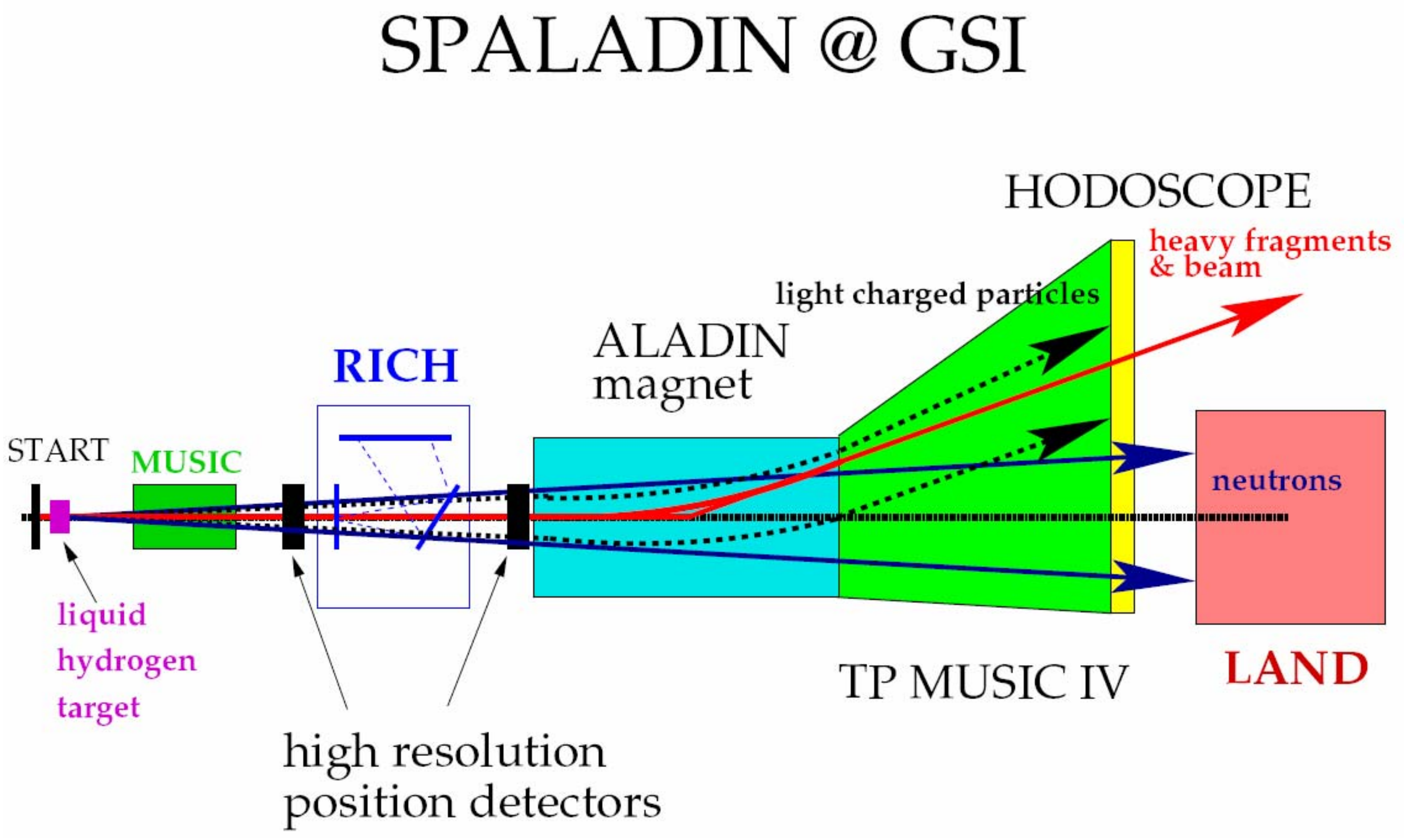

**For some models $B_{exp}$ - $B_{mac}$ shows global tendencies:**

**Variation of $B_{mac}$ with $N$-$Z$ not correct!**

**Method more powerful than fit of $B_f$.**

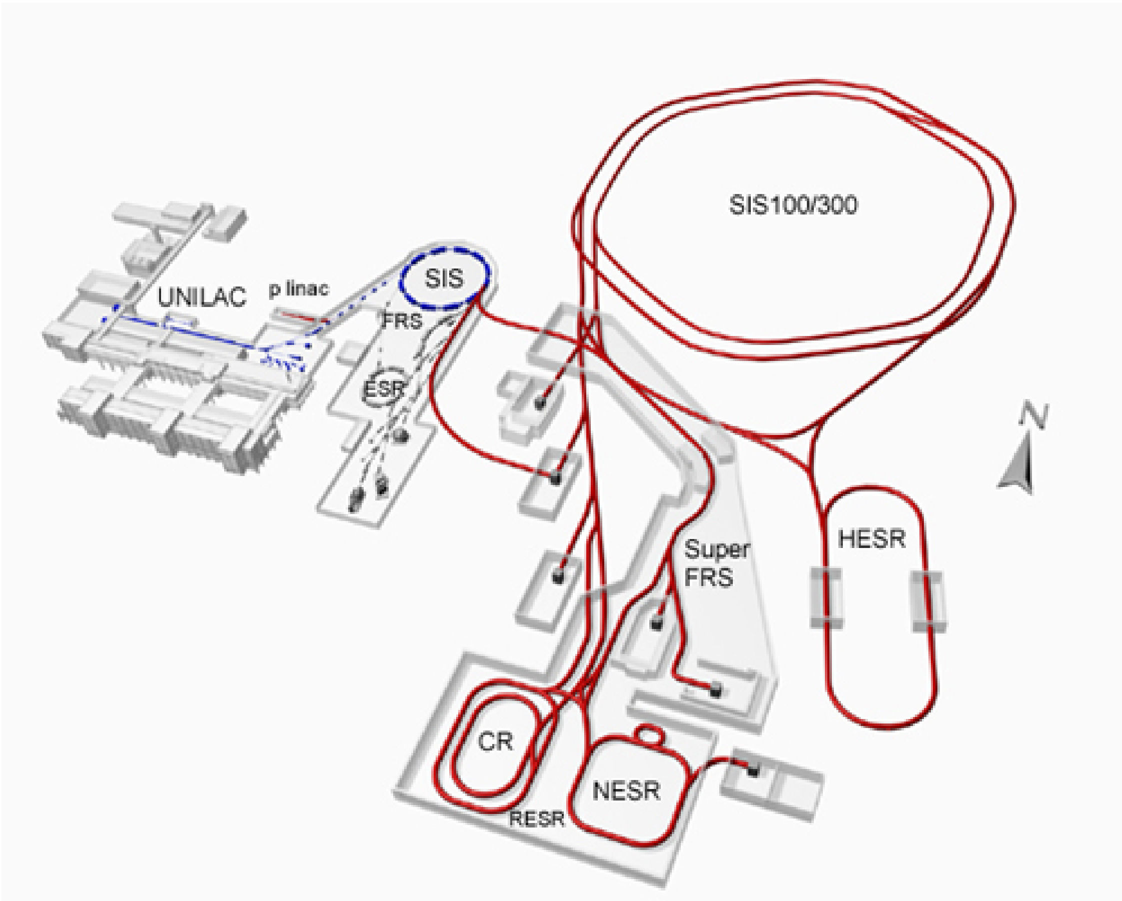
Al. Kelic and K.-H. Schmidt
Phys. Lett. B

## Large-acceptance spectrometer (in preparation)




**Detection of neutrons, charged particles / but limited mass resolution**

# The FAIR project

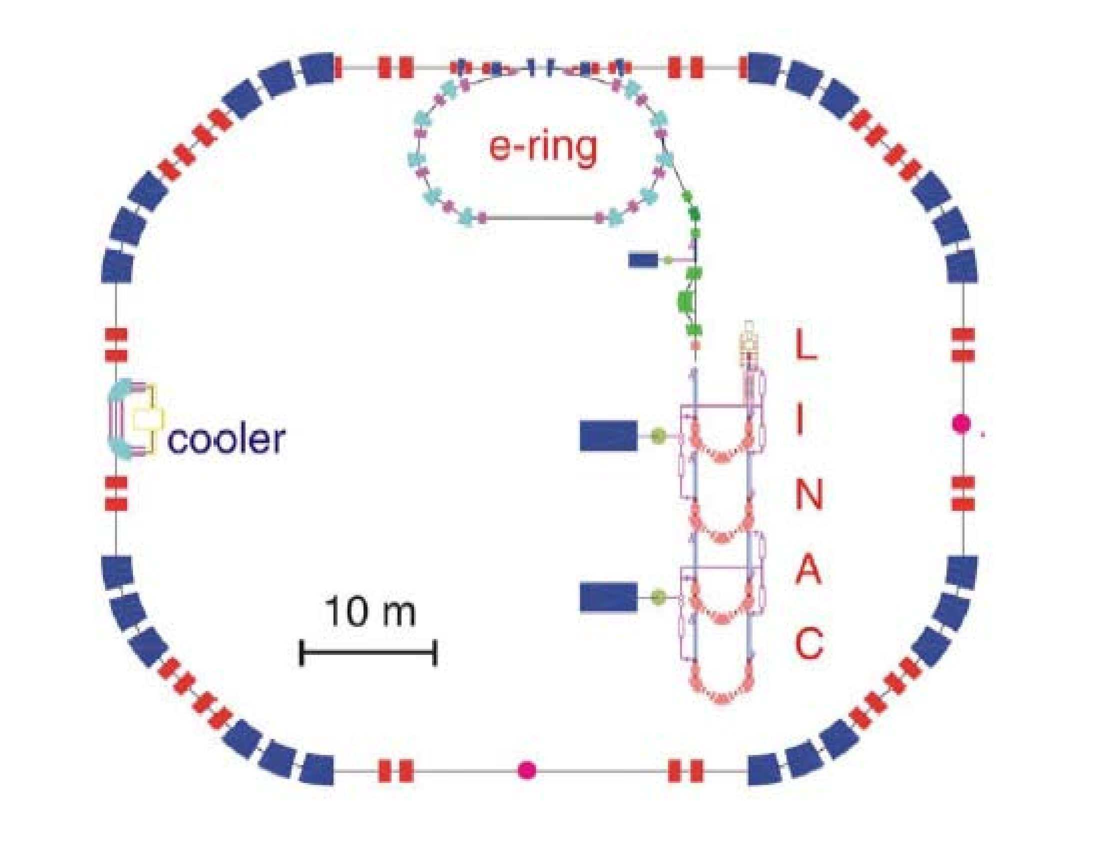



**Beams with higher energy and higher intensity**

**Spectrometers with larger acceptance / higher resolution**

**Storage rings, electron — ion collider**

## Electron-ion collider – the ideal tool ?




**Determination of the excitation energy by inelastic electron electron scattering.**

**No angular straggling in target.**
**No contribution from nuclear reactions.**

**Needs of a spectrometer with large acceptance for the fission fragments.**

# Conclusion

- **The HI-accelerator and spectrometer complex of GSI Darmstadt is unique world-wide**
- **Break-through in measuring full nuclide distributions in spallation reactions in a French-Spanish-German collaboration**
- **Comprehensive data tables established (→ www-w2k.gsi.de/charms)**
- **New insight into global features of spallation and fission**
- **Model for nuclide production in fission on the basis of $E_{pot}$ and $\rho$**
- **Successful modelling of all aspects of spallation-fission reactions**
- **Powerful method for testing predictive power of fission-barrier models**
- **Even better experimental conditions in the future FAIR facility**

# The CHARMS collaboration

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