Fission of Radioactive Beams and Dissipation in Nuclear Matter

Andreas Heinz
Wright Nuclear Structure Laboratory,
Yale University

for the **CHARMS** Collaboration

4th International Conference on *Fission Properties of Neutron-Rich Nuclei*, November 11-17, 2007, Sanibel Island, Florida

CHARMS

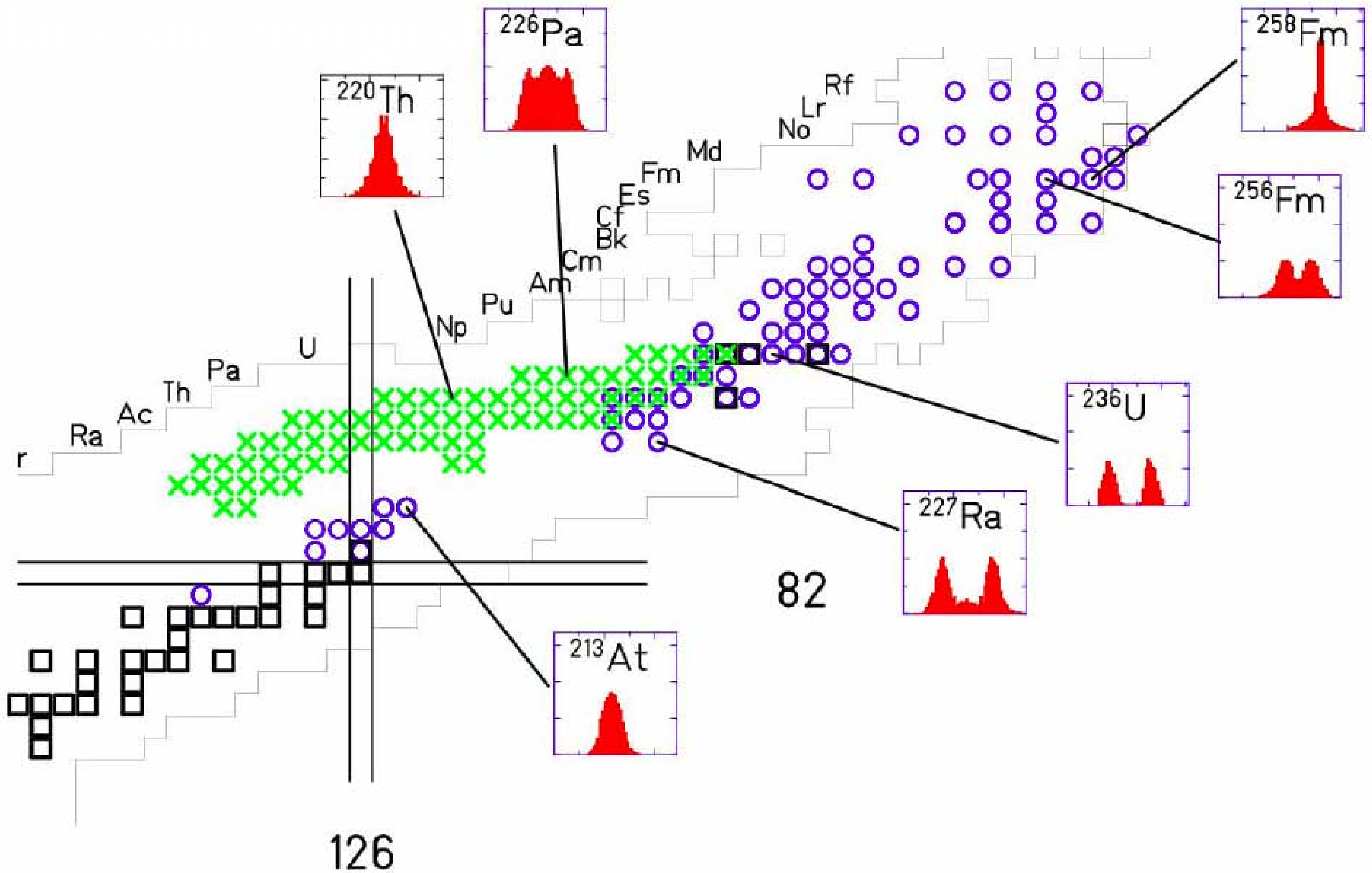
Collaboration for High-Accuracy Experiments on Nuclear Reaction Mechanisms with Magnetic Spectrometers

P. Armbruster[1], A. Bacquias[1], L. Giot[1], V. Henzl[1,12], D. Henzlova[1,12], A. Kelić[1], S. Lukić[1], R. Pleskač[1], M.V. Ricciardi[1], K.-H. Schmidt[1], O. Yordanov[1], J. Benlliure[2], J. Pereira[2,12], E. Casarejos[2], M. Fernandez[2], T. Kurtukian[2], C.-O. Bacri[3], M. Bernas[3], L. Tassan-Got[3], L. Audouin[3], C. Stéphan[3], A. Boudard[4], S. Leray[4], C. Volant[4], C. Villagrasa[4], B. Fernandez[4], J.-E. Ducret[4], J. Taïeb[5], C. Schmitt[6], B. Jurado[7], F. Reymund[8], P. Napolitani[8], D. Boilley[8], A. Junghans[9], A. Wagner[9], A. Kugler[10], V. Wagner[10], A. Krasa[10], A. Heinz[11], P. Danielewicz[12], L. Shi[12], T. Enqvist[13], K. Helariutta[14], A. Ignatyuk[15], A. Botvina[16], P.N. Nadtochy[1]

[1]GSI, Darmstadt, Germany
[2]Univ. Santiago de Compostela, Sant. de Compostela, Spain
[3]IPN Orsay, Orsay, France
[4]DAPNIA/SPhN, CEA Saclay, Gif sur Yvette, France
[5]DEN/DMS2S/SERMA/LENR, CEA Saclay, Gif sur Yvette , France
[6]IPNL, Universite Lyon, Groupe Materie Nucleaire 4, Villeurbanne, France
[7]CENBG, Bordeau-Gradignan, France
[8]GANIL, Caen France
[9]Forschungszentrum Rossendorf, Dresden, Germany
[10]Nuclear Physics Institute, Rez, Czech Republic
[11]Wright Nuclear Structure Laboratory, Yale University, New Haven, USA
[12]NSCL and Physics and Astronomy Department, Michigan State University, East Lansing, USA
[13]CUPP Project, Pyhasalmi, Finland
[14]Univeristy of Helsinki, Helsinki, Finland
[15]IPPE Obninsk, Russia
[16]Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia

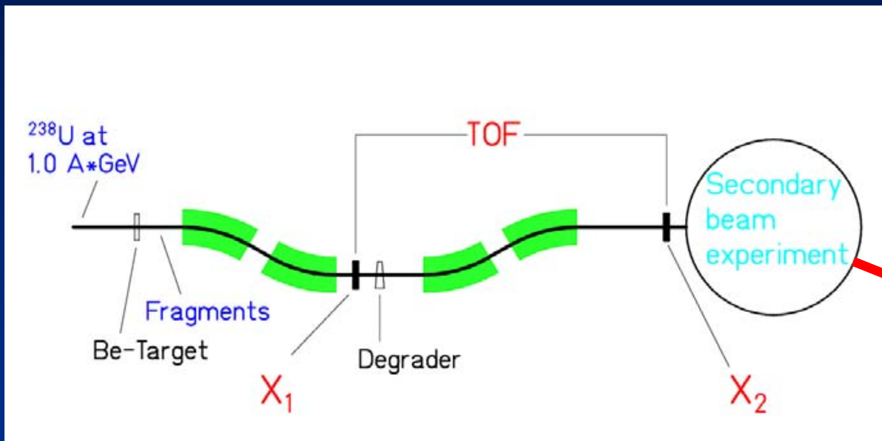
CHARMS and Nuclear Fission

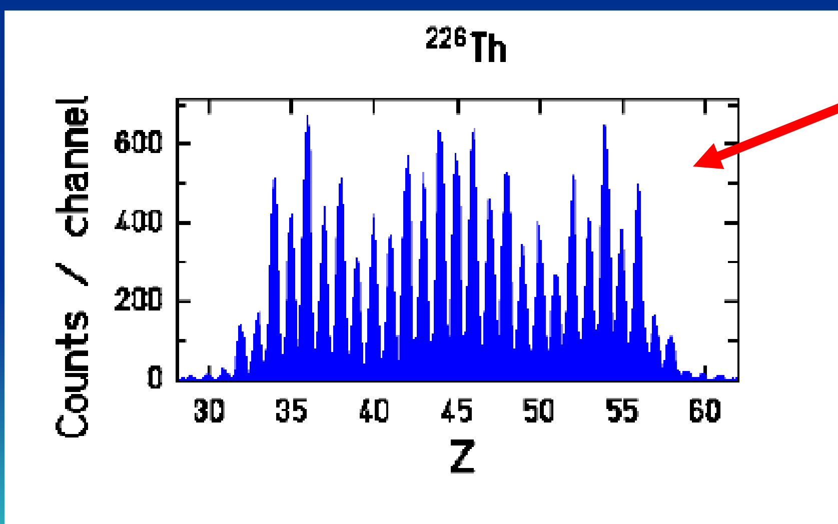
- Shell structure and pairing in nuclear fission
- Production of heavy nuclei
- Fission dynamics – dissipation in nuclear matter
- Fission and the r-process
- Influence of fission on the production of RIBs



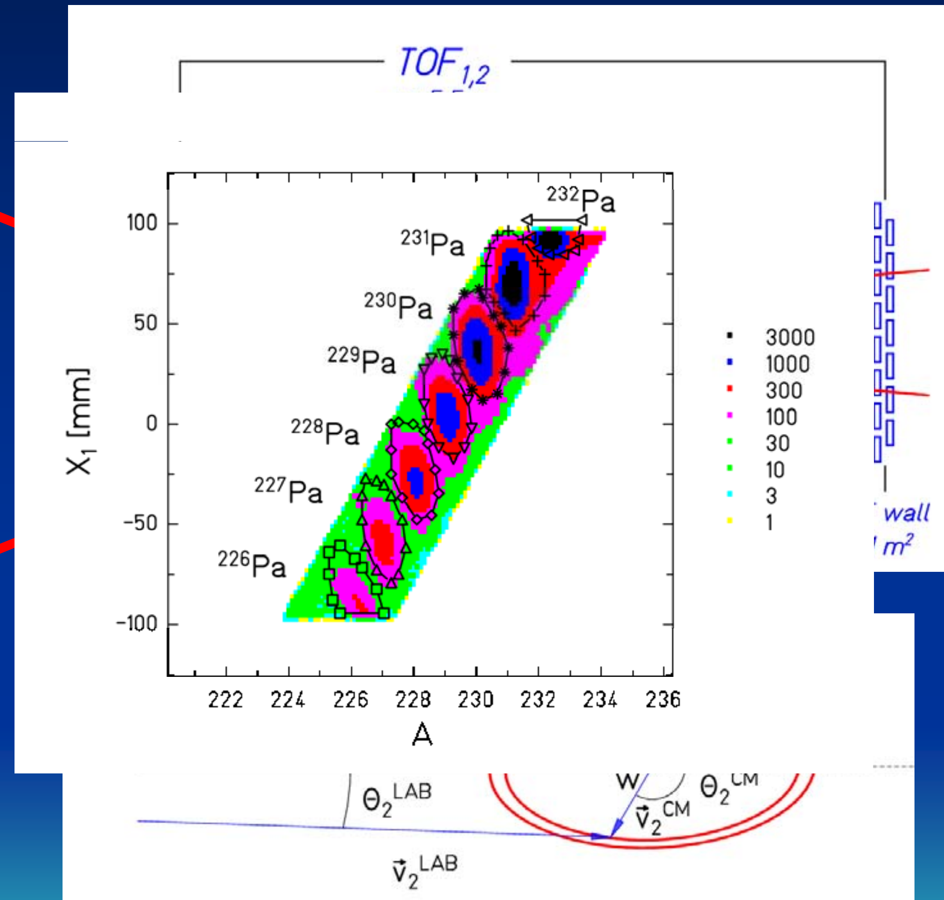
226Pa
220Th
258Fm
256Fm
Rf
Lr
No
Md
Fm
Es
Cf
Bk
Cm
Am
Pu
Np
U
Pa
Th
Ac
Ra
r
236U
227Ra
82
213At
126

Experiment



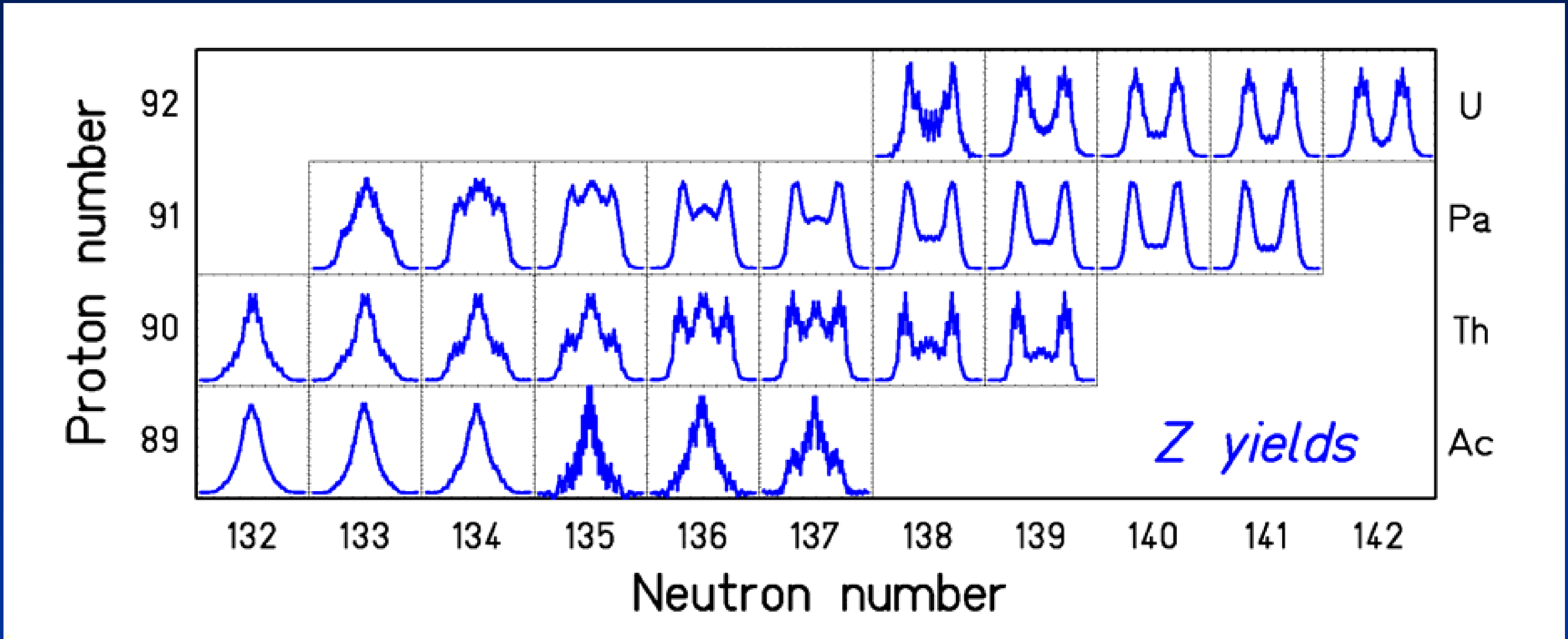


Charge distributions



Total Kinetic Energy (TKE) distributions

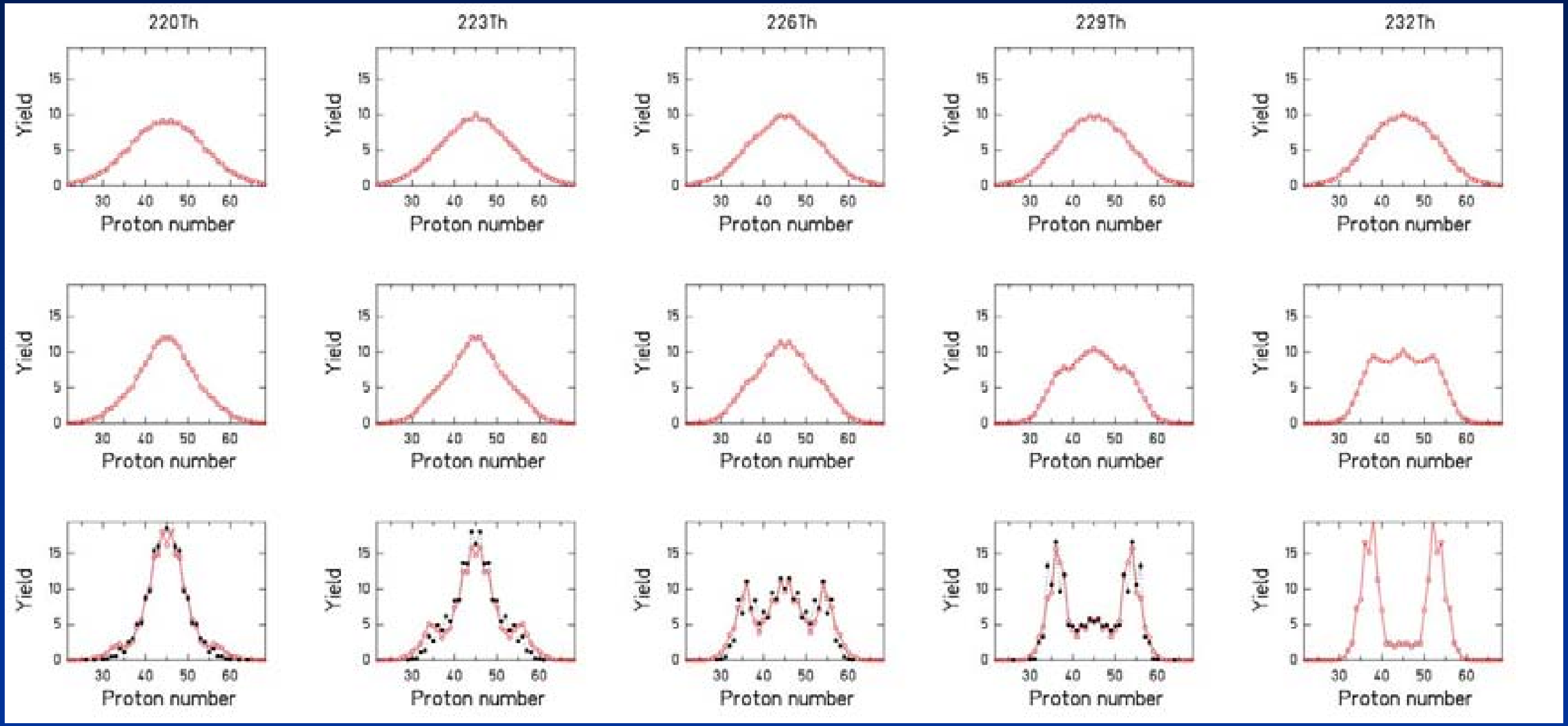
Fission Fragment Charge Distributions



Systematic investigation of shell effects and pairing in fission.

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

Modeling multi-modal fission



E* = 60 MeV

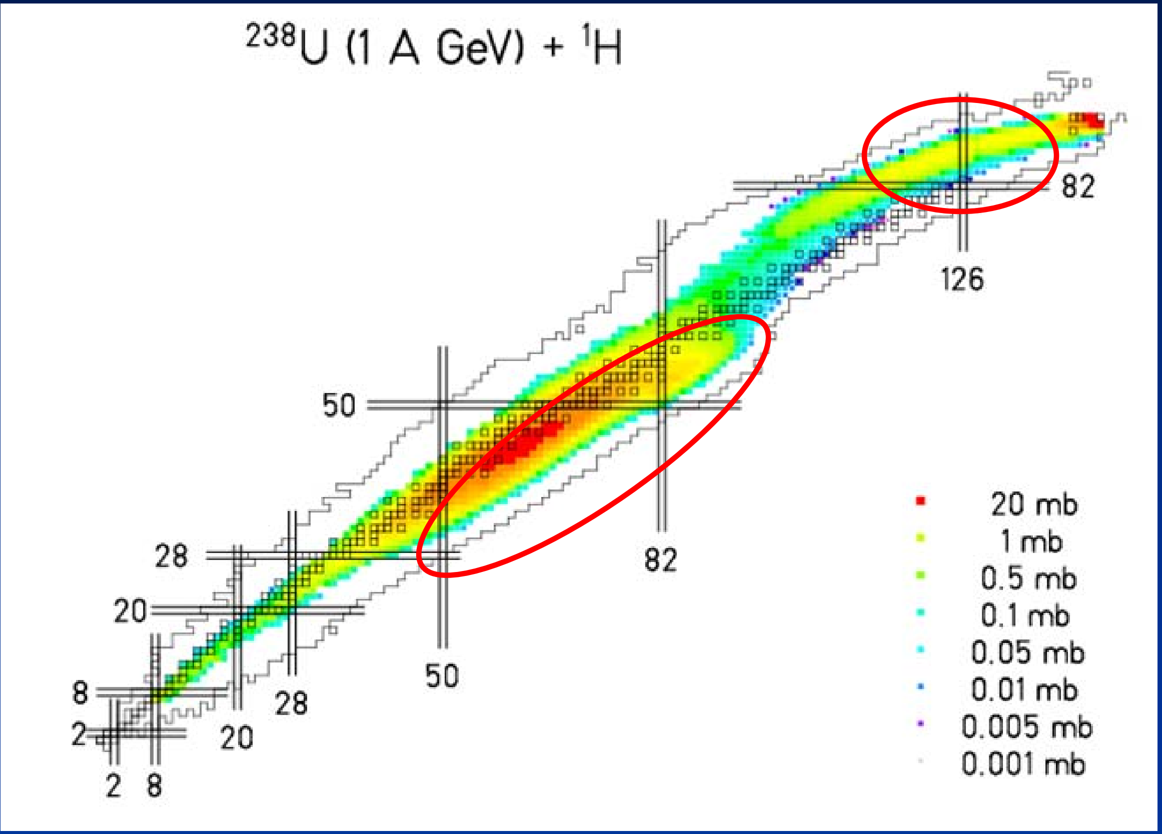
20 MeV

10 MeV

black: data,

red: simulation with ABLA07

Spallation of ^{238}U – Production of RIBs



Influence of fission hindrance!

Data measured at GSI*

* Ricciardi et al, Phys. Rev. C 73 (2006) 014607; Bernas et al., Nucl. Phys. A 765 (2006) 197; Armbruster et al., Phys. Rev. Lett. 93 (2004) 212701; Taïeb et al., Nucl. Phys. A 724 (2003) 413; Bernas et al., Nucl. Phys. A 725 (2003) 213

www.gsi.de/charms/data.htm

More than 1000 different nuclides observed.

Features of spallation-evaporation / -fission / -IMF emission

→ **rates for the next generation of RIB facilities!**

Dissipation

Transport theories

Energy in collective degrees of freedom ↔ Energy in single-particle degrees of freedom

↑

Dissipation

$$\frac{dE_{coll}}{dt} = \beta\left[E_{coll}^{eq} - E_{coll}\right]$$

Reduced dissipation coefficient

Fission and Dissipation

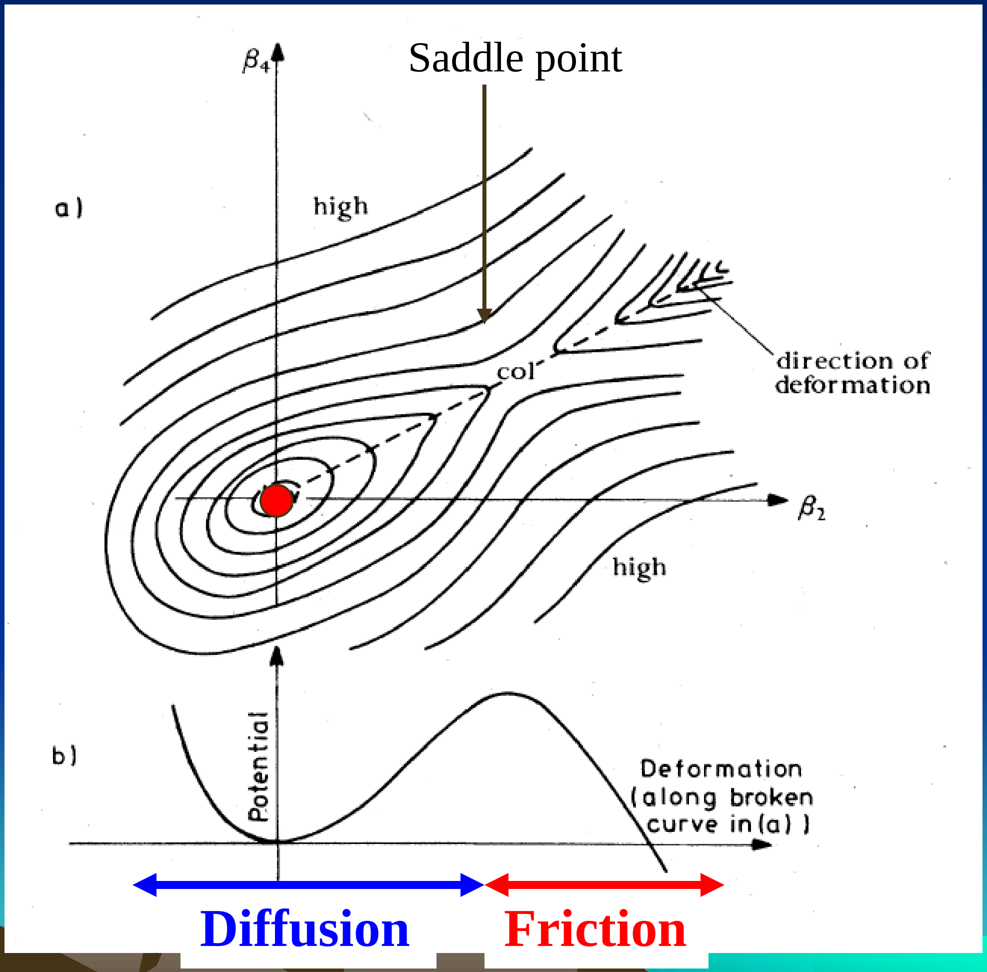
Centroid of the probability distribution!

Motion is governed by:

- dissipation
- phase space

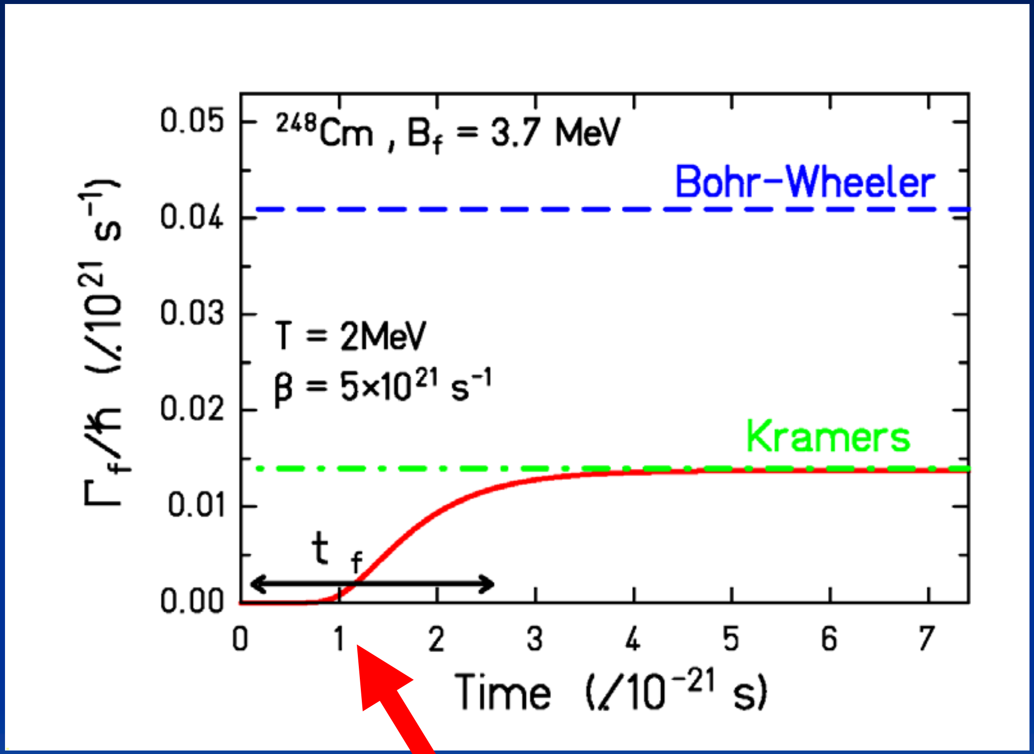
Analogy: Brownian Motion

- Fokker-Planck
- Langevin



Bjornholm, Lynn; Rev. Mod. Phys. 52, 725 (1980)

Escape Rate



C. Schmitt

Bohr-Wheeler (1939):

Transition-state method

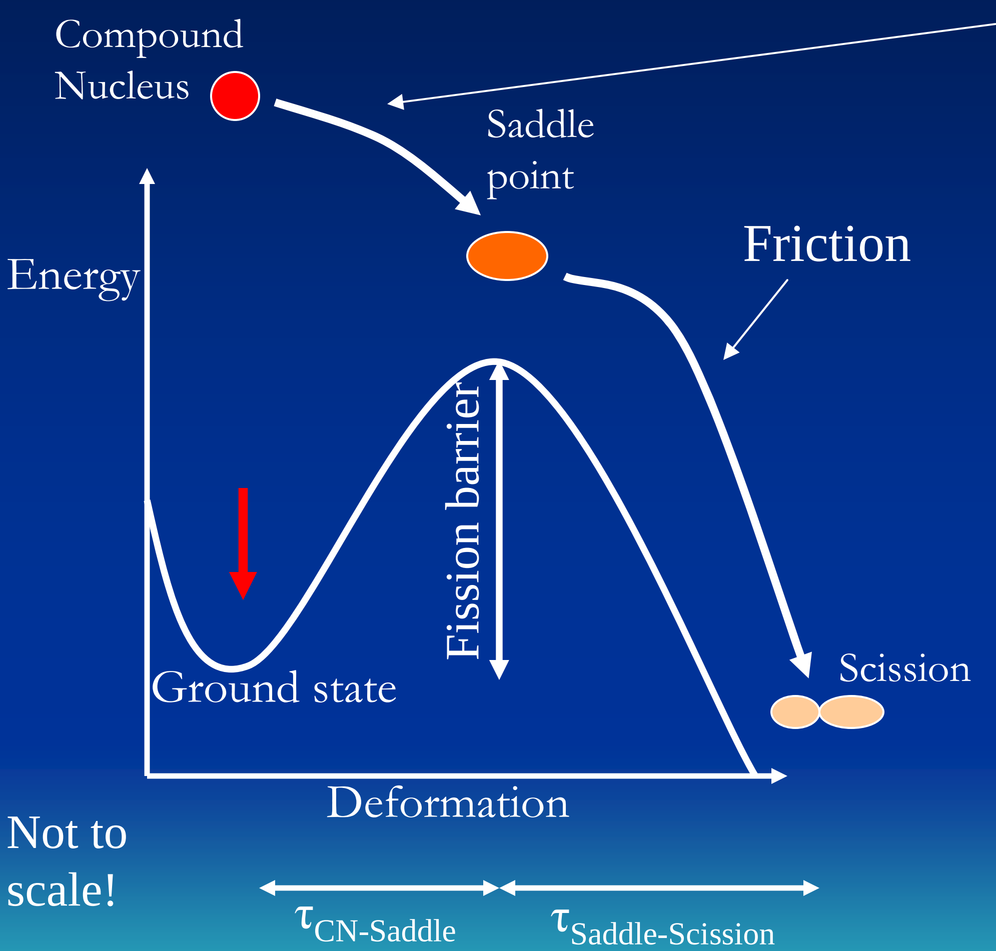
Quasi-stationary (Kramers 1940):

Fission width is reduced due to trajectories back into the well.

Transient time:

Time the system needs to adjust to the potential under the influence of a fluctuating force.

Excitation Energies and Time Scales



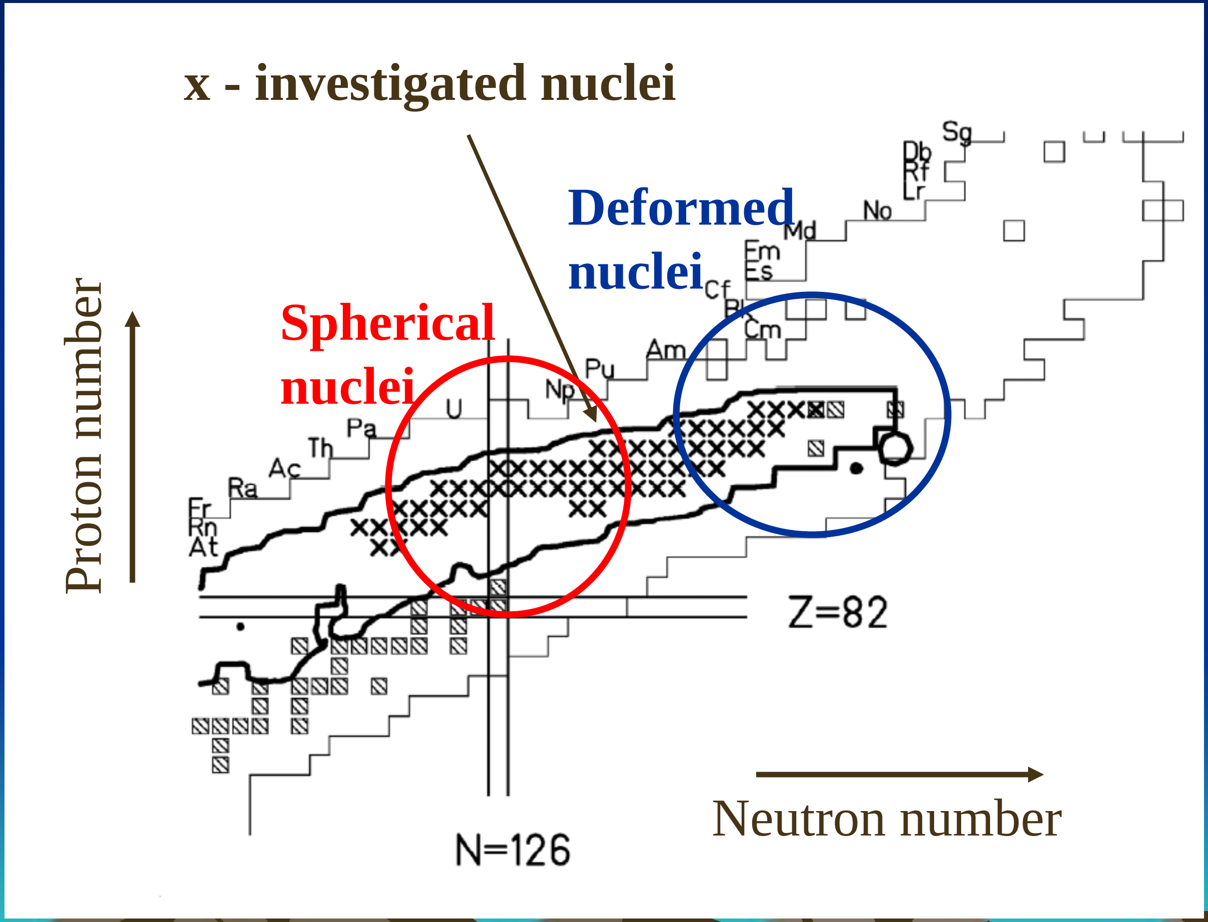
Fluctuating Forces:

- increases time scale
- decreases excitation energy by particle evaporation

What is the influence of the compound nucleus deformation on the transient time?

Investigated Nuclei

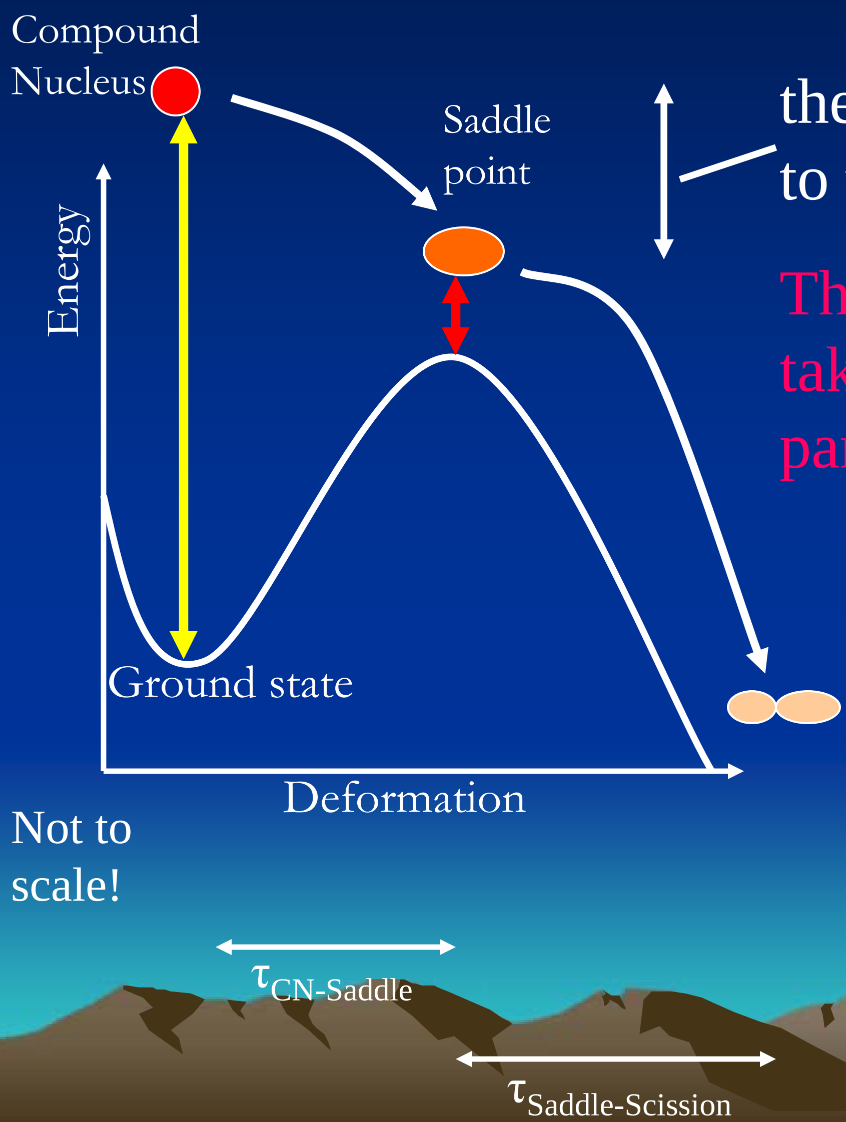
^{238}U @ 1 A GeV on ^{9}Be: projectile fragmentation



Heavy nuclei near N=126:

- Highly fissile
- 45 secondary beams with $|\beta_2| \leq 0.15$
- ^{238}U ground state: $\beta_2 \approx 0.23$

Measuring a Temperature Difference



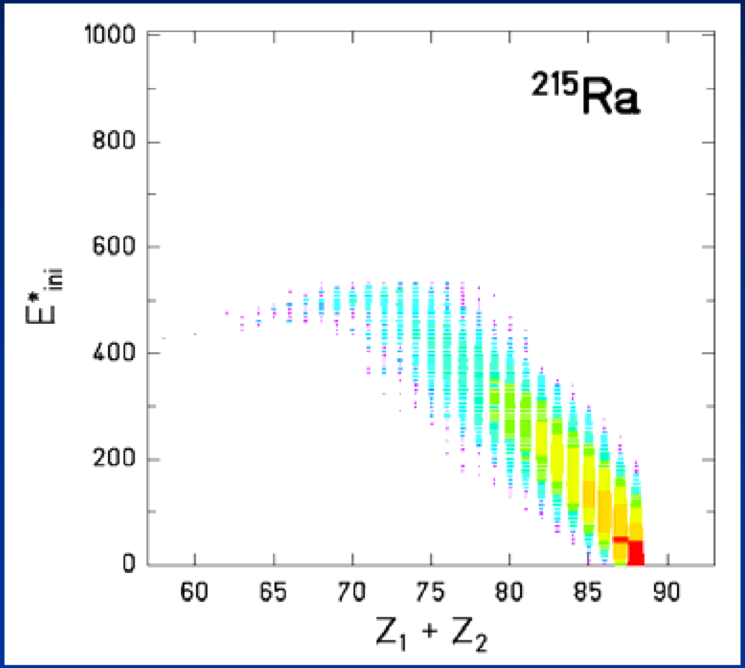
the energy the nucleus looses on its way to the saddle point (via evaporation):

The longer the motion to the saddle takes the more energy will be lost by particle evaporation!

→ Measure the temperature of the compound nucleus.

→ Measure the temperature at the saddle!

Fission Fragment Charges and Compound Nucleus Excitation Energy



Abrasion-Ablasion model

The sum of the fission fragment charges is a measure of the energy of the compound nucleus!

Deformation Induced by Projectile Fragmentation

➢ Nearly spherical pre-fragments!

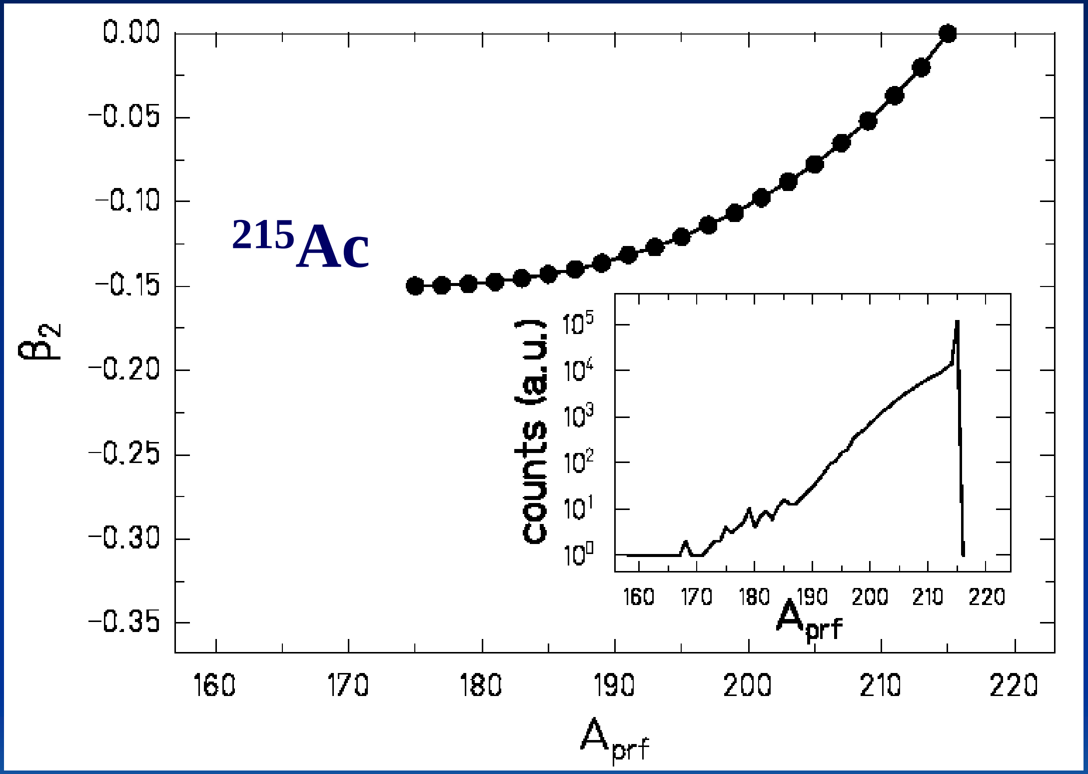
➢ Saddle point: $\beta_2 \approx 0.6$ - 0.8

➢ Access to compound nuclei which are:

❖ highly excited

❖ highly fissile

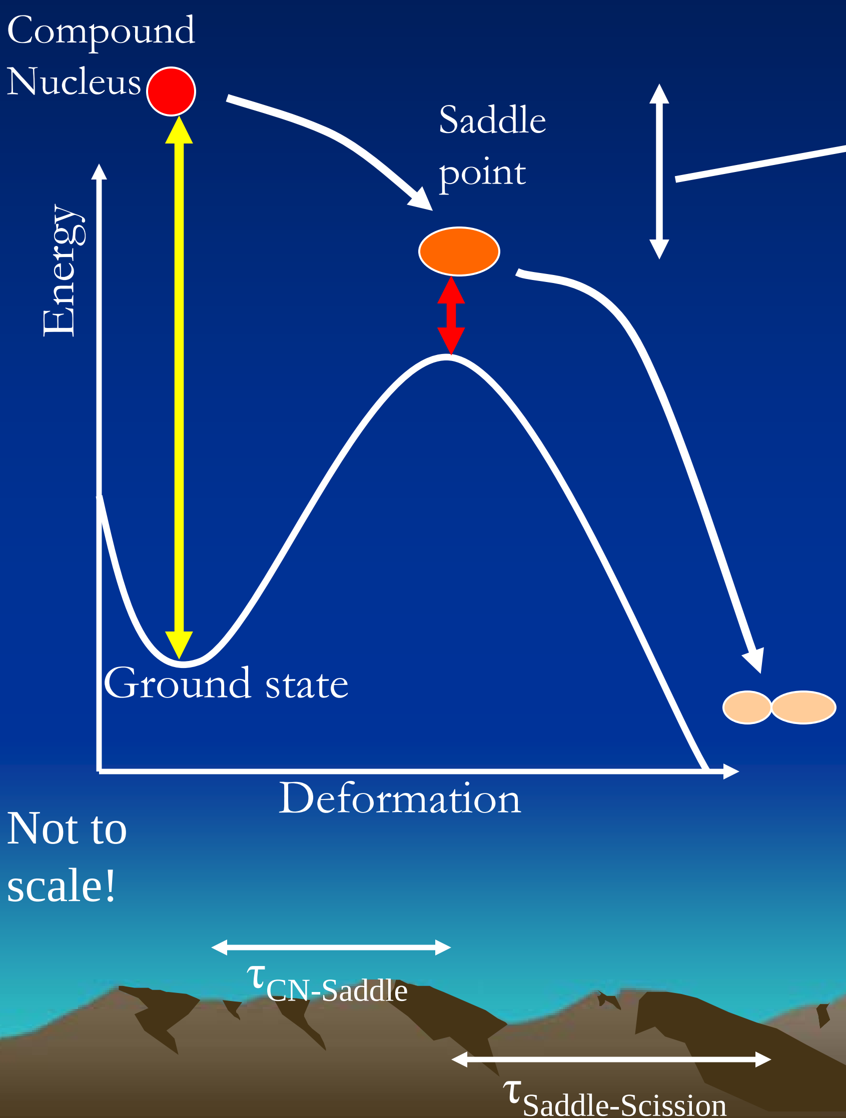
❖ nearly spherical



P.N. Nadtochy

Assumption: $\tau_{thermal} << \tau_{coll}$

Temperature Difference



Energy difference we want to measure:

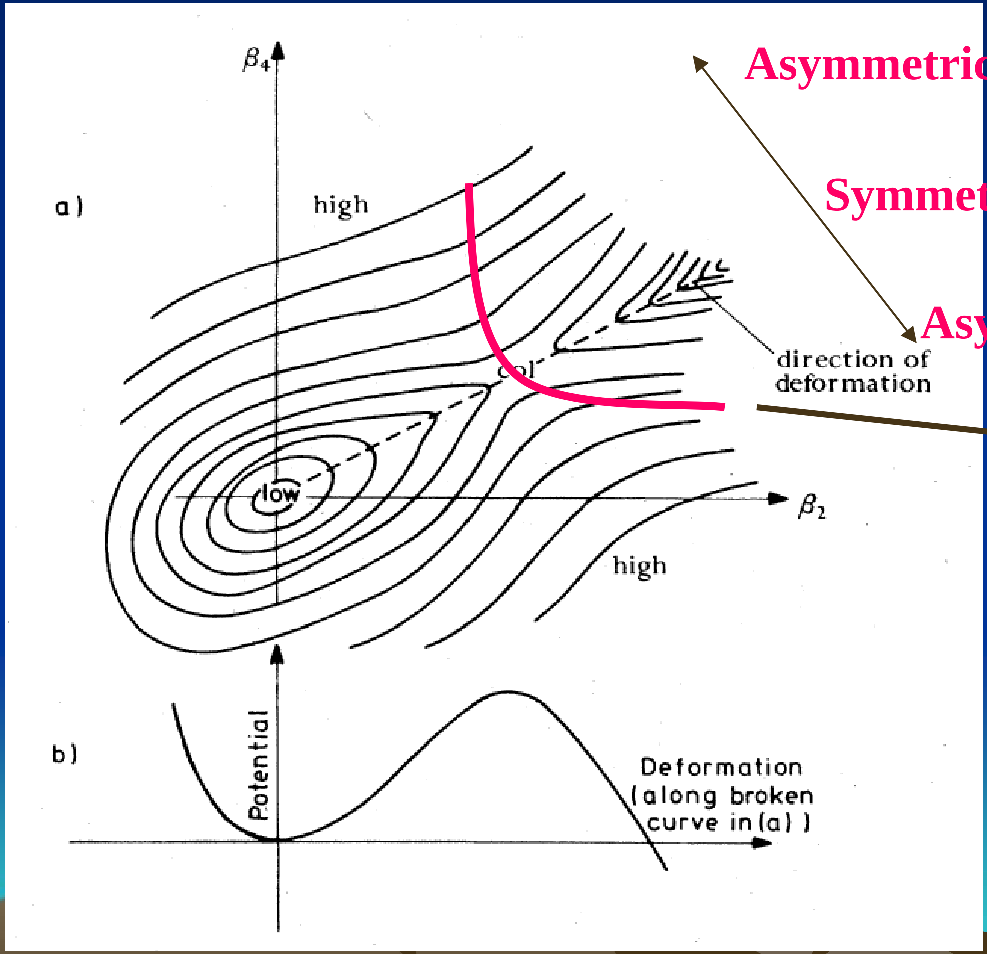
Compound nucleus excitation energy

→ use Z_1+Z_2

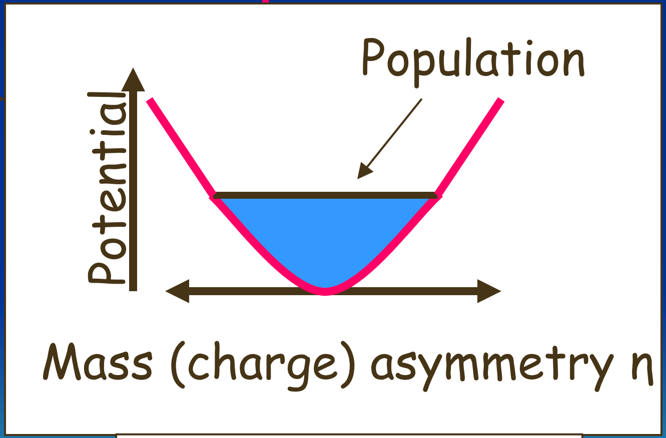
Saddle point excitation energy

→ use width of the charge distribution

Charge Width as a Thermometer



A. Ya. Rusanov et al. Phys. At. Nucl. 60, 683 (1977)

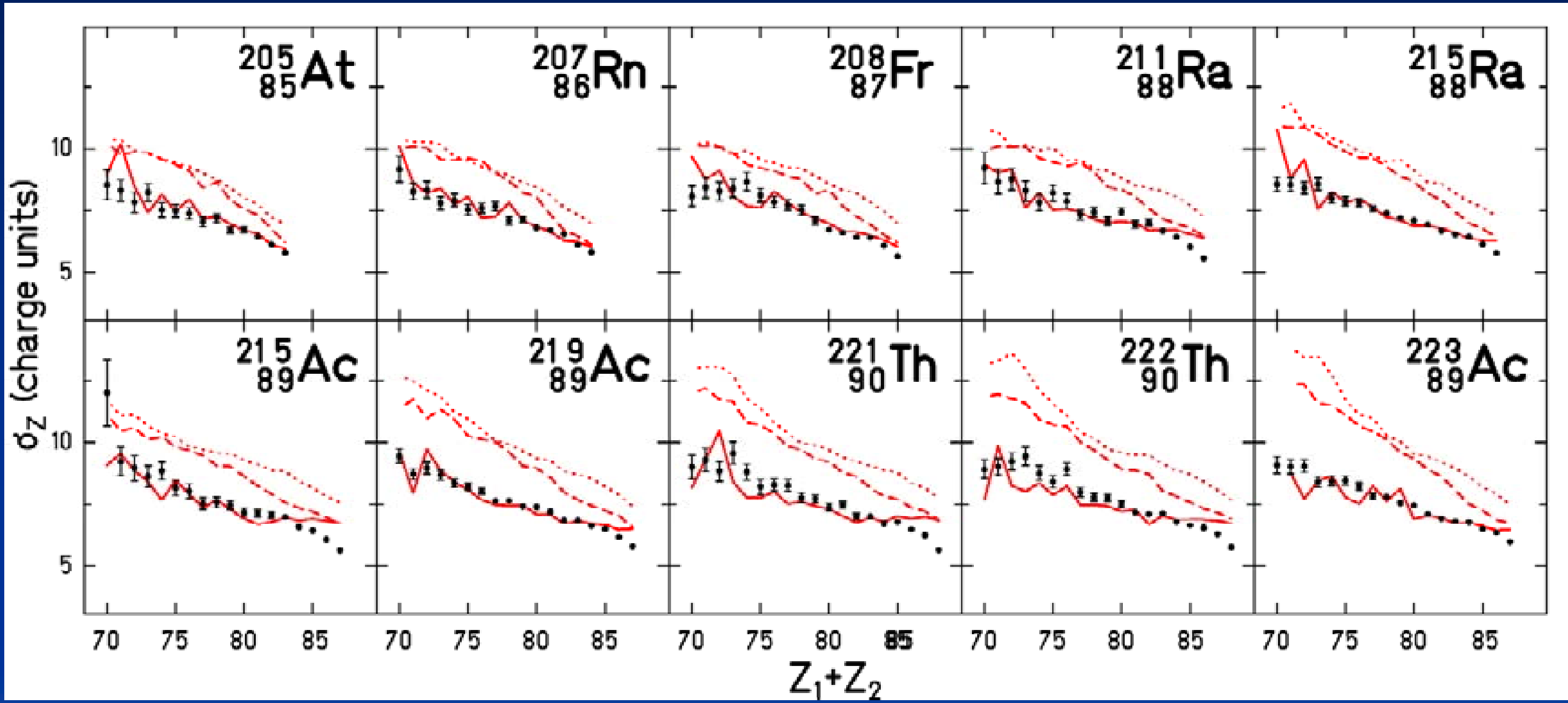


$$\sigma_Z^2 = \left(\frac{Z_{fiss}}{A_{fiss}}\right)^2 \frac{T_{saddle}}{\left.\frac{d^2V}{d\eta^2}\right|_{\frac{A_{fiss}}{2}}}$$

Bjornholm, Lynn; Rev. Mod. Phys. 52, 725 (1980)

Charge Width: Results

CN excitation energy



Calculations: Abrasion-Ablation model (ABRABLA)

C. Schmitt et al., PRL 99 (2007) 042701

········	**Statistical Model**
– – –	**Kramers**
——	**β = 4.5 x 10^{21} s^{-1}**

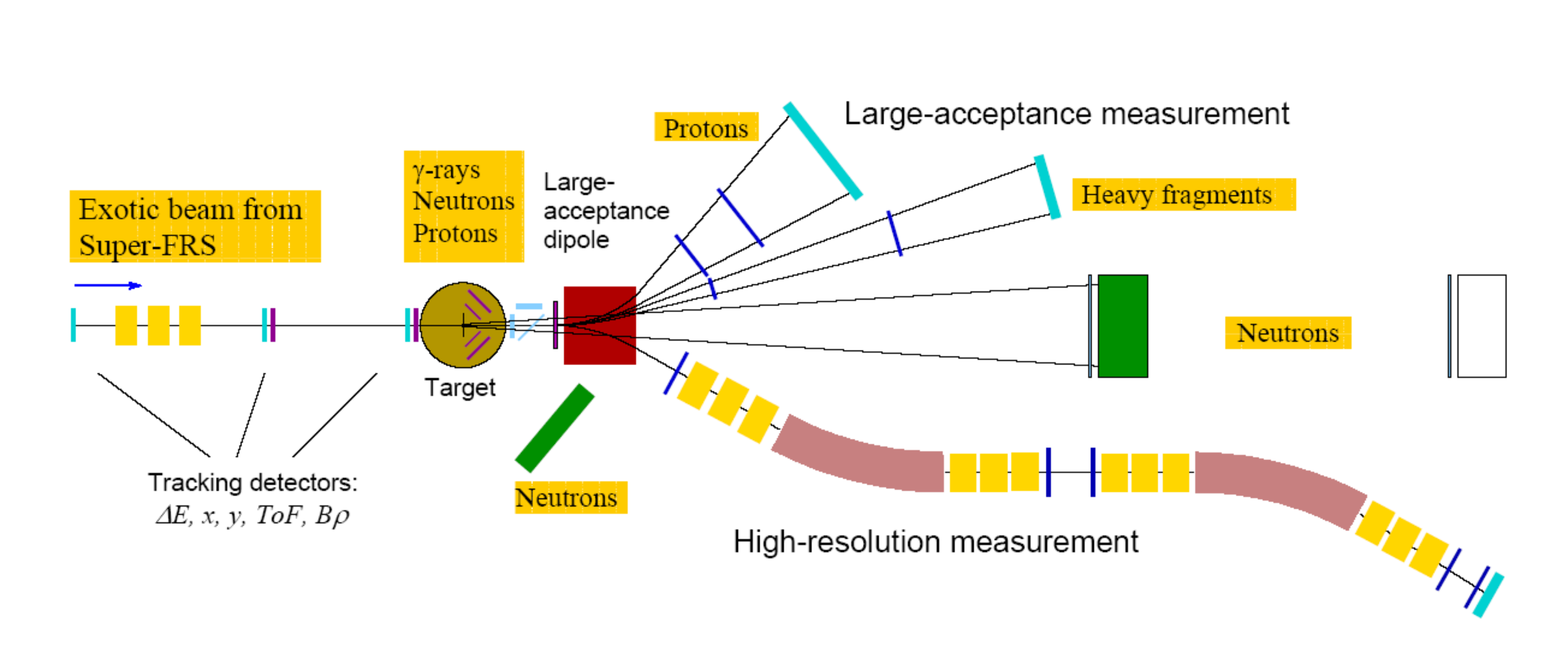
Results

- Compound nucleus temperature up to 5.5 MeV
- Saddle point temperature up to 3 MeV
- This work: $<\tau_{trans}> = (3.3\pm0.7)x10^{-21}$ s
- ^{238}U: $<\tau_{trans}> = (1.7\pm0.4)x10^{-21}$s

B. Jurado et al., PRL 93, 072501(2004)

- $\beta= (4.5 \pm0.5)$ x 10^{21} s^{-1}
- Over-damped motion at small deformation and high excitation energies?

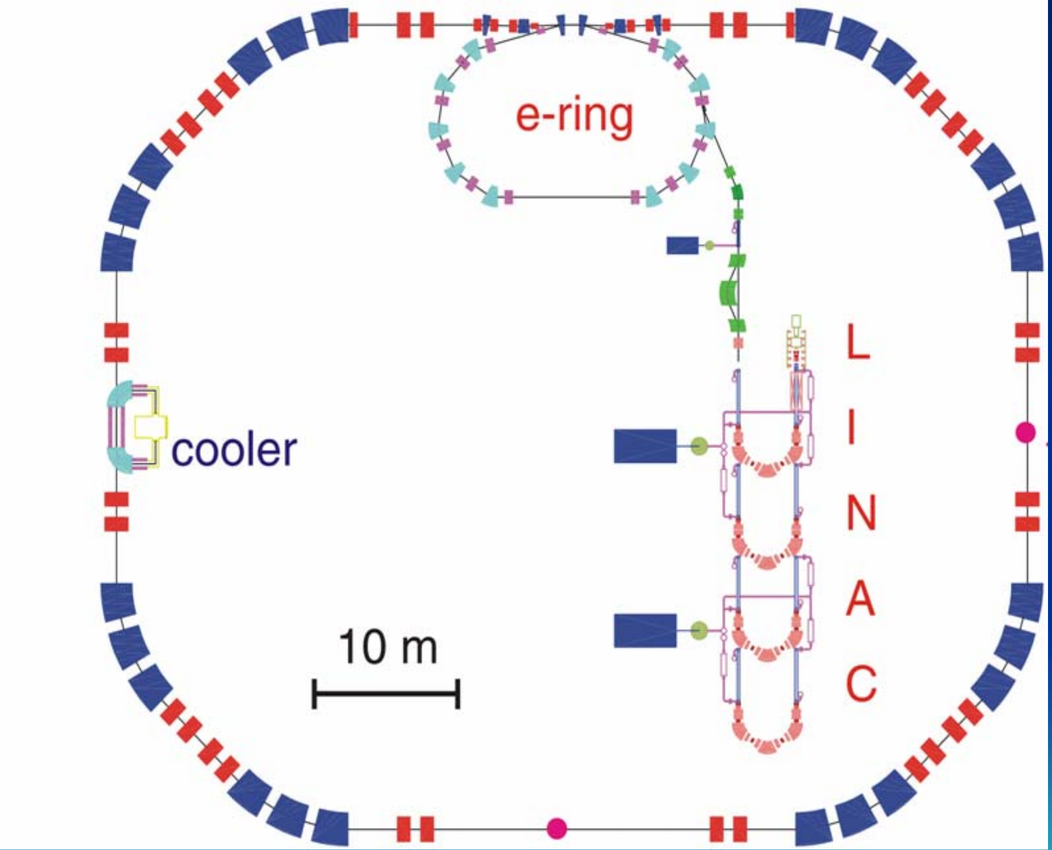
The Future (Part I): R^3B



Observables:

- **Charge and Mass of (both?) fission fragments**
- **Total kinetic energies**
- **Neutrons, gamma radiation, fission cross sections, …**

Future (Part II): Electron-Ion scattering in a Storage Ring: ELISe



- 125-500 MeV electrons
- 200-740 MeV/u RIBs

- different excitation mechanism

- no energy straggling in the target

→ direct measurement of the excitation energy!

Summary

- In-flight fission of relativistic beams expands the experimental toolbox in fission research.
- The fission fragment charge sum is a key observable.
- First experimental evidence of the influence of deformation on the transient time.
- There is a lot more to come in the future!