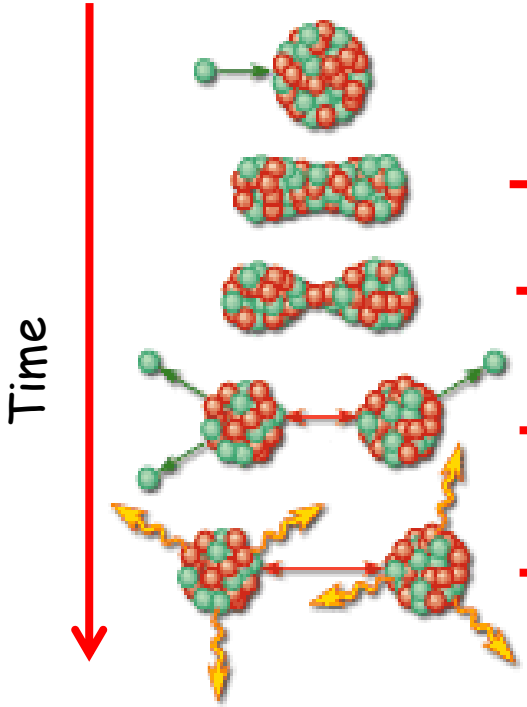
Fission studies at HIE-ISOLDE with the TSR

B. Jurado[1], P. Marini[1], F. Farget[2], M. Grieser[3], R. Reifarth[4], M. Aiche[1], A. Andreyev[5], L. Audouin[6], G. Belier[7], A. Chatillon[7], S. Czajkowski[1], L. Mathieu[1], Y. Nishio[8], J. Taieb[7], I. Tsekhanovich[1]

1) CENBG, Chemin du Solarium, B.P. 120, 33170 Gradignan, France
2) GANIL, bd. Henri Becquerel, 14076 Caen, France
3) Max-Planck Institut für Kernphysik, 69117 Heidelberg, Germany
4) Goethe Universität Frankfurt, 60438 Frankfurt, Germany
5) University of York, Y0105DD, UK
6) IPN d'Orsay, 91406 Orsay Cedex, France
7) CEA/DAM-DIF, 91297 Arpajon, France
8) Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan

The fission process at low energy



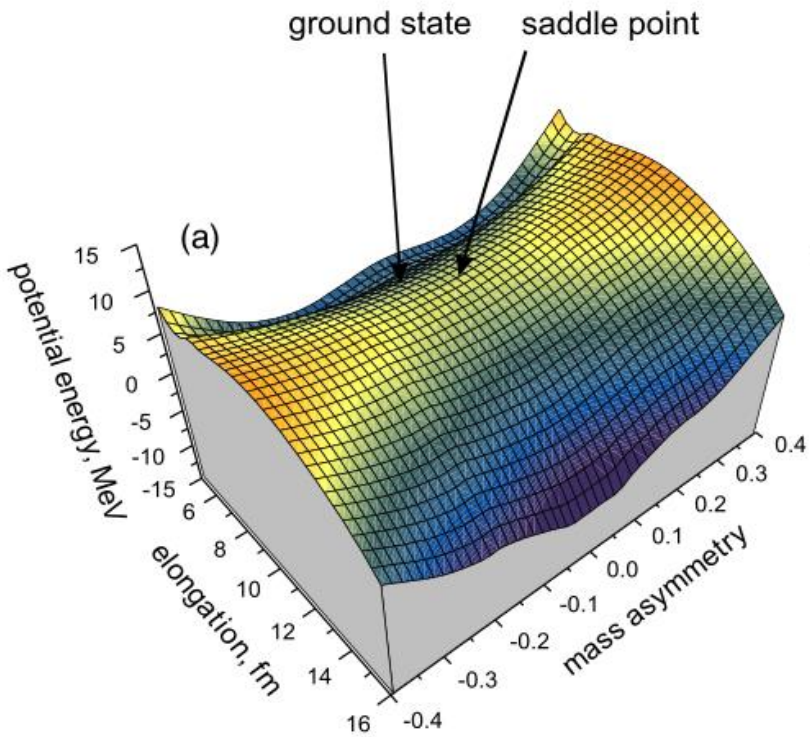
Fragments start to emerge, they are deformed

Fragments separate at scission

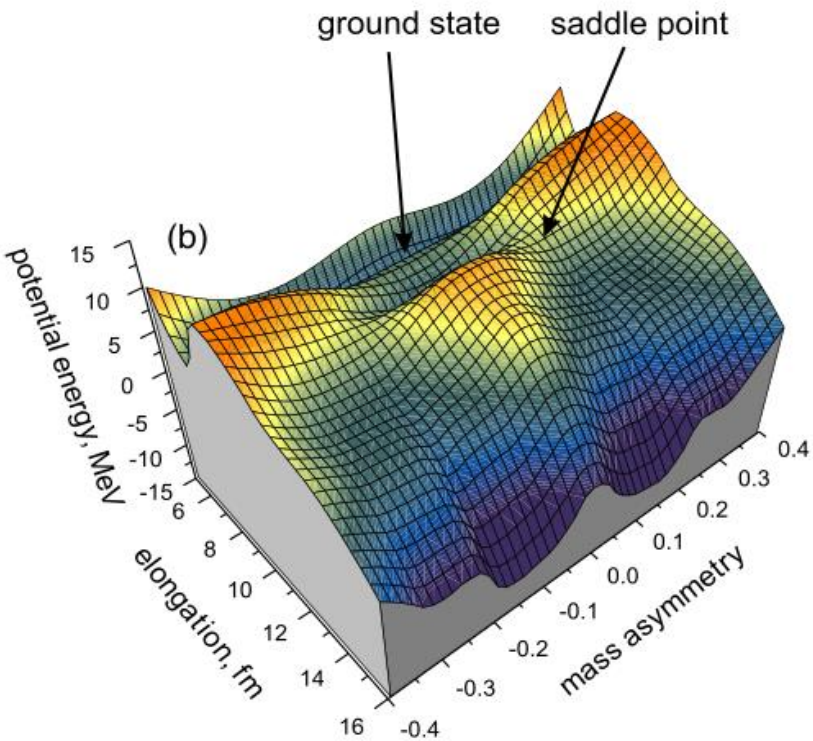
Fragments recover smaller deformation
E* released by neutron emission

E* released by gamma-ray emission

Potential-energy landscape for fission



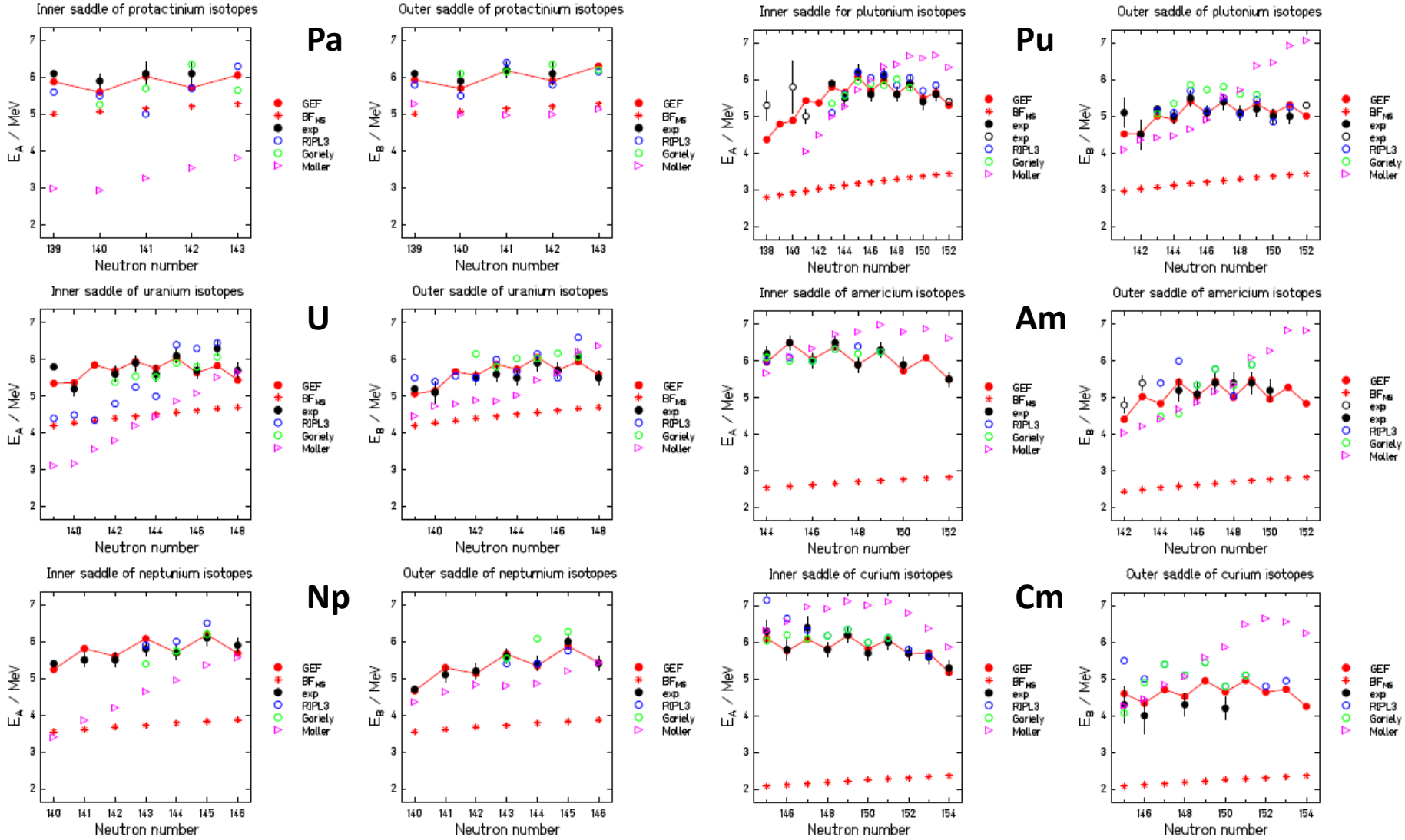
Liquid-drop potential



With shell effects

A. V. Karpov, A. Kelic, K.-H. Schmidt, J. Phys. G: Nucl. Part. Phys. 35 (2008) 035104

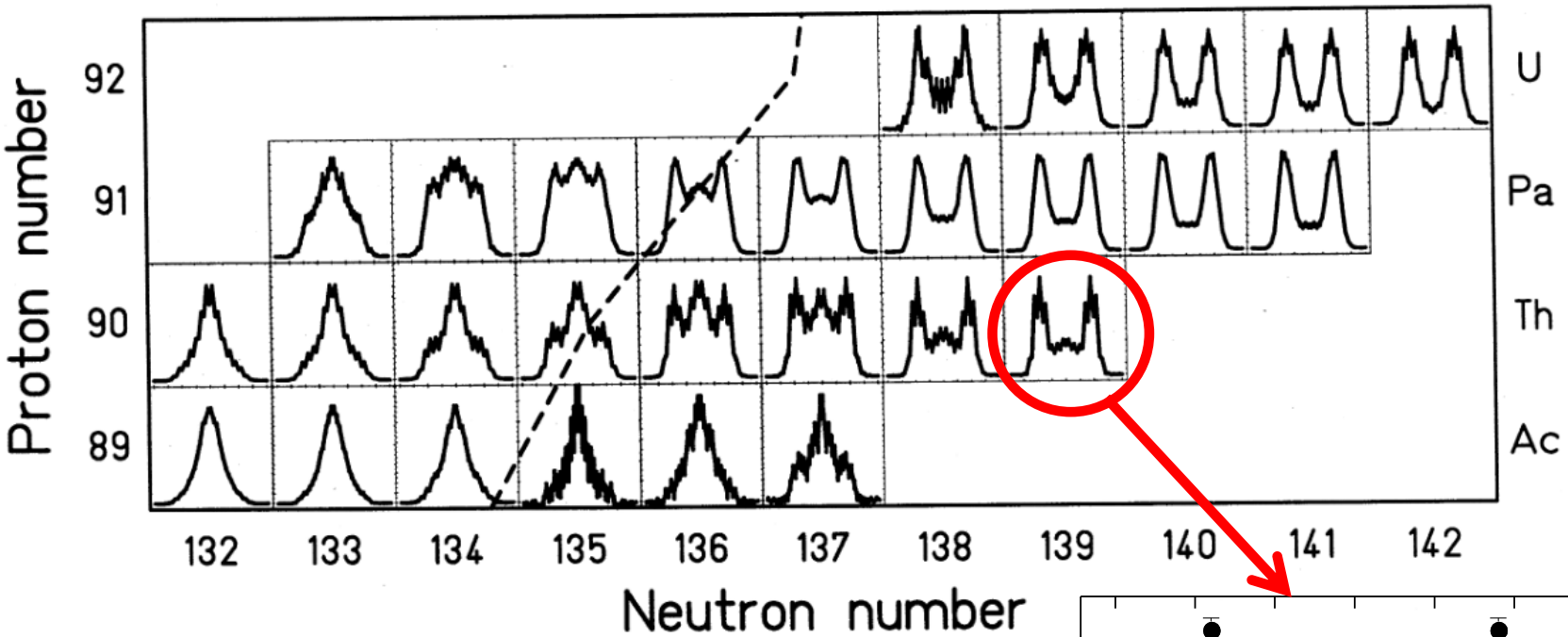
Interest of systematic fission studies over long isotopic chains: fission barriers

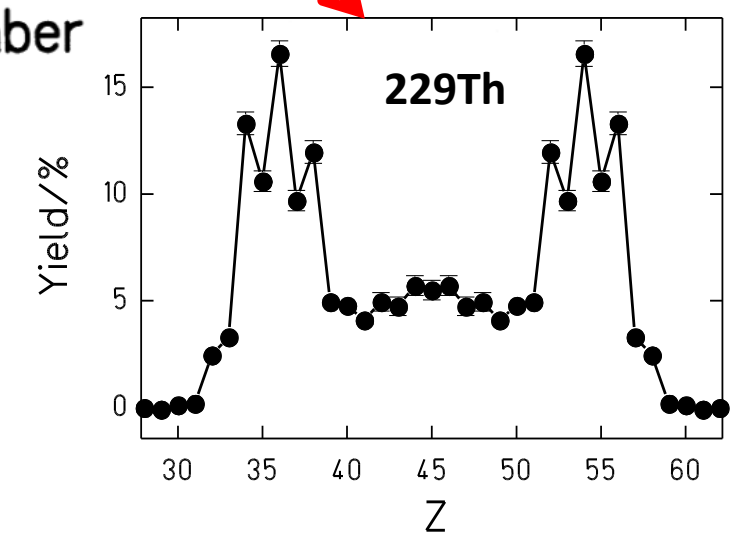


Unique possibility to study shell and pairing effects at large deformation!

Interest of systematic fission studies over long isotopic chains: elemental fission-fragment yields

K.-H. Schmidt et al., Nucl. Phys. A 665 (2000) 221

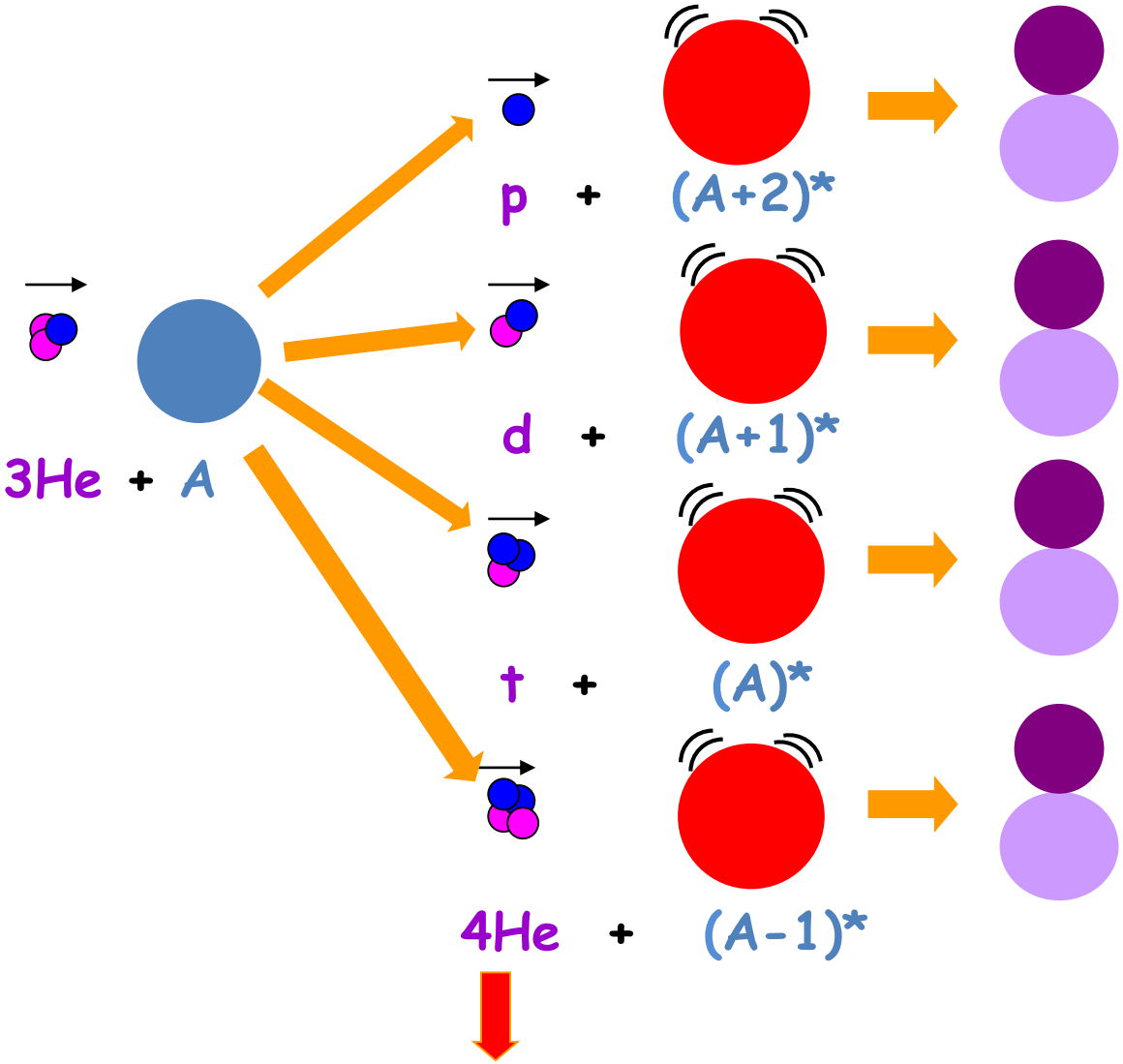




Interplay between macroscopic, shell and pairing effects!

Fission probabilities

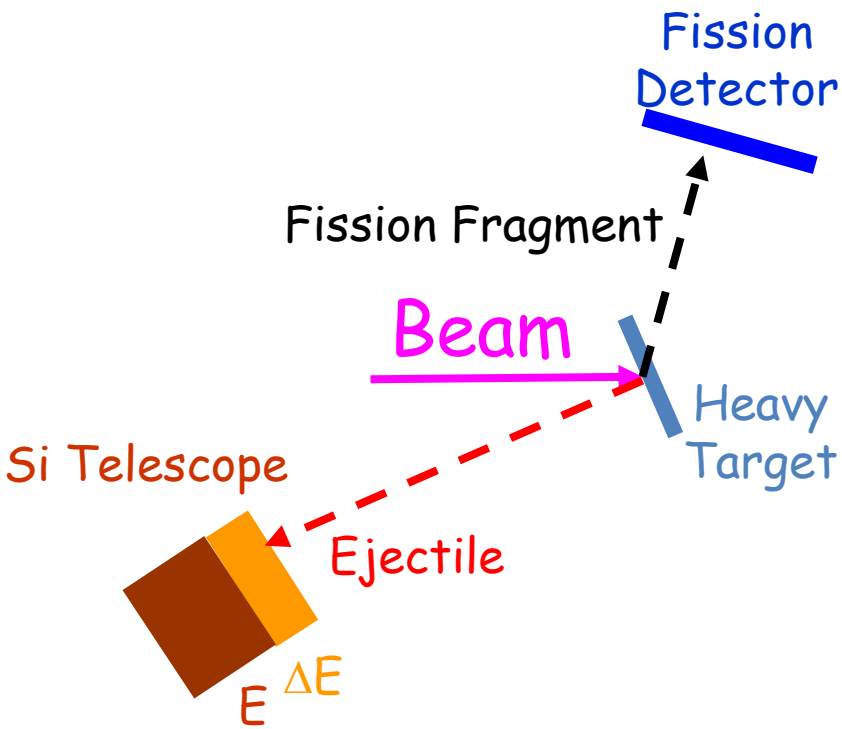
Transfer-induced fission reactions

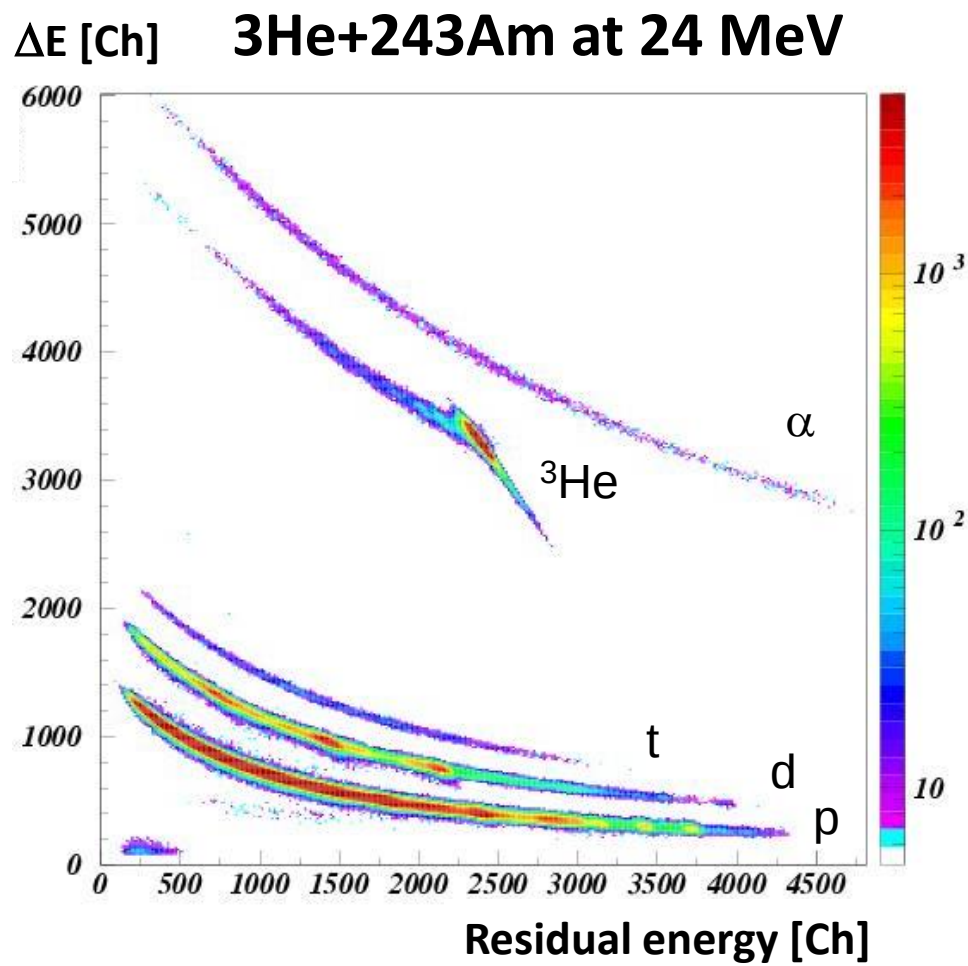


Ejectile: identification of fissioning nuclei and determination of E*

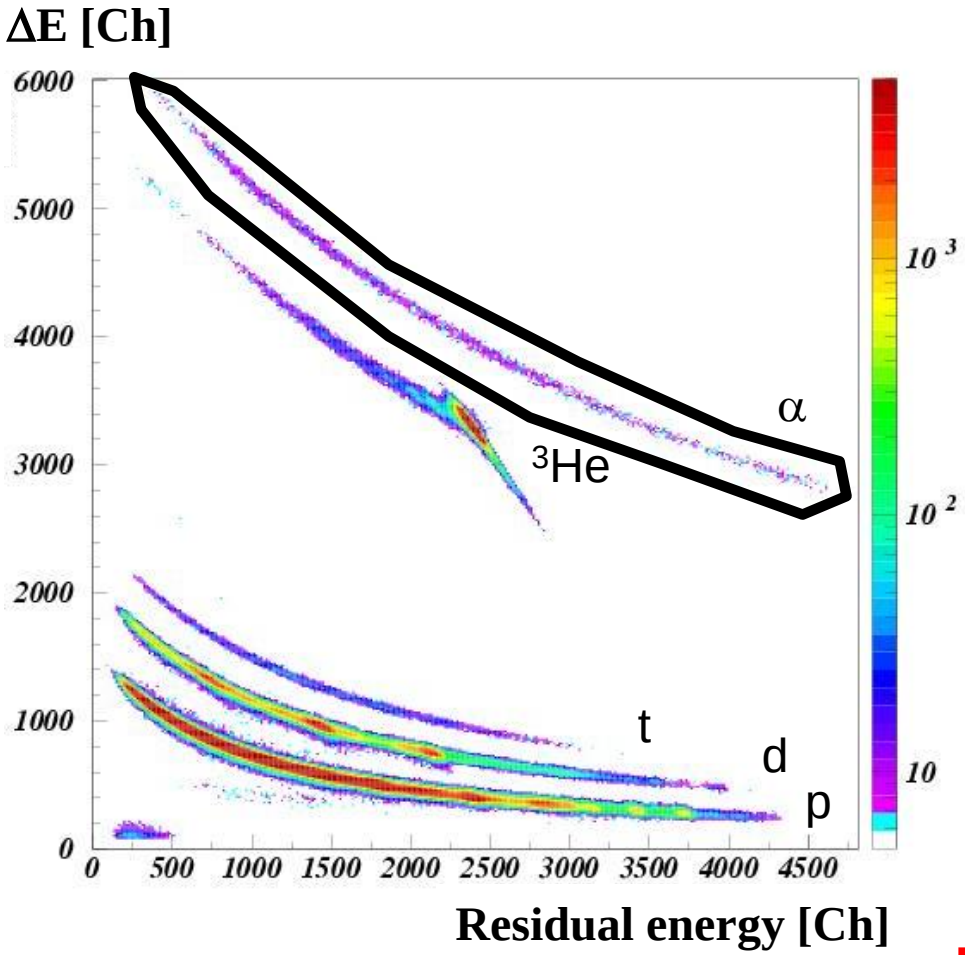
- Various fissioning nuclei can be produced simultaneously with one single projectile-target combination
- Wide range of excitation energy can be populated with one single beam energy

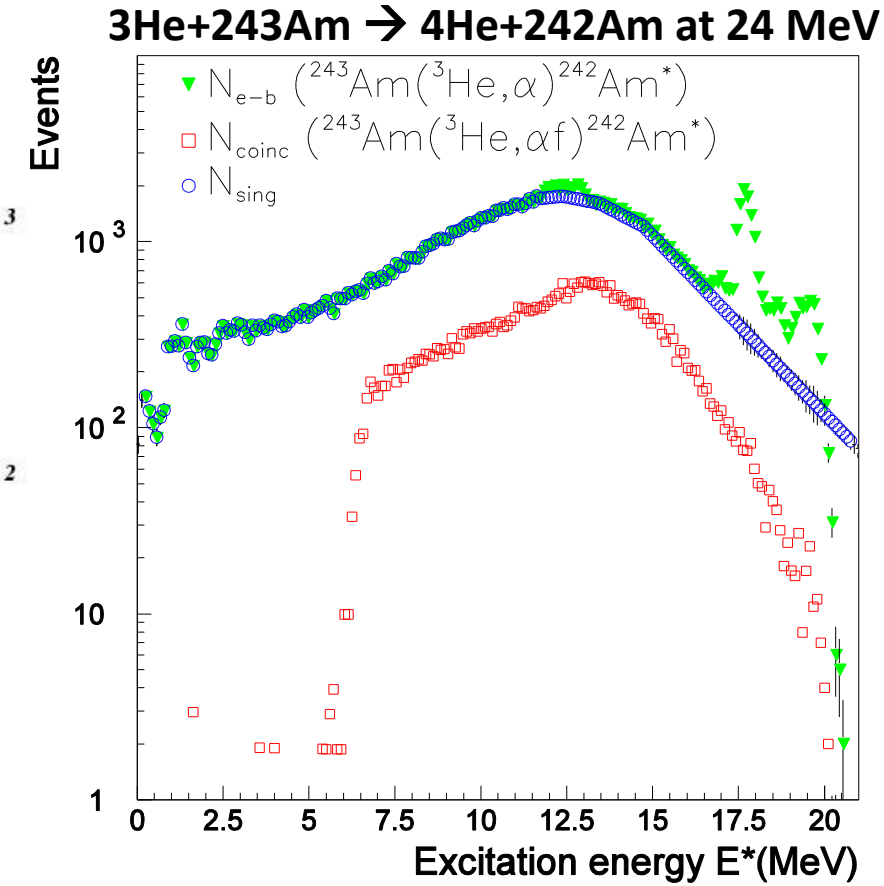
Typical setup for fission probability measurements in direct kinematics





Determination of fission probabilty



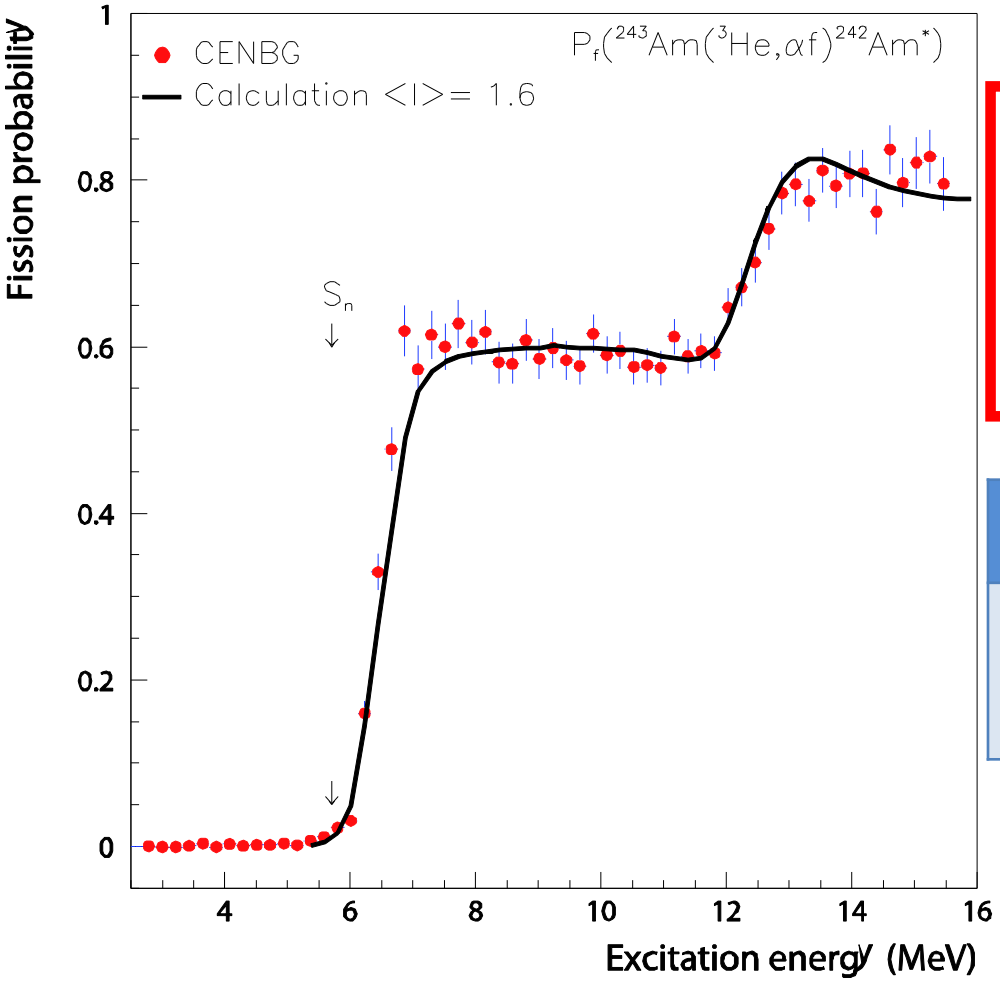


$$P_{fission}(E^*) = \frac{N^{coin}_{ejec-fission}(E^*)}{N_{ejec}(E^*)\cdot \varepsilon_{fission}(E^*)}$$

Excitation-energy resolution of the order of 100 keV or better is needed!
Target-contaminant issue!

Exploring the fission barrier via the fission probability

3He+243Am → 4He+242Am at 24 MeV



Comparison with a statistical model calculation gives barrier heights and level structure information on top of the barrier.

First barrier	Second barrier
6.4 ± 0.1 MeV	5.8 ± 0.7 MeV

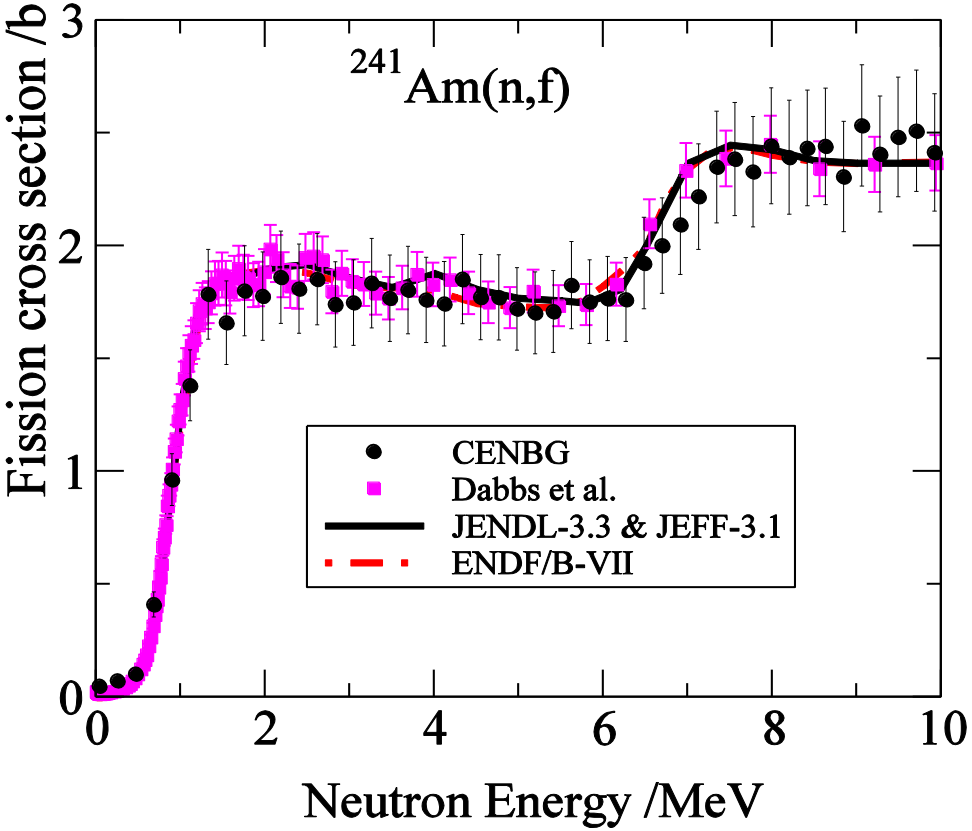
G. Kessedjian, B. Jurado et al., Phys. Rev. C 91 (2015) 044607

Derivation of neutron-induced fission cross sections

Compound nucleus concept (statistical equilibrium), decay independent from formation:

$$\sigma_{n,f}^{A}(E_n) = \underbrace{\sigma_{CN}^{A+1}(E_n)}_{\text{Theory}} \cdot \underbrace{P_f^{A+1}(E^*)}_{\text{Experiment}}$$

Optical model



Possibility to determine neutron-induced cross sections of very short-lived nuclei!!
Interesting for astrophysics and reactor physics!

G. Kessedjian, B. Jurado et al., Phys. Lett. B 692 (2010) 297

Main limitations of direct kinematics experiments

- Only a limited number of fissioning nuclei can be investigated because of the lack of targets

- Background due to target backing and target contaminants.

Transfer-induced reactions in inverse kinematics with radioactive ion beams

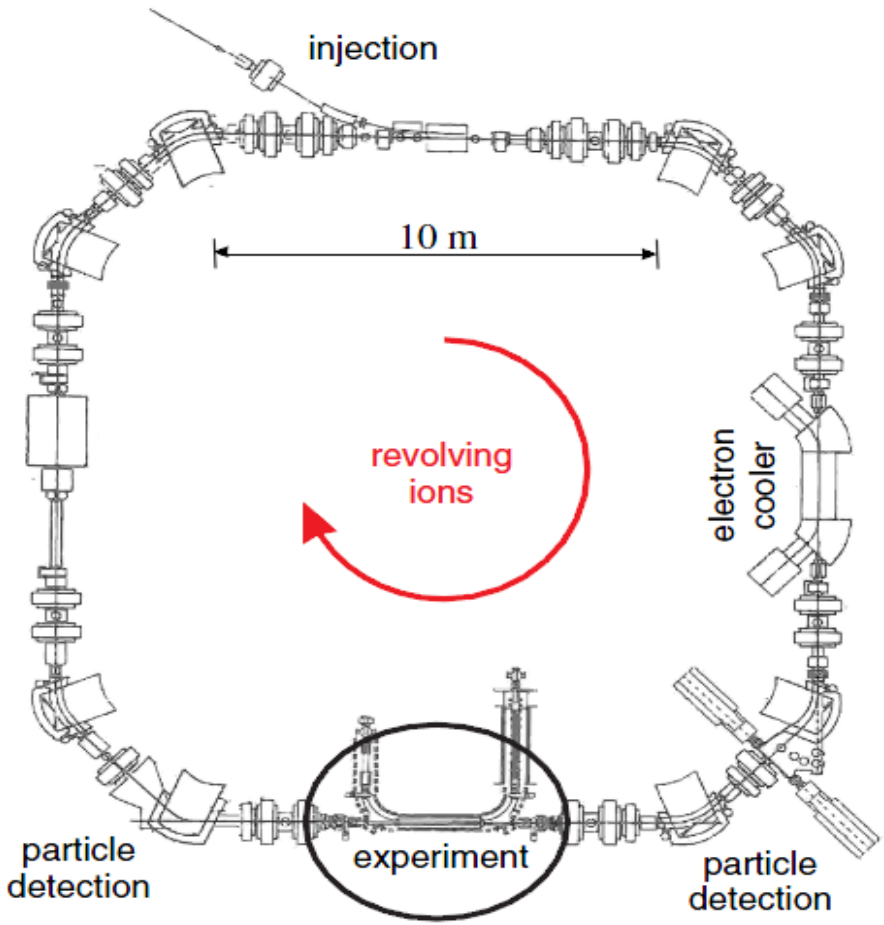
HIE-ISOLDE heavy beams:

Element	Isotopic chain	Half lifes
Rn (Z=86)	$^{204-212}$Rn $^{219-221}$Rn	$2.4h \leq T_{1/2} \leq 28.5min$ $3.96s \leq T_{1/2} \leq 25min$
Fr (Z=87)	$^{207-213}$Fr $^{220-228}$Fr	$14.8s \leq T_{1/2} \leq 20min$ $27.4s \leq T_{1/2} \leq 21.8min$
Ra (Z=88)	$^{221-222,224-226,228}$Ra	$28s \leq T_{1/2} \leq 1600y$

Systematic studies over unprecedented isotopic chains, access to unexplored regions!!!

With transfer reactions we can increase the Z and N slightly but would it be possible to produce and accelerate even heavier nuclei, e.g. Ac, Th, Pa, U?

Interest of using the Test Storage Ring (TSR)



- Use of cooled beams →Much better E* resolution (needed to explore the fission threshold)

- In-ring measurements with gas-jet targets→ Pure targets (no contaminants, no backing), limited straggling!!

- Experiment to demonstrate the feasibility : 232Th+3He → because data already exists to which we can compare!

$^{232}Th+^{3}He$, populated reactions

Reaction	Q-value [MeV]
$^{232}Th+^{3}He \rightarrow ^{232}Th+^{3}He'$	0
$^{232}Th+^{3}He \rightarrow ^{231}Th+^{4}He$	14.14
$^{232}Th+^{3}He \rightarrow ^{232}Pa+t$	-0.513
$^{232}Th+^{3}He \rightarrow ^{233}Pa+d$	-0.244
$^{232}Th+^{3}He \rightarrow ^{234}Pa+p$	2.75
$^{232}Th+^{3}He \rightarrow ^{235}U$	9.46

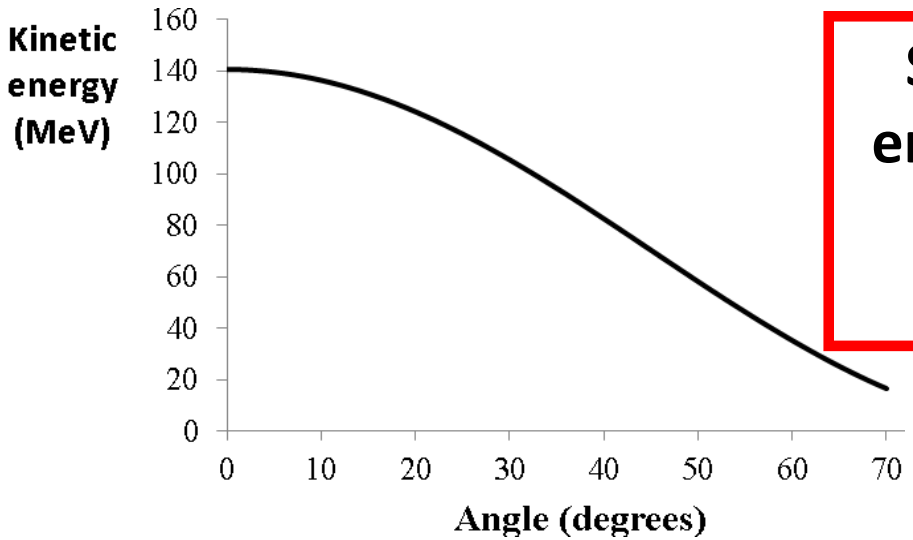
Cross section (^{3}He,xf)
~10 mb

Fusion-fission cross section
~800 mb at 10 A MeV
~500 mb at 9 A MeV

Optimum beam energy 9 A MeV

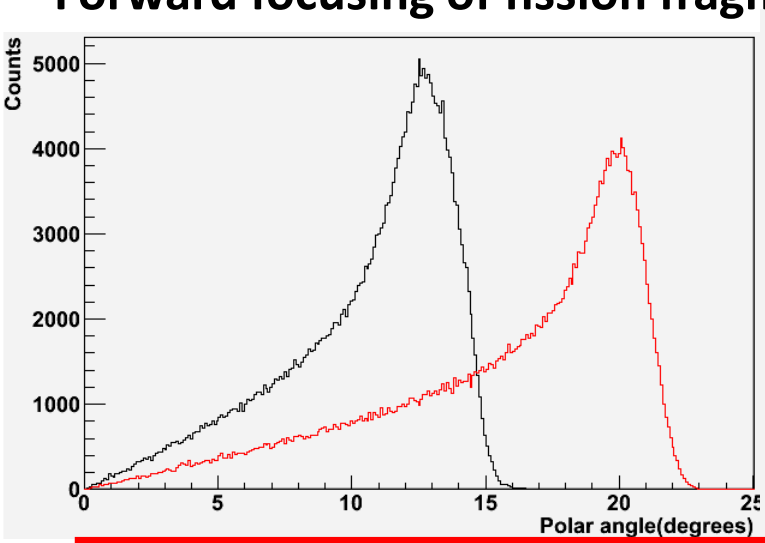
Kinematics considerations

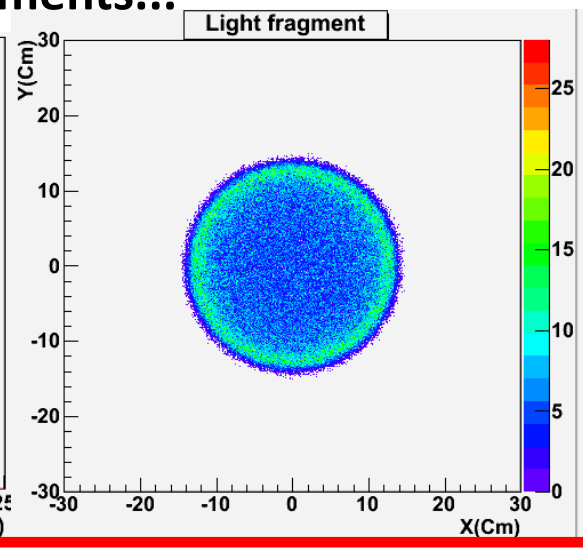
232Th+3He→231Th+4He at 9 A MeV and E*= 5 MeV

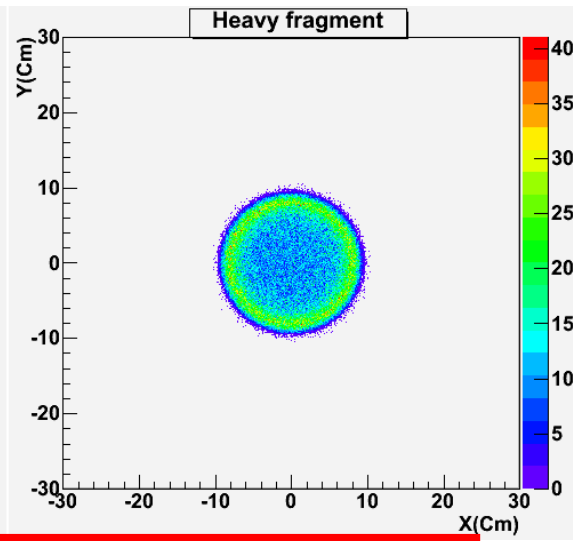


Strong dependence of kinetic energy of target-like nuclei with angle.
High segmentation required!

Forward focusing of fission fragments...

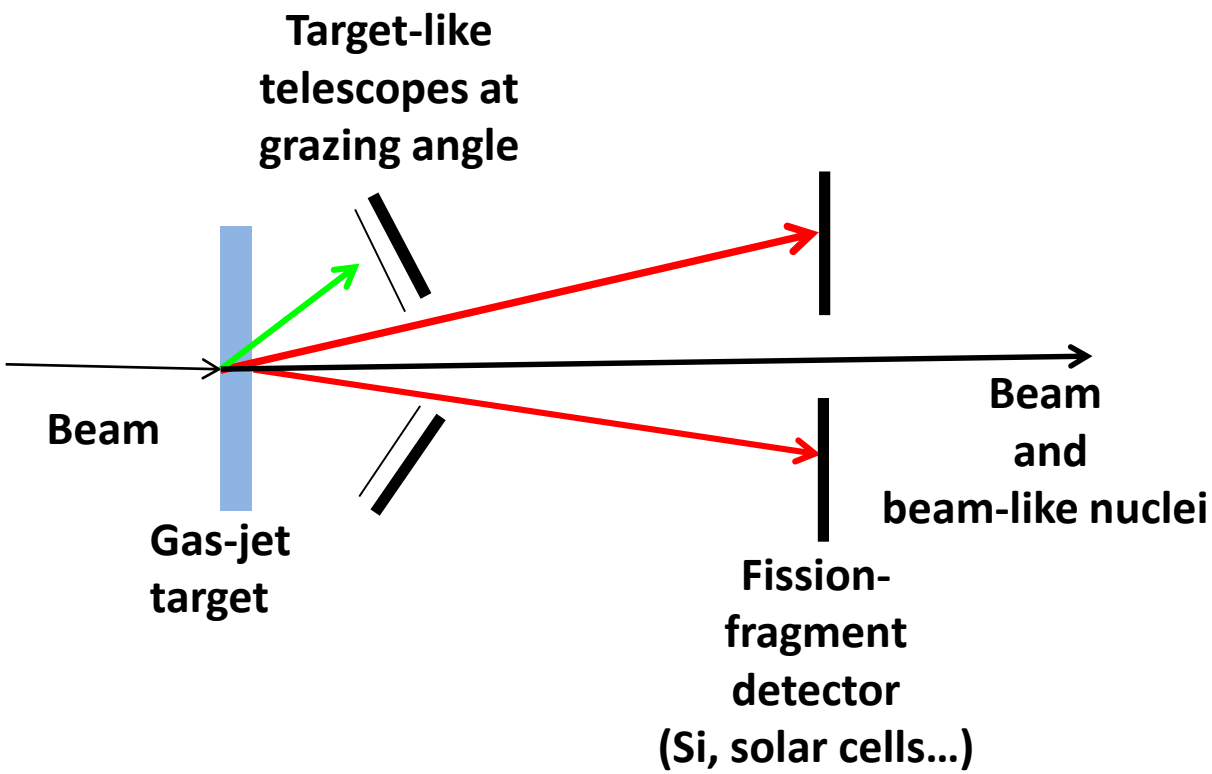






Very high fission efficiency: 97% at 35 cm and 53% at 70 cm!

Possible set-up for fission-probability measurements in the TSR



Counting rates:

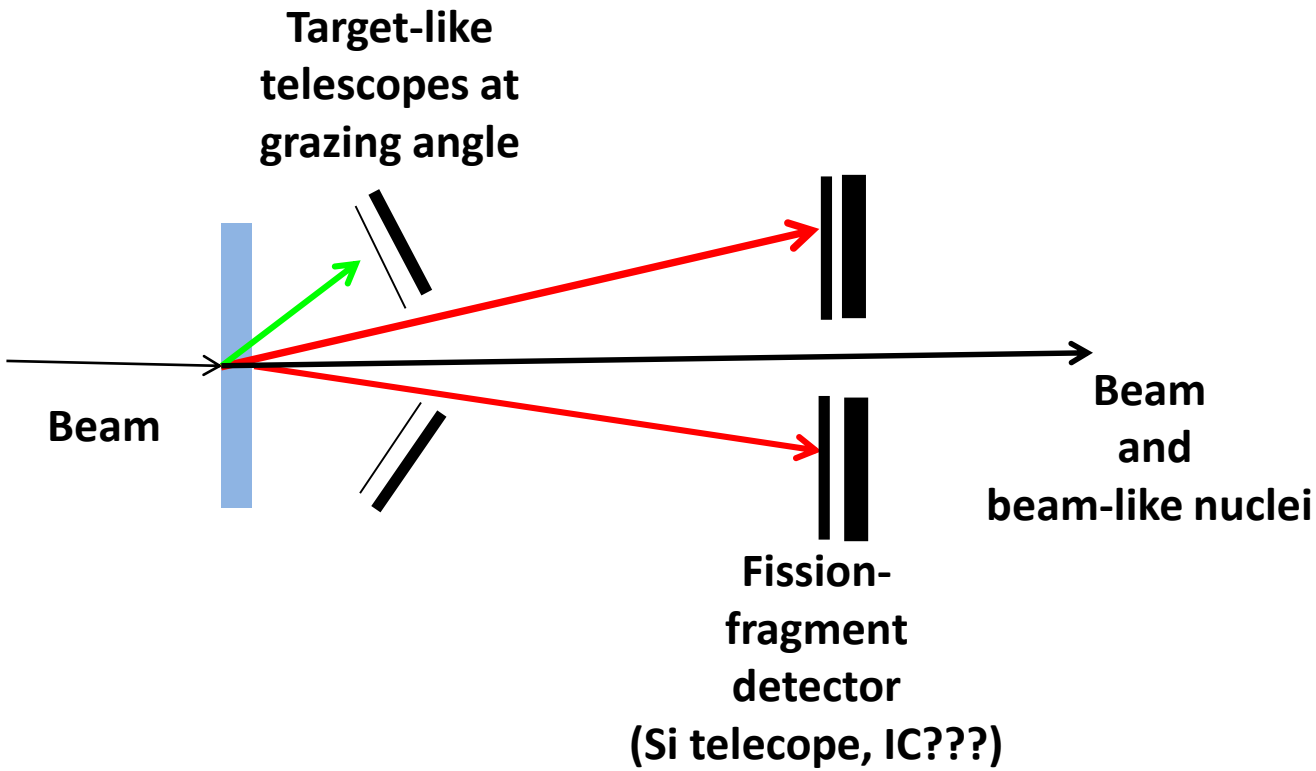
Fission cross section for a transfer channel ~1 mb

10% solid angle of 3He-like telescope, 45% fission efficiency

Required luminosity for measurement in 10 days: ~ $1 \cdot 10^{27}$ $cm^{-2} \cdot s^{-1}$

Maximum possible luminosity estimated by Manfred: ~ $1.8 \cdot 10^{27}$ $cm^{-2} \cdot s^{-1}$

More sophisticated setup: identification in charge of fission fragments…



Measurements of yields as a function of E*, unique! Not possible at GSI…

Identify light fragments in charge with a high-quality Si telescope?
Use of gaseous detectors in UHV??

Conclusions

- **Fission probabilities and fission-fragment elemental distributions are very sensitive to the potential energy and allow one to investigate the interplay between macroscopic, shell and pairing effects at very large deformation**
- **These quantities are interesting for applications in nuclear technology and for astrophysics**
- **HIE-ISOLDE offers a unique possibility to perform systematic fission studies over unprecedented long isotopic chains in unexplored regions**
- **HIE-ISOLDE + TSR is just the right place to do fission probability measurements of RIB: good E* resolution and pure targets!**
- **Interest in developing more and more sophisticated in-ring set-ups to measure more and more fission observables...**