Transfer induced fission of very neutron-deficient nuclei - a method to measure fission barrier height

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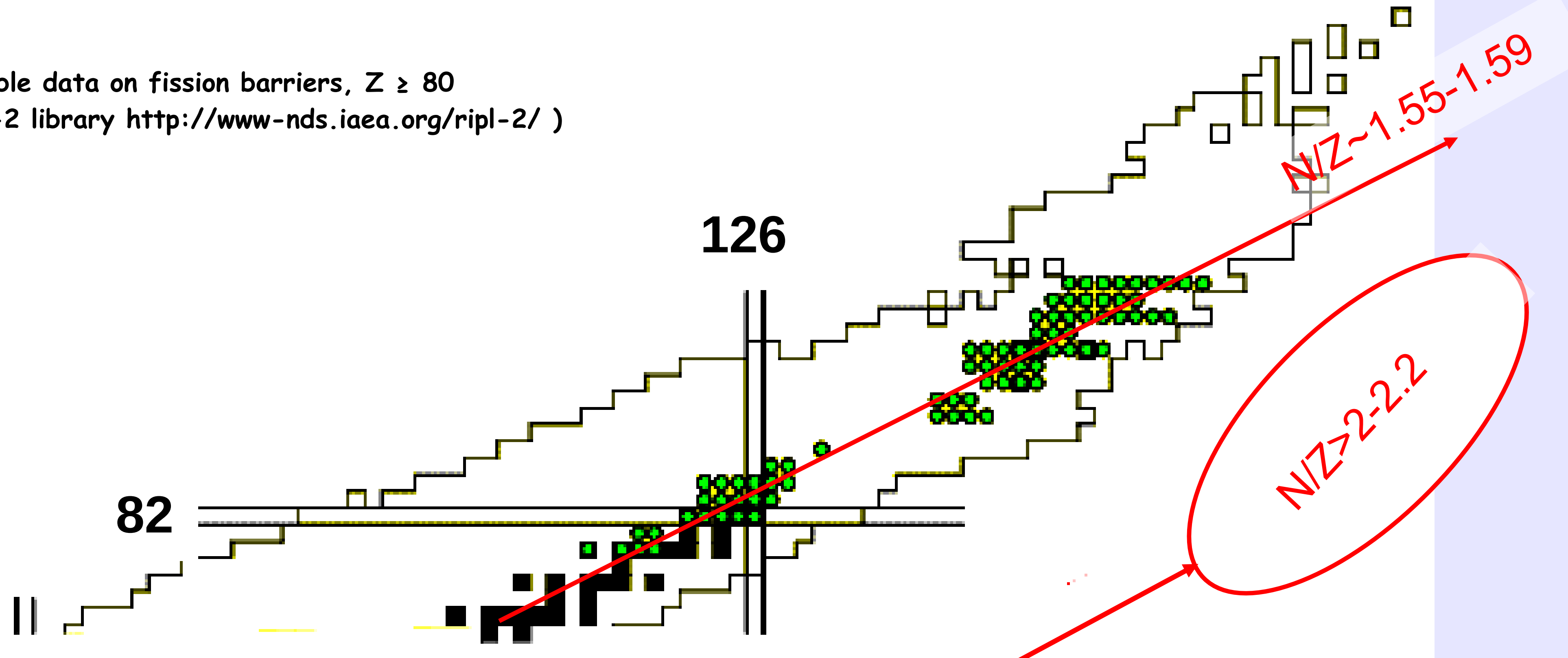
Fission barriers – what do we know about them?

- Experimentally fission barriers B_f are known only in the vicinity of the beta stability line (e.g. N/Z(^{238}U)=1.59)
- Theoretical models for B_f have been 'tuned' by using these data

Available data on fission barriers, Z ≥ 80
(RIPL-2 library http://www-nds.iaea.org/ripl-2/)



- For the r-process calculations we need fission data far away from stability: e.g. ^{260}Po or ^{270}U (N/Z>2!) – they might not be accessible in the Lab at all! – Use calculations?

Fission barriers of neutron-deficient nuclei

- extracted from evaporation residue cross sections (in channels with emission of several nucleons) using statistical model
- lower than predictions of model calculations by 15-25 % (Sierk), 30-40 % (Cohen-Plasil-Swiatecki).
- are the macroscopic barriers wrong or is it a problem with description of fission decay width ?

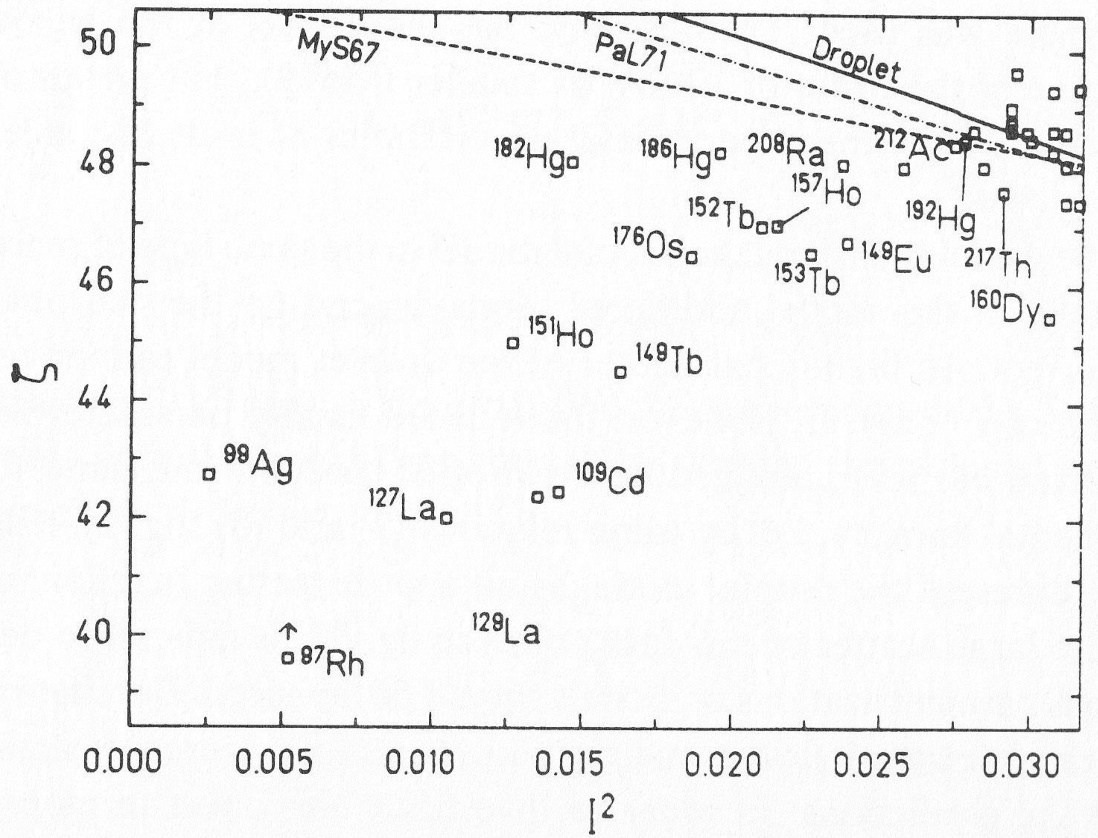


Fig. 7. Neutron-deficient part of fig. 5. The data points are marked with the element symbol and the mass number.

M. Dahlinger, D. Vermeulen and K.H. Schmidt, Nucl. Phys. A 376 (1982) 94

Statistical model

Survival probability is calculated as a product of emission probabilities over the whole cascade

cascade). The probability of a given decay channel i is

$$P_i(l) = \Gamma_i(l)/\Gamma_{tot}(l) \tag{7}$$

where $\Gamma_i(l), \Gamma_{tot}(l)$ represent the width of a decay channel i and the total decay width at a given de-excitation stage. The partial emission widths for particle emission are determined as

$$\Gamma_i(E,l) \propto (2l+1)(2s_i+1) \int_0^{E-E_B(l)-E_{rot}(l)} \rho(E - E_B(l) - E_{rot}(l) - \epsilon)\epsilon\sigma_i d\epsilon \tag{8}$$

and the fission width as

$$\Gamma_f(E,l) \propto (2l+1) \int_0^{E-B_f(l)-E_{rot}(l)} \rho(E - B_f(l) - E_{rot}(l) - \epsilon) d\epsilon \tag{9}$$

where ρ is the level density calculated using the Fermi gas formula [23] and σ_i the inverse cross section for particle emission, l again denotes the angular momentum, s_i the spin of the particle, E_B the binding energy of the particle, E_{rot} the rotational energy

$$E_{rot}(l) = \frac{\hbar^2 l(l+1)}{2\mathcal{J}} \tag{10}$$

Fission barrier is used as a cutoff parameter in the formula for fission width !
However, interplay with the level density parameter in fission channel (a_f/a_n) !

Evaporation residue cross sections – an example

22Ne+190Os → 212Rn*

Measured at VASSILISSA (Dubna)

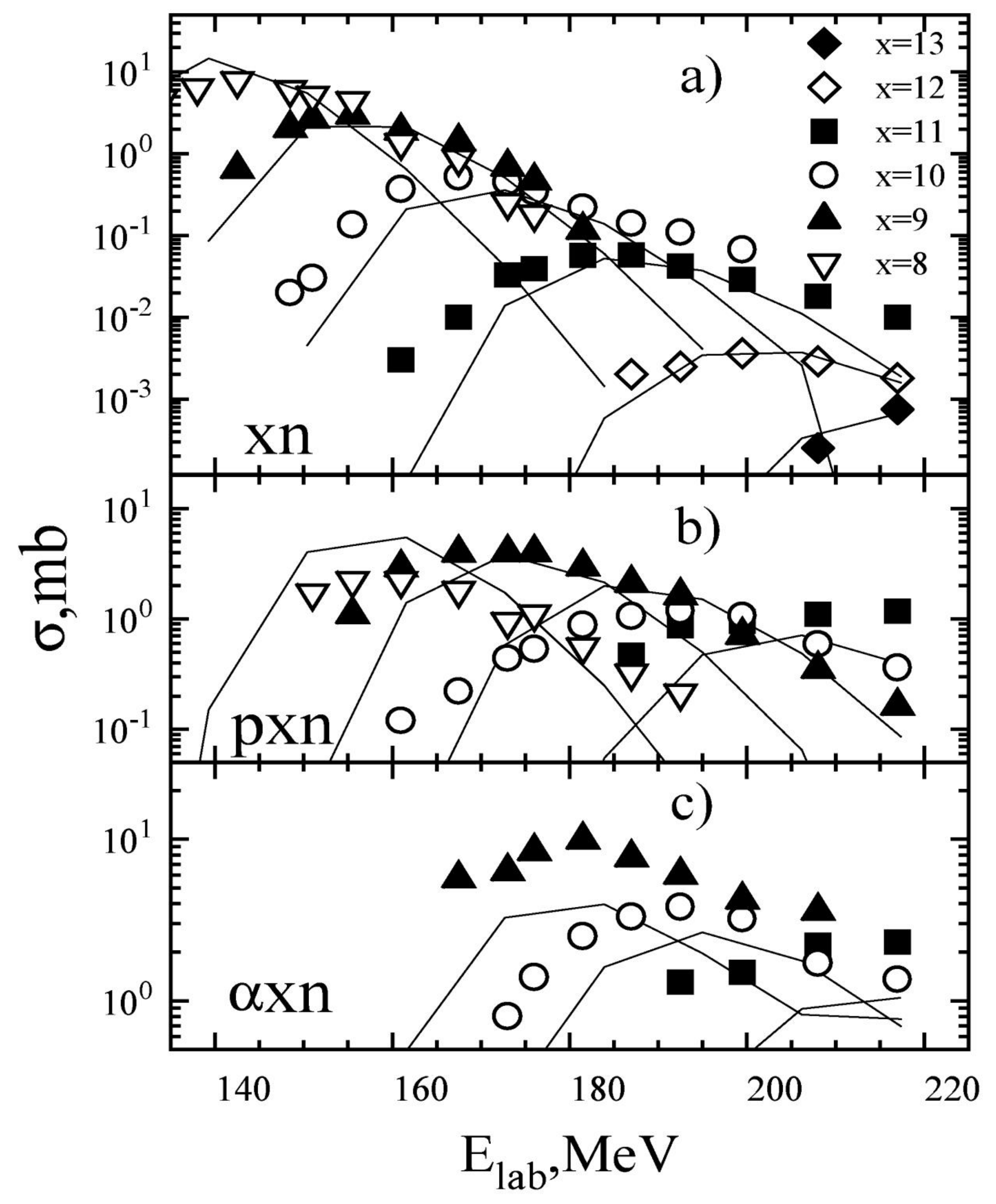
Up to 13 neutrons emitted

Γ_n/Γ_{tot} close to 1

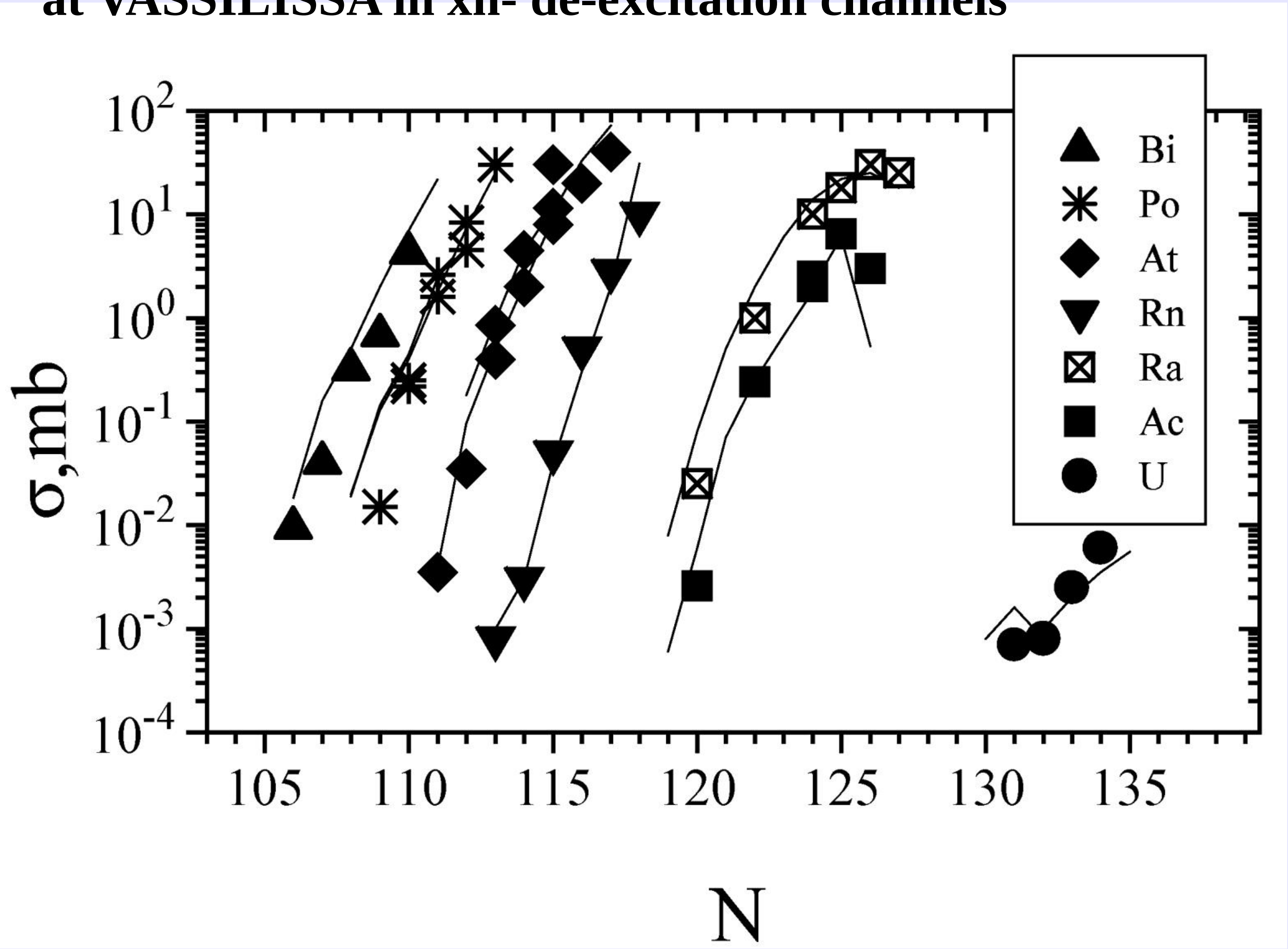
Fission barrier needs to be scaled down by 25 – 40 %

a_f/a_n close to 1 at high excitation energies

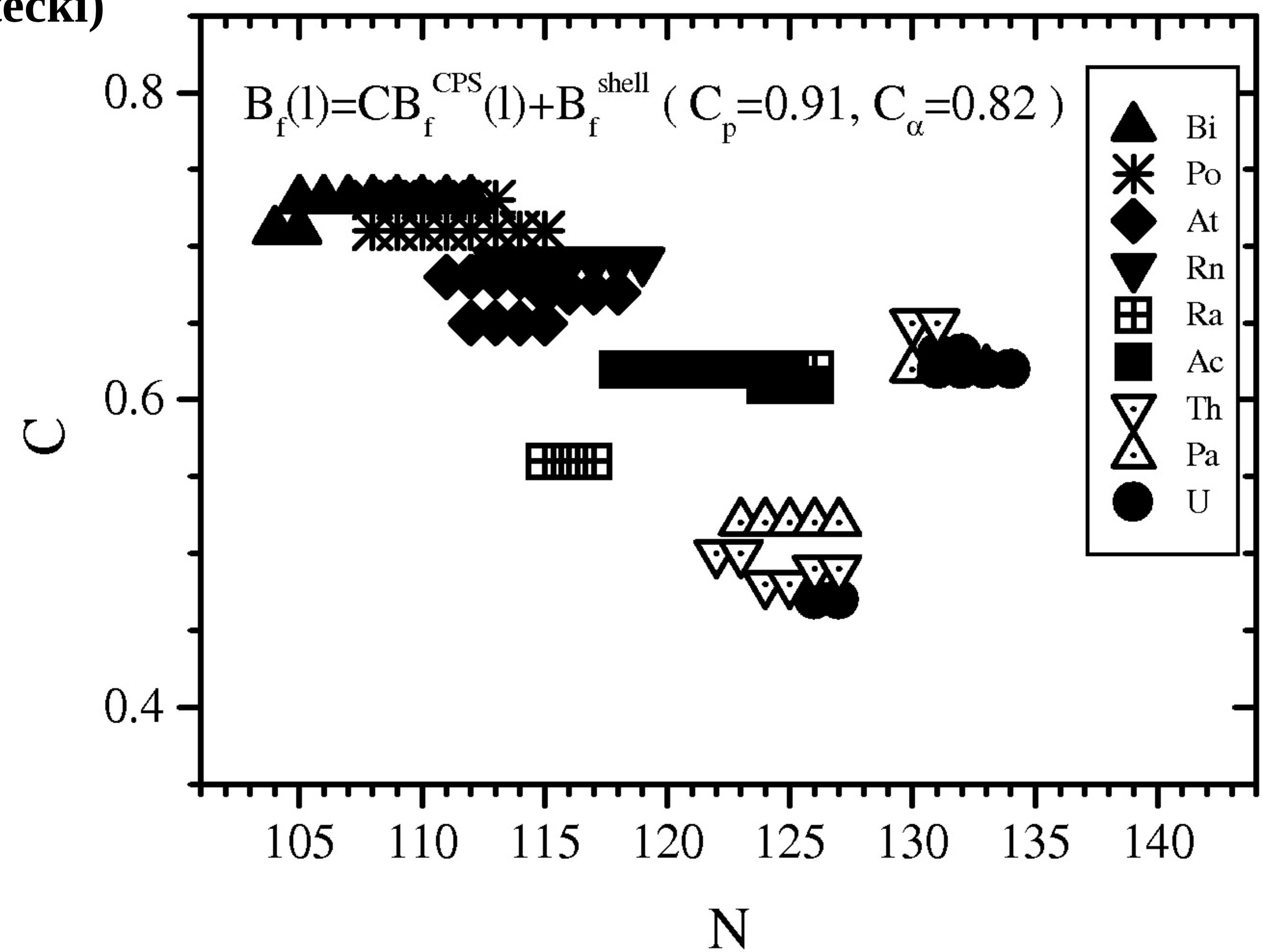
To reproduce pxn, αxn channels emission barriers need to be scaled down



Systematics of evaporation residue cross sections measured at VASSILISSA in xn- de-excitation channels



Systematics of extracted fission barriers – scaling factor C applied to macroscopic part (rotating liquid-drop barriers of Cohen-Plasil-Swiatecki)



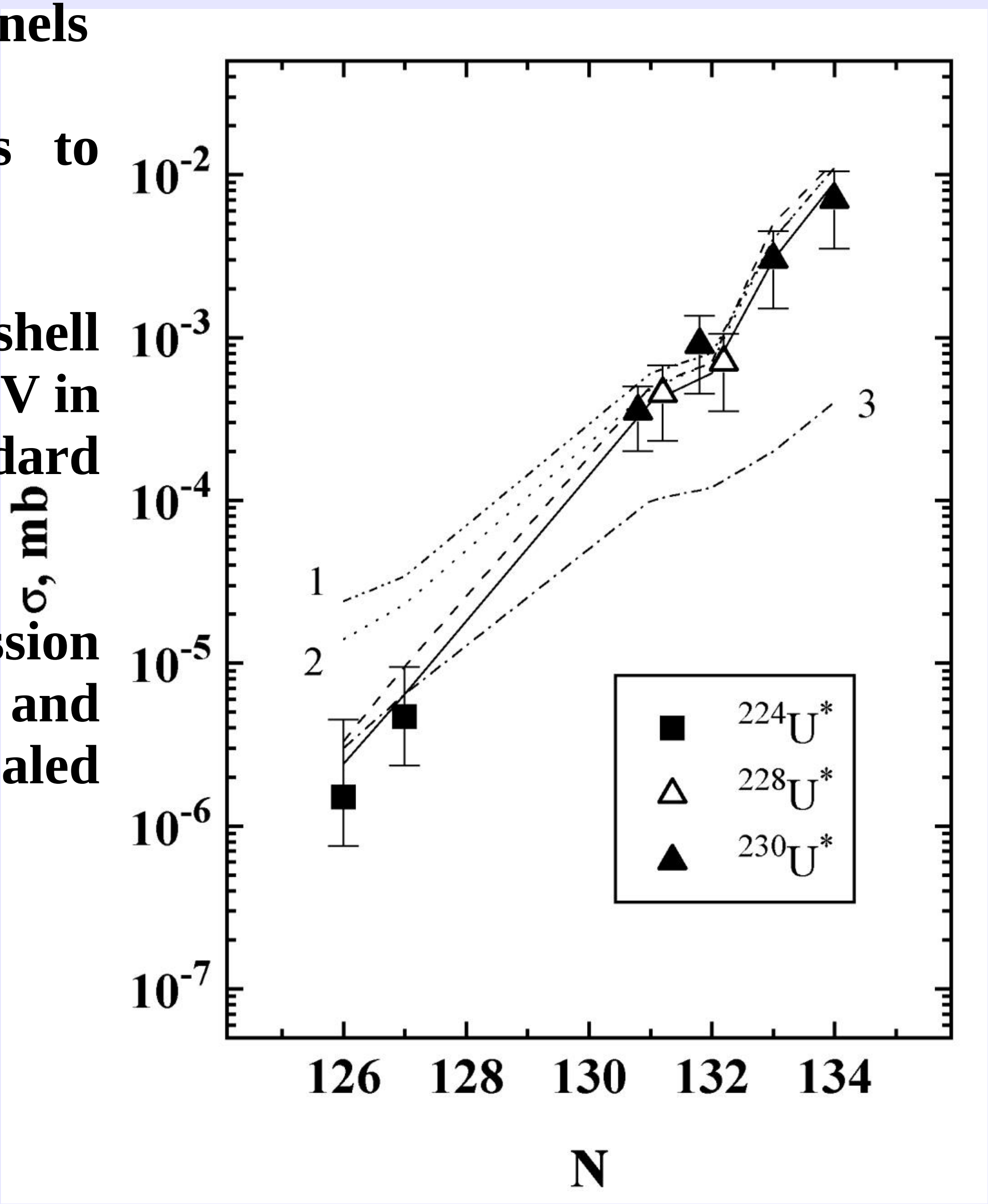
Different values on and off the N=126 neutron shell !
Why macroscopic barrier would be influenced by shell structure ?

Uranium isotopes produced in xn-channels

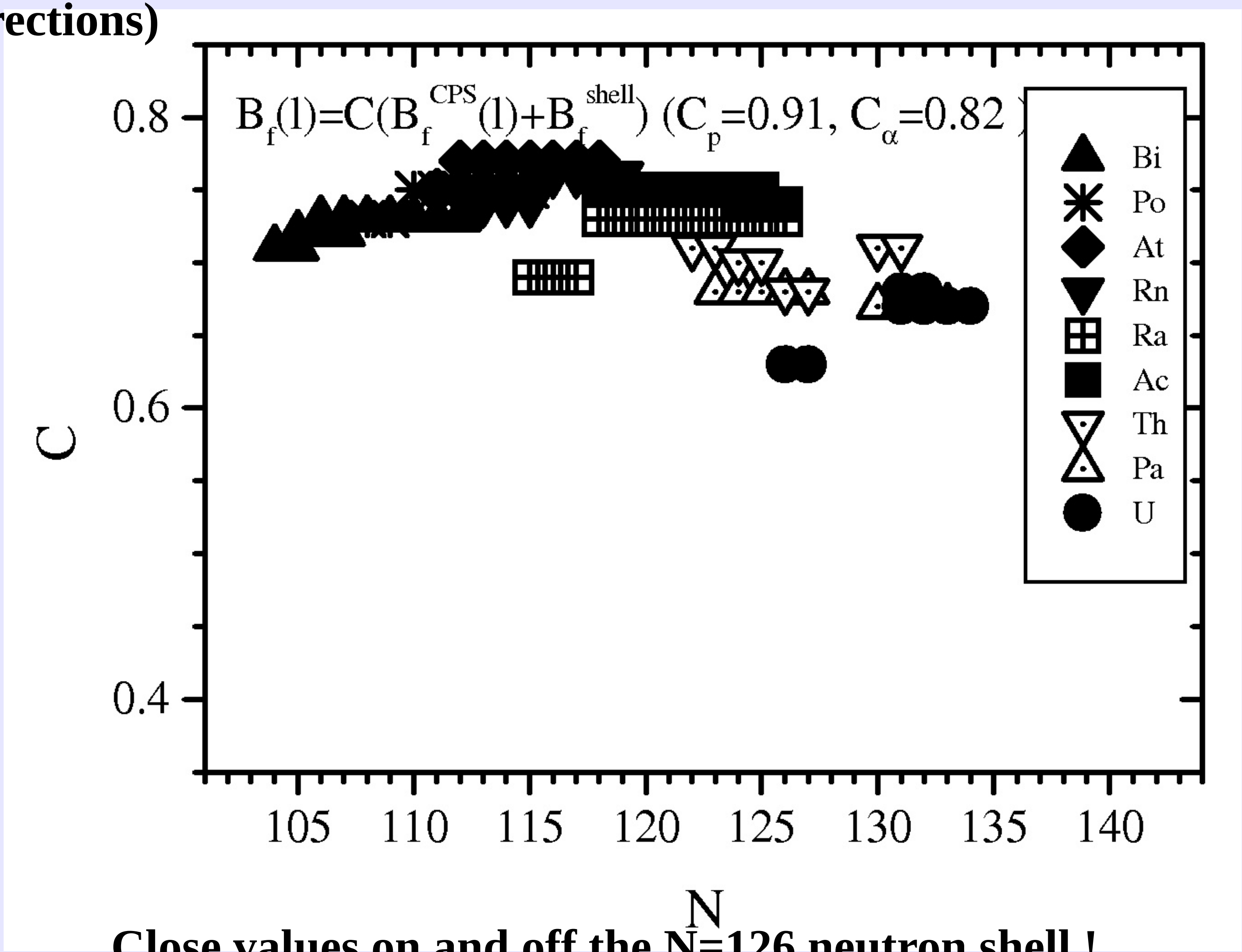
Largest variation of scaling factors to macroscopic part of fission barriers

Excluded the "disappearance" of shell structure (K.H. Schmidt et al., D=6 MeV in the Ignatyuk's formula instead of standard value D=18.5 MeV)

Common scaling factor if full fission barrier (sum of macroscopic barrier and ground-state shell correction) is scaled down.



Systematics of extracted fission barriers – scaling factor C applied to full fission barrier (sum of liquid-drop barriers of Cohen-Plasil-Swiatecki and g.s. shell corrections)



Close values on and off the N=126 neutron shell !
What is the physics behind such scaling ?
Implications for synthesis of super-heavy nuclei ?

Conclusions I:

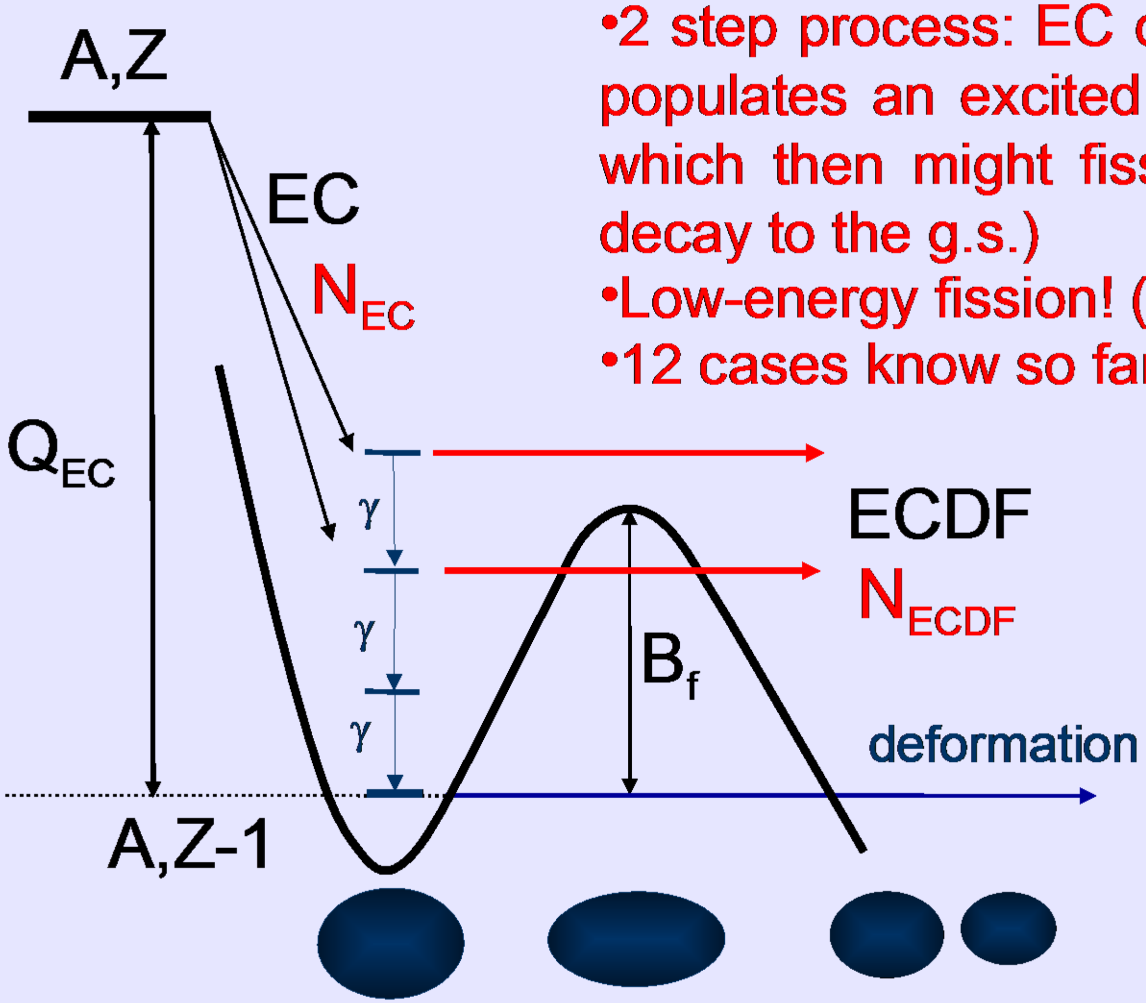
Fission barrier heights extracted from evaporation residue cross sections using statistical model indicate discrepancy with model values.

However, similar result from really low energy fission (E^* < 10 MeV, ideally below neutron separation energy) is needed as confirmation !!!

Electron-Capture Delayed Fission (ECDF, $T_{1/2}(ff)=T_{1/2}(EC)$)

Discovery: parent isotopes ^{232,234}Am(1966, Dubna)

•2 step process: EC decay of a parent (A,Z) nucleus populates an excited state in the (A,Z-1) daughter, which then might fission (in competition with the γ decay to the g.s.)
•Low-energy fission! (E*~5-10 MeV)
•12 cases know so far (neutron-def. Uranium region)



EC-delayed branch

$$P_{ECDF} = \frac{N_{ECDF}}{N_{EC}}$$

P_{ECDF} depends strongly on:
- Q_{EC} of the parent: the higher Q_{EC}, the larger the P_{ECDF}
- B_{fis} of the daughter: the lower B_{fis}, the larger the P_{ECDF}
- Actually, $Q_{EC}-B_{fis}$ is important

ECDF Probability: Feeding Part & Decay Part

$$P_{ECDF} = \frac{N_{ECDF}}{N_{EC}} = \frac{\int_0^{Q_{EC}} \mathbf{F}(Q_{EC}-E)\cdot S_\beta(E)\,\frac{\Gamma_f(E)}{\Gamma_{tot}(E)}\,dE}{\int_0^{Q_{EC}} \mathbf{F}(Q_{EC}-E)\cdot S_\beta(E)\,dE}$$

F(Q_{EC}-E) – phase space factor for EC/**β**$^+$ decay, $(Q_{EC}-E)^2$ for EC, $(Q_{EC}-E)^5$ for **β**$^+$

$S_\beta(E)$ – **β**-strength function (nuclear matrix element)

Measurement of P_{EDCF} allows to deduce Fission Barrier B_f

Fission barriers extracted from probability of EC-delayed fission for ^{180}Tl:

Experimental value : for ^{180}Tl - $P_{bdf} = 3.2(2) \cdot 10^{-5}$

Fission barrier of ^{180}Hg- HIVAP-like statistical model analysis (fission and gamma emission included, variant A, pairing gap in the saddle the same as in g.s.) :

- flat strength function (in the range Δ - Q_{EC}), $B_f = 7.34$ MeV
- strength func., Möller et al., parent nucl. with g.s. deformation, $B_f = 6.76$ MeV
- strength func., Möller et al., daughter nucl. with g.s. deformation, $B_f = 7.23$ MeV
- strength func., Staudt et al., $B_f = 6.77$ MeV

Theoretical values

Möller et al., 2009, $B_f = 9.81$ MeV

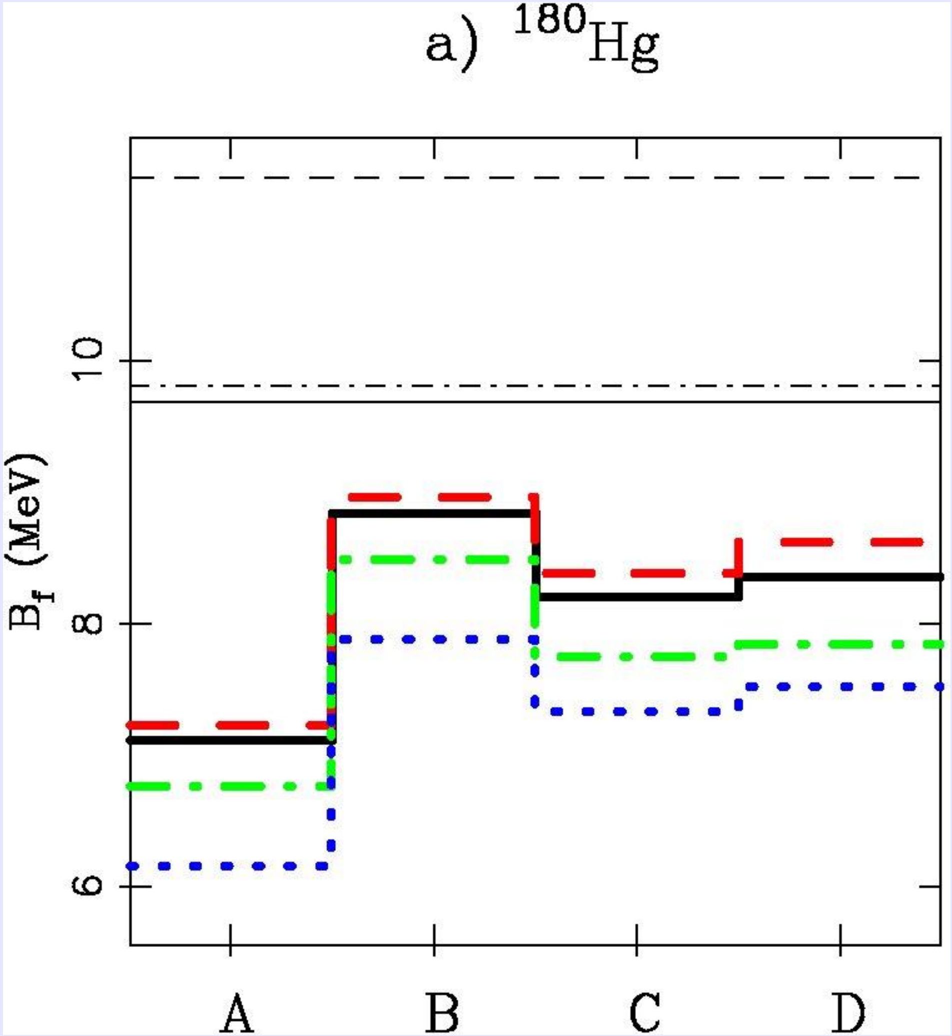
B_f(Sierk), shell corr. Möller and Nix 1981, $B_f = 9.69$ MeV

B_f(Cohen,Plasil,Swiatecki), shell corr.Myers and Swiatecki 1967, $B_f = 11.40$ MeV

EC-delayed fission of ^{180}Tl

$P_{bdf} = 3.2(2) \cdot 10^{-5}$
(obtained by the experiment IS466 at ISOLDE)

- used to deduce fission barrier height of the daughter isotope ^{180}Hg.
- four alternative strength functions (thick lines) and four variants of statistical calculations (A-D) are used to determine the fission barrier. A-C – Fermi-gas level density formula, D – Gilbert-Cameron formula, pairing see explanation below figure.
- deduced fission barriers appear to be 10-40 % smaller than theoretical estimates (thin lines), thus apparently confirming the results from compound nucleus reactions.
- uncertainty in determined fission barrier heights results dominantly from uncertainty concerning the magnitude of the pairing gap in the saddle configuration. Possible solution: study fission of odd-odd nuclei
- analogous results for ^{178}Tl, ^{188}Bi, ^{196}At



FG level density, full pairing at the saddle	FG level density, no pairing at the saddle	FG level density, no pairing at all	G-C level density, no pairing at the saddle

Fission barriers extracted from probability of EC-delayed fission for ^{178,}Tl:

Experimental value : for ^{178}Tl - P_{bdf} = 1.5(6) . 10^{-3}

Fission barrier of ^{178}Hg- HIVAP-like statistical model analysis (fission and gamma emission included, variant A, pairing gap in the saddle the same as in g.s.) :

- variant A, flat strength function (in the range Δ - Q_{EC}), B_f = 6.48 MeV
- variant B, flat strength function (in the range Δ - Q_{EC}), B_f = 8.22 MeV
- variant C, flat strength function (in the range Δ - Q_{EC}), B_f = 7.50 MeV
- variant D, flat strength function (in the range Δ - Q_{EC}), B_f = 7.36 MeV

Theoretical values

Moller et al., 2009, B_f = 9.32 MeV

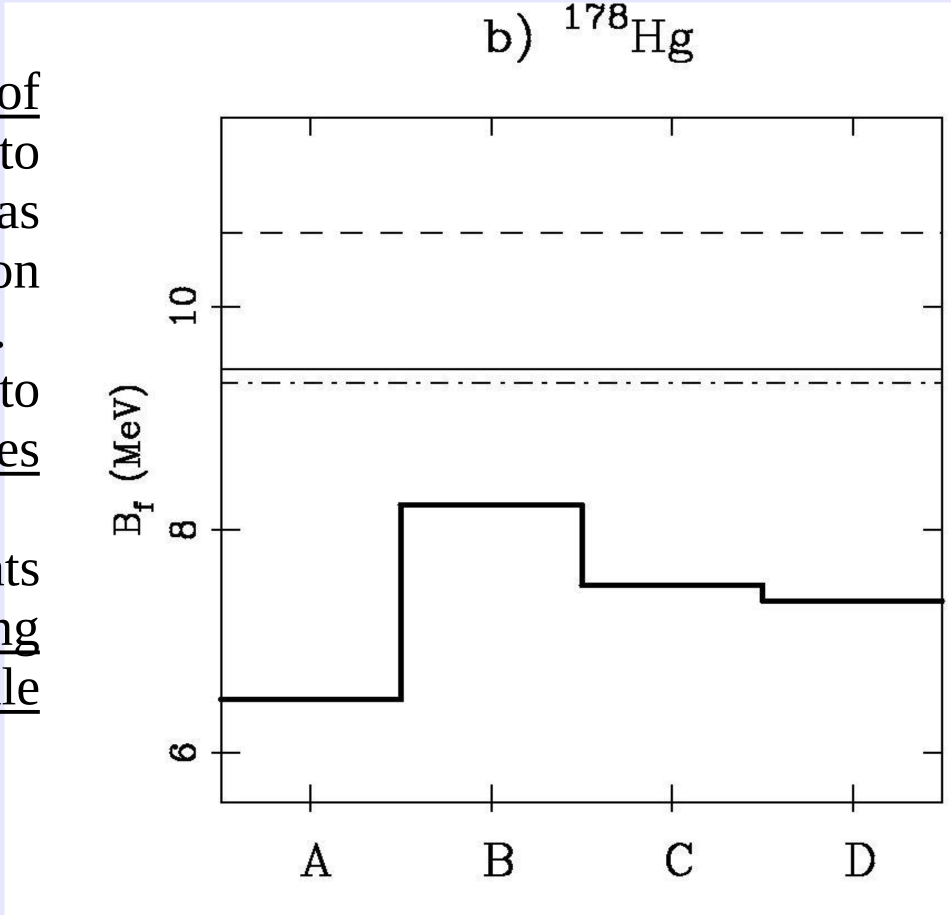
B_f(Sierk), shell corr. Moller and Nix 1981, B_f = 9.44 MeV

B_f(Cohen,Plasil,Swiatecki), shell corr.Myers&Swiatecki 1967, B_f = 10.67 MeV

EC-delayed fission of ^{178}Tl

$P_{bdf} = 1.5(6) \cdot 10^{-3}$

- used to deduce fission barrier height of the daughter isotope ^{178}Hg.
- flat strength function and four variants of statistical calculations (A-D) are used to determine the fission barrier. A-C – Fermi-gas level density formula, D – Gilbert-Cameron formula, pairing see explanation below figure.
- deduced fission barriers (thick lines) appear to be 12-30 % smaller than theoretical estimates (thin lines).
- spread in determined fission barrier heights results dominantly from uncertainty concerning the magnitude of the pairing gap in the saddle configuration.



A	B	C	D
FG level density, full pairing at the saddle	FG level density, no pairing at the saddle	FG level density, no pairing at all	G-C level density, no pairing at the saddle

Conclusions II:

Fission barrier heights extracted from beta-delayed fission using statistical model appear to confirm discrepancy with model values.

However, values of fission barrier heights can not be determined unambiguously due to uncertainty in beta-strength function and pairing gap in the saddle configuration

Still, some nontrivial shapes of beta-strength function can lead to fission barriers heights close to model values

Some other low energy fission data is needed for definite proof. Ideally at low beam energy close to the threshold to have full control of reaction kinematics and energy balance, thus a direct measurement.

Accepted recently as HIE-ISOLDE experiment IS581 !!!

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

(d,p)-transfer induced fission of heavy radioactive beams (based on LoI INTC-I-095 and INTC-I-119)

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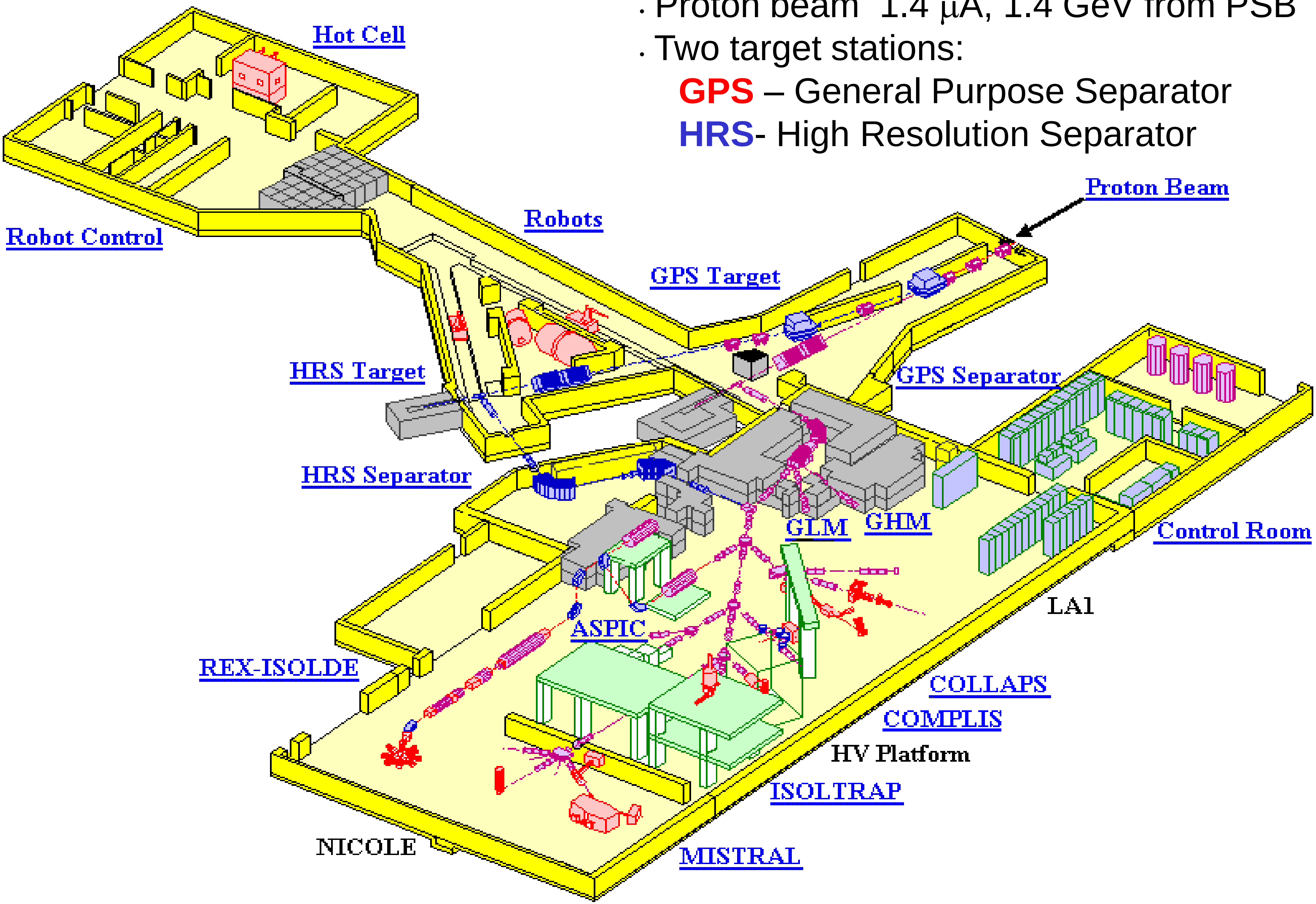
Abstract

(d,p)-transfer induced fission is proposed as a tool to study low energy fission of exotic heavy nuclei. Primary goal is to directly determine the fission barrier height of proton-rich fissile nuclei, preferably using the radio-active beams of isotopes of odd elements, and thus confirm or exclude the low values of fission barrier heights, typically extracted using statistical calculations in the compound nucleus reactions at higher excitation energies. Calculated fission cross sections in transfer reactions of the radioactive beams show sufficient sensitivity to fission barrier height. In the probable case that fission rates will be high enough, mass asymmetry of fission fragments can be determined. Results will be relevant for nuclear astrophysics and for production of super-heavy nuclei. Transfer induced fission offers a possibility for systematic study the low energy fission of heavy exotic nuclei at the ISOLDE.

ISOLDE

- Proton beam 1.4 μA, 1.4 GeV from PSB
- Two target stations:
  - **GPS** – General Purpose Separator
  - **HRS**- High Resolution Separator



Nuclear Physics **A376** (1982) 94–130

EMPIRICAL SADDLE-POINT AND GROUND-STATE MASSES AS A PROBE OF THE DROPLET MODEL

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Received 7 September 1981

Experimentally measured fission barriers

Most of the known fission barriers were obtained more than 30 years ago (summarized by Dahlinger et al.) . Since then very little progress was made, due to problems with methodology.

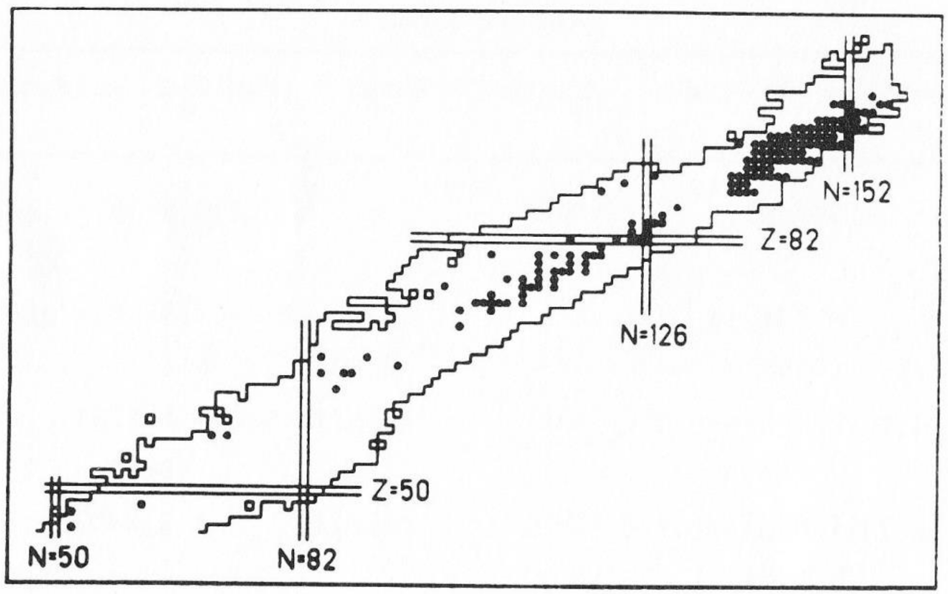


Fig. 2. Part of the chart of the nuclides. Nuclei for which the fission barrier was determined experimentally are indicated by an asterisk.

Direct measurement of fission barriers

Best and unambiguous method of measurement, possible when Coulomb barrier is lower than fission barrier, which can be observed as a fission threshold. Possible with light beams, preformed using restricted set of stable target nuclei.

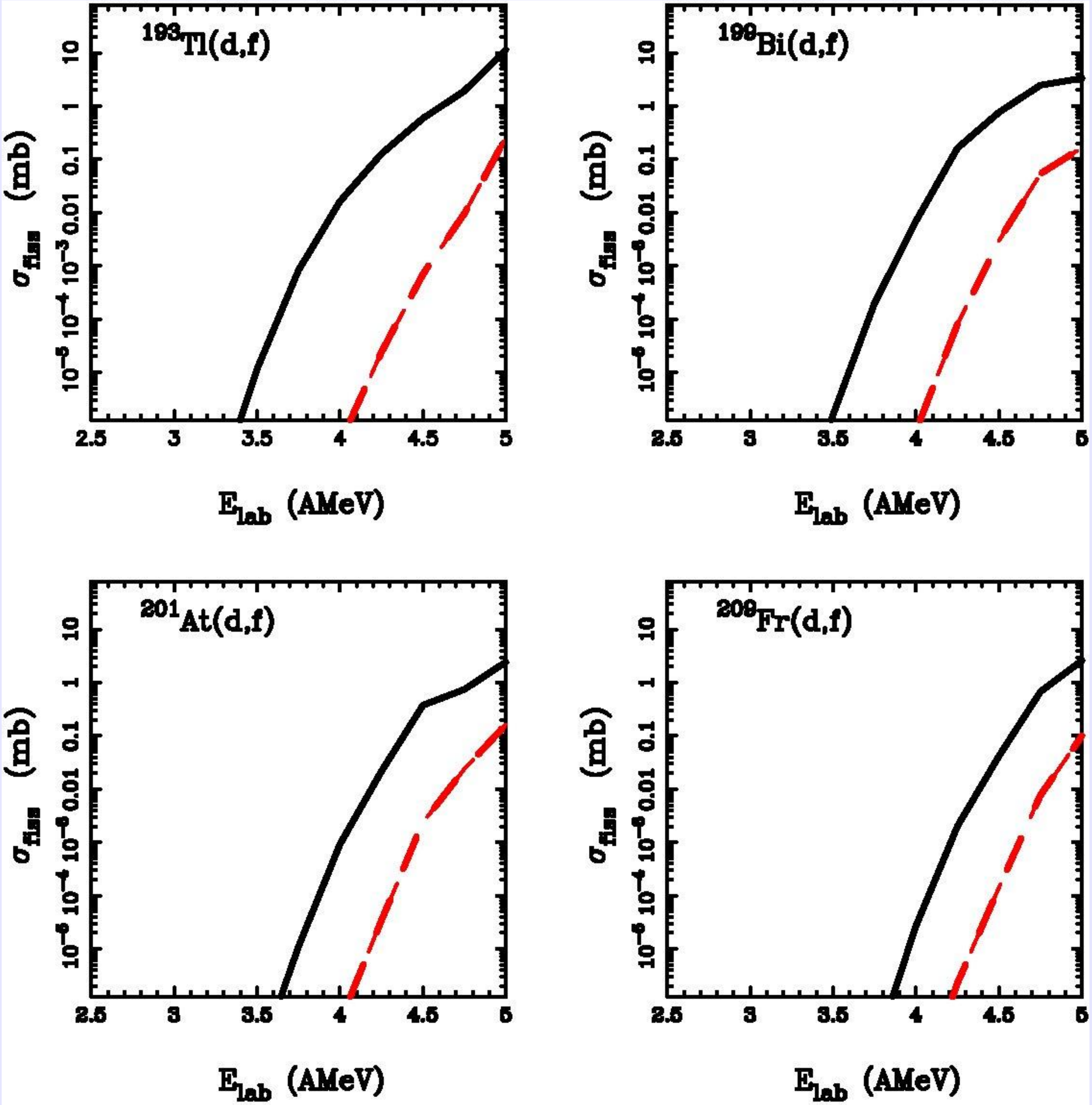
Among others, the **(d,pf) reaction was used for nuclei heavier than radium**, where fission barriers are low and comparable to Coulomb barrier.

In normal kinematics, this method can not be used for exotic nuclei.

New method: (d,p)-transfer induced fission of heavy radioactive beams in inverse kinematics (at HIE-ISOLDE)

It is of primary interest to observe **transfer-induced fission of odd elements such as Tl, Bi, At or Fr**, since in this case the estimated fission barriers will not be influenced by uncertainty in estimation of the pairing gap in the saddle configuration.

Observed fission rates of these beams can be used to **directly determine values of the fission barrier heights**.



Use of (d,p)-transfer induced fission with RI beams (in inverse kinematics) allows to:

- avoid uncertainty due to unknown beta-strength function, encountered in beta-delayed fission

$$P_{\mathrm{LEf}}(E_{beam}) = \frac{\int\limits_{0}^{\mathrm{E}^*_{\mathrm{max}}} (d\sigma_{(d,p)}(E_{beam})/dE^*) \frac{\Gamma_{\mathrm{f}}(E^*)}{\Gamma_{\mathrm{f}}(E^*)+\Gamma_{\gamma}(E^*)} dE^*}{\int\limits_{0}^{\mathrm{E}^*_{\mathrm{max}}} (d\sigma_{(d,p)}(E_{beam})/dE^*) dE^*},$$

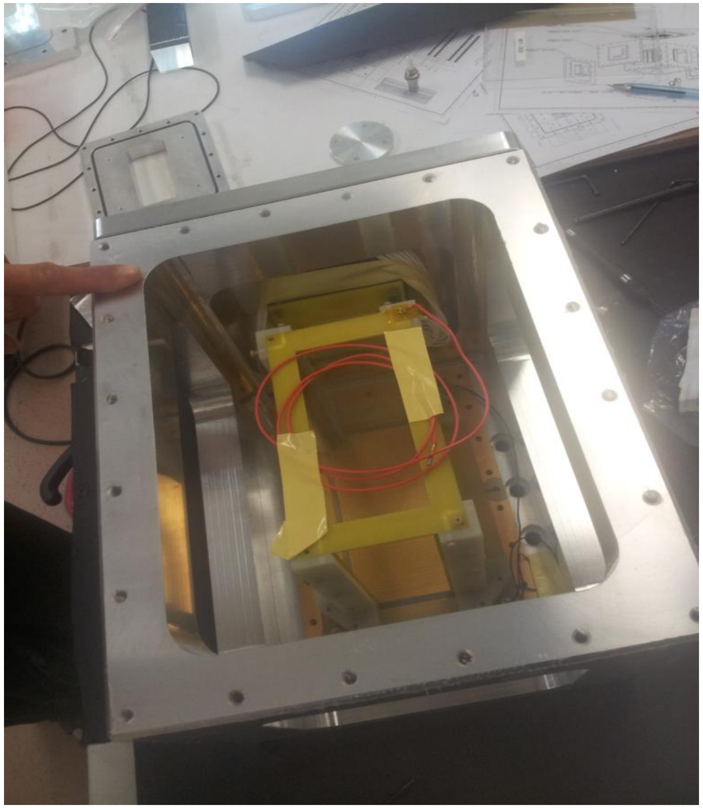
- obtain precise values of fission barrier heights for odd-odd fissioning nuclei without pairing gap in the saddle configuration (in the beta-delayed fission only even-even nuclei are accessible)

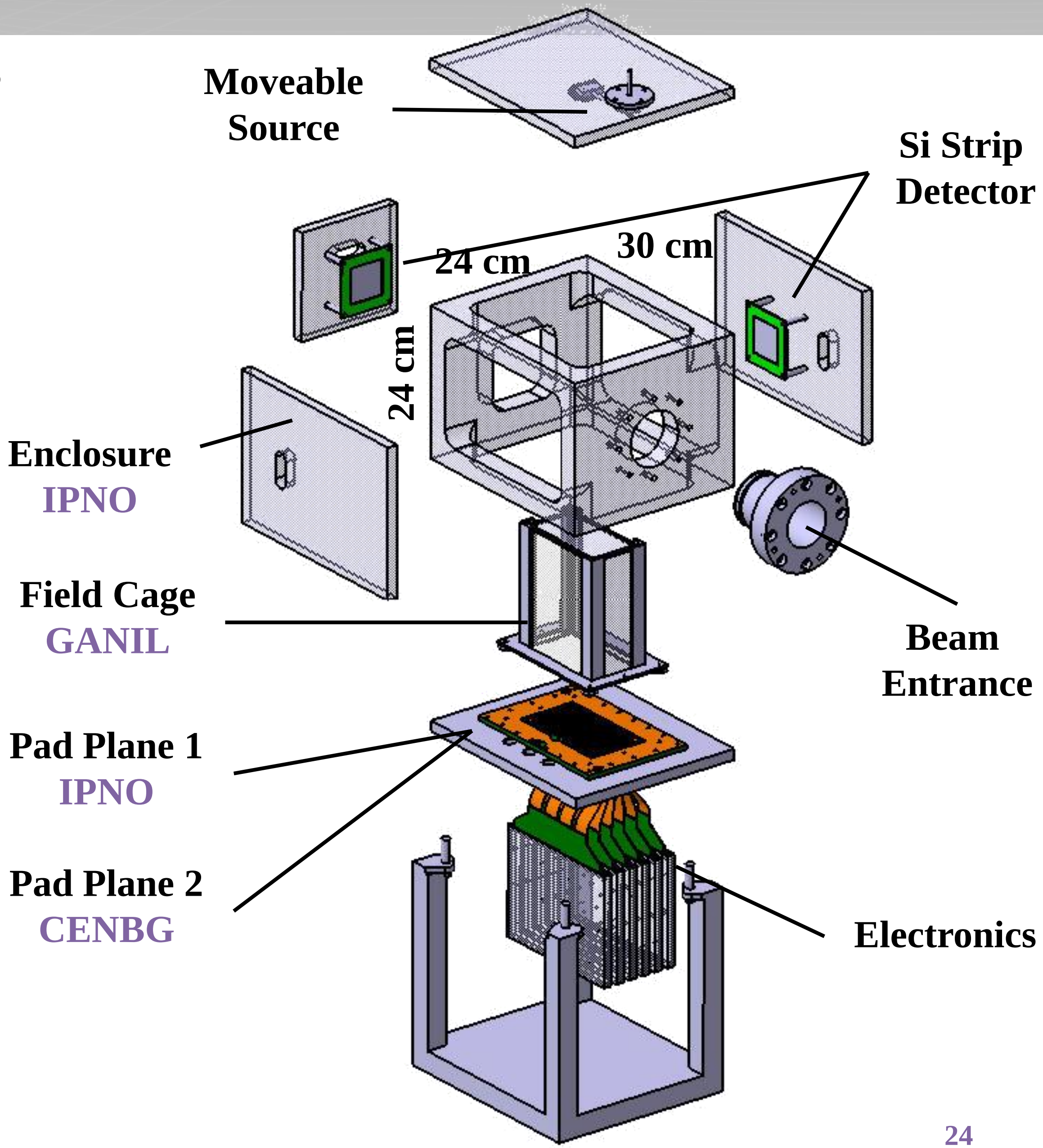
State-of-the-art equipment: **ACTAR TPC offers several advantages, namely higher observed fission rates and the possibility to obtain the fission cross sections for a range of beam energies in one measurement.**

- using deuterium gas with pressure 500 mbar, with effective target thickness 1.6 mg/cm^2 of deuterium (target chamber length parallel to beam axis of about 25 cm corresponding to the dimensions of ACTAR TPC), the beam slows down **from the initial energy of 5 AMeV to about 4.1 AMeV.**
- the reaction vertex can be reconstructed with a resolution better than 3 mm, allowing to **measure more than 60 points of the excitation function over the energy range of interest.**
- a rate ranging from about **two events/minute at highest beam energy bin down to one event per hour for the lowest energy** bin can be calculated assuming the **beam intensity (10^6 pps)** and fission barrier reduced by 20%. Such rates enable to **determine fission mass asymmetry**. Without reduction of the fission barrier, total expected fission rate can be still estimated to some hundreds of fissions per hour.
- active target **ACTAR TPC provides the needed sensitivity, allowing to resolve the long-standing question concerning the observed fission barriers of proton-rich nuclei by way of their direct measurement.**

ACTAR TPC Demonstrator

- 12 × 6 cm2; 2 × 2 mm2 × 2,048 pads
- Test high-density connection
  - High-density connector (IPNO)
  - Direct insertion to Micromegas
- Test GET electronics





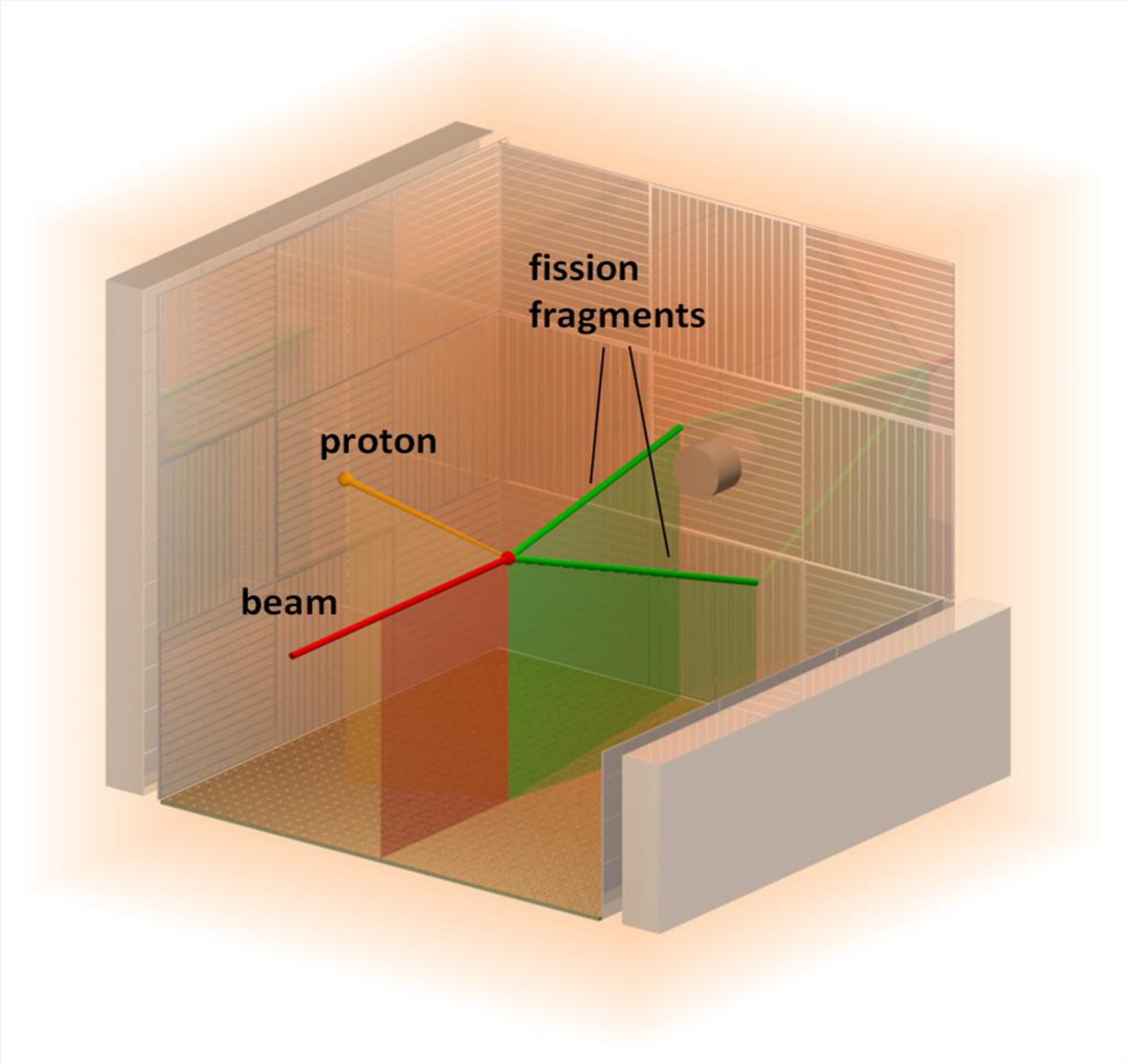
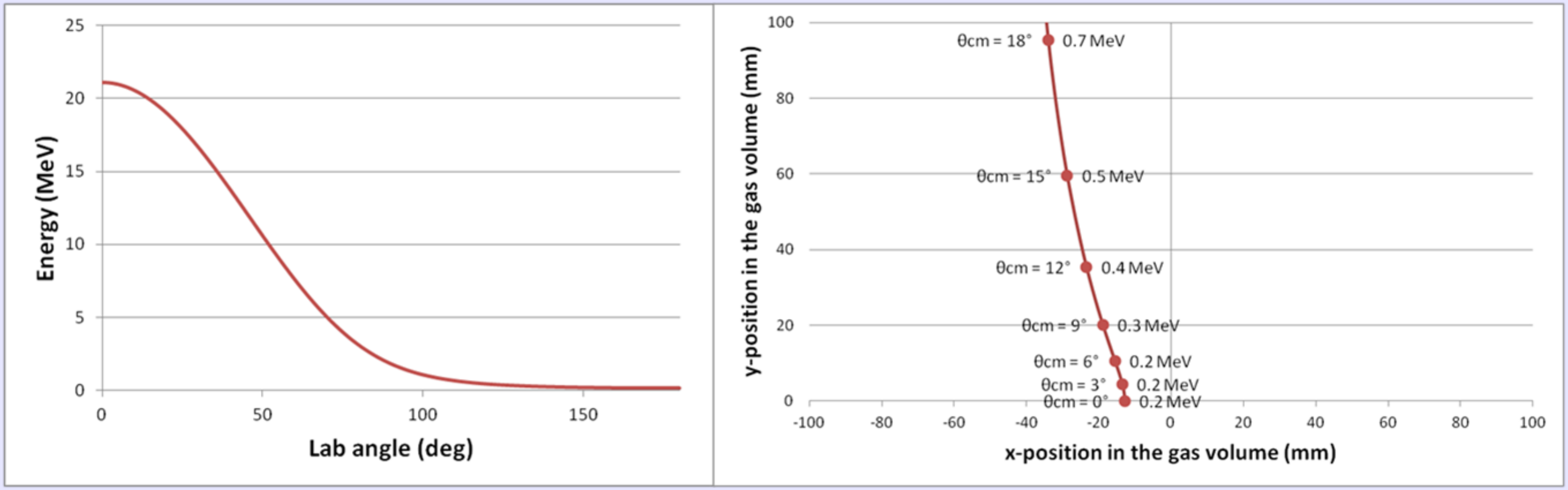


Figure 2: Configuration of ACTAR TPC for the measurement of the transfer-induced fission events. The two fission fragments are detected in the forward-placed silicon array; the proton from the transfer is either stopped in the volume (as shown) or detected in the Si-CsI telescope arrays surrounding the active volume (only partly shown).



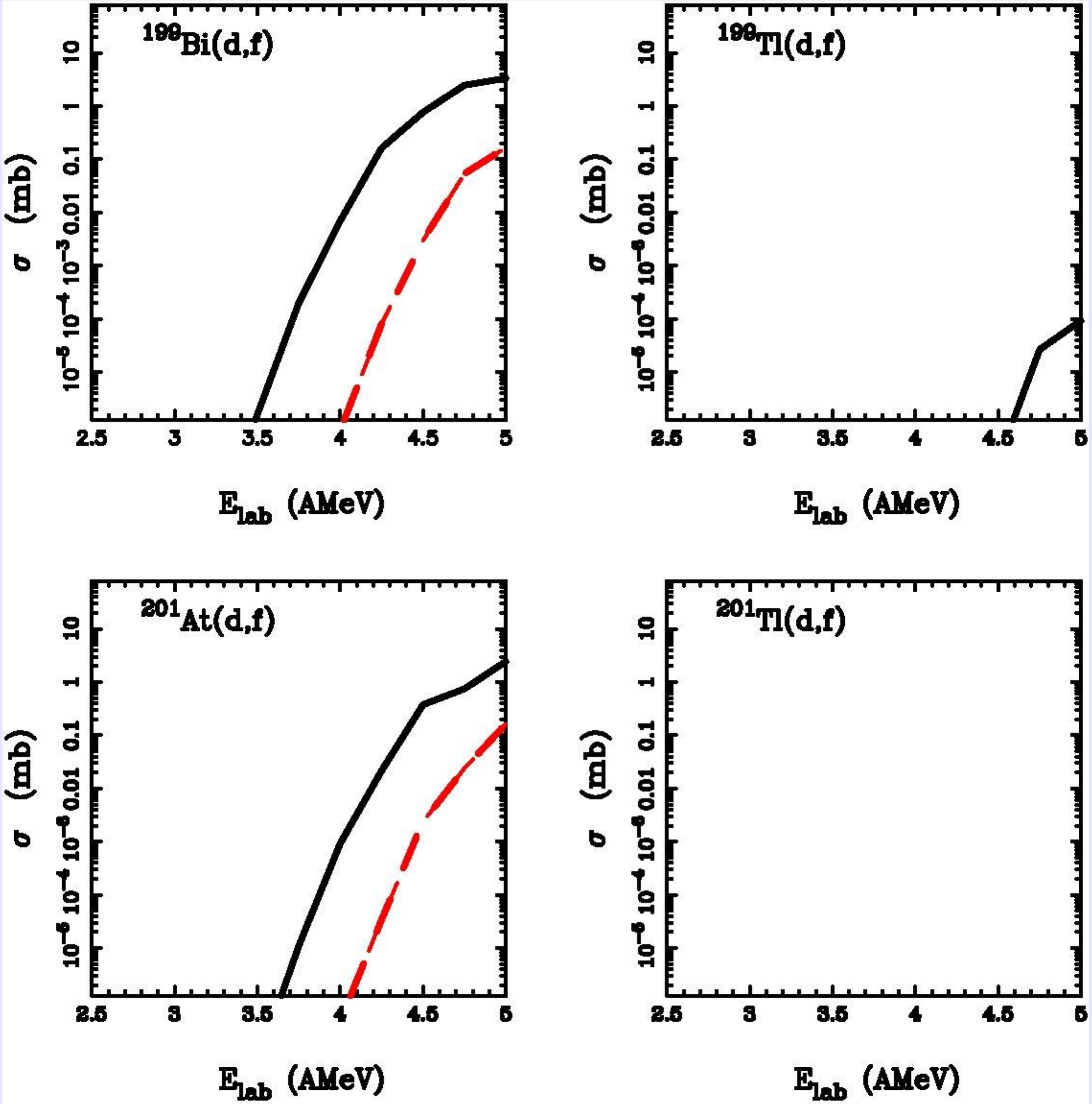
Φιγυρε 3: Λεφτ: κινεματιχσ (Ενεργψ ϖσ. λαβ ανγλε) οφ προτονσ φρομ ^{193}Tl(d,p)^{194}Tl in inverse kinematics, for a beam energy of 4.5 AMeV and a Q value of -2.5 MeV (corresponding to excitation energies in ^{194}Tl around 8 MeV). Right: stopping position of protons, emitted in the gas volume at position (0,0), for the kinematics shown on the left. The ranges are calculated using SRIM. The size of the graph (200mm x 100mm) correspond to one side, with respect to the beam axis, of the active volume in ACTAR TPC.

The excitation energy of the fissile ^{194}Tl nucleus can be calculated from the available beam energy at the moment of the reaction (directly depending on the position of the vertex) and the Q-value of the (d,p) transfer reaction; the latter is reconstructed from the angle and energy of the emitted proton. For transfer to states at energies above the fission barrier the Q-value is negative: most protons are emitted at backward angles with a low energy, between 100 keV and 2 MeV. The protons can be either stopped in the gas, or escape the active volume (see figure 3); in the first case their specific energy loss (about 10 to 15 keV/mm) is sufficient to generate a signal from which the track length and angle are reconstructed; in the second case they are detected in a segmented telescope array placed around the active volume.

TAC comment: Tl contamination of ^{199}Bi and ^{201}At beams

No problem at all! ^{199}Tl and ^{201}Tl beams won't fission below 5 AMeV !

Still, Tl contamination needs to be reduced as much as possible.



28 shifts (almost 10 days) of beamtime at HIE-ISOLDE approved by INTC

HIE-ISOLDE (phase 2) with post-accelerated beams with energy up to 5.5 AMeV is expected to be operational in the second half of 2015

Funding for ACTAR TPC secured via EU ERC project money (G. Grinyer, R. Raabe)

Experiment can be carried out upon the availability of the ACTAR demonstrator, in late 2015 or in 2016

Besides fission barriers, also mass distributions of fission fragments will be obtained

Conclusions III:

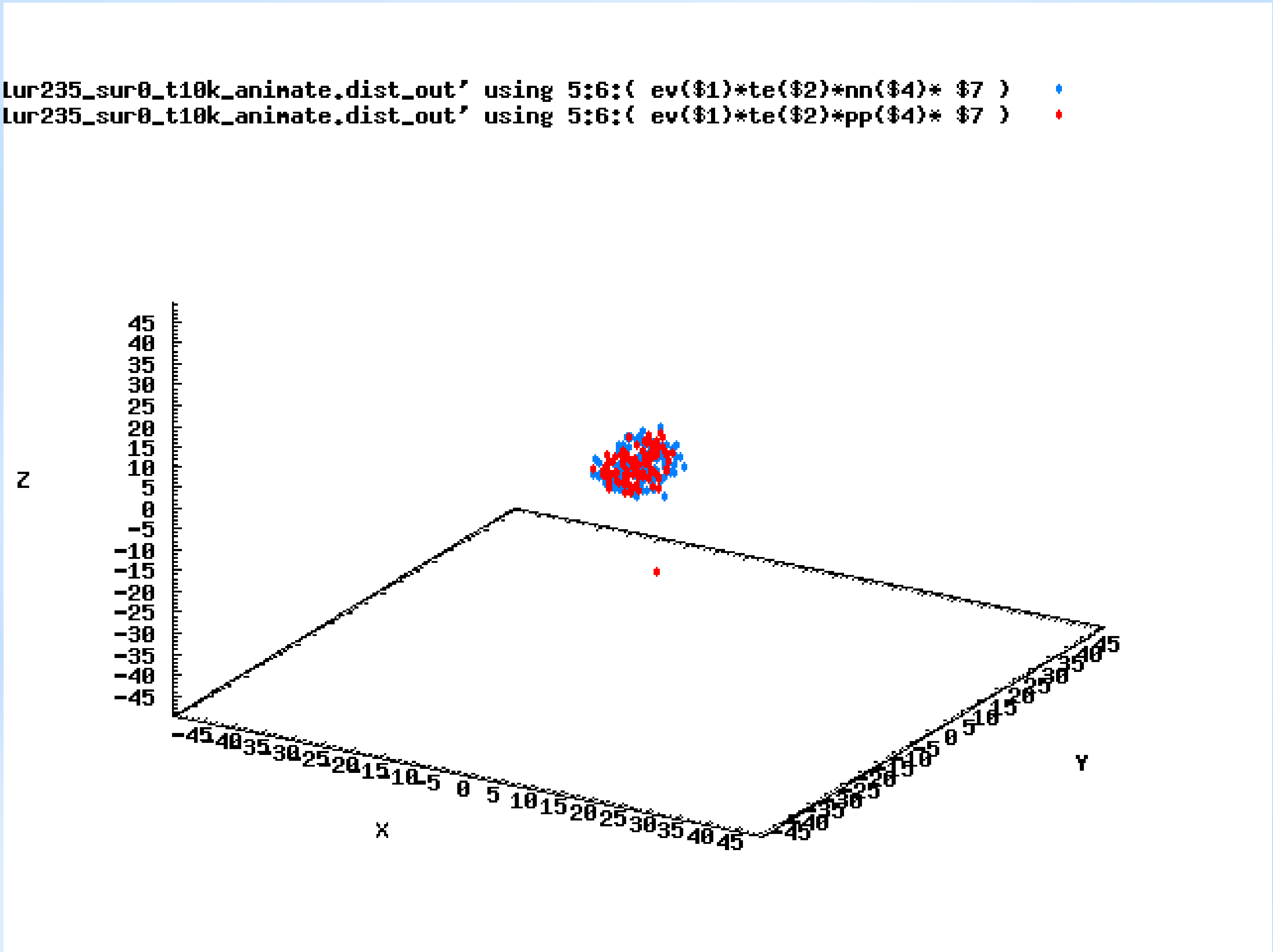
Fission barrier heights can be extracted at HIE-ISOLDE from the excitation function of (d,p)-transfer induced fission in inverse kinematics between RI beam energies 4 – 5 AMeV using the active target (ACTAR TPC chamber)

Precise values of fission barrier heights will be determined for odd-odd fissioning nuclei without pairing gap in the saddle configuration

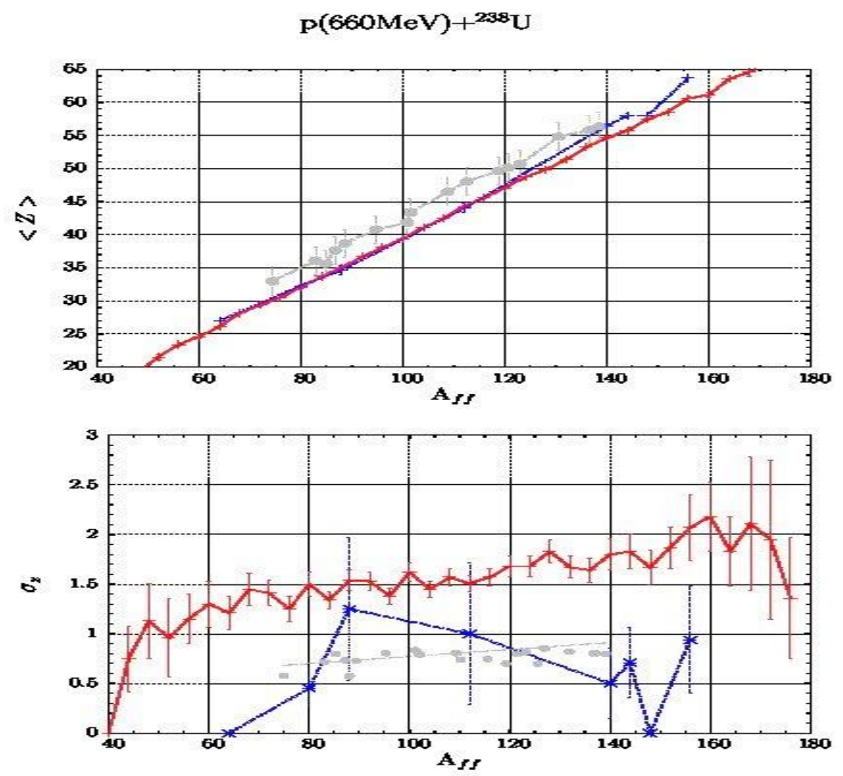
Implications for nuclear astrophysics and for search of new methods of synthesis of super-heavy nuclei

Experiment will be carried out in 2015-2016 and, hopefully, the issue will be settled for good.

p (30 MeV) + 235U, CoMD simulation of nuclear fission



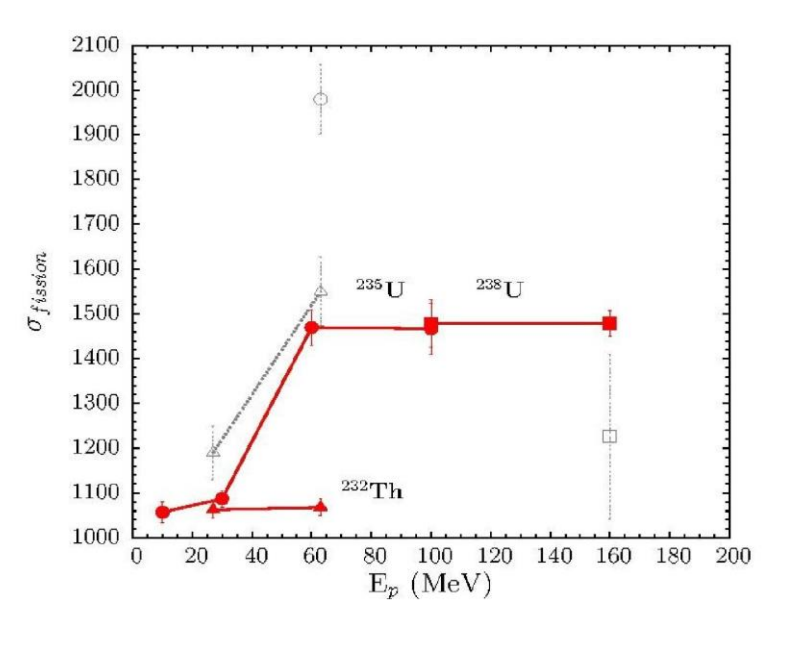
Comparison between theoretical and experimental results:
p (660 MeV) + 238U

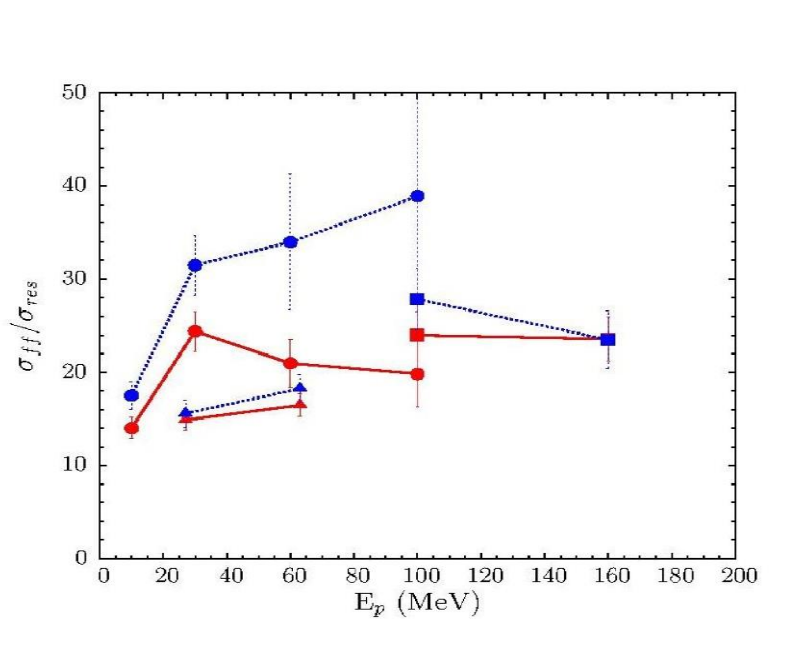


Red line: standard Vsym ~ ρ
Blue line: standard Vsym ~ ρ
strict selection in Zfiss = 93

Grey dots: Exprimental data: [12] A. R. Balabekyan, et Al Phys. Atom. Nucl. 73, 1814-1819 (2010)

Total fission cross section and fission cross section/residue cross section





Red line: standard Vsym ~ ρ

Blue line: soft Vsym ~ $\rho^{1/2}$

Circles: fission of 235U

Squares: fission of 238U

Triangles: fission of 232Th

Open symbols: experimental data

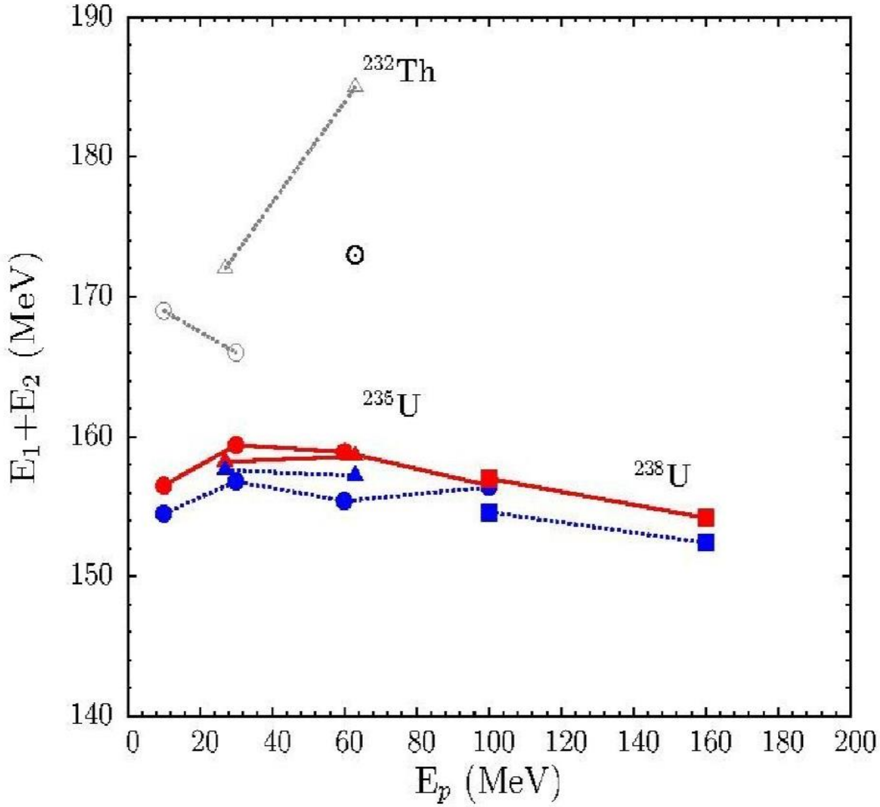
[12] A. R. Balabekyan, et Al Phys. Atom. Nucl. 73, 1814-1819 (2010)

[1] P. Demetriou et al Phys. Rev. C 82, 054606 (2010)

[10] M. C. Duijvestijn, et Al Physical Review. C 64, 014607 (2001)

Sensitivity of the ratio fission cross section/residue cross section to the choice of the nucleon-nucleon symmetry potential

Total kinetic energy of the fission fragments



Red line: standard Vsym ~ ρ

Blue line: soft Vsym ~ $\rho^{1/2}$

Circles: fission of 235U

Squares: fission of 238U

Triangles: fission of 232Th

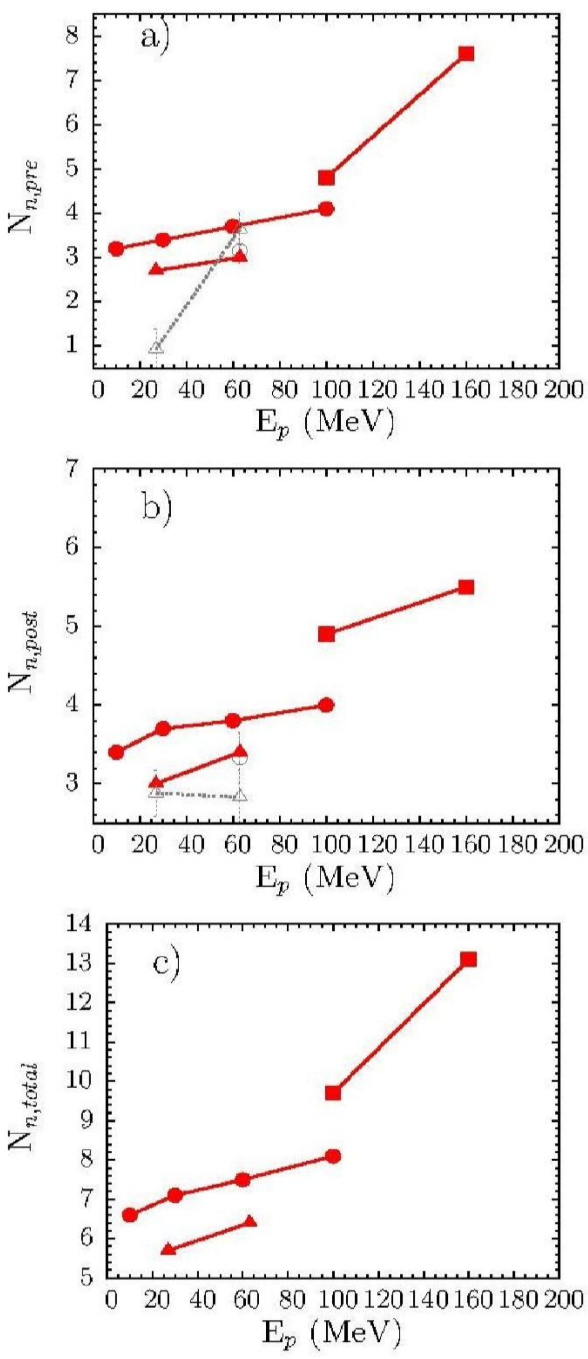
Open sympbols: experimental data

P. Demetriou et al Phys. Rev. C 82, 054606 (2010)

M. C. Duijvestijn, et Al Physical Review. C 64, 014607 (2001)

S.I. Mulgin et Al Nuclear Physics A, 824, 1–23, (2009)

Neutron multiplicity



Red line: standard Vsym ~ ρ

Circles: fission of 235U
Squares: fission of 238U
Triangles: fission of 232Th

Open symbols: experimental data

[1] P. Demetriou et al Phys. Rev. C 82, 054606 (2010)
[10] M. C. Duijvestijn, et Al Physical Review. C 64, 014607 (2001)

CoMD appears to describe correctly the collective dynamics

No assumption concerning viscosity are made, evolution of mean field appears to be sufficient

Besides fission, CoMD describes correctly mass distributions of projectile-like nuclei in reactions 86Kr+58,64Ni,112,124Sn at 15 AMeV

A mean field model capable to describe collective dynamics both in fission and in damped nucleus-nucleus collisions

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