Determination of fission barrier height of 210Fr via neutron measurement

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Fission barriers of neutron-deficient nuclei

Largely unknown, previous attempts in compound nucleus reactions and beta-delayed fission indicate reduction by 15-30%, but both methods suffer from large uncertainty due to ambiguous model description.

In compound nucleus reactions, statistical model of de-eexcitation provide parameters redundant to fission barrier e.g. af/an. With specific choice of af/an theoretical estimates of fission barriers can be reproduced (see e.g. D.D.Bogdanov, M. Veselsky et al., Phys.Atomic Nuclei 62, 1794 (1999)).

In beta-delayed fission only even-even nuclei fission. Pairing strength at the saddle point is unknown (see e.g. M. Veselsky et al., PRC 86, 024308 (2012)).

Proper description of fission barriers of neutron-deficient nuclei can allow better prediction also on neutron-rich side, where fission is one of the main sources of neutrons for r-process nucleosynthesis (so-called “fission recycling”)

Experiment IS581 “(d,p)-transfer induced fission of heavy radioactive beams”

Proposal accepted in 2013 by INTC

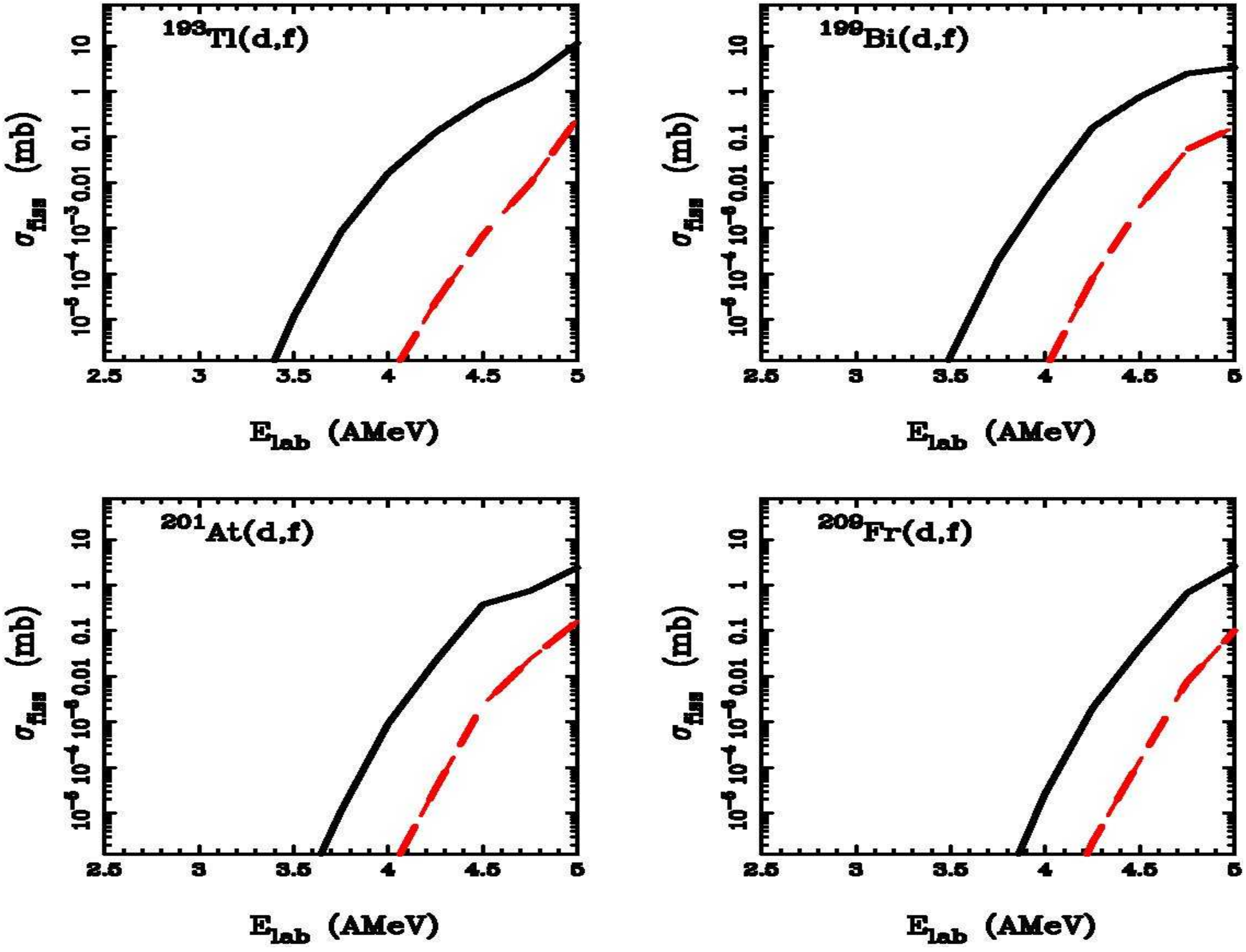
GACR grant No. 21-24281S for 2021 – 2023

First part of the beamtime at HIE-ISOLDE performed in 2021

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

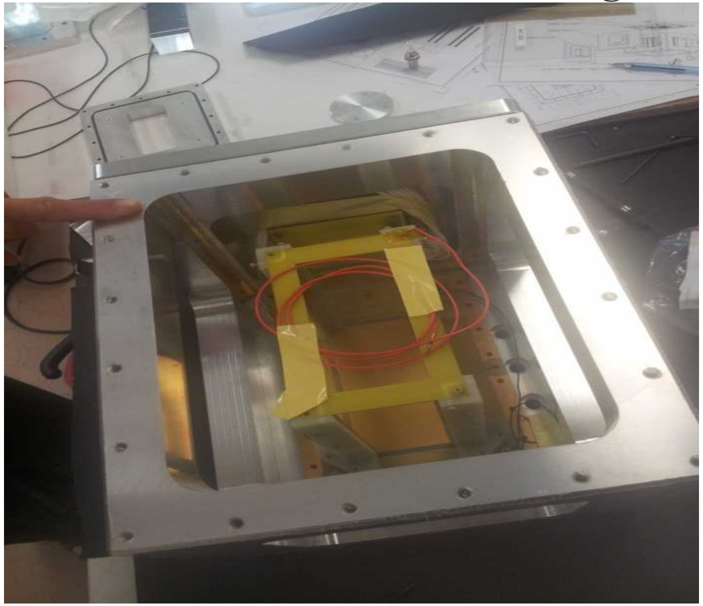
It is of primary interest to observe **transfer-induced fission of odd elements such as Tl, Bi, At or Fr**, since in this case the estimated fission barriers will not be influenced by uncertainty in estimation of the pairing gap in the saddle configuration.

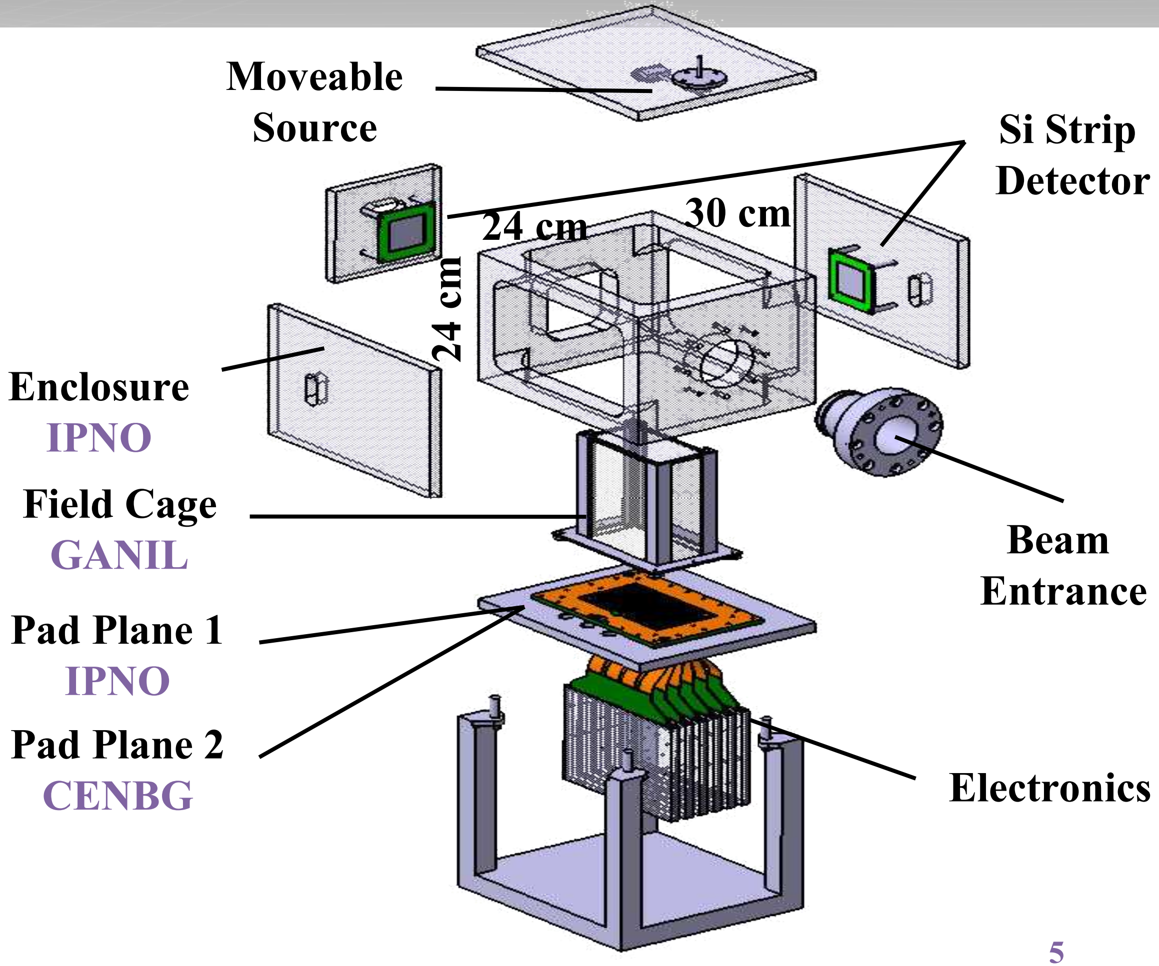
Observed fission rates of these beams can be used to **directly determine values of the fission barrier heights**.

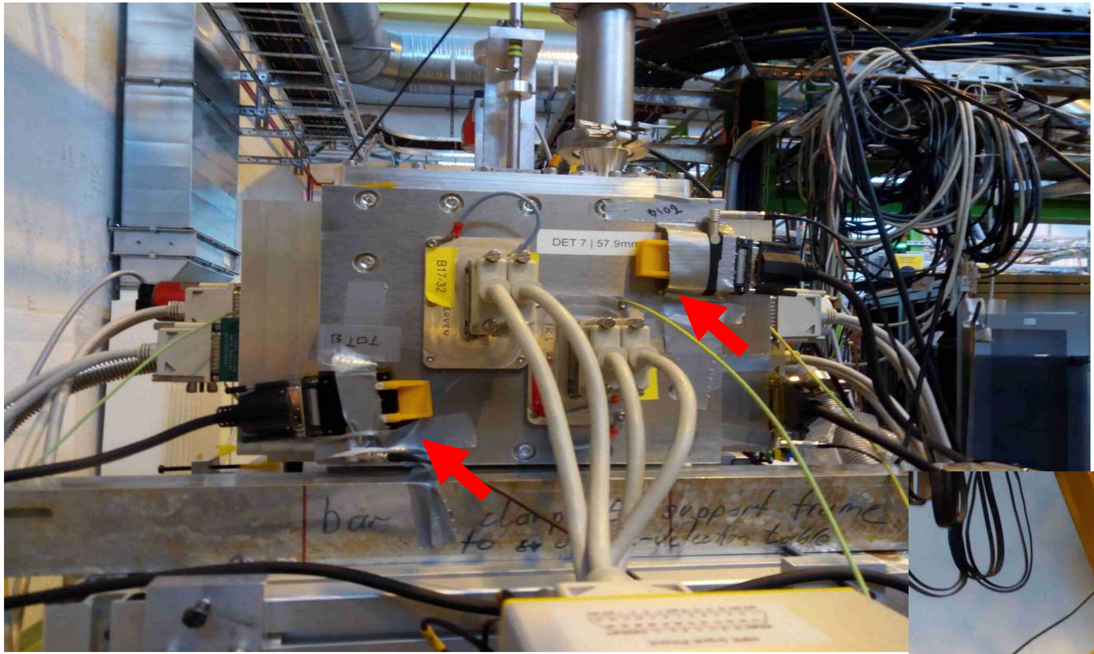


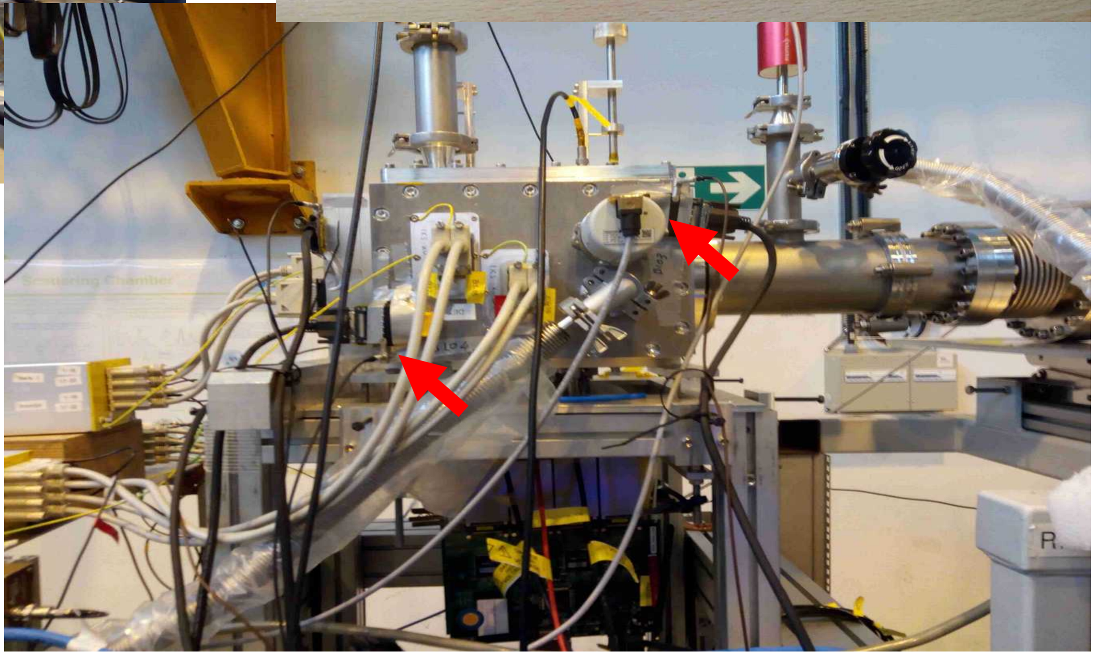
ACTAR TPC Demonstrator

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









4 TPX3 pixel detectors placed on the body of ACTAR TPC chamber.

Polyethylene converter used for detection of fast neutrons, this method used successfully to detect fusion neutrons in high-power laser experiment.

209Fr beam at 7.6 MeV/nucleon, max. intensity 10^6/s

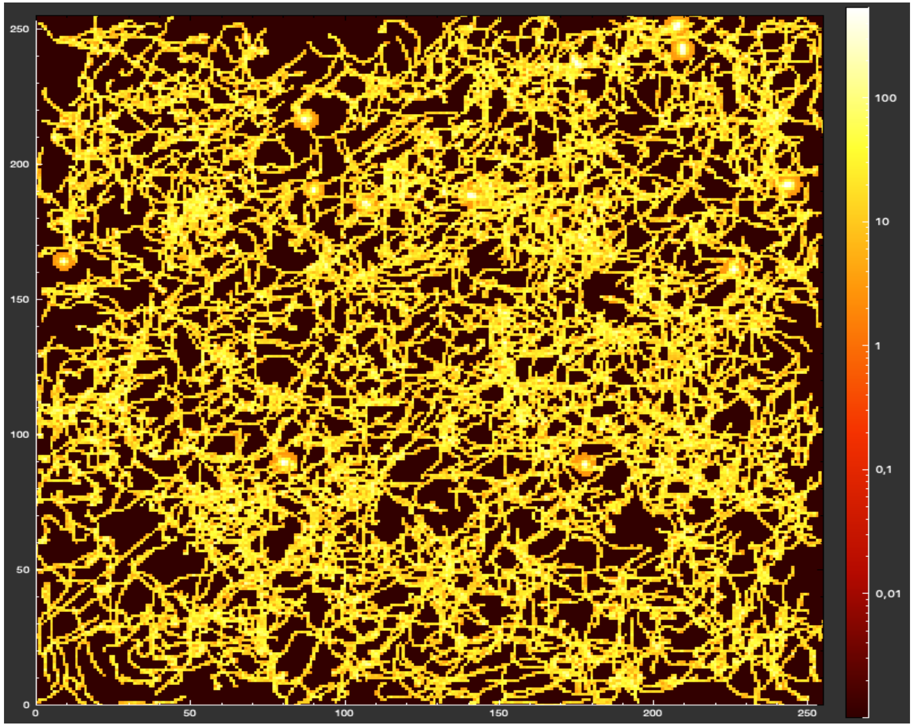
D_2 pressures 500 and 800 mbar

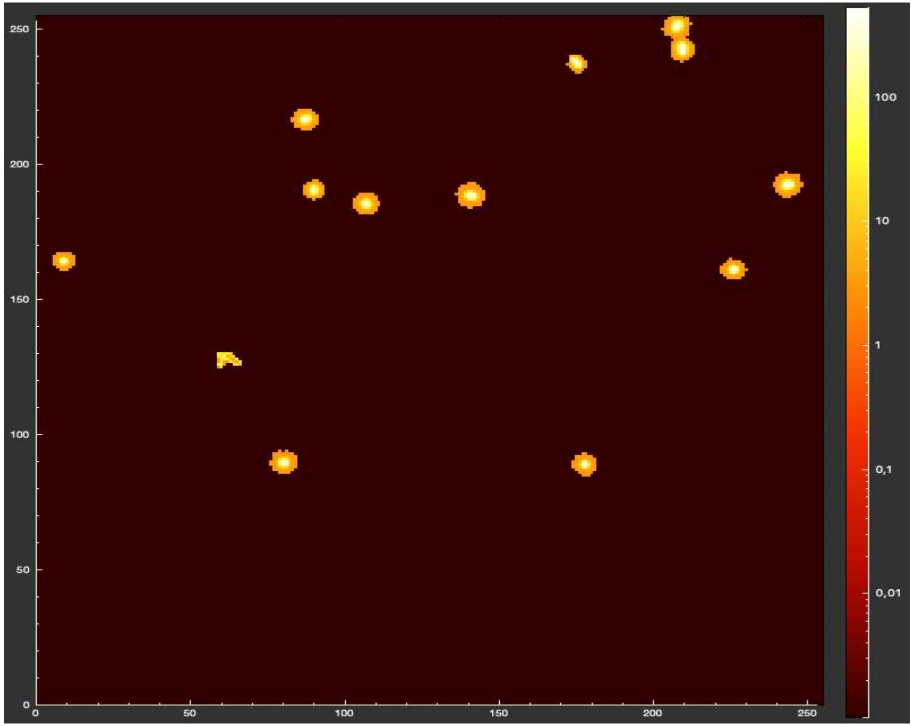
Fast neutrons detected at 4 positions

Fast neutron background negligible

Analysis of hits in TPX3 pixel detectors

- selection by cluster size, energy, “roundness”
- software by L. Meduna and P. Manek, analysis performed by P. Rubovic with support from P. Burian





Fast neutrons detected almost exclusively with beam on, practically no fast neutron Background.

Detector in this configuration used successfully In high-power laser experiment !.

Simulations:

Beam energy losses from Srim (500 and 800 mbar)

(d,p) and (d,n) cross sections from Talys ((d,np) at 1 %)

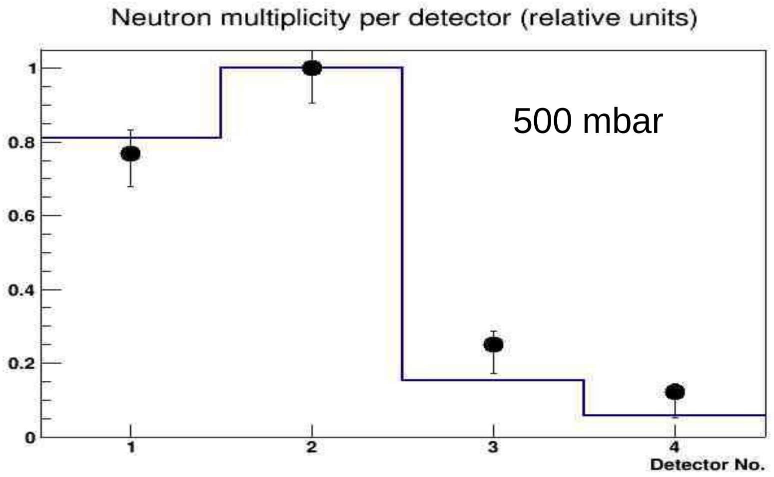
2-body kinematics, emission of neutrons

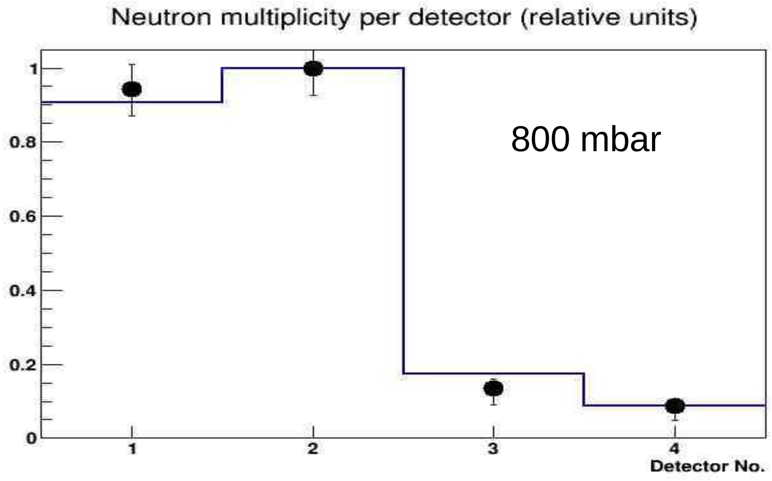
Excitation energy vs fission barrier (Sierk scaled down by 0 – 25 %)

Fragment mass distributions and TKE from PhD thesis of Bockstiegel (GSI)

Emission of neutrons from fragments (neutron multiplicity up to 2)

Geometric acceptance of Timepix3 detectors



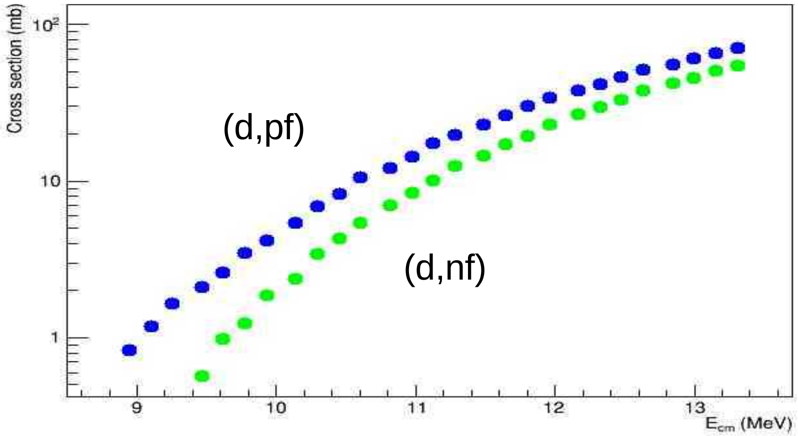


Successful simulation:

Bf = 85% of B_f(Sierk)
n-multiplicity = 2

D_2 pressure	C=0.85	C=1.00	Exp.
500 mbar	181	144	191±14
800 mbar	238	218	228±15

TABLE I. Neutron multiplicity for detector #2 for two different pressures and simulations with two values of fission barrier height scaling C=0.85,1.00 vs. experimental values.



Determined fission barrier heights :

10.67 MeV for 210Fr

8.54 MeV for 210Ra

Reduction comparing to theoretical estimates:

Macroscopic Sierk model + ground state shell correction

15% when full barrier is scaled
25% when only macroscopic barrier is scaled

Macroscopic Cohen-Plasil-Swiatecki model + ground state shell correction

20% when full barrier is scaled
30% when only macroscopic barrier is scaled

Moller et al., 2009

30-35% reduction

Determination of fission barrier height of ^{210}Fr via neutron measurement

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Fission barrier heights of short-lived nuclei away from line of β-stability are not known reliably. Low-energy fission of ^{210}Fr, produced by (d,p)-transfer reaction of the re-accelerated unstable beam ^{209}Fr was investigated at HIE-ISOLDE. Four Timepix3 pixel detectors were installed on the body of the ACTAR TPC demonstrator chamber. Polyethylene converters were used for the detection of fast neutrons. Since no significant background was observed, it was possible to measure the spatial distribution of emitted neutrons reflecting the fission excitation function. Subsequent simulations employing the results of Talys code and available data on fission fragment distributions allowed to estimate directly the value of fission barrier height for the neutron-deficient nucleus ^{210}Fr. This first direct measurement of the fission barrier height for extremely neutron-deficient nucleus confirmed the reduction of the fission barrier compared to available theoretical calculations by 15 - 30 %.

End of the story ? Not really !

Measurement of fission barrier height is crucial for understanding of nucleosynthesis of heaviest elements, but does the fission in the astrophysical environment proceed like in the terrestrial laboratory ?

First step – study of fusion of hyper-heavy nuclei in neutron star environment, continuation of previous work concerning production of superheavy elements, neutron star medium simulated, Coulomb screening implemented (done already, M. Veselsky et al., Phys. Rev. C 106, L012802 (2022))

Second step – simulation of fission under conditions occurring in neutron star mergers, specifically ejecta where nucleosynthesis is supposed to take place (work in progress)

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

(d,p)-transfer induced fission of heavy radioactive beams (continuation of LoI INTC-I-095, synergy with INTC-I-119)

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Motivation: Experimentally measured fission barriers needed !

Most of the known (directly measured) 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.
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. **Inverse kinematics is needed !**

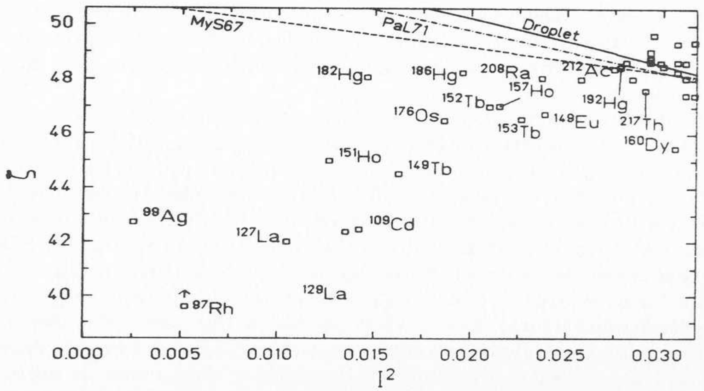
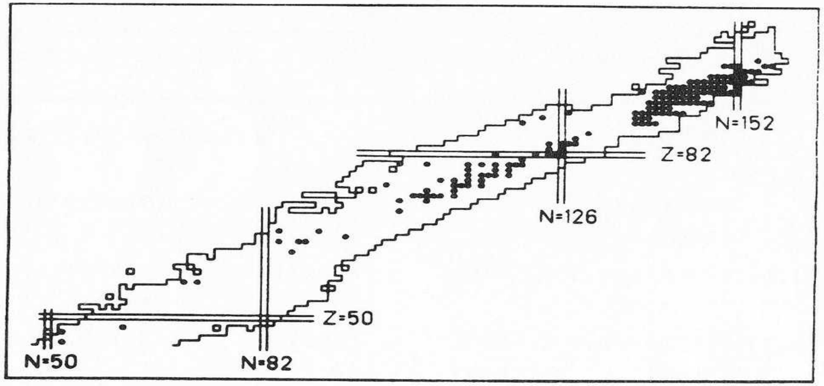


Fig. 7. Neutron-deficient part of fig. 5. The data points are marked with the element symbol and the mass number.

M. Dahlinger et al. / Saddle-point and ground-state masses

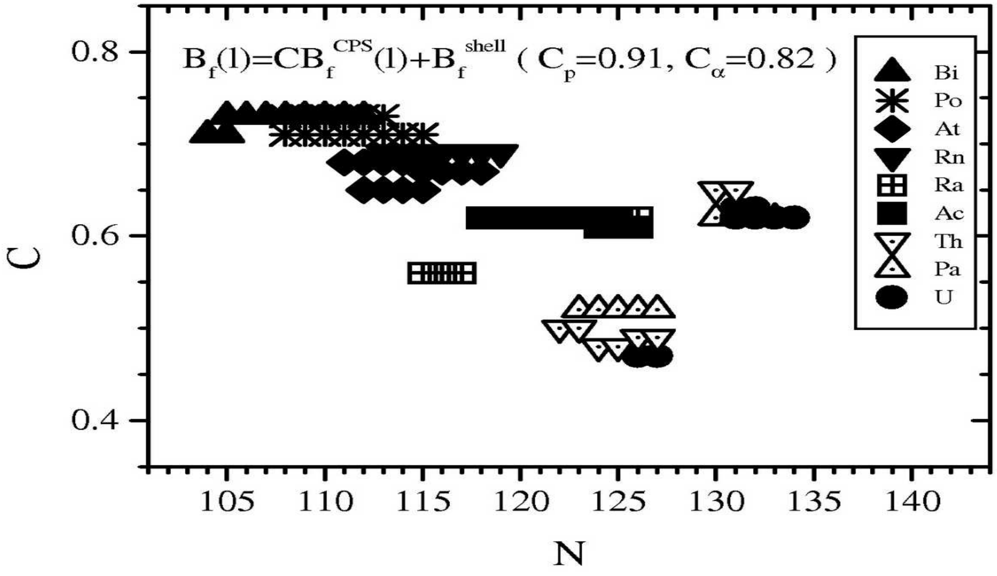


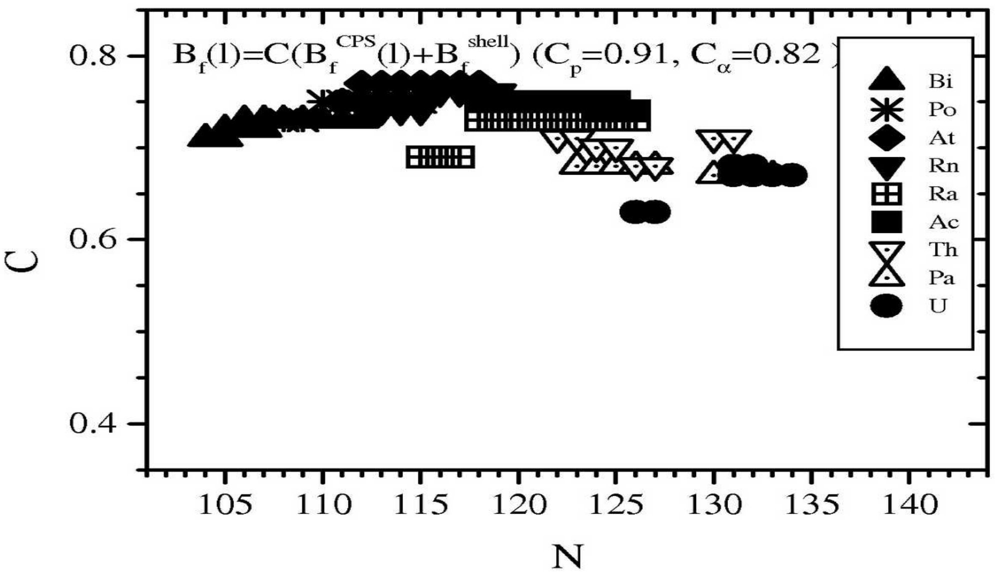
Part of the chart of the nuclides. Nuclei for which the fission barrier was determined experimentally are indicated by an asterisk.

Until recently, **neutron-deficient fissile nuclei (Z > 70) were reachable only via compound nucleus reactions**. In variance to region of beta-stable nuclei, **fission barriers extracted using statistical model are lower than the predicted fission barriers** by 15-20 (Sierk) or 30-40 % (Cohen-Plasil-Swiatecki).
Are the predicted fission barriers wrong or is it a problem with description of fission decay width ? The extracted values **need to be verified independently, using low energy fission.**

Fission barriers of neutron-deficient nuclei

Neutron-deficient fissile nuclei (Z > 70) are reachable via compound nucleus reactions. In this region Coulomb barrier exceeds expected fission barriers and these are extracted using statistical model. In variance to region of beta-stable nuclei, extracted fission barriers are lower than predictions of model calculations. In order to predict cross sections standard practice is to scale down the predicted fission barriers by 20 (Sierk) to 30 % (Cohen-Plasil-Swiatecki).
Question remains, what are the reasons for this, are the macroscopic barriers wrong or is it a problem with description of fission decay width ? In any case the extracted values need to be verified independently, ideally using the process leading to low excitation energies.



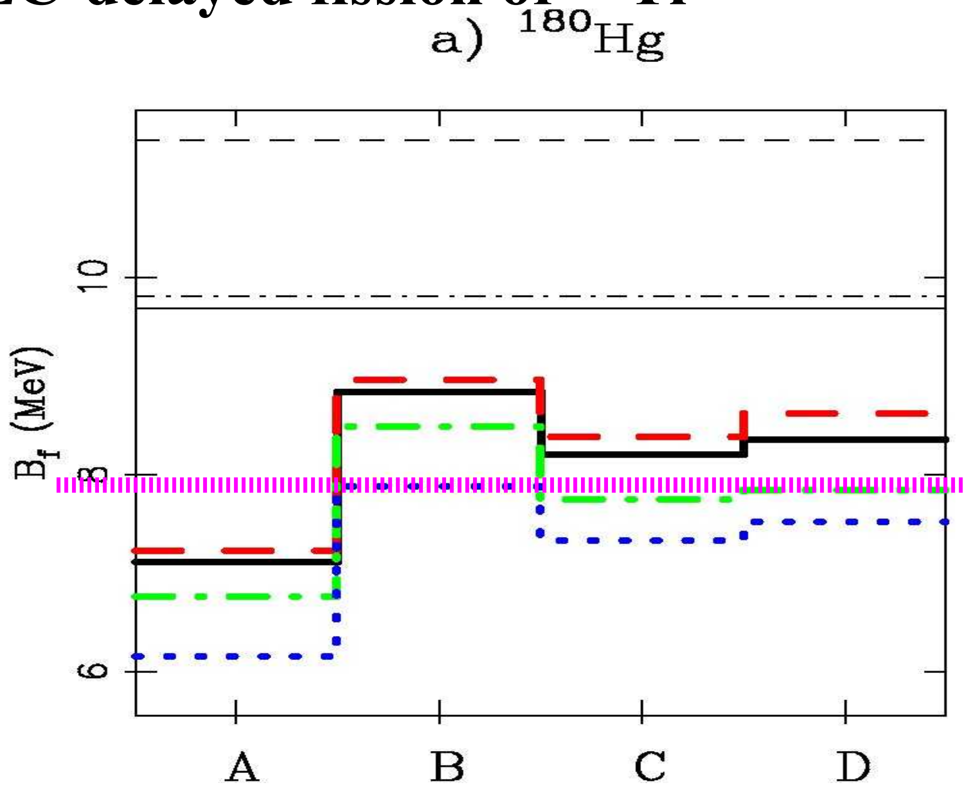


Data for xn emission channels of CN reactions obtained at VASSILISSA, Dubna

Recent effort at ISOLDE (M. Veselsky et al., PHYSICAL REVIEW C 86 (2012) 024308): Fission barrier determination in 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