Residual nuclei produced in fragmentation and fission reactions

NuSPRASEN

Nuclear Structure Physics, Reactions, Astrophysics and Superheavy Elements Network

Workshop on Nuclear Reactions (Theory and Experiments)
Warsaw 22-24 January 2018

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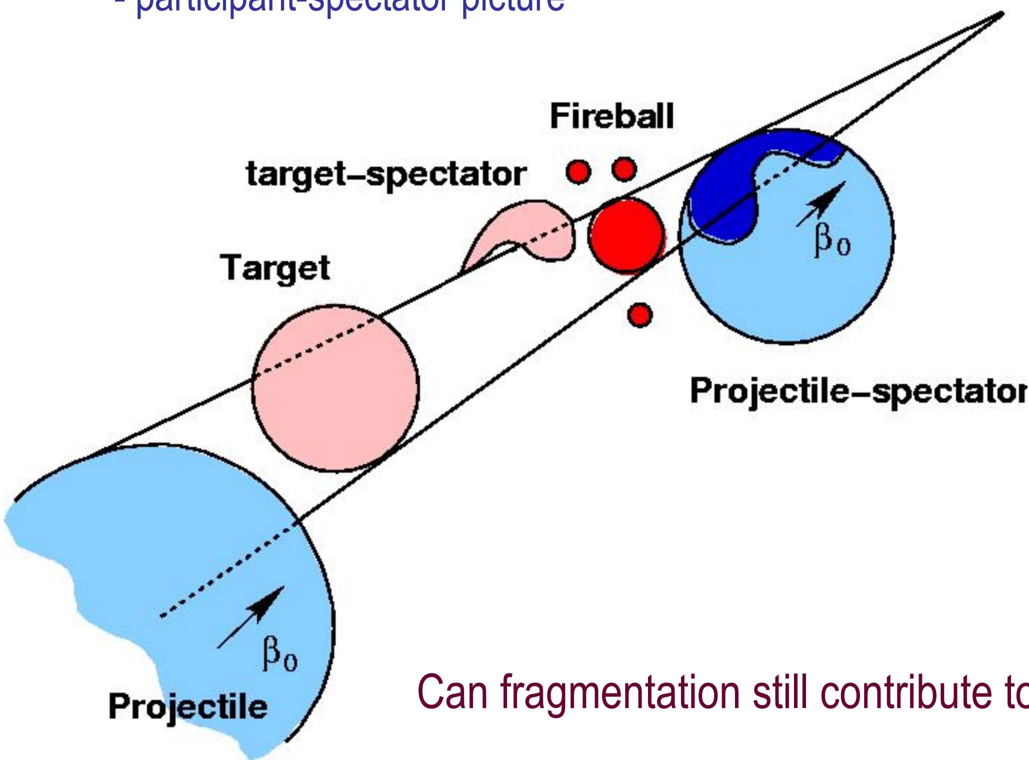
Fragmentation reactions

Heavy-ion induced reactions.

- kinetic energies above the Fermi energy up to few GeVs per nucleon
- peripheral or mid-peripheral collisions
- participant-spectator picture

Two-stage reaction scheme:

- abrasion
- ablation (evaporation, fission, multi-fragmentation)



J. Hufner, Phys. Rep. 125, 1985

"Can we expect a simple description of a complicated process like fragmentation? I think yes. A simple description works because the process is extremely complicated and phase space dominates over dynamics."

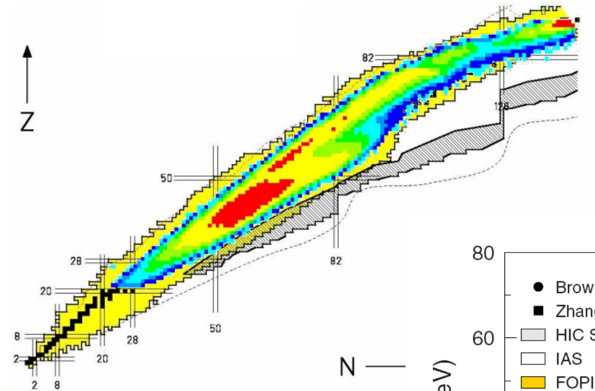
year ~ 2000

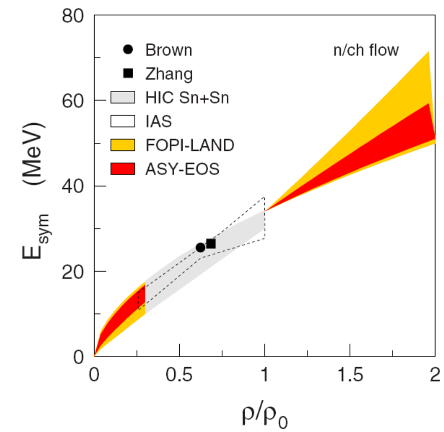
Can fragmentation still contribute to explore new frontiers in nuclear physics?

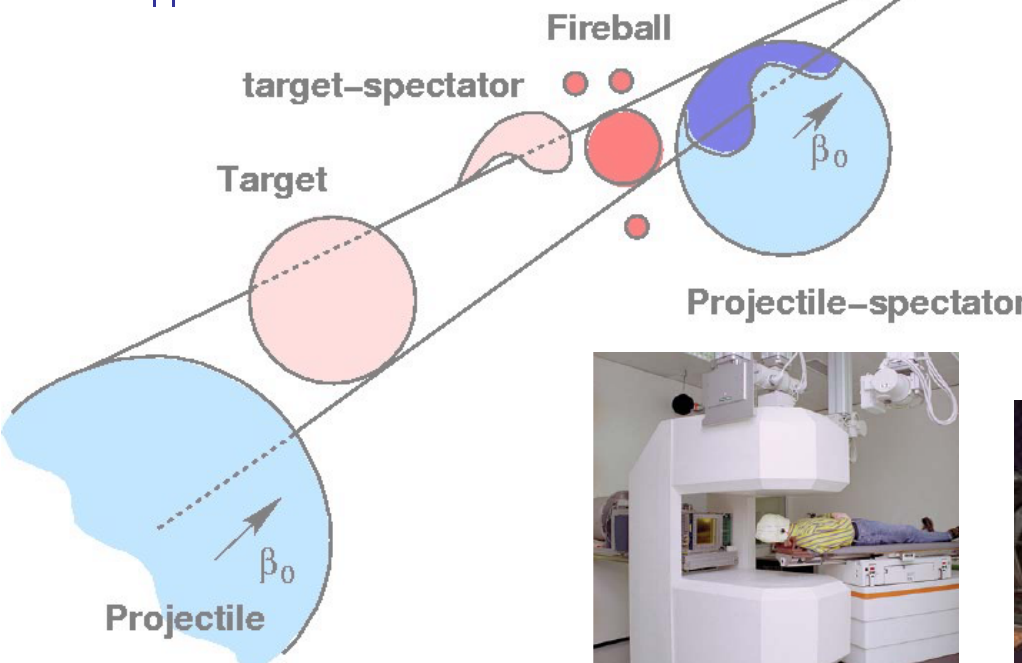
Fragmentation reactions

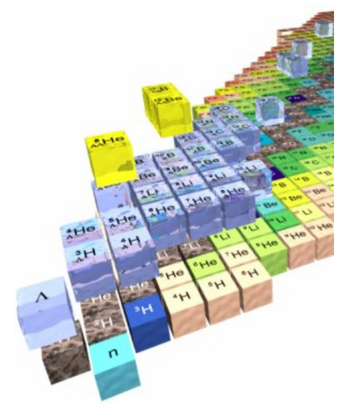
Key features of fragmentation reactions:

- large isospin range → Nuclei far from stability
- large dynamical range → Hot and dense matter; EoS
- subnucleonic degrees of freedom → Hypernuclei, in-medium nucleon resonances
- applications



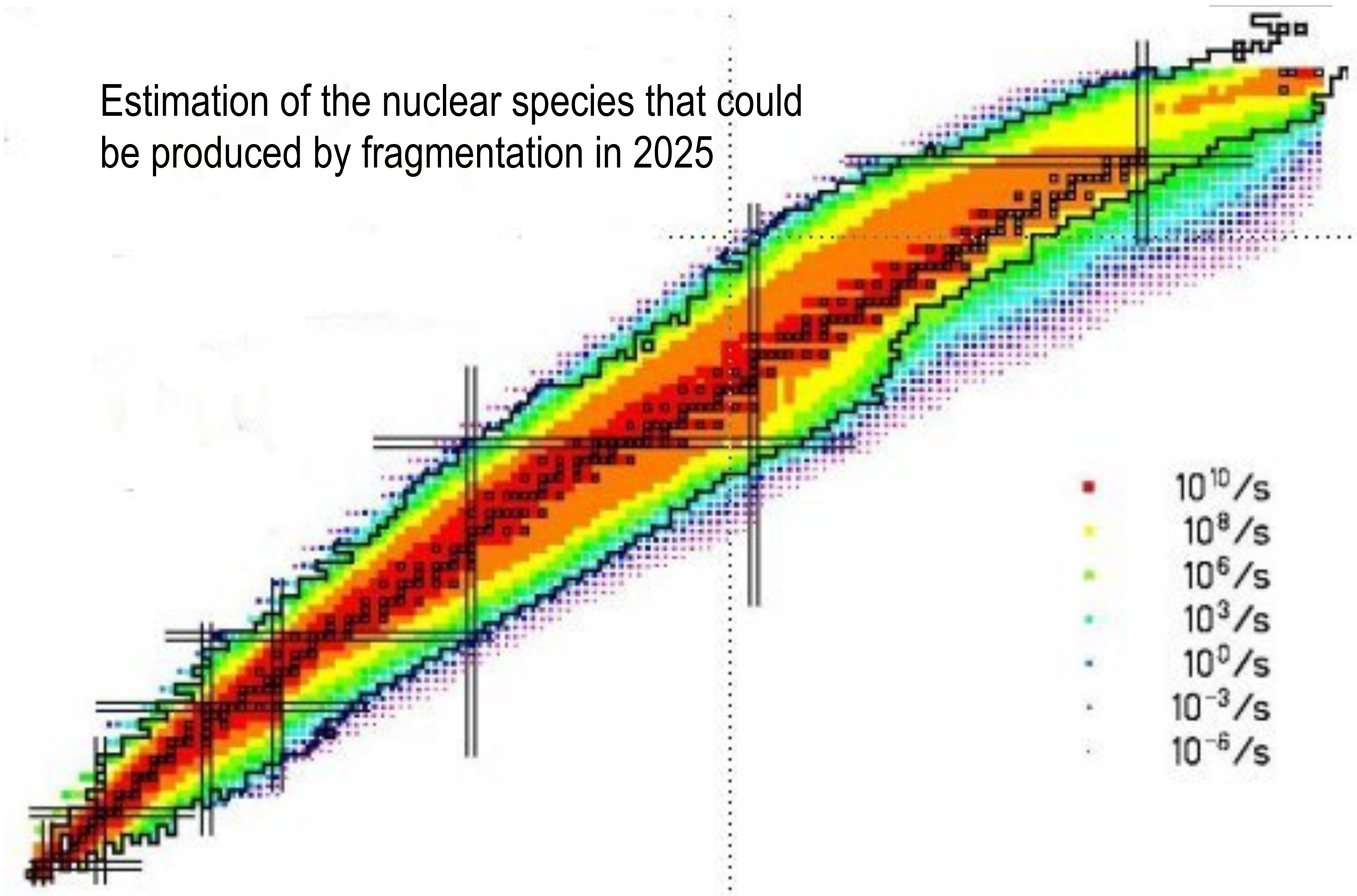






Exploring the limits of the nuclear chart

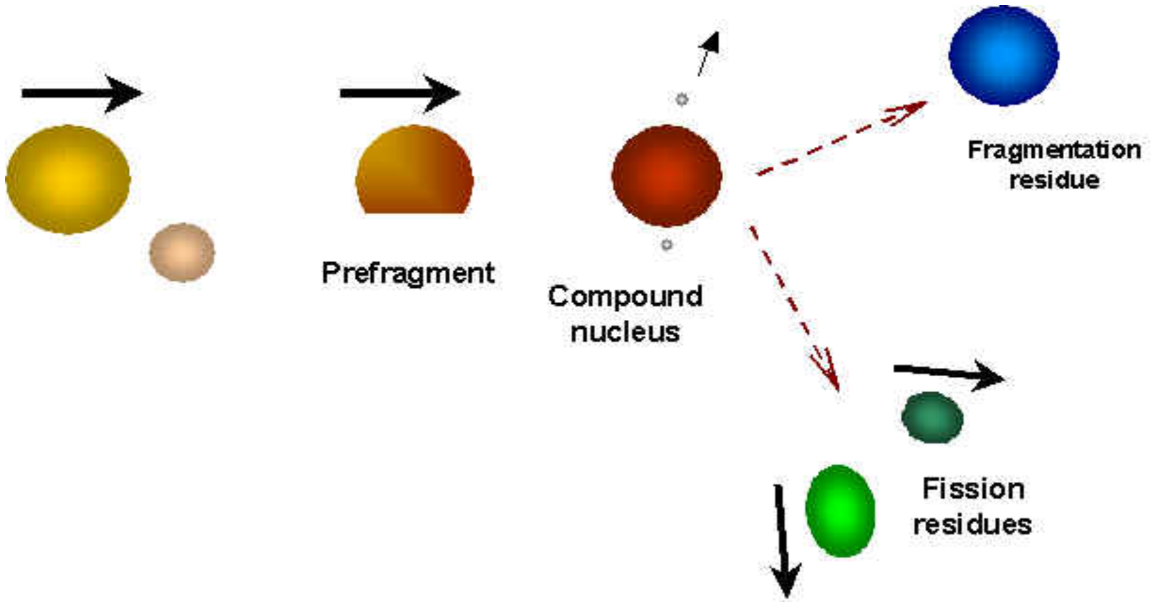
Estimation of the nuclear species that could be produced by fragmentation in 2025



Describing fragmentation reactions: models

Two-step approach: abrasion+ablation

$$\sigma(Z_f, N_f) = \sigma^{abrasion}(Z_f, N_f) P^{survival}(Z_f, N_f, E^*, J)$$



Describing fragmentation reactions: models

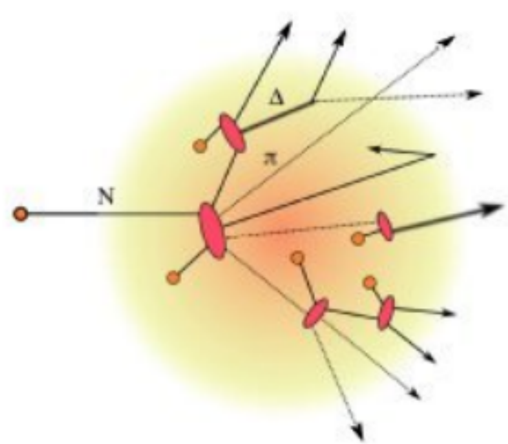
Abrasion stage

Glauber approach

$$\sigma^{abrasion}(Z_f, N_f) = \binom{Z_p}{Z_f}\binom{N_p}{N_f}\int d^2b[1 - P_b(b)]^{(Z_p - Z_f)} P_p(b)^{Z_f}[1 - P_n(b)]^{(N_p - N_f)} P_n(b)^{N_f}$$

$$P_p(b) = \int dsdz\rho_p{}^P(s,z)exp\left[-\sigma_{pp} Z_T \int dz\rho_p{}^T(b-s,z) - \sigma_{pn} N_T \int dz\rho_n{}^T(b-s,z)\right]$$

$$P_n(b) = \int dsdz\rho_n{}^P(s,z)exp\left[-\sigma_{pn} Z_T \int dz\rho_p{}^T(b-s,z) - \sigma_{nn} N_T \int dz\rho_n{}^T(b-s,z)\right]$$



Intra-Nuclear Cascade models

- Numerical integration of the transparency functions in Glauber's approach
- Explicit treatment of subnucleonic degrees of freedom: pions, hyperons, ..
- Semiclassical approach neglecting the mean-field dynamics.

Transport models based on the Vlasov-Uehling-Uhlenbeck theory

Describing fragmentation reactions: models

Ablation stage

Statistical emission of nucleons and clusters: Hauser & Fesbach formalism

$$\Gamma_\mu(E^*,J) = \frac{1}{2\pi\rho(E^*,J)} \int_0^{E^*-B_\mu-E^\nu{}_C} \sum_{J_f=0}^{\infty} \sum_{J_\mu=|J-J_f|}^{J+J_f} \sum_{\ell_\mu=|J_\mu-S_\mu|}^{J_\mu+S_\mu} T_{\ell_\mu}(\epsilon_\mu)\rho_f(E^*-B_\mu-E^\mu{}_C-\epsilon_\mu,J_f)d\epsilon_\mu$$

- Main parameters: transmission coefficients, level densities and binding energies

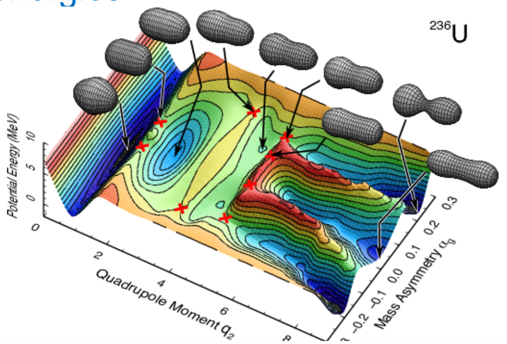
Fission: Bohr&Wheeler + fission yield model

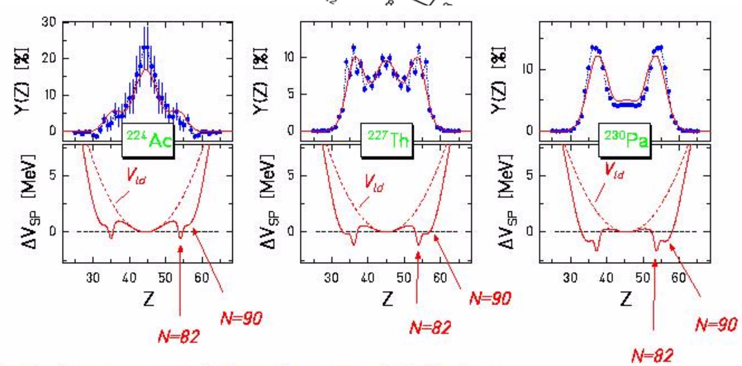
$$\Gamma_{fis.} = \frac{1}{2\pi\rho(E^*,J)} \int d\epsilon\rho_{sad.}(E^*-B_{fis.}(J)-\epsilon)$$

- Main parameters: level densities and fission barriers

$$Y(E^*,N) = \frac{\int_0^{E^*-V(E^*,N)}\rho_N(U)dU}{\sum_{N=0}^{N_{CN}}\int_0^{E^*-V(E^*,N)}\rho_N(U)dU}$$

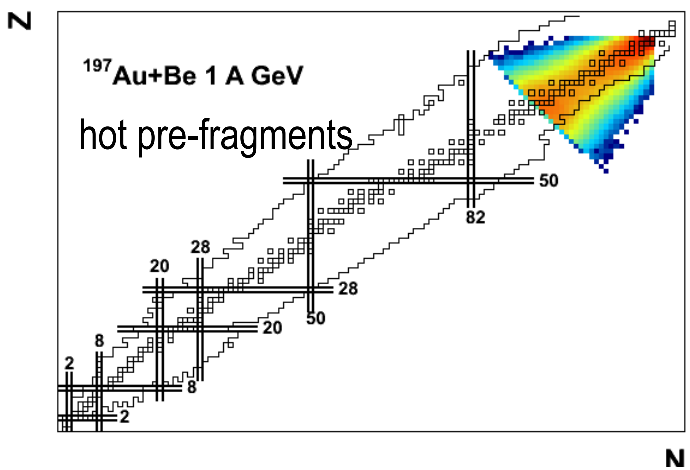
- Main parameters: level densities and mass asymmetry potential





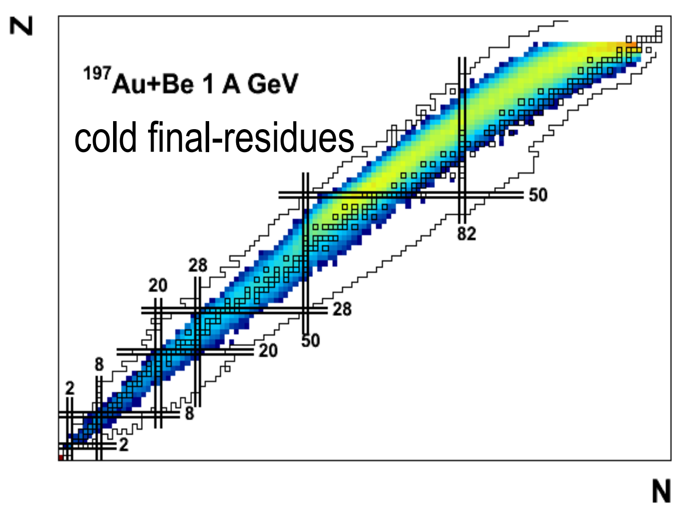
Fragmentation yields: key features

Large range in isospin



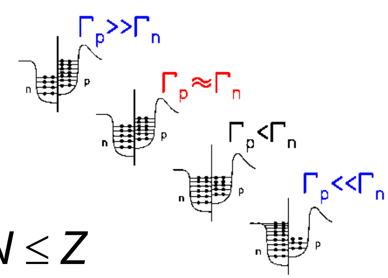
- the abrasion process is ruled by geometrical considerations and the neutron-proton abundance:

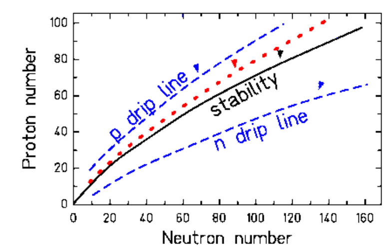
$$P(N-n, Z-z) = \frac{\binom{Z}{z}\binom{N}{n}}{\binom{A}{a}} \qquad A = Z + N \qquad a = z + n$$



- the ablation process reduces the isospin fluctuations:

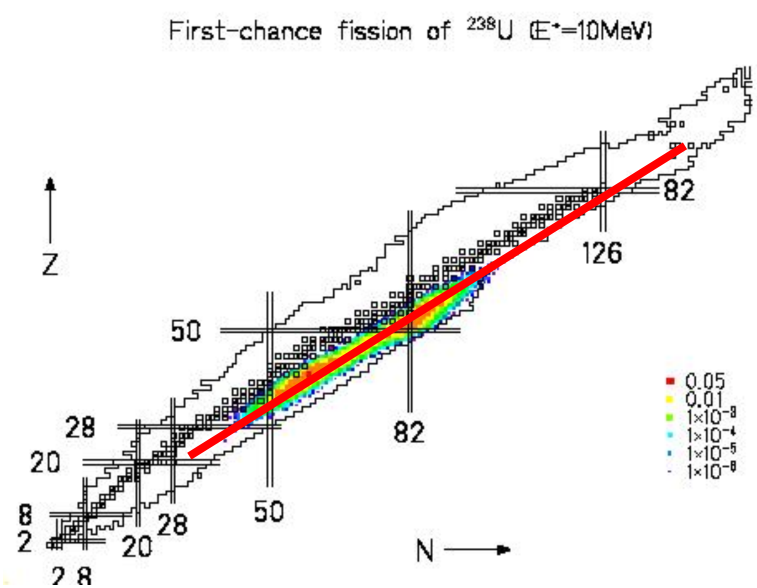
$$\Gamma_n \approx \Gamma_p \quad \Rightarrow \quad B_n \approx B_p + E_C \quad N \leq Z$$

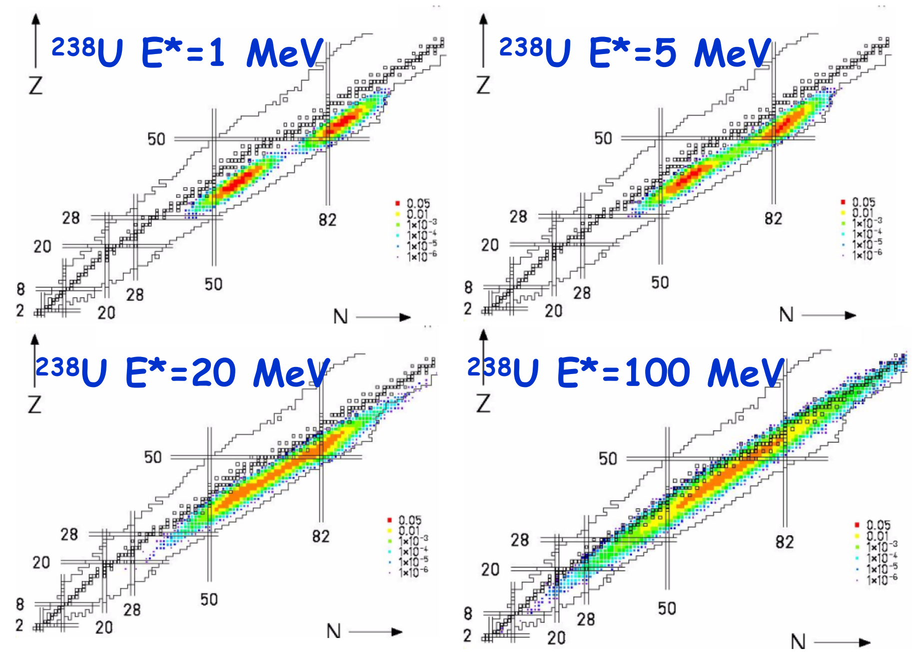




Fission yields: key features

Large neutron excess

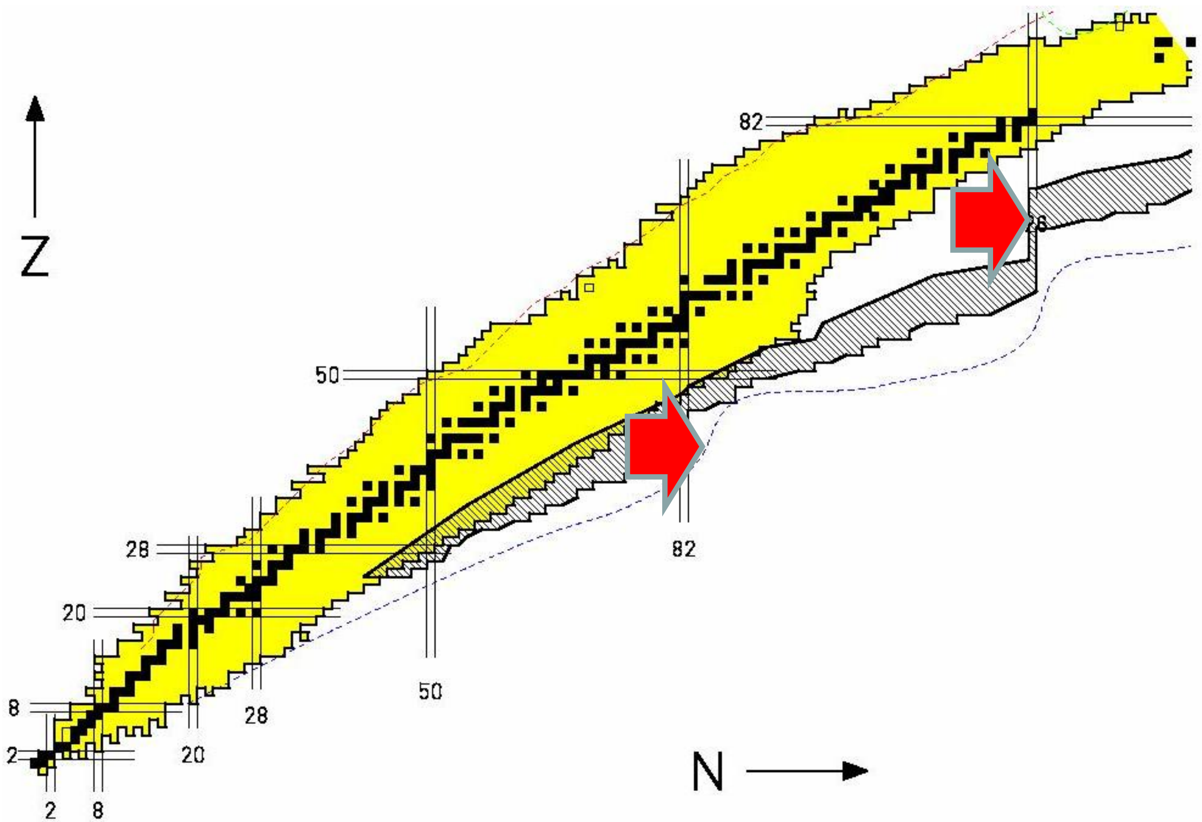




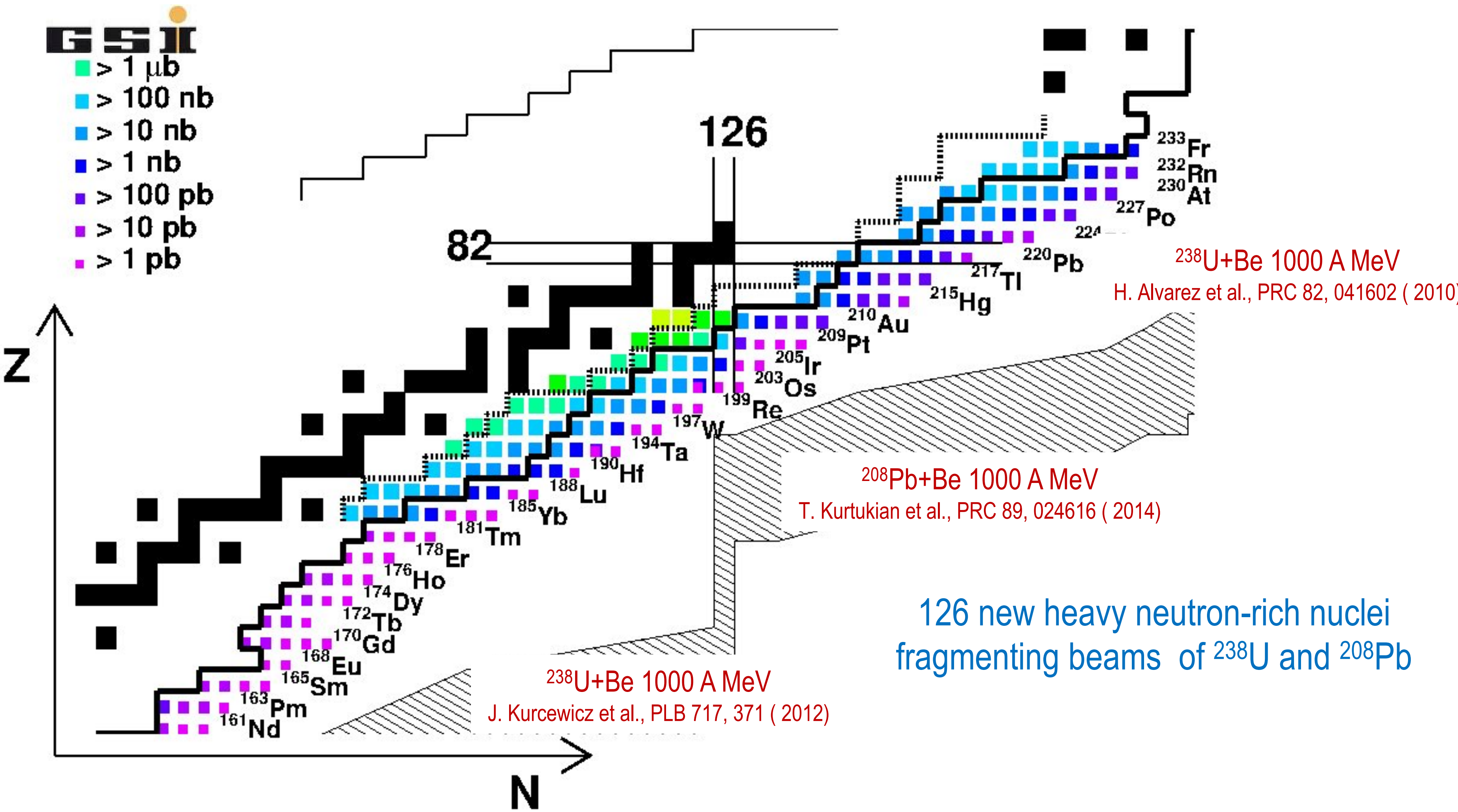
- Final fission fragments almost preserve the N/Z of the fissioning nucleus

- Excitation energy broadens the range in A and N/Z covered by fission fragments, but neutron evaporation will reduce the neutron-excess.

Fragmentation and fission yields beyond present limits



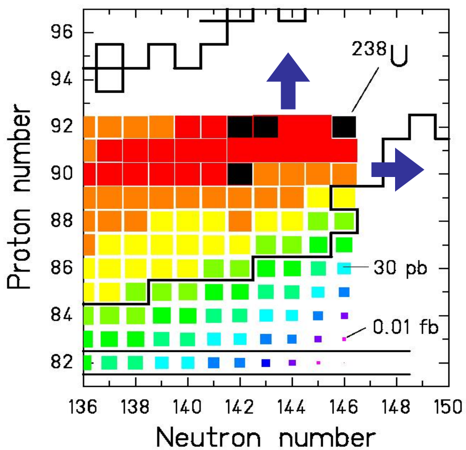
Fragmentation: heavy neutron-rich nuclei

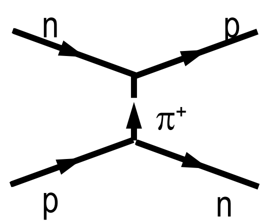


126 new heavy neutron-rich nuclei fragmenting beams of ^{238}U and ^{208}Pb

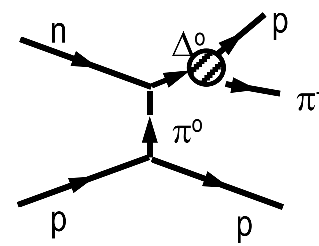
Fragmentation: heavy neutron-rich nuclei

Charge-exchange reactions

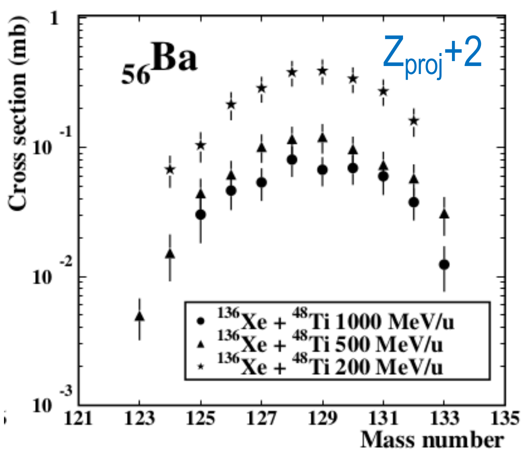


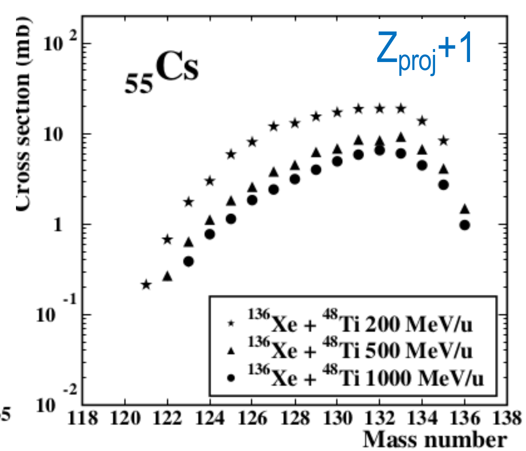


quasi-elastic
charge exchange



inelastic
charge exchange





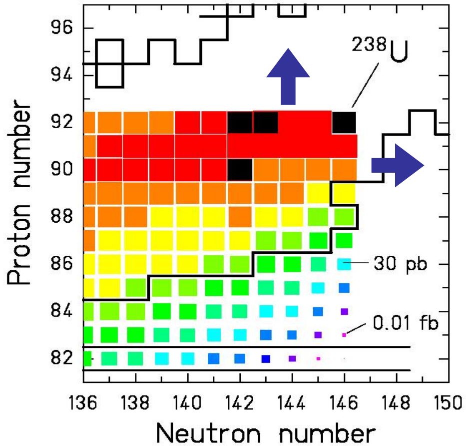
- Up to Z_{proj}+2 has been observed in fragmentation reactions.

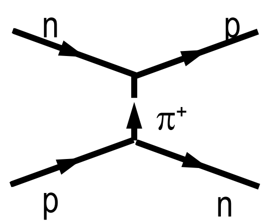
- Cross sections are higher at lower energies.

- Cross sections decrease by around a factor 50 per additional charge.

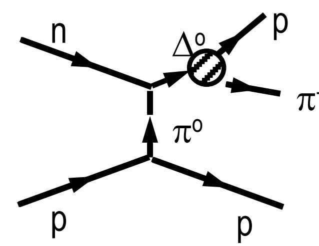
Fragmentation: heavy neutron-rich nuclei

Charge-exchange reactions

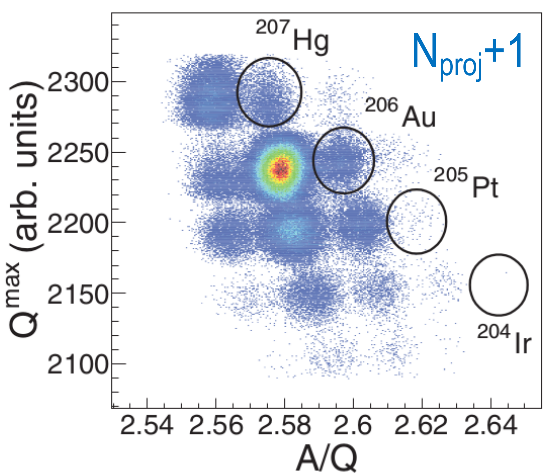


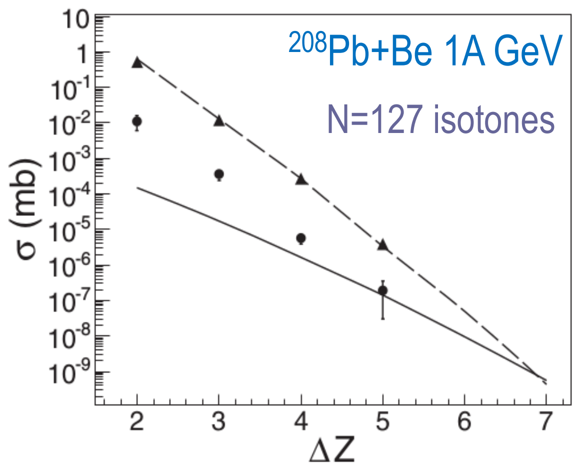


quasi-elastic
charge exchange



inelastic
charge exchange

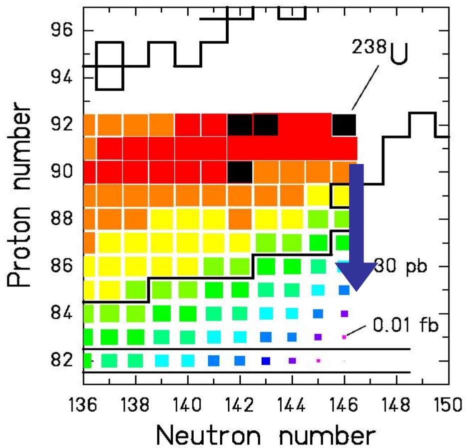




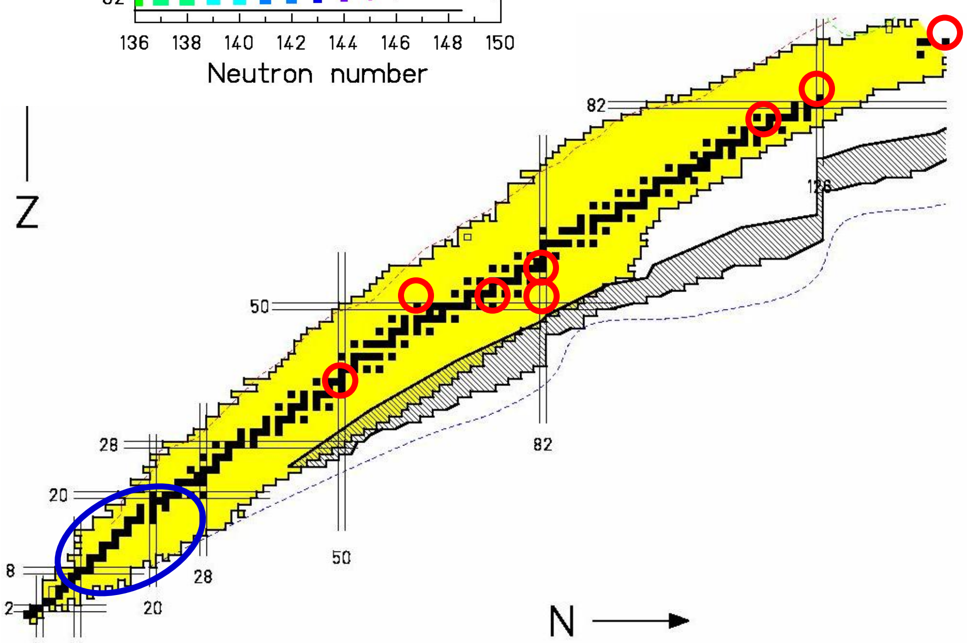
- Up to N_{proj}+1 has been observed.
- Cross sections are lower than for proton pick-up.

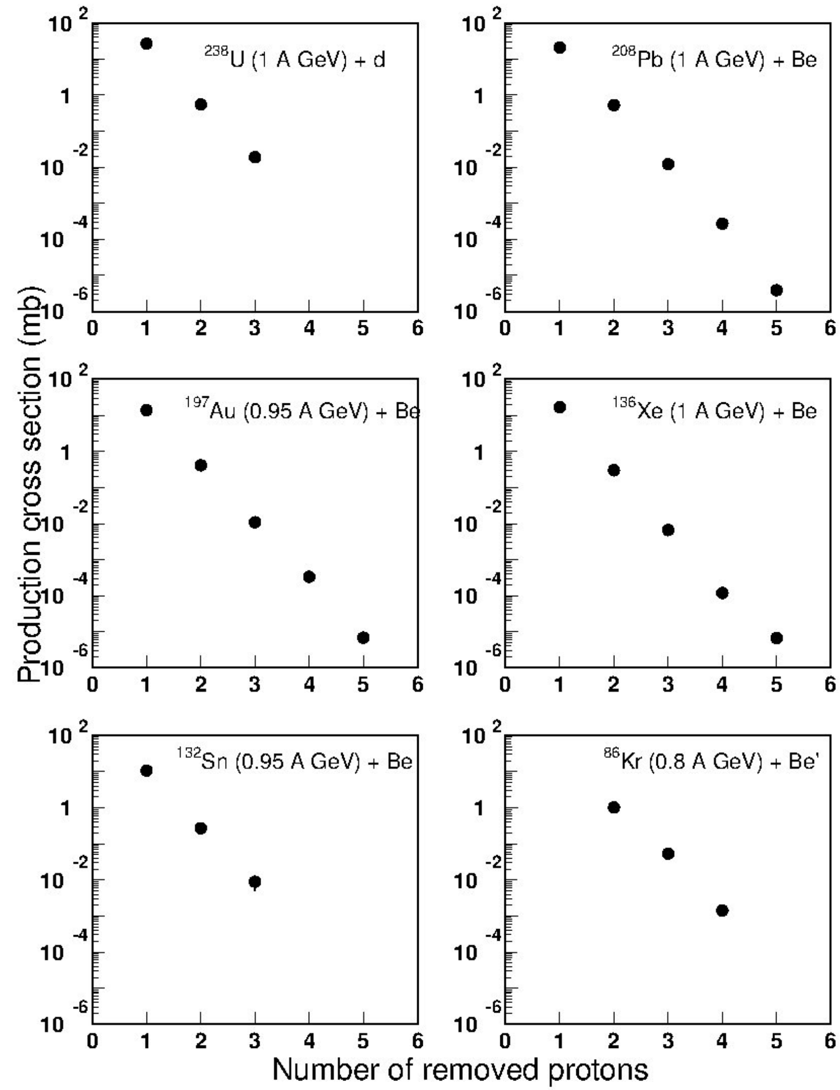
Fragmentation: heavy neutron-rich nuclei

Cold-fragmentation reactions



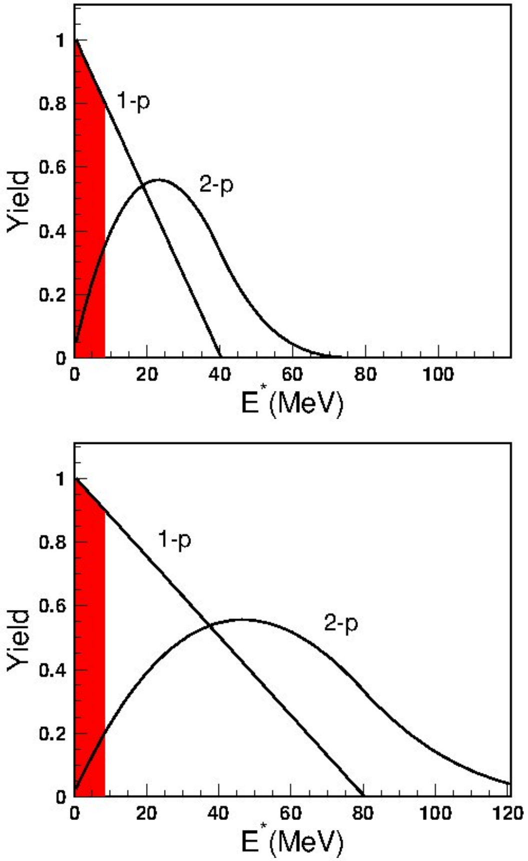
Protons are removed while the remnants do not get excited

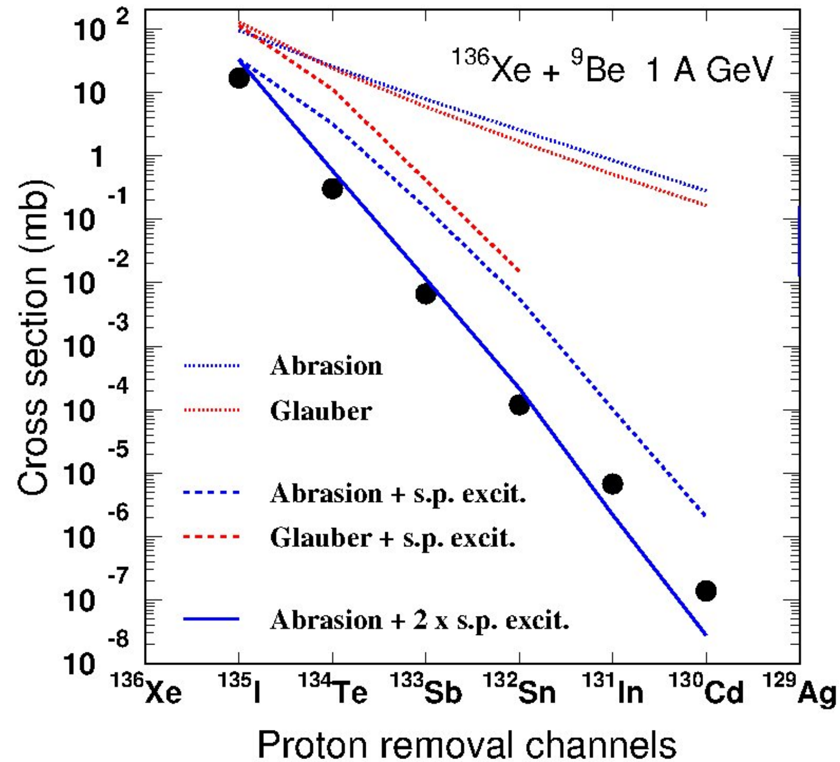




Fragmentation: heavy neutron-rich nuclei

Cold-fragmentation reactions





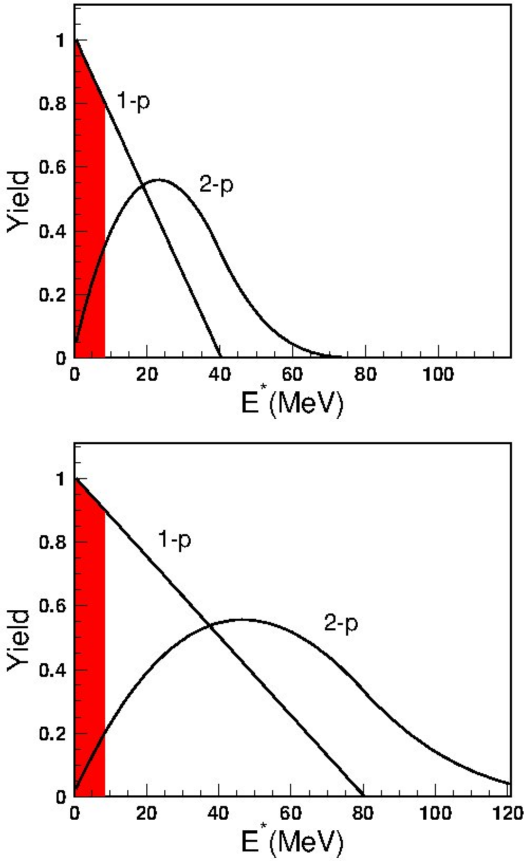
Excitation energy gained by the remnants seems to be larger than expected from particle-hole excitations

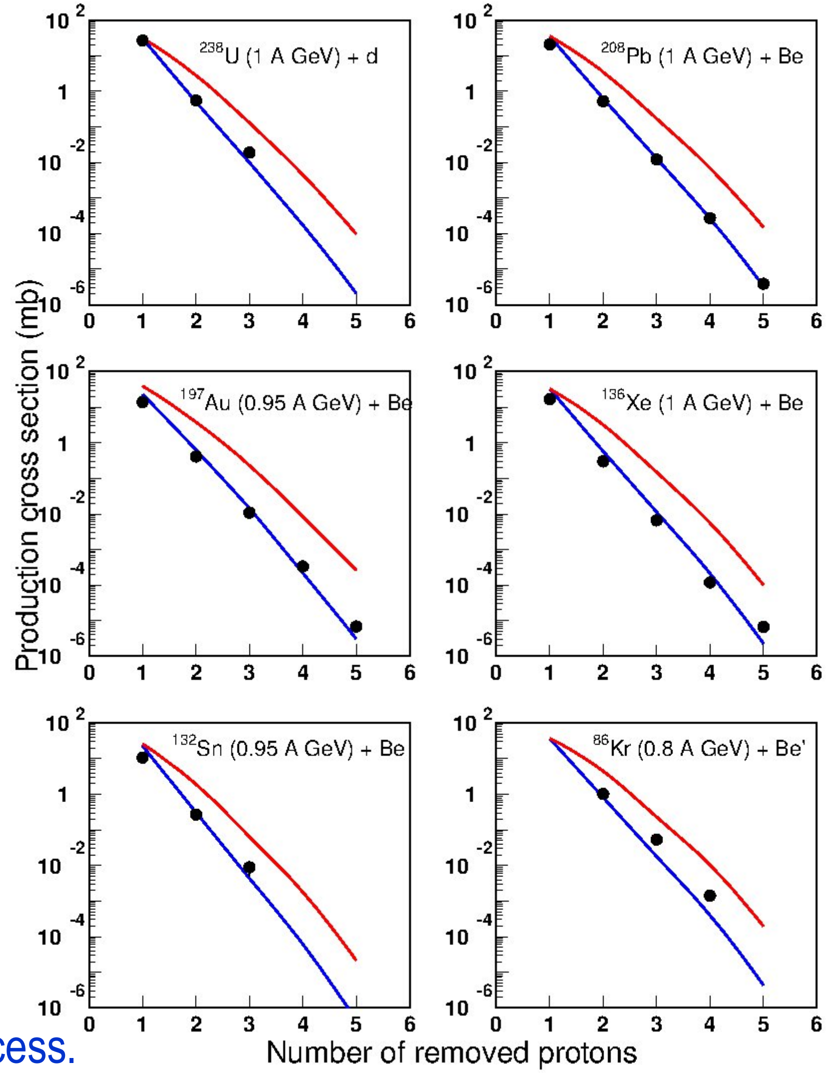
J. Benlliure et al., PRC 78, 054605 (2008)

K.-H. Schmidt et al., PLB 300, 313 (1993)

Fragmentation: heavy neutron-rich nuclei

Cold-fragmentation reactions

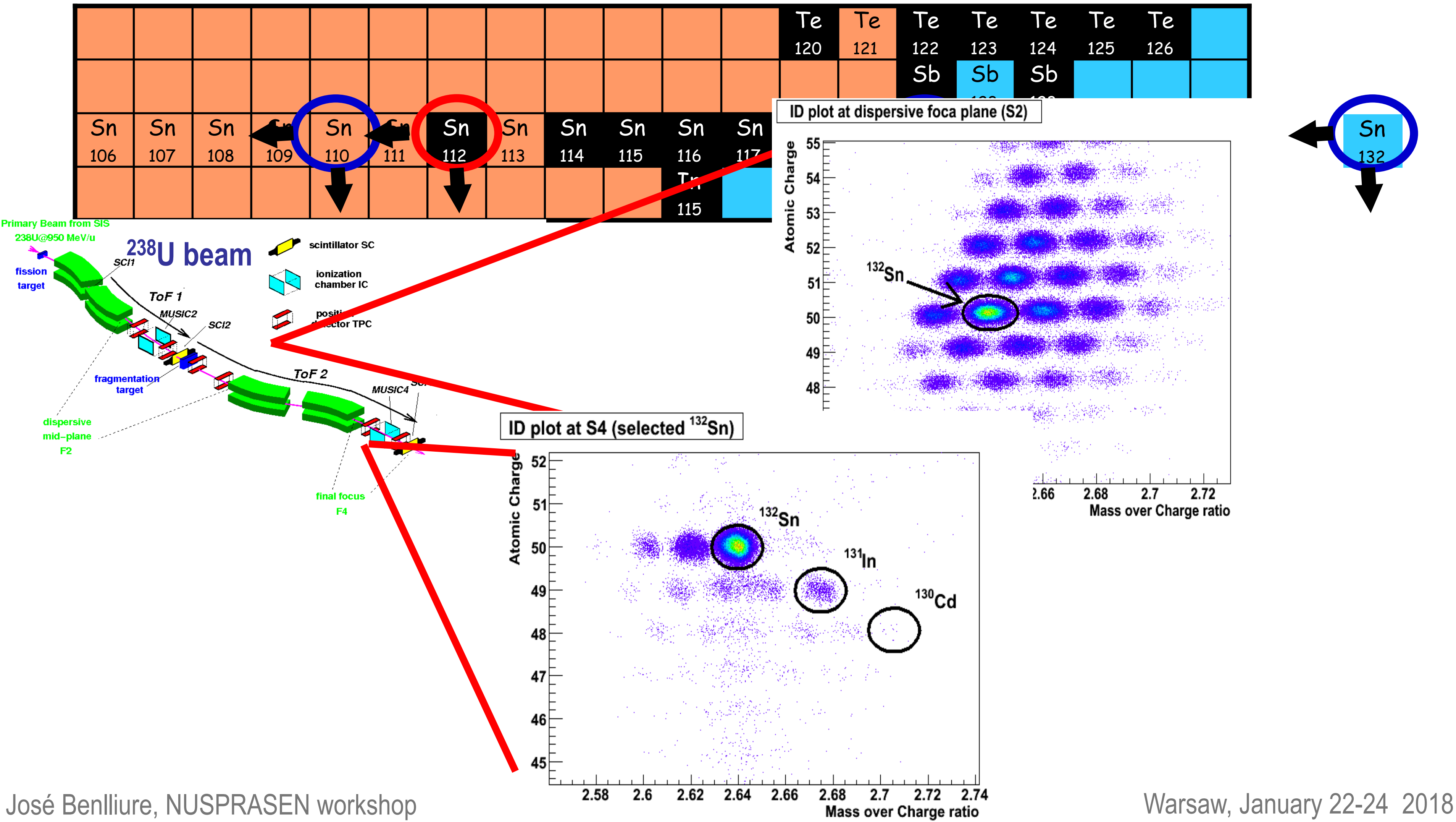




The persistence of this effect should be checked with lighter projectiles and as a function of the neutron excess.

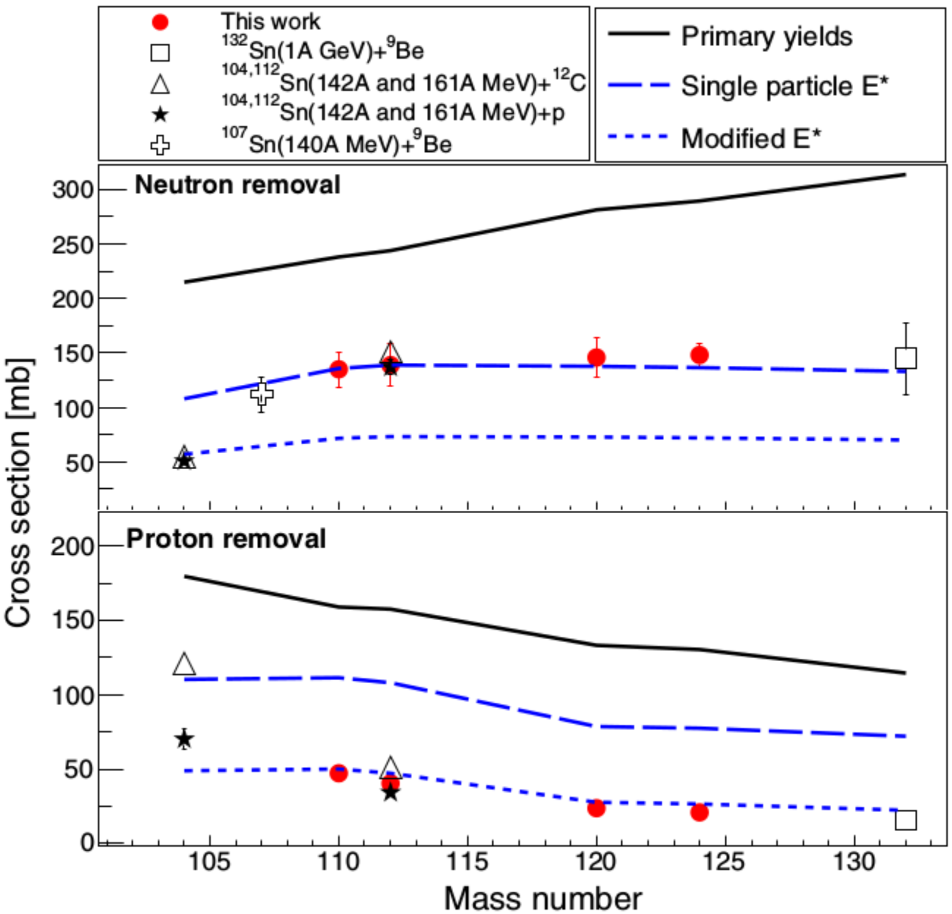
Fragmentation: medium-mass neutron-rich nuclei

Isospin dependence of the nucleon-removal process



Fragmentation: medium-mass neutron-rich nuclei

Isospin dependence of the nucleon-removal process



- Neutron knock-out is fairly well described by Glauber-type calculations and single-particle energies.

- Proton knock-out is over-predicted by a factor 2.

- This tendency reverses for neutron-deficient nuclei.

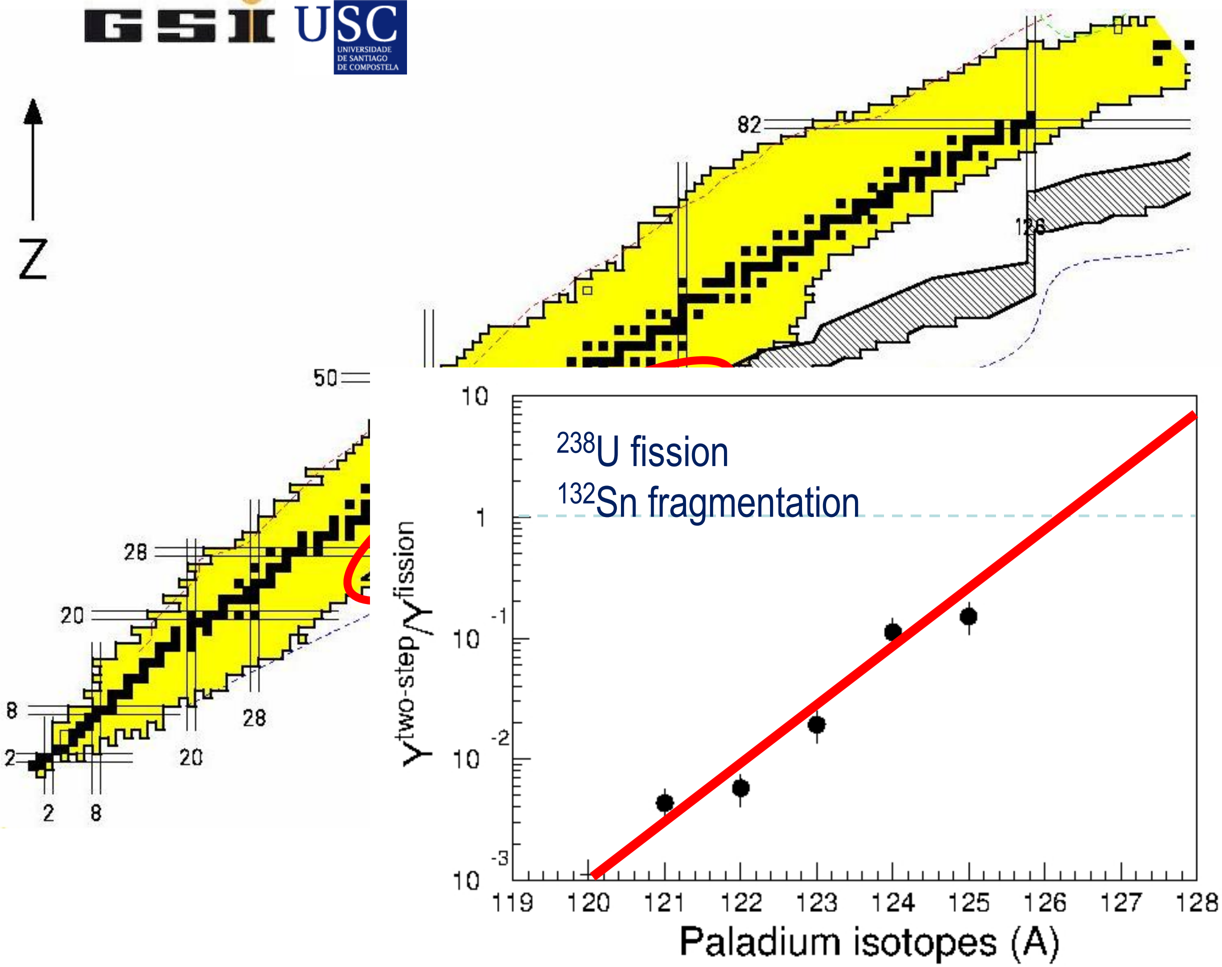
- Similar results are obtained with intra-nuclear cascade model calculations describing inelastic NN collisions and multi-nucleon scattering effects.

The excitation energy induced by the knock-out of deeply bound nucleons seems to exceed the single-particle approach and could be a signature of SRC.

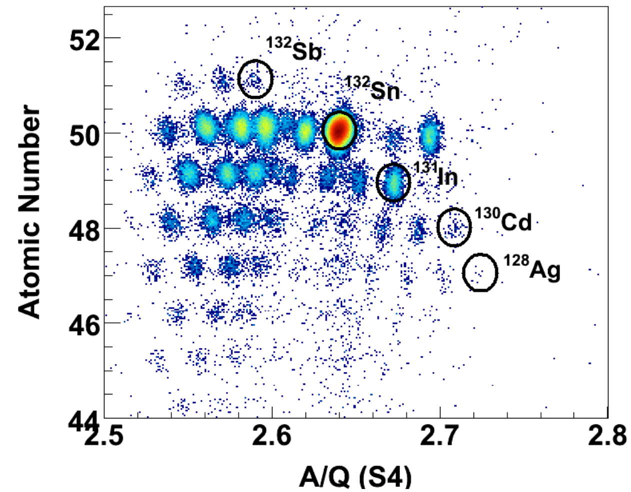
J.L. Rodríguez et al., PRC 96, 034303 (2017)

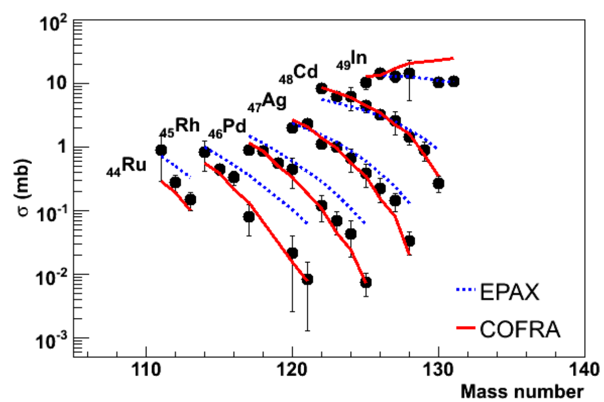
Fragmentation: medium-mass neutron-rich nuclei

Two-step reaction: fission+fragmentation



Fragmentation of neutron-rich fission fragments ^{132}Sn+Be @ 1 A GeV

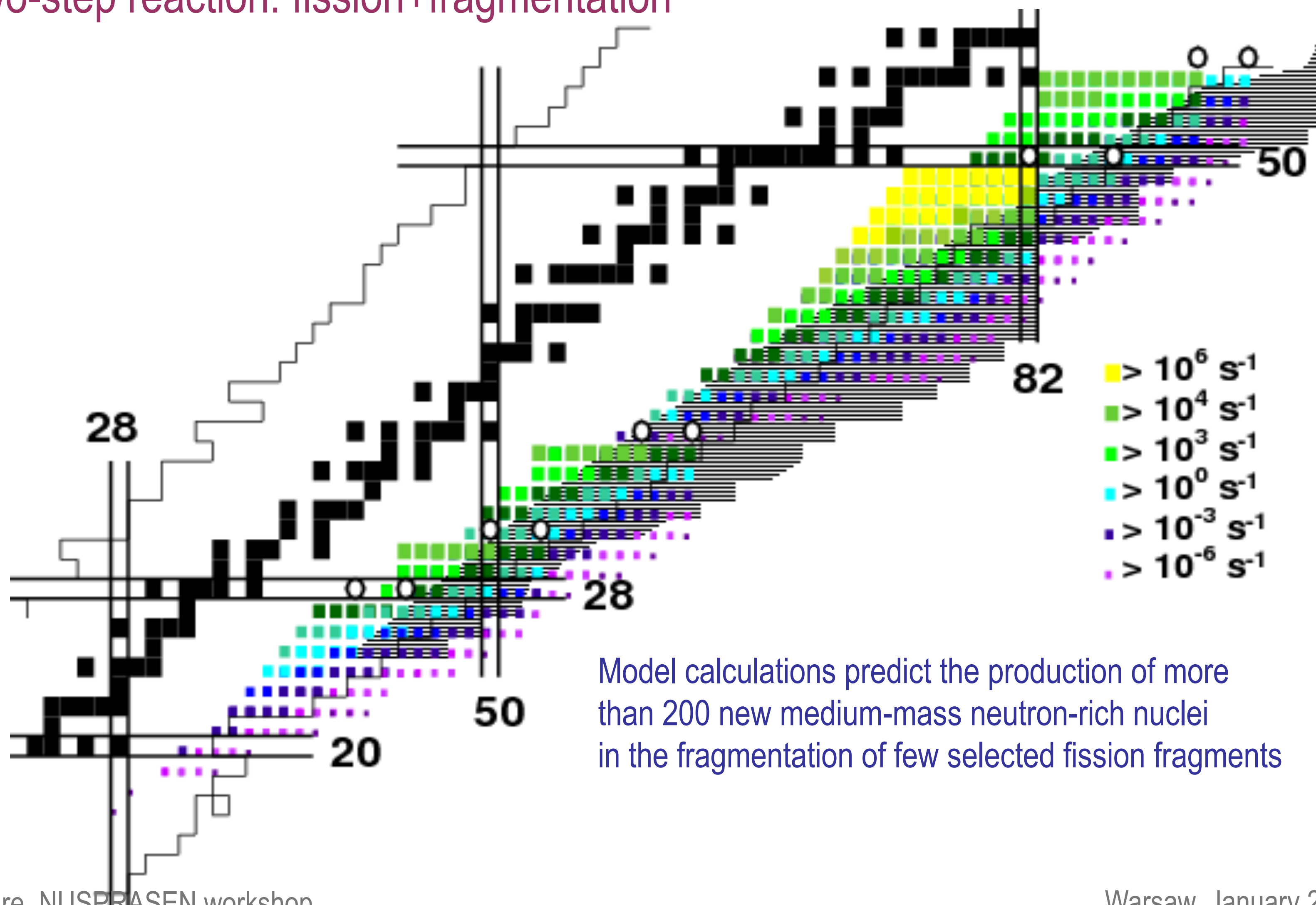




D. Pérez et al., PLB 703, 552 (2011)

Fragmentation: medium-mass neutron-rich nuclei

Two-step reaction: fission+fragmentation



Model calculations predict the production of more than 200 new medium-mass neutron-rich nuclei in the fragmentation of few selected fission fragments

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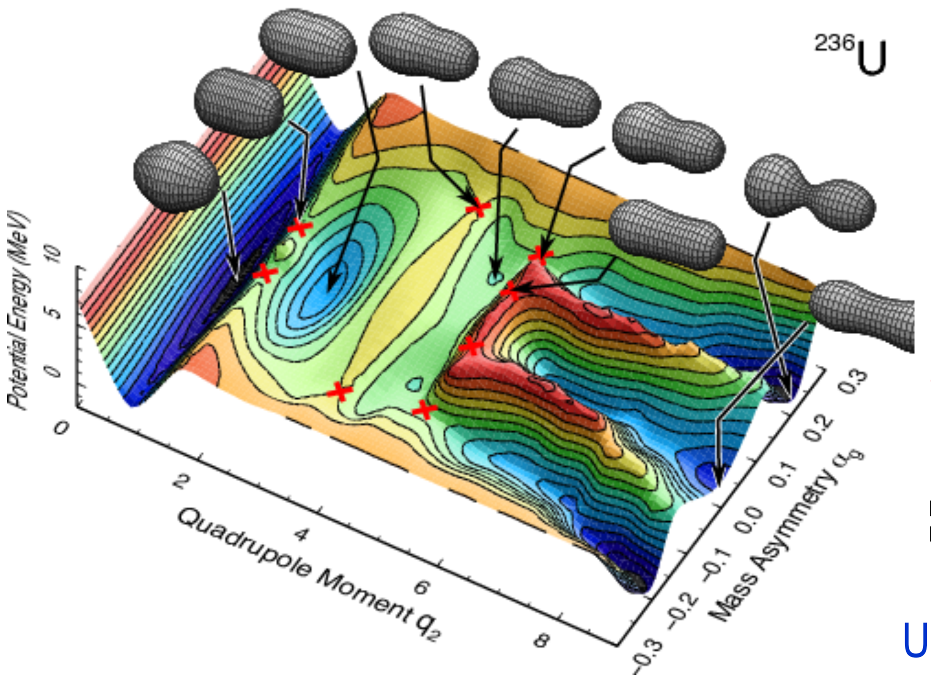
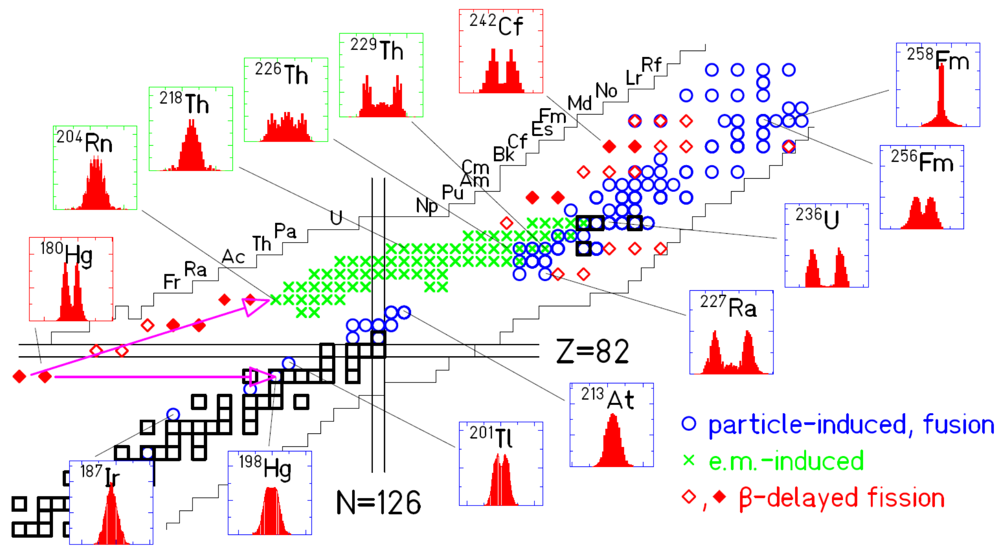
Fission yields

Provide information on the **potential energy surface** defining the fission process:

- **Macroscopic component**: liquid-drop
- **Microscopic components**: shell structure



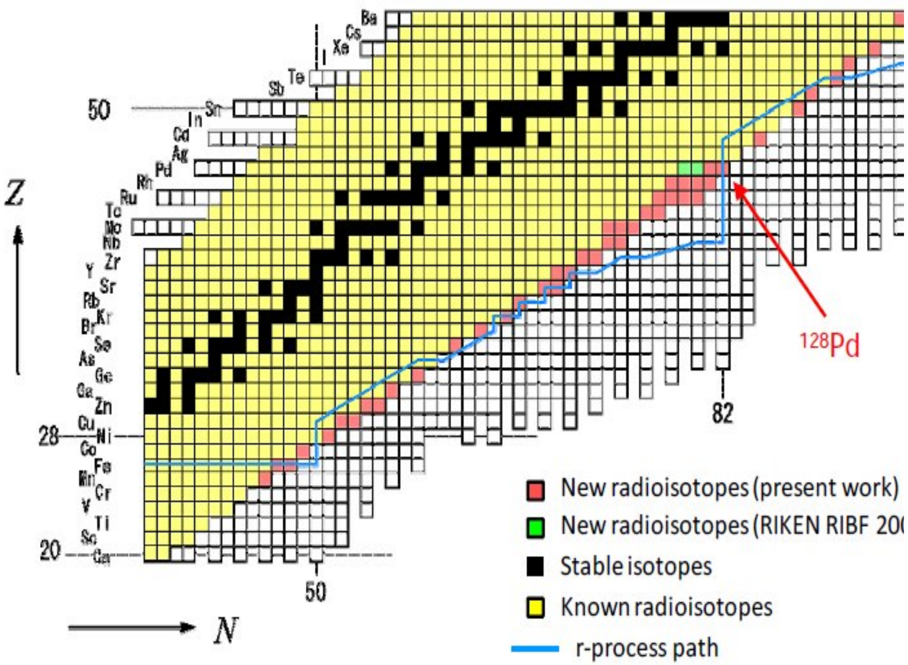


Until recently, experiments only provided information on the mass or the charge of the final fission fragments

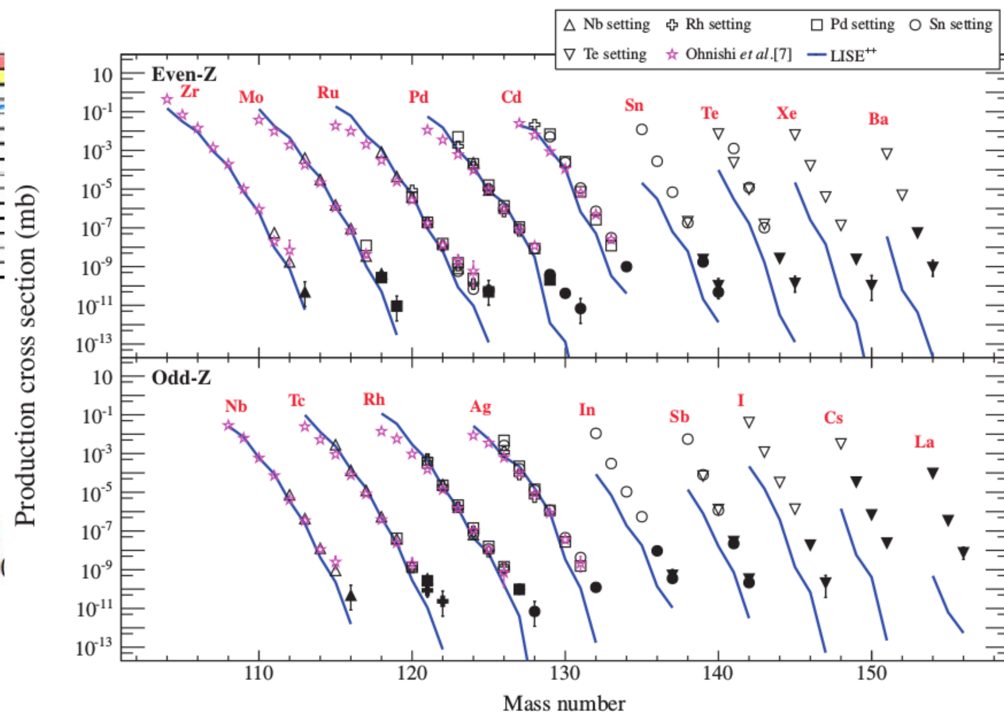
Fission yields

The limits of the nuclear chart

45 (2010) + 65 (2018) new medium-mass neutron-rich nuclei
in fission induced by in-flight fragmentation of ^{238}U at RIBF/RIKEN



T. Ohnishi et al., J. Phys. Soc. Jpn, 79, 073201 (2010)



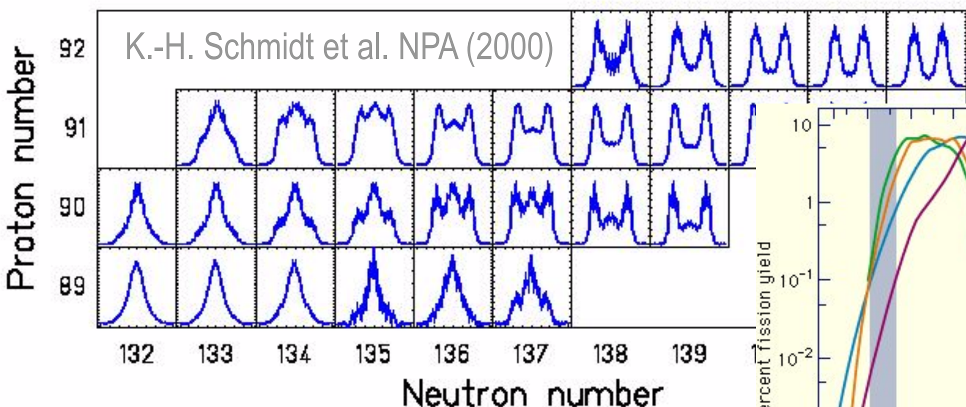
Y. Shimizu et al., J. Phys. Soc. Jpn, 87, 014203 (2018)

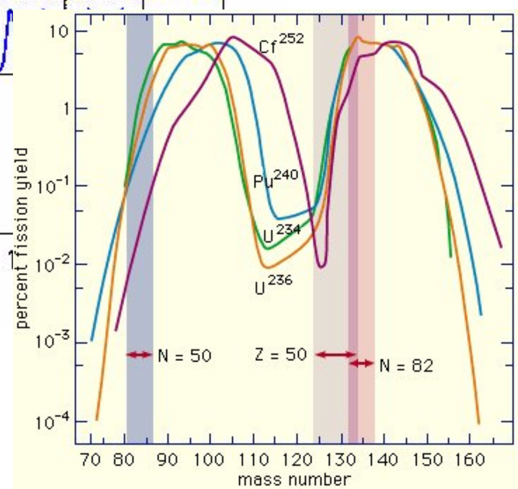
N. Fukuda et al., J. Phys. Soc. Jpn, 87, 014202 (2018)

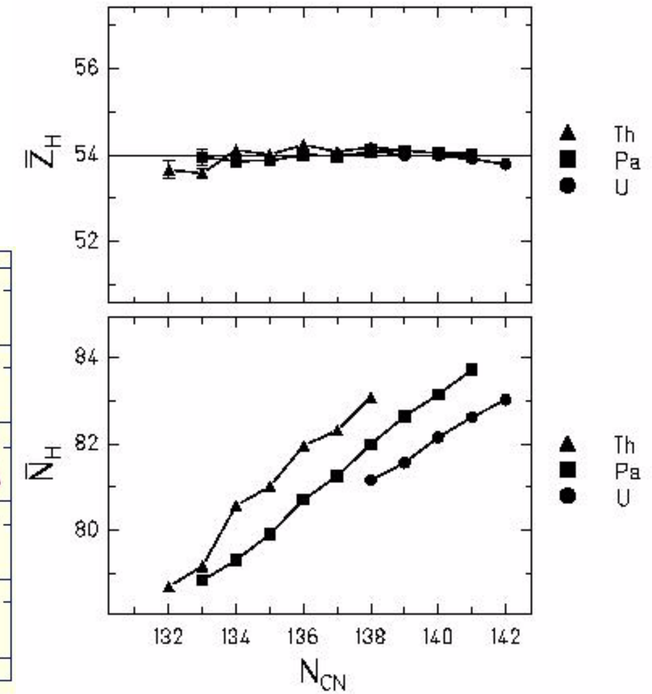
Fission yields

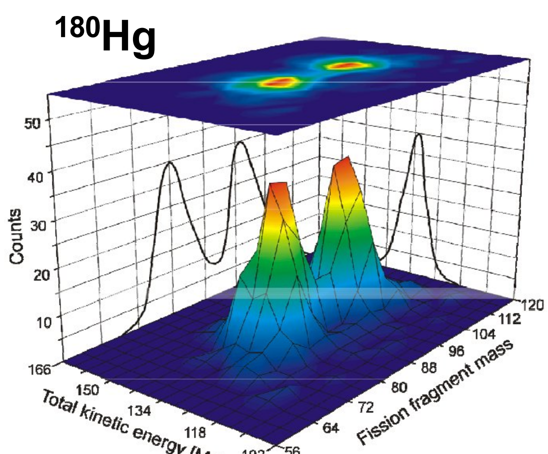
Present challenges: structural effects in the potential energy surface

Charge distributions do not show evidences for the shell closure at Z=50, neither the deduced (UCD) neutron distributions at N=82,86







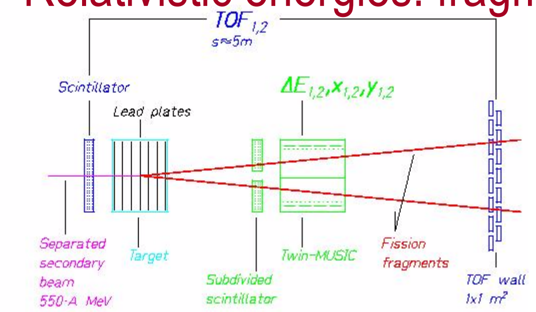


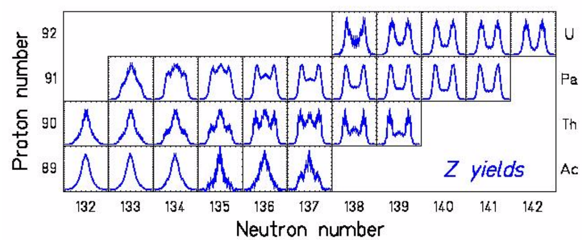
New type of asymmetric fission in neutron-deficient nuclei βDF

A. Andreyev et al. PRL 105, 252502 (2010)
L. Ghys et al., PRC 90, 044305 (2014)

Fission yields in inverse kinematics

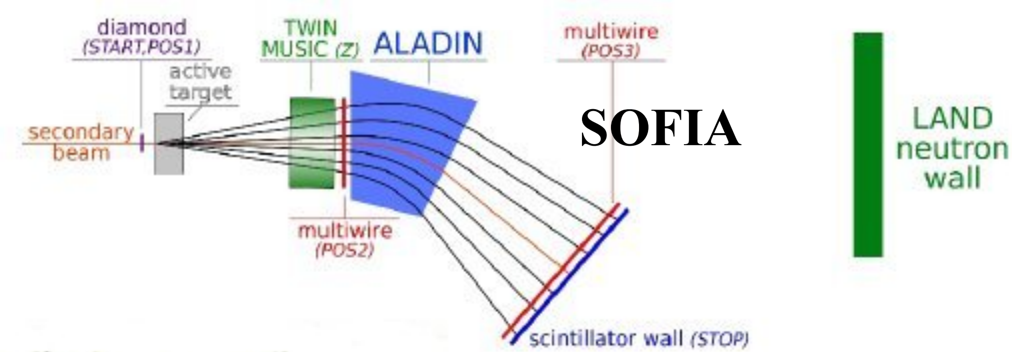
Relativistic energies: fragmentation or Coulex



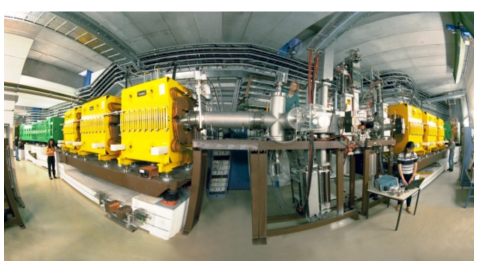


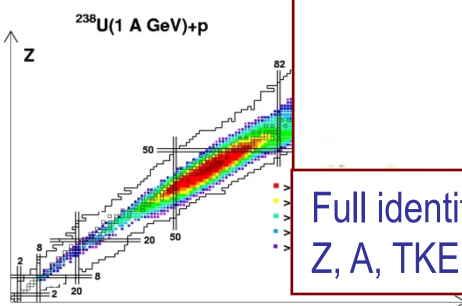
- structural effects in fission

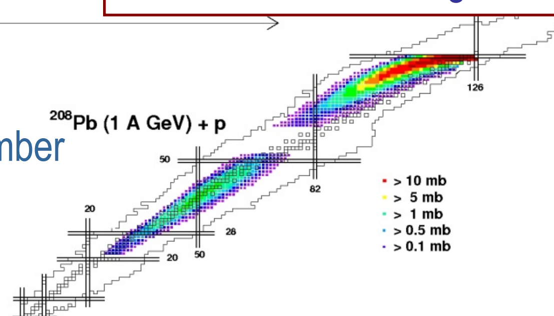
- detection of both fission fragments
- but only the atomic number is determined



Full identification of both fission fragments
Z, A, TKE, neutrons, gammas, light-charged particles







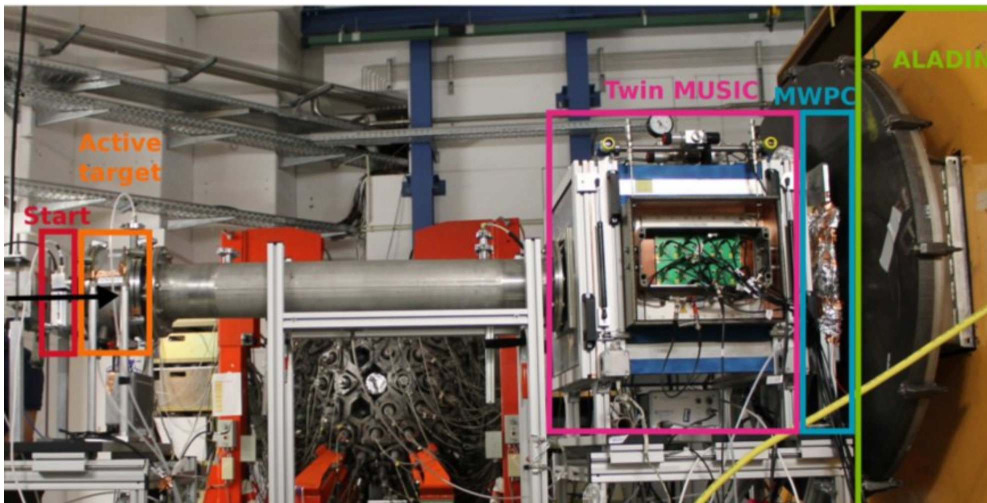
- full identification in mass and atomic number
- but only one fragment is measured

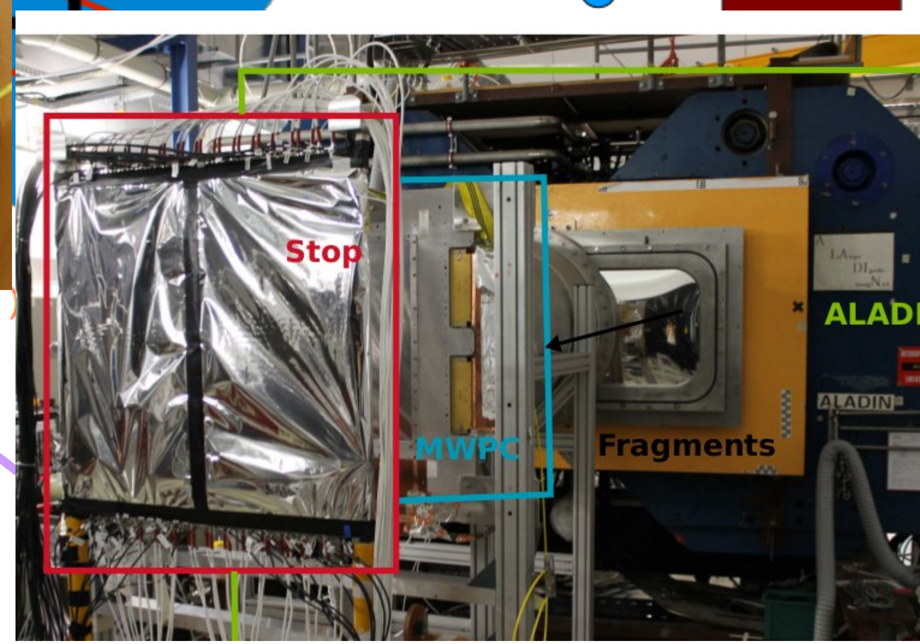
- dynamics of fission at high excitation energy

Fission yields: the SOFIA experiment @ GSI

Compete identification in A, Z of both fission fragments together with light-charged particles and neutrons

J. Taieb, CEA (France)





(Xi, Yi)

Star

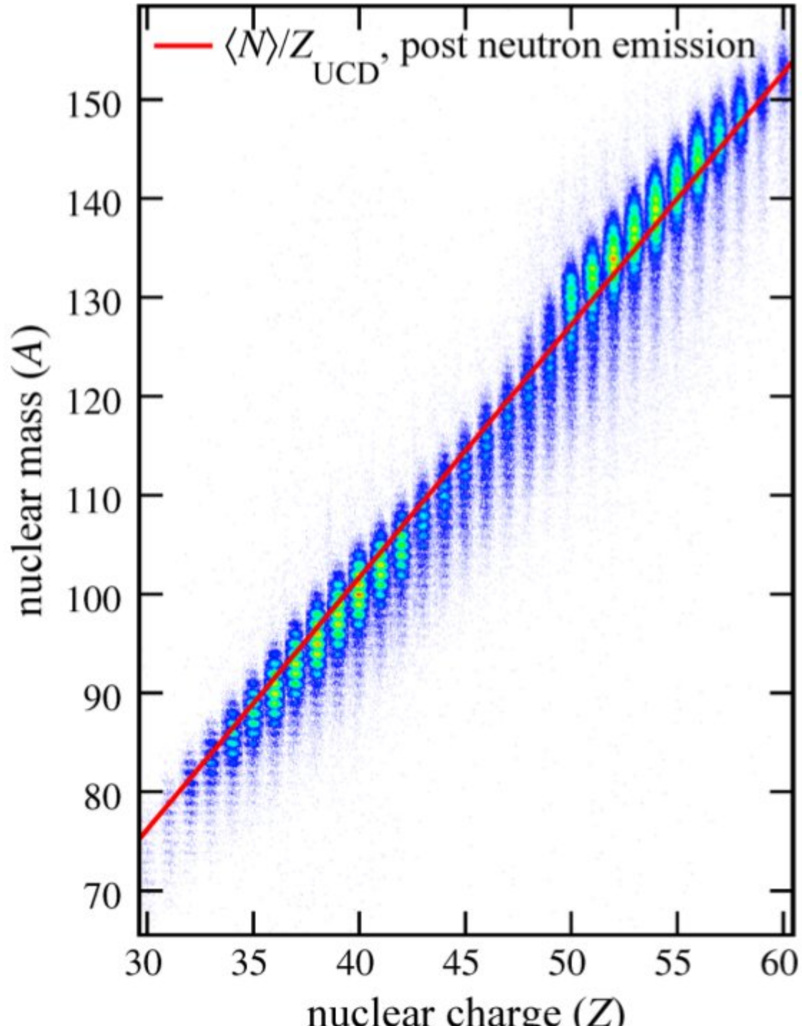
7 m

- Energy-loss resolution: ~ 1.2 %
- Position resolution: ~ 200 μm
- Time-of-flight resolution: ~ 40 ps
- Limited straggling (helium pipes)

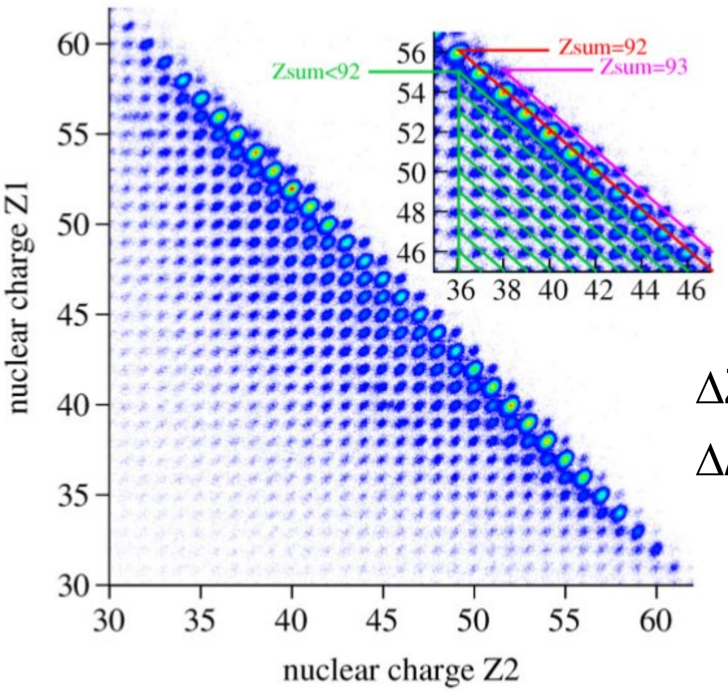
Stop

Fission yields: the SOFIA experiments at GSI

Complete identification of both fission fragments



For the first time both fission fragments were identified in atomic and mass number and their velocities were determined with good accuracy.



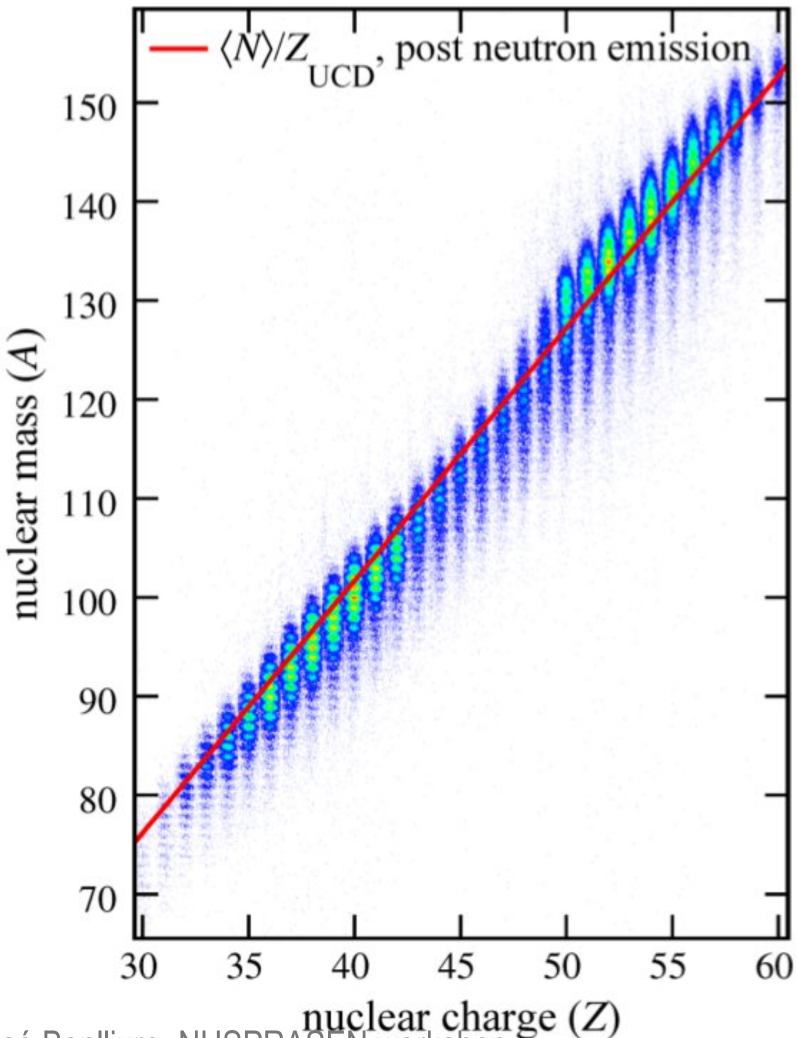
$\Delta Z \sim 0.4$

$\Delta A \sim 0.6$

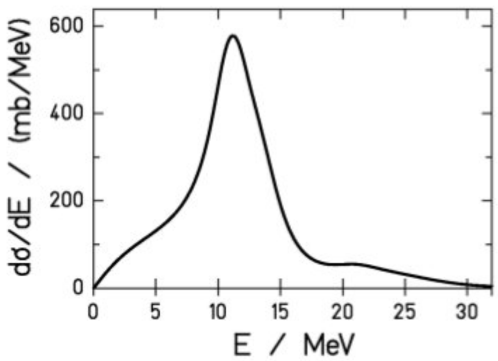
E. Pellereau et al., Phys. Rev. C 95, 054603 (2017)
J.L. Rodriguez et al., Phys. Rev. C 91, 064616 (2015)

Fission yields: the SOFIA experiments at GSI

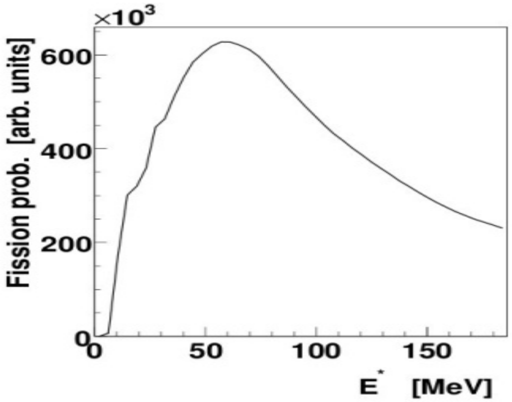
Complete identification of both fission fragments



- Coulex



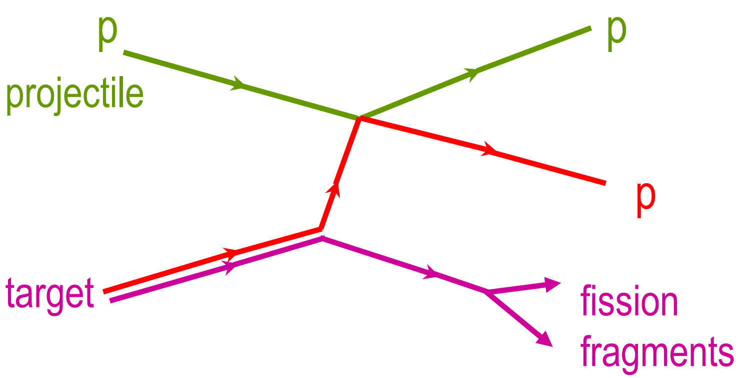
- Nuclear fission



Limited control on the fissioning nucleus.

Fission studies @ R3B/FAIR

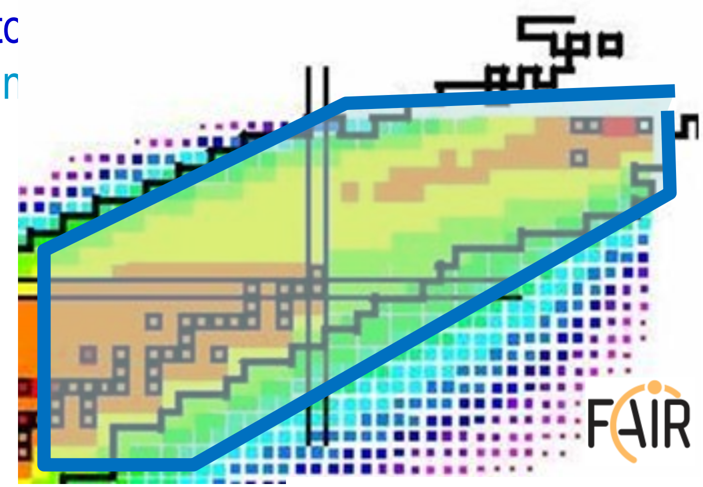
(p,2p) and (p,pn) quasi-free scattering induced fission (~ 500 MeV)



- ✓ Well defined kinematical conditions
  - Momentum and E* of the recoiling nucleus
- ✓ Relatively large cross sections
  - 10 – 50 mb
- ✓ Large range in excitation energy
  - up to 60 MeV
- ✓ Possibility tc
  - inverse kir

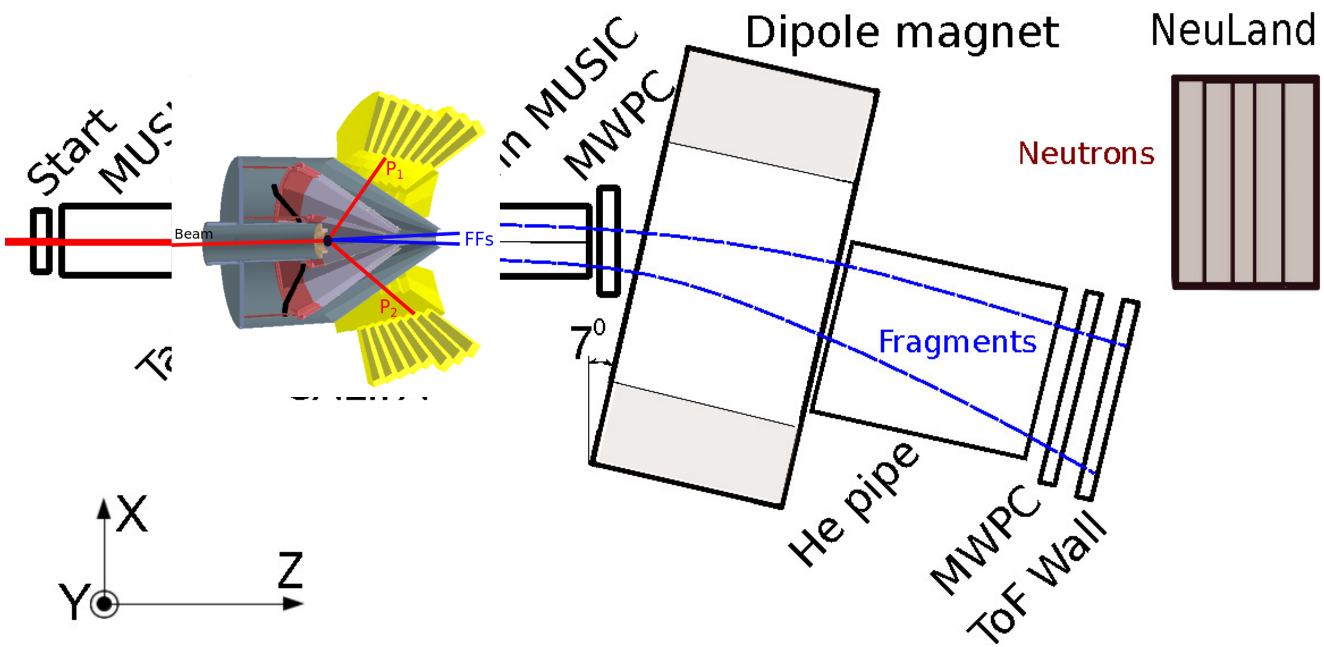
Missing energy

$$T_{p_{in}} + M\left({}^{A}Z\right) = E^{*} + M\left({}^{A-1}Z-1\right) + T_{p_1} + T_{p_2}$$



Fission studies @ R3B/FAIR

Coupling CALIFA-tracker + GLAD + NeuLAND + SOFIA



- ✓ Characterization of the fissioning nucleus (A, Z, E*) → (p,2p) with CALIFA+tracker
- ✓ Characterization of the fission fragments (A, Z, TKE, ν) → SOFIA + NeuLAND

Conclusions

✓ Fragmentation reactions have a large impact in several areas of Nuclear Physics research: nuclei far from stability, hot and dense nuclear matter, hypernuclei,… , and in applications.

✓ Several new-generation RIB facilities are taken advantage of this reaction mechanism: RIBF, FRIB and FAIR.

✓ This reaction mechanism is fairly well described by Glauber-type calculations, although the detailed investigation of the nucleon removal indicates the limitations of the single-particle picture used for describing remnants excitations.

✓ Charge-exchange, cold-fragmentation and fission-fragmentation reactions will make possible to extend the present limits of the chart of nuclei.

✓Fission yields are still challenging for theory and experiments: role of shell effects.

✓ Inverse kinematics represents a real break-through for the measurement of fission yields

✓ The SOFIA setup at GSI/FAIR recently provided the first complete characterization of both fission fragments in A, Z and TKE and it will be upgraded coupling this device to the R3B experiment.