Future Prospects for Secondary-Beam Production

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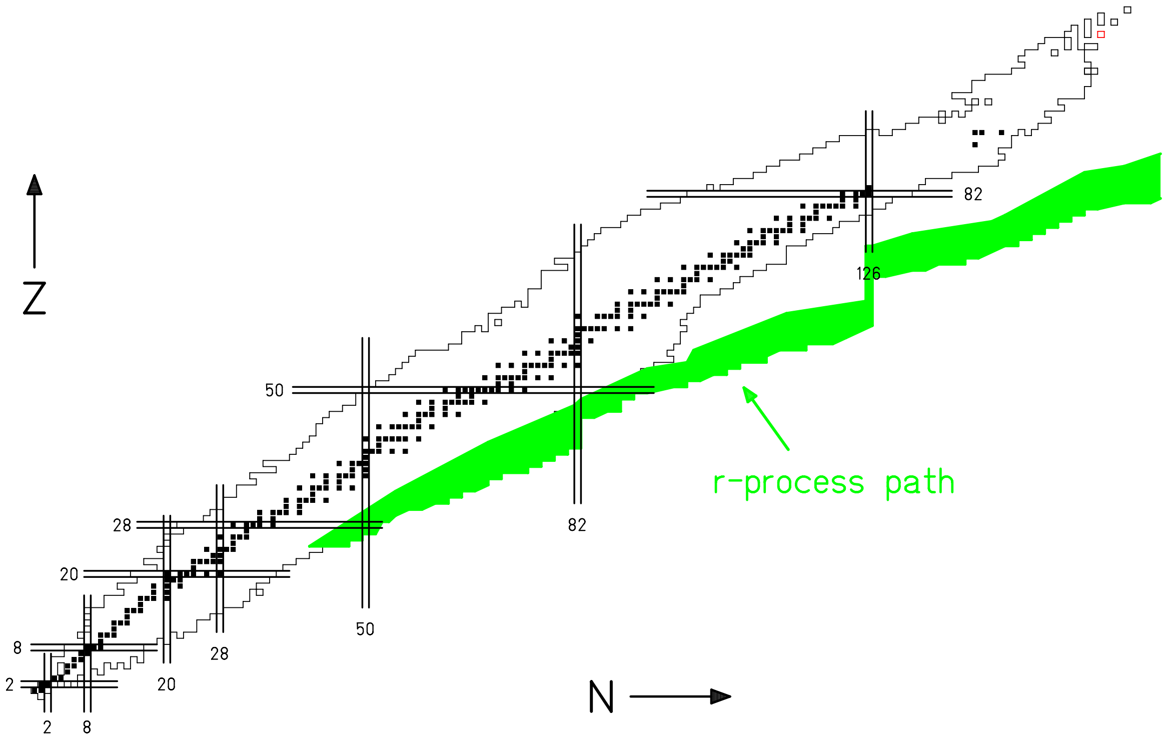
New-generation secondary-beam facilities based on
in-target production, extraction and reacceleration or
in-flight production and separation.

Aim to find general possibilities and limitations.

General arguments for an "optimum" beam energy.
Reaction probabilities and heat load.

Characteristics of the reaction mechanisms.
Systematic experimental survey.
Special considerations for neutron-rich nuclei.

Finding best conditions to go beyond the present limits

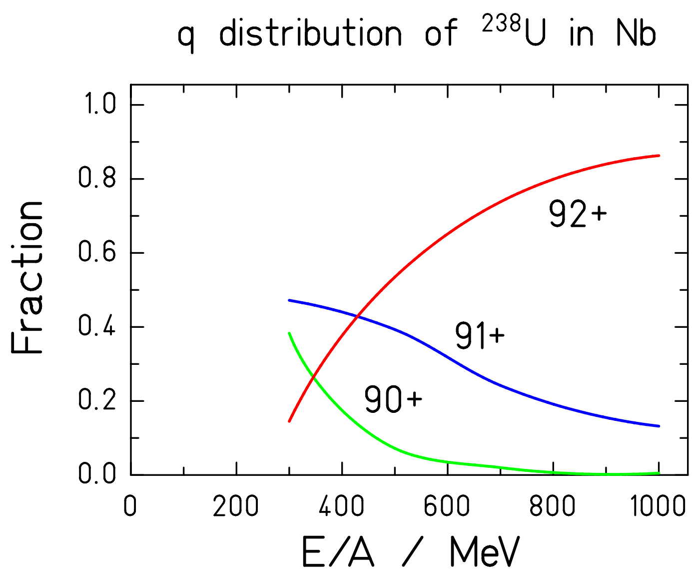


Even nature did not reach the neutron drip line (r-process)

How to produce these neutron-rich nuclei in laboratory?

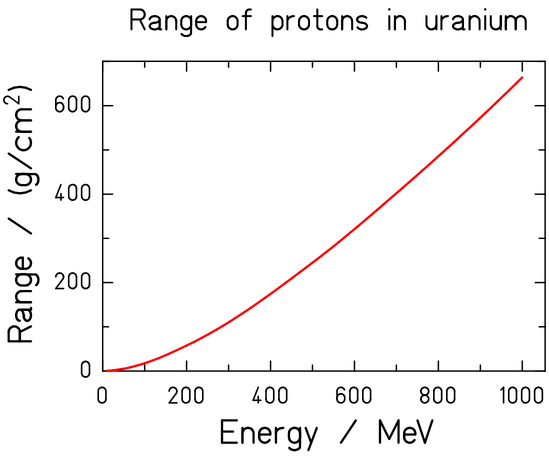
Ionic charge states

- *Heavy reaction products need to be relativistic for in-flight separation*

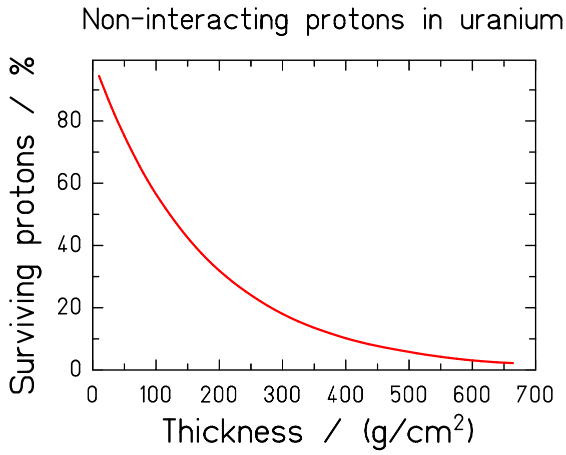


Range and usable target thickness

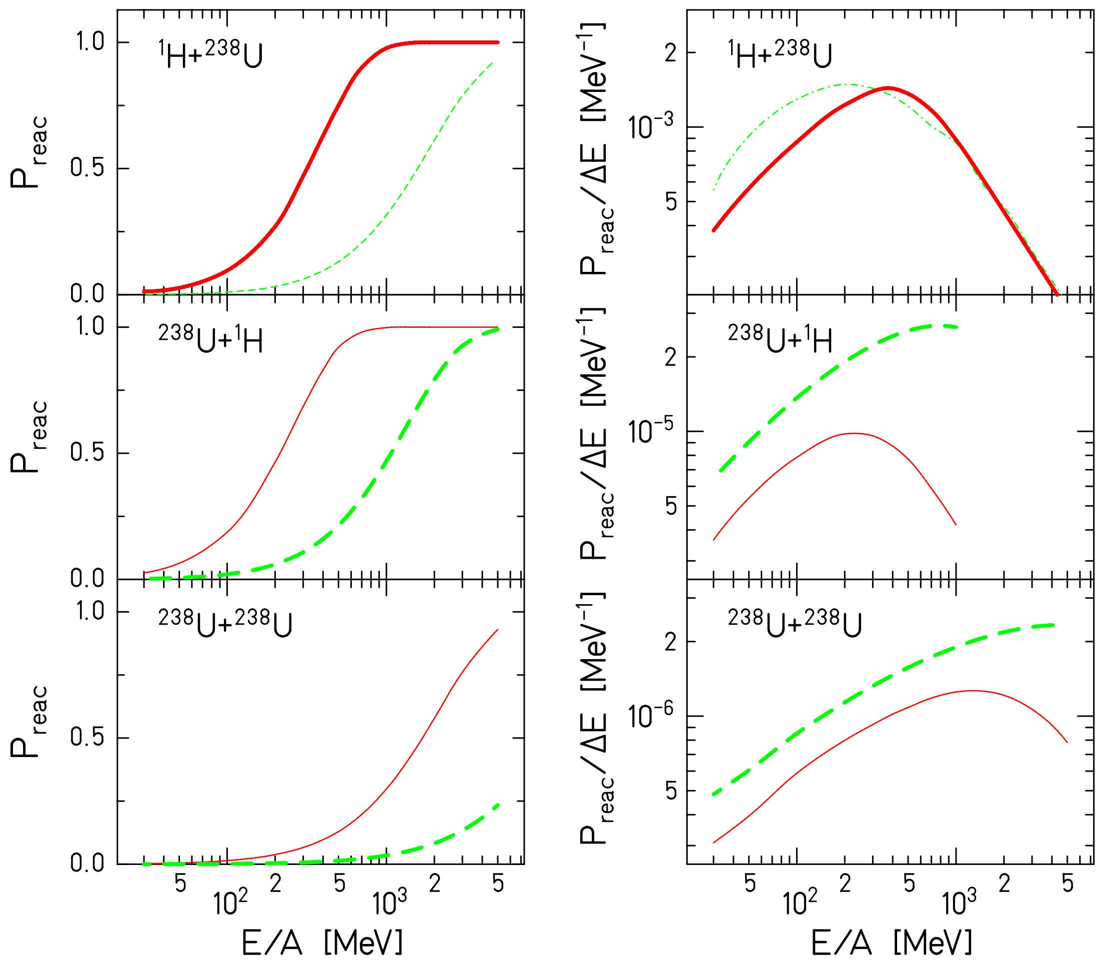
- *Range increases strongly with energy*



- *Usable target thickness limited by reaction probability*



General arguments for an "optimum" beam energy



Preac = nuclear-reaction probability of projectile
ΔE = energy deposit in target per projectile
Red lines: target thickness = range of projectiles
Green lines: target thickness = 0.1 × range of projectiles

High reaction probabilities and low heat load at E ≈ 1 A GeV.

Reaction mechanisms

E/A **<** ***E**$_{fermi}$*

Low reaction probabilities

Reactions controlled by nuclear potential and binding energies

Fusion, deep inelastic, transfer, fission

E/A **>** ***E**$_{fermi}$*

High reaction probabilities

Two stages:

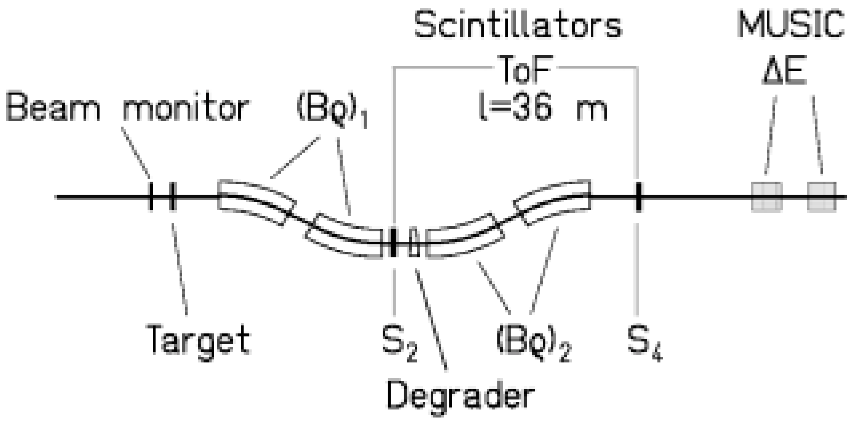
1. Collisions of individual nucleons

Target (resp. projectile) fragmentation

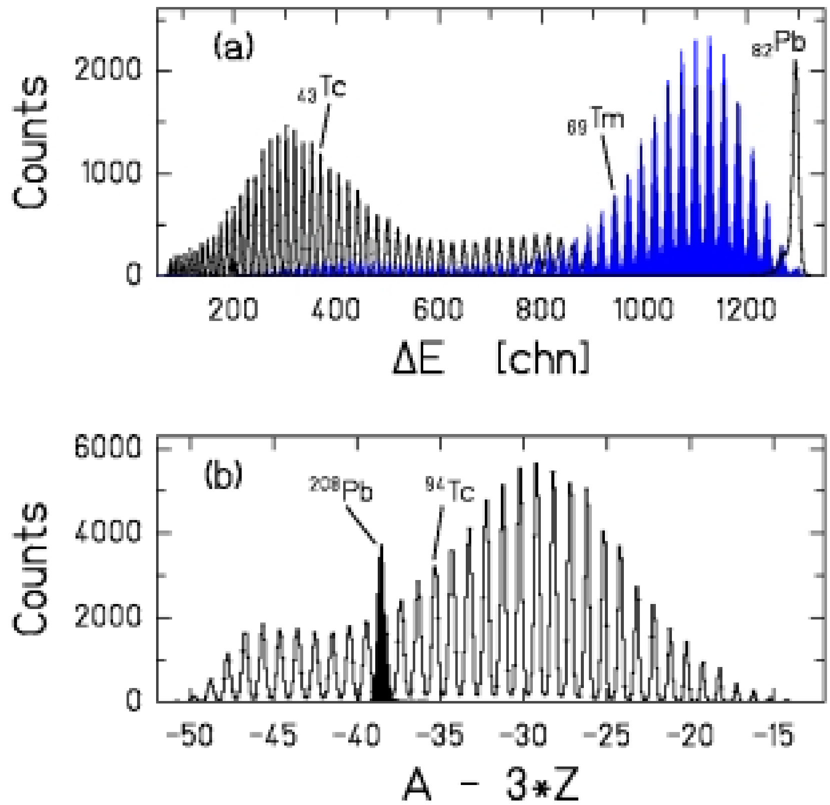
2. Deexcitation: nuclear potential and binding energies are again important

Deexcitation of prefragments by evaporation-fission competition

Complete identification of fragmentation residues by the fragment separator at GSI

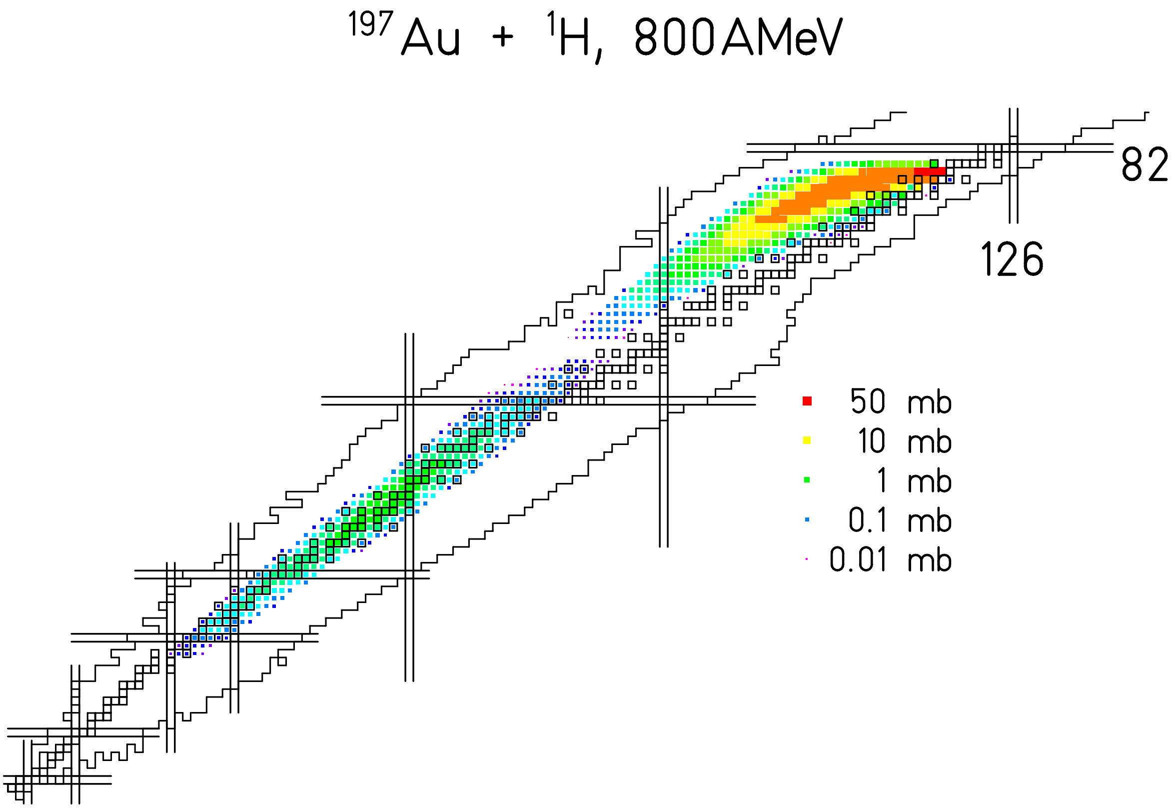


The fragment separator with the detector equipment.



The resolution in nuclear charge (above) and mass (below)

Proton-induced fragmentation of gold

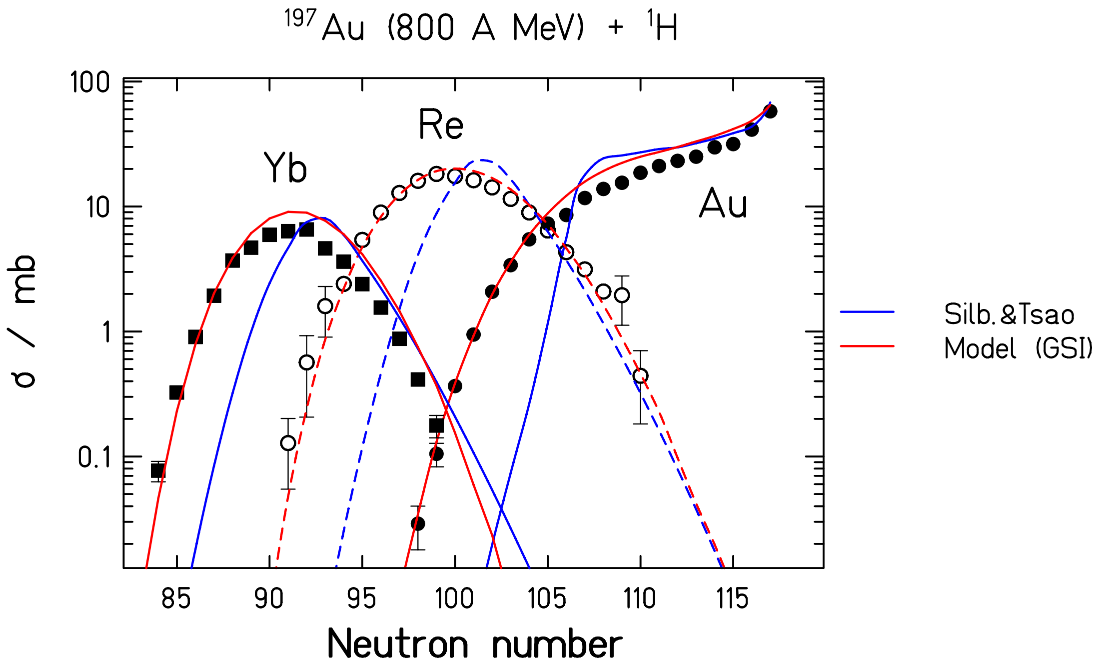


Data from F. Rejmund et al., submitted to Nucl. Phys. A

and J. Benlliure et al. submitted to Nucl. Phys. A

Full isotopic distribution mapped

Comparison with previous knowledge

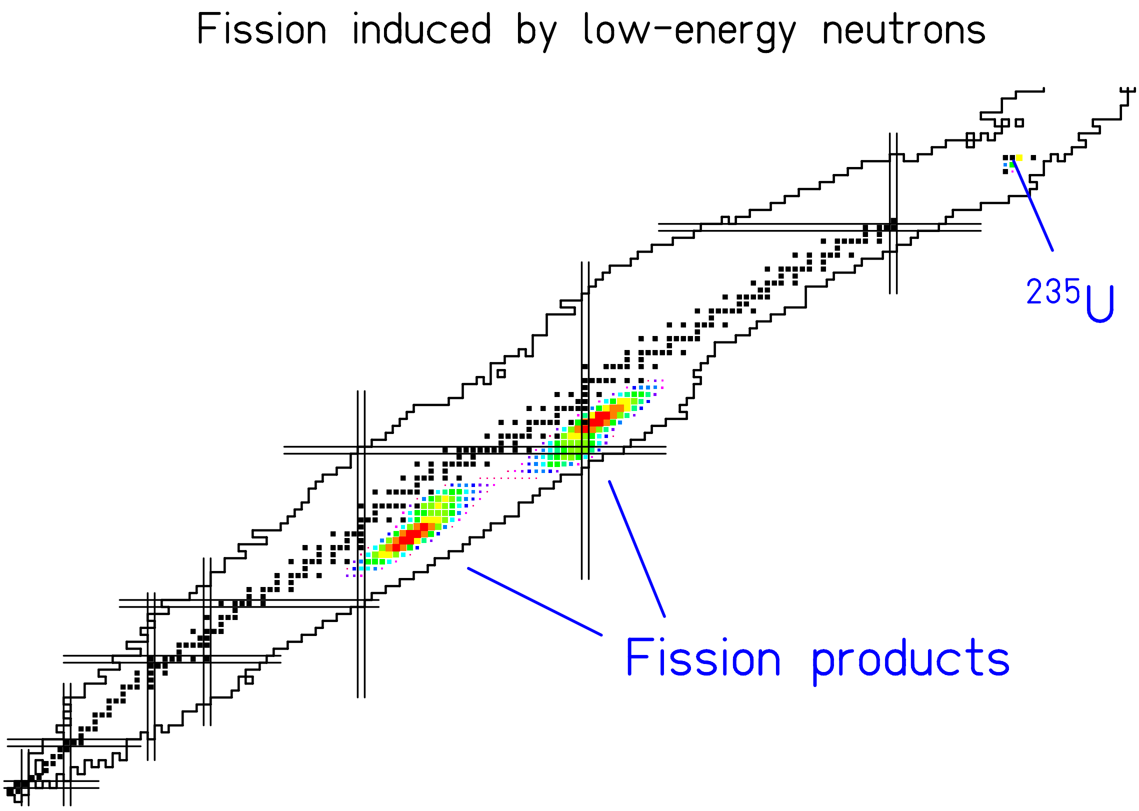


Data from F. Rejmund et al., submitted to Nucl. Phys. A

Compared to the systematics of Silberberg and Tsao and a recent model calculation performed at GSI.

The data provide completely new experimental information!

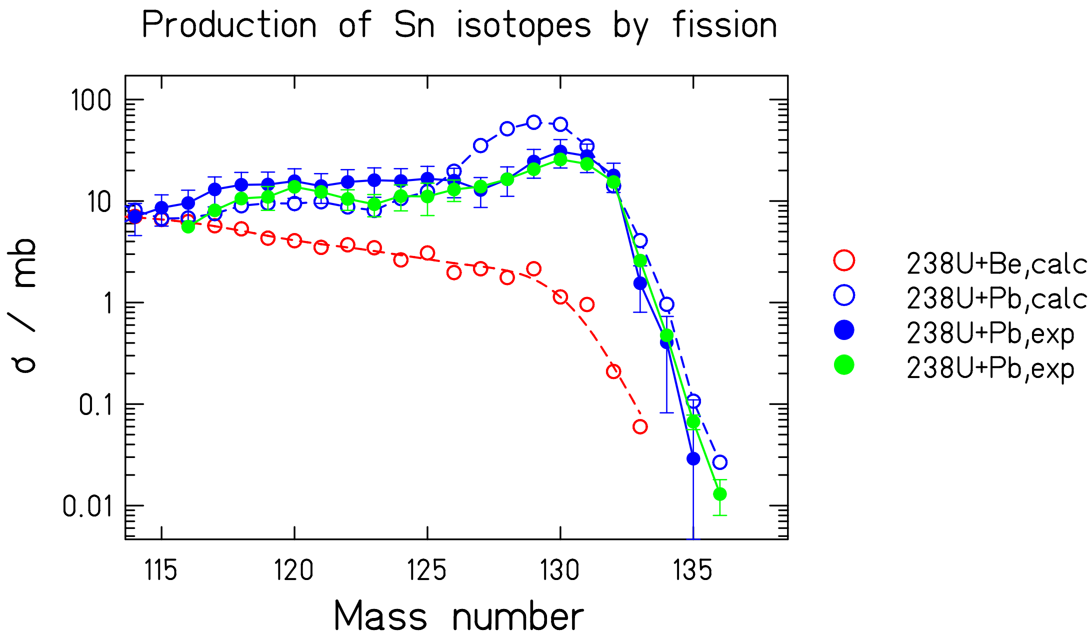
Fission of actinides

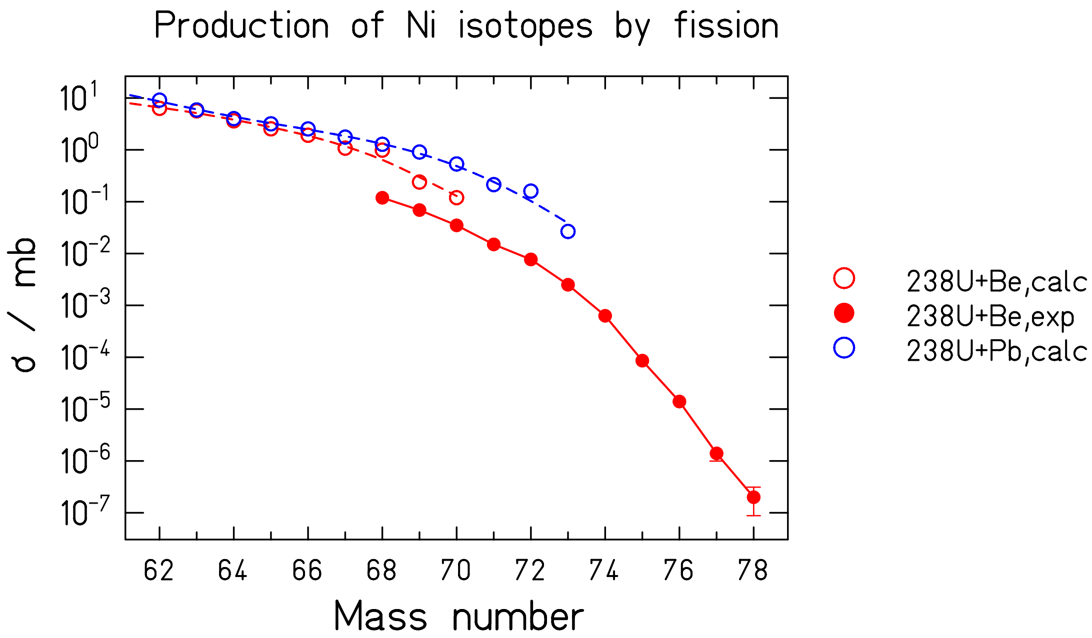


Fission of actinides from low excitation energies
induced by neutrons, protons, electrons, photons.

Production of moderately neutron-rich isotopes of a few elements.

Exploring the limits of neutron-rich isotopes by fragmentation-fission reactions

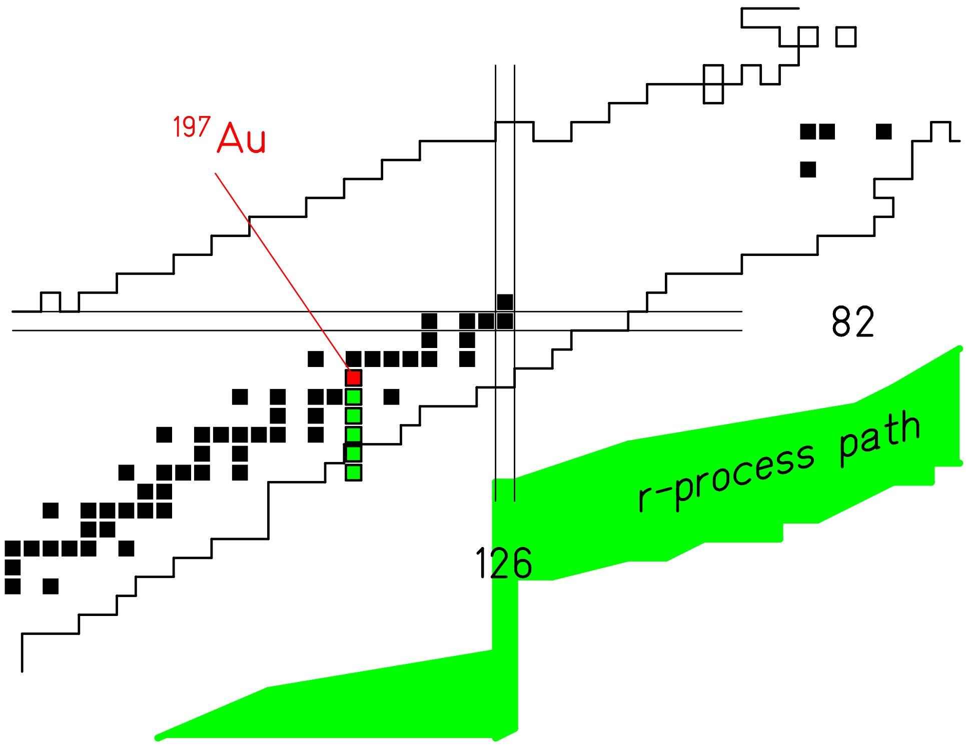


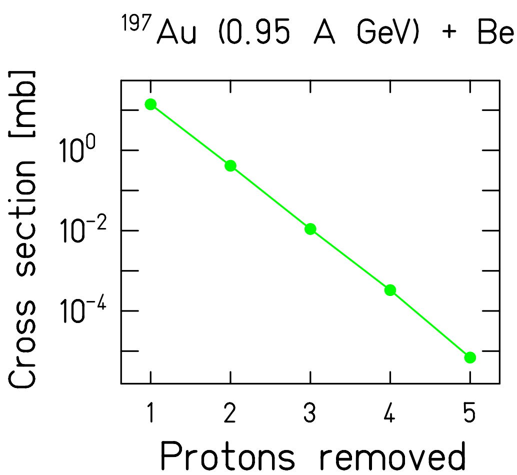


Data from T. Enqvist et al., Nucl. Phys. A 658 (1999) 47,
J. Benlliure et al., Eur. Phys. J. A (1998) 193,
C. Engelmann et al., Z. Phys. A 352 (1995) 351.

Steep decrease of cross sections due to limitation of charge polarisation in fission.

Dedicated study of proton-removal channels

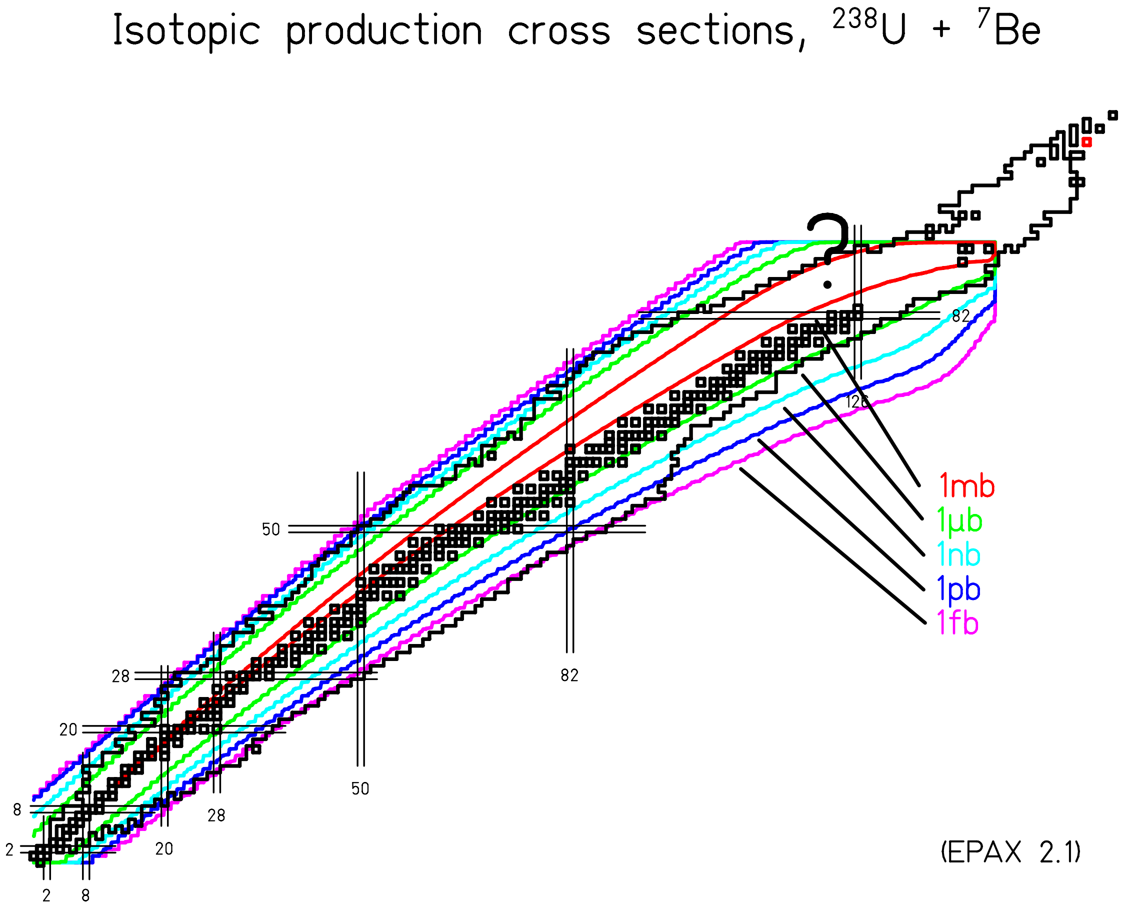




Data from J. Benlliure et al., Nucl. Phys. A 660 (1999) 87.

Abrasion of protons only, no evaporation of neutrons
=> "Cold Fragmentation".
Promising results for producing neutron-rich nuclei.

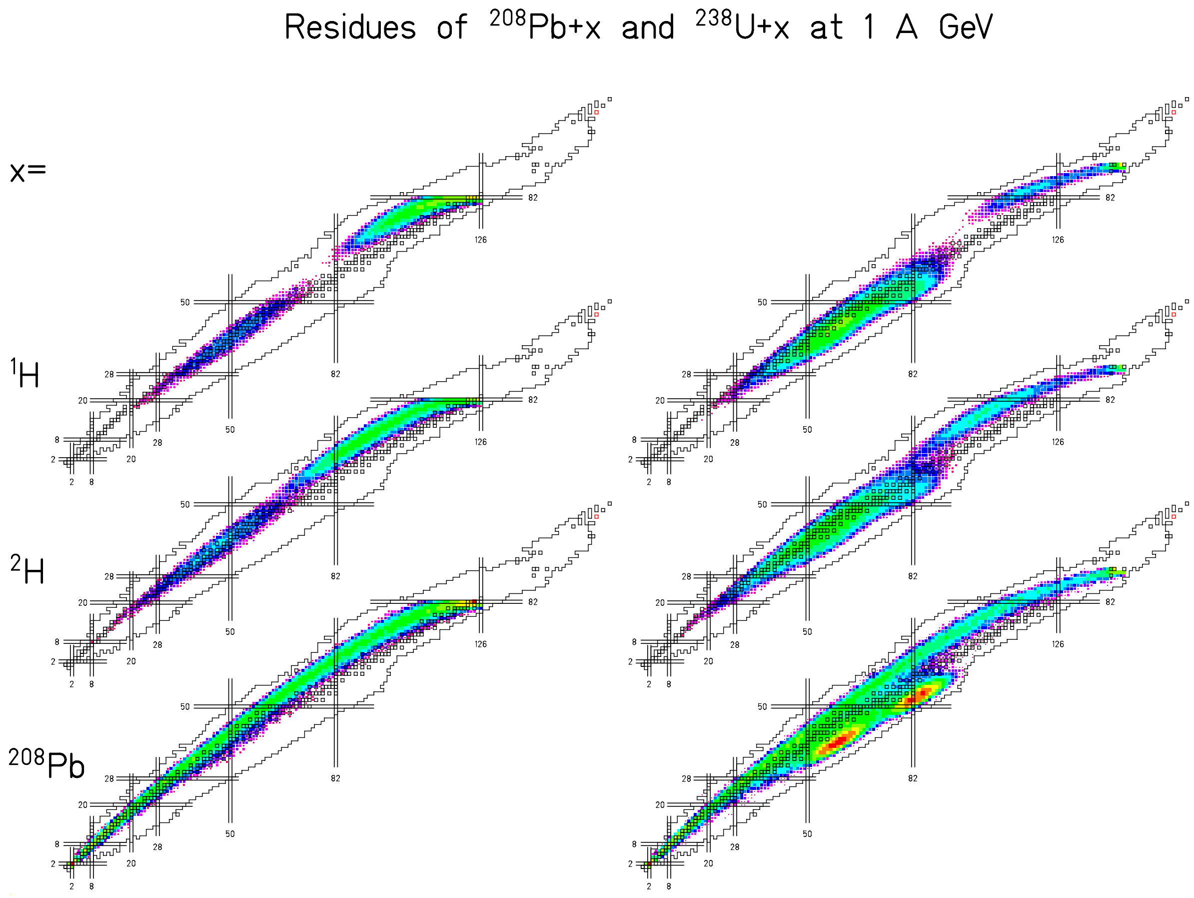
Expected production cross sections by cold fragmentation



The empirical systematics EPAX which has carefully been adjusted to available experimental data has been used to estimate isotopic production cross sections of extremely neutron-rich isotopes by cold fragmentation. Since EPAX does not consider fission, the prediction of neutron-deficient isotopes is not realistic.

K. Sümmerer, B. Blank, Phys. Rev. C 61 (2000) 034607

Calculated isotopic production yields



Systematic overview on calculated isotopic production cross sections in different reactions. For clarity only cross sections above 100 μb are shown.

The model is described in
J. Benlliure, A. Grewe, M. de Jong, K.-H. Schmidt, S. Zhdanov, Nucl. Phys. A 628 (1998) 458

Conclusion

Highest reaction rates, lowest heat load of target, best condition for in-flight separation at E/A ≈ 1 GeV.

Different reaction mechanisms below and above Fermi energy.

Fusion (E/A ≈ 5 MeV) for Z > 92 and possible for proton-rich.

Fission of actinides for medium-mass nuclei (up to N/Z ≈ 1.6), induced in different ways.

Peripheral nuclear collisions at E/A ≈ 1 GeV for all nuclei with Z < 92 and N < 146 (from extremely proton-rich to extremely neutron-rich).
Choice of projectile-target combination is crucial!