β-delayed fission studies utilising Multi-Nucleon-Transfer Reactions

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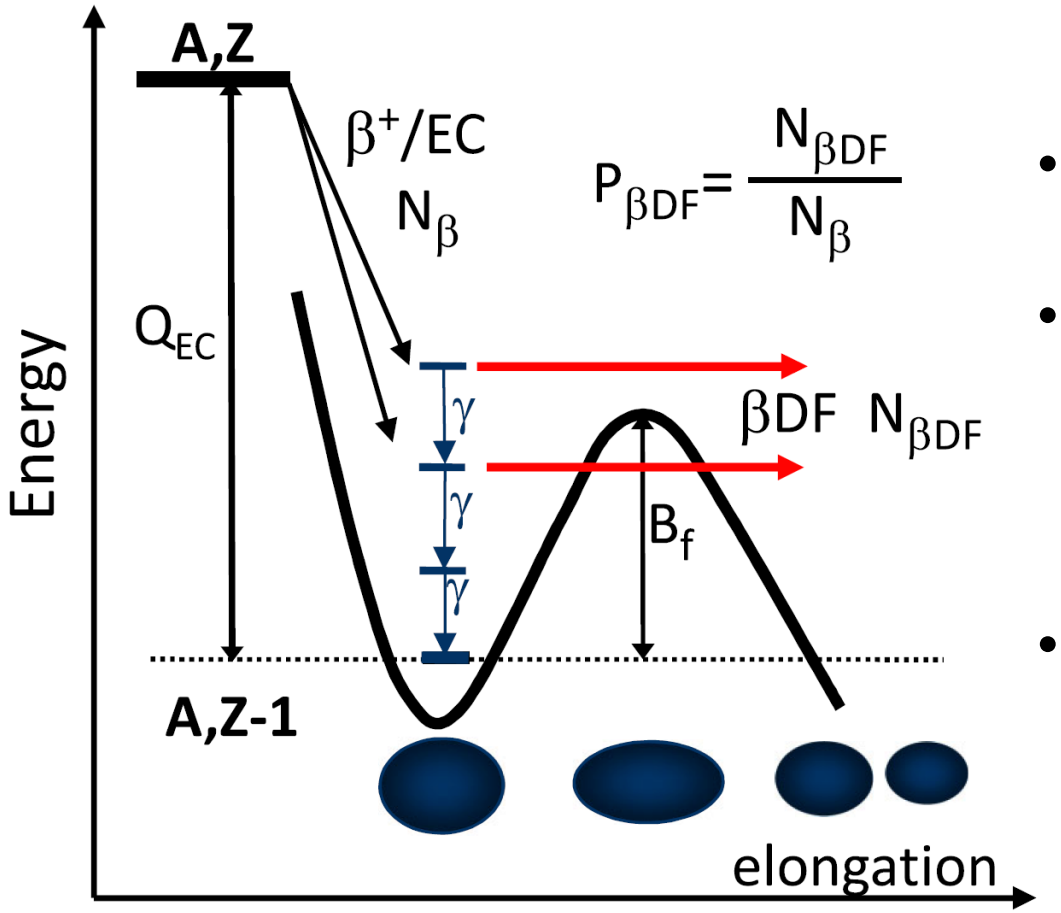
β-delayed fission

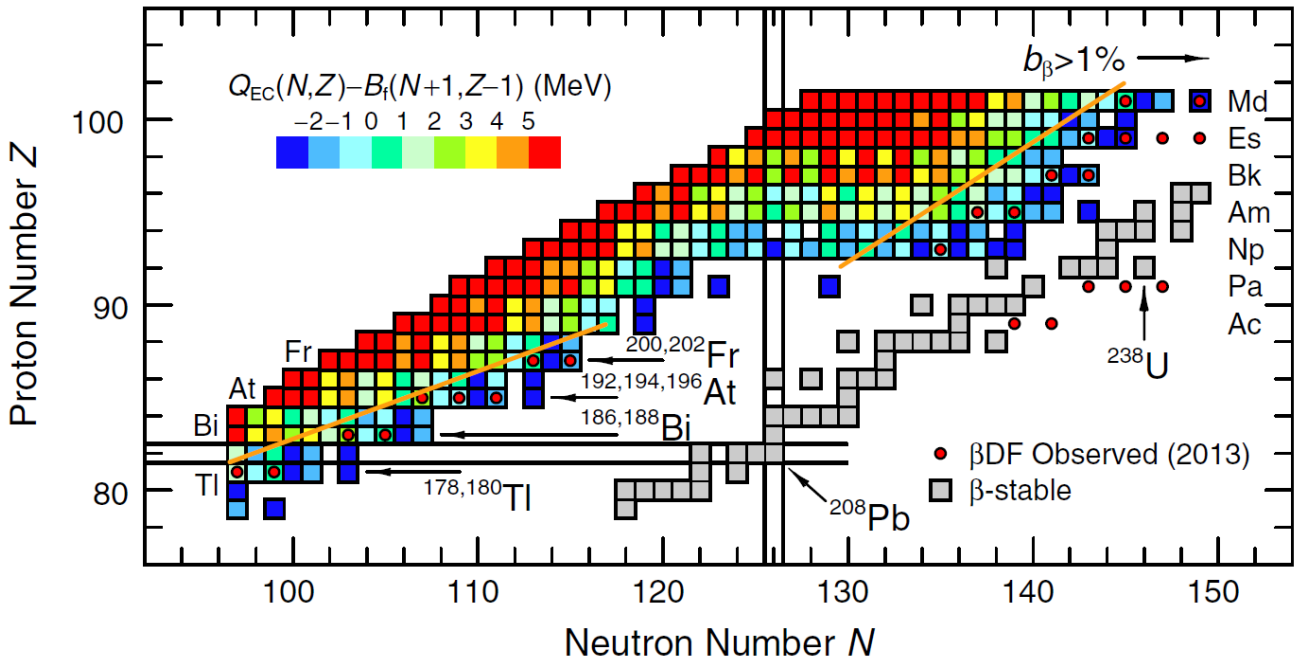


- 2 Step decay process
- Dependent on the state populated by β-decay
- If $E_x \sim B_f$ fission can happen spontaneously or in competition with other decay modes
- βdf is a low energy process
  - E_x limited to Q_β
  - Typically in ranges of 3-6MeV and 9-12MeV for transuranium and lead regions respectively for nuclei studied

[1] A. N. Andreyev, *et al.*, Rev. Mod. Phys. **85**, 1541 (2013).

Necessary conditions

- Parent nucleus must have a non-zero β-decay branch
- Q_β of the parent must be comparable to the B_f of the daughter
- If both conditions are met βdf probability will depend on S_β and competition with other de-excitation modes

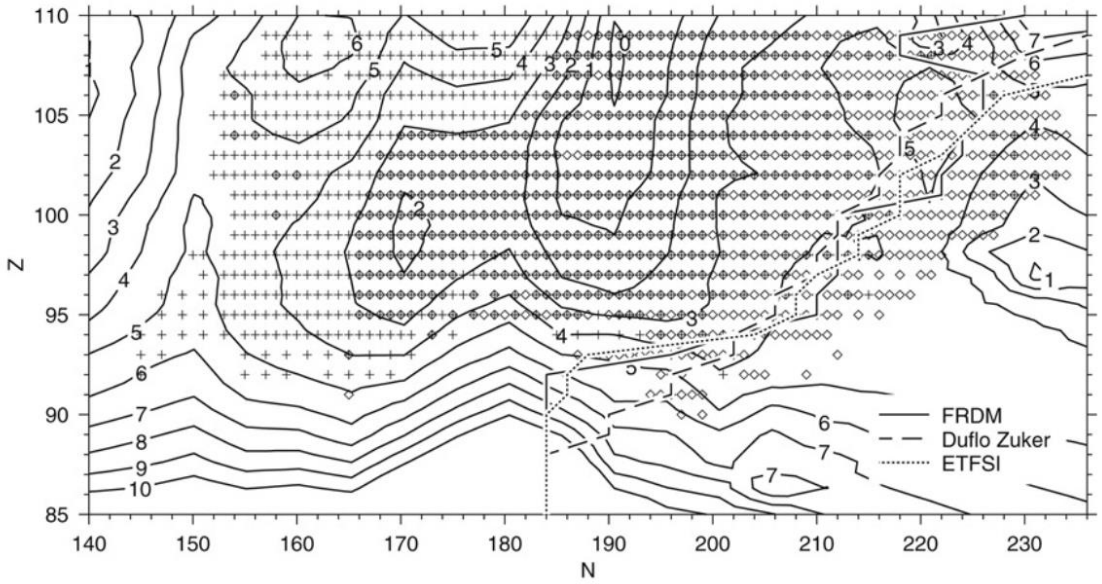


Known βdf nuclei marked with circles. β branching ratio greater than 1% to the right of orange line

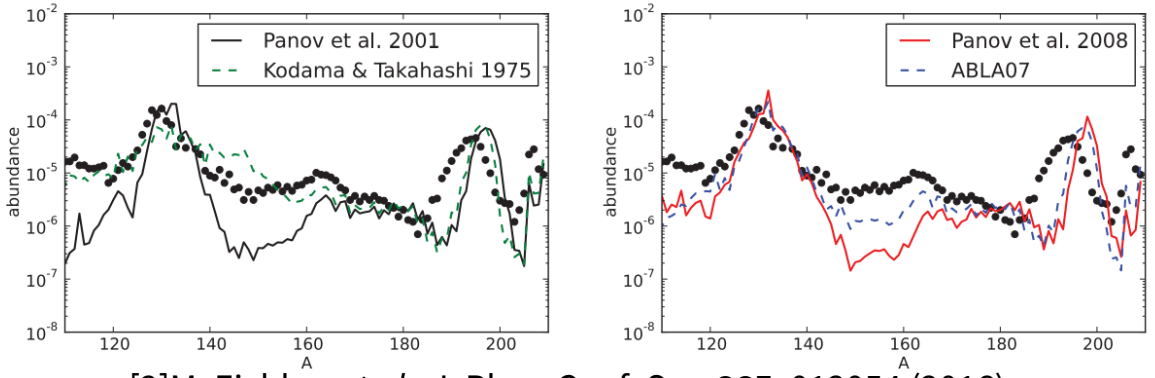
A. N. Andreyev, *et al.*, Rev. Mod. Phys. **85**, 1541 (2013).

βdf in the *r*-process

- Fission can set an end point on the *r*-process path
- Beyond the N=184 shell neutron-induced fission takes place
  - Releasing up to 20 neutrons
- Fission yields can affect the yields around the second and rare-earth *r*-process peaks



G. Martínez-Pinedo, *et al.*, Prog. Part. Nucl. Phys. **59**, 199 (2007).



[2]M. Eichler, *et al.*, J. Phys. Conf. Ser. **665**, 012054 (2016).

Production methods in use

Charged particle induced

- Fusion evaporation and transfer reactions

$^{10,11}B + {}^{230}Th \rightarrow {}^{232,234}Am$ $^{18}O + {}^{232}Th \rightarrow {}^{230}Ac$

Kuznetsov, V. I., *et al.*, Phys. Part. Nucl. **30**, 666 (1996).
Y. Shuanggui, *et al.*, Eur. Phys. J. A **10**, 1 (2001).

Spallation reactions

- 1-GeV protons on a thick UC_x target

Previously used in the study of ^{180}Tl

A. N. Andreyev, *et al.*, Phys. Rev. Lett. **105**, 252502 (2010).

Gamma/Neutron Induced Reactions

$^{238}U(\gamma,np)^{236}Pa$

Gangrskii, *et al.*, *Yad. Fiz.;(USSR)* 27.4 (1978).

Radiochemical separation

- Use naturally occurring long-lived precursors

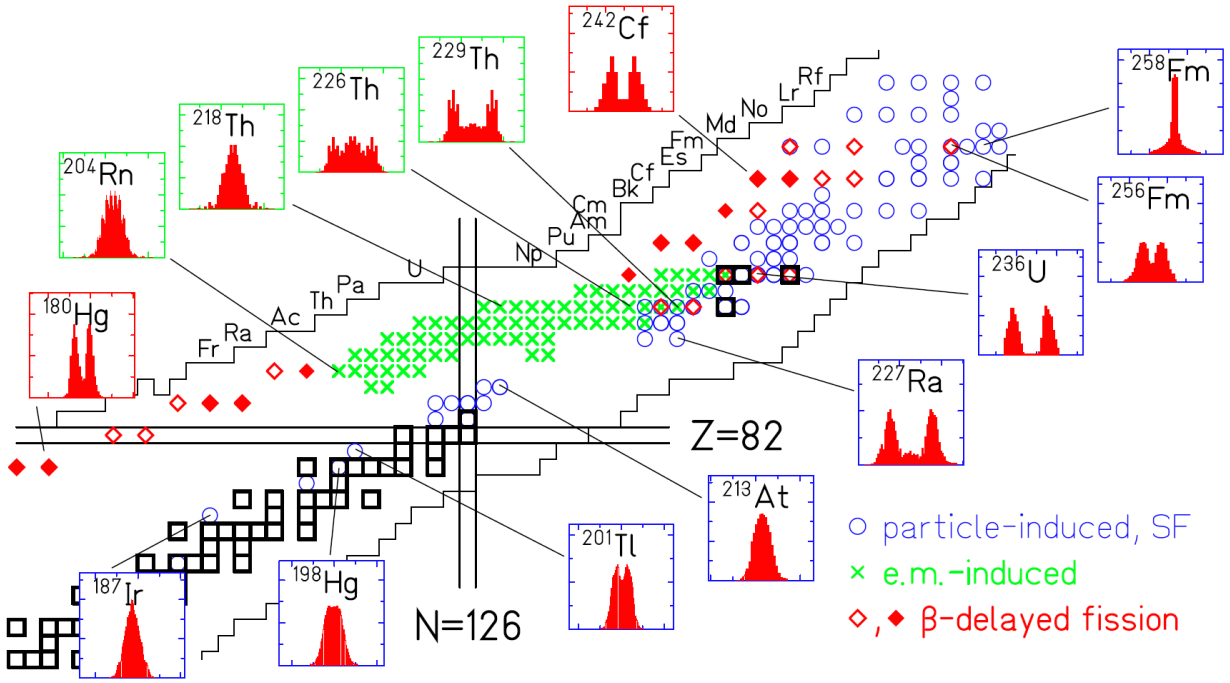
$^{232}Th \rightarrow {}^{\alpha 228}Ra \rightarrow {}^{\beta 228}Ac$

X. Yanbing, *et al.*, Phys. Rev. C **74**, 047303 (2006).

Known βdf nuclei

- Known cases are found primarily in 2 regions
  - Neutron-deficient lead region
  - Neutron-deficient transuranium region

- Only two cases found in neutron-rich nuclei
  - $^{228,\ 230}$Ac
  - Studies of neutron-rich nuclei are limited by the experimental challenges in reaching the region in which βdf can be appreciably observed

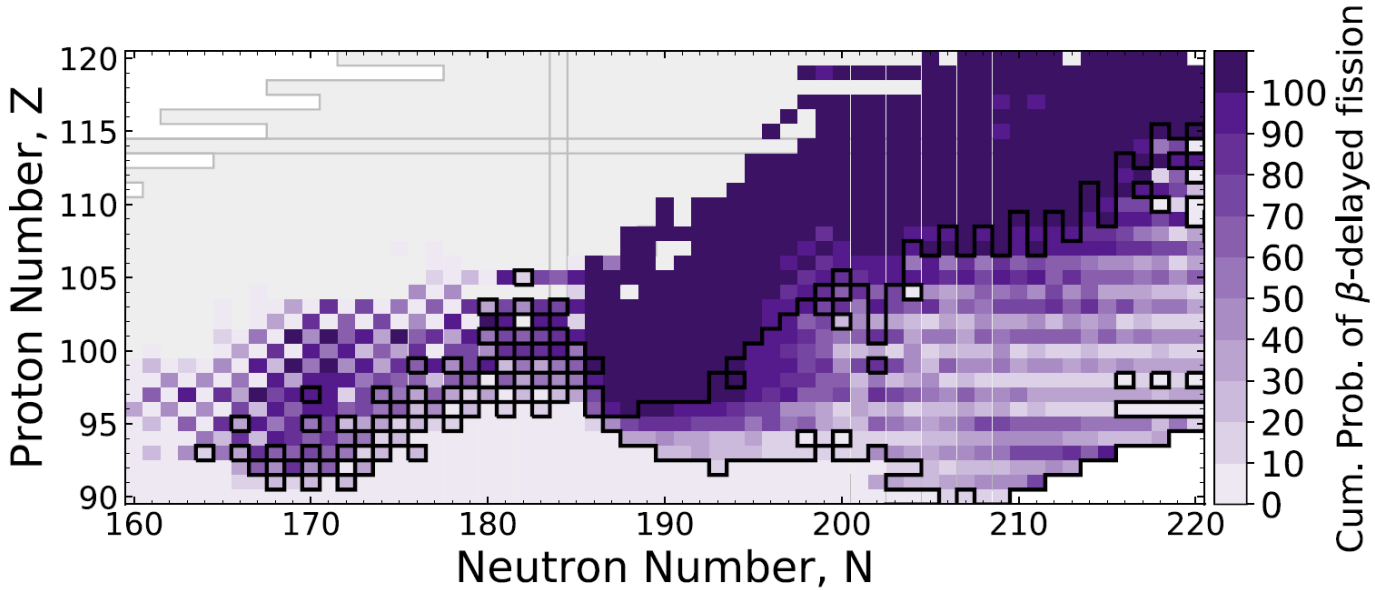


Diamonds: 26 known DF cases; the fissioning daughter is indicated. Filled diamonds: 11 daughter nuclides for which mass distribution was measured.

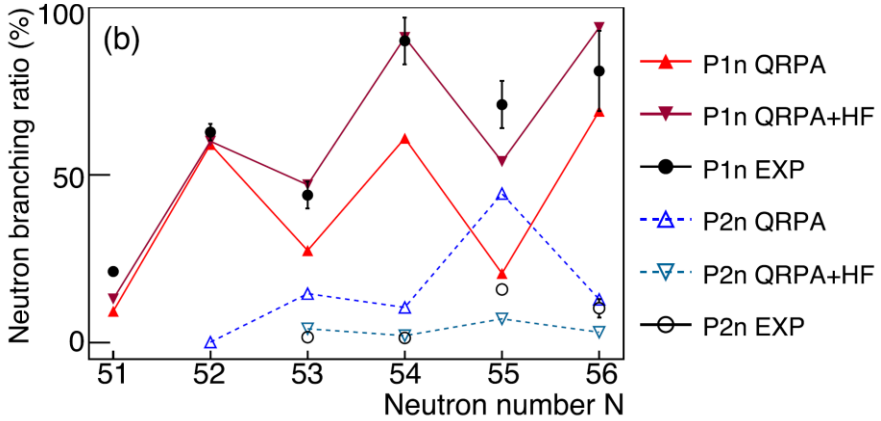
A. N. Andreyev, *et al.*, Rev. Mod. Phys. **85**, 1541 (2013).

βdf in neutron-rich transuranium isotopes

- FRDM+QRPA+HF predicts a region of high βdf probability
  - HF framework models competition between different de-excitation modes



[1]M. R. Mumpower, *et al.*, Astrophys. J. **869**, 14 (2018).

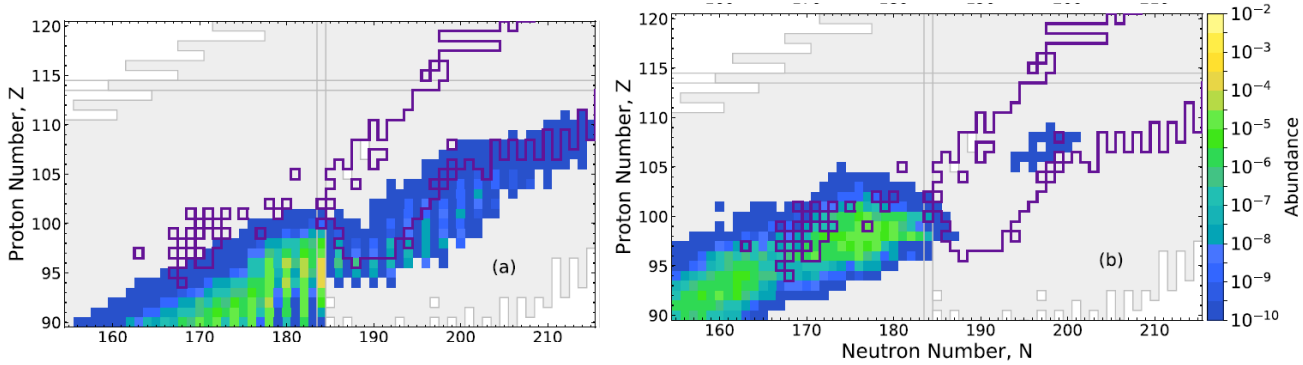


[2] R. Yokoyama, *et. al*, Phys. Rev. C **100**, 1 (2019).

- Same methodology used to describe competition between delayed 1 and 2 neutron emission

Impact on *r*-process

- r-process path can encounter the region of high P_{f}
- There is a shift to lighter masses
- Abundance distribution sensitive to fission yields



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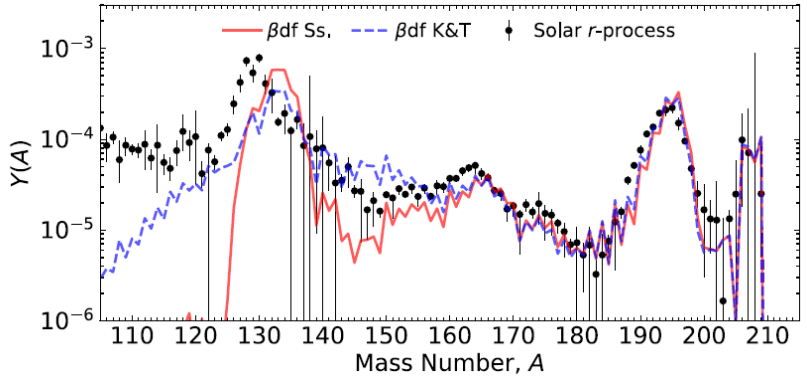
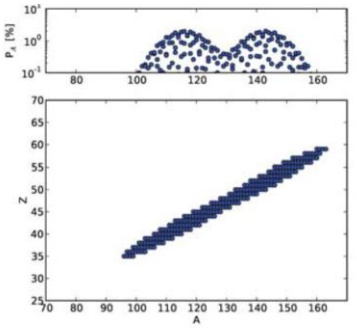


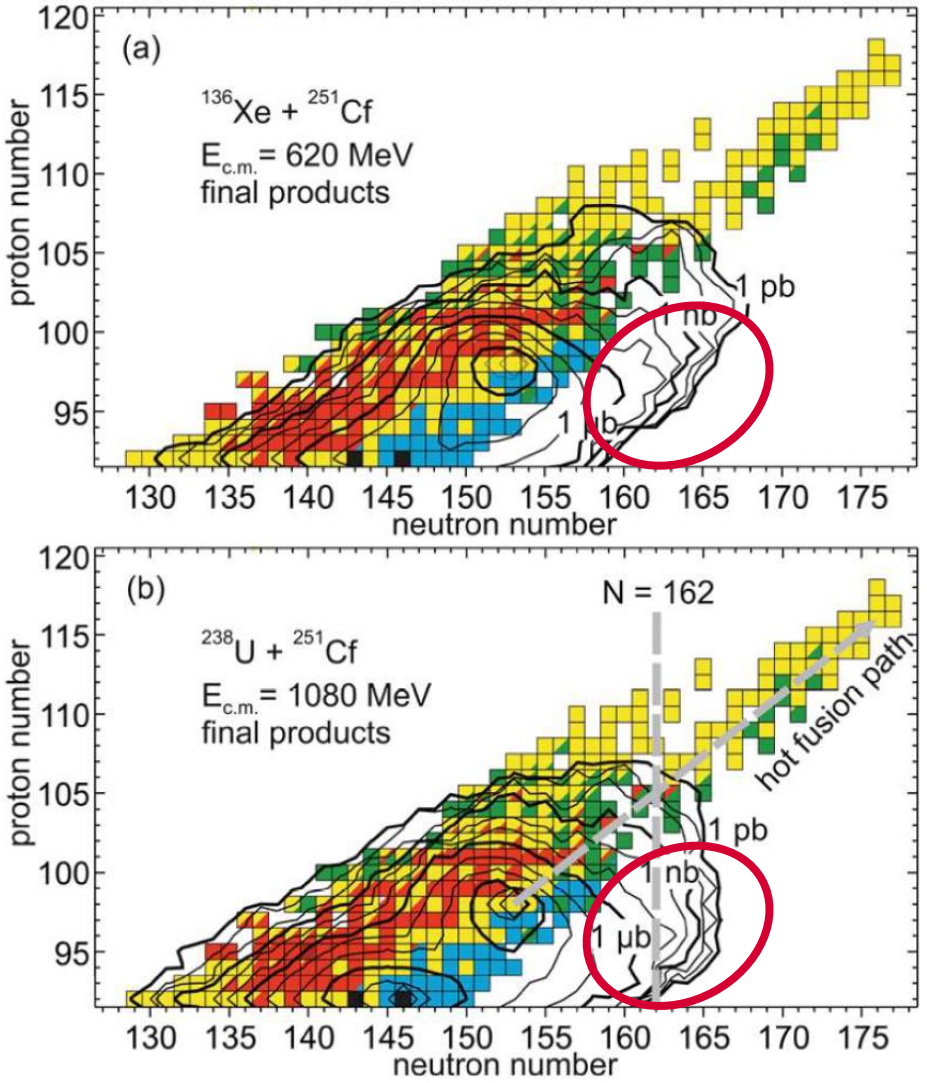
[1]M. R. Mumpower, *et al.*, Astrophys. J. **869**, 14 (2018).



[2]M. Eichler, *et al.*, J. Phys. Conf. Ser. **665**, 012054 (2016).

Accessibility with MNT reactions

- Multi-Nucleon-Transfer reactions are efficient tools for producing neutron rich nuclei
- The cross section drops quickly for masses greater than the target nuclei
  - Heavy target for producing heavy nuclei
  - ^{251}Cf target can provide high cross sections
- Cross sections ~1 μb for nuclei on the edge of the high βdf region



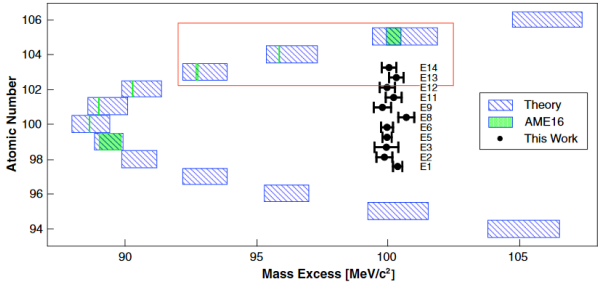
https://doi.org/10.1142/9789811209451_0035

Separation methods

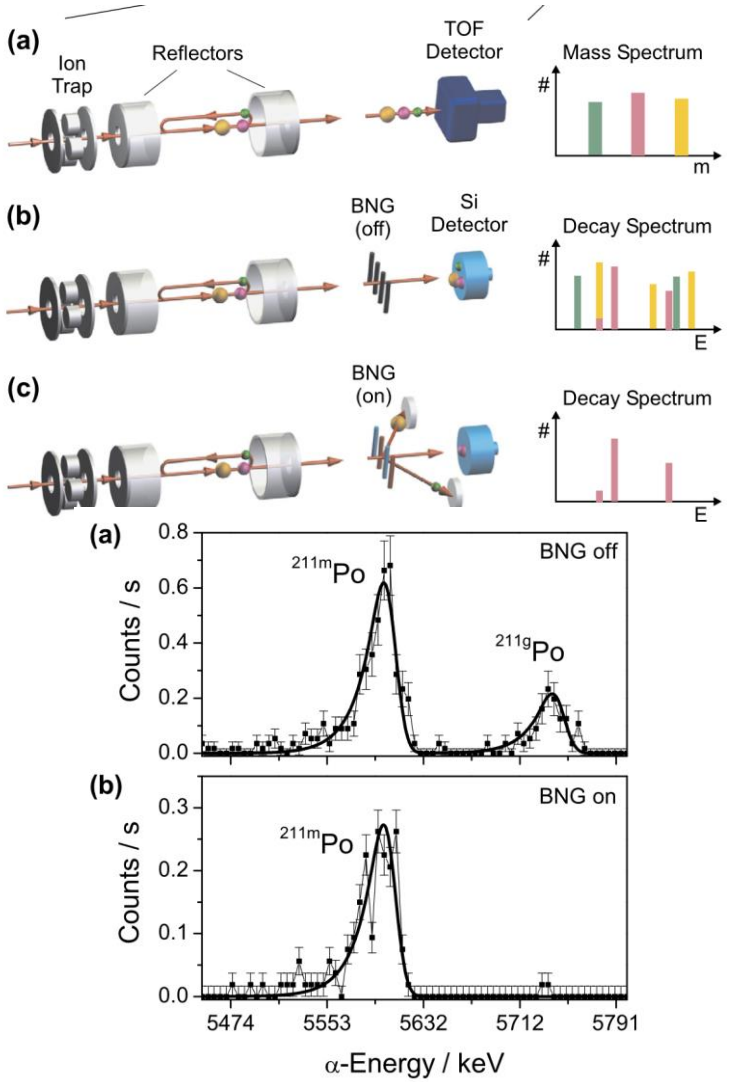
- MNT reaction product captured in a stopping cell
- Transported to an MR-TOF-MS

- High-precision mass measurements of MNT products

- Identification of isotopes based on mass data



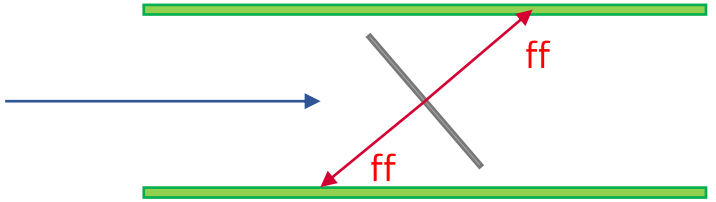
P. Schury, T. Niwase, M. Wada, *et al.*, Phys. Rev. C **104**, L021304 (2021).

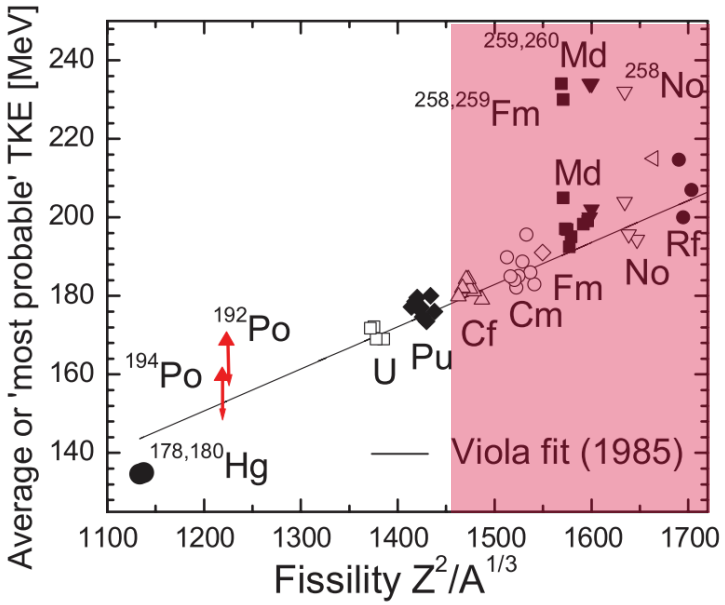


T. Dickel, *et al.*, Phys. Lett. Sect. B. **744**, 137 (2015).

Detection methods

- Isomerically pure beam deposited onto thin foil
- Foil between two DSSD
- Fission products measured in coincidence
  - Total kinetic energy measured
- Expected energy based on the fissility $\frac{Z^2}{A^{1/3}}$ ~150 MeV

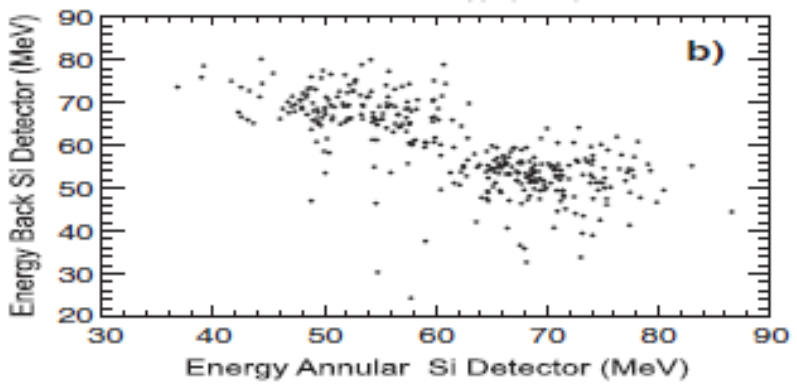


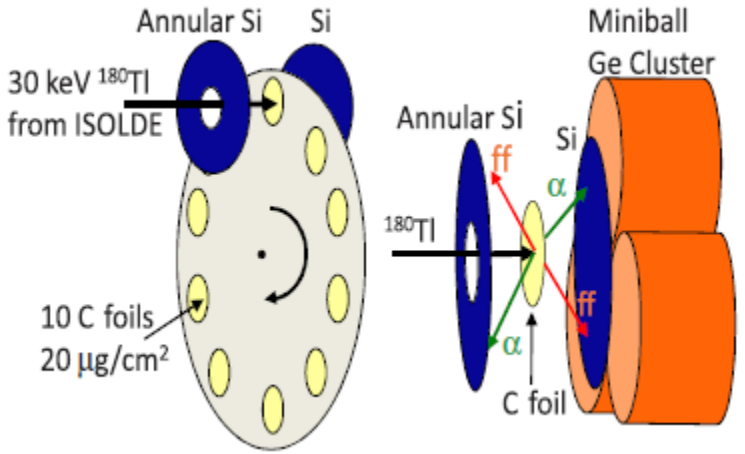


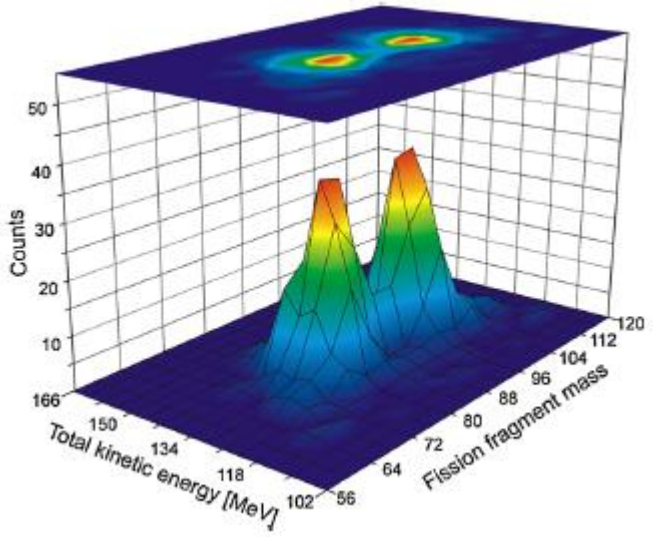
A. N. Andreyev, *et al.*, Phys. Rev. C **87**, 014317 (2013).

Example of a similar setup

- A similar setup was used at ISOLDE for studies of ^{180}Tl
  - A. N. Andreyev, *et al.*, Phys. Rev. Lett. **105**, 252502 (2010).
- Simultaneous measurement of both fission fragments and the TKE allowed the mass yields to be determined (No Z information)







Summary

- βdf provides a method of observing fission at low excitation energies
- Fission plays an important role in the *r*-process
- Studying the nuclei which undergo fission is not feasible with fragmentation/ fusion evaporation reactions
- MNT reactions can provide an efficient way for producing these nuclei for study