Fission Properties of Neutron-Rich Nuclei

Walter F. Henning
(RIKEN, ANL, TU Munich)

Fission Properties of Neutron-Rich Nuclei

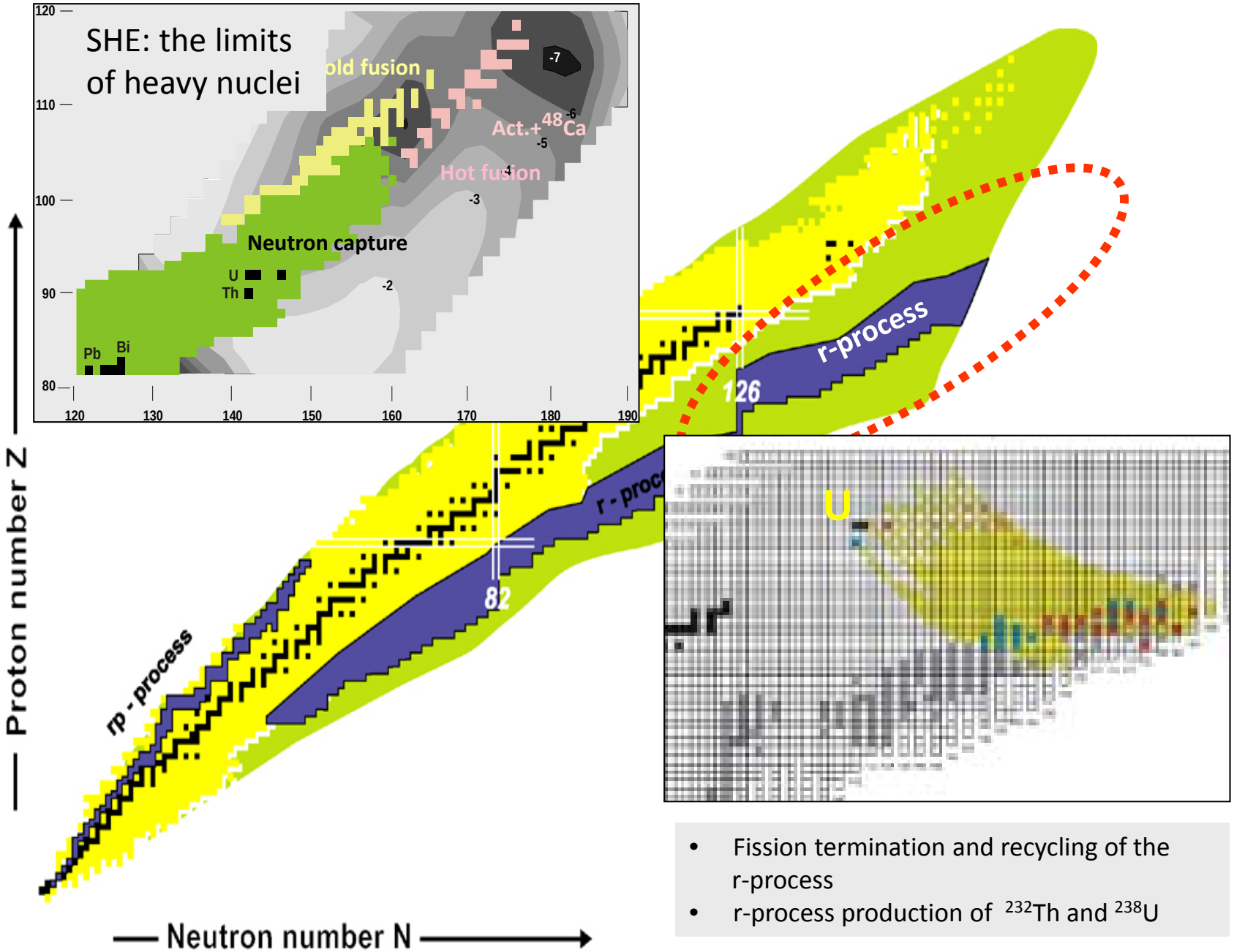
Motivation

Predictions from recent theory

Experimental fission barriers

Proposed approach to n-rich isotopes

Summary and outlook



- Fission termination and recycling of the r-process
- r-process production of ^{232}Th and ^{238}U

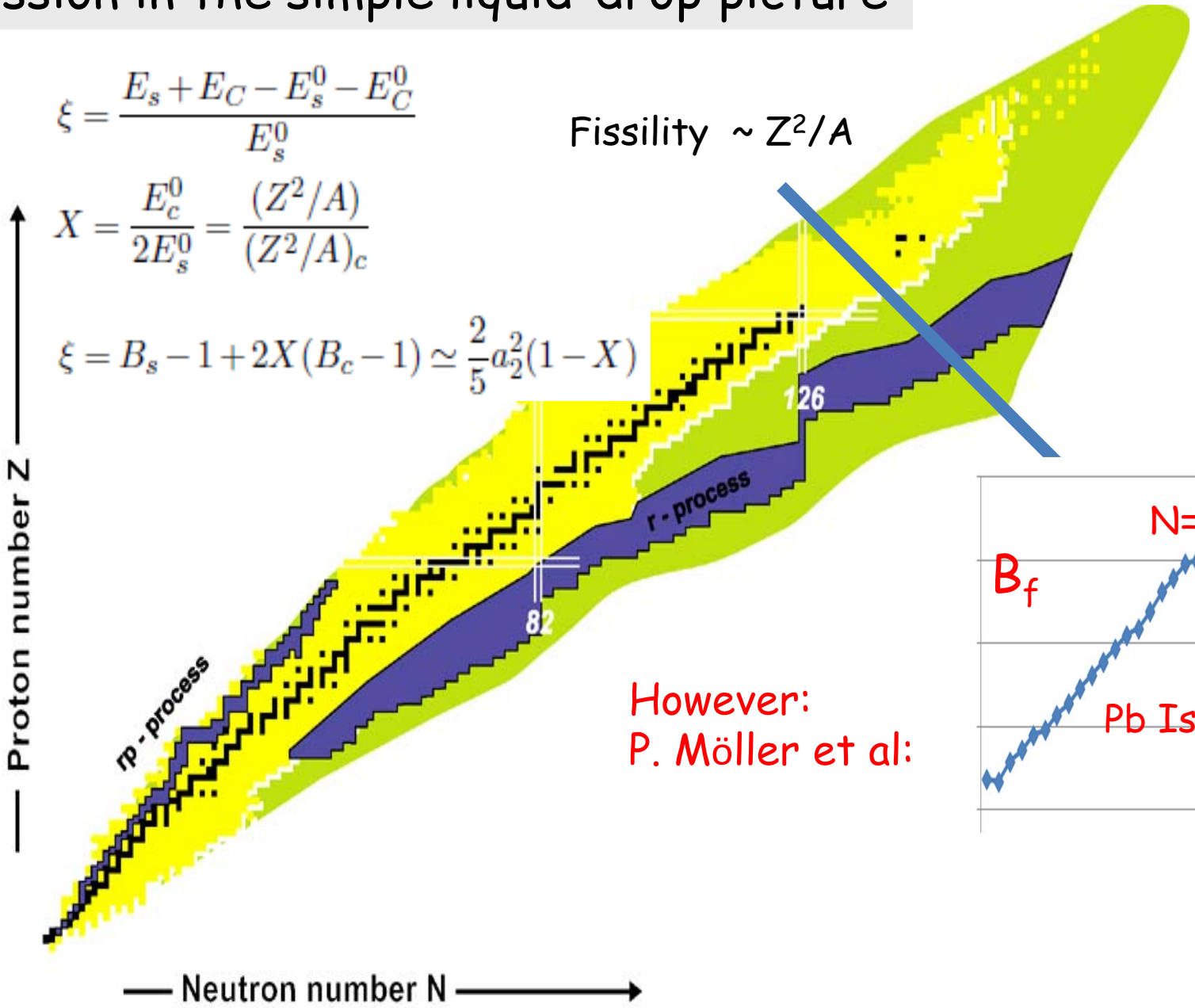
Fission in the simple liquid-drop picture

$$\xi = \frac{E_s + E_C - E_s^0 - E_C^0}{E_s^0}$$

$$X = \frac{E_c^0}{2E_s^0} = \frac{(Z^2/A)}{(Z^2/A)_c}$$

$$\xi = B_s - 1 + 2X(B_c - 1) \simeq \frac{2}{5}a_2^2(1-X)$$

Fissility ~ Z^2/A



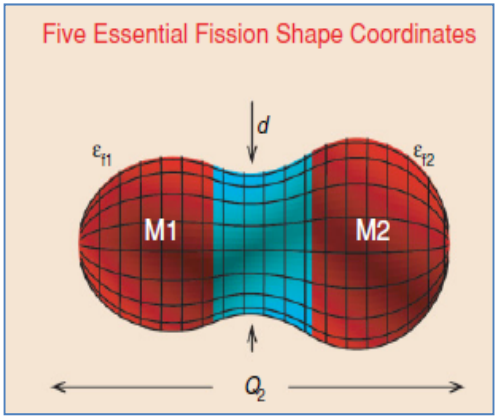
However:
P. Möller et al:

Predictions from recent theory

PHYSICAL REVIEW C 79, 064304 (2009)

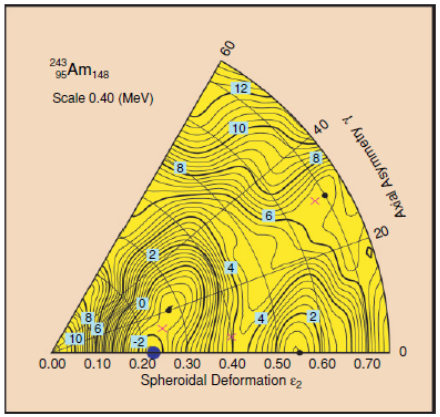
Heavy-element fission barriers

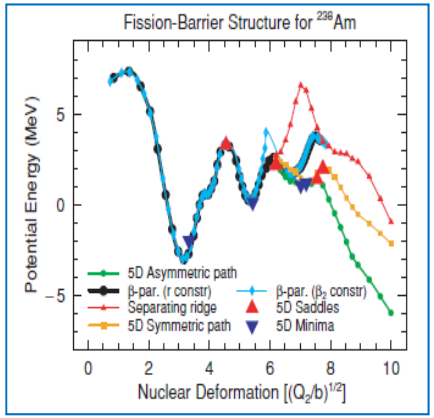
Peter Möller,[1,*] Arnold J. Sierk,[1] Takatoshi Ichikawa,[2] Akira Iwamoto,[3] Ragnar Bengtsson,[4] Henrik Uhrenholt,[4] and Sven Åberg[4]

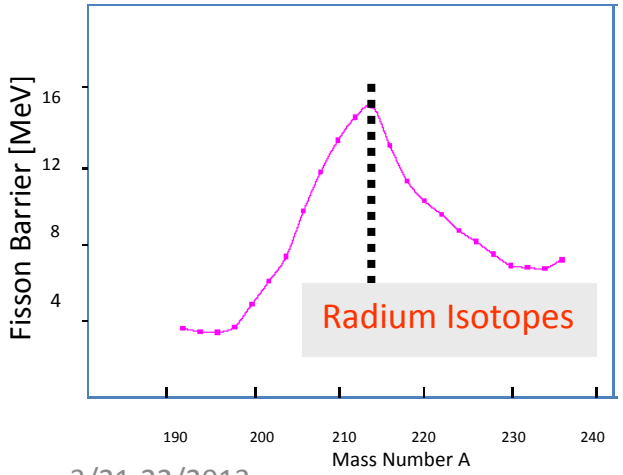


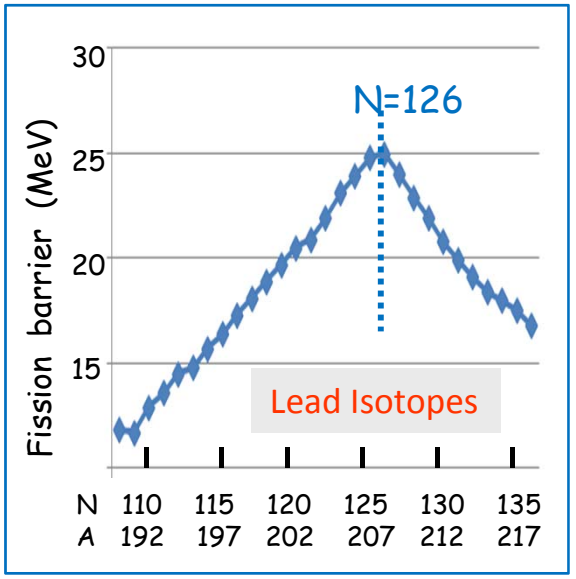
Microscopic features:
Cross sections for reflection-symmetric and –asymmetric fission depend on relative level densities at saddles as well as barrier heights and widths.

- Calculation of microscopic level densities based on single particle levels and many-particle-many-hole excitations
- Pairing individually for all configurations within BCS formalism.









PHYSICAL REVIEW C **83**, 034305 (2011)

Surface symmetry energy of nuclear energy density functionals

N. Nikolov,[1,2] N. Schunck,[1,2,3] W. Nazarewicz,[1,2,4] M. Bender,[5] and J. Pei[1,2]

PHYSICAL REVIEW C **85**, 024304 (2012)

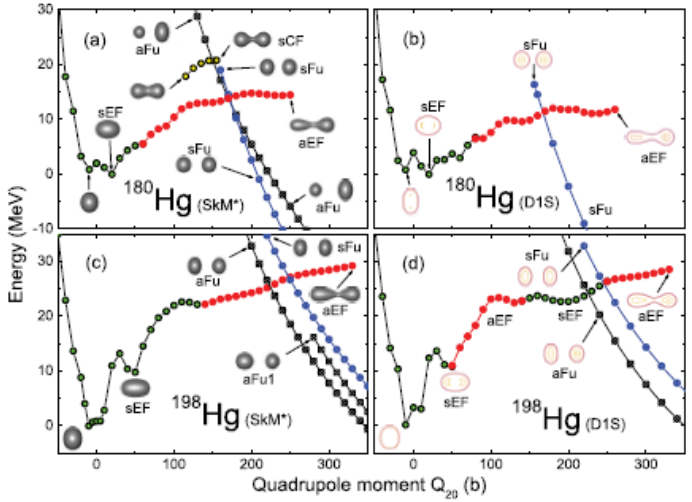
Nuclear energy density optimization: Large deformations

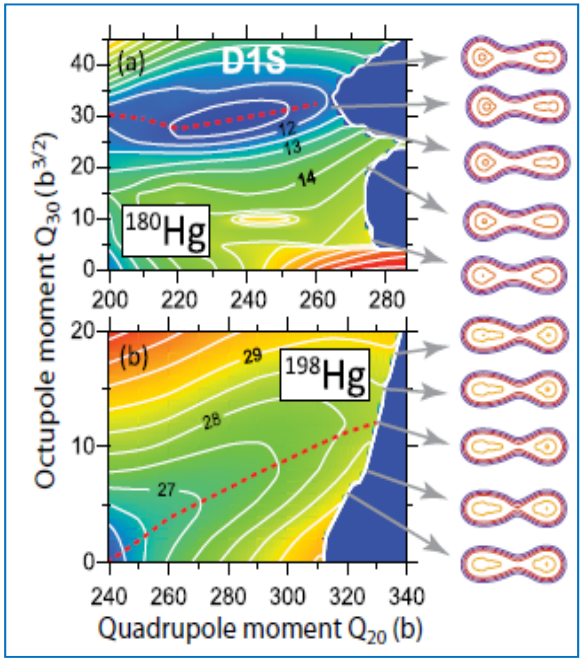
M. Kortelainen,[1,2] J. McDonnell,[1,2] W. Nazarewicz,[1,2,3] P.-G. Reinhard,[4] J. Sarich,[5] N. Schunck,[1,2,6] M. V. Stoitsov,[1,2] and S. M. Wild[5]

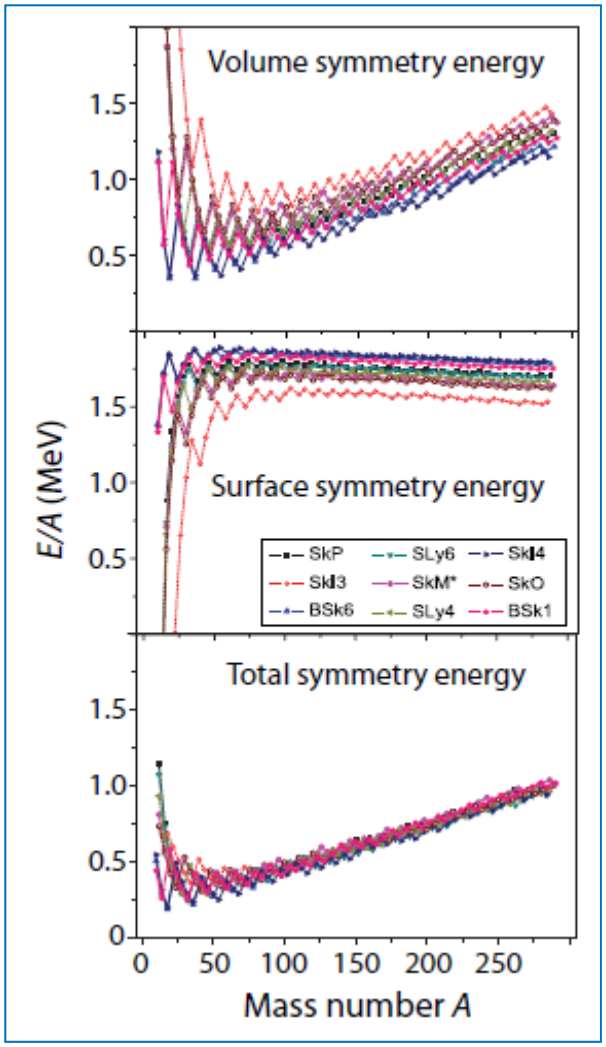
PHYSICAL REVIEW C **86**, 024601 (2012)

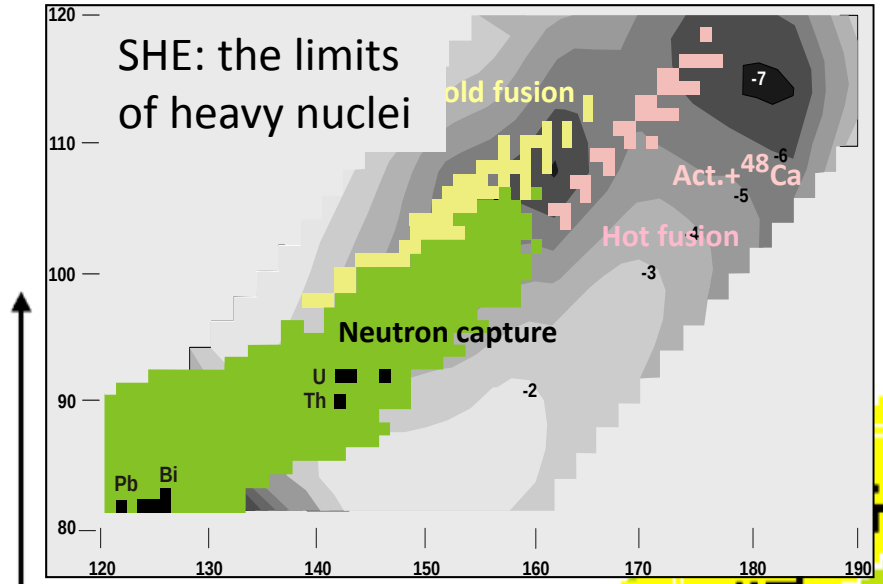
Fission modes of mercury isotopes

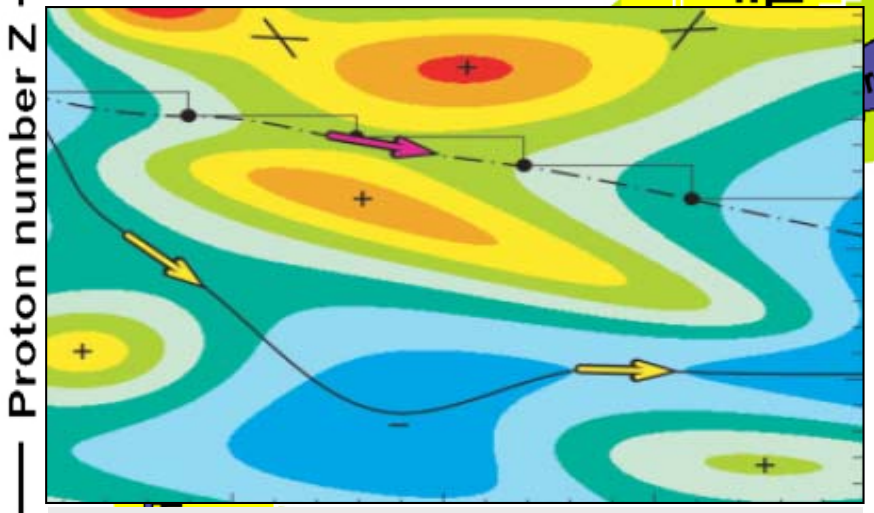
M. Warda,[1] A. Staszczak,[1,2,3] and W. Nazarewicz[2,3,4]

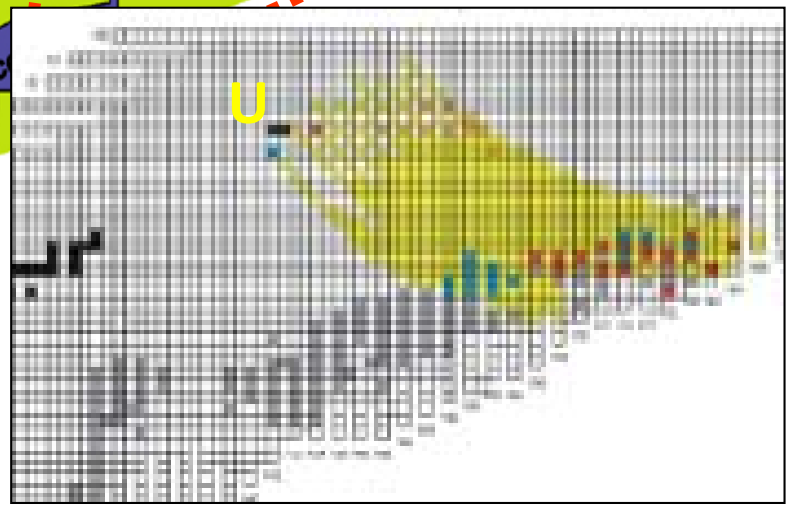








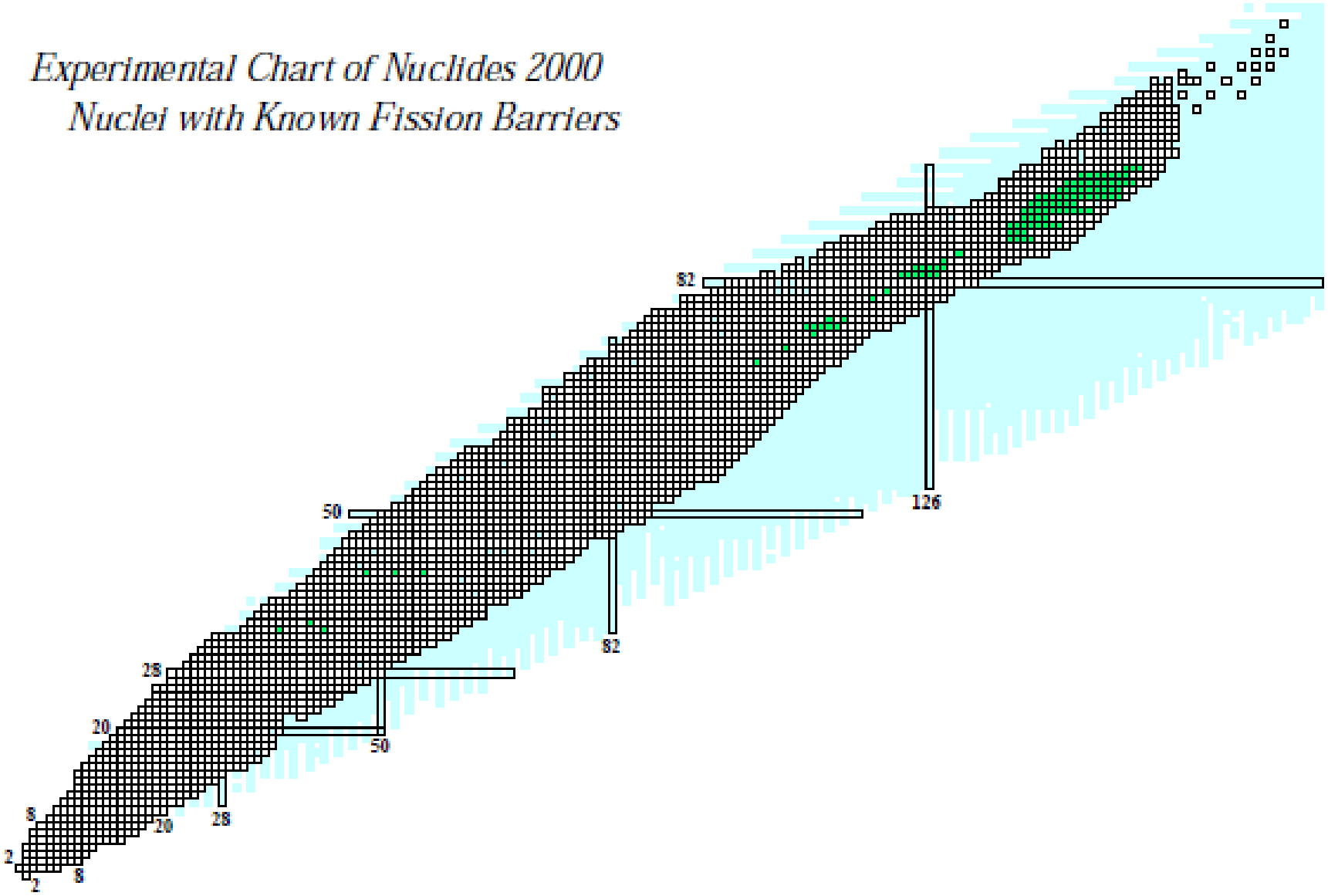




Theory of Nuclear Fission: Understanding the structure and dynamics of THE proto-typical many-body process of the nucleus

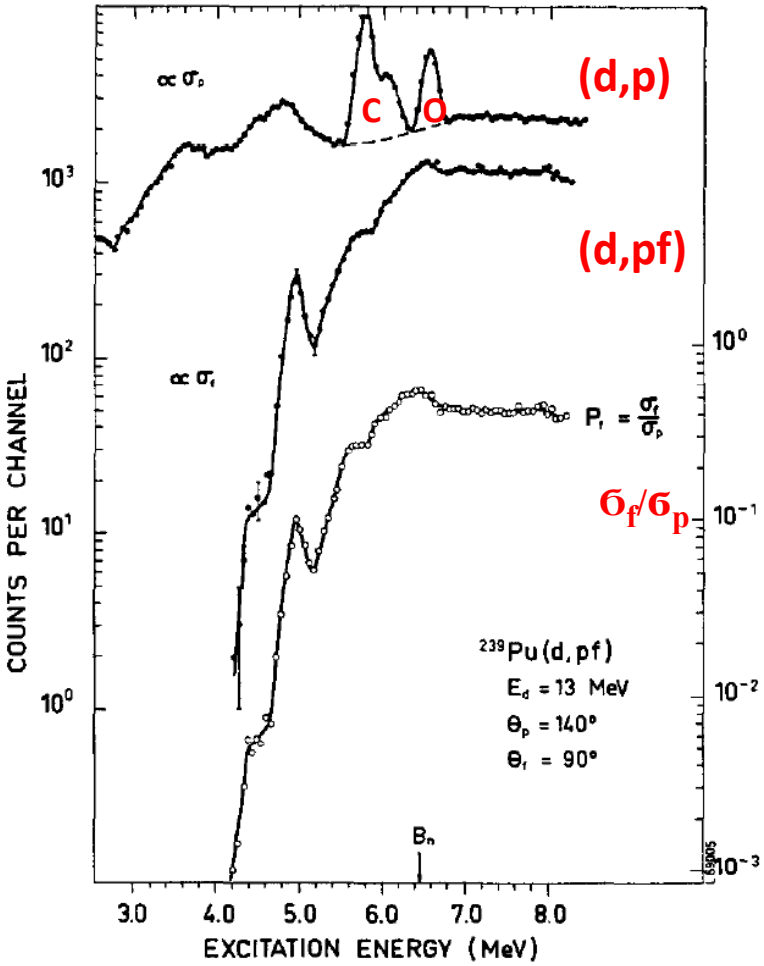
- Fission termination and recycling of the r-process
- r-process yield for ^{232}Th and ^{238}U

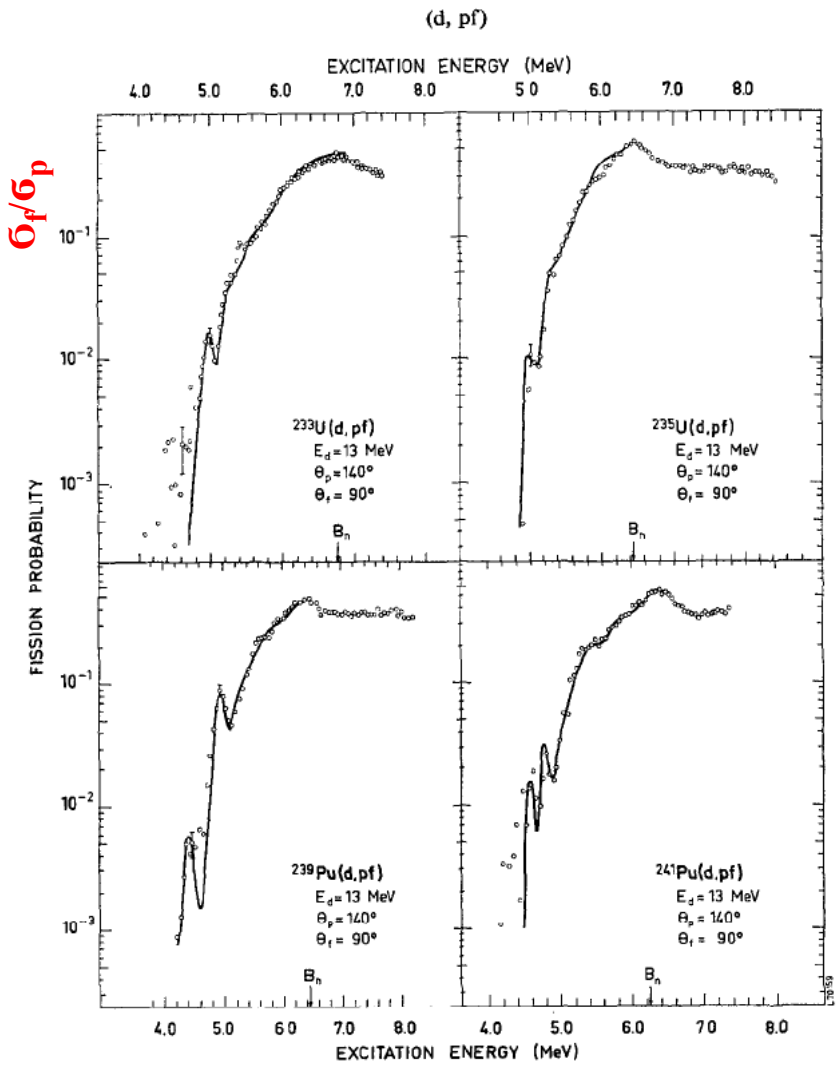
Experimental determination(s) of fission barriers


Experimental Chart of Nuclides 2000
Nuclei with Known Fission Barriers
2
2
8
8
20
20
28
28
50
50
82
82
126

Earlier fission barrier studies at low energies employing direct nucleon-transfer reactions

B.B. Back et al.; Nucl. Phys. **A165** (1971) 449
E. Konecny et al.; Phys. Lett. B **45** (1073) 329



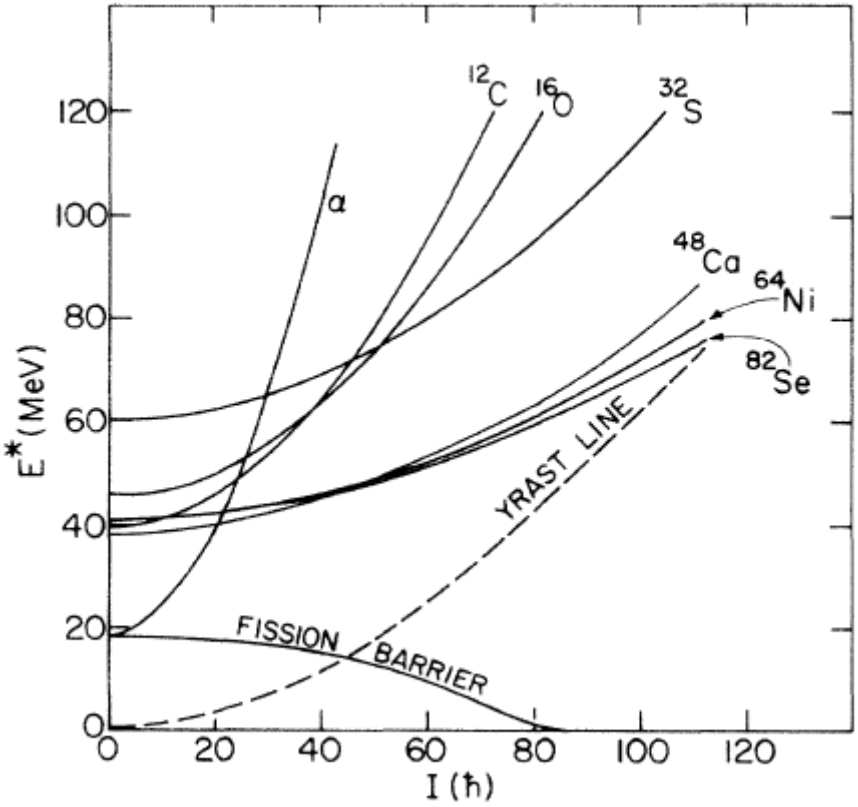


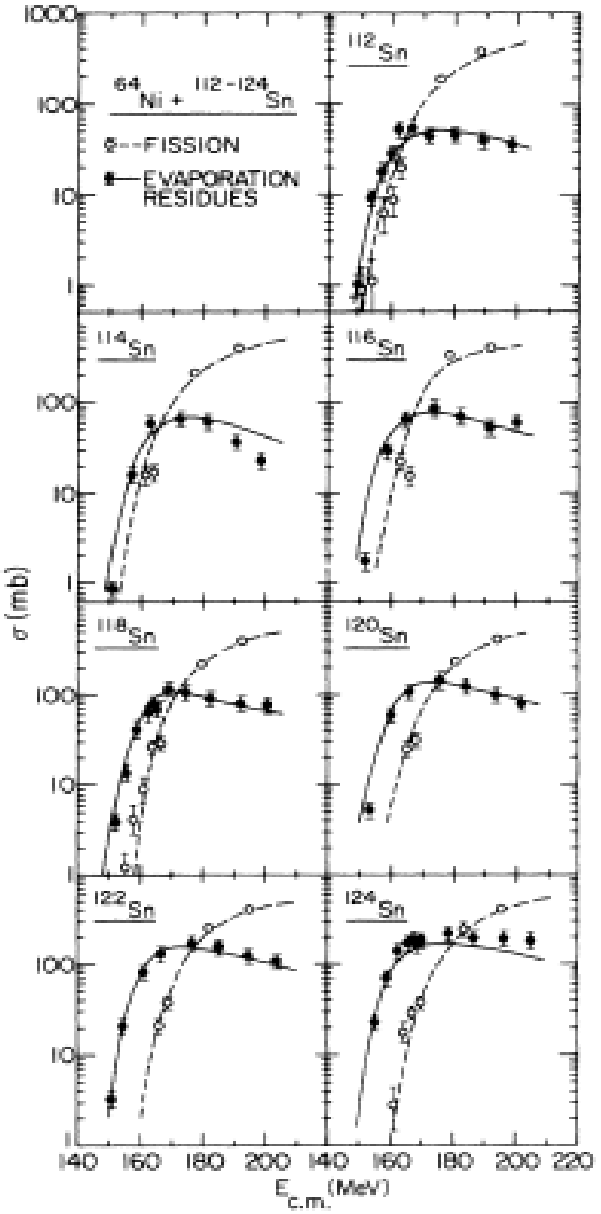
PHYSICAL REVIEW C VOLUME 34, NUMBER 6 DECEMBER 1986

Fission following fusion of Ni + Sn

K. T. Lesko,* W. Henning, K. E. Rehm, G. Rosner,† J. P. Schiffer,
G. S. F. Stephans,‡ and B. Zeidman
Argonne National Laboratory, Argonne, Illinois 60439

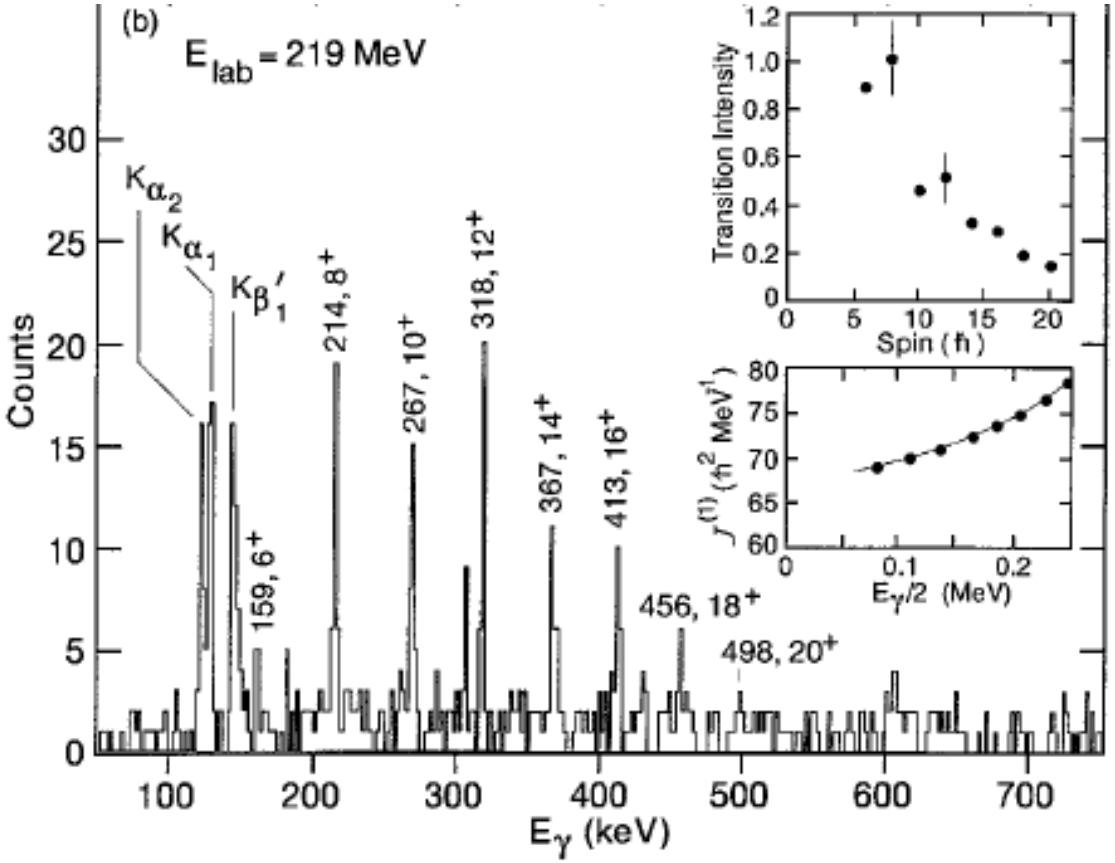
W. S. Freeman
Fermi National Accelerator Center, Batavia, Illinois 60510

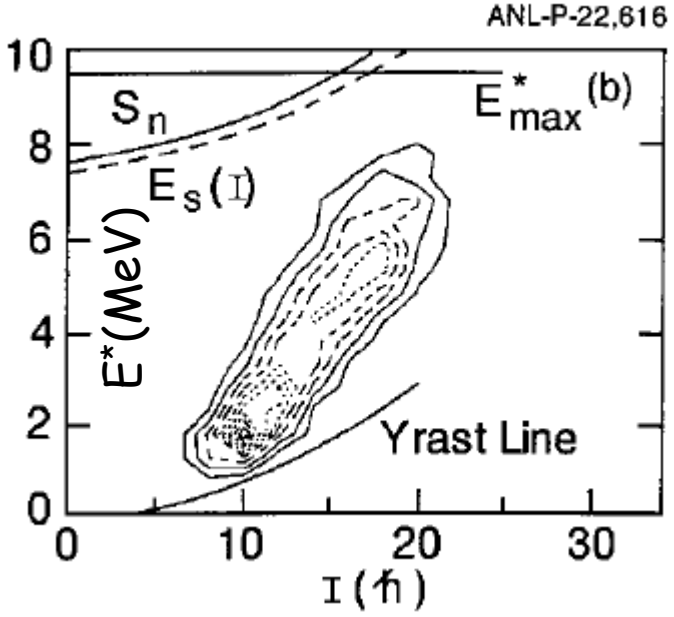




Entry Distribution, Fission Barrier, and Formation Mechanism of ^{254}No

P. Reiter,[1,2] T. L. Khoo,[1] T. Lauritsen,[1] C. J. Lister,[1] D. Seweryniak,[1] A. A. Sonzogni,[1] I. Ahmad,[1] N. Amzal,[3] P. Bhattacharyya,[4] P. A. Butler,[3] M. P. Carpenter,[1] A. J. Chewter,[3] J. A. Cizewski,[1,5] C. N. Davids,[1] K.Y. Ding,[5] N. Fotiades,[5] J. P. Greene,[1] P. T. Greenlees,[3] A. Heinz,[1] W. F. Henning,[1] R.-D. Herzberg,[3] R.V. F. Janssens,[1] G. D. Jones,[3] H. Kankaanpää,[7] F. G. Kondev,[1] W. Korten,[6] M. Leino,[7] S. Siem,[1,8] J. Uusitalo,[1] K. Vetter,[9] and I. Wiedenhöver[1]

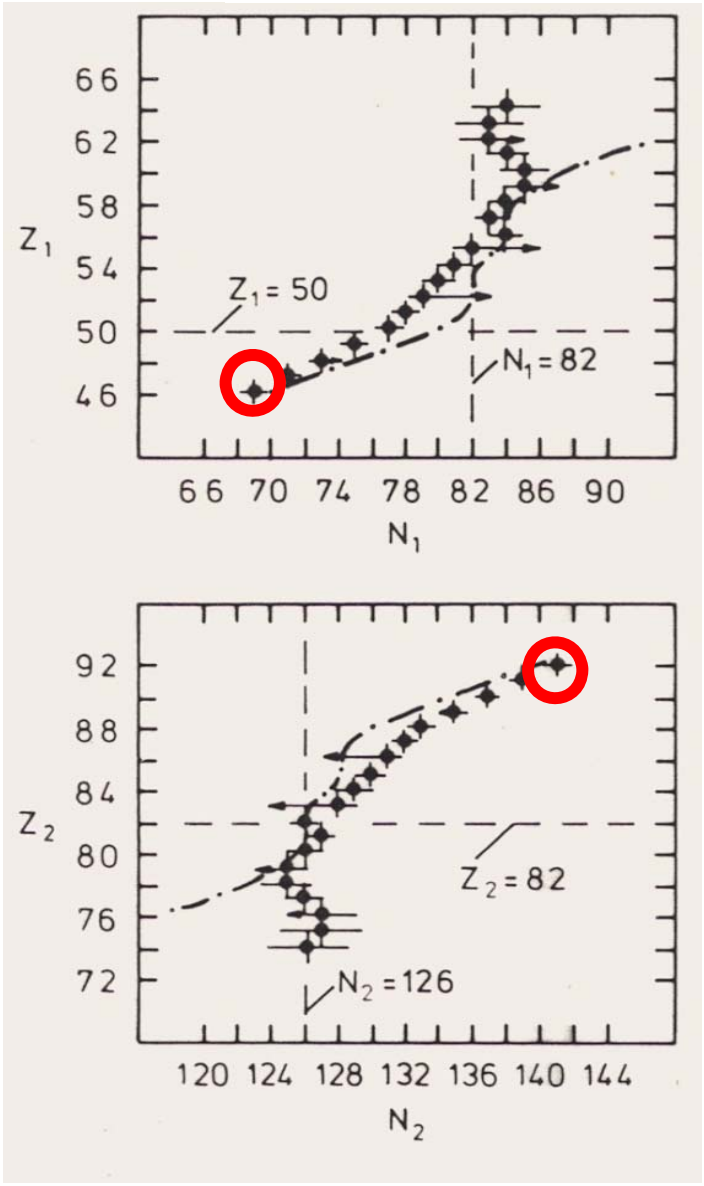




Z. Phys. A – Atomic Nuclei 336, 217–222 (1990)

Excitation-energy sharing in uranium induced dissipative collisions*

G. Beier, J. Friese, W. Henning**, P. Kienle**, H.J. Körner, W. Wagner. W.A. Maver. and W. Maver

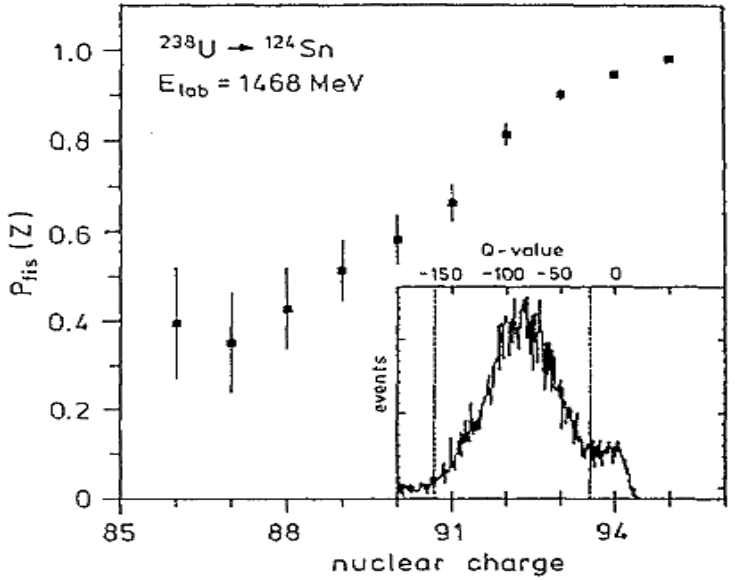


$^{238}U + ^{110}Pd$

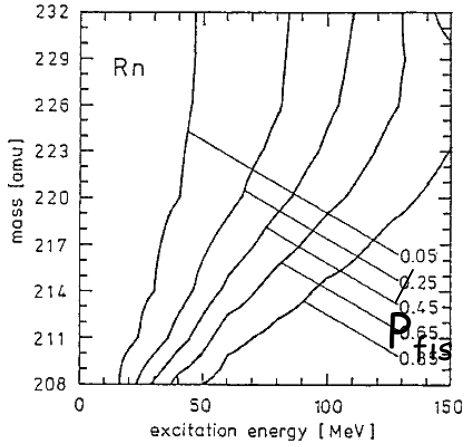
E_{lab} = 5.87 MeV/u

$130° < \Theta_{c.m.} < 165°$

$Q \leq -25$ MeV



Fission probabilities as a function of nuclear charge of the DI product



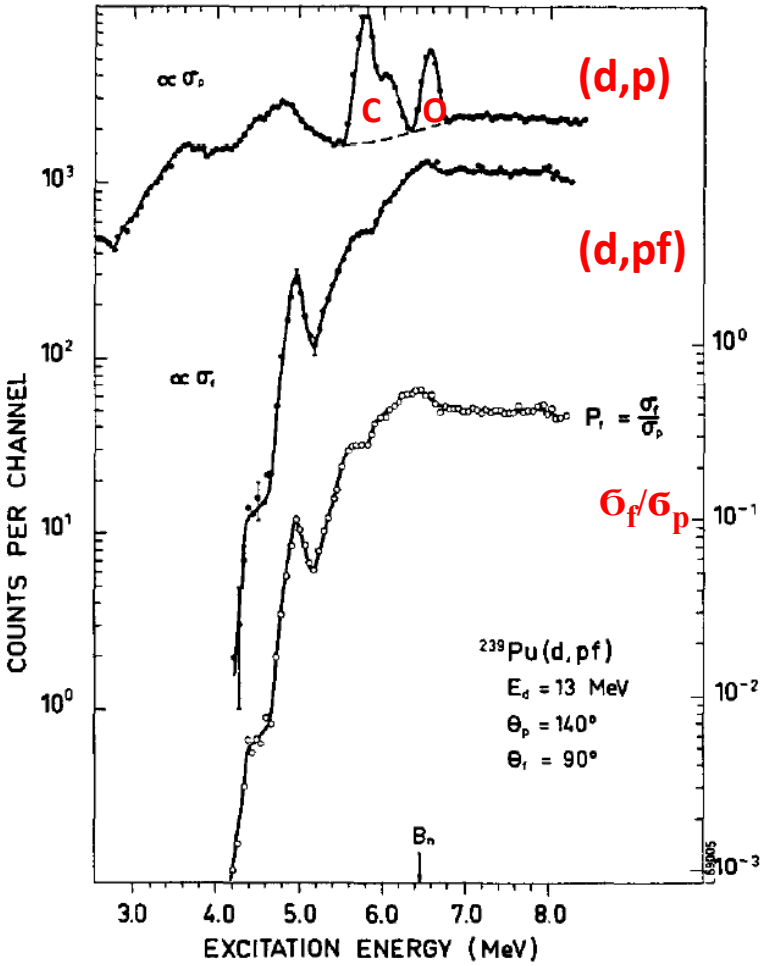
Contour plot of fission probabilities as a function of excitation energy

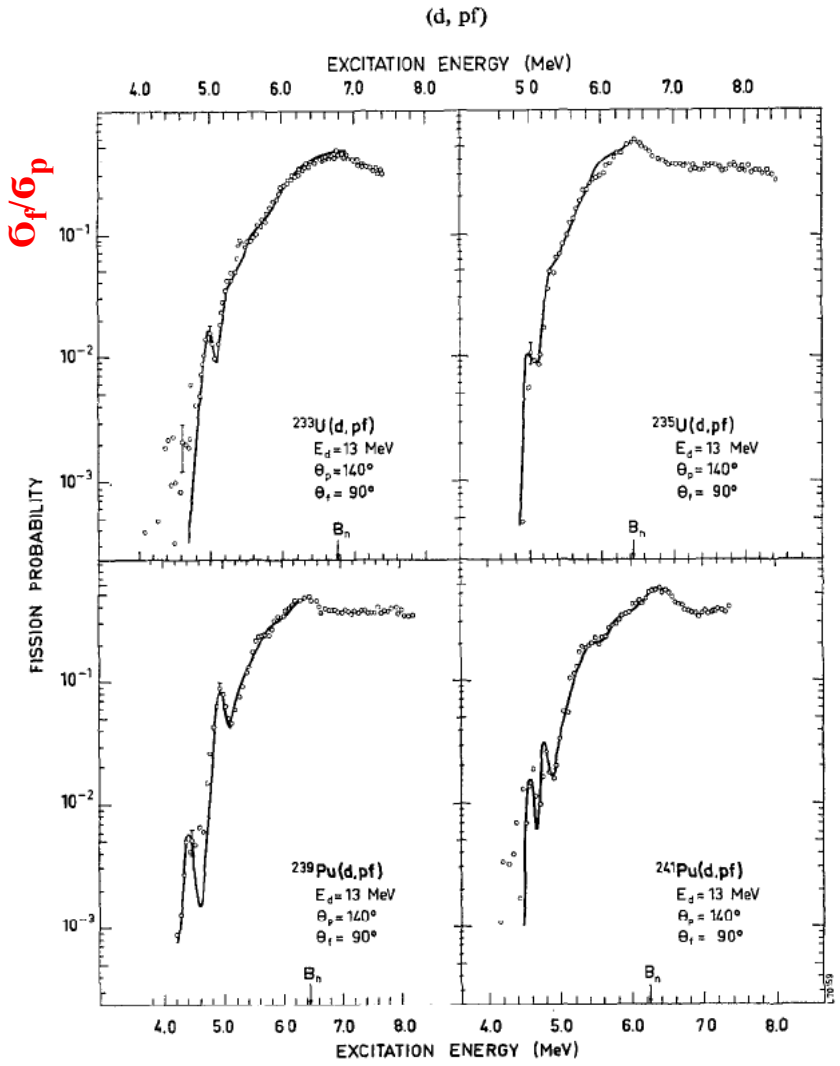
How can we experimentally determine fission barriers of neutron-rich nuclei?

Earlier fission barrier studies at low energies employing direct nucleon-transfer reactions

→ RIBs and inverse kinematics

B.B. Back et al.; Nucl. Phys. **A165** (1971) 449
E. Konecny et al.; Phys. Lett. B **45** (1073) 329

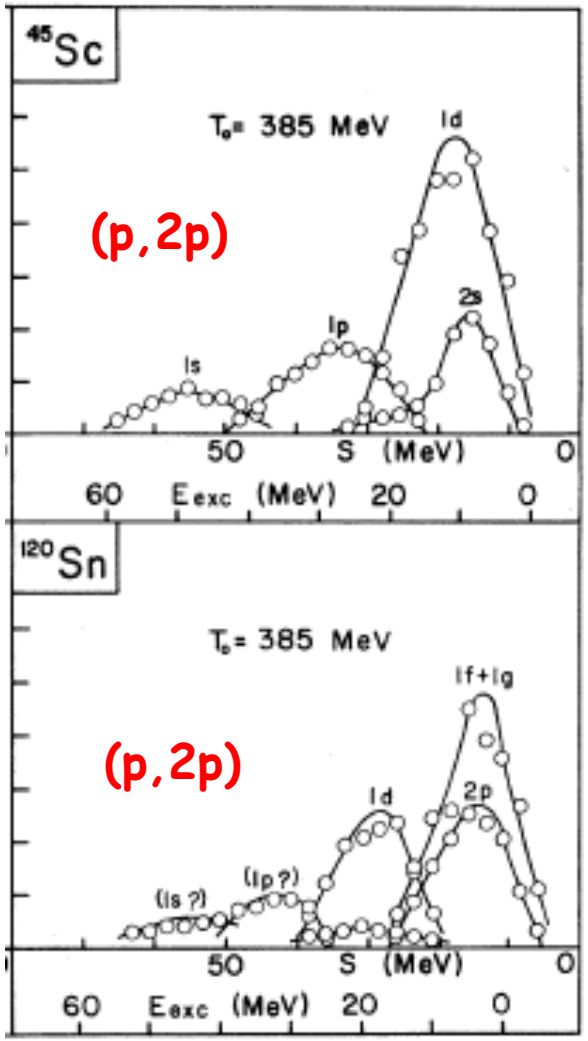


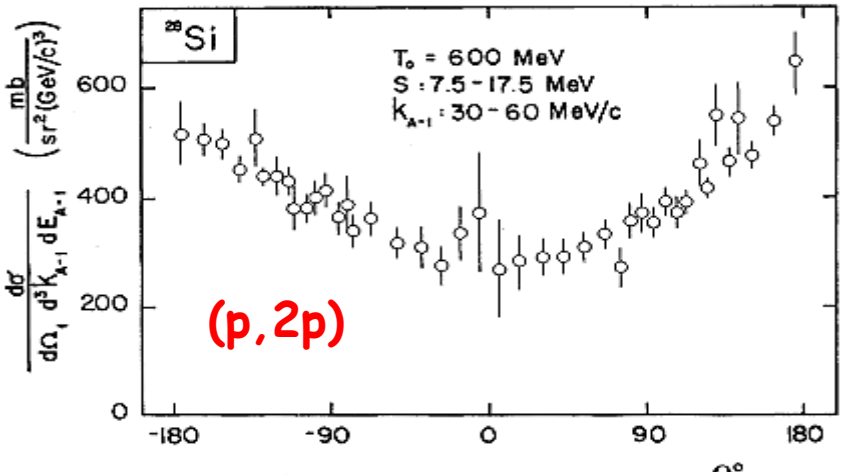


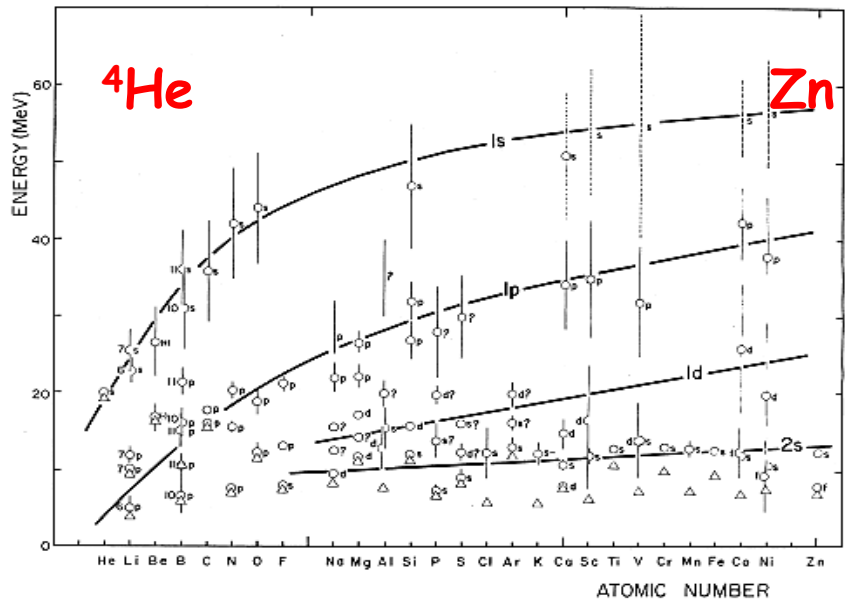
REVIEWS OF MODERN PHYSICS VOLUME 45, NUMBER 1 JANUARY 1973

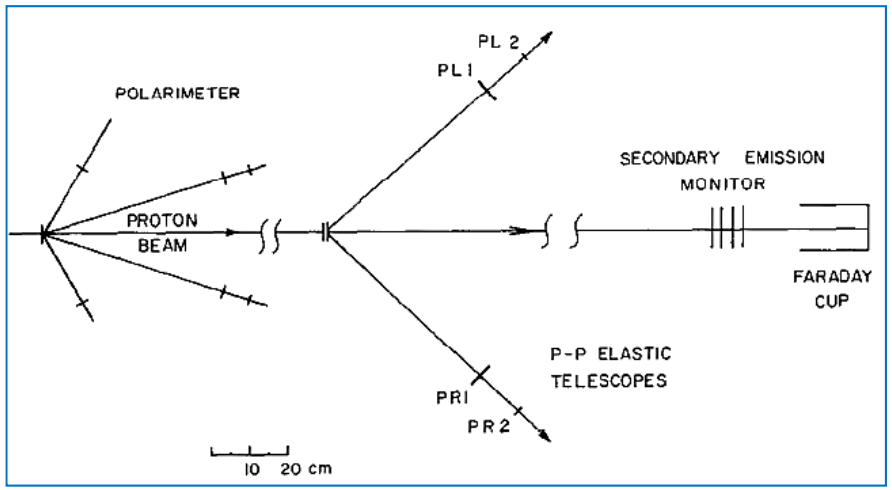
Quasi-Free Scattering and Nuclear Structure. II.

GERHARD JACOB* AND TH. A. J. MARIS









Nuclear Physics **A412** (1984) 189–194

THE DIFFERENTIAL CROSS SECTION FOR PROTON–PROTON ELASTIC SCATTERING AT 90° c.m. BETWEEN 300 AND 500 MeV

D. OTTEWELL and P. WALDEN

TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada V6T 2A3

E.G. AULD, G. GILES, G. JONES, G.J. LOLOS, B.J. McPARLAND and W. ZIEGLER

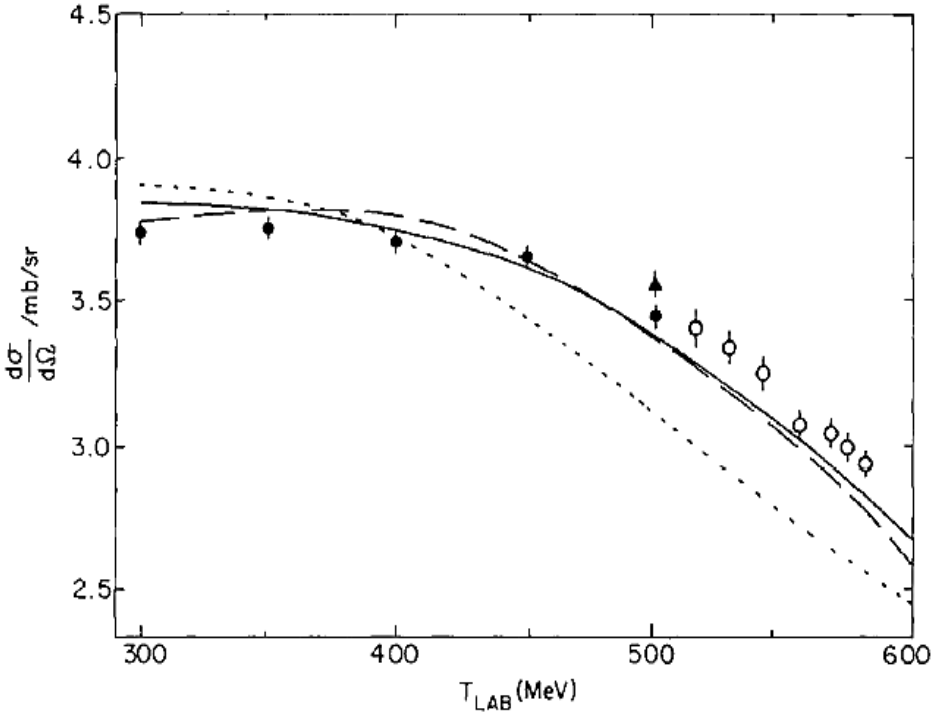
Physics Department, University of British Columbia, Vancouver, BC, Canada V6T 2A6

and

W. FALK

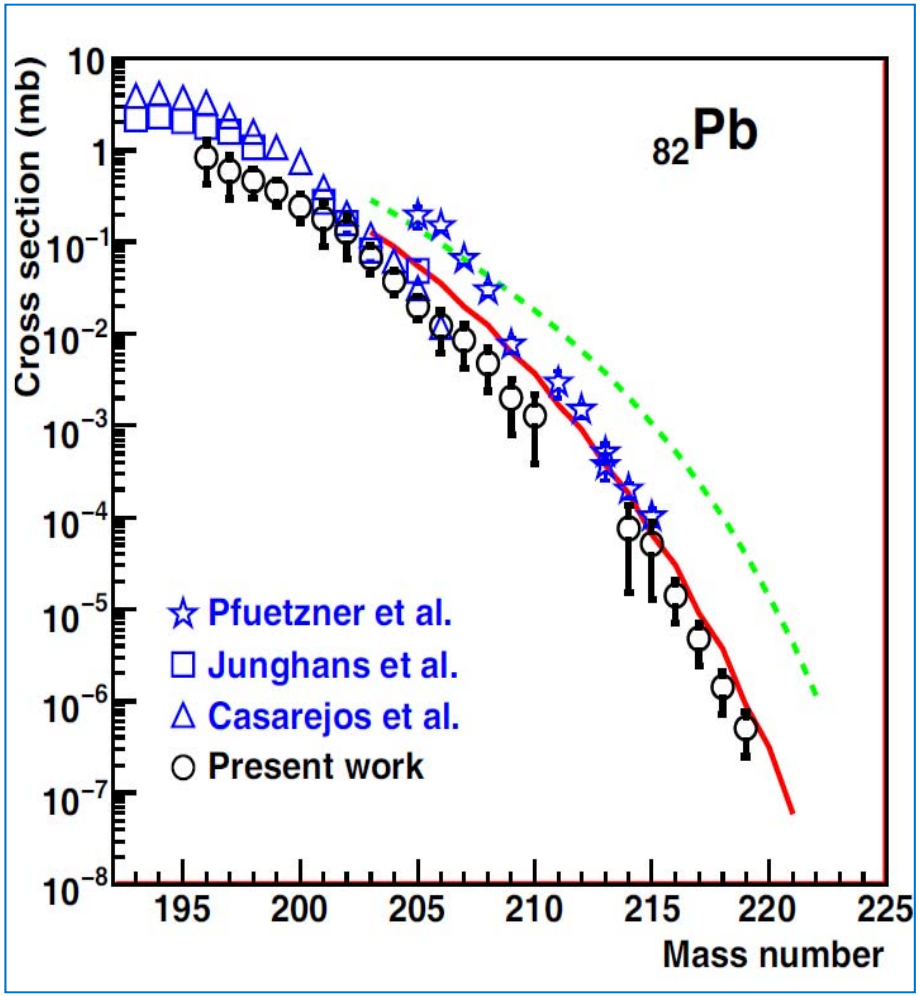
Physics Department, University of Manitoba, Winnipeg, Man., Canada R3T 2N2

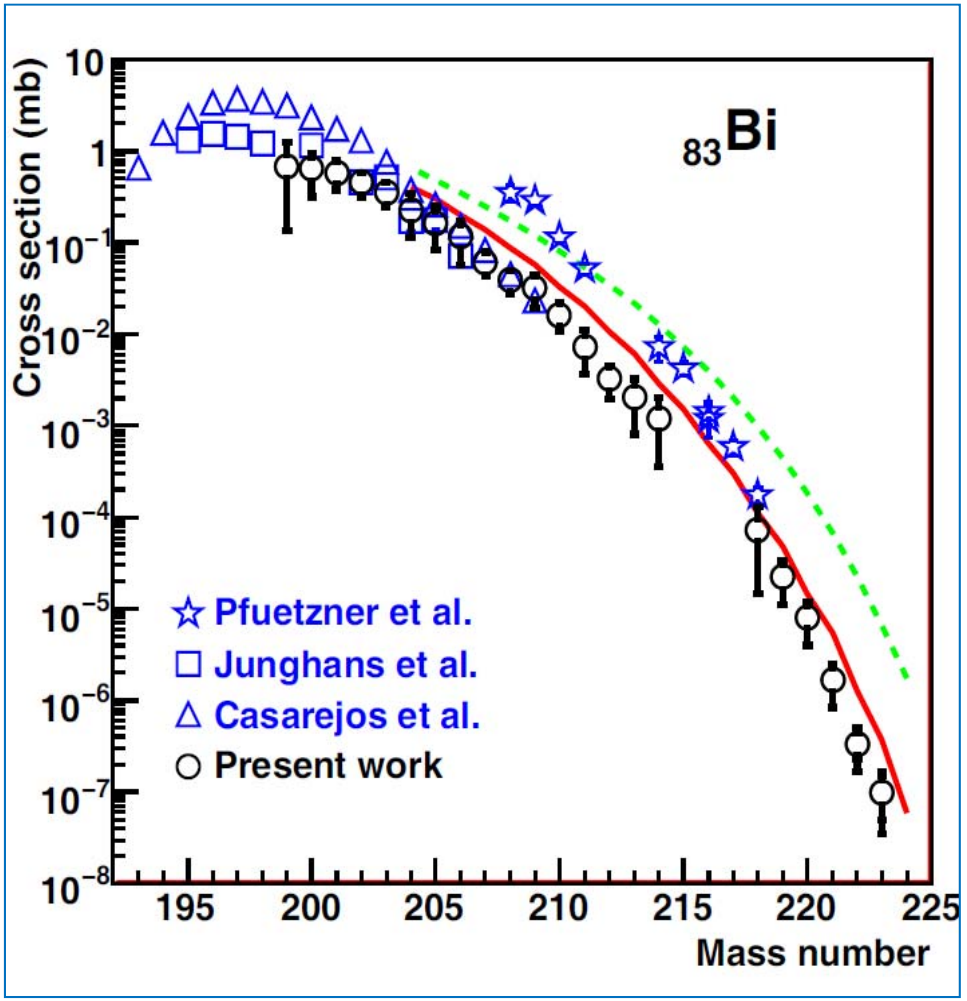
E_p (MeV)	Carbon $d\sigma/d\Omega$ (mb/sr)	pp elastic $d\sigma/d\Omega$ 90° c.m. (mb/sr)
300	0.432 ± 0.007	3.769 ± 0.019
350	0.509 ± 0.009	3.759 ± 0.019
400	0.568 ± 0.010	3.742 ± 0.019
450	0.604 ± 0.010	3.682 ± 0.019
500	0.638 ± 0.011	3.471 ± 0.018



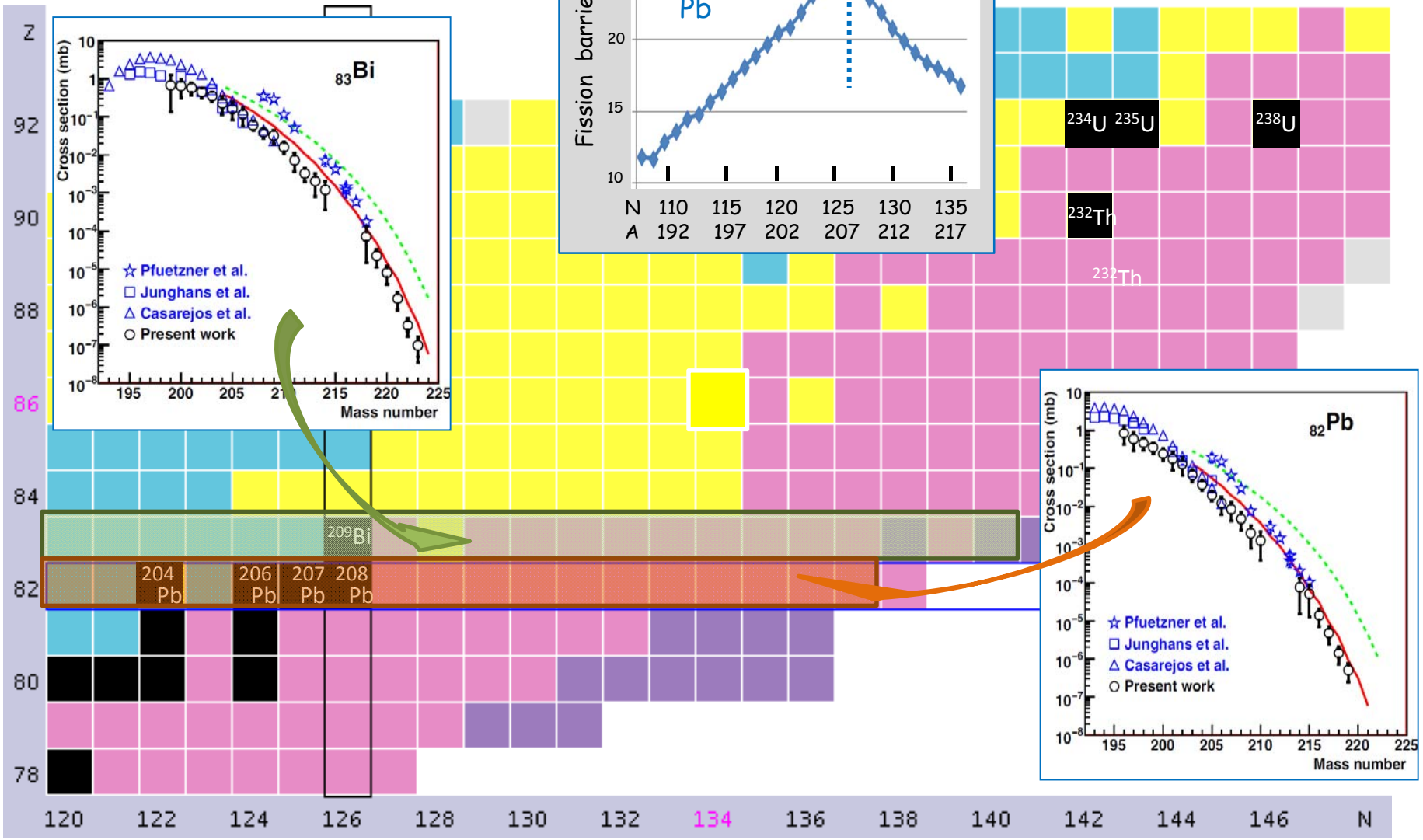
Production Cross-sections of Neutron-Rich Pb and Bi Isotopes in the fragmentation of ^{238}U

H. Alvarez-Pol et al.; Eur. Phys. J. A **42** (2009) 485

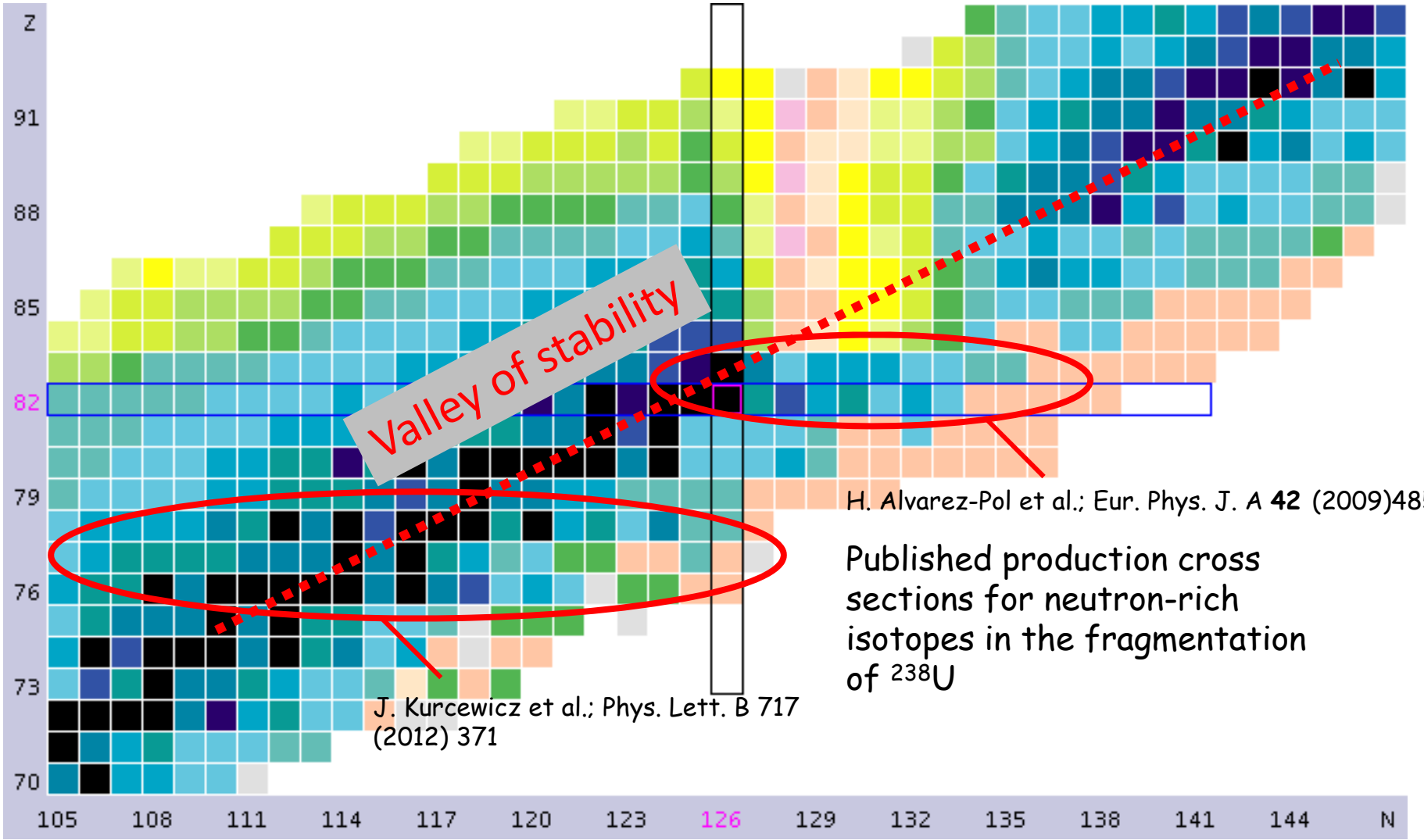




Pb and Bi isotopes observed in ^{238}U fragmentation



Neutron rich regions with known production cross sections from ^{238}U fragmentation



Countrate estimates:

Fragmentation yield for ^{238}U beam and σ=100nb

10 pnA ^{238}U
250 mg/cm^2 Be target
100 nb fragment cross section (~ ^{198}Pt, ^{214}Pb, ^{217}Bi)
1 day beam on target

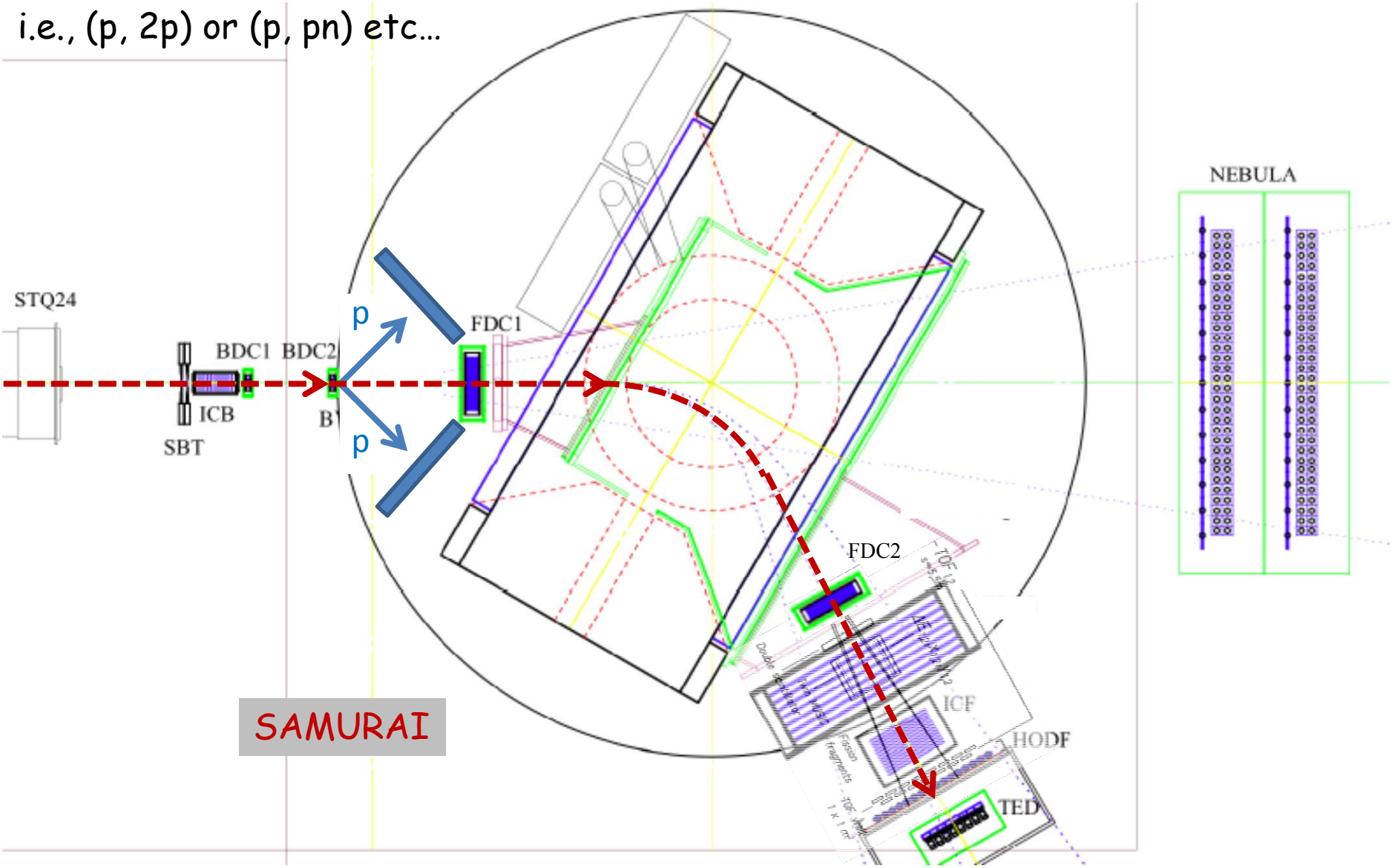
N=8.6 x 10^6 fragment events per day

Fission yield for (p,2p)

8.6 x 10^6/day (^{214}Pb or ^{217}Bi)
1g/cm^2 H_2 target
100μb/MeV (p,2pf) cross section
1 day beam on target

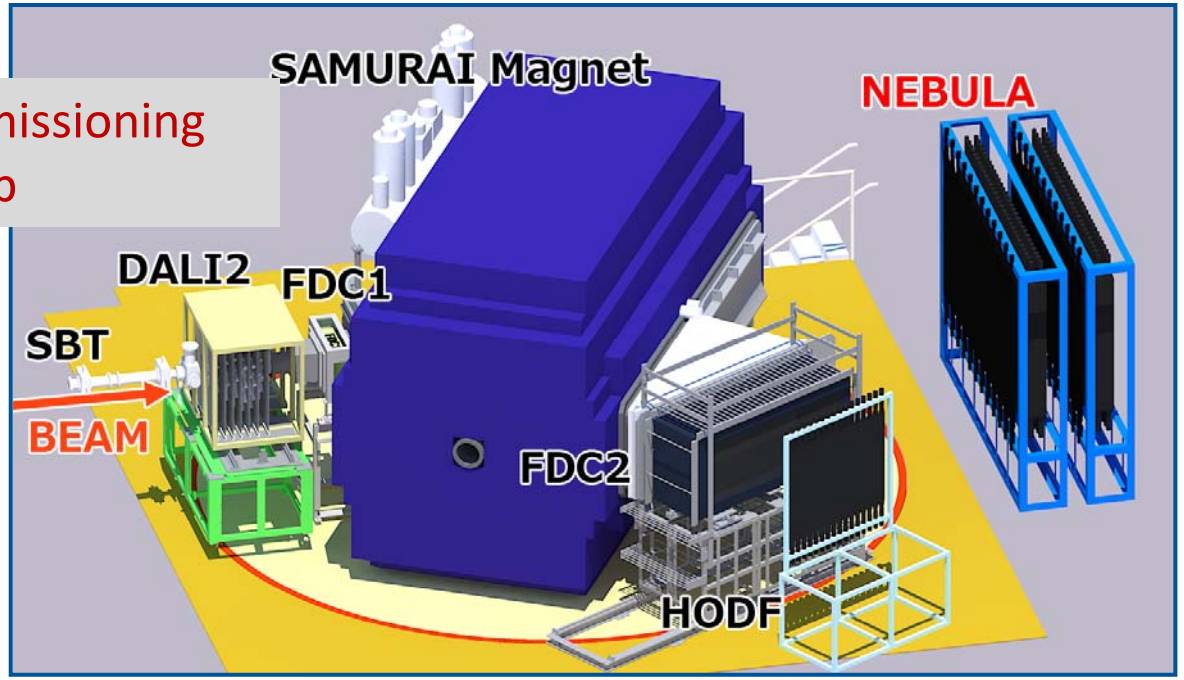
N=5 x 10^2 events/day•MeV

Approach at high energies with RIBs
in inverse kinematics: nucleon knockout
i.e., (p, 2p) or (p, pn) etc…

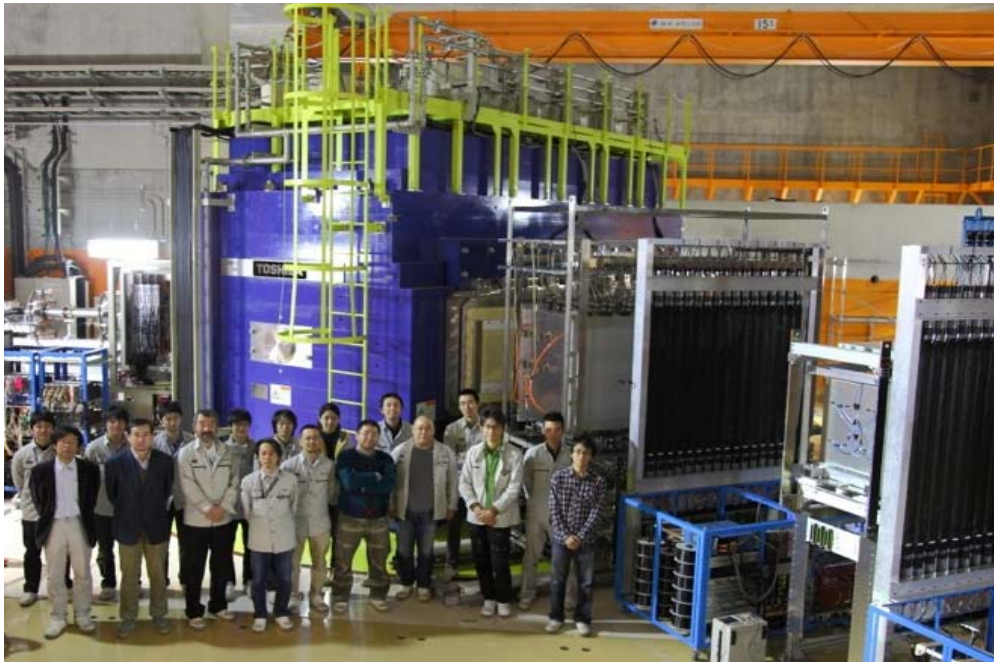


SAMURAI Commissioning May 2012

Commissioning Set-up



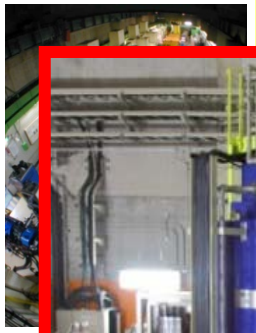
- All the detectors and DAQ commissioned with beam and calibrated
- HI-neutron coincidences
  - $^{17}C \rightarrow {}^{16}C+n$ $^{15}B+n$
  - $^{15}C \rightarrow {}^{14}C+n$
  - $^{14}Be \rightarrow {}^{12}Be+2n$



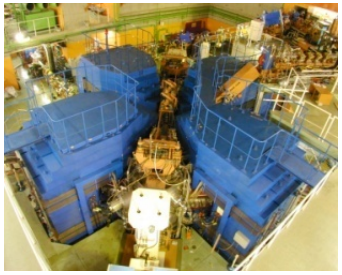
- **RIKEN**: K. Yoneda, N. Fukuda, N. Inabe, T. Isobe, T. Kubo, K. Kusaka, T. Motobayashi, J. Ohnishi, H. Otsu, H. Sato, Y. Shimizu, H. Suzuki, H. Takeda, S. Takeuchi
- **Tohoku U**: T. Kobayashi, K. Takahashi, K. Sekiguchi
- **Tokyo Tech**: T. Nakamura, N. Kobayashi, Y. Kondo, R. Minakata, S. Nishi, S. Ogoshi, T. Sako, R. Tanaka
- **Kyoto U**: Y. Matsuda, T. Murakami
- **Kyushu U**: T. Teranishi
- **France**: F. Delaunay, J. Gibelin, M. Miguel
- **Germany**: T. Aumann, Y. Togano
- **Korea**: Y. Sato, J. Hwang, S. Kim

RIBF Layout

RILAC

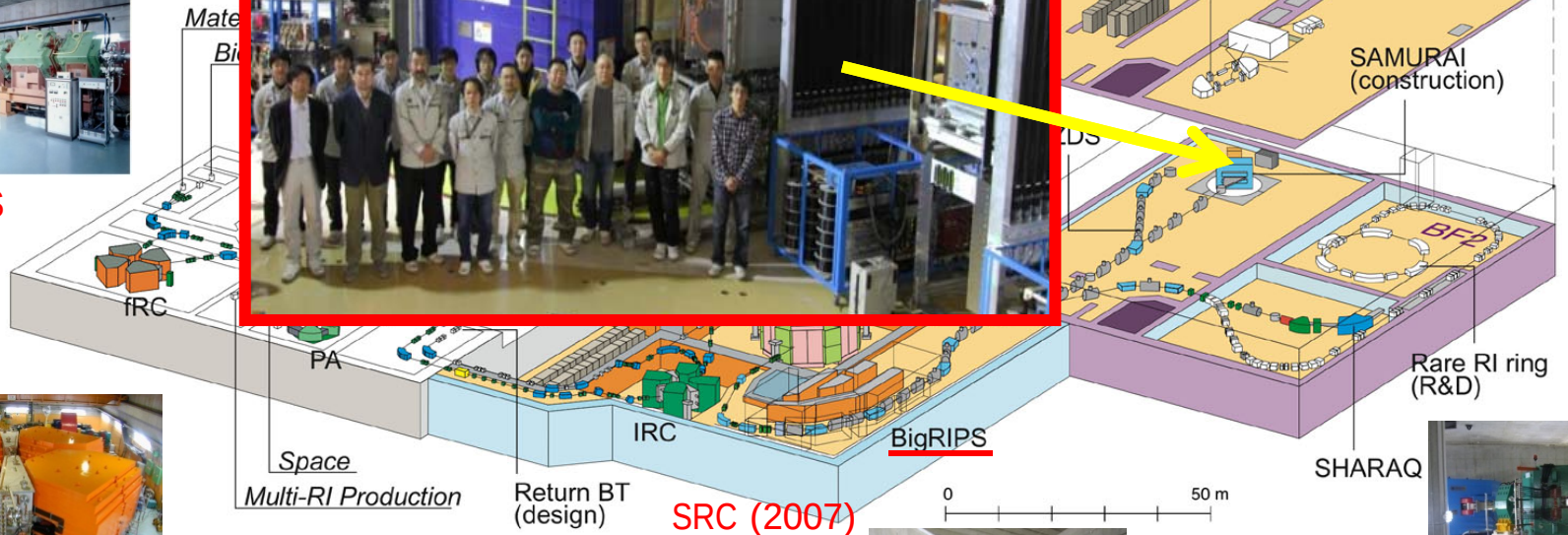


RRC



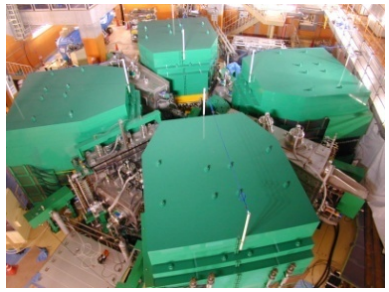
ZeroDegree (ZDS) (2008)

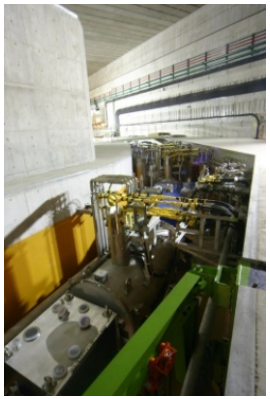
RIPS



fRC

IRC

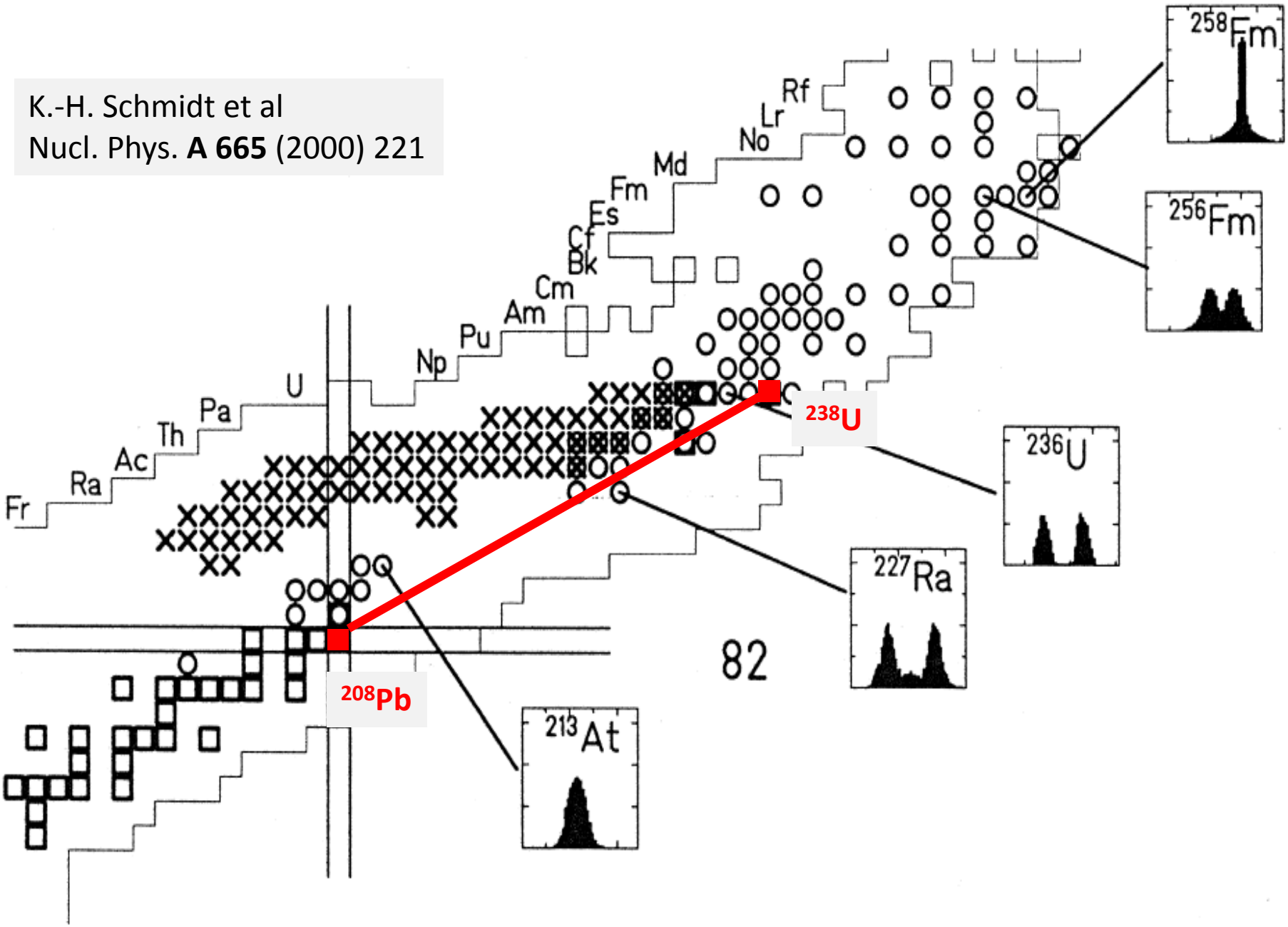




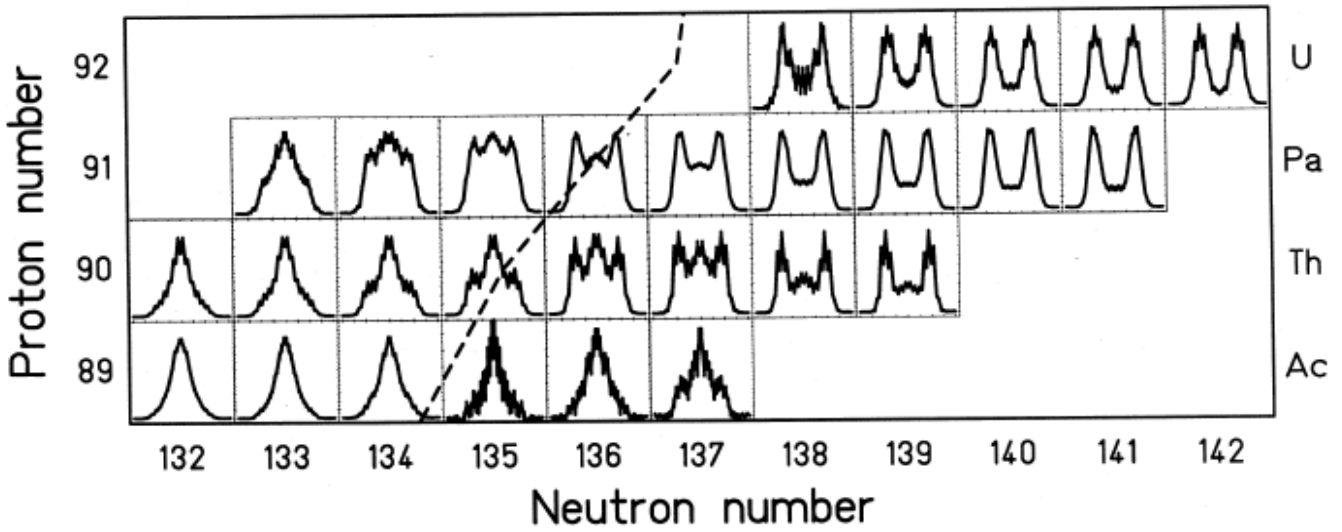
BigRIPS
(2007)

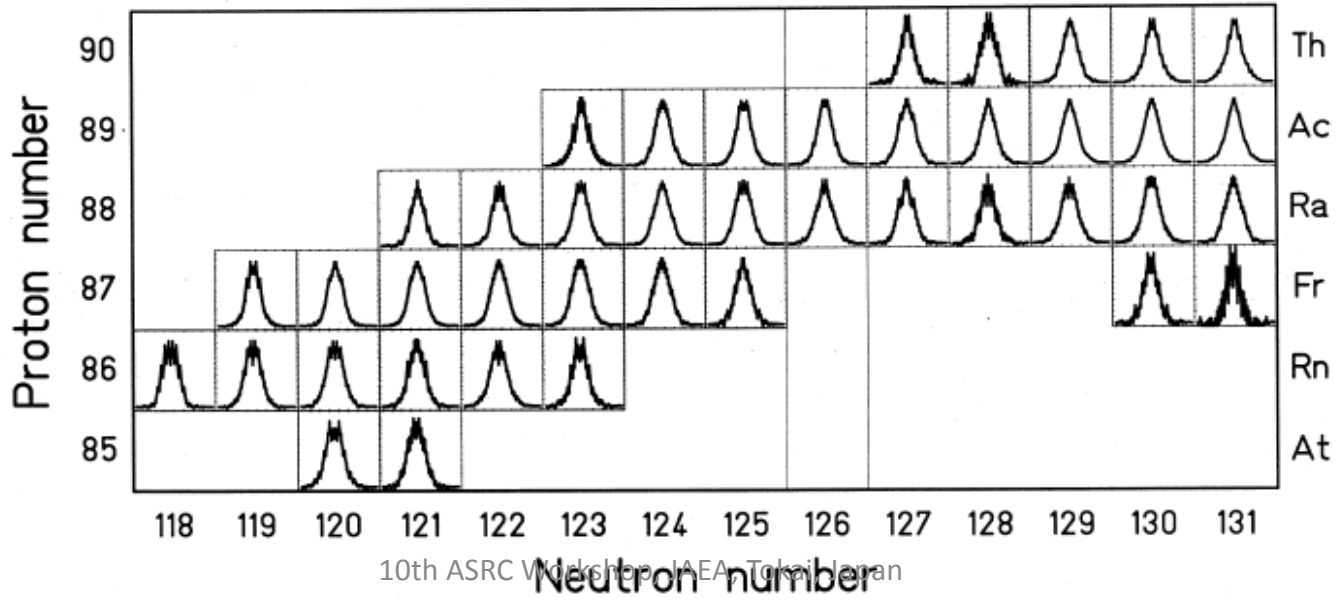
SHARAQ
(2009)

K.-H. Schmidt et al
Nucl. Phys. **A 665** (2000) 221

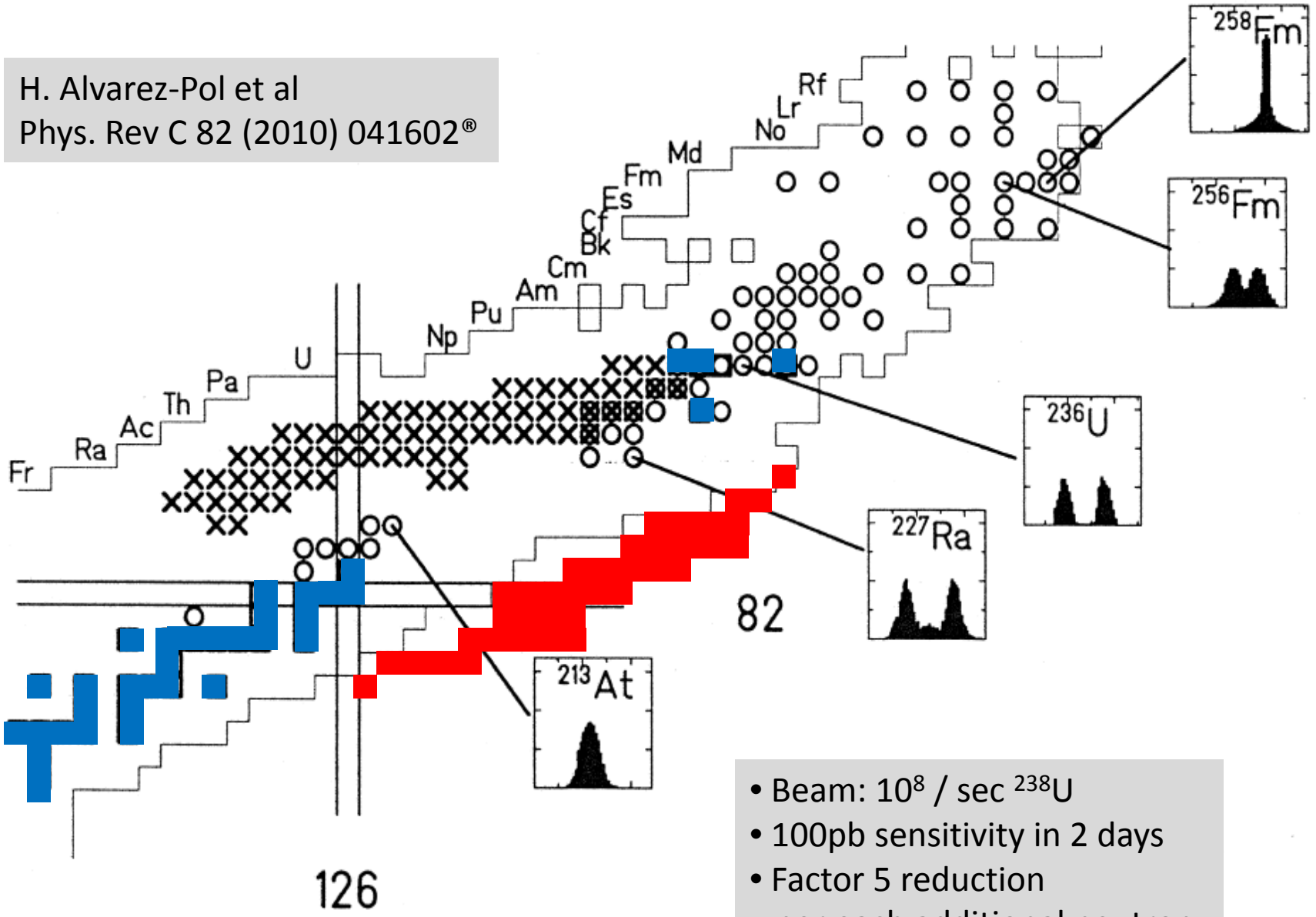


Fission-Fragment Mass Distribution

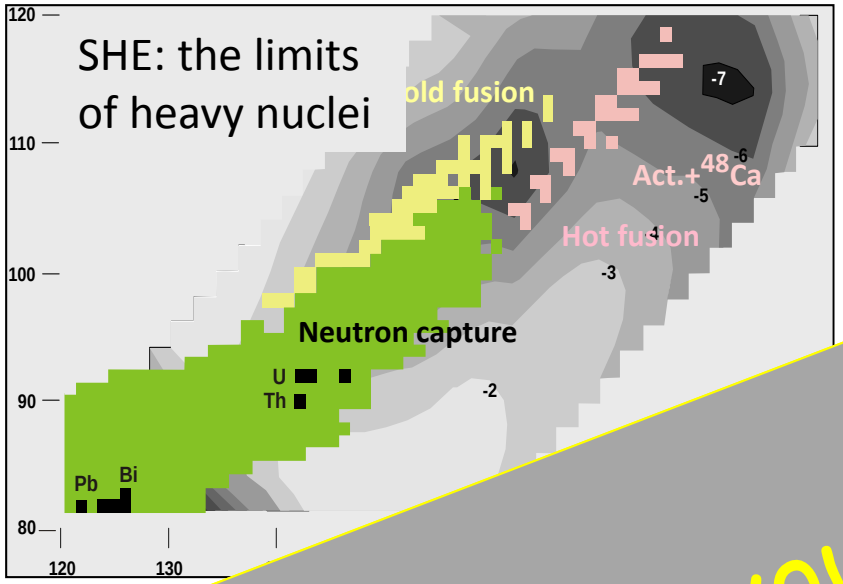




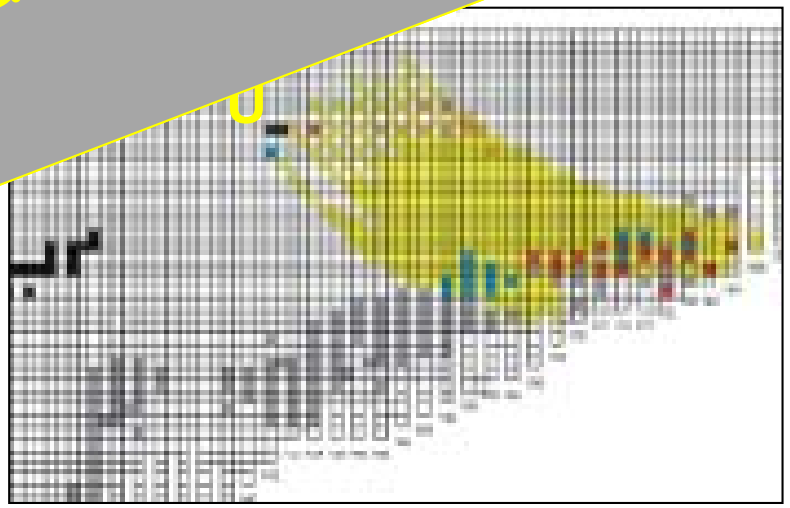
H. Alvarez-Pol et al
Phys. Rev C 82 (2010) 041602®



- Beam: 10^8 / sec ^{238}U
- 100pb sensitivity in 2 days
- Factor 5 reduction
  per each additional neutron



Thank you for your attention!



Theory of Nuclear Fission: Understanding the structure and dynamics of THE proto-typical many-body process of the nucleus

- Fission termination and recycling of the r-process
- r-process yield for ^{232}Th and ^{238}U

Neutron number N