International Symposium

“Super-Heavy Nuclei"

Super-Heavy Nuclei: Current Status and Future Developments

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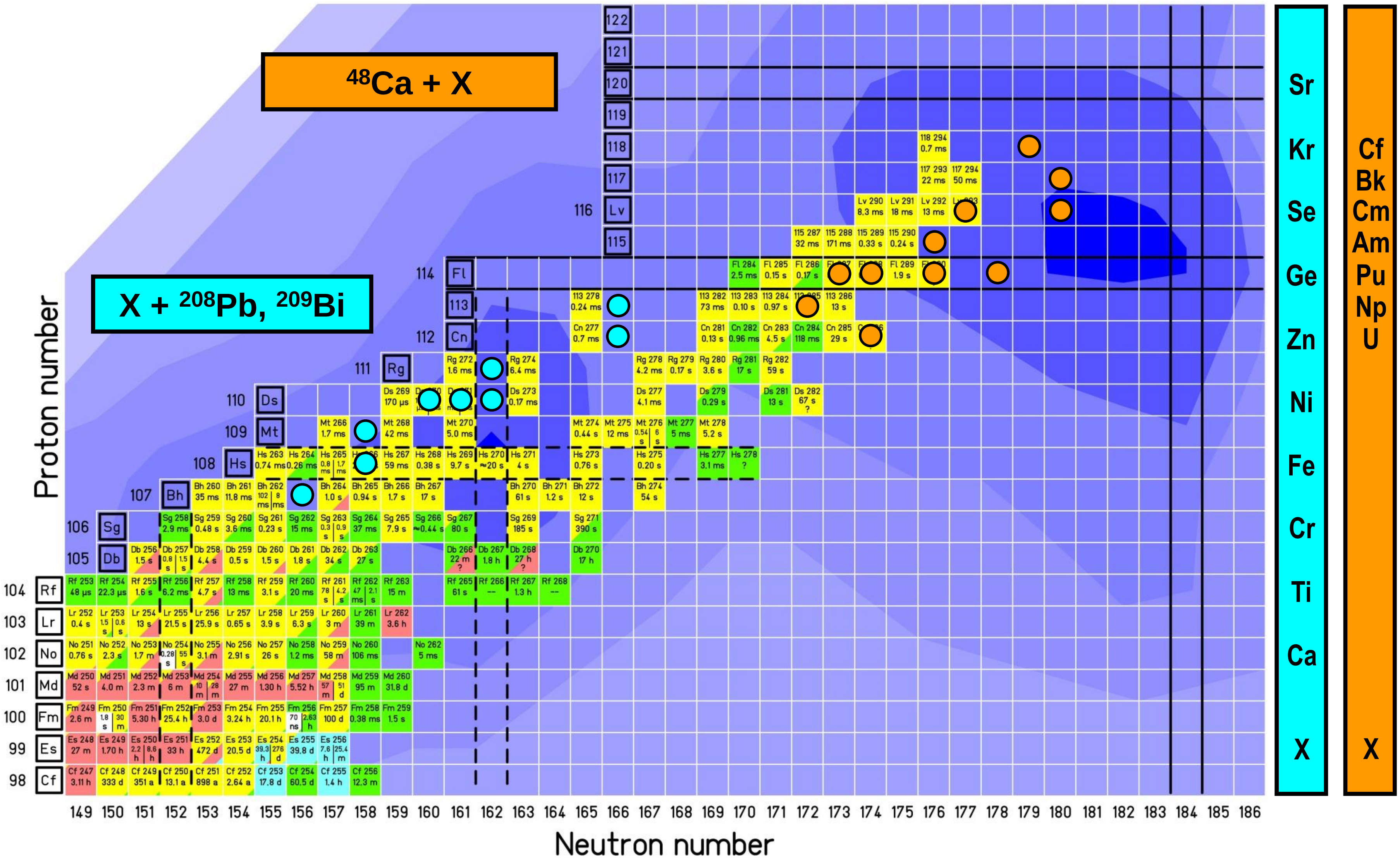
Texas A&M University, College Station, Texas 77840, USA

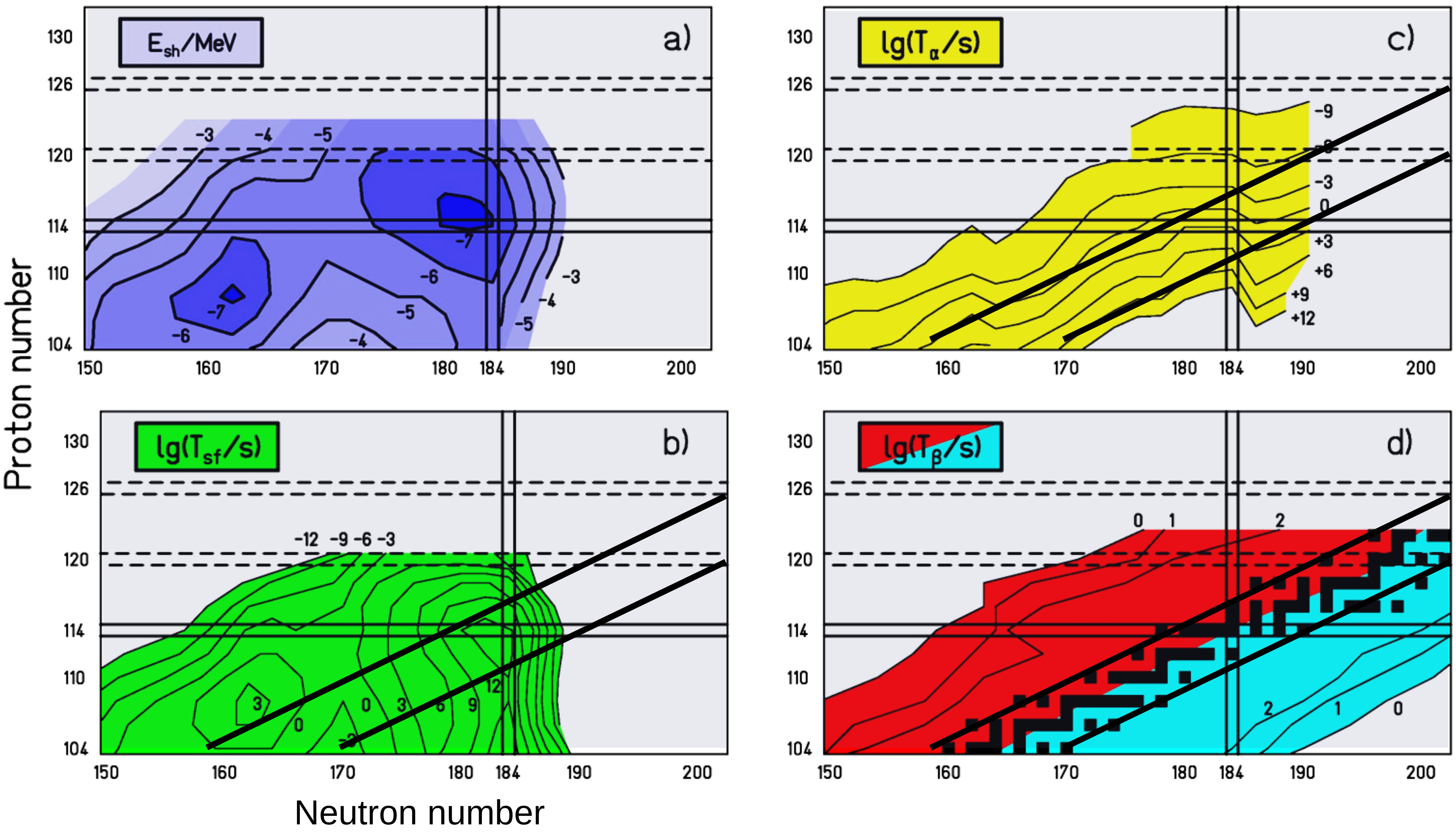
March 31 – April 2, 2015

Results from cold and hot fusion



Predictions of the macroscopic-microscopic model

Calculation: R. Smolanczuk, A. Sobiczewski et al.; P. Möller et al.



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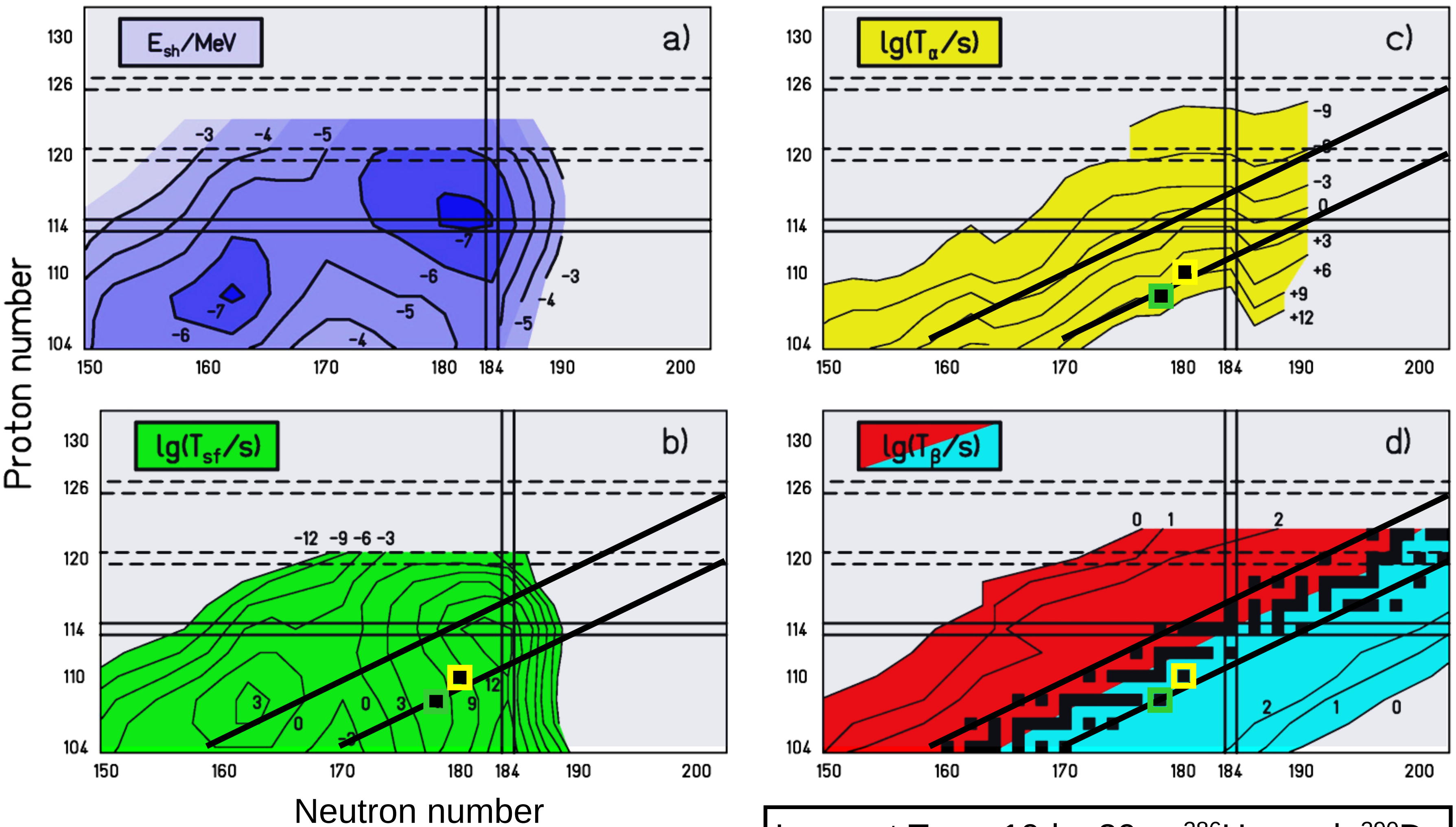
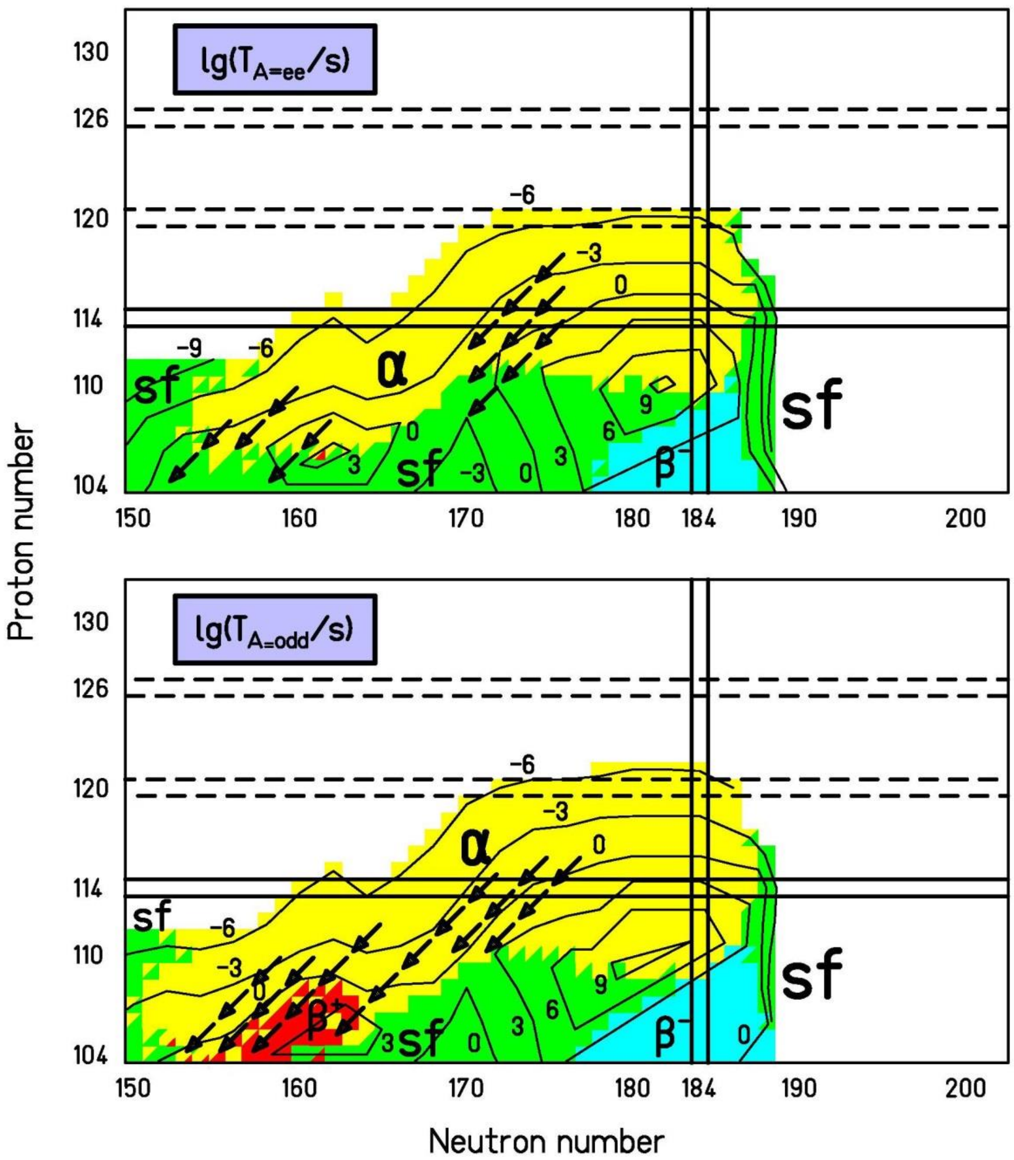


Longest $T_{1/2}$ = 10d – 30y: ^{286}Hs and ^{290}Ds

So far, good agreement with experiment

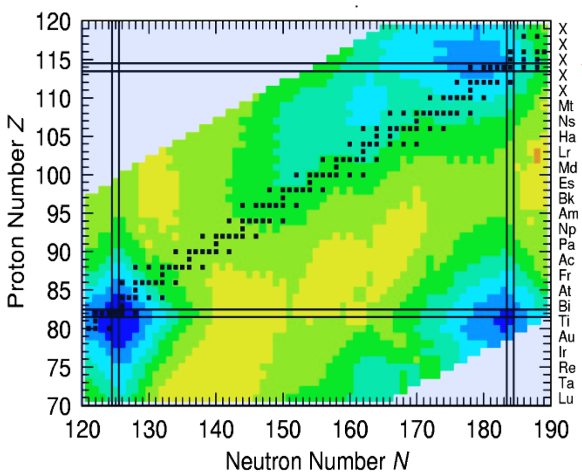


even-even

odd-A

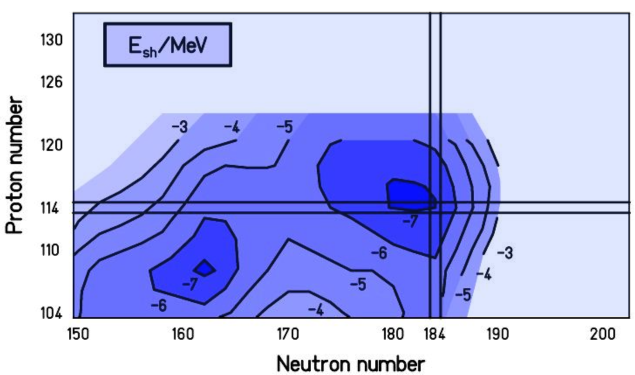
Shell effects in different models

Macroscopic-microscopic



114

P. Möller, 1995



114

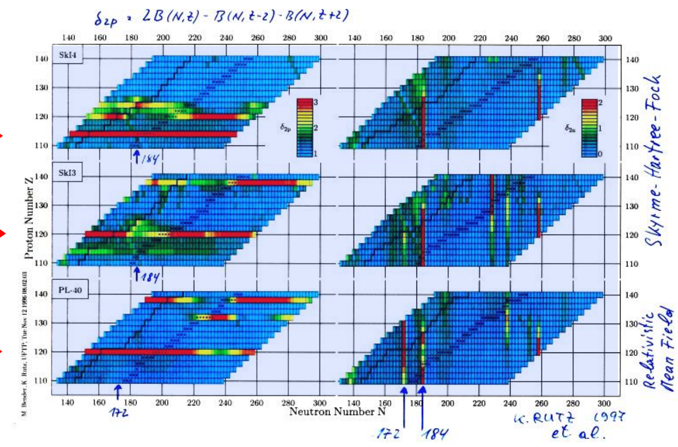
A. Sobiczewski et al., 1995

Mean field

114

120

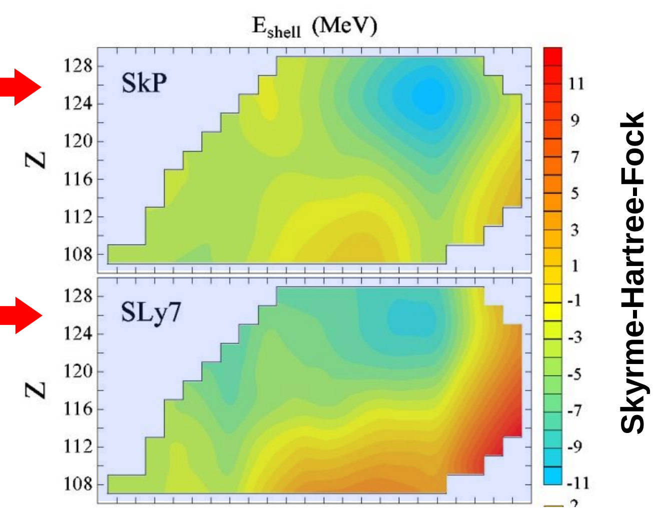
120



K. Rutz, W. Greiner et al., 1997

126

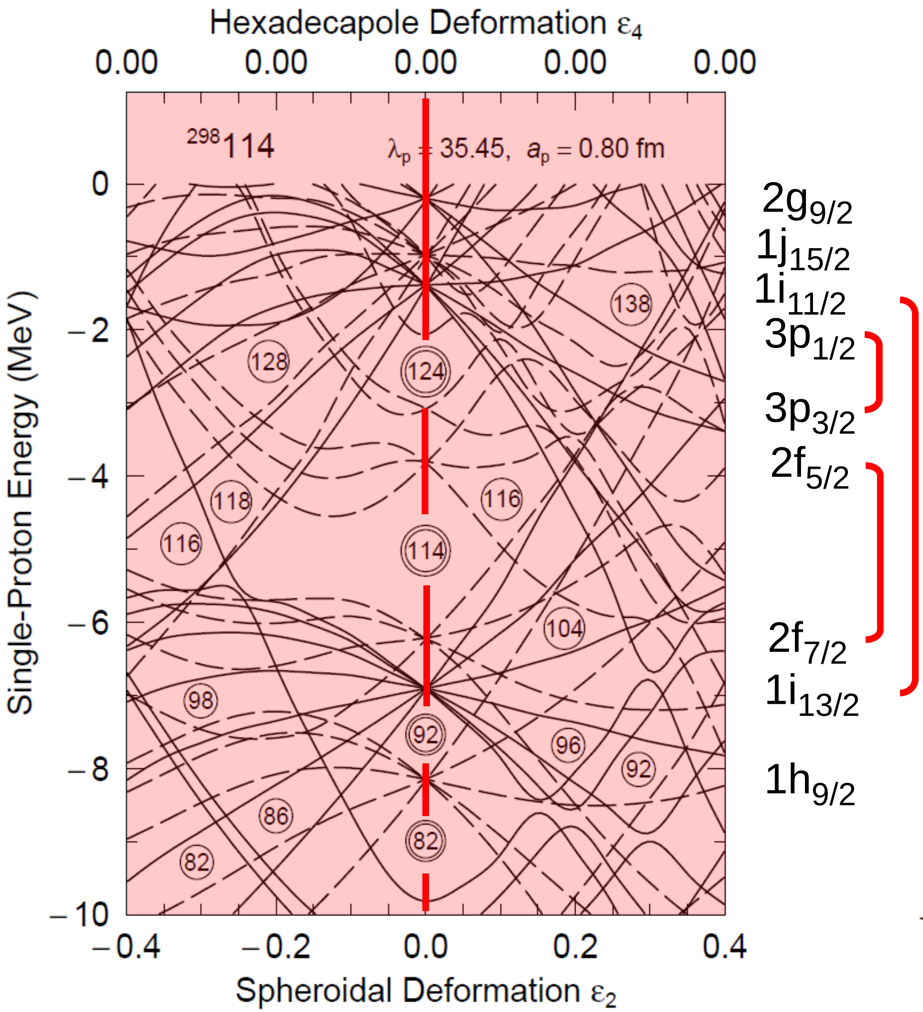
126



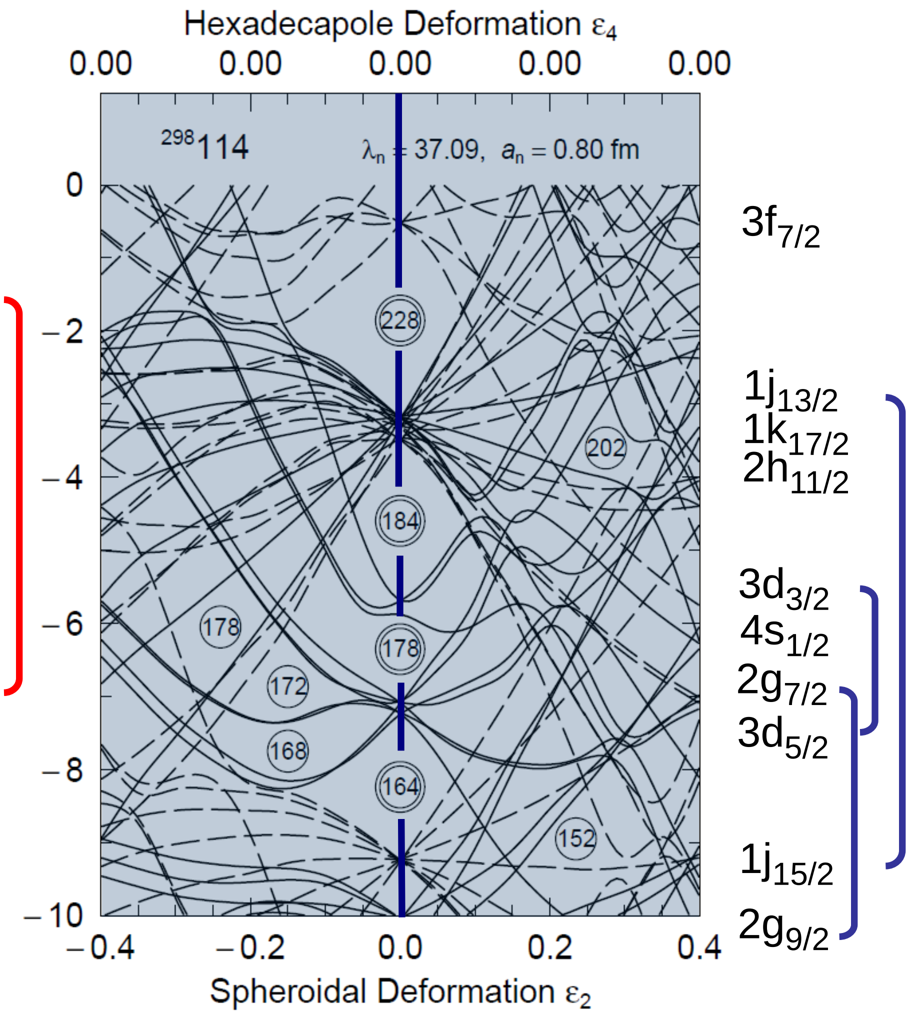
S. Cwiok et al., 1998

Single particle energies

Protons, Z = 114

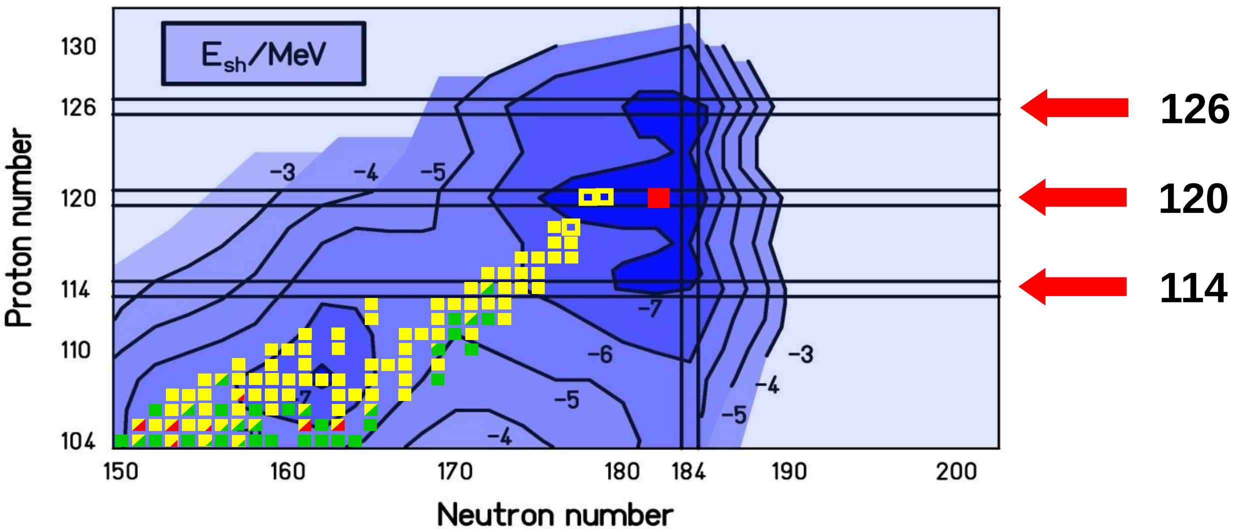


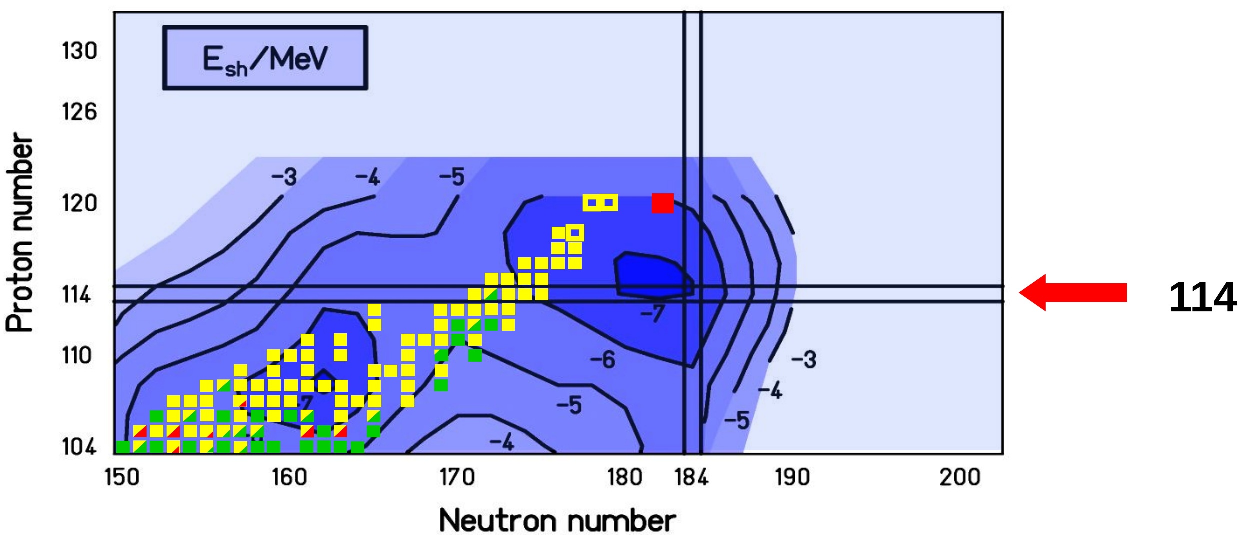
Neutrons, N = 184



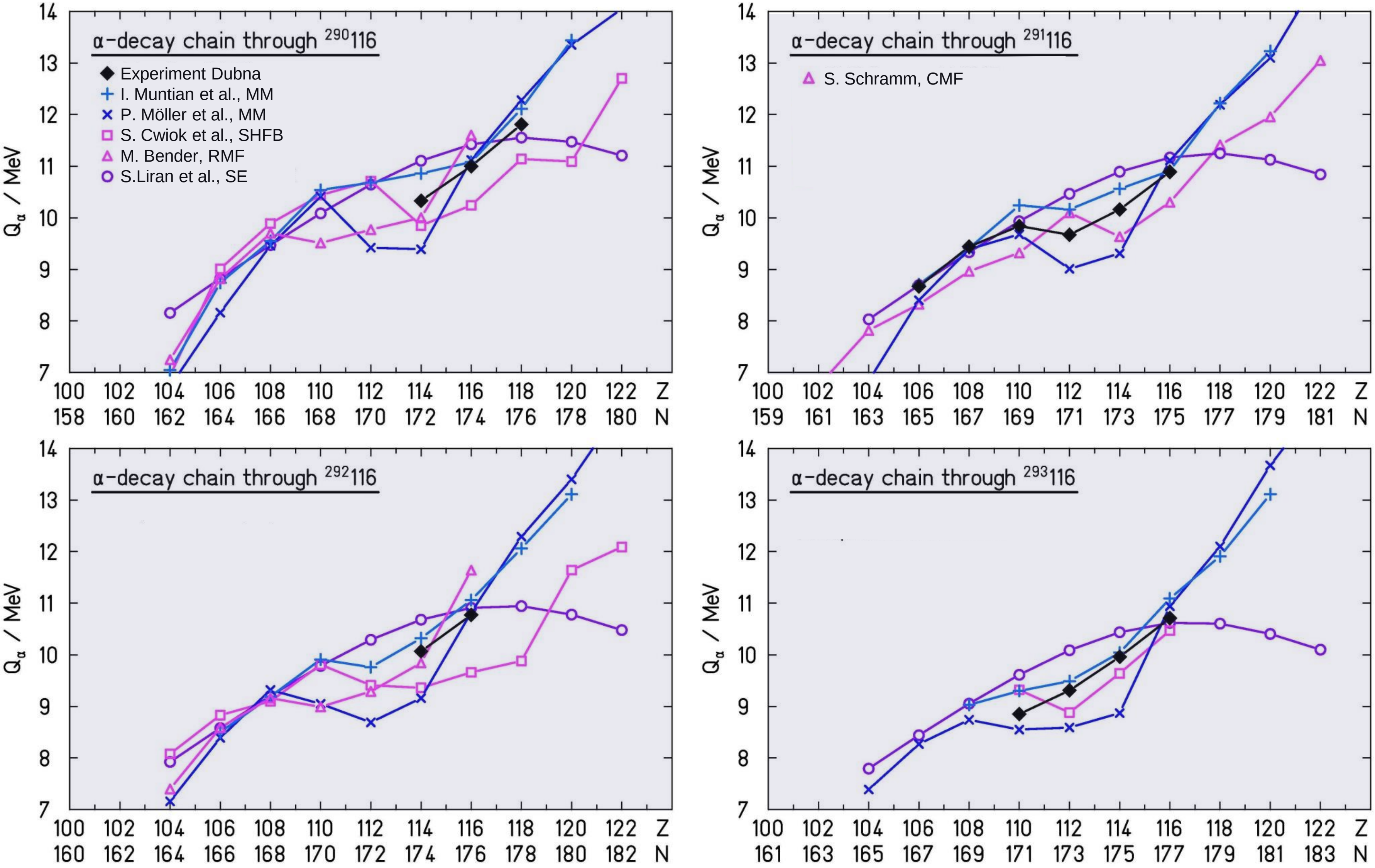
P. Möller et al, 1997

Hypothesis: structured island of SHN?

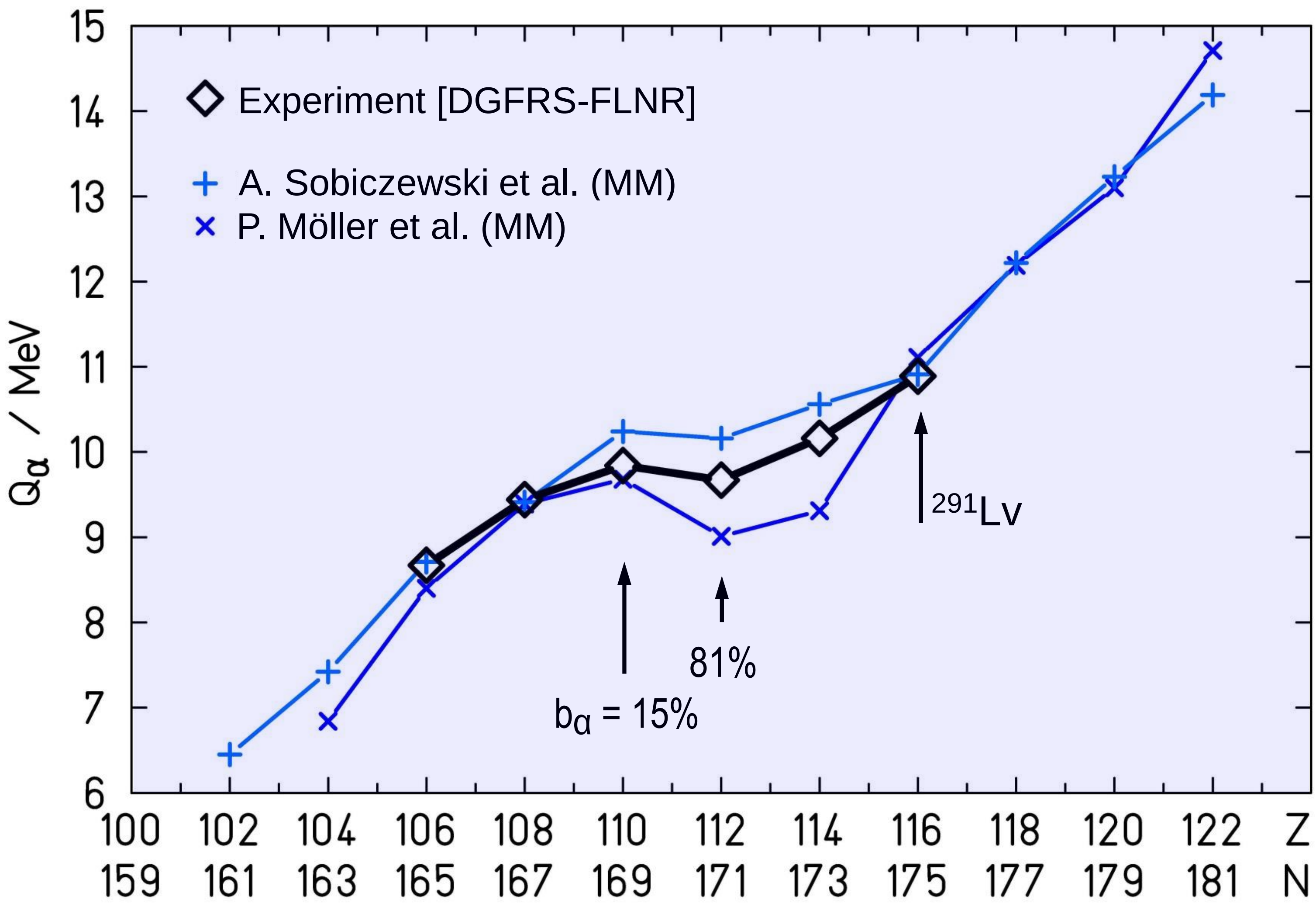




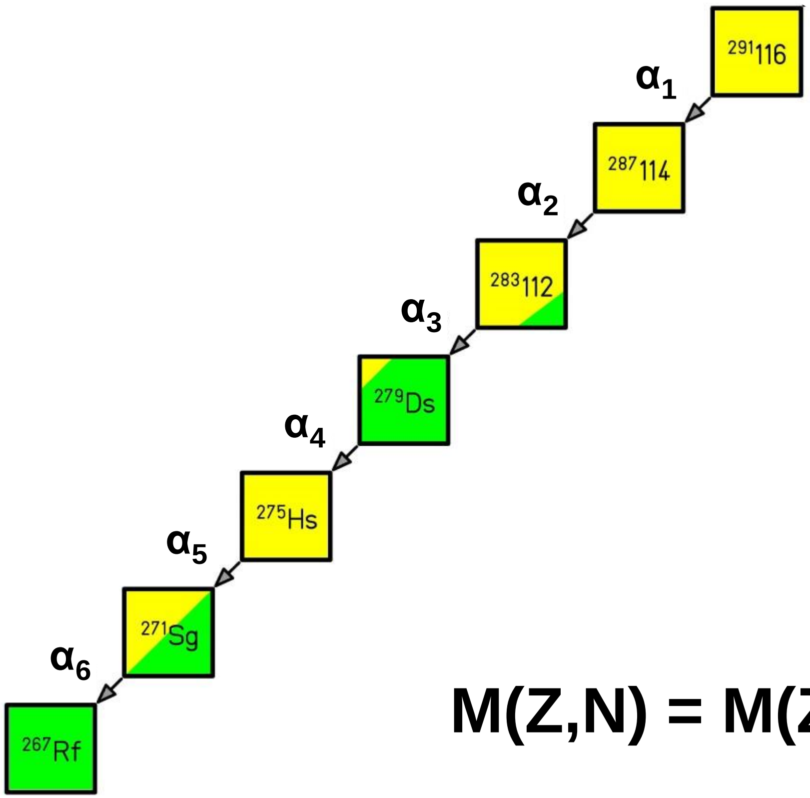
Q_α values: experiment and theory



Alpha-decay chain passing ^{291}Lv



Masses and shell-correction energies

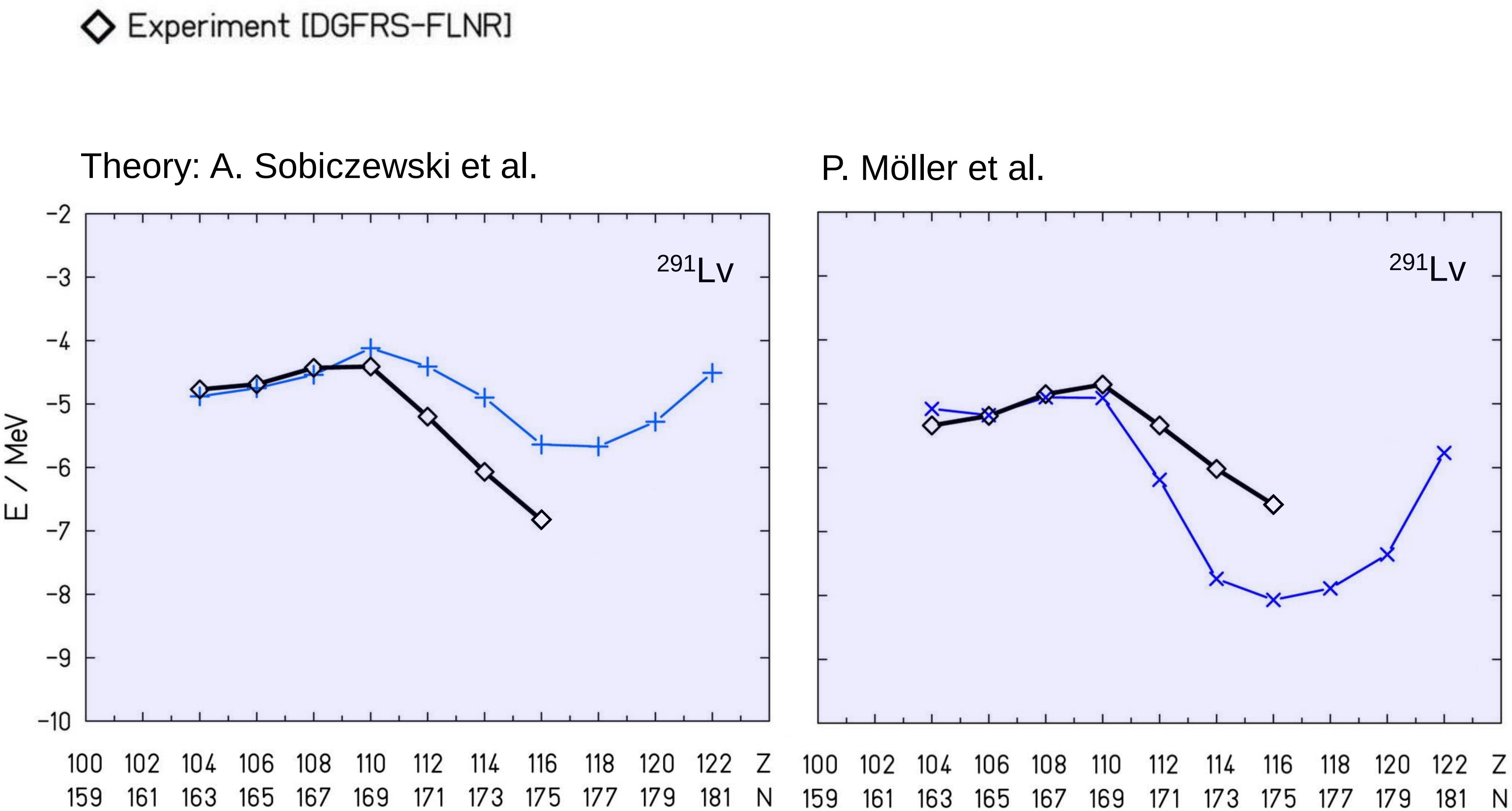


$$M(Z,N) = M(Z\text{-}2,N\text{-}2) + M(2,2) + Q\alpha\ (Z,N)/c^2$$

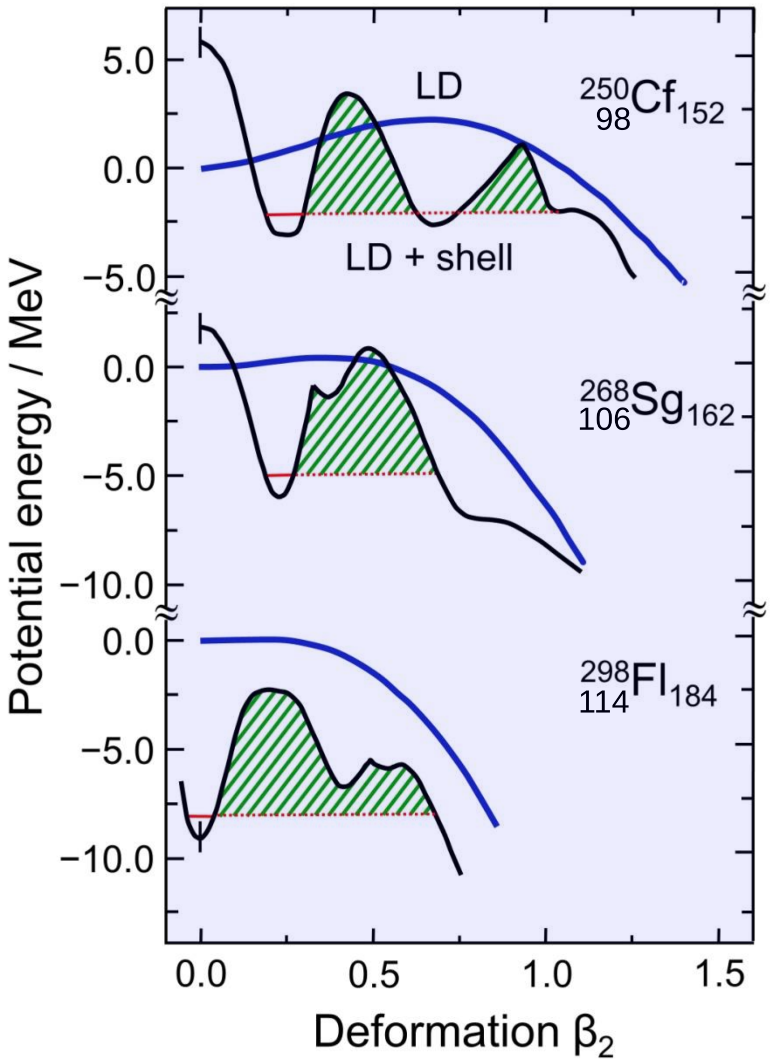
$$E_{mic}/c^2 = M(Z,N) - M_{LD,theory}$$

Unknown mass of end point adjusted to theoretical value

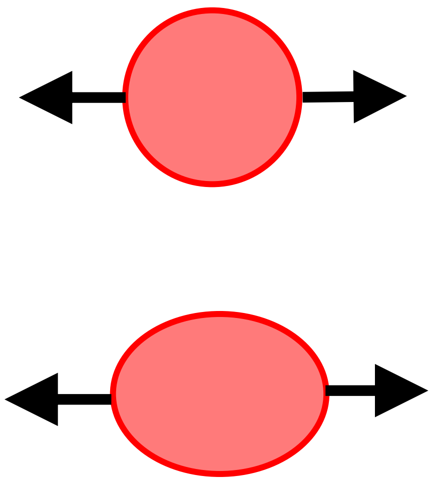
Model-dependent experimental shell-correction energies



Shell-correction energy and fission barrier

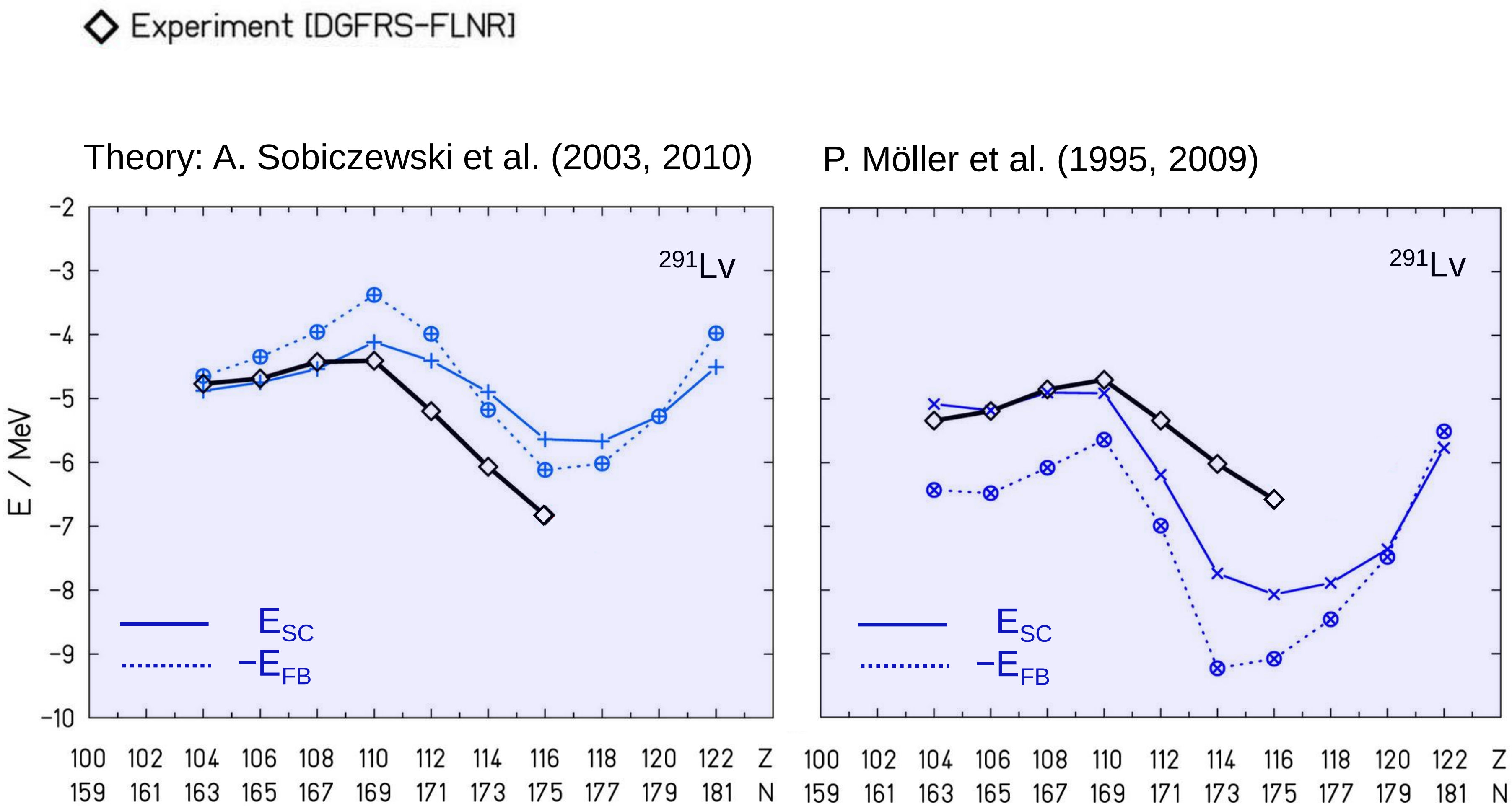


$$T_{1/2} \sim \exp\int B[V(r)-V_0]^{1/2}dr$$

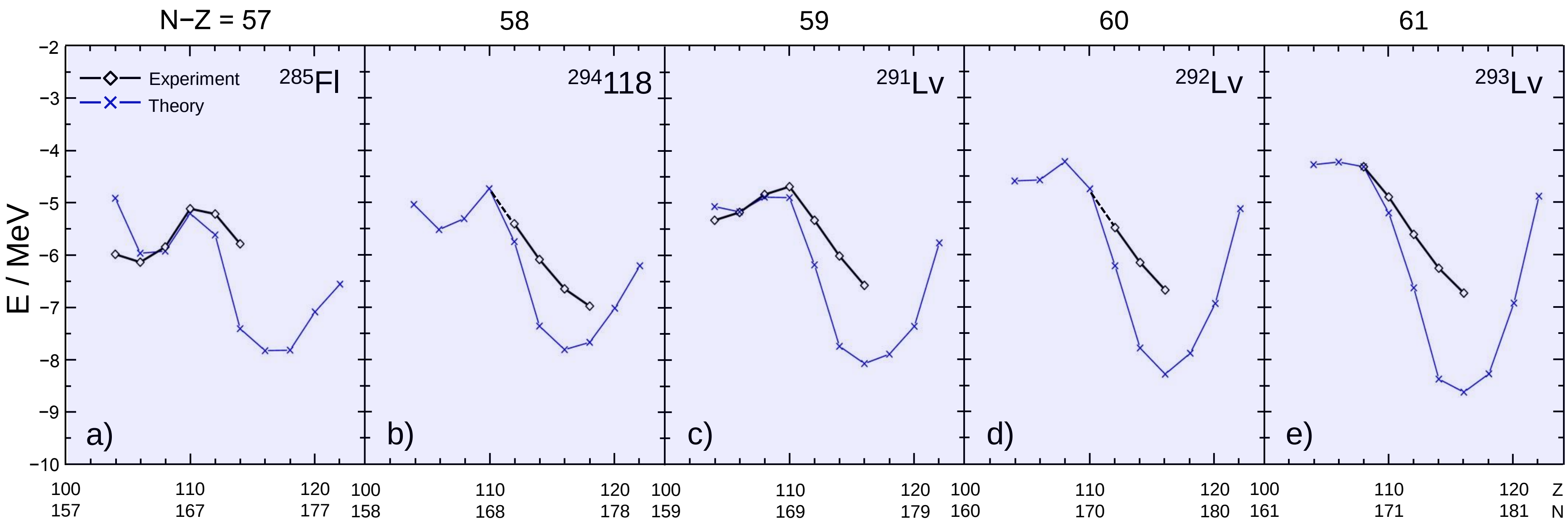


A. Sobiczewski et al.

Shell-correction energies and fission barriers

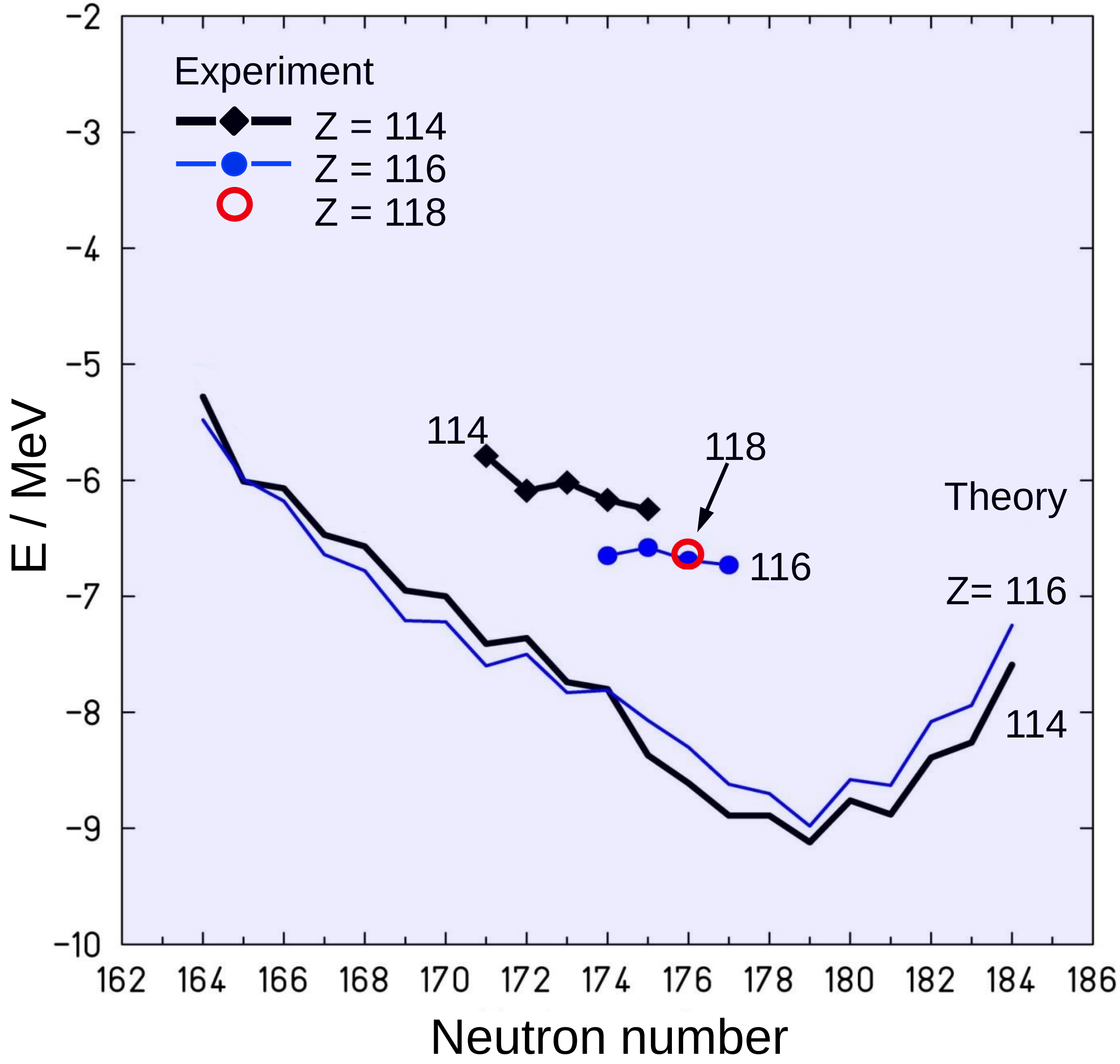


Shell-correction energies, experiment and theory



Q_α from experiment: Yu.Ts. Oganessian et al. (1999-2015)
Theory, FRDM: P. Möller et al., (1995)

Shell-correction energies, experiment and theory



Q_α from experiment:
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Theory, FRDM:
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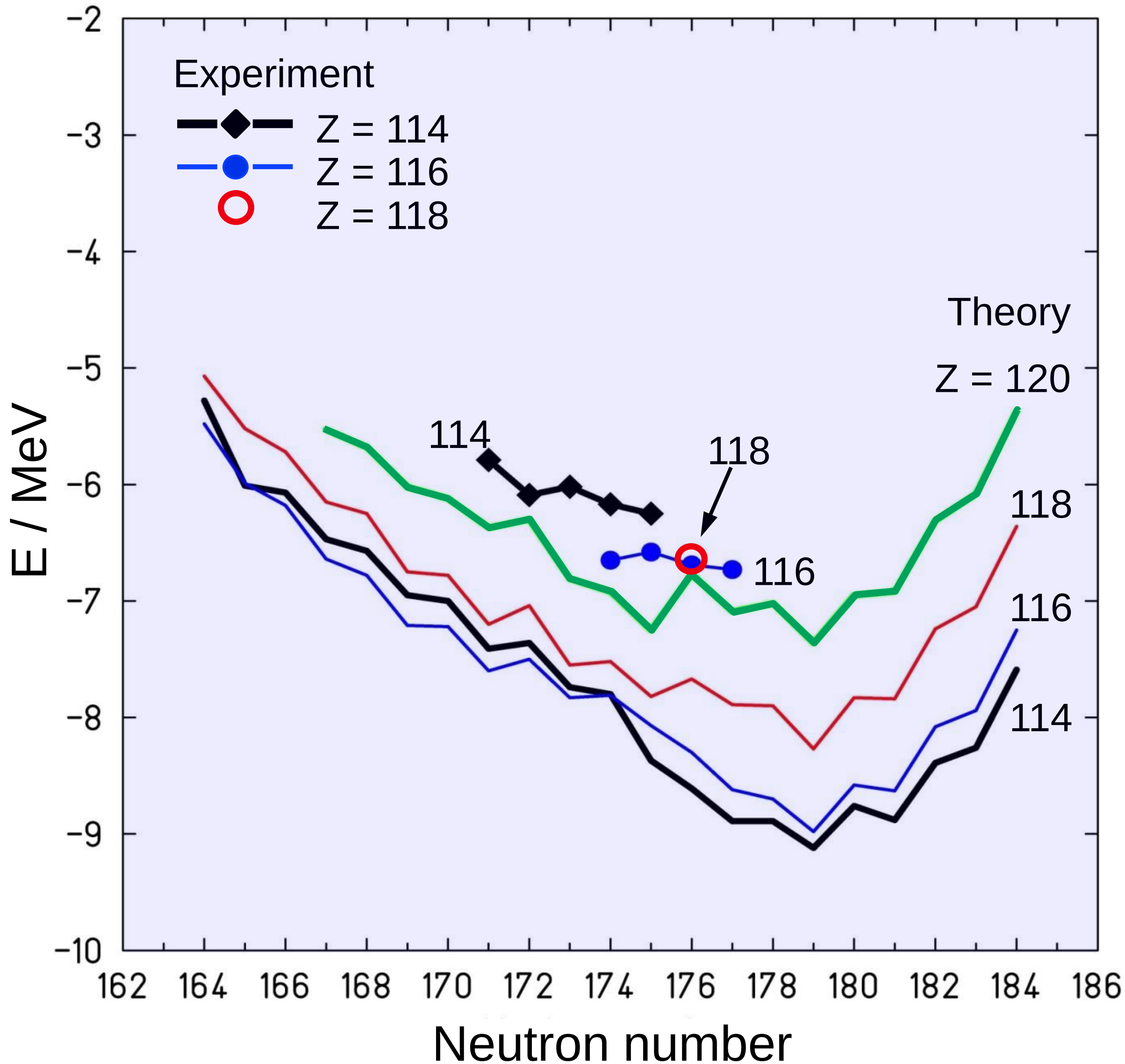
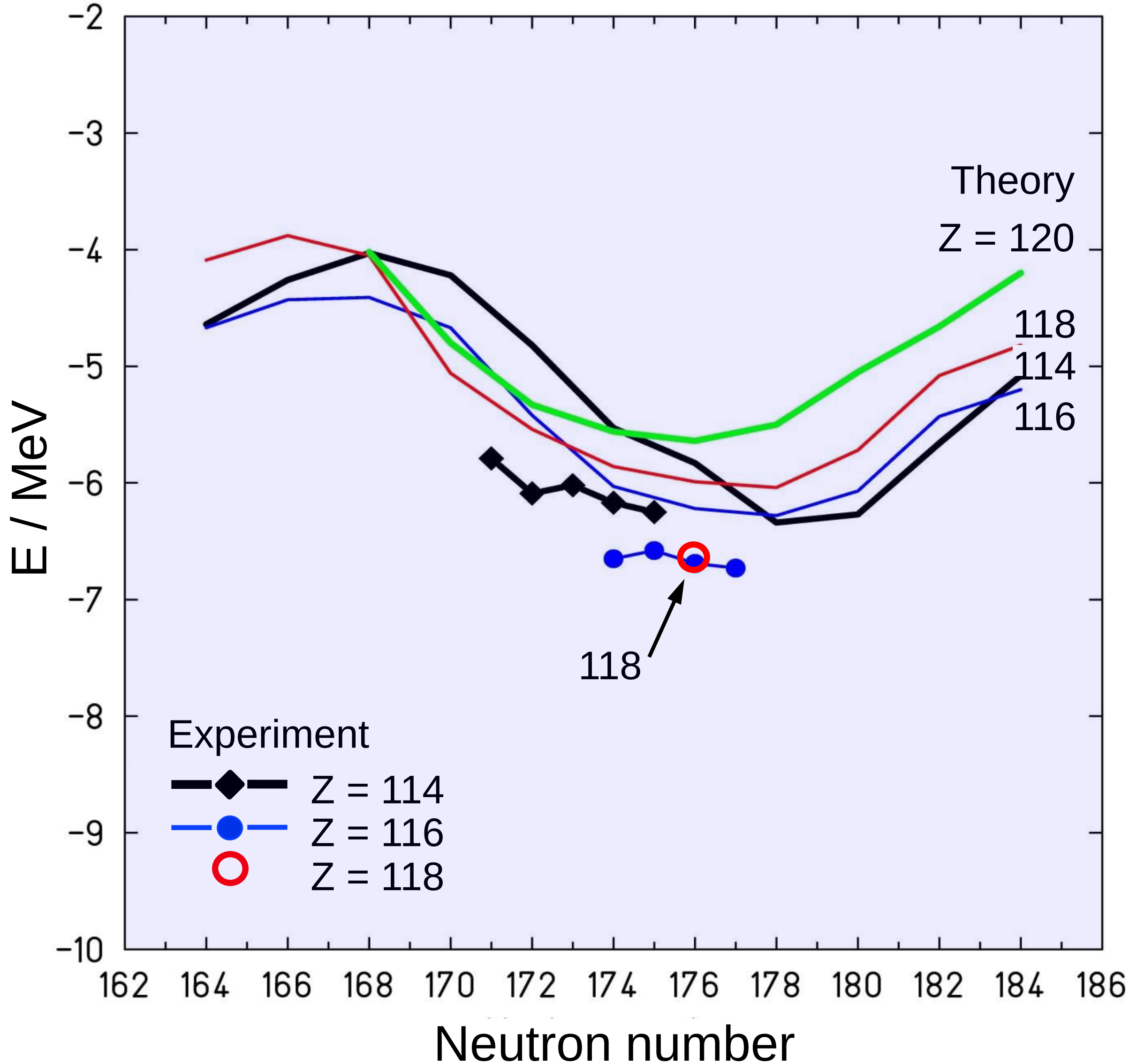
Shell-correction energies, experiment and theory



Q_α from experiment:
Yu.Ts. Oganessian et al.
(1999-2015)

Theory, FRDM:
P. Möller et al., (1995)

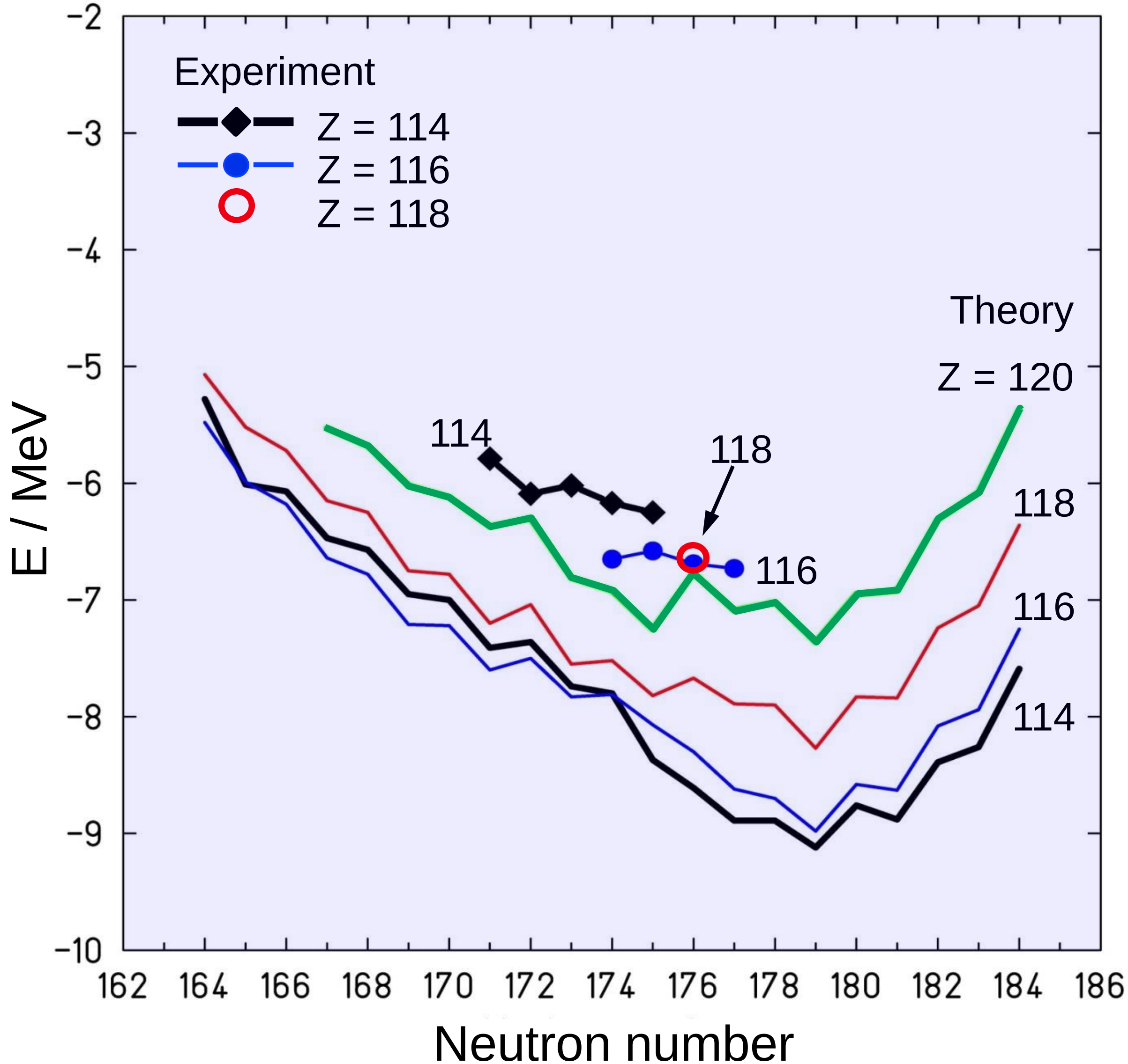
E_{SC} experiment and $-E_{FB}$ theory



Q_{α} from experiment:
Yu.Ts. Oganessian et al.
(1999-2015)

Theory, −fiss. barriers:
M. Kowal,
A. Sobiczewski et al.,
(2010)

Neutron-binding energy



Isotope	$B_{1n,exp}$ / MeV	$B_{1n,theory}$ / MeV
^{286}Fl	−7.81	−7.47
^{287}Fl	−5.62	−6.07
^{288}Fl	−7.44	−7.35
^{289}Fl	−5.54	−6.03
mean	−6.60	−6.73
^{291}Lv	−5.74	−6.08
^{292}Lv	−7.52	−7.64
^{293}Lv	−5.64	−5.92
mean	−6.30	−6.55

Q_α from experiment:
Yu.Ts. Oganessian et al.
(1999-2015)

Theory, FRDM:
P. Möller et al., (1995)

Calculations reproduce well σ (114, 116) with FB (FRDM)

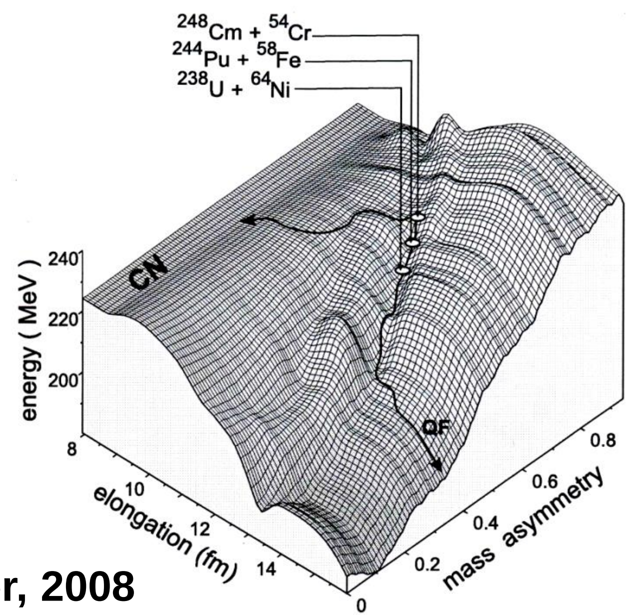
$$\sigma_{\mathrm{ER}}^{xn}(E) = \frac{\pi}{k^2} \sum_{l=0}^{\infty} (2l+1) P_{\mathrm{cont}}(E, l) P_{\mathrm{CN}}(E^*, l) \, P_{xn}(E^*, l)$$

capture formation survival

Competing: quasi-elastic quasi-fission fission

Conclusion:

Lower CN fission barriers demand less quasi-fission and/or less damping (E*) at flerovium and livermorium

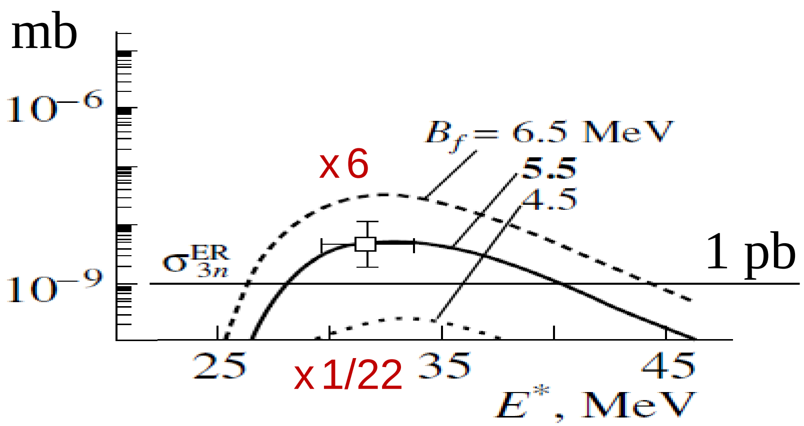


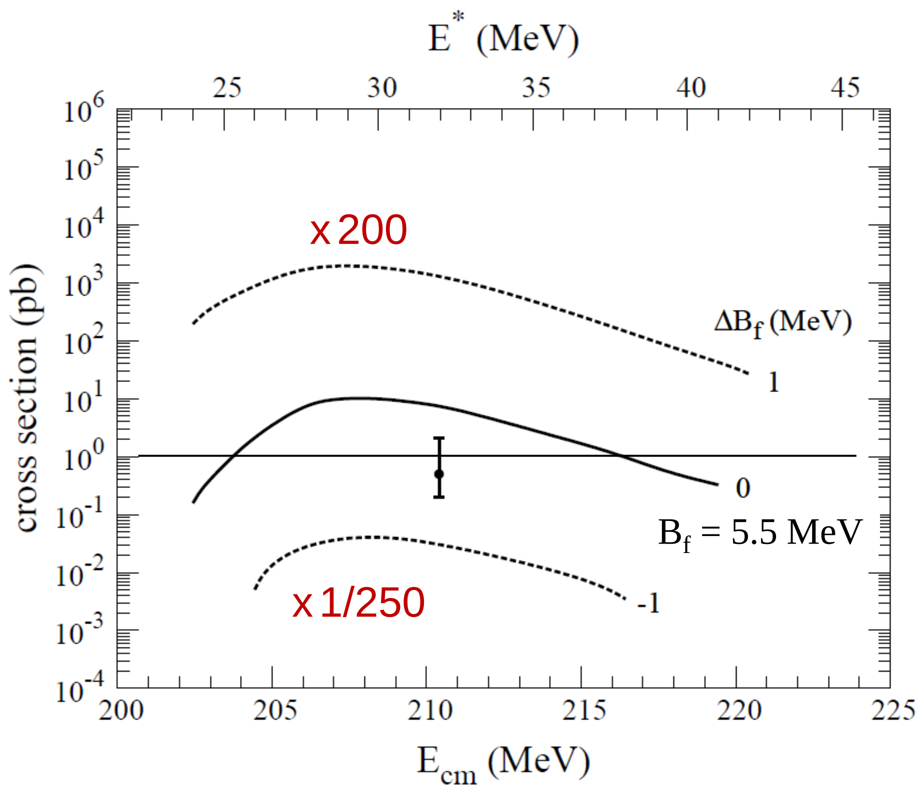
V. Zagrebaev and W. Greiner, 2008

ER cross-section as function of fission barrier

$^{48}Ca + ^{238}U \Rightarrow ^{283}Cn + 3n$

$^{48}Ca + ^{249}Cf \Rightarrow ^{294}118 + 3n$





V.I. Zagrebeav et al.,
Phys. At. Nucl. 66,1033 (2003)

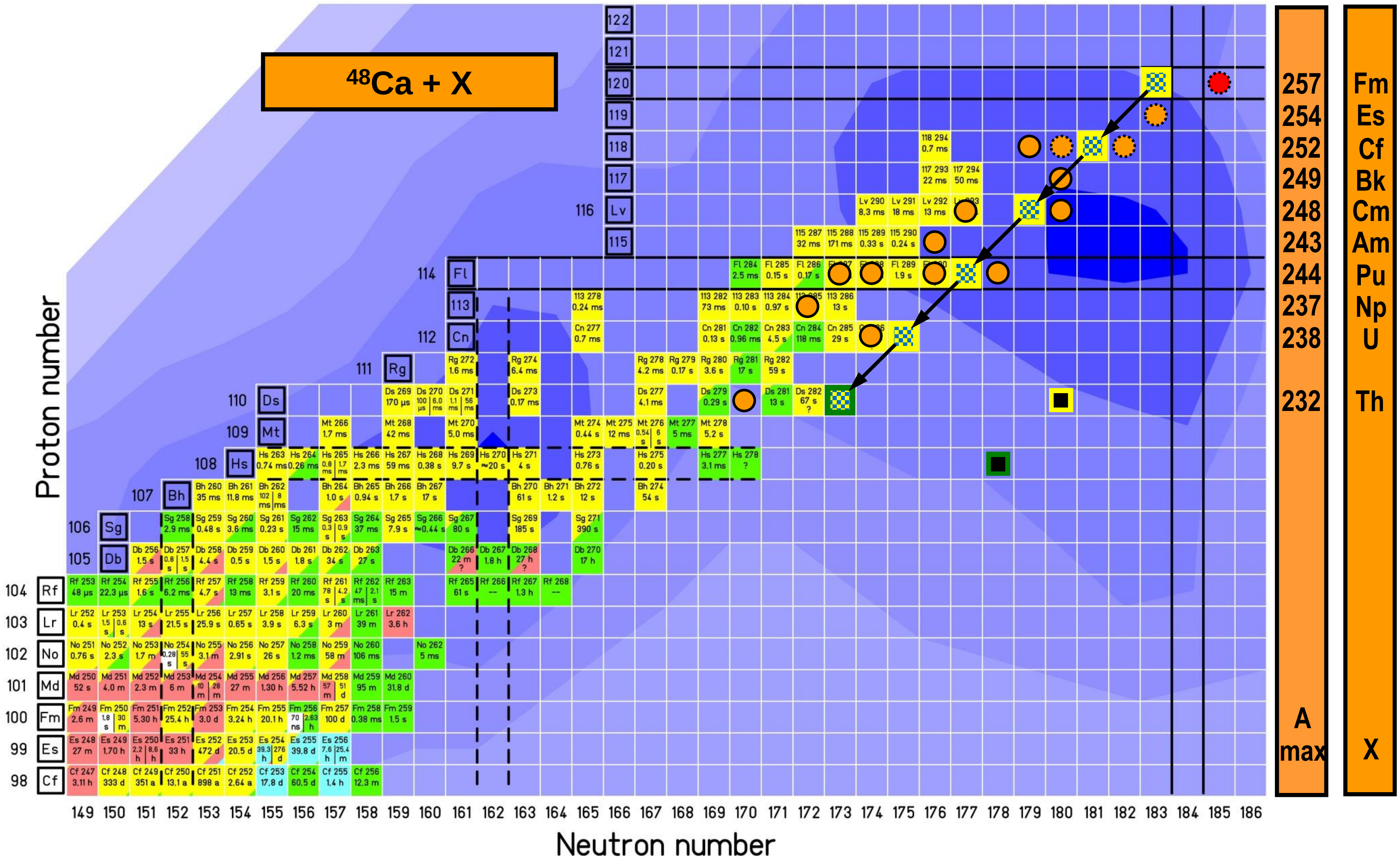
V.K. Siwek-Wilczńyska et al.,
Int. J. Mod. Phys. E 19, 500 (2010)

Requirements for confirmation

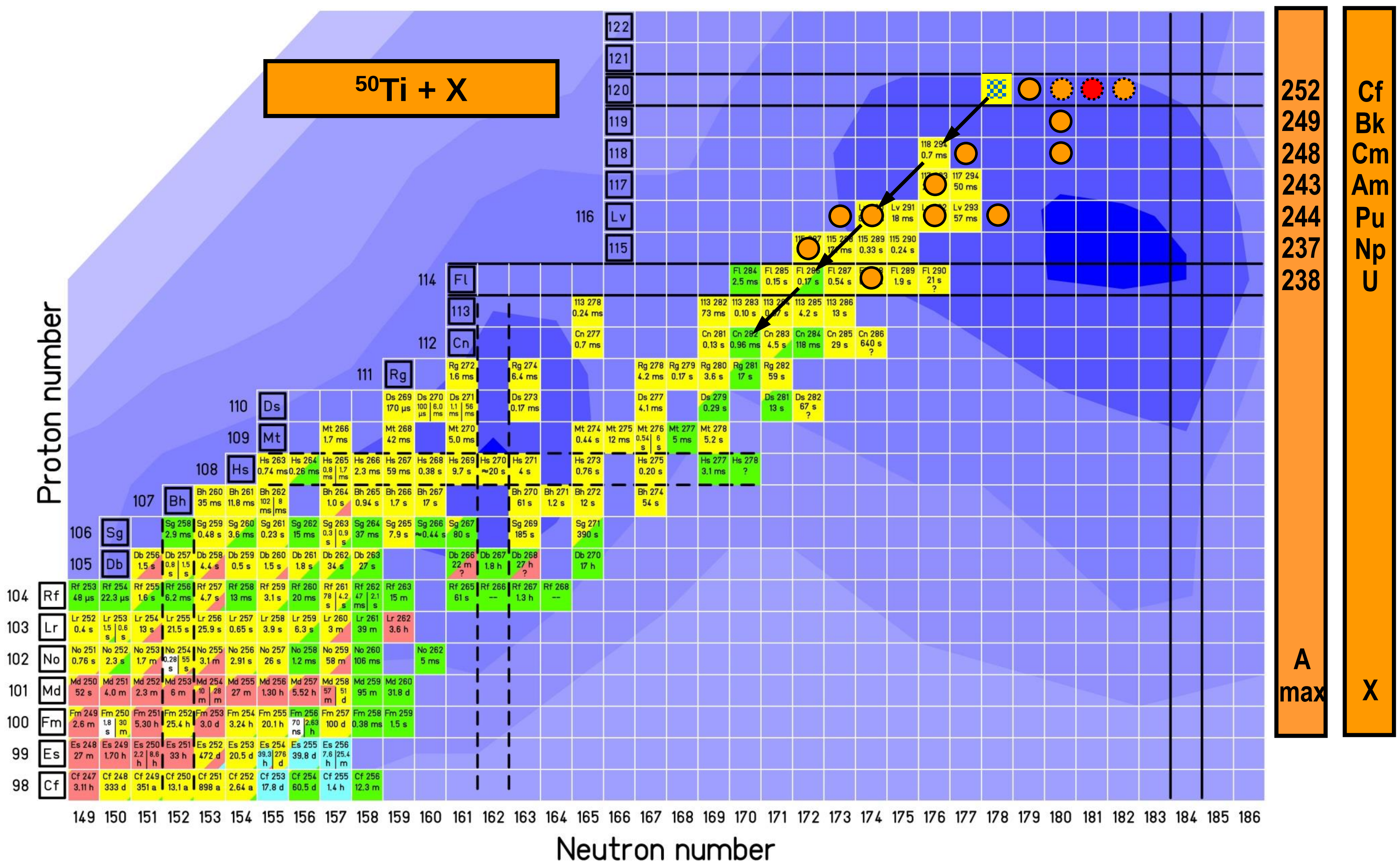
1. Decay data of more isotopes of 118 and of the new element 120

2. Masses of nuclei at the end of the chains

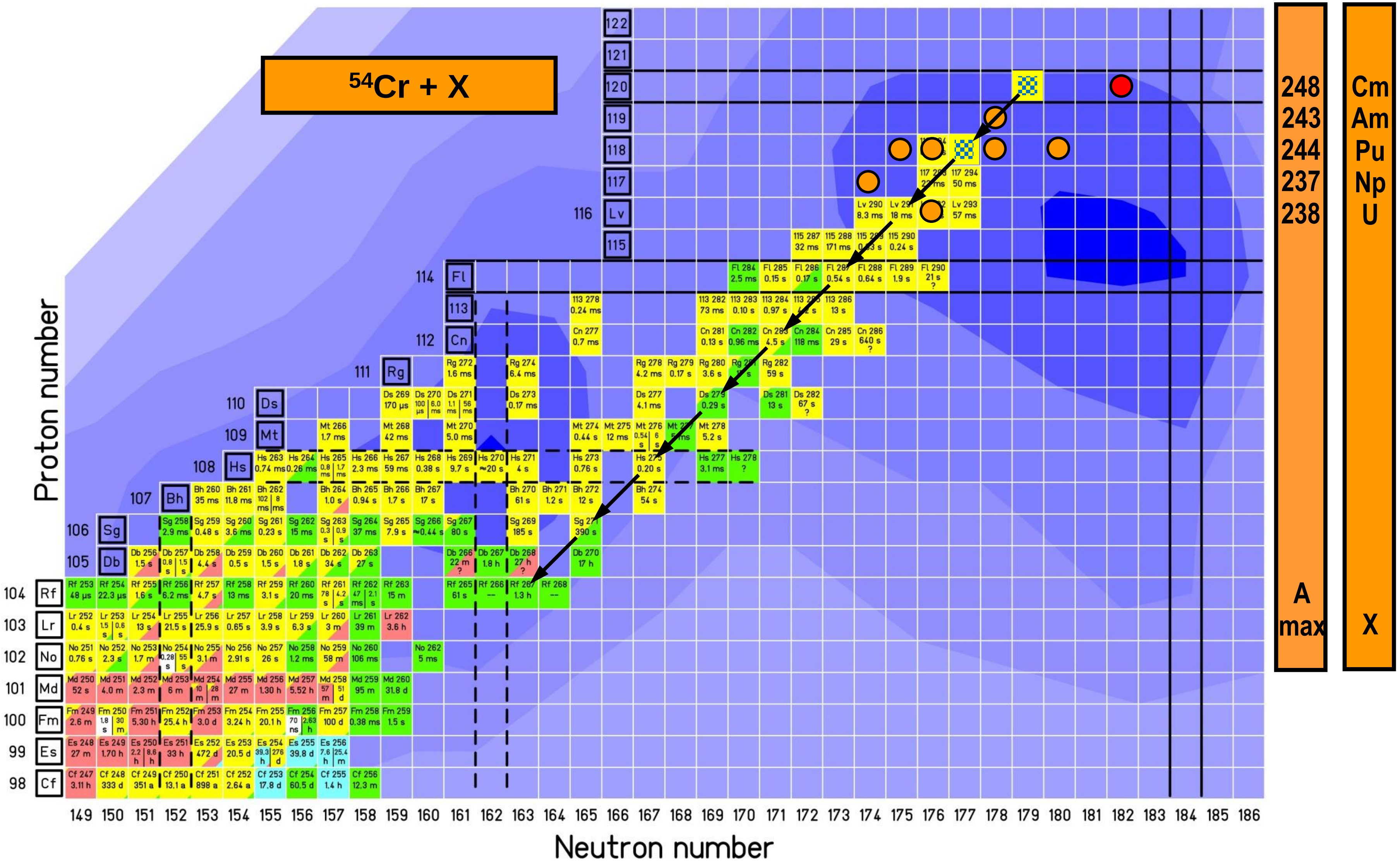
$^{48}Ca + ^{257}Fm \Rightarrow ^{305}120^{*}$ (E^{*} = 26 MeV)



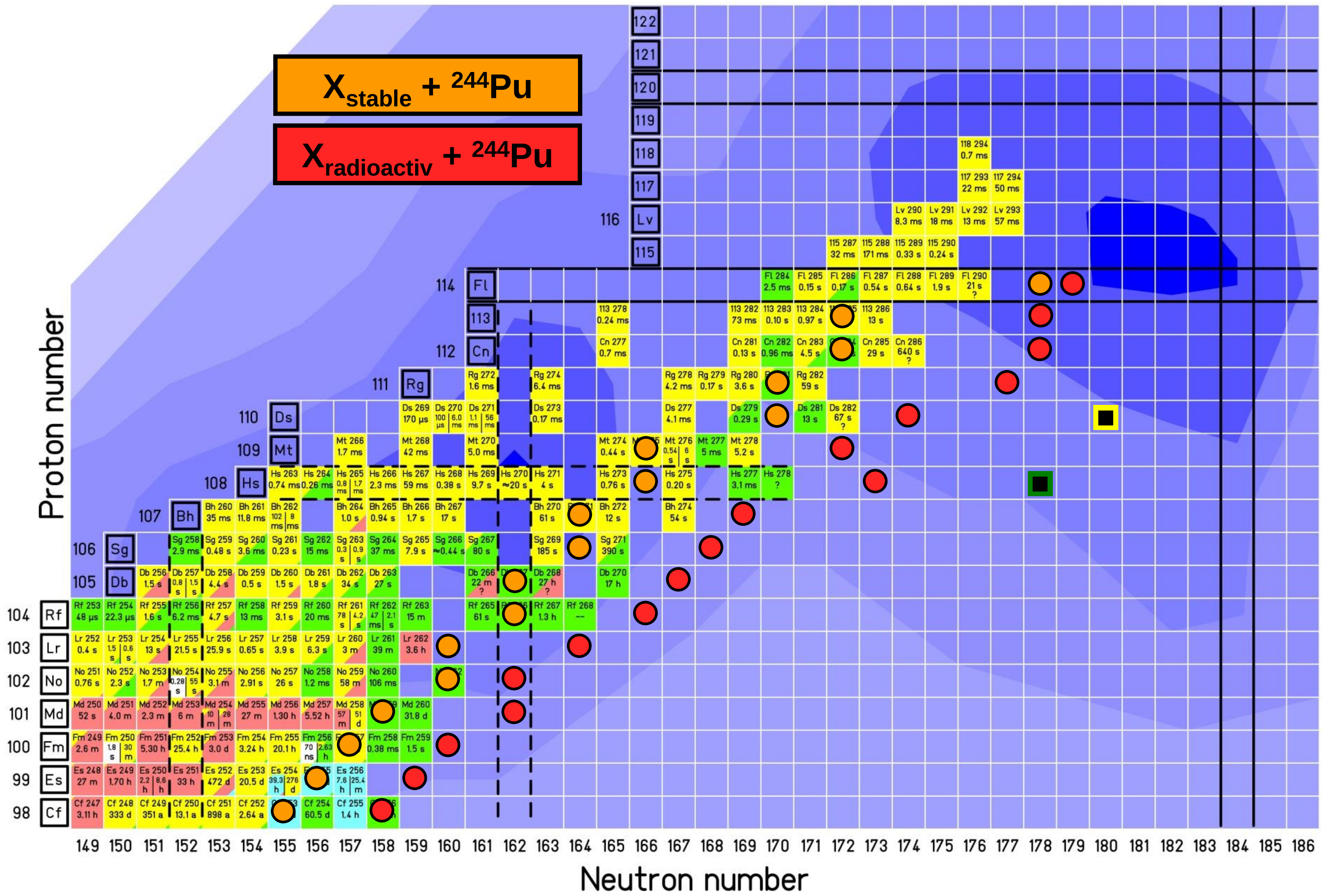
$^{50}Ti + ^{251}Cf \Rightarrow ^{301}120^*$ (E* = 30 MeV)



$^{54}Cr + ^{248}Cm => ^{302}120^*$ (E* = 31 MeV)



Most neutron-rich isotopes with radioactive beams



10^9 / s (RIA)

A max	A max	X
48	49	Ca
41	47	K
40	46	Ar
37	44	Cl
36	40	S
31	37	P
30	37	Si
27	32	Al
26	30	Mg
23	28	Na
22	26	Ne
19	23	F
18	20	O
15	19	N
13	16	C
11	14	B
9	12	Be

SHIP Z = 120 Collaboration (2015)

S. Hofmann, S. Heinz, R. Mann, J. Maurer, G. Münzenberg, W. Barth, H.G. Burkhard, L. Dahl, B. Kindler, I. Kojouharov, R. Lang, B. Lommel, J. Runke, C. Scheidenberger, K. Tinschert
GSI, Darmstadt, Germany

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LLNL, Livermore, USA

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ORNL, Oak Ridge [a]and Univ. of Tennessee [b]and Univ. of Warsaw

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University Mainz, Germany

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Joint Institute for Nuclear Research, Dubna, Russia

J.H. Hamilton
Vanderbilt University, Nashville, USA

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University Bratislava, Slovakia

J. Uusitalo
University Jyväskylä, Finland

K. Morita
RIKEN, Saitama, Japan

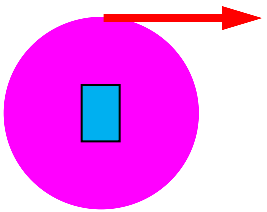
K. Nishio
JAEA, Tokai, Japan

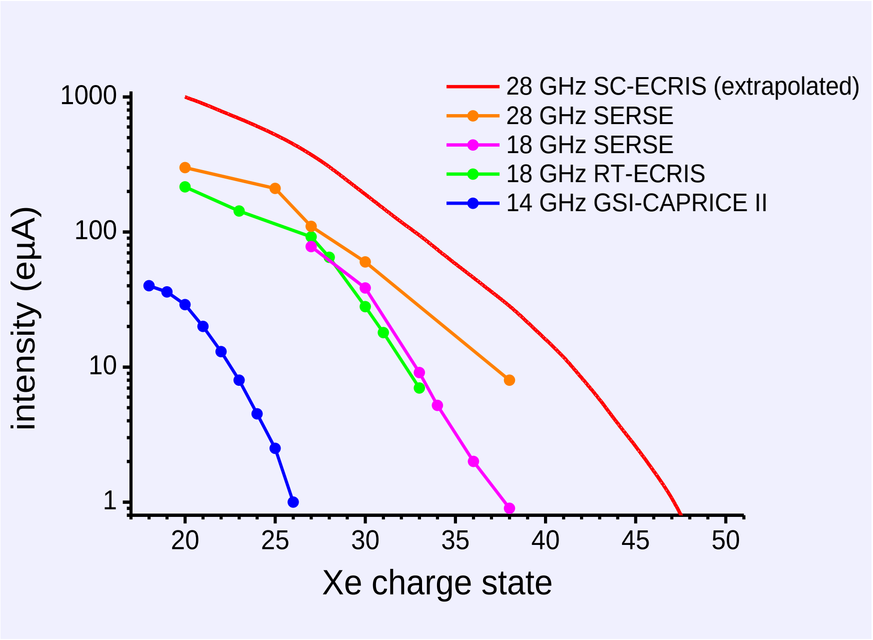
Ion source and accelerator

Ion-source
Penning and/or
ECR

CW-Linac
normal or
superconducting

Cyclotron





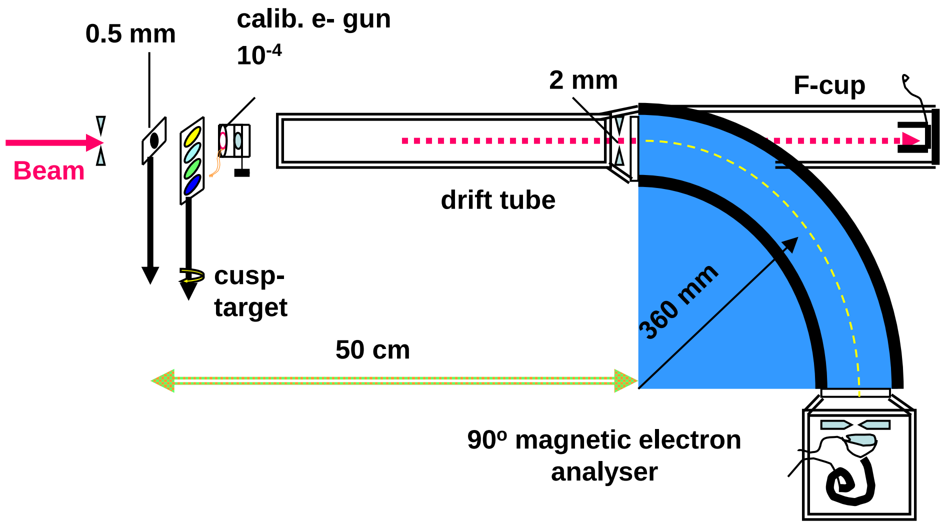
NEW: HIGH BEAM CURRENTS

5 – 10 *p*μA

Dedicated to low energy heavy ion physics
SHN and SHE experiments

Minimum and maximum energy
Space-charge limit, high/low charge state
Maximum A/q

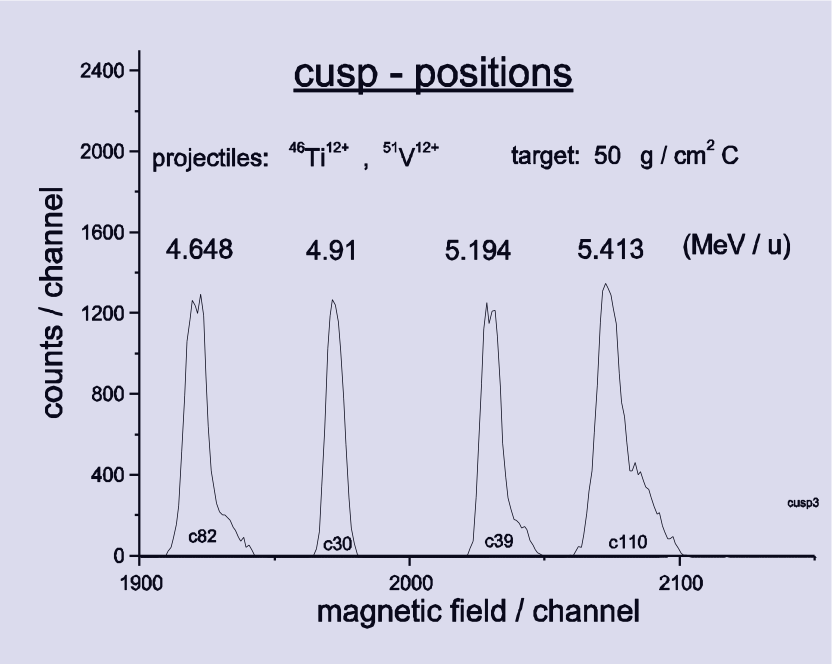
Projectile energy control using cusp-electrons



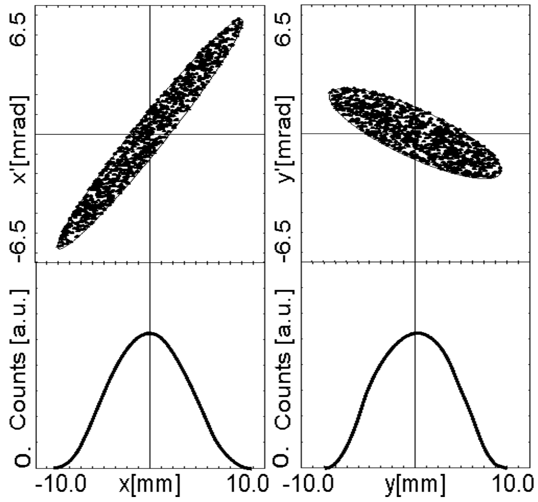
Measuring time: ~ 1 minute

Beam current: ≥ 0.1 *p*μA

Precision: ≤ 10^{-3}



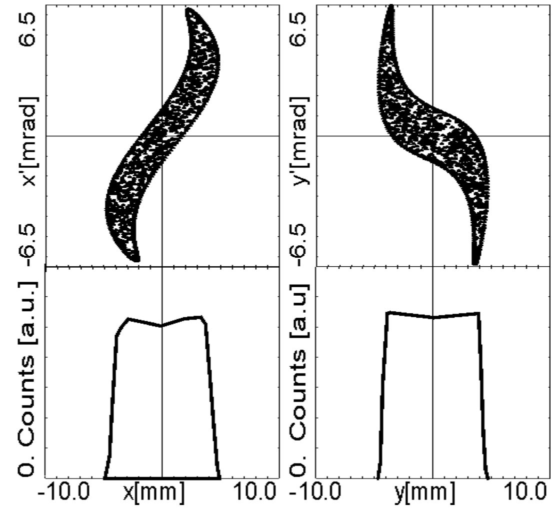
Transverse beam shaping with octupole lenses



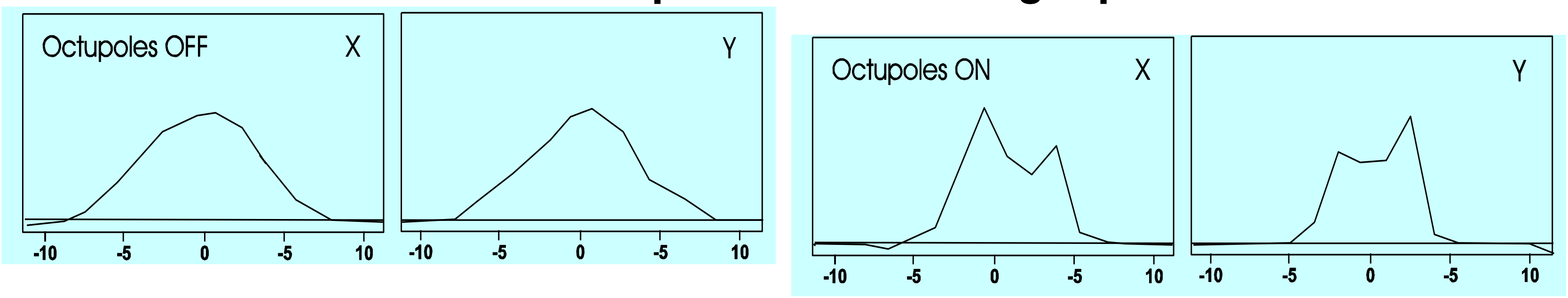
$B_x = G(y^3 - 3x^2y)$

$B_y = G(3y^2x - x^3)$

G: pole tip field



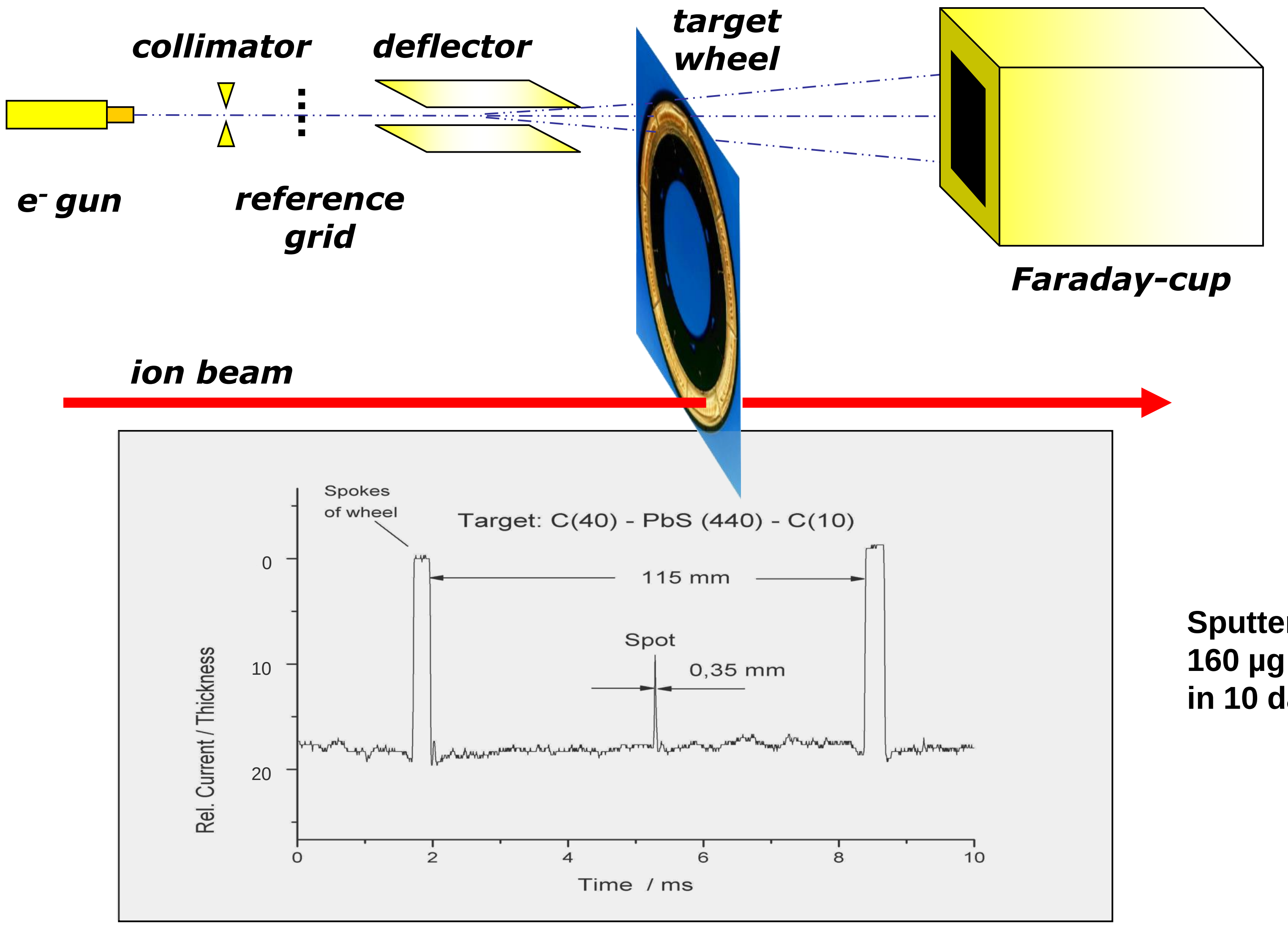
Measured beam profiles at the target position



Reduction of tails as source of background

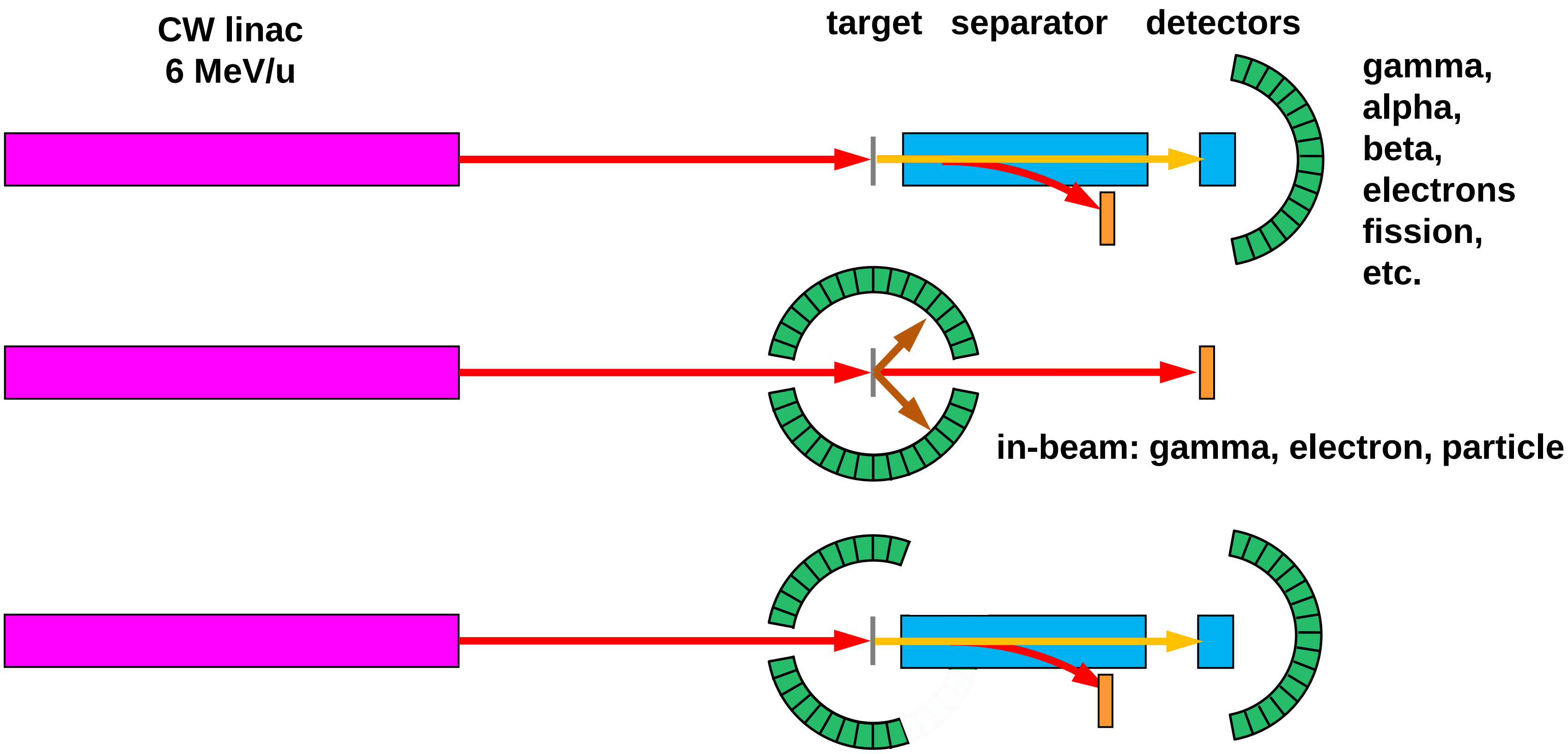
J. Klabunde, GSI Internal Report INJ 01-1001 (2001)

On-line target control



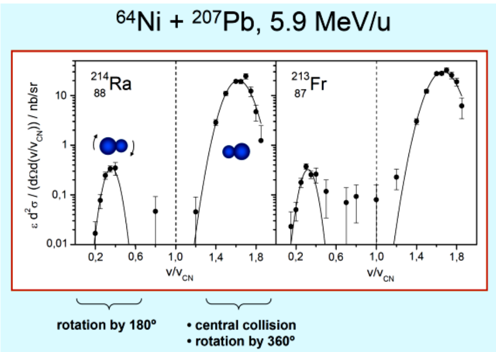
Sputtering from $CmO_{1.75}$:
160 µg
in 10 days at 5 pµA

Typical low-energy heavy-ion experiments

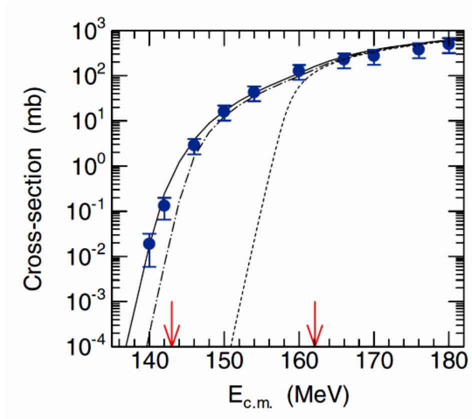


Typical experiments

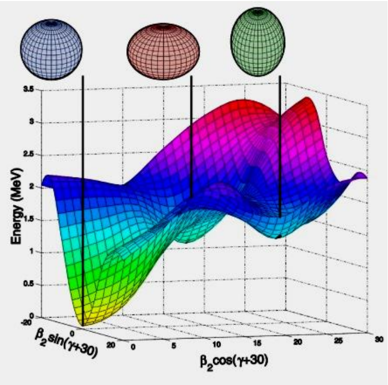
Tranfer-reactions:



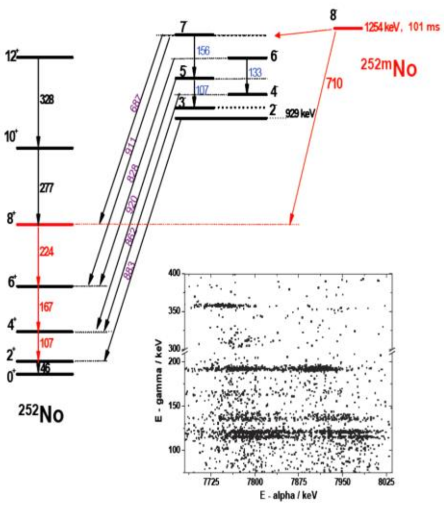
Subbarrier fusion:



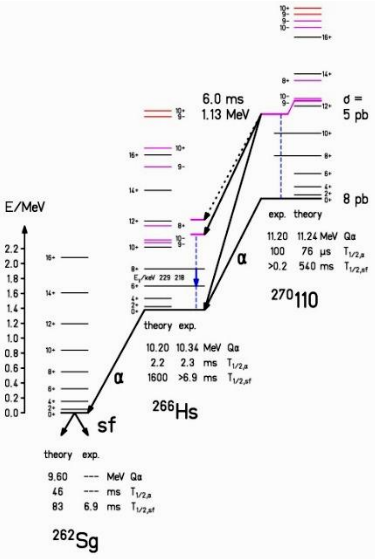
Proton radioactivity, beta-delayed fission, shape co-existence:



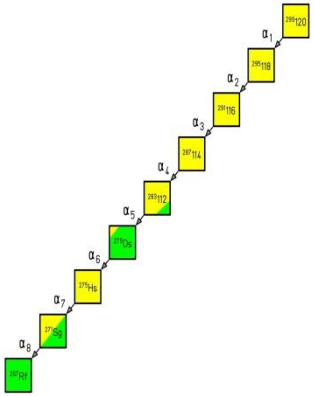
Spectroscopy:



K-isomers:



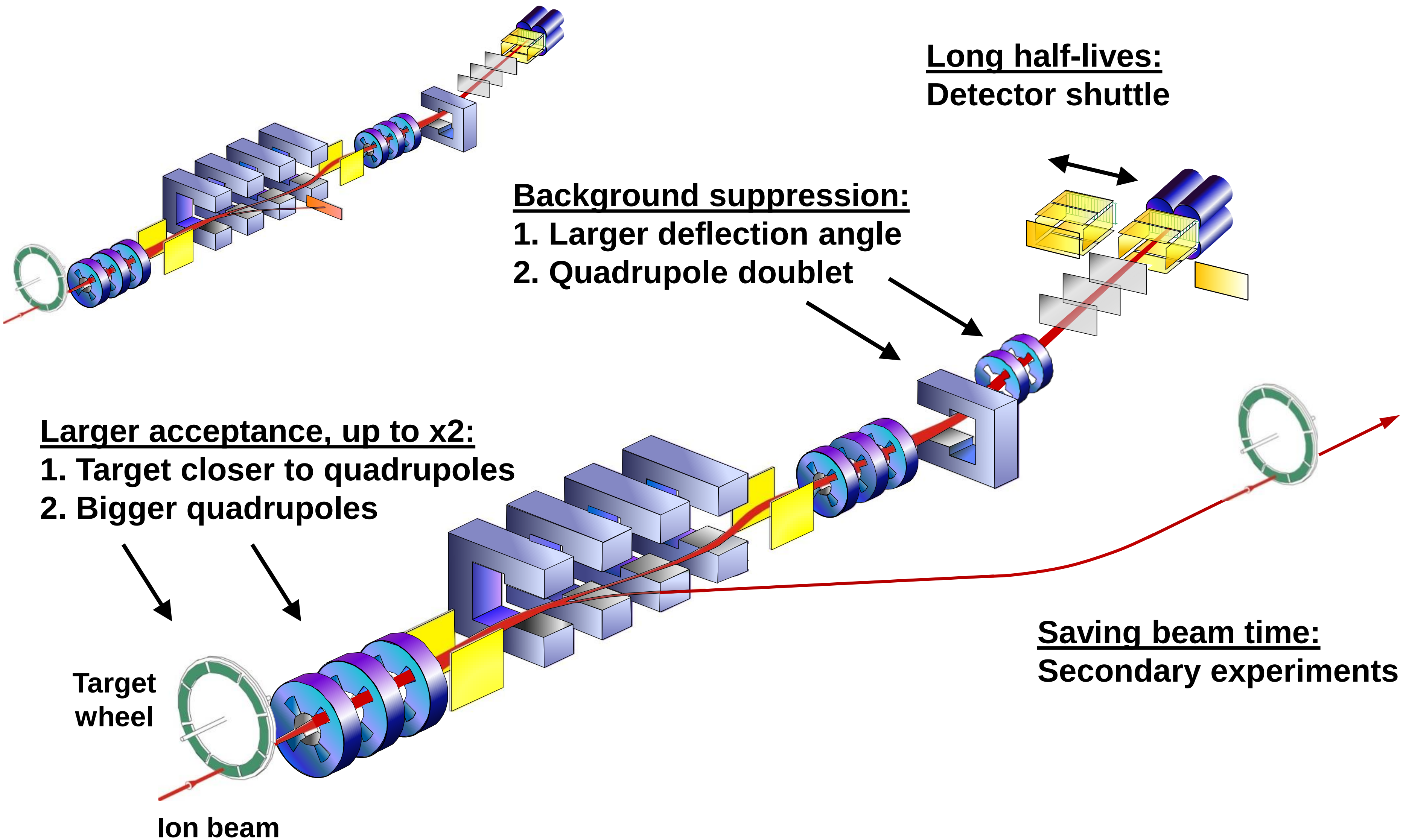
Decay chains:



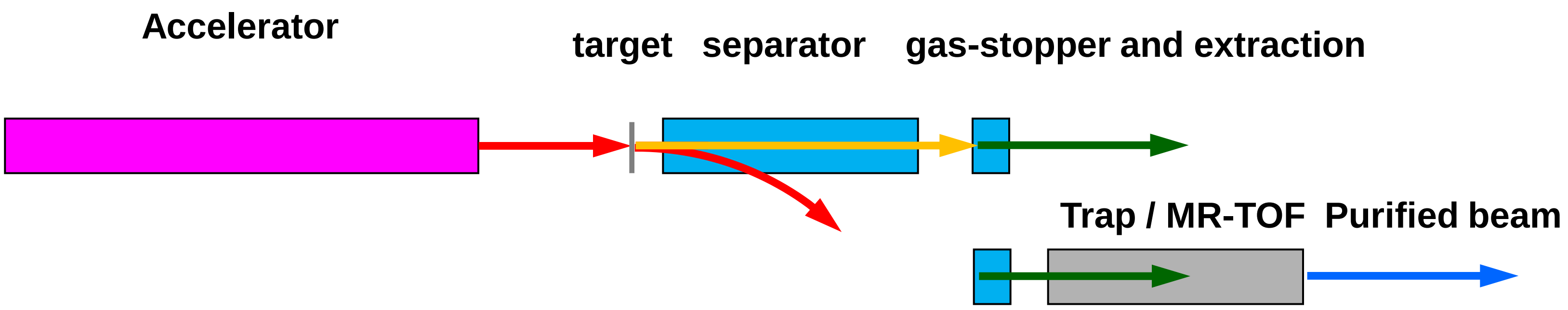
Experiments:

Argonne
Berkeley
Darmstadt
Dubna
GANIL
JAEA
Jyväskylä
RIKEN
and others

Improvement of the separator, example SHIP



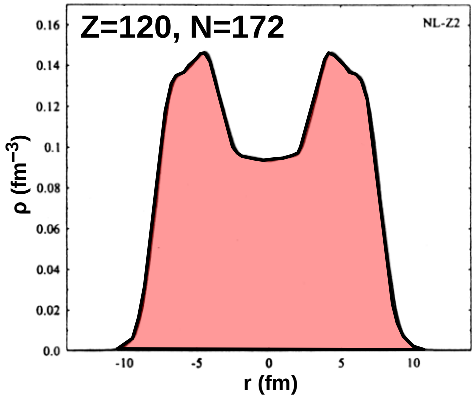
Experiments after stopping in gas



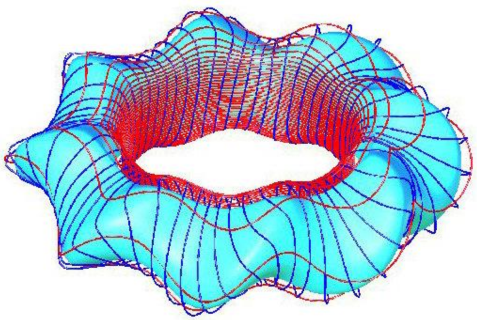
Penning Trap or Multi-Reflection TOF
for precision mass spectroscopy and isobaric purification:
Short and long lifetimes, independent from decay mode

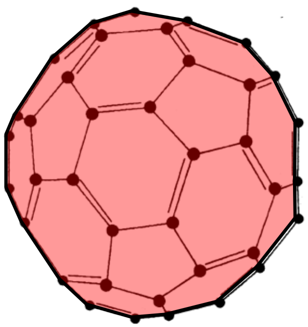
Collinear laser spectroscopy
Alpha-, beta-, gamma-spectroscopy
Conversion electron spectroscopy
Fission-fragment mass measurement
Atomic beams, Stern-Gerlach experiment

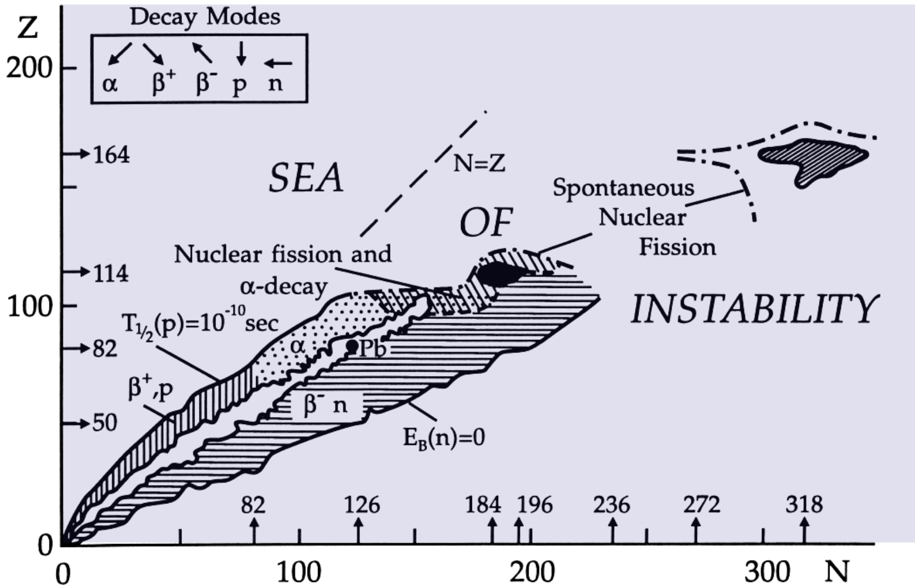
Trying to square the circle



Properties of some collective excitations ...
S. Mişicu, T. Bürvenich, T. Cornelius, W. Greiner
Inst. für Theoretische Physik, Univ. Frankfurt
J. Phys. G: Nucl. Part. Phys. 28, 1441 (2002)



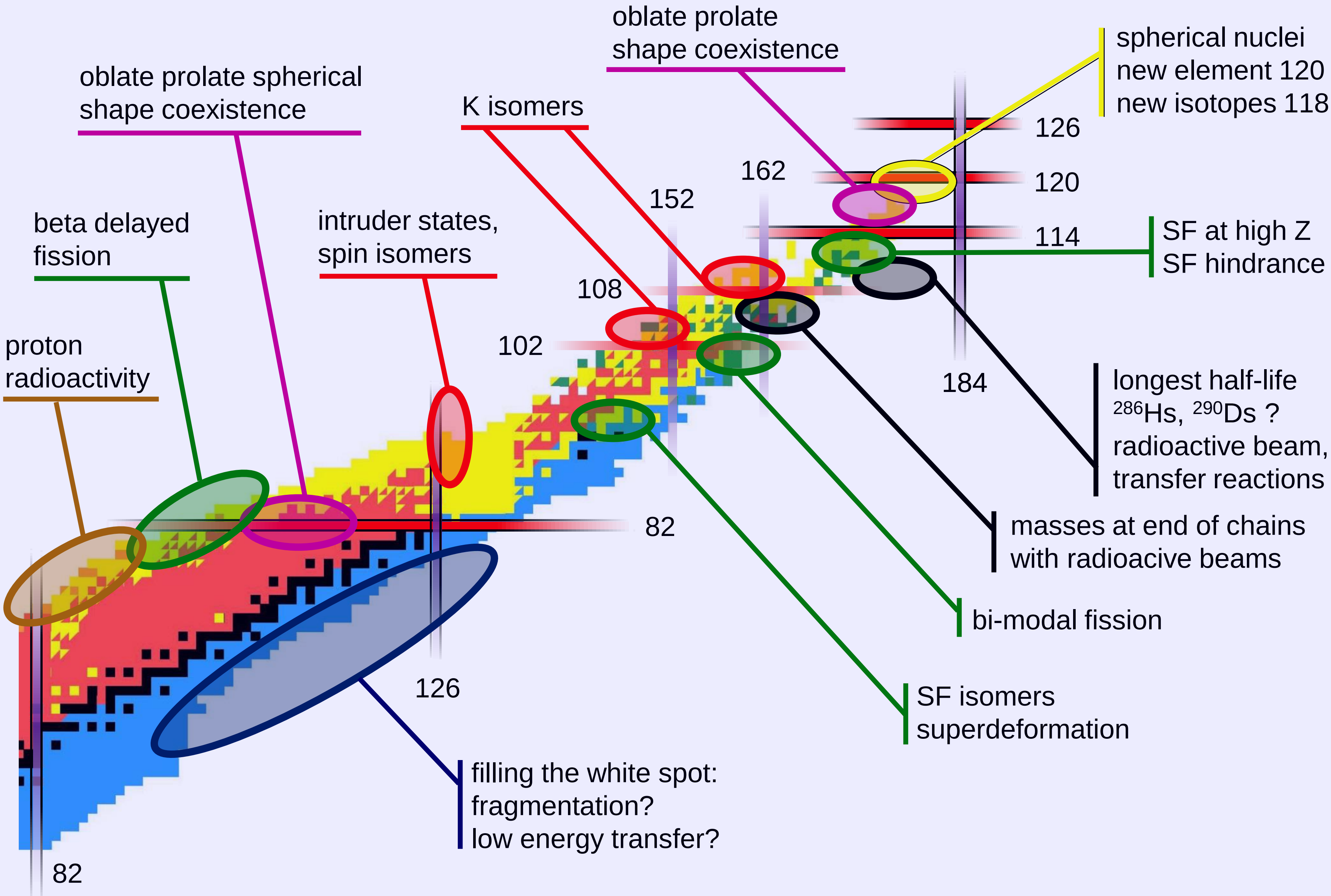




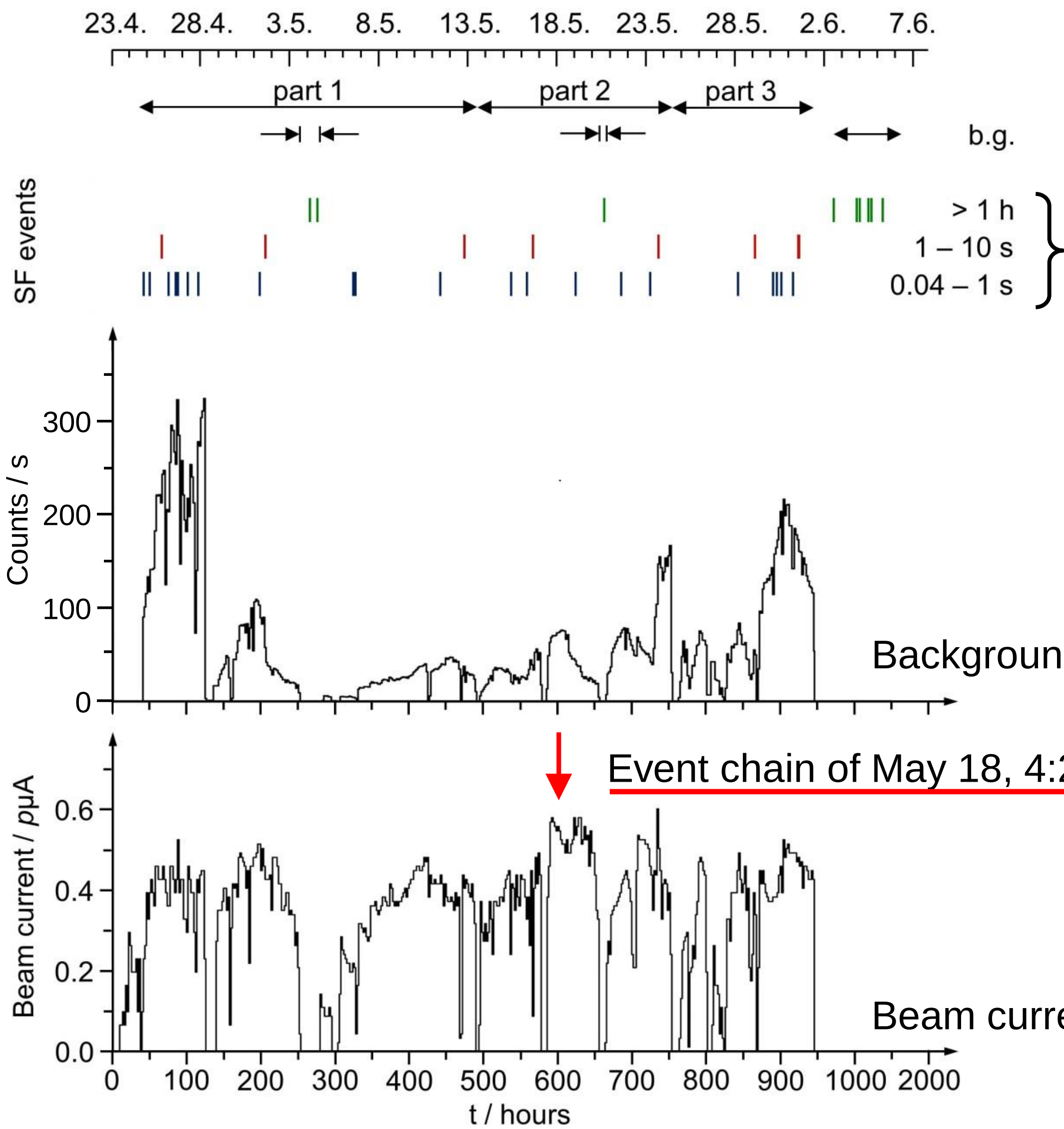
W. Greiner, 1965-70

Toroidal and Spherical Bubble Nuclei
C.Y. Wong
Oak Ridge National Laboratory, Oak Ridge
Wong, C.Y.: Ann. Phys. 77, 279 (1973)

Summary of results and projects for the future



$^{54}Cr + ^{248}Cm => ^{302}120^*$, 38 (34) days in 2011



SF events

Background of target-like nuclei

Event chain of May 18, 4:20 h: three signals within 279 ms, detector strip 16, 24.2 mm from bottom

Beam current

Results from $^{54}Cr + ^{248}Cm$

Properties of events measured during the $^{54}Cr + ^{248}Cm$ experiment at SHIP on May 18, 2011 at 4:20 h.

Assignment	E / MeV	Δ t	Position[a)]	Remarks[b)]
ER ?	26.0	–5.4 s	16–22.6	TOF 1 and 2, no VETO
α 1 ?	13.14 ± 0.03	0 s	16–22.8	no TOF, no VETO
α 2 ?	11.81 ± 0.04[c)]	261 ms	16–25.4	no TOF, no VETO
α 3, ^{291}Lv ?	10.70 ± 0.03	18.4 ms	16–24.4	no TOF, no VETO[d)]
SF ?	223 ± 35[e)]	12.0 min	16–24.7	no TOF, no VETO

a) Given is the strip number of the stop detector and vertical position y in mm;
Resolution (FWHM) in vertical direction: 0.4 mm (ER–α, α – α);
2.9 mm (ER,α – esc-α, E_α <2 MeV);
1.2 mm (ER,α – SF).

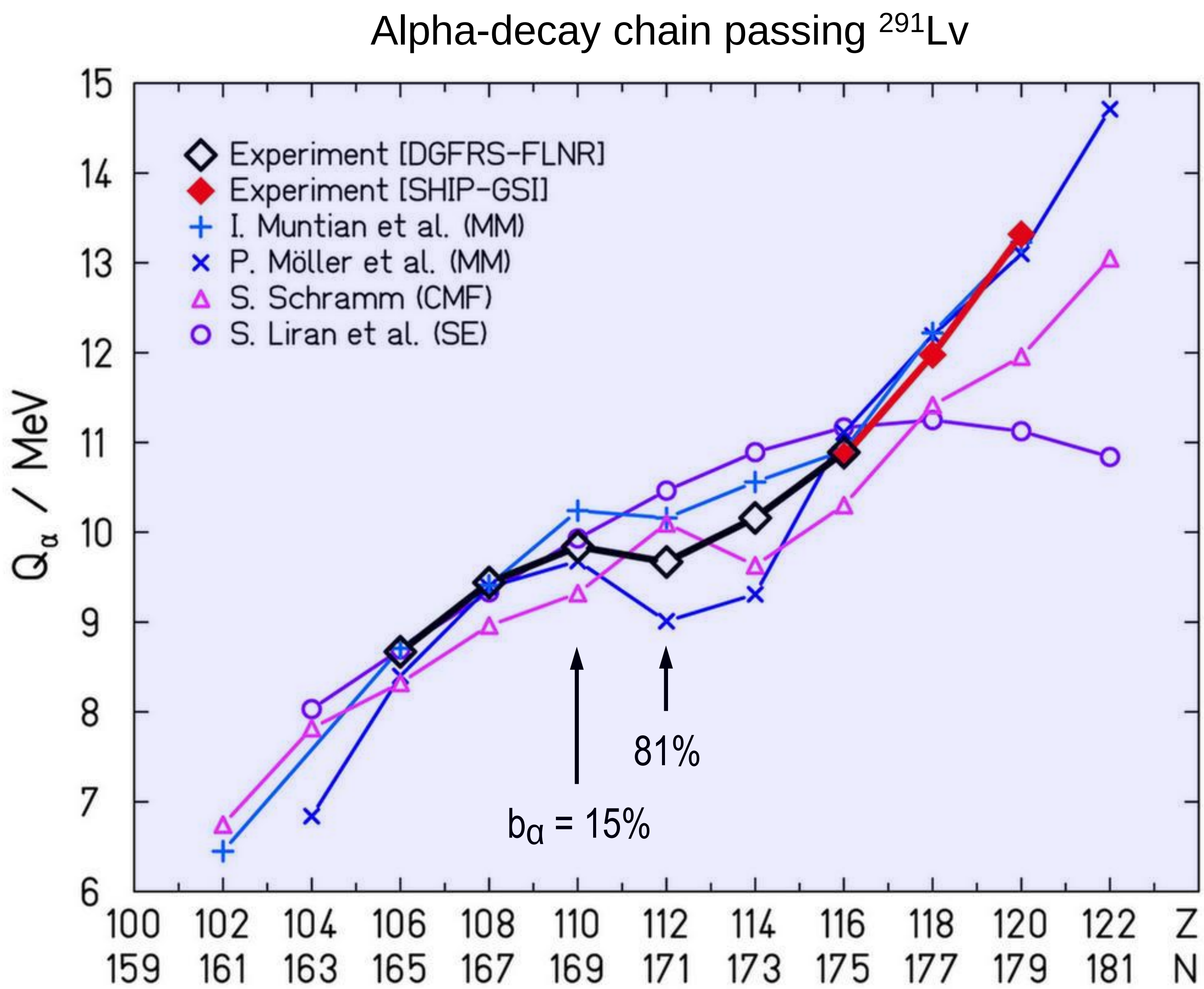
b) All five events were registered during the 0.3–5.5 ms beam pulses

c) Escape α, 4.93 MeV in stop detector plus 6.88 MeV in box-detector segment number 27.

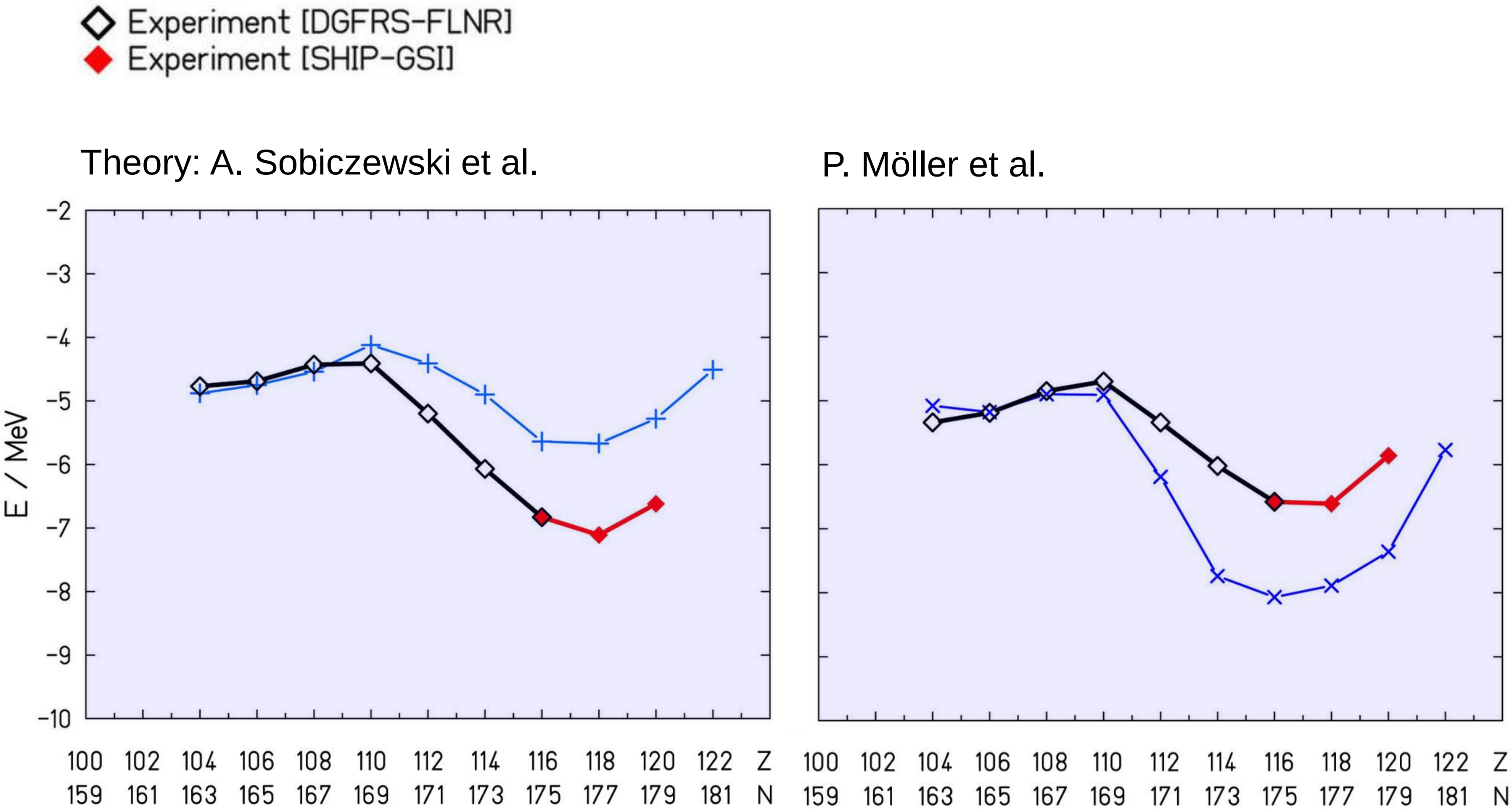
d) In the same event was detected a 993-keV signal in one of the Ge detectors. Its relative time in the α-γ TAC spectrum is five standard deviations from the center of the prompt peak. The time resolution was 110 ns (FWHM). Therefore, the signal is considered as a chance event.

e) In the case of SF: 158-MeV height of signal plus 65-MeV energy deficit.

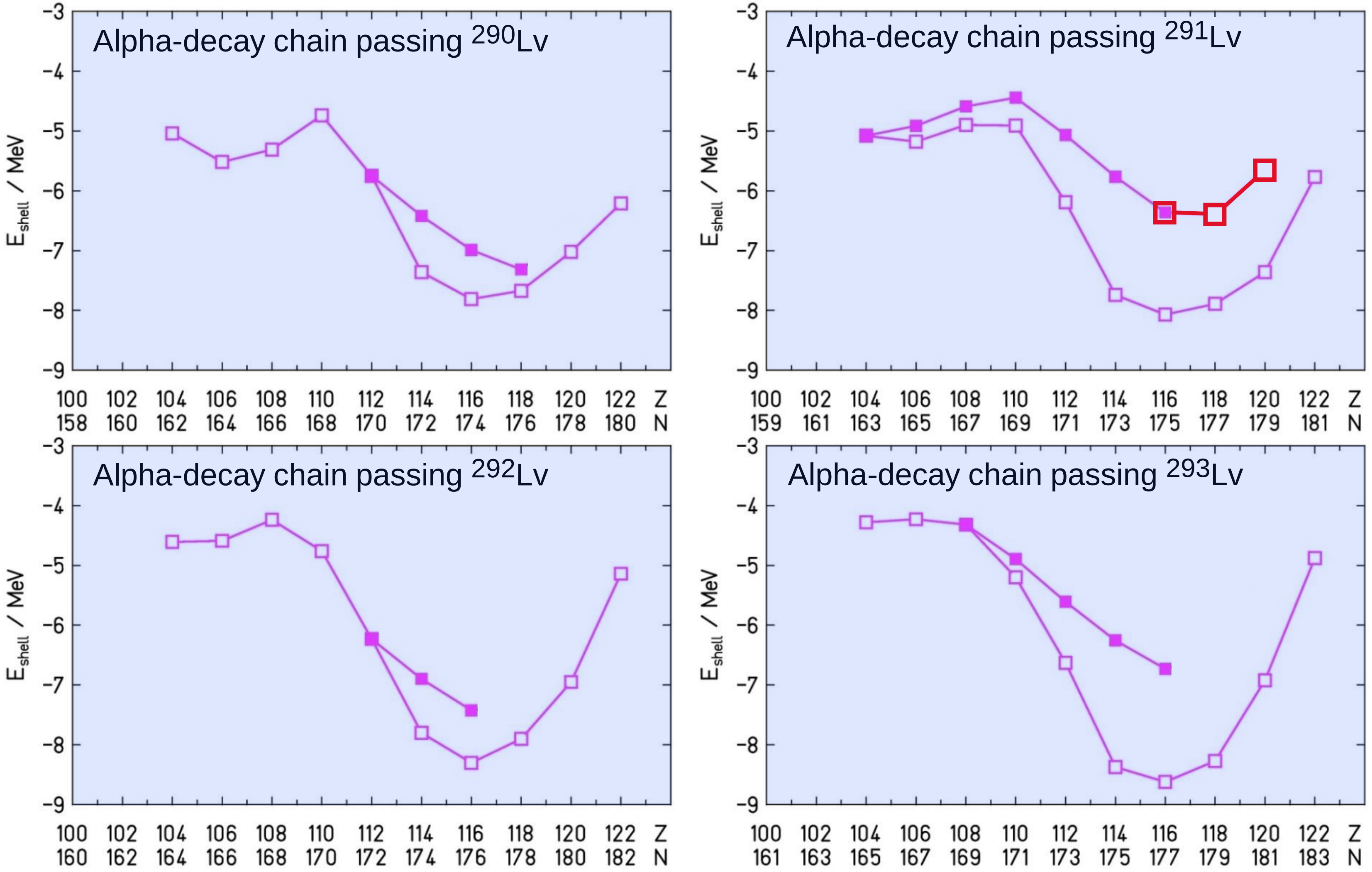
Q_α values: experiment and theory



Shell-correction energies



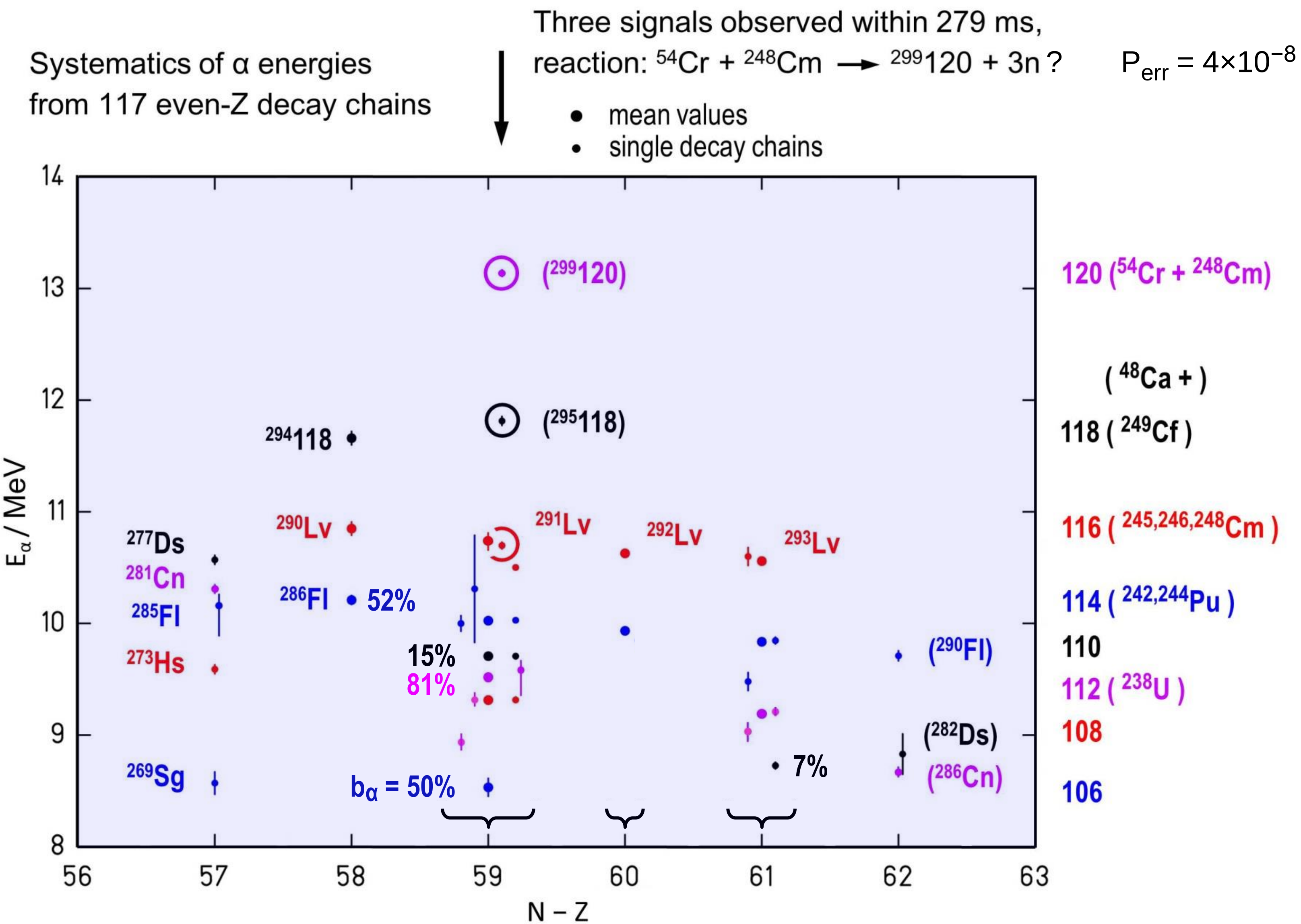
Shell correction energies, theory and "experiment"



Theory: P. Möller et al., FRDM 1995

Experiment: DGFRS, SHIP

Review of measured alpha-energy systematics



Review of measured alpha-energy systematics