Decay Properties of SHE

Fritz Peter Heßberger
GSI – Helmholtzzentrum für Schwerionenforschung mbH,
D-64291 Darmstadt, Germany
Helmholtz – Institut Mainz, D-55099 Mainz, Germany

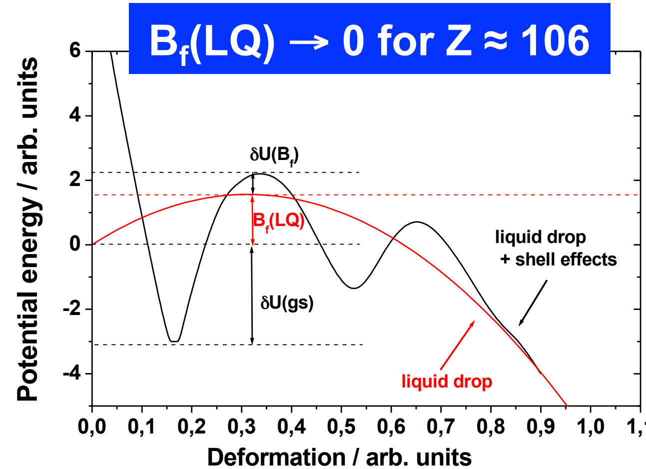
FUSHE 2012
ENSAR-ECOS Workshop on Future SuperHeavy Element Strategy

Erbismühle – Weilrod, Germany
13. – 16. May 2012

Version 15. 5. 2012

Physics Motivation for Decay and Nuclear Structure Investigations in the Region of SHE

Why Decay and Nuclear Structure investigations ?



→Atomic nucleus is quantum mechanical ensemble of nucleons (protons, neutrons)

→Properties determined by ‚fundamental‘ interactions
- nucleon – nucleon interaction
- Coulomb interaction
- spin – orbit interaction
- ….

→Understanding decay properties and nuclear structure – Understanding ‚fundamental‘ interactions

→Superheavy nuclei (SHE) = ensembles of ‚extremely‘ large numbers of protons and neutrons

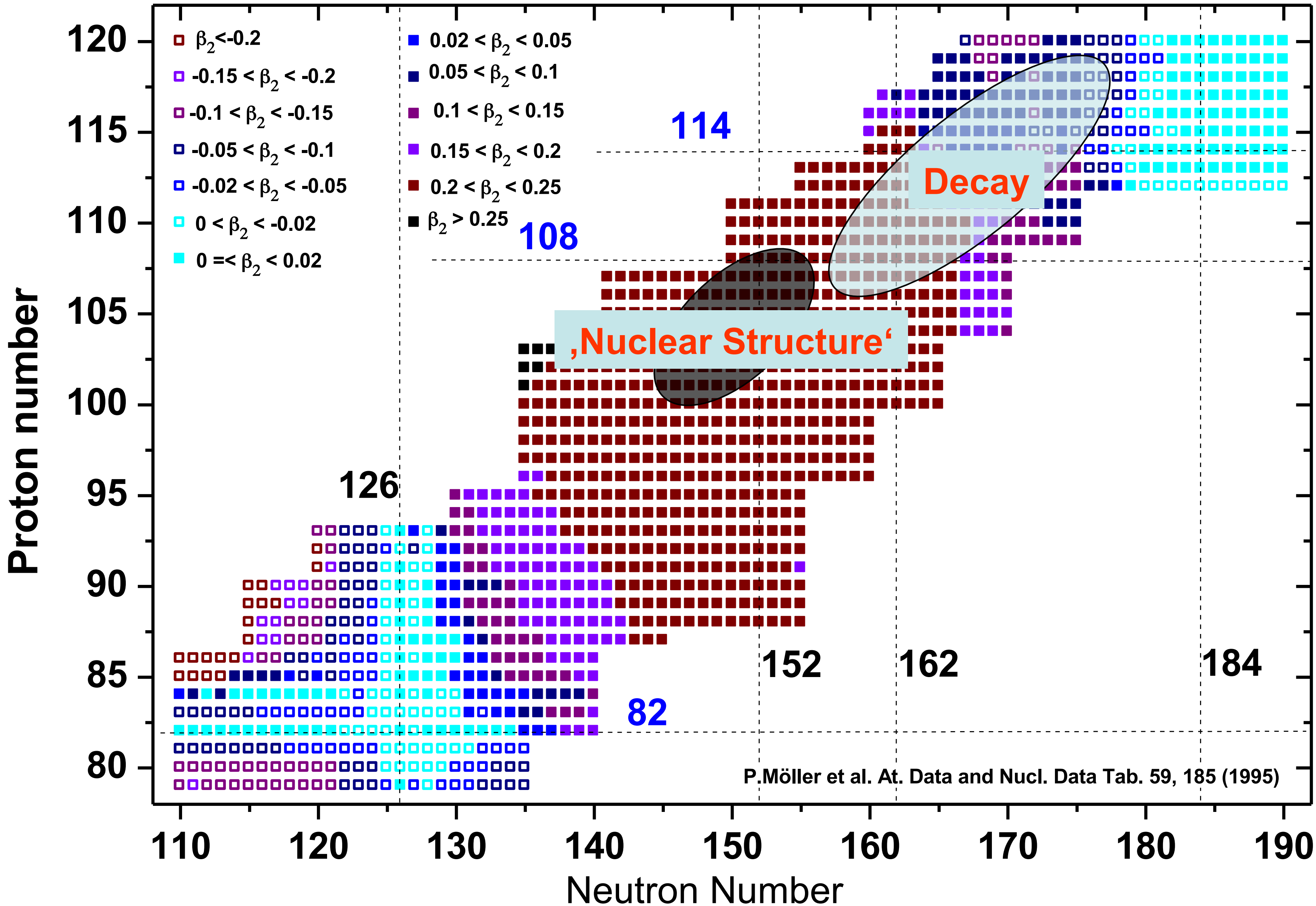
→Nuclear stability limited by fission
- Fission barriers in SHE determined by shell structure; B_{sf} depends on single particle levels

→ mass excess (-> determines Q-values for α- and β- decay)

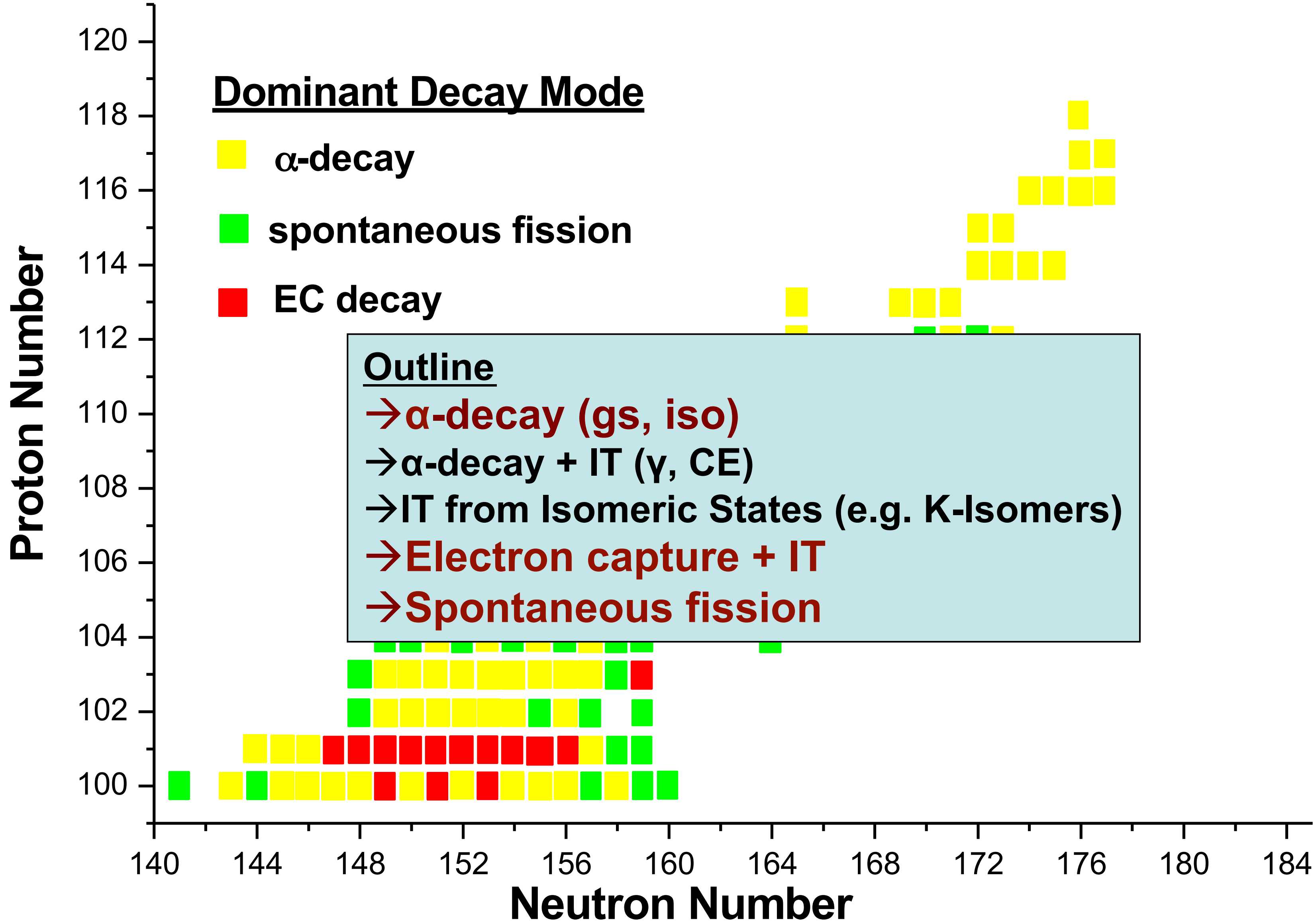
→Understanding ‚basic‘ decay properties essential for understanding limits of stability

→Understanding nuclear structure is essential for understanding properties and stability of SHE

Playground for Decay and Nuclear Structure Investigations



Decay Modes of SHE



Outline

→α-decay (gs, iso)

→α-decay + IT (γ, CE)

→IT from Isomeric States (e.g. K-Isomers)

→Electron capture + IT

→Spontaneous fission

Decay spectroscopy

→ α- and α - γ – spectroscopy

Q-values, shell crossings;
Information on low lying Nilsson levels from energy and HF for α-decay as well as from energy, intensity and multipolarity of γ-rays.

→ systematic trends in odd mass – even Z nuclei along isotone line
→ systematic trends in odd mass – odd Z nuclei along the isotope line

Comparison with theory

→ Spontaneous fission

Fission barriers, hindrance factors, TKE

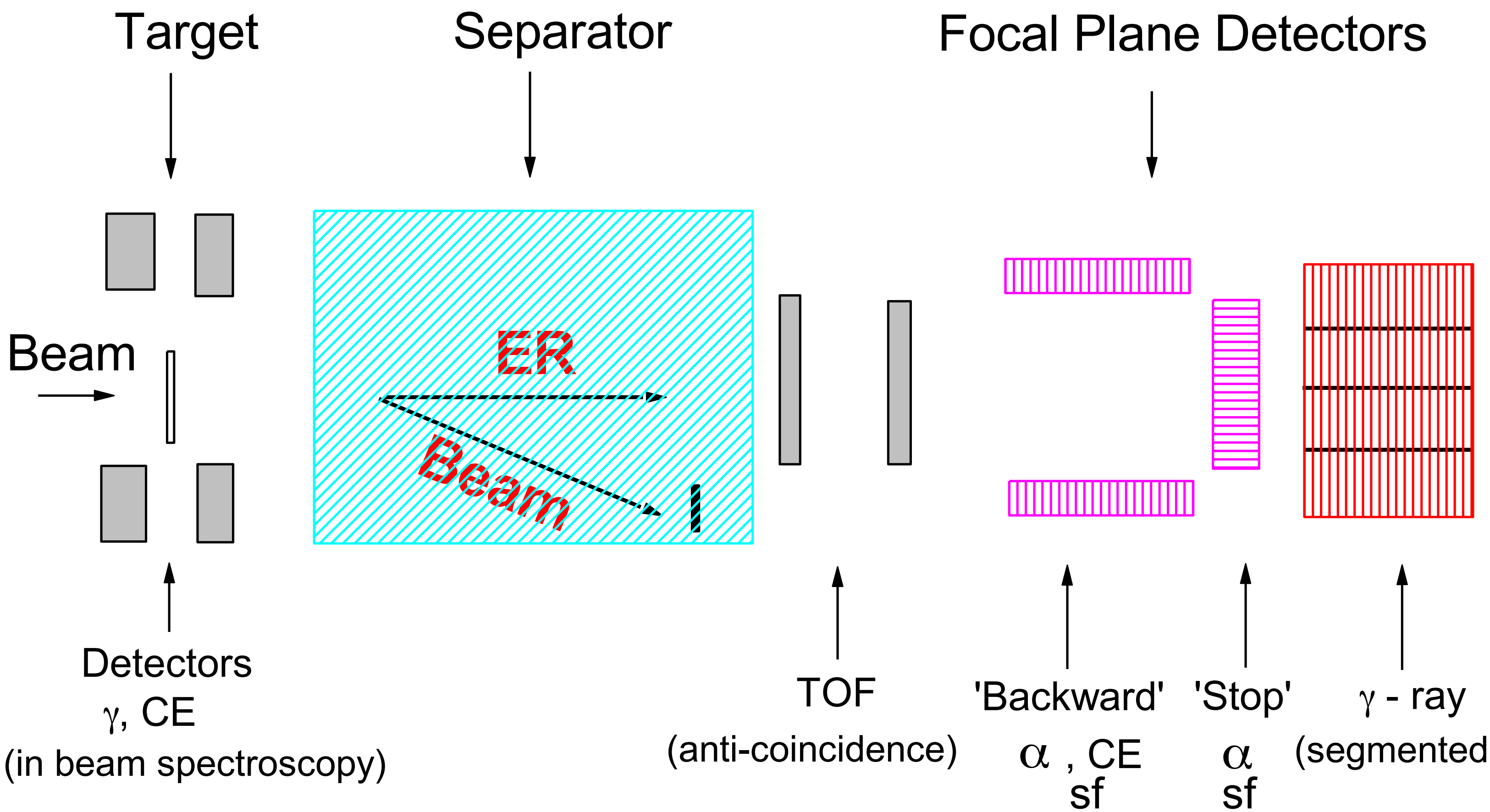
→ EC – decay

Often population of higher lying levels than by α-decay with notable intensities; similar information,
implantation method requires CE – K X-ray – γ- coincidences for identification

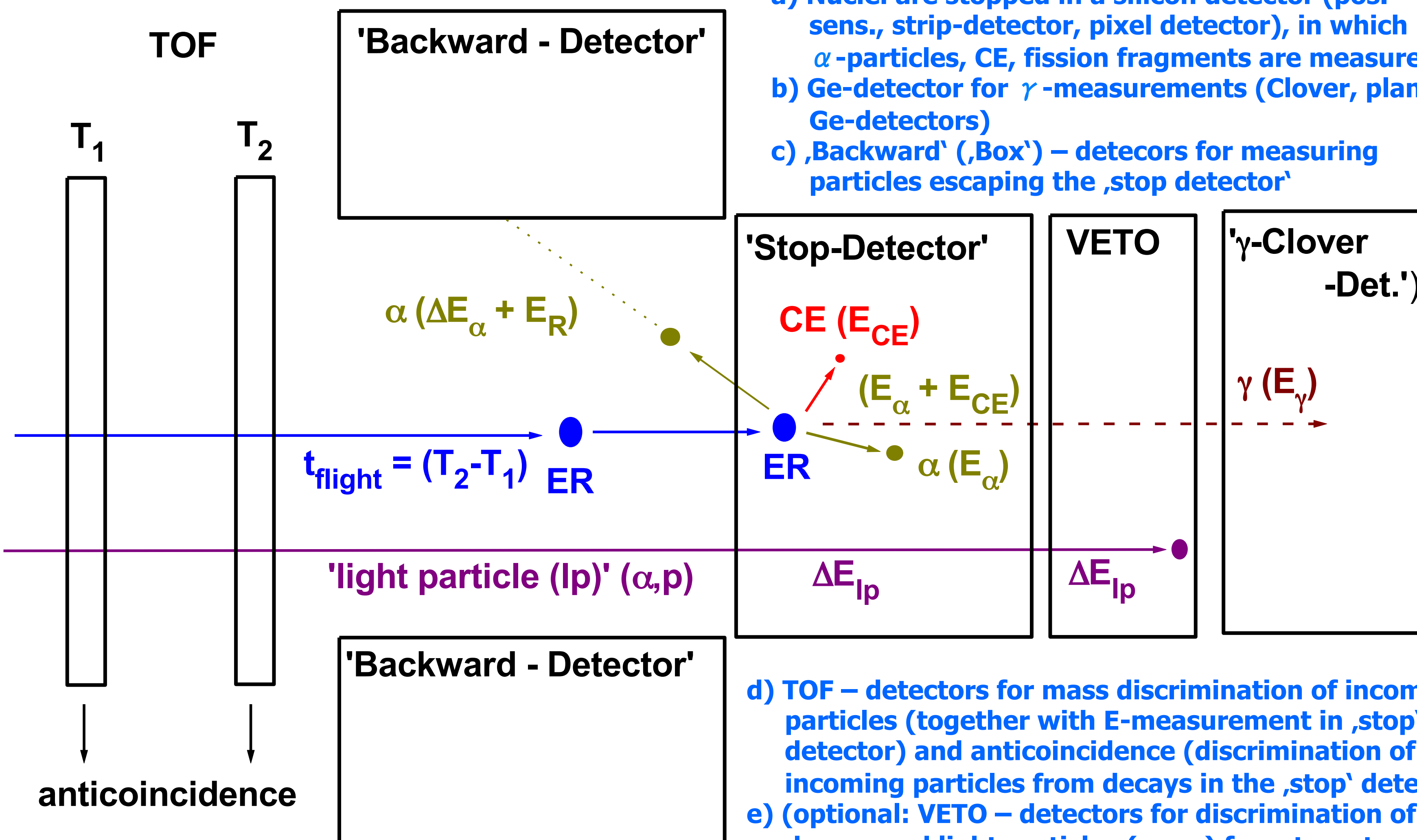
→ K – Isomers

Multi – quasiparticle (2q-proton, 2q-neutron, ...) configurations, typically at $E^* > 1$ MeV; information on lower lying qp-states, Nilsson levels, level ordering, vibrational states and bands built up on them
CE – γ coincidences required

Schematic Experimental Set-up for SHE – Decay measurments



Experimental Set-up – Detector system



Basic principle:

a) Nuclei are stopped in a silicon detector (pos. sens., strip-detector, pixel detector), in which α-particles, CE, fission fragments are measured

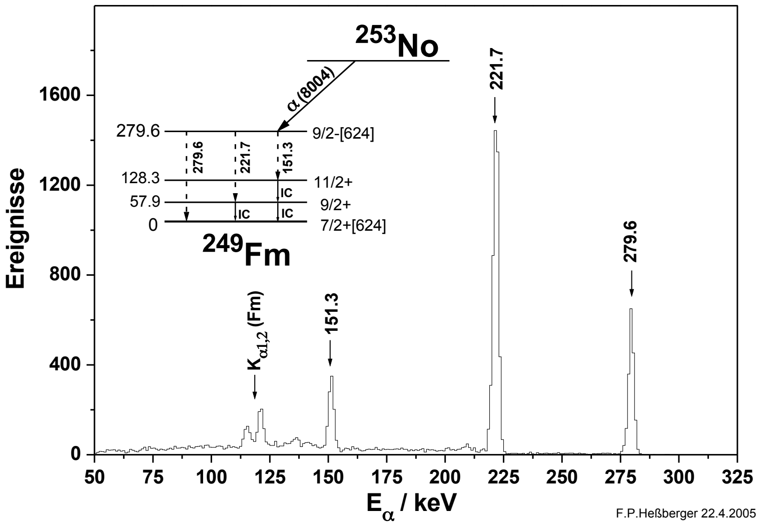
b) Ge-detector for γ-measurements (Clover, planar Ge-detectors)

c) ‚Backward' (‚Box') – detecors for measuring particles escaping the ‚stop detector'

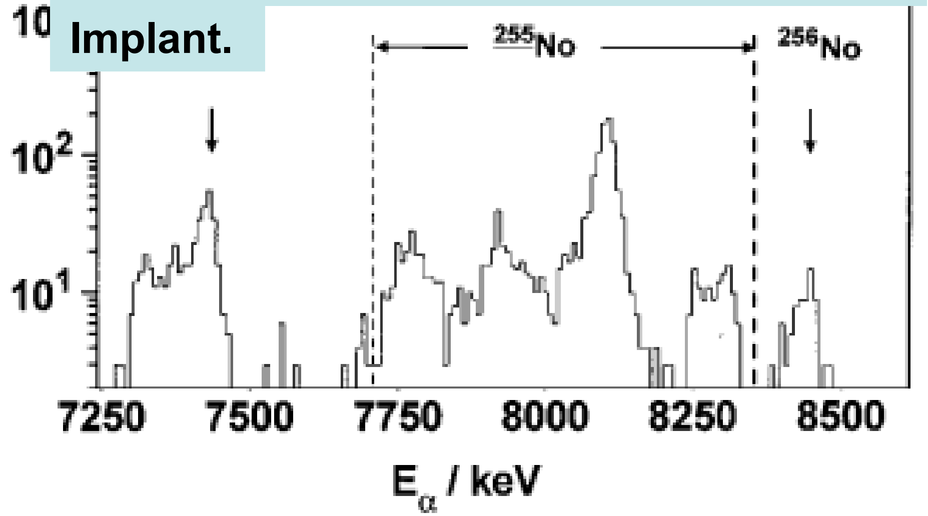
d) TOF – detectors for mass discrimination of incoming particles (together with E-measurement in ‚stop' detector) and anticoincidence (discrimination of incoming particles from decays in the ‚stop' detector)

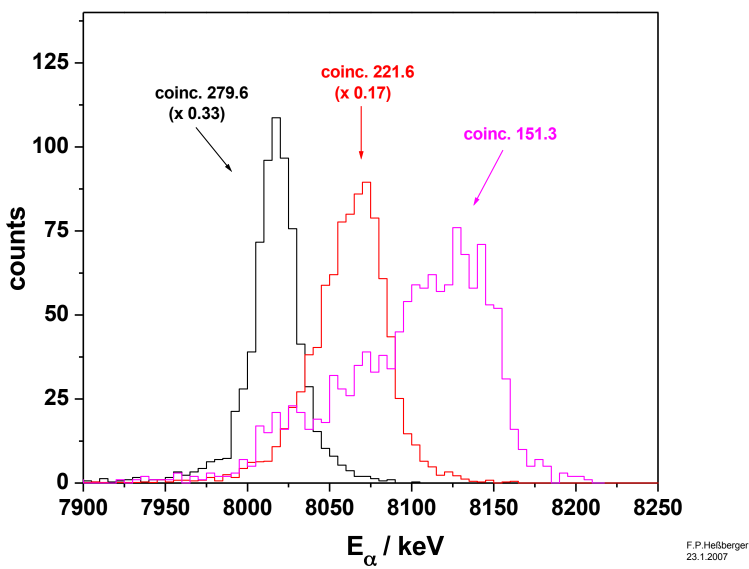
e) (optional: VETO – detectors for discrimination of decays and light particles (p, α ..) from target area

Energy summing α-particles and CE

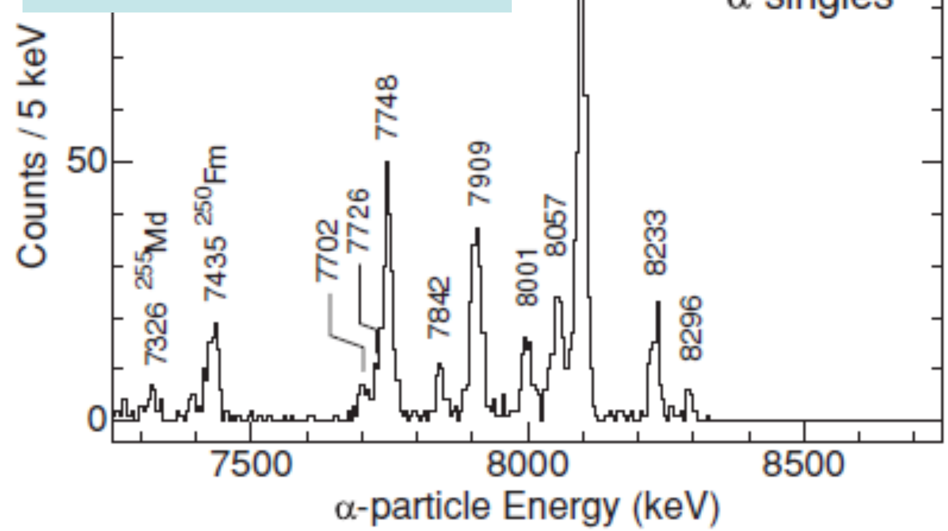


F.P. Heßberger et al. EPJ A 29, 165 (2006)
Implant.

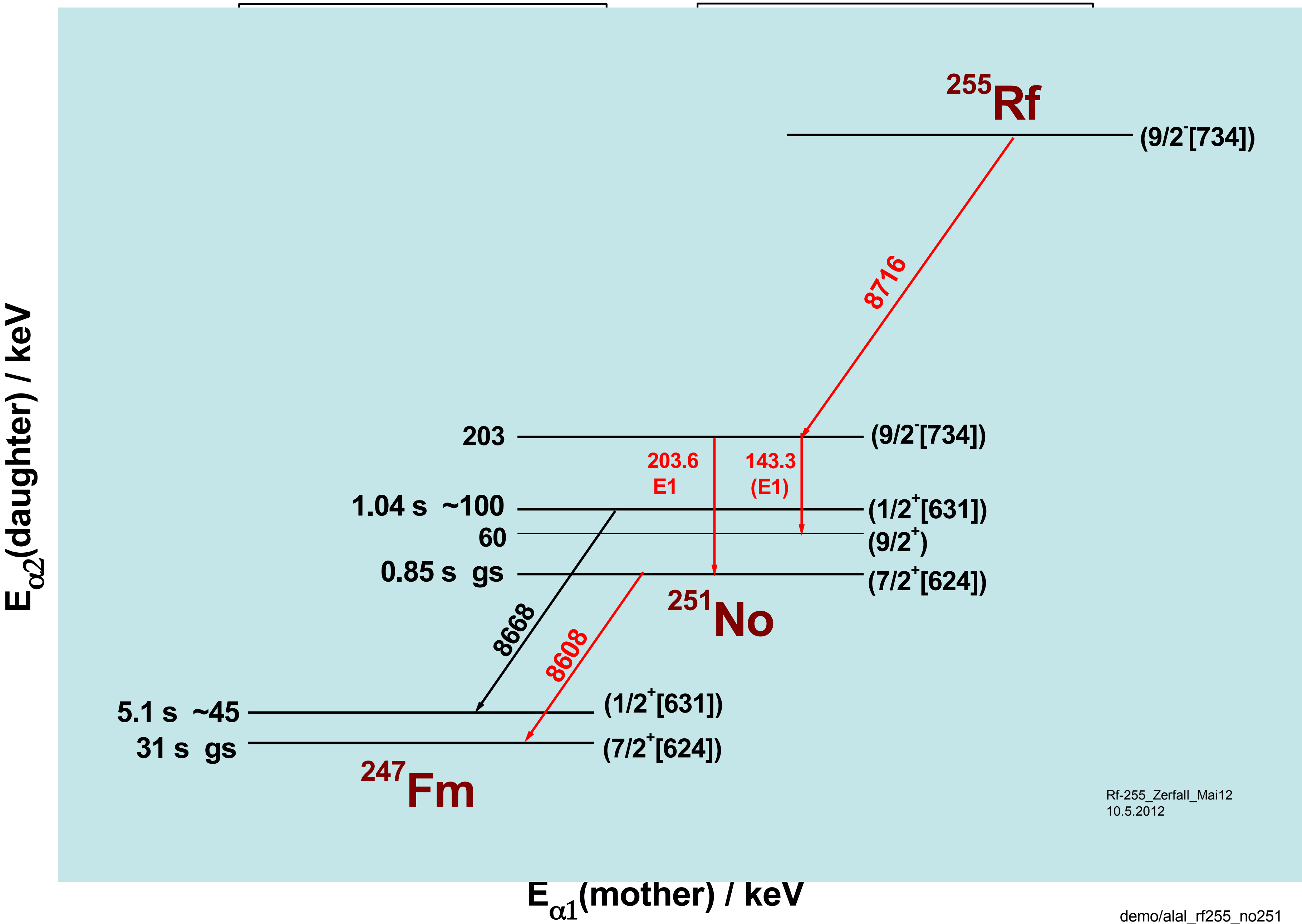




M. Asai et al.
PRC 83, 014315 (2011)
He-Jet



Identification of Isomeric States by α - α Correlations



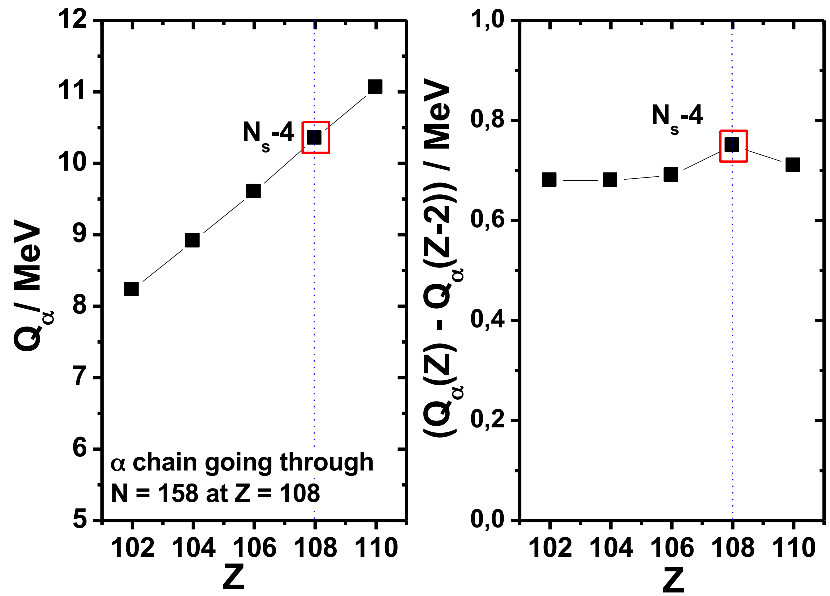
demo/alal_rf255_no251
11.6.2007

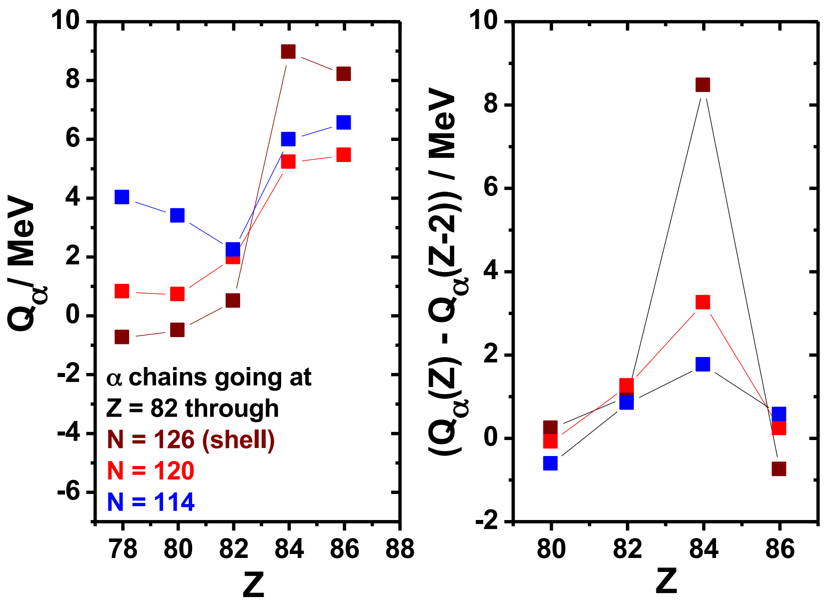
Probing Shell crossing by α - decay

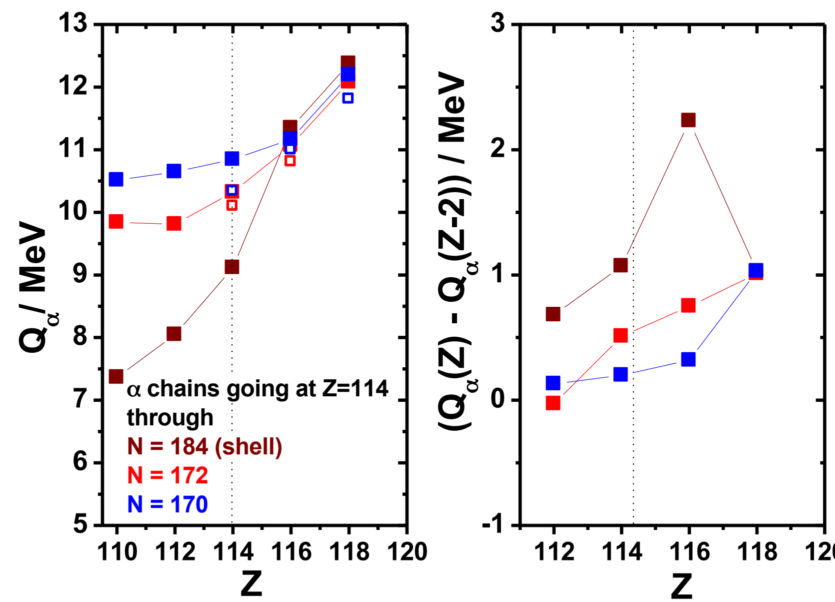
→ Q_α – values reflect differences in masses and are thus extremely sensitive to changes in shell effects

→ strong changes of Q_α – values when crossing shell; effect strongest when crossing p-shell at n-shell; effect diminishs at departing from n-shell

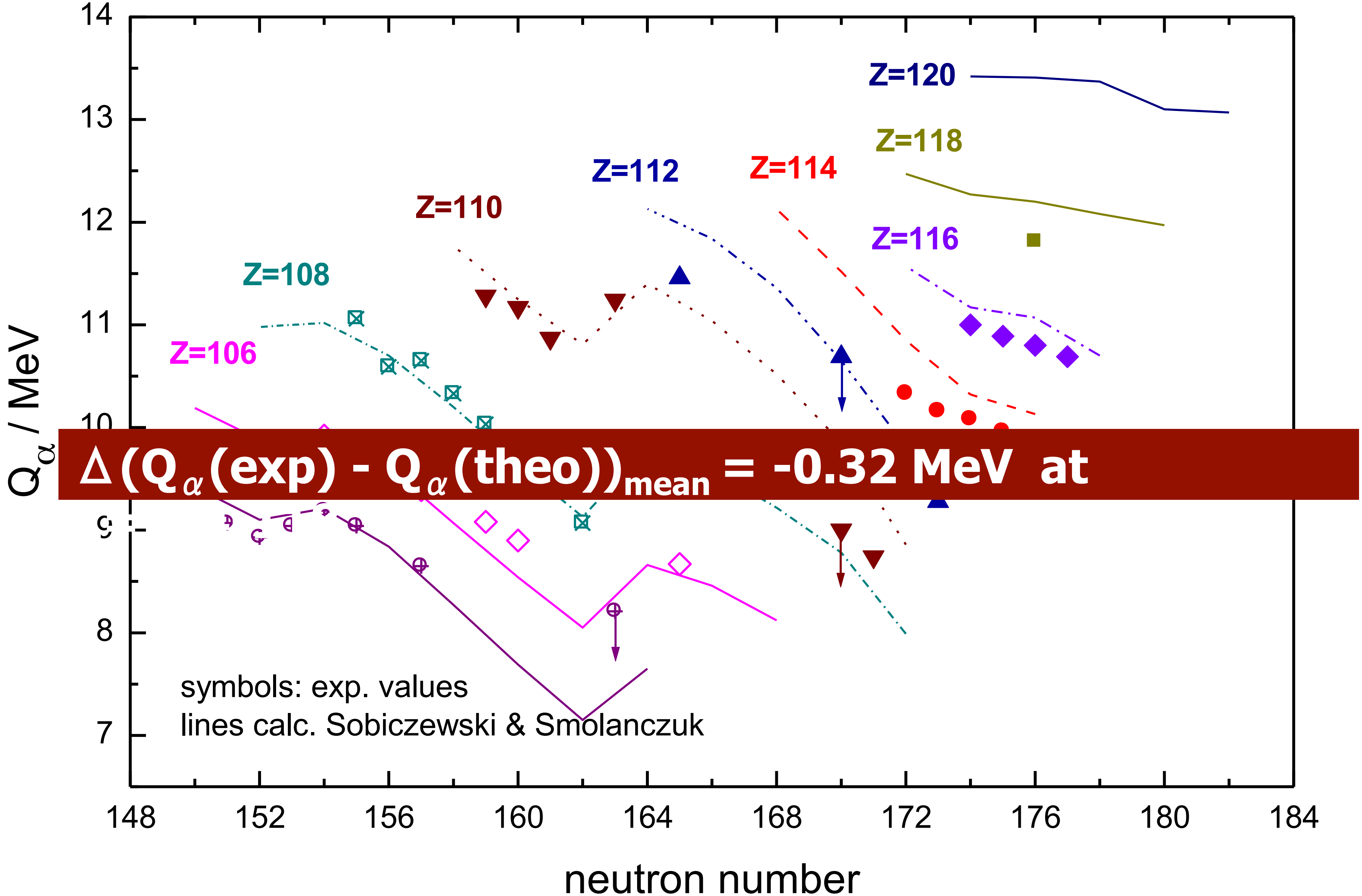
→ **At N = 172,170 no significant effect of p-shell Z=114 on Q_α – values expected**





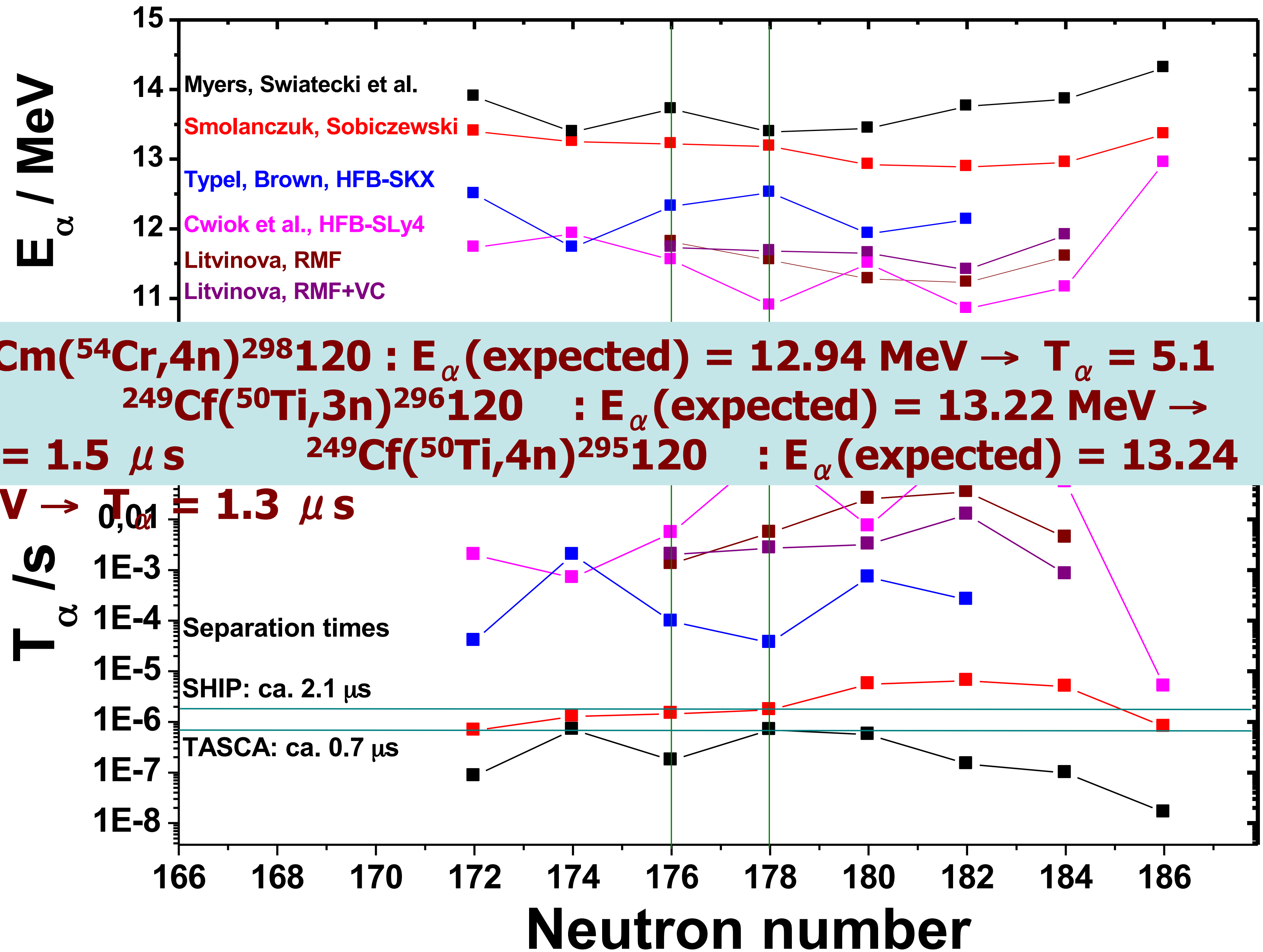


Alpha - decay energies of SHE



$\Delta(Q_\alpha(exp) - Q_\alpha(theo))_{mean}$ = -0.32 MeV at

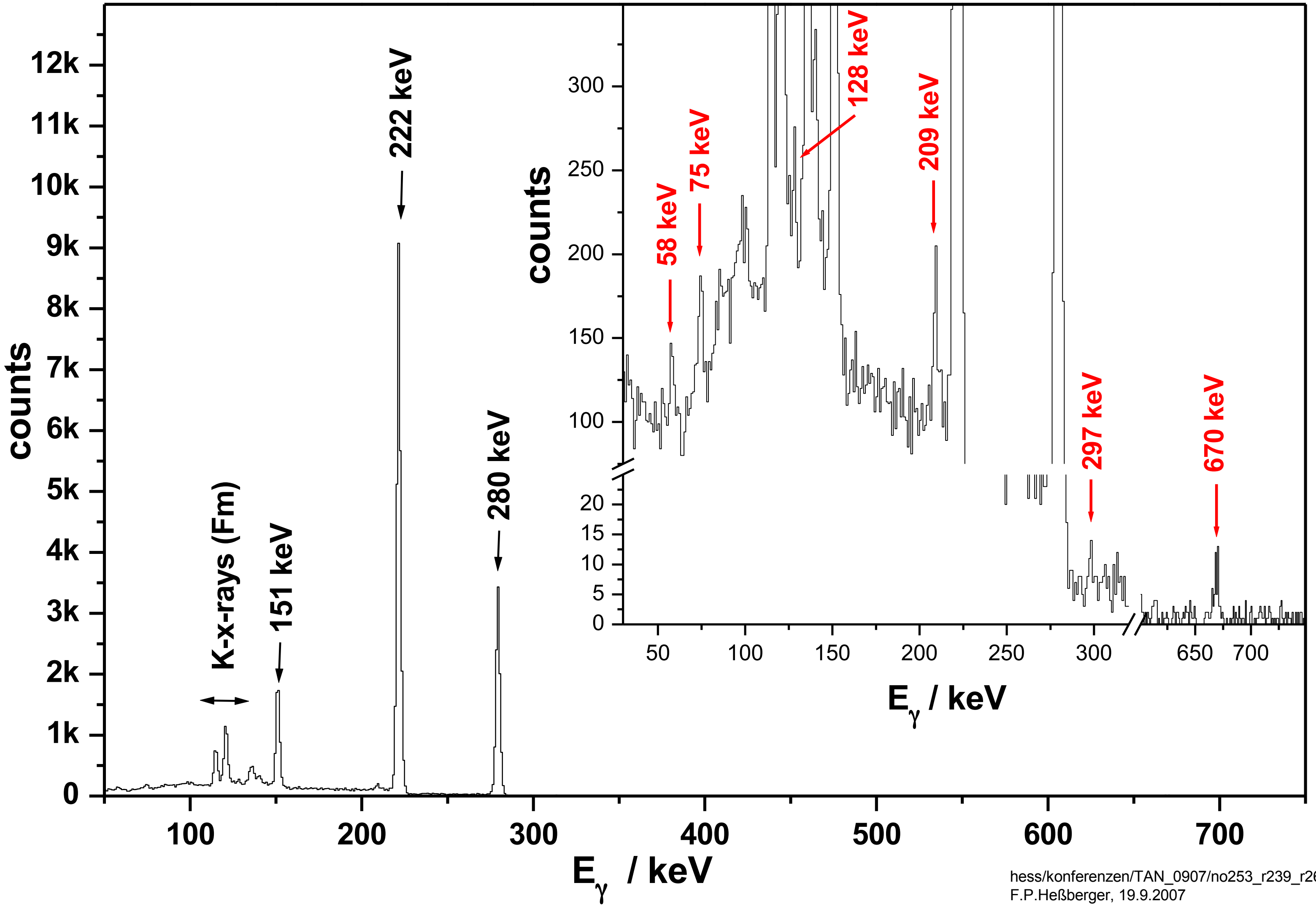
E_α- and $T_{1/2}$- values expected for Z = 120 isotopes



$^{248}Cm(^{54}Cr,4n)^{298}120$: E_α(expected) = 12.94 MeV → T_α = 5.1 μs $^{249}Cf(^{50}Ti,3n)^{296}120$: E_α(expected) = 13.22 MeV → T_α = 1.5 μs $^{249}Cf(^{50}Ti,4n)^{295}120$: E_α(expected) = 13.24 MeV → T_α = 1.3 μs

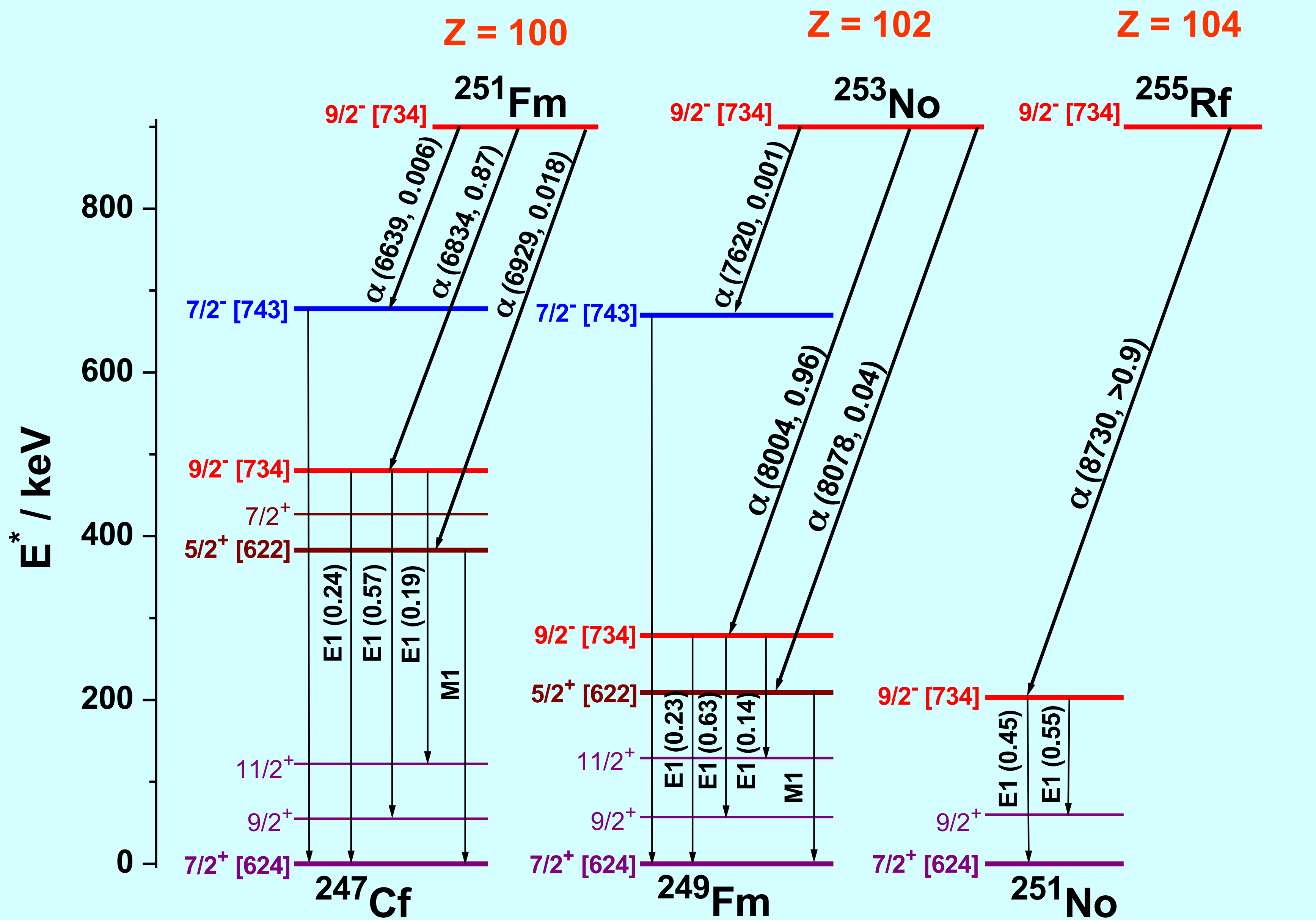
α-γ- decay spectroscopy

$^{207}Pb(^{48}Ca,2n)^{253}No$: σ ≈ 900 nb h; 330 000 α-decays collected in 96 h irrad. time



hess/konferenzen/TAN_0907/no253_r239_r260
F.P.Heßberger, 19.9.2007

Decay Properties of N=151 Isotones

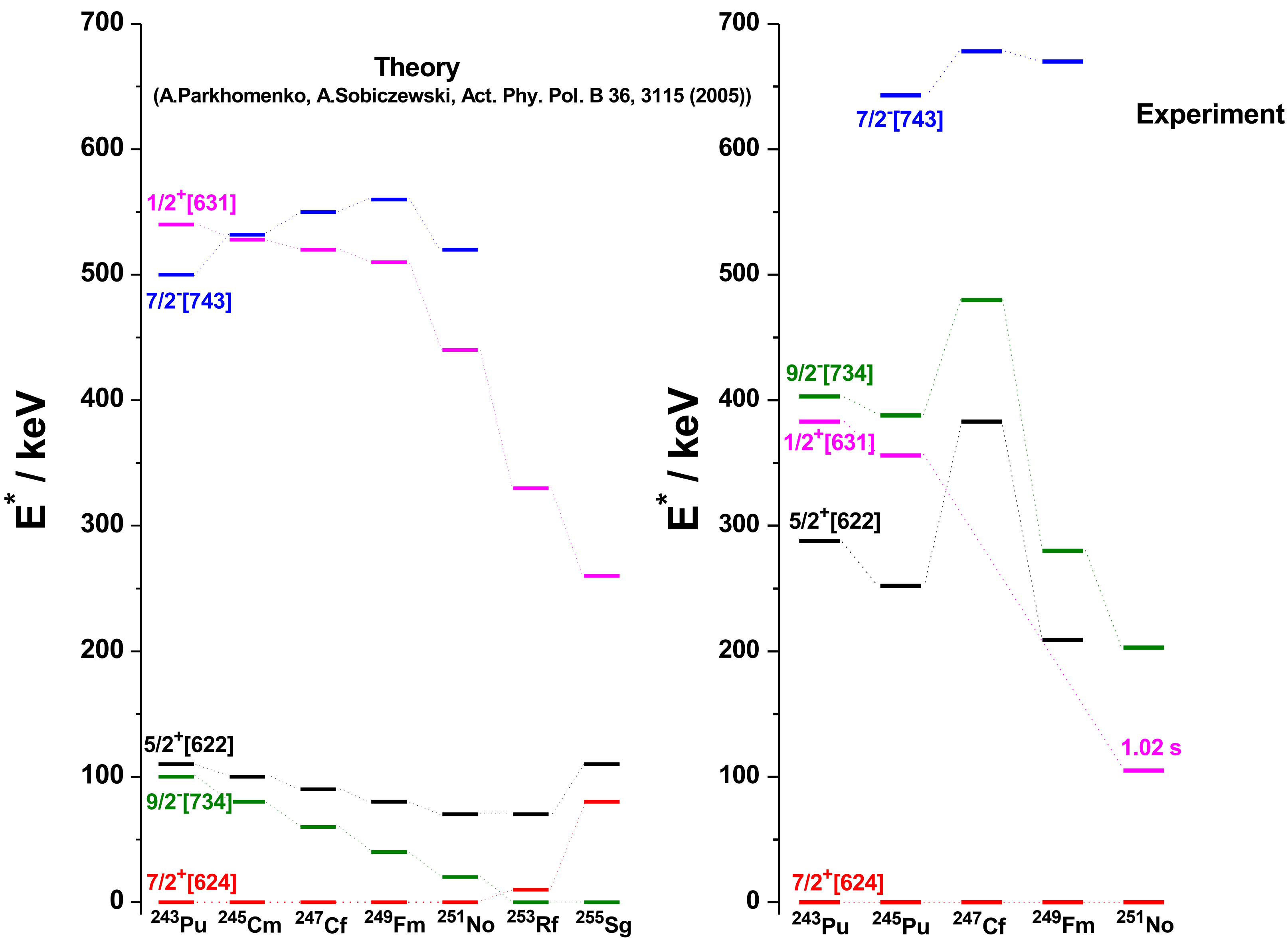


I. Ahmad et al.
PR C 8, 737 (1973)

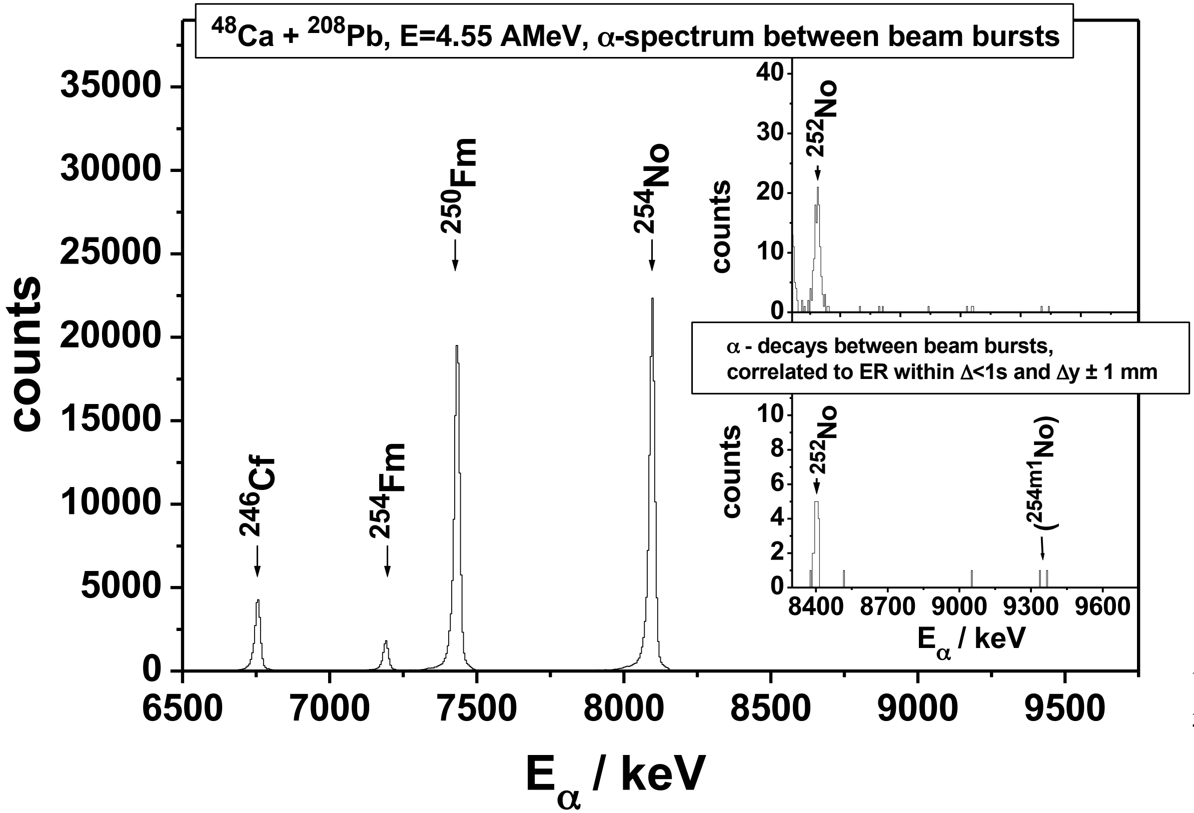
F.P. Heßberger
EPJ D 45, 33 (2007)

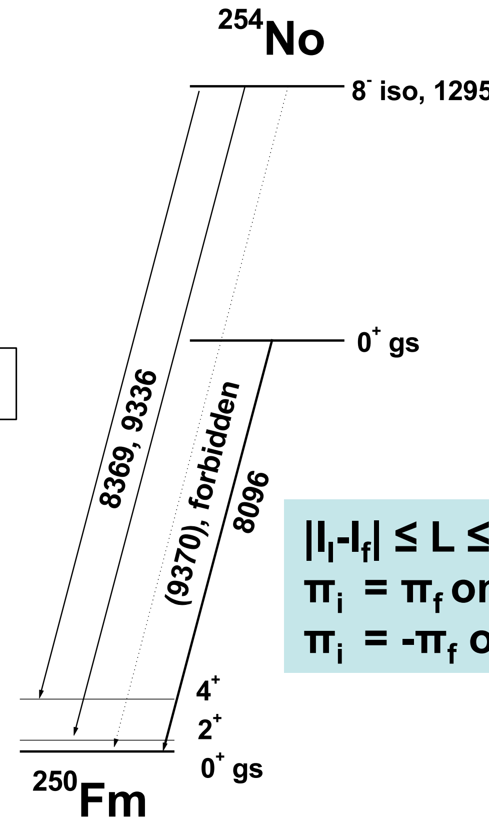
F.P.Heßberger et al.
EPJ A 30, 561 (2006)

Systematics of low lying Nilsson-levels in N=149 isotones



α – decay of K - Isomers





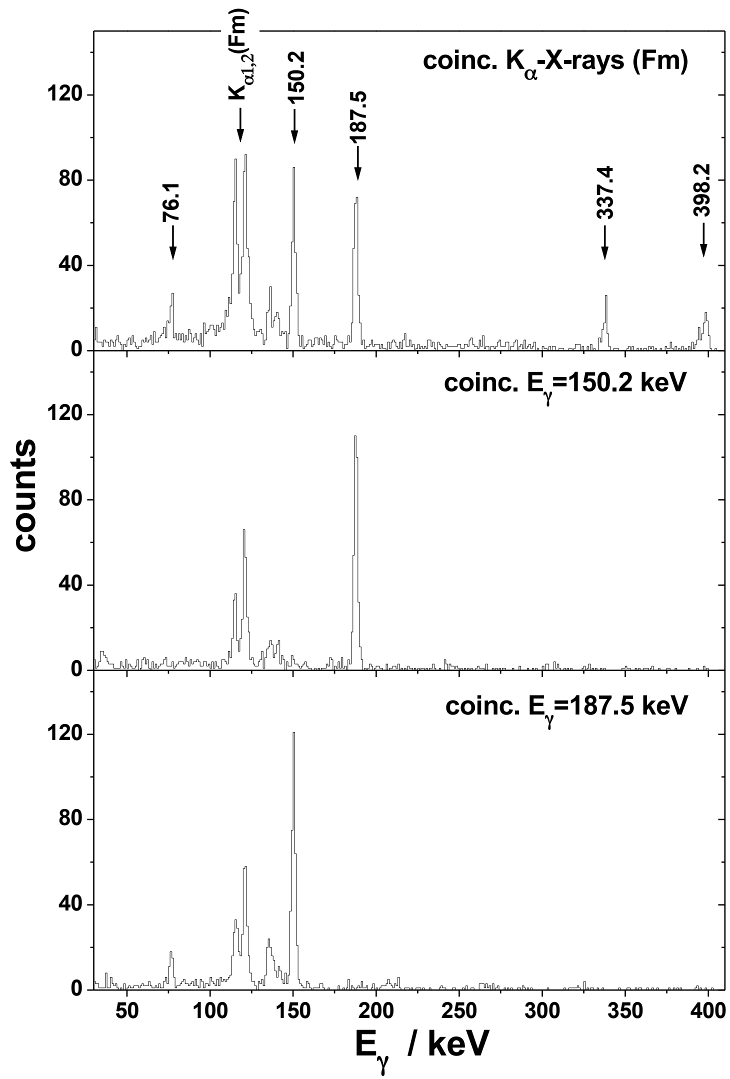
$|I_i - I_f| \leq L \leq I_i + I_f$
$\pi_i = \pi_f$ only even L
$\pi_i = -\pi_f$ only odd L

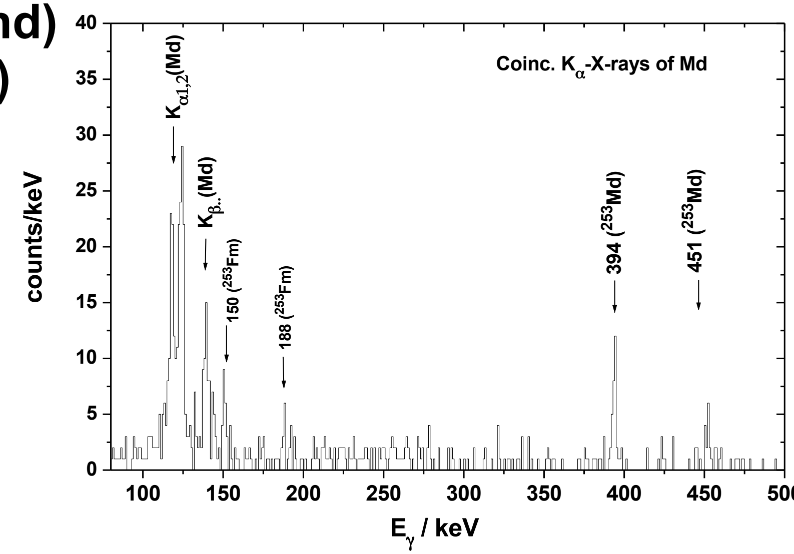
^{254m1}No:
Indication for small α-decaybranch, $b_\alpha \leq 10^{-4}$;
probably $8^- \rightarrow 2^+$ transition;
$T_\alpha \geq 2780$ s;
HF $\geq 7 \times 10^5$

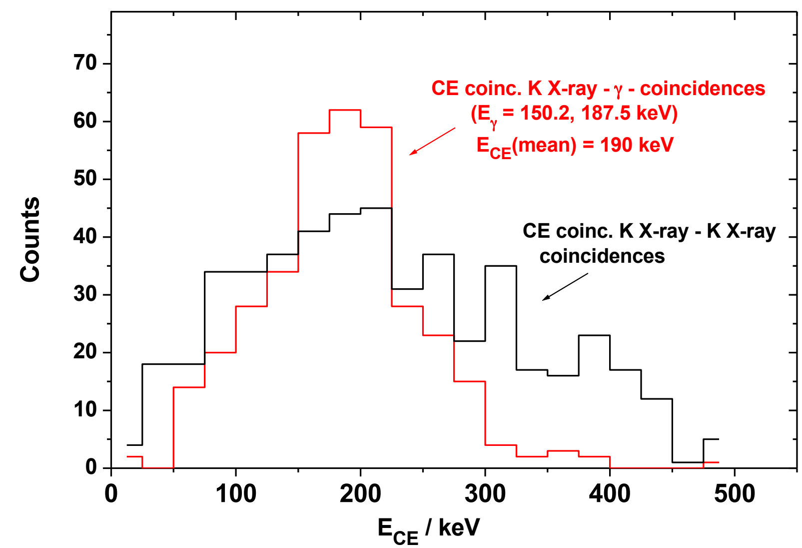
^{254m}2No:
No indication for α decay
$b_\alpha < 4 \times 10^{-4}$;
$T_\alpha > 0.5$ s
HF > 106

EC decay study of $^{253}No \rightarrow {}^{253}Md \rightarrow {}^{253}Fm$

Problem: coinc. CE – γ – needed (background)
coinc. X-ray – γ – needed (Z ident.)







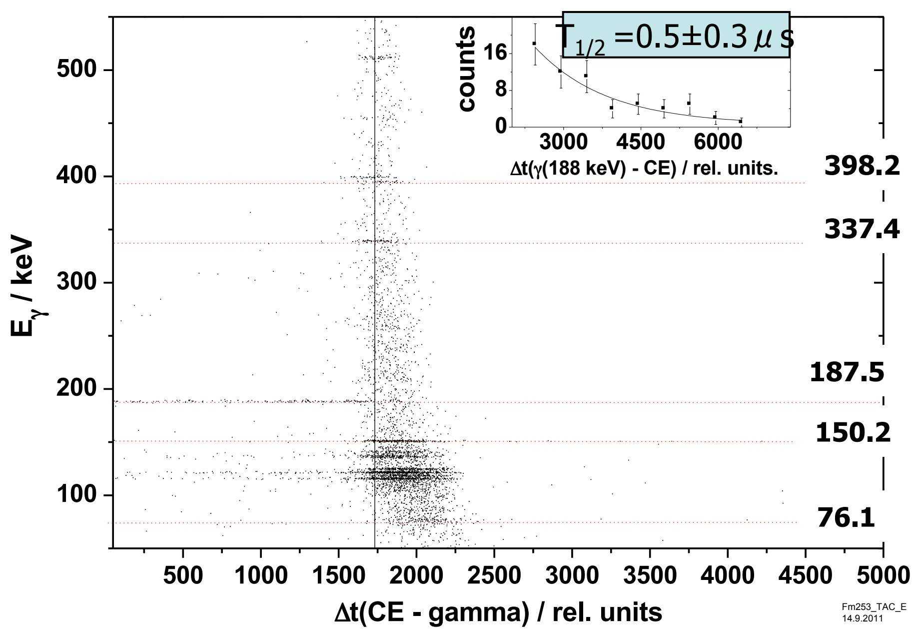
Energy levels in Fm-253

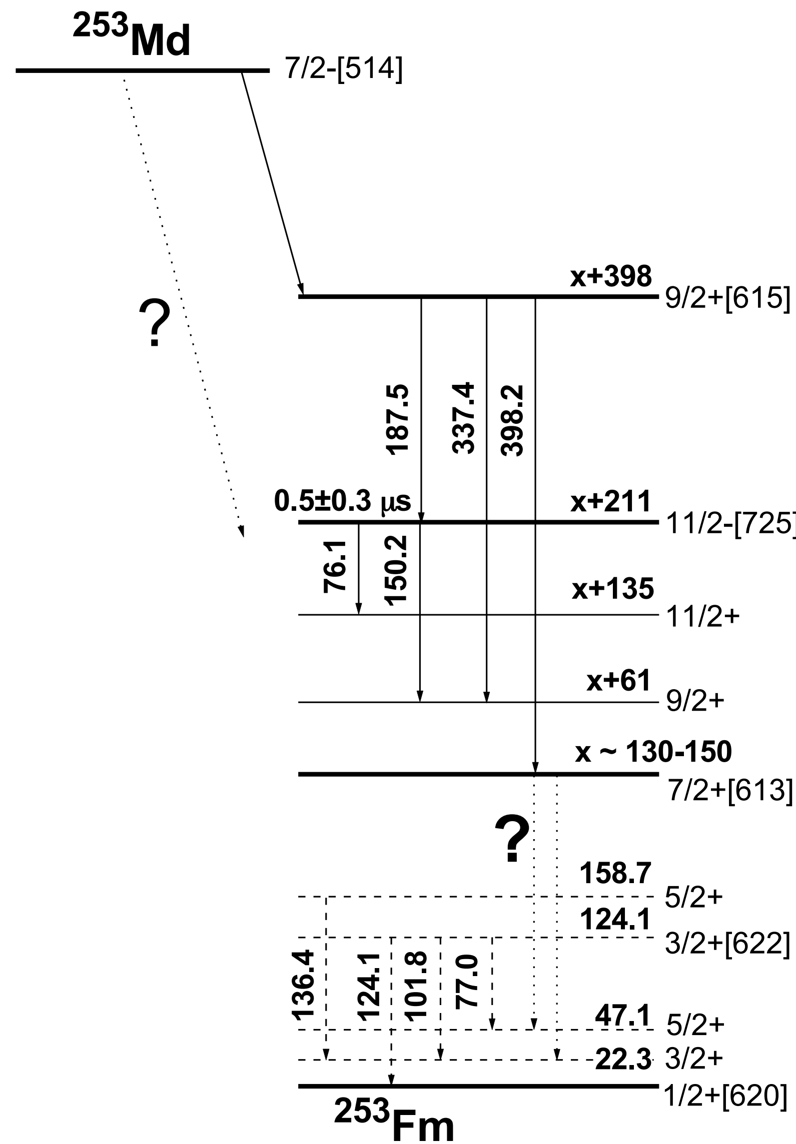
→ 11/2-[725] isomeric state identified; decay pattern established on the basis of systemtics (^{251}Cf)

→No connections to ‚low energy level‘ studied by Asai et al. via α-decay of ^{257}No established

→ CE energy suggests 7/2+[613] at ≈140 keV

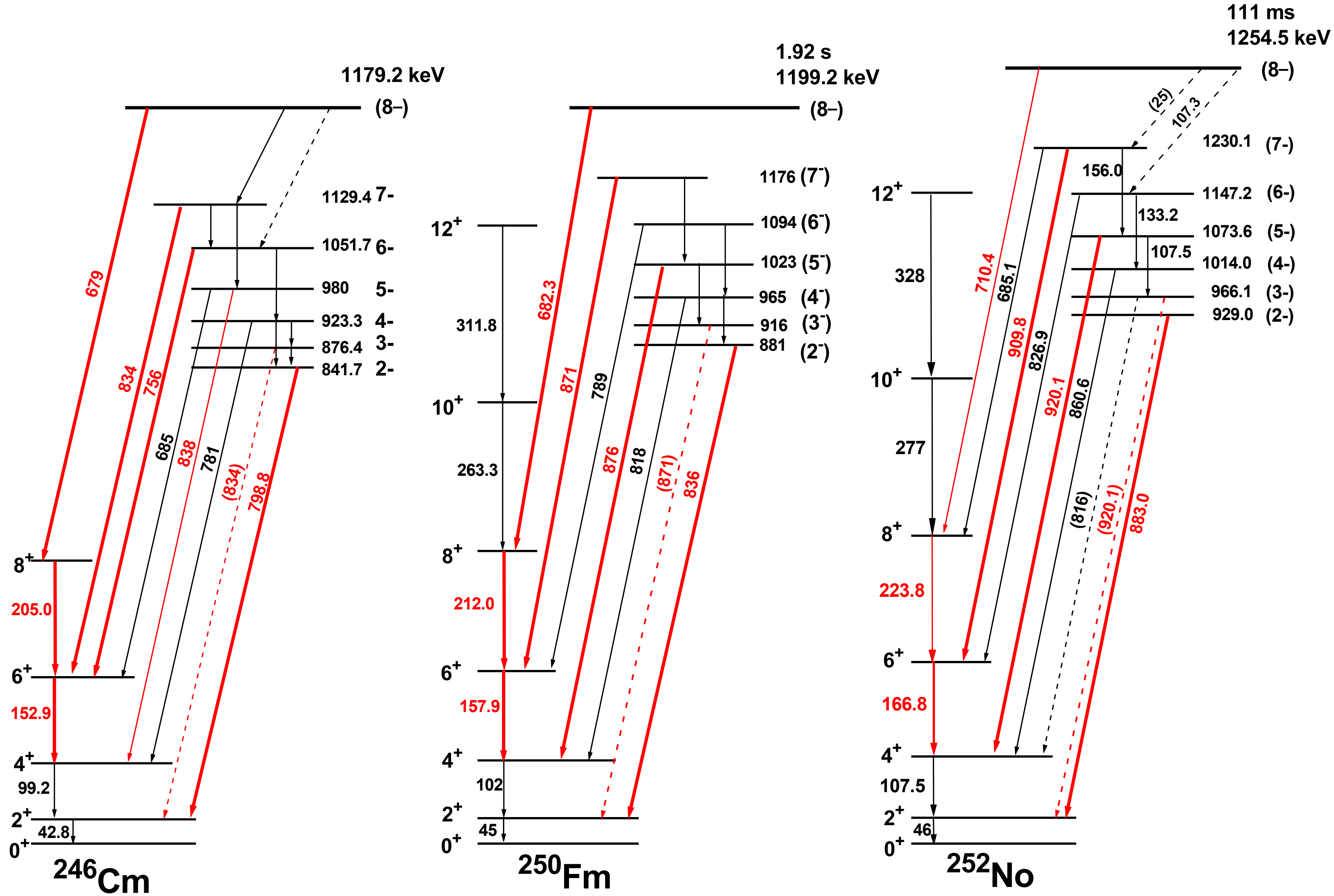
→ strong X-ray – X-ray coincidences suggest also EC-decay in a so far not identified level





Systematics in structures of K - isomers

Similar decay schemes of the $K^{\pi} = 8^{-}$ - isomers suggests same configurations

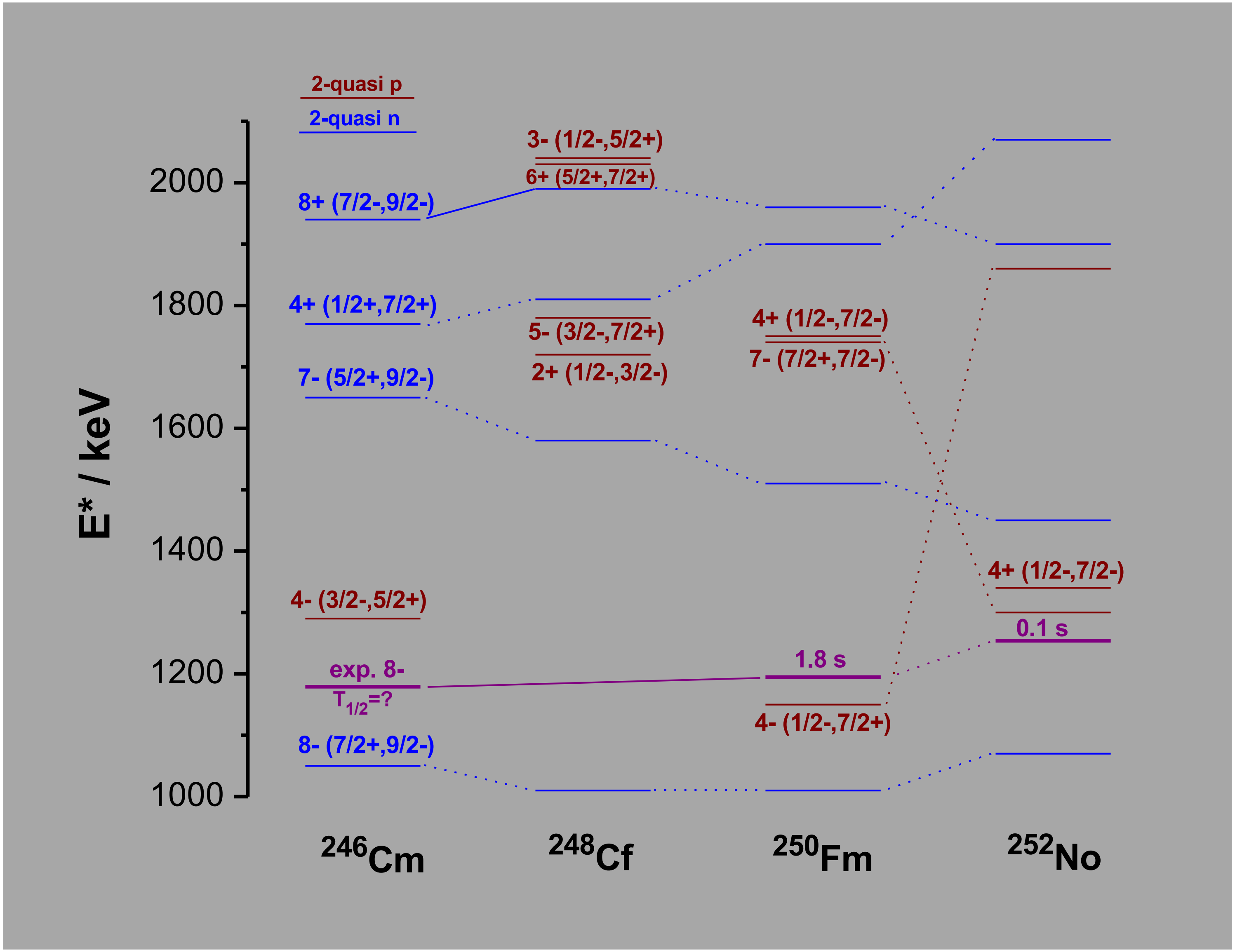


L.G. Multhauf et al., PR C3,1338 (1971)
A.P.Robinson et al. PR C78, 034308 (2008)

P.T. Greenlees et al. PR C78, 021303(R) (2008)

B. Sulignano et al. EPJ A33, 327 (2007)

K-isomers in N=150 isotones



Decay schemes of ^{252}No and ^{250}Fm similar; but different to that of ^{254}No !!
Suggests similar structure of isomers in ^{252}No and ^{250}Fm.

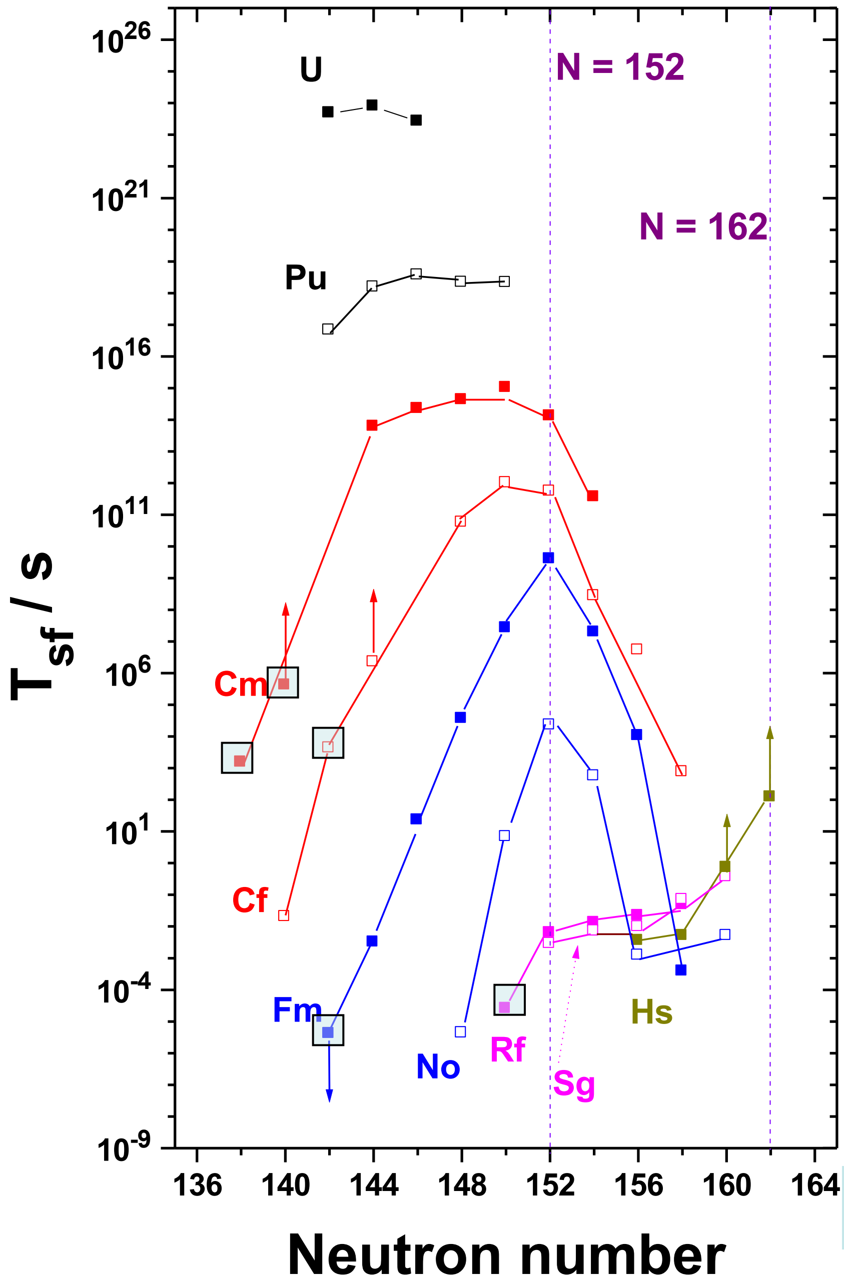
Supported by calculations; lowest 2quasi particle con-figuration predicted as 2quasi neutron state with $I^{\pi} = 8^{-}$.

Common trend in N=150 isotones ?

→ next heavier candidate is ^{254}Rf ($T_{1/2}$ = 23 µs (sf))

calc. J.-P. Delaroche et al.
Nucl. Phys. A 771, 103 (2006)

SF halflife systematics of ee - nuclei



Features

→ strong enhancement of fission half-lives at the deformed neutron shell N = 152 for No, Fm, Cf, (Cm)

→ enhancement at N = 152 vanishes at Z = 104 (Rf)

→ steep decrease of fission halflives on the ‚neutron deficient' side and partly on the neutron rich side

→ rather flat behavior of fission half-lives at N = 152 – 158 for Rf and Sg

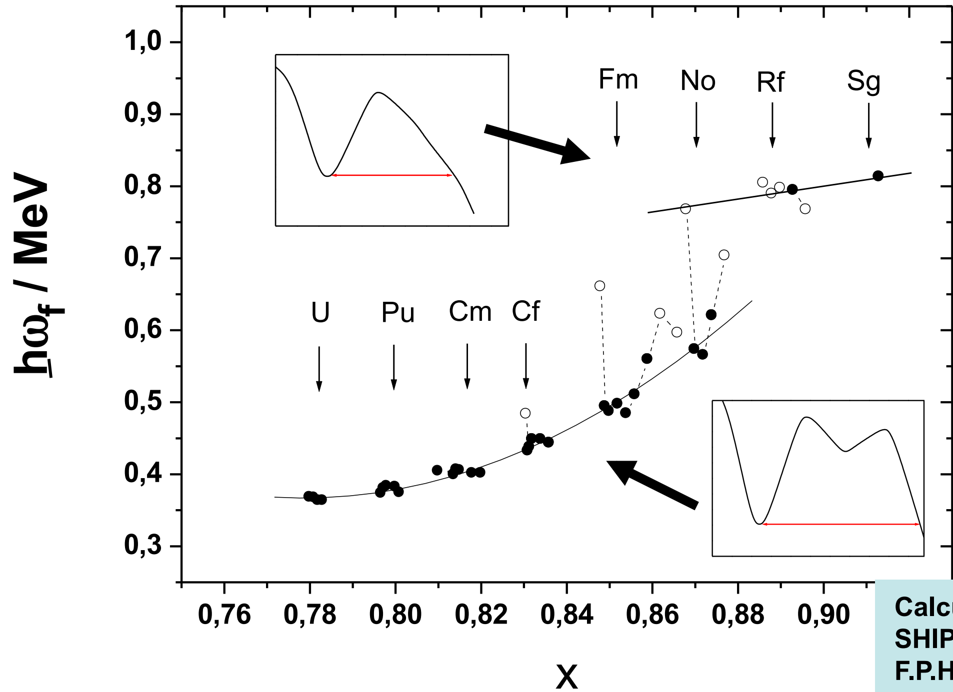
→ increase of fission half-lives towards the deformed neutron shell indicated for Rf, Sg, Hs, (No)

SHIP Data (neutron deficient side): J. Khuyagbaater et al. EPJA 37, 177 (2008), EPJA 46, 59 (2010), F.P. Heßberger et al. Z. Phys. A 359 (1997)

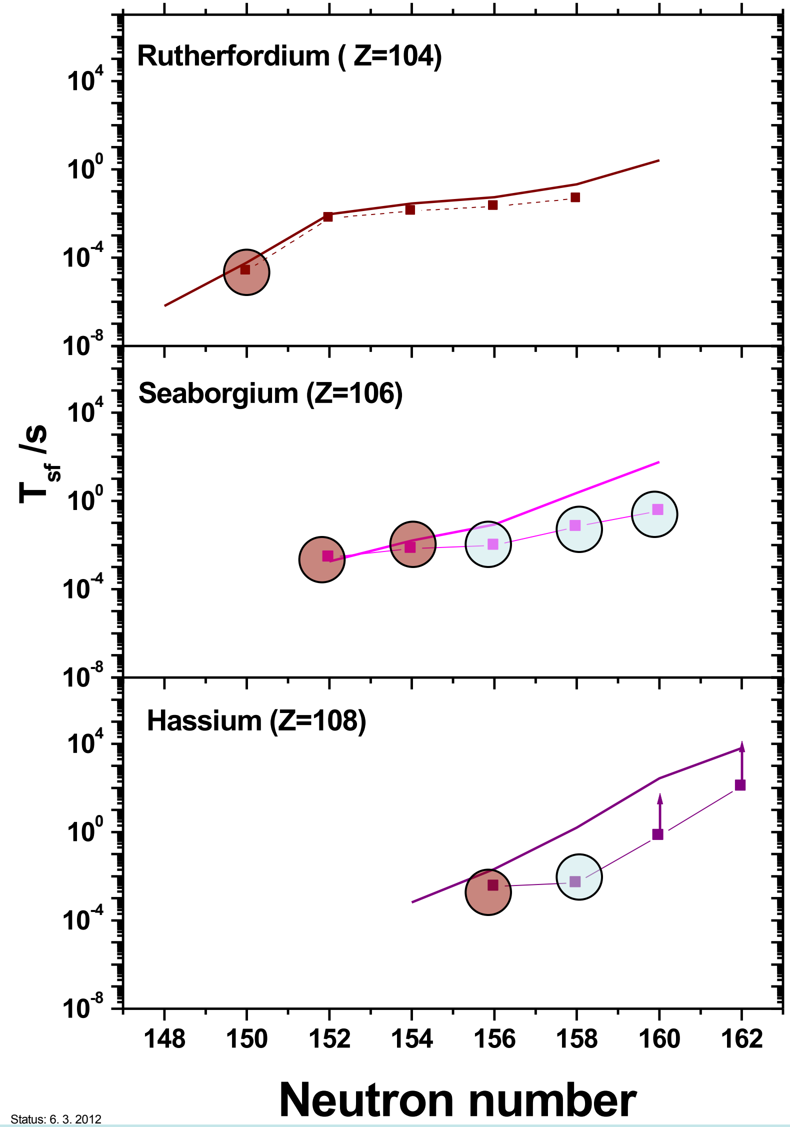
SF halflife systematics of ee - nuclei

Influence of N = 152 shell on SF half-lives disappeared at Z = 104 → 2nd barrier drops below gs (Oganessian et al. 1975, Randrup et al. 1973); effect visible in change of barrier curvature $\hbar\omega_f$ (Heßberger 1985)

Calculations of Smolanczuk et al. (1995) reproduce well SF known in 1995, (● = discovered at SHIP before 1995), deviations for SF discovered after 1995 (○)



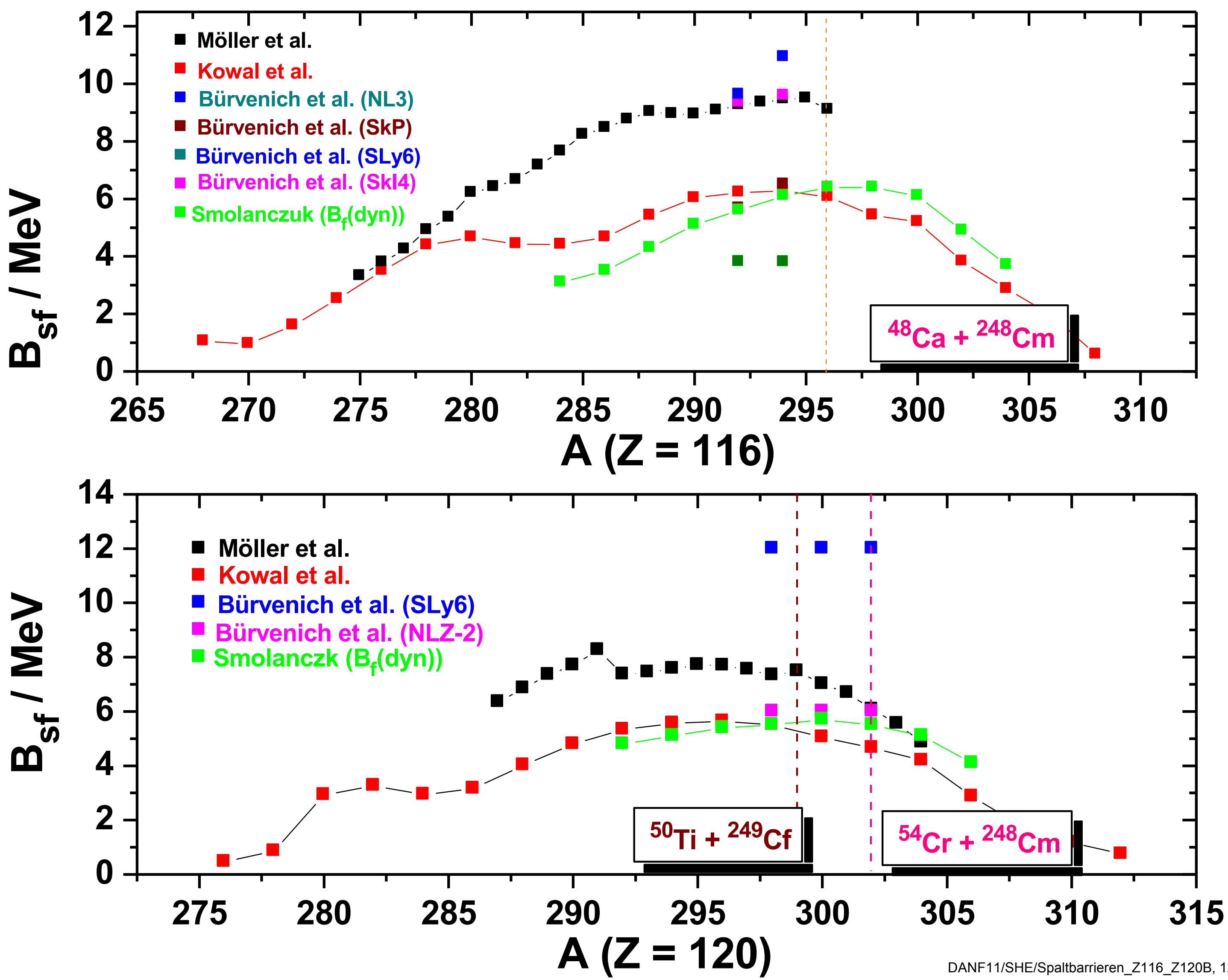
F.P. Heßberger, GSI-Report GSI-85-11 (1985)



Status: 6. 3. 2012

Calculations: R. Smolanczuk et al. PRC 52, 1871(1995)
SHIP-Data: G.Münzenberg et al. ZPA 332,227 (1985), ZPA 324,489 (1986), F.P.Heßberger et al. ZPA 359, 417 (1997), S.Hofann et al. EPJA 10, 57 (2001) K.Nishio et al. EPJA 29, 561 (2006), D.Ackermann et al. To be published

Fission Barriers of SHE

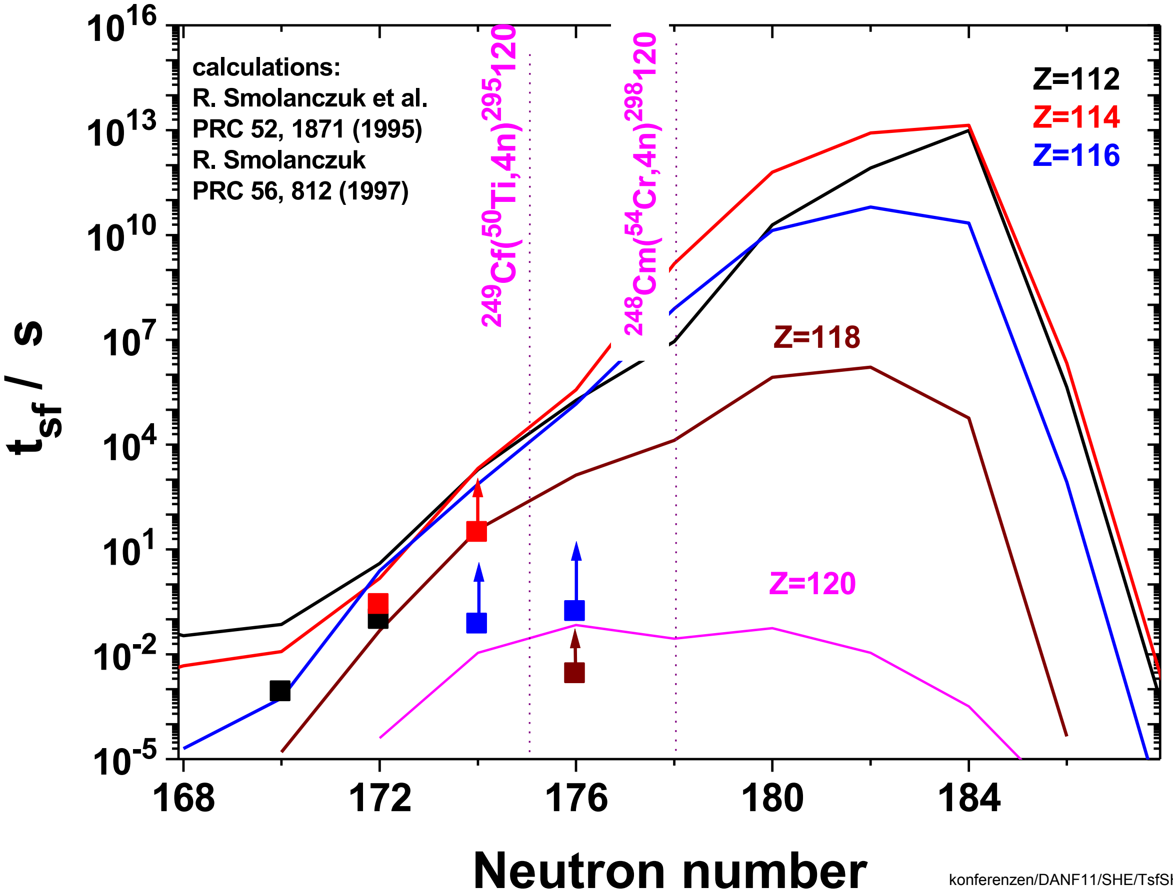


DANF11/SHE/Spaltbarrieren_Z116_Z120B, 12.9.2011

Fission Halflives of SHE

No fission observed for $^{288}114$, $^{290,292}116$, $^{294}118$: lower limits: $>10^{-3} \times T_{sf}$(theo)
T_{sf} of $^{286}114$, ^{282,284}Cn 1-2 orders of magnitude <u>lower</u> than T_{sf}(theo)

Presently exp. on synthesis of El. 120 by ^{248}Cm(^{54}Cr, xn)$^{302-x}$120 (SHIP) and ^{249}Cf(^{50}Ti,xn)$^{299-x}$120 (TASCA) and El. 119 by ^{249}Bk(^{50}Ti,xn)^{299}119 (start on April 26, 2012 (TASCA)) going on at GSI



Predicted (MM) T_{sf} (T_α) for Element 120 isotopes:

^{298}120: 28 ms (1-10 μs)

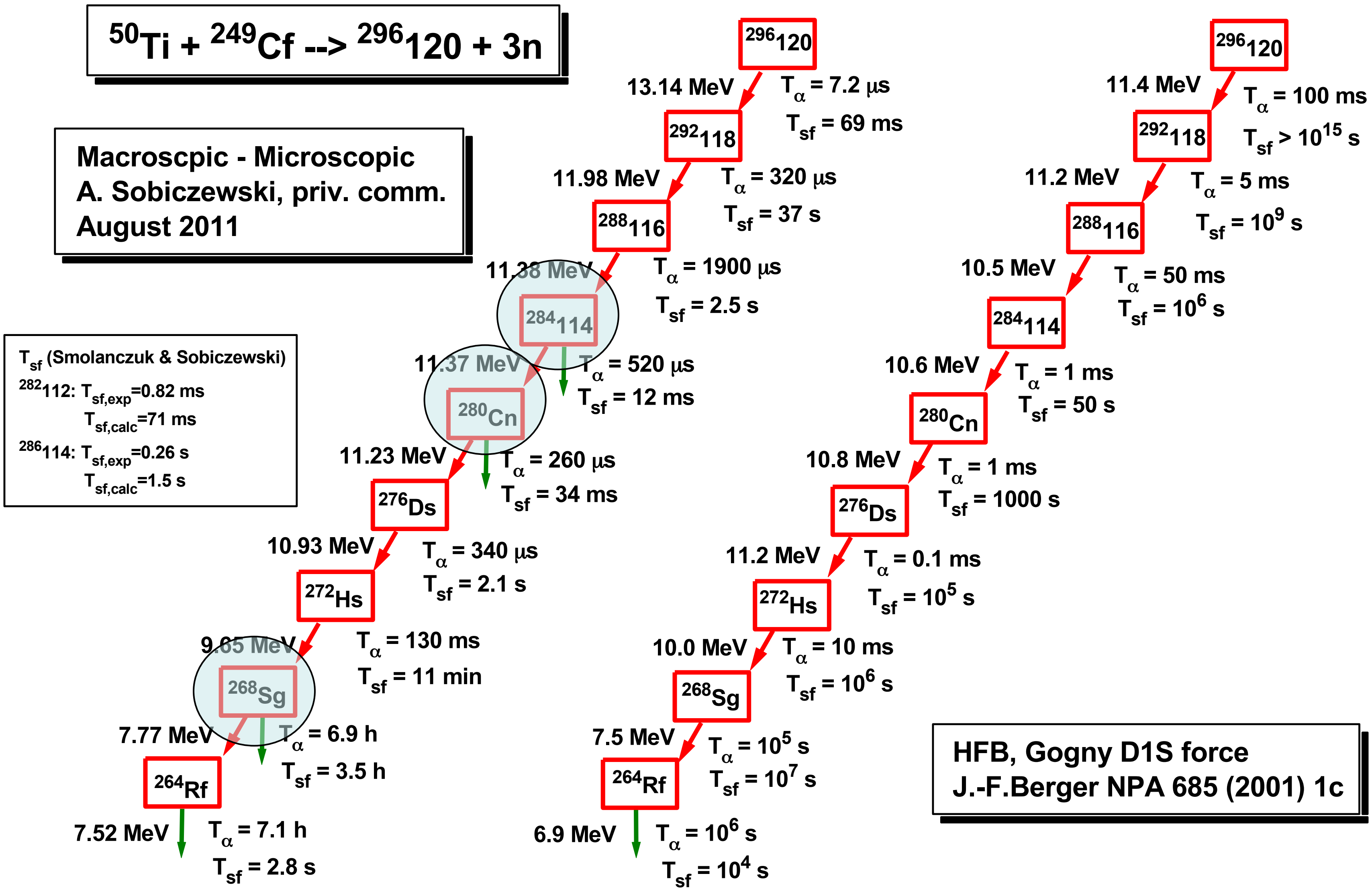
^{295}120: odd-mass nucleus
27 ms(ee) x HF
HF ≈ 1000
(42 μs)

^{296}120: 69 ms
(≈7 μs)

Taking differences of expected values and calculations and variances of fission barrier predictions still can be expected:

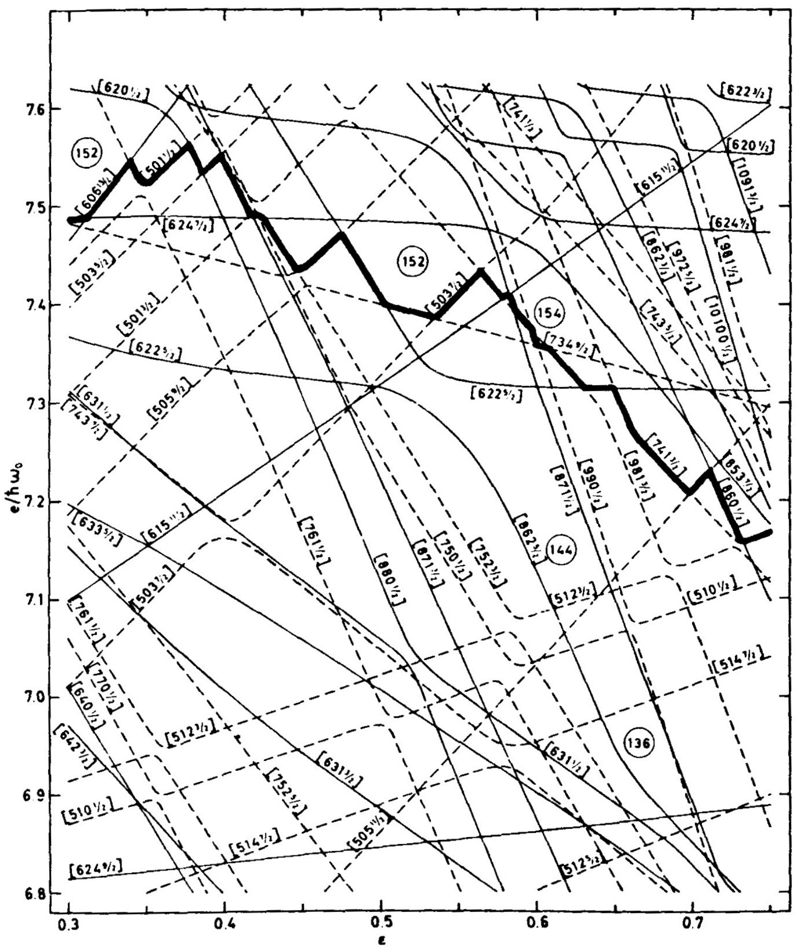
Element 120 isotopes decay by α - emission

Expected Decay Chain for $^{296}120$

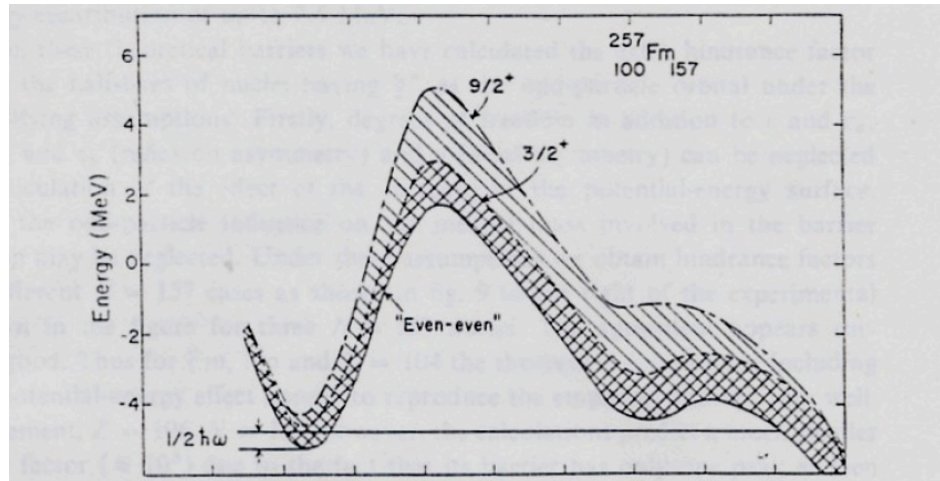


Nuclear Structure and spontaneous fission

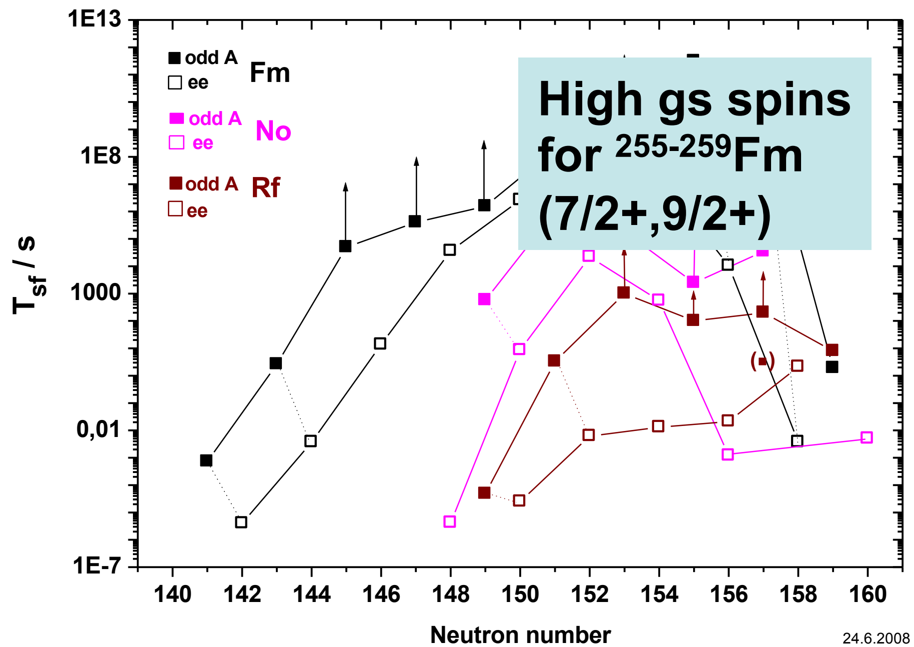
Due to angular momentum conservation fission of nuclei with odd Z, odd N cannot follow the most energetic favourable path
→ effective enhancement of fission barrier (‚specalisation energy‘)
→ enhancement of fission life-times



R. Vandenbosch, J.R. Huizenga, Nuclear Fission (1973)



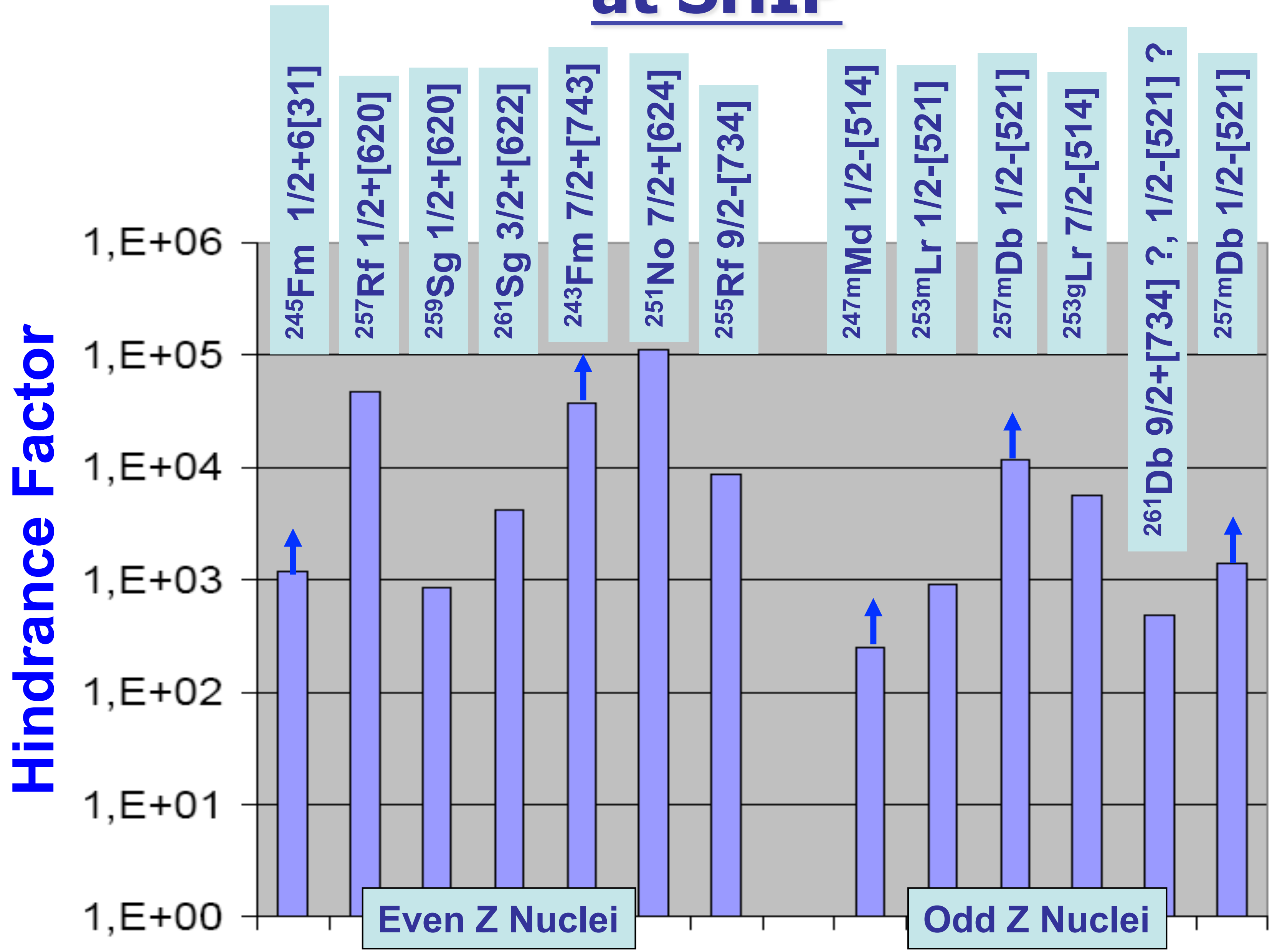
J. Randrup et al. NPA 217, 221 (1973)



High gs spins for $^{255-259}$Fm (7/2+,9/2+)

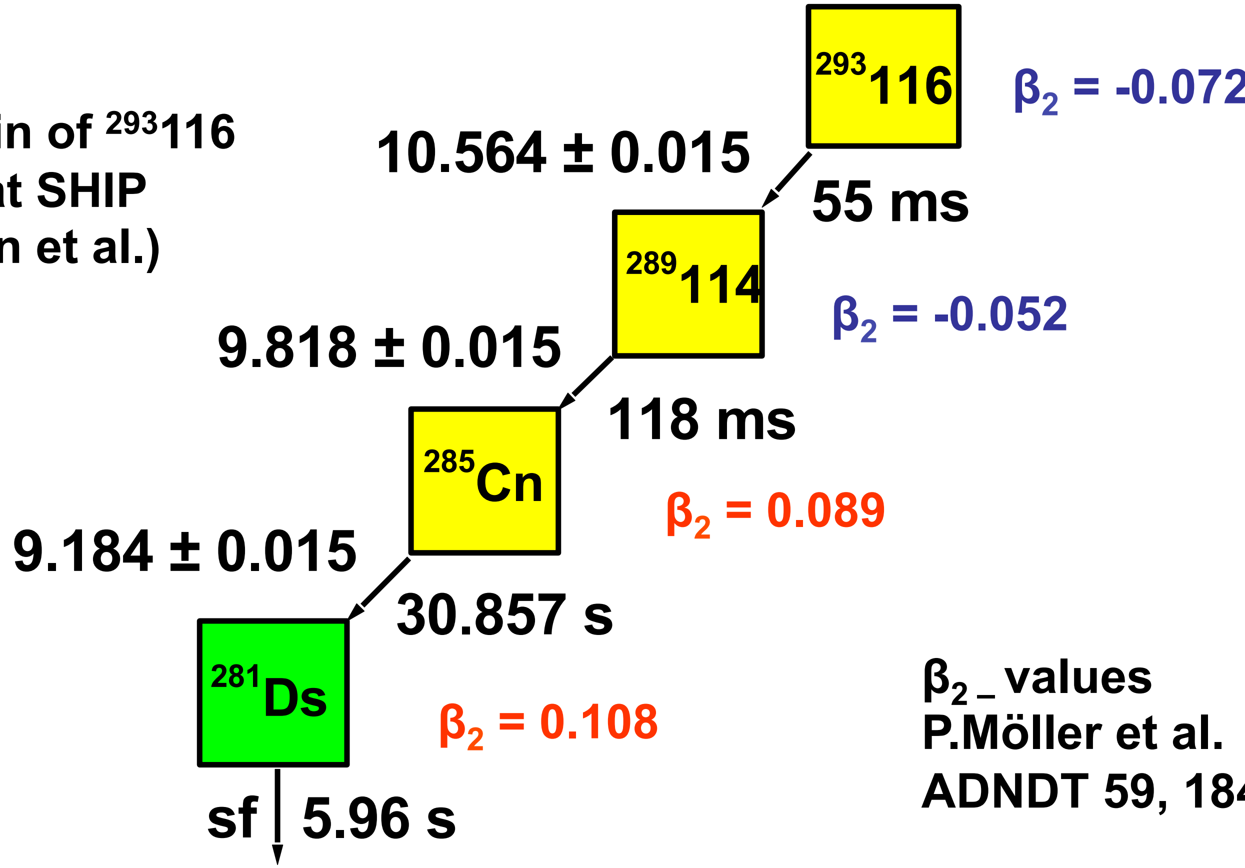
24.6.2008

SF hindrance of odd-A nuclei investigated at SHIP



SF hindrance of oblate nuclei

Example:
Decay chain of ^{293}116
observed at SHIP
(S.Hofmann et al.)

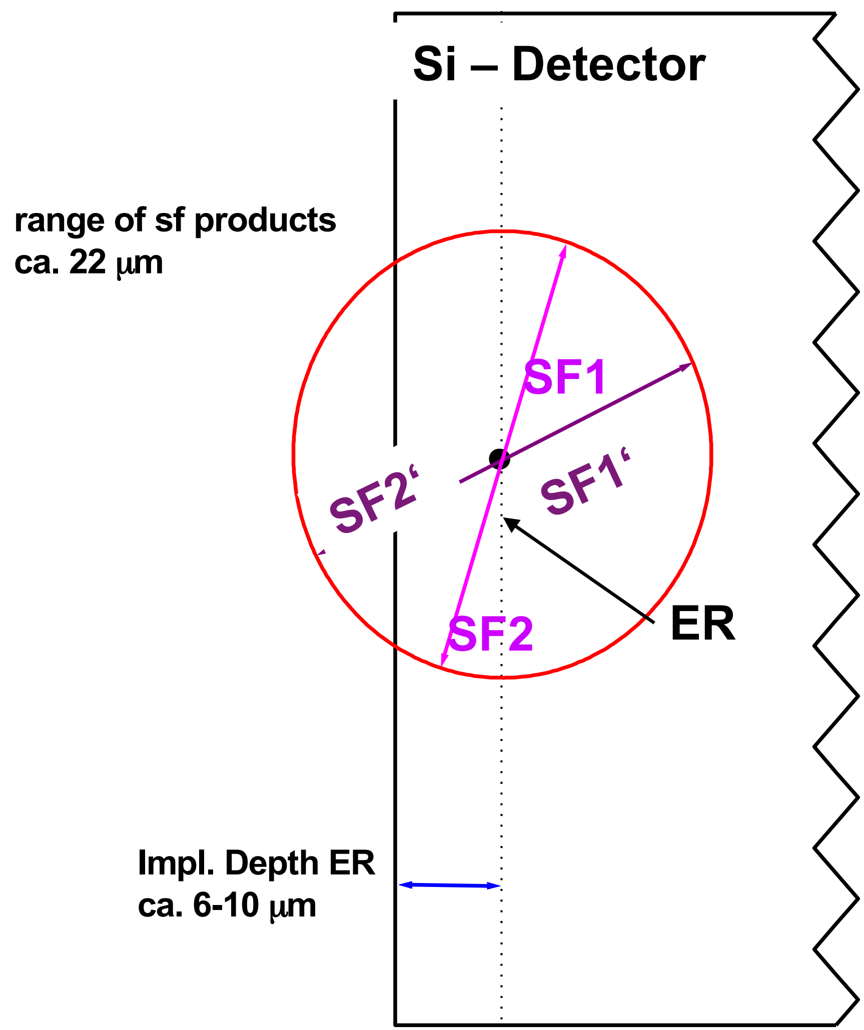


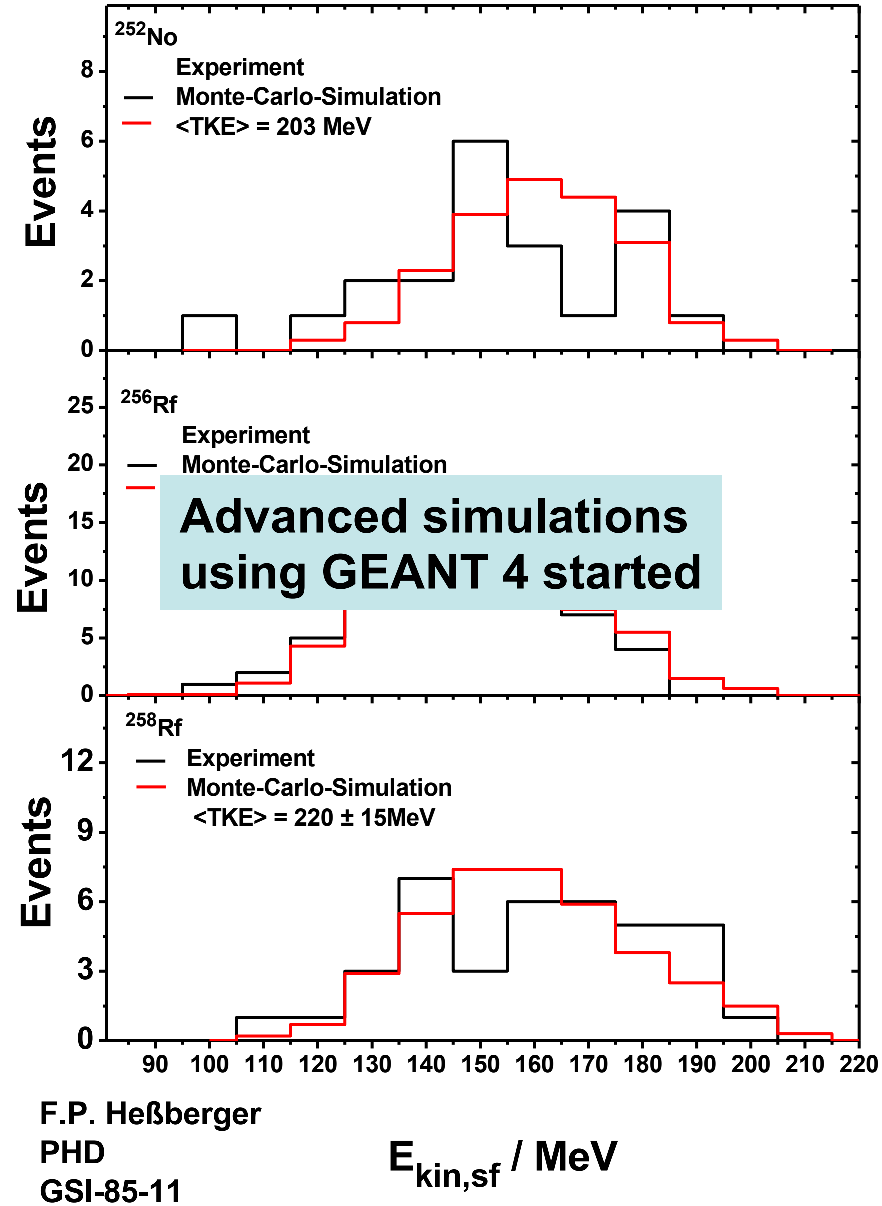
β_2 _ values
P.Möller et al.
ADNDT 59, 1845 (1995)

^{48}Ca + ^{248}Cm --> ^{293}116 + 3n
Decay chain No. 6; 8. 7. 2010 19:54 h

TKE - Distributions

Implantion depth of ER < range of SF products → p(sf1+sf2) ≈ 40 %; large PHD due to high ionisation density

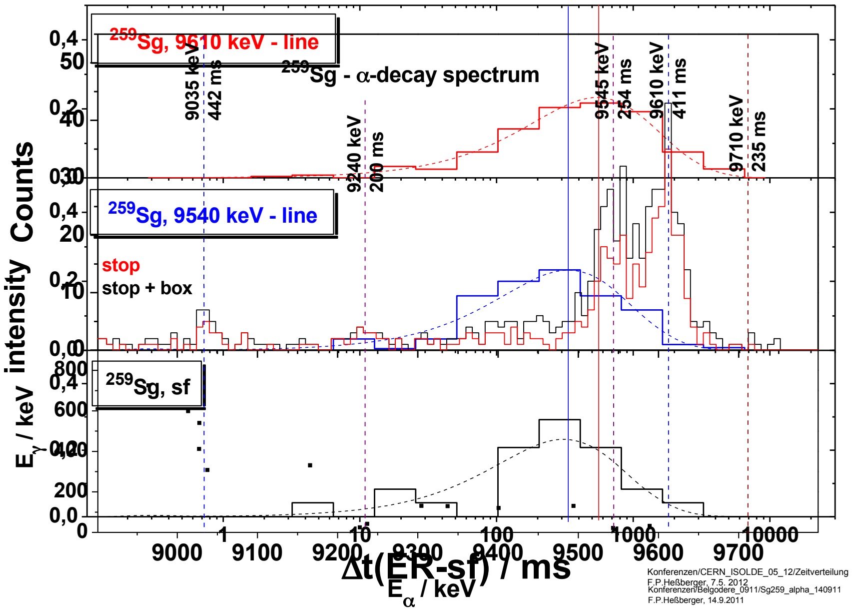




Advanced simulations using GEANT 4 started

F.P. Heßberger
PHD
GSI-85-11

SF properties of ^{259}Sg



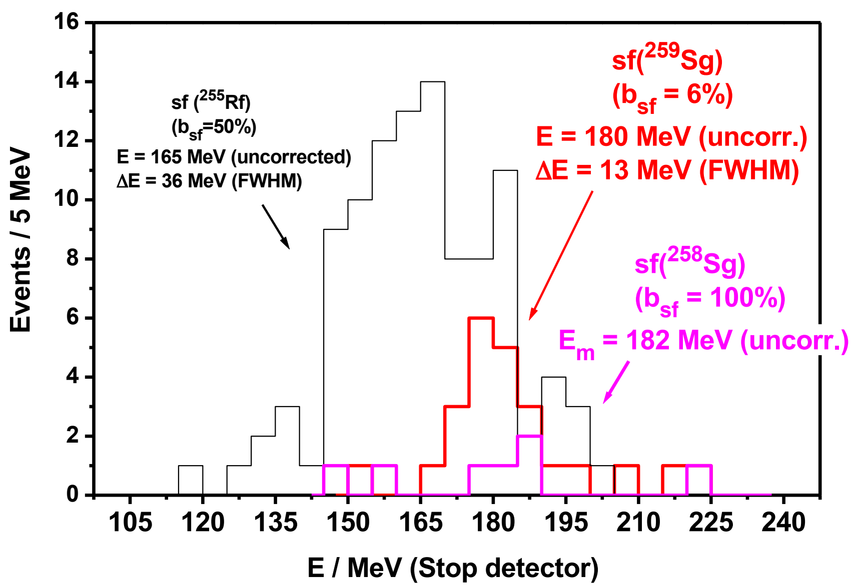
Fission Properties of ^{259}Sg

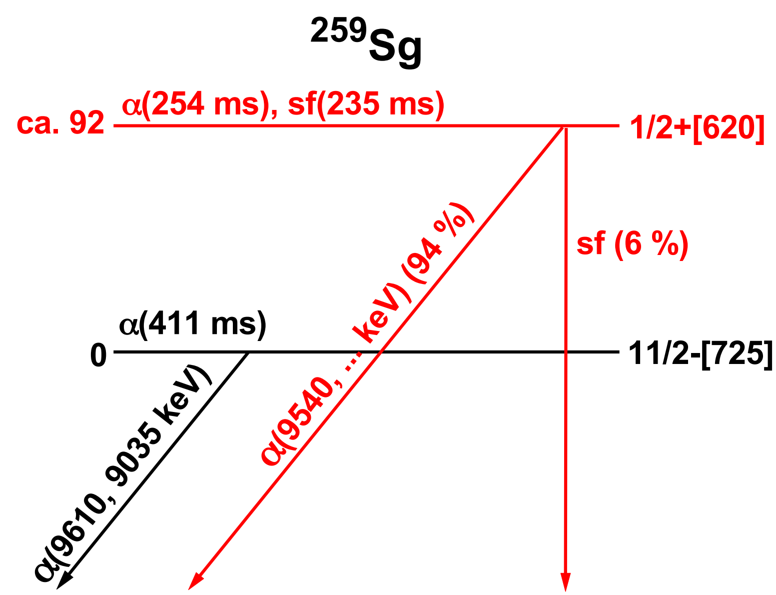
a) $b_{sf} \approx 6\%$

b) $T_{1/2}$ = 235 +62/-41 ms

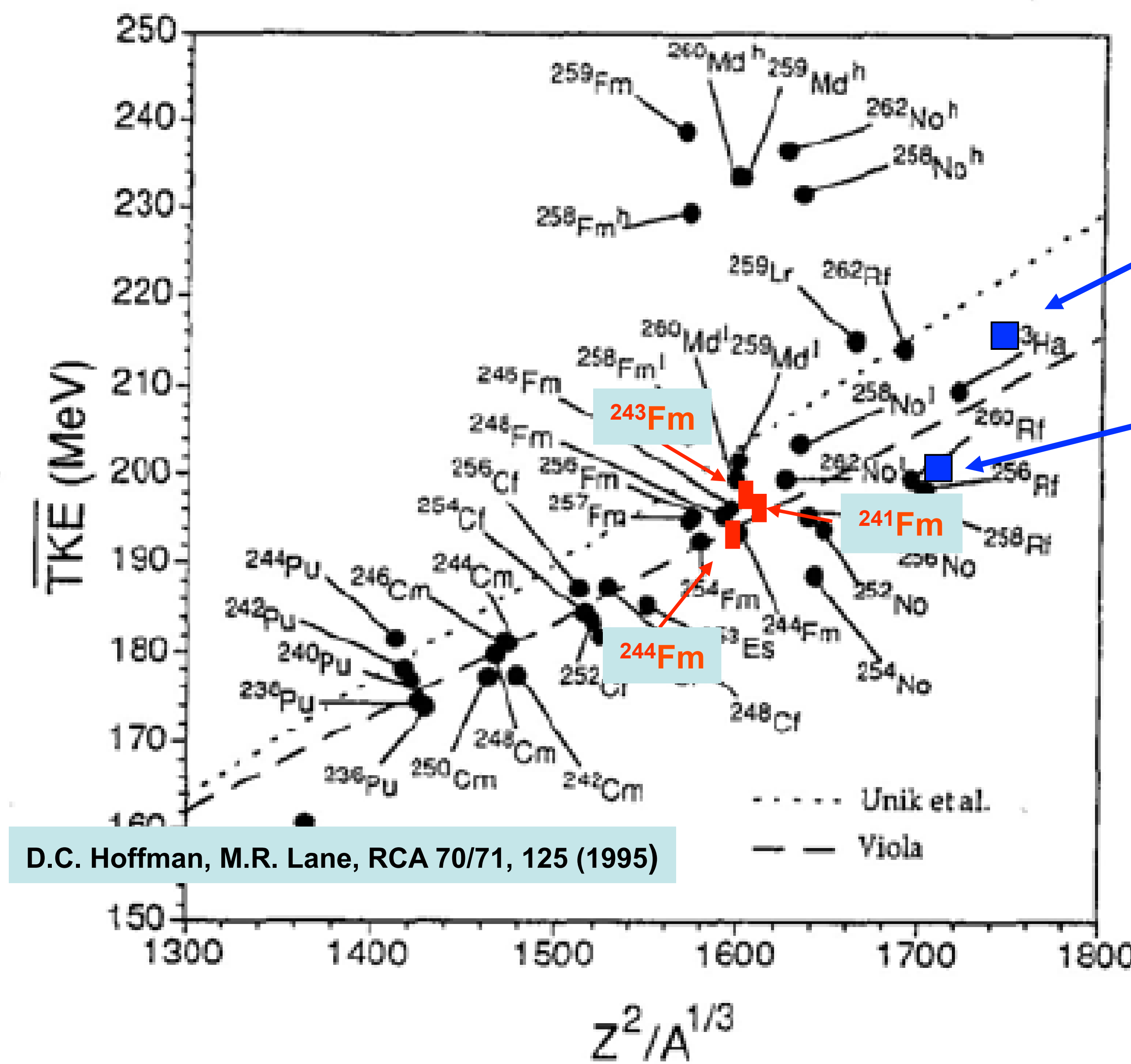
c) TKE (sf, ^{259}Sg) ≈ 12% higher than TKE(sf, ^{255}Rf)

d) TKE distrib. for sf of ^{259}Sg narrower than for sf of ^{255}Rf
→ transition from asymmetric to symmetric fission assumed





TKE - Distributions



≈ 215 MeV (^{259}Sg) (preliminary)

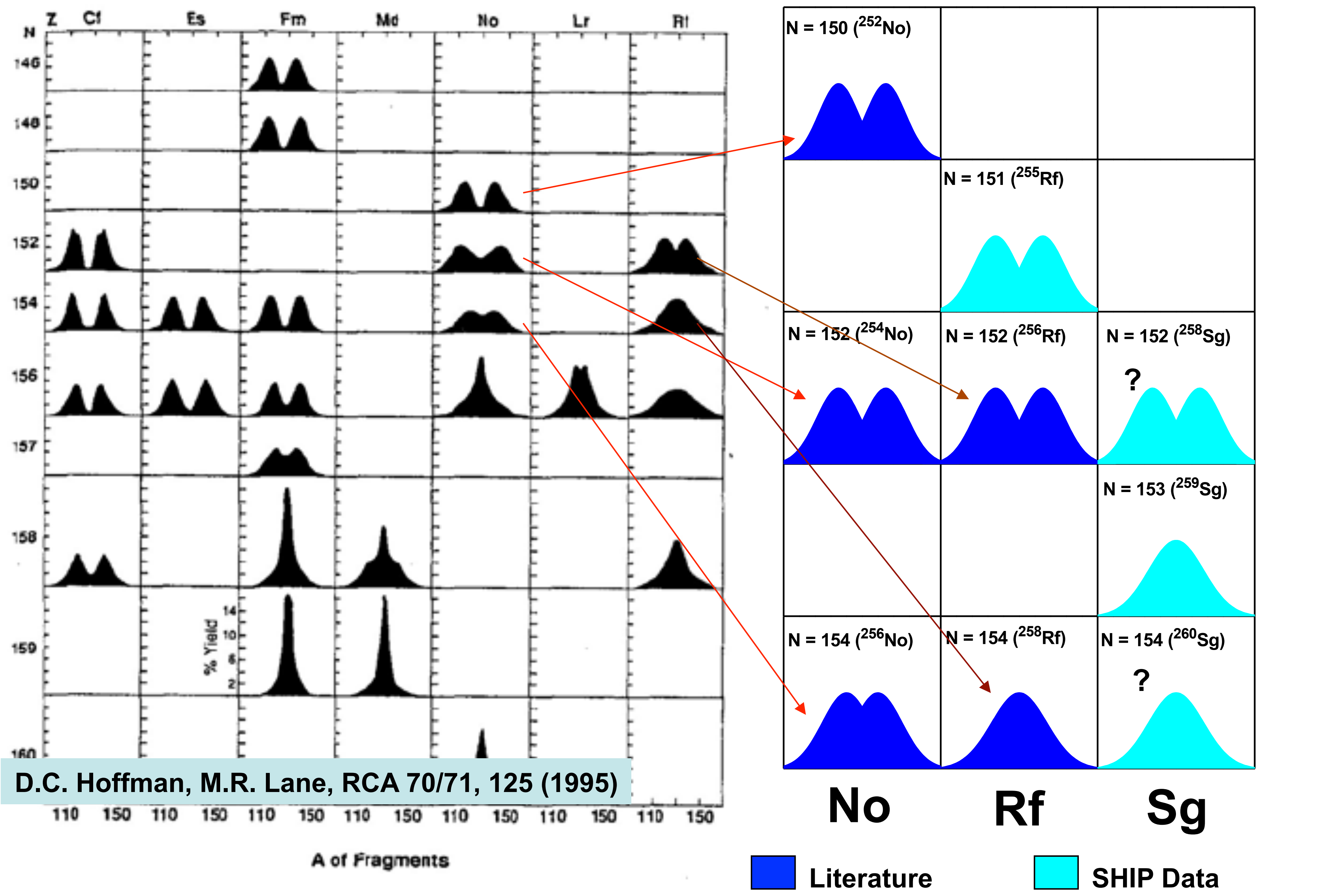
≈198 MeV (^{255}Rf) (preliminary)

Published Results:
(J. Khuyagbaatar et al. EPJ A 37, 177 (2008))

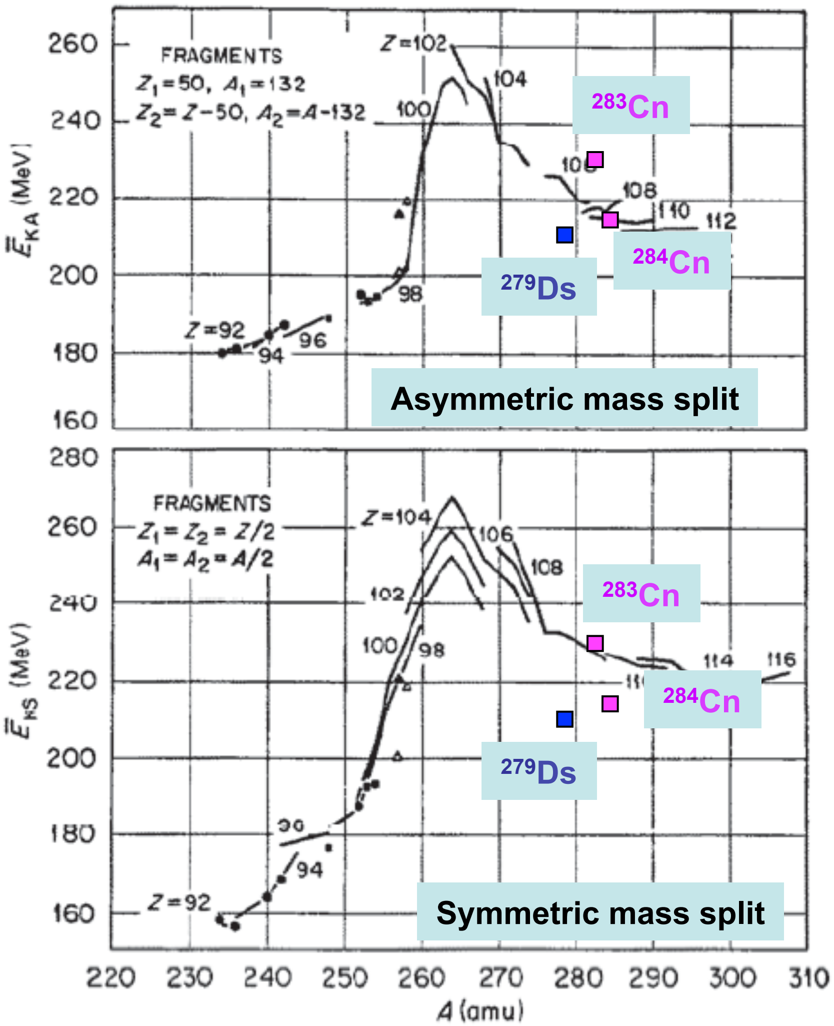
^{244}Fm: 193 ± 12 MeV (194 MeV*)
^{243}Fm: 198 ± 15 MeV
^{241}Fm: 196 ± 10 MeV

*Literature

Transition from asymmetric to symmetric fission

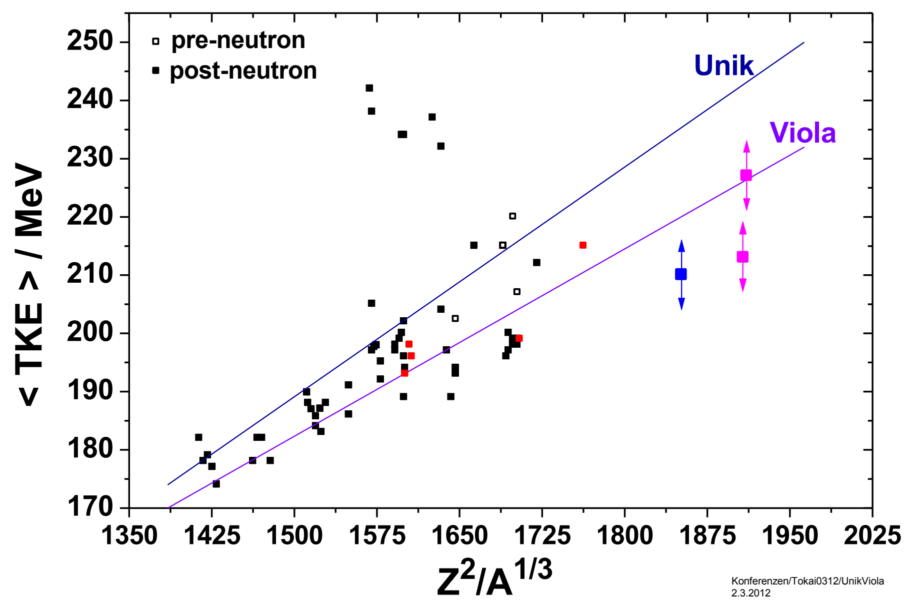


TKE of Superheavy Elements



H.W. Schmitt, U. Mosel, NP A186, 1 (1972)

Estimation of TKE on basis of few events is dangerous !!
Nevertheless:
data indicate that fission energies of ^{283,284}Cn and ^{279}Ds follow the trend of predictions by Schmitt and Mosel and Viola systematics



SHIP Data: S. Hofmann et al. EPJA 32, 251 (2009)
S. Hofmann et al., in press

Spontaneous Fission of K - Isomers

K – isomers are multi qp – configurations
➔ SF expected to be strongly hindered

^{254m1}No: Assigned as 2qp – state with $K^{\pi} = 8^{-}$

Previous limit: $b_{sf} \lesssim 2 \times 10^{-3}$ (Yu. A. Lazarev et al. Phys. Scr. 39, 422 (1989)
$b_{sf} = (2.0 \pm 1.2) \times 10^{-4} \rightarrow T_{sf} \approx 1400$ s; $T_{sf,calc} \approx 1$ s $\rightarrow$ HF ≈ 1400
$T_{sf}(iso) / T_{sf}(gs) \approx 0.06$

^{254m2}No: Assigned as 4qp – state with $K^{\pi} = 16^{-}$ or 16^{+}
$b_{sf} \lesssim 1.3 \times 10^{-4} \rightarrow T_{sf} \gtrsim 1.5$ s; $T_{sf,calc} \lesssim 0.5$ µs $\rightarrow$ HF > 3×10^{6}

Previously known:

^{256m}Fm
$E^* = 1425$ keV, $K^{\pi} = 7^{-}$, $T_{1/2} = 70$ ns
$b_{sf} = 2 \times 10^{-5} \rightarrow T_{sf} = 3.5$ s
$T_{sf} = 10400$ s
$T_{sf}(iso) / T_{sf}(gs) \approx 0.00034$

Challenges & Future Requirements

- Mapping the Charts of Nuclei
  → Connecting the ‚Dubna-Island' to the known ridge
- Location of the spherical proton and neutron shells
  → Element 120 isotopes' properties are decisive
- (Detailed) Understanding of nuclear structure required
  (also with respect of development of nuclear theories)
  → In-beam spectroscopy
  → decay spectroscopy
- Spontaneous fission properties
  → halflives, TKE, mass splits

- Higher beam intensities required (also for chem., atom. phys., masses)
  →(at GSI) new cw – Linac
- overcomes disadvantages of implantation technique
- isotonic and isobaric ‚clean' samples for spectroscopy
- new separators
- ‚dual use' of the beam

7.5 AMeV cw – LINAC for the GSI – SHE Program

Proposal submitted September 2009 (W. Barth, GSI) (not yet funded)

<u>Cooperation:</u> GSI Darmstadt, Helmholtz Institute Mainz, Inst. Applied Phys. Goethe Universität Frankfurt

Main Features:

(→ new 28 MHZ ECR source, in progress)
(→ new RFQ, in commissioning)
→ energy range 3.5-7.3 AMEV
→ 100% duty cycle (presently 25%)
→ intensity increase (> x10)
→ improved beam quality

General parameters of superconducting energy variable heavy ion linac

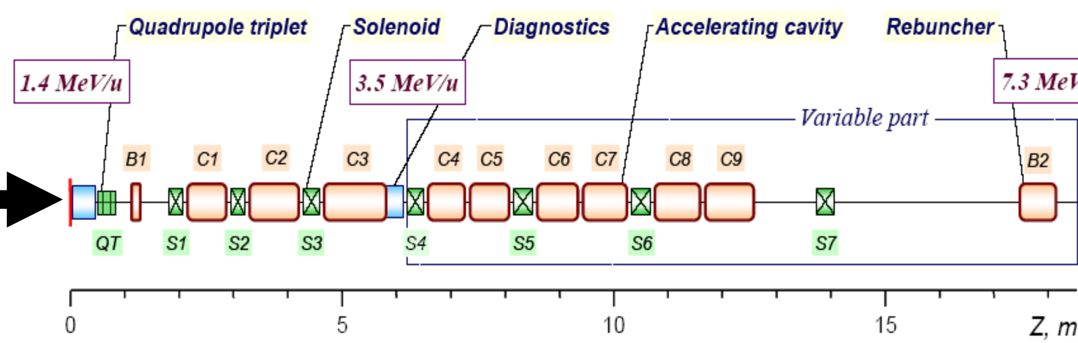
Charge-to-mass ratio		1/6
Operating frequency	*MHz*	216.816
Beam current	*mA*	1
Injection energy	*MeV/u*	1.39
Input transverse emittance (norm., from HLI)	*mm·mrad*	0.8·π
Input longitudinal emittance (norm., from HLI)	*keV/u·ns*	1.9
Output energy	*MeV/u*	3.51 – 7.30
Output energy spread	*keV/u*	± 3
Transverse rms emittance growth	*%*	5
Longitudinal rms emittance growth	*%*	6
Total length with debunching drift	*m*	18.5
Length of accelerating part	*m*	12.7
Number of SC accelerating cavities		9
Number of SC solenoids		7

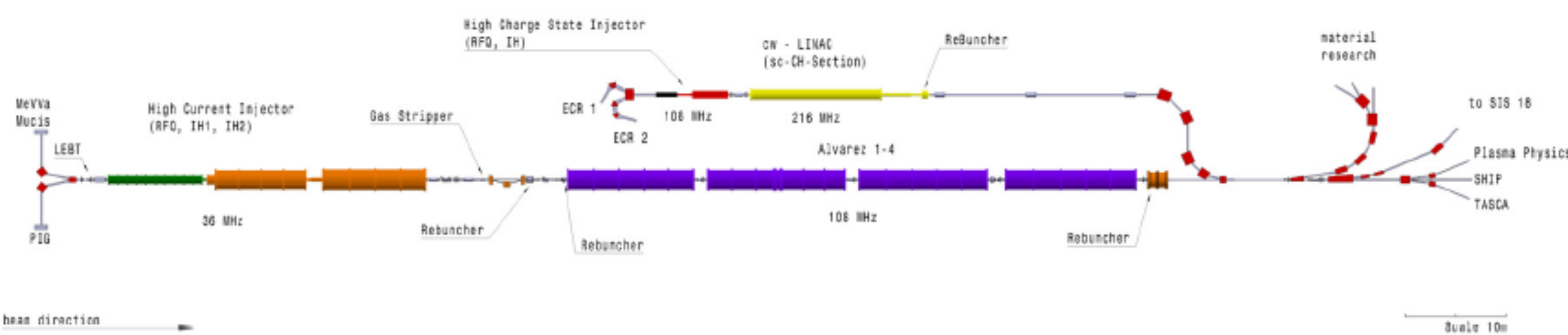
<u>Upgrade – presently in progress</u>

28 GHz ECR – source +

→

High Charge Injector (RFQ, IH)

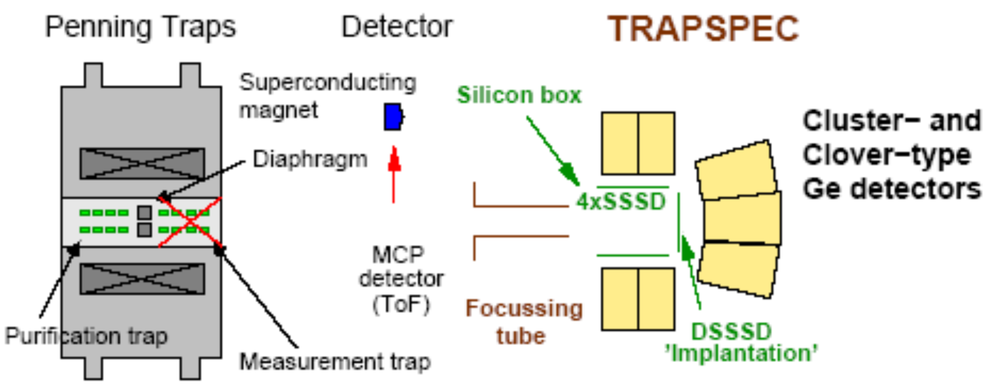




TRAP assisted spectroscopy

First Commissioning Experiment in September 2009:

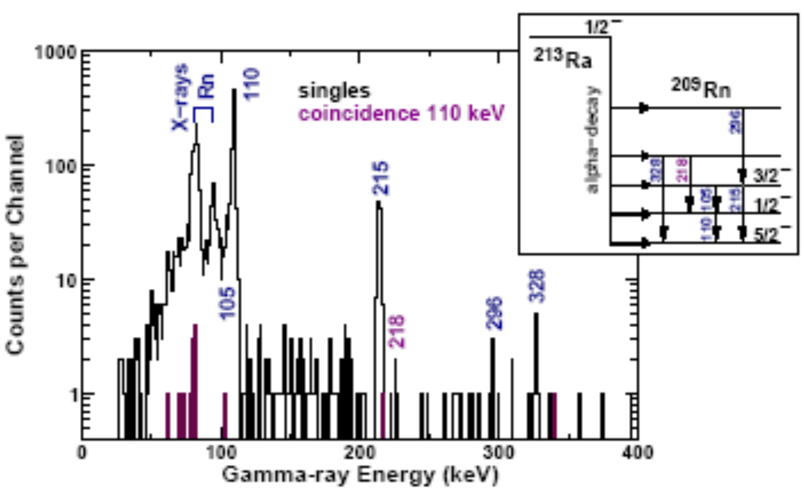
$^{170}Er(^{48}Ca,5n)^{213}Ra$

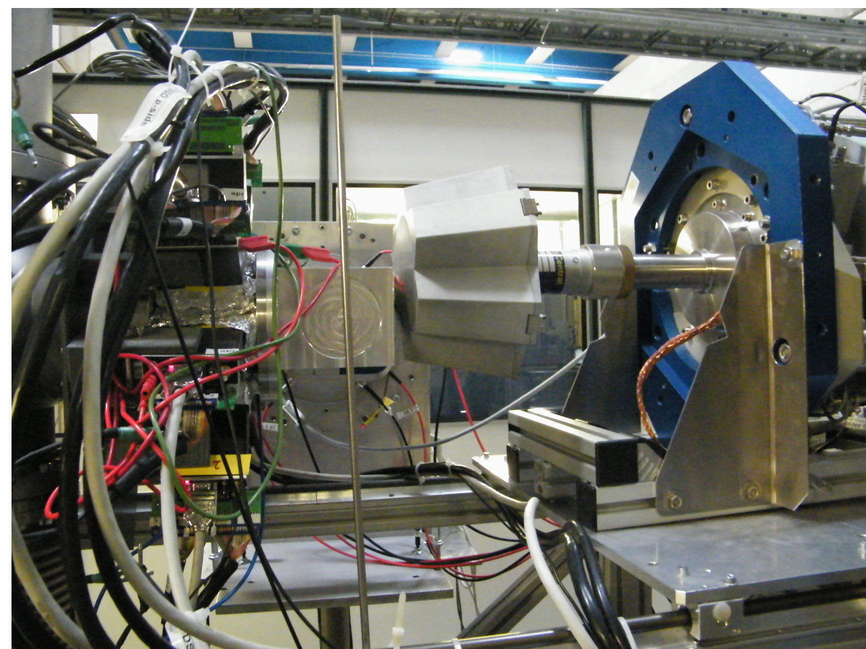


Main features:

→ Clean samples, mass separated (no admixtures with isotones)

→ Avoid energy summing of α-particles with conversion electrones

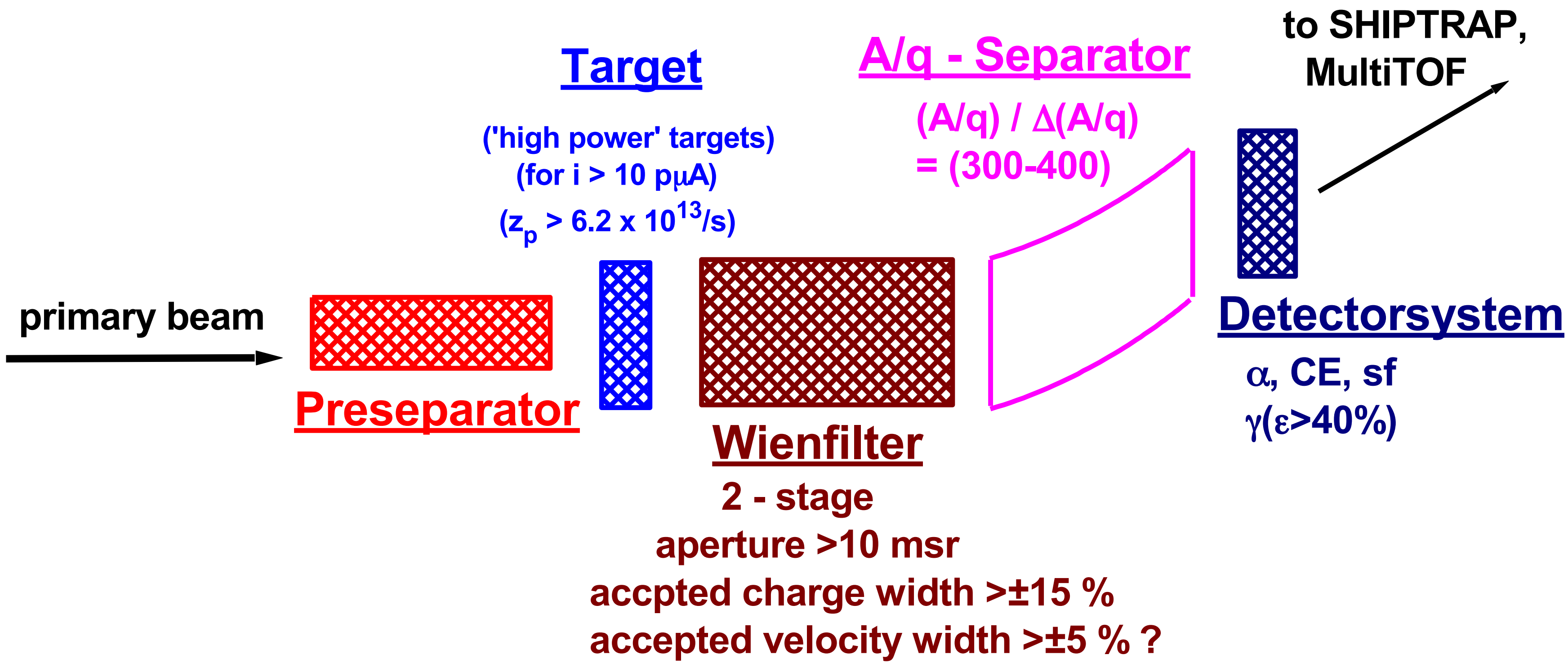




New Separators

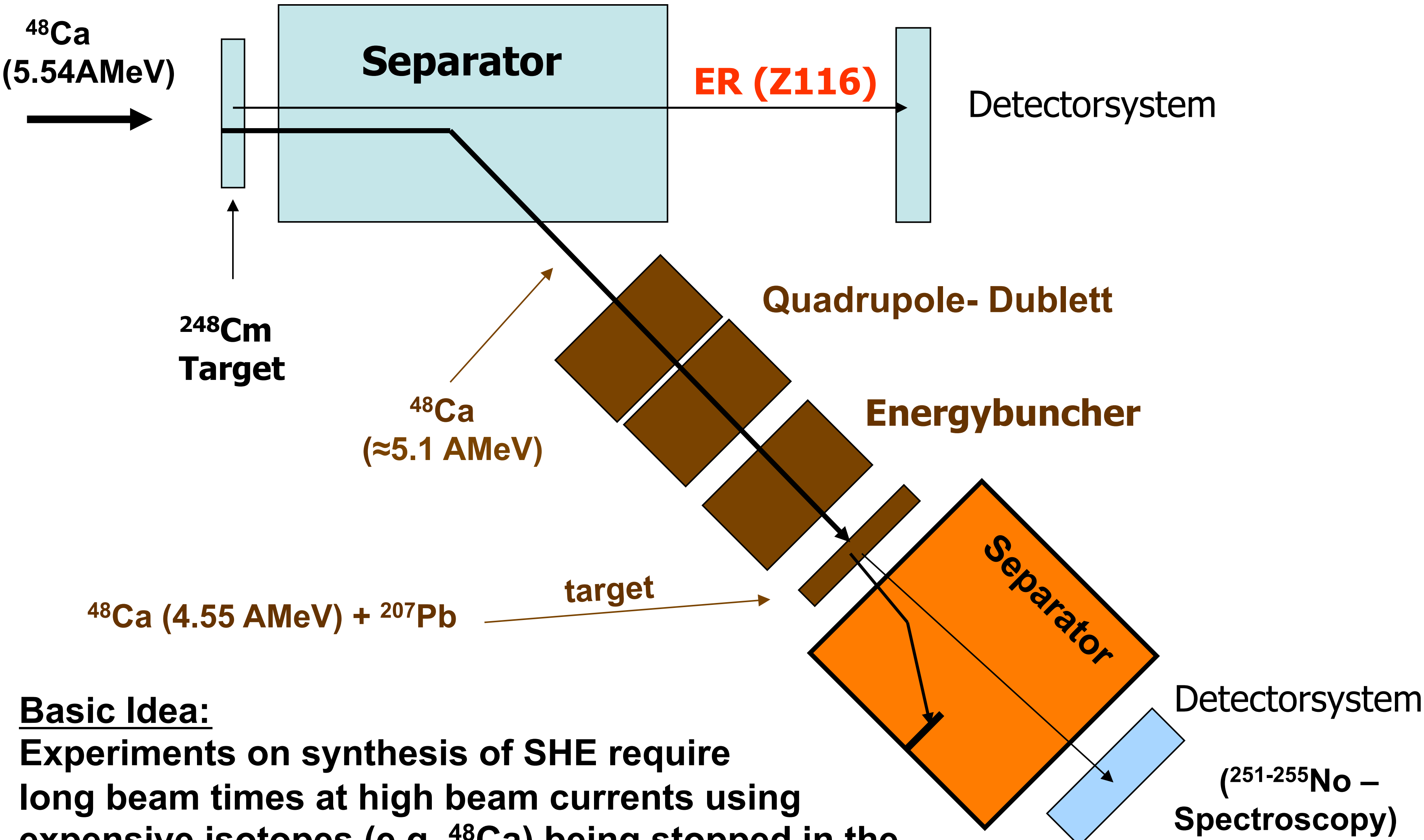
(under consideration)

Replacement of SHIP,
in operation since 1976



F.P. Heßberger, Proc. Int. Conf. ‚Beyond 2010‘, Cape Town, SA, Feb. 2010, (World Scienfic), 675 (2011)

Reactions using ‚Secondary Beams‘



Basic Idea:

Experiments on synthesis of SHE require long beam times at high beam currents using expensive isotopes (e.g. ^{48}Ca) being stopped in the Beamdump; a second use seems appropiate.

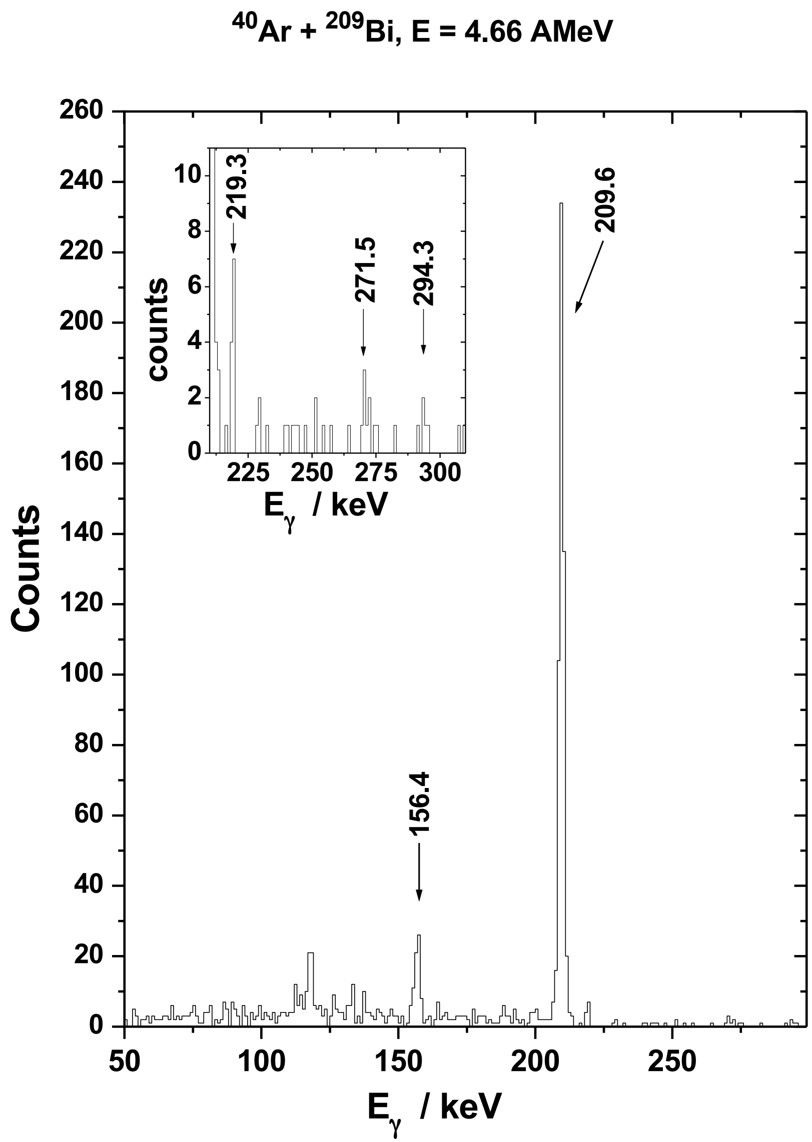
Conclusion

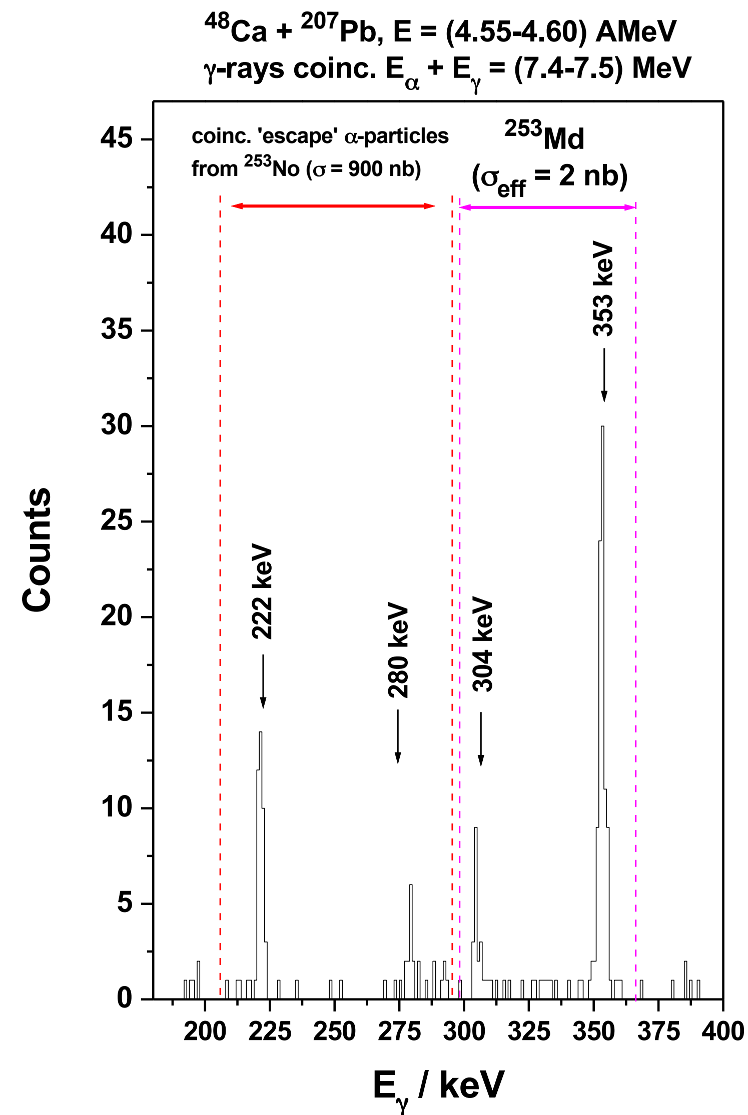
On and on `cause the road is never ending

- at least we know that we are on our way !

Fiddler‘s Green - On and on

Systematics of Nilsson-Levels in Es - Nuclei
Studied by α-γ Coincidence Measurements of Md-Isotopes

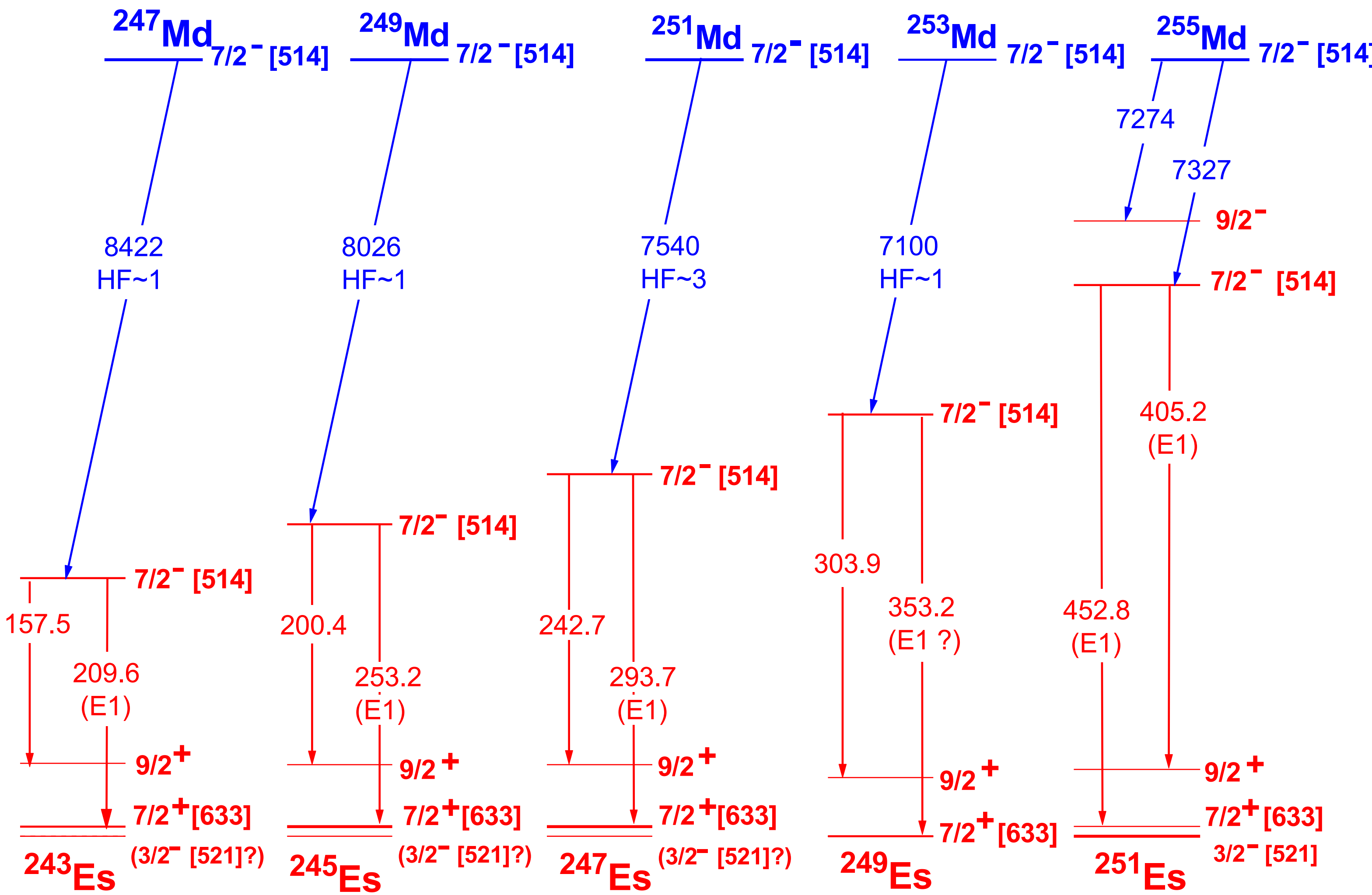




konferenzen/TAN0907/Md253alga
F.P.Heßberger 18.9.2007

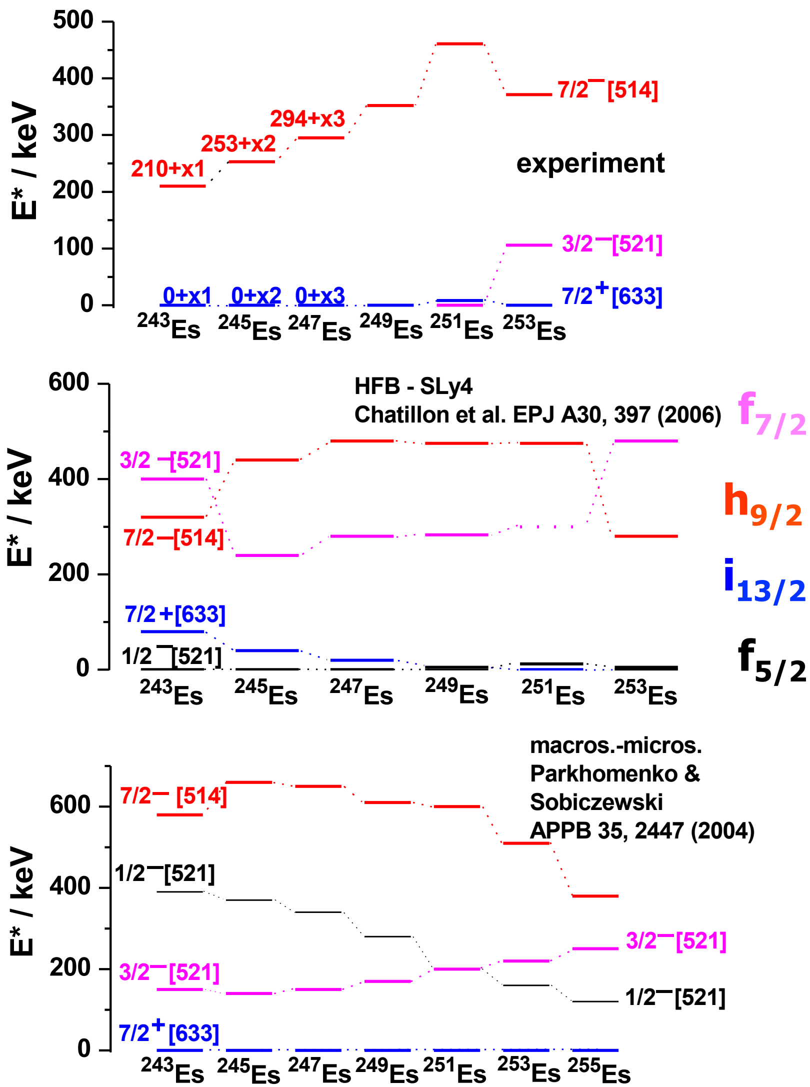
Decay schemes of odd-mass Md-isotopes

(simplified)

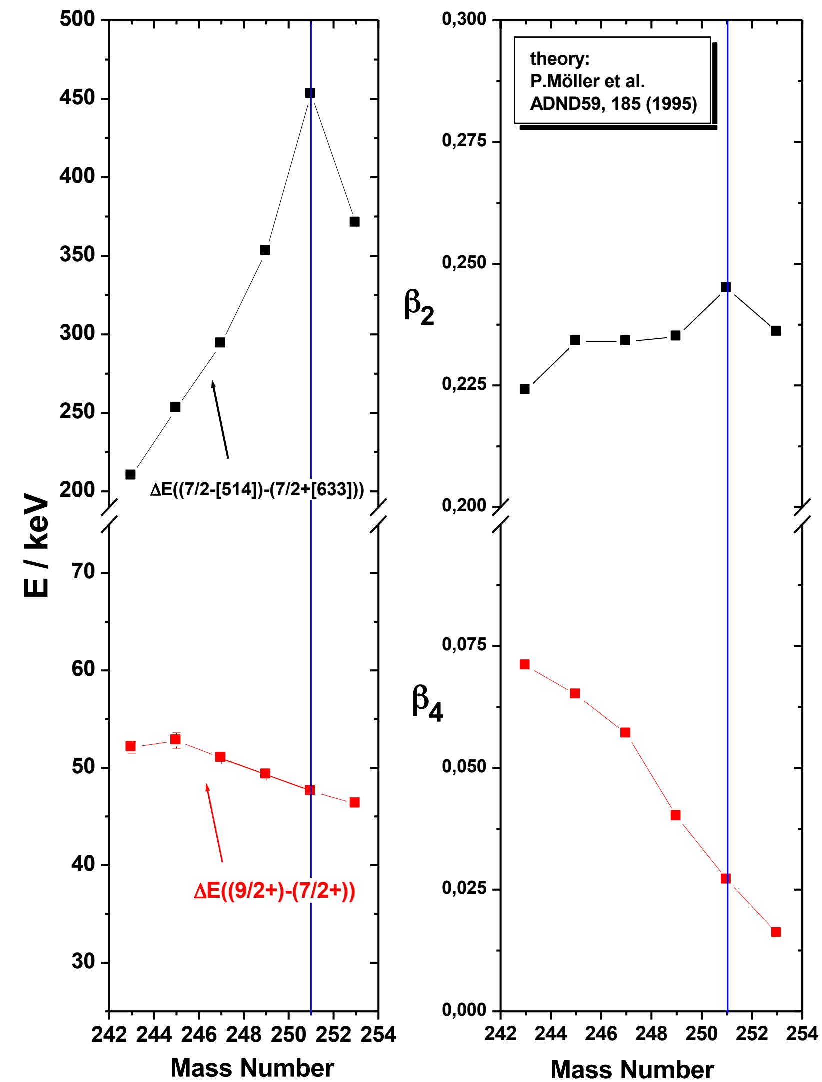


graph/demo/nivmend
F.P.Heßberger 2.6.2006

Nilsson levels in odd-mass Es – isotopes exp. results and theoretical predictions



STrukturSWK/Abbildungen/mdvergleich, F.P.Heßberger 18.2.2010



StrukturSWK/Abbildungen/Es_Isotope_deformation
18.2.2010