Exploration of Nuclear Structure and Decay of Heaviest Elements at GSI - SHIP

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NN2015
12th International Conference on Nucleus – Nucleus Collisions
Catania, Italy
21 – 26 June 2015

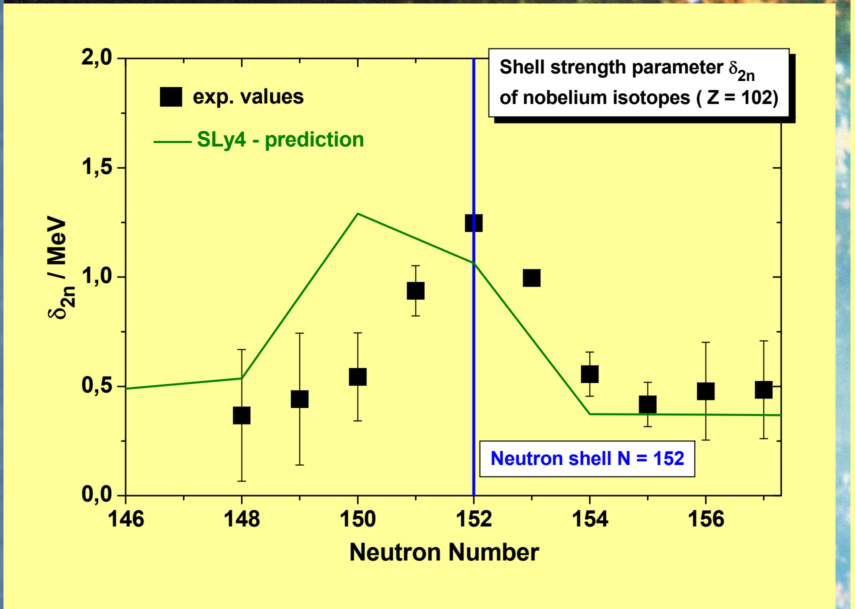
Version 18. 6. 2015

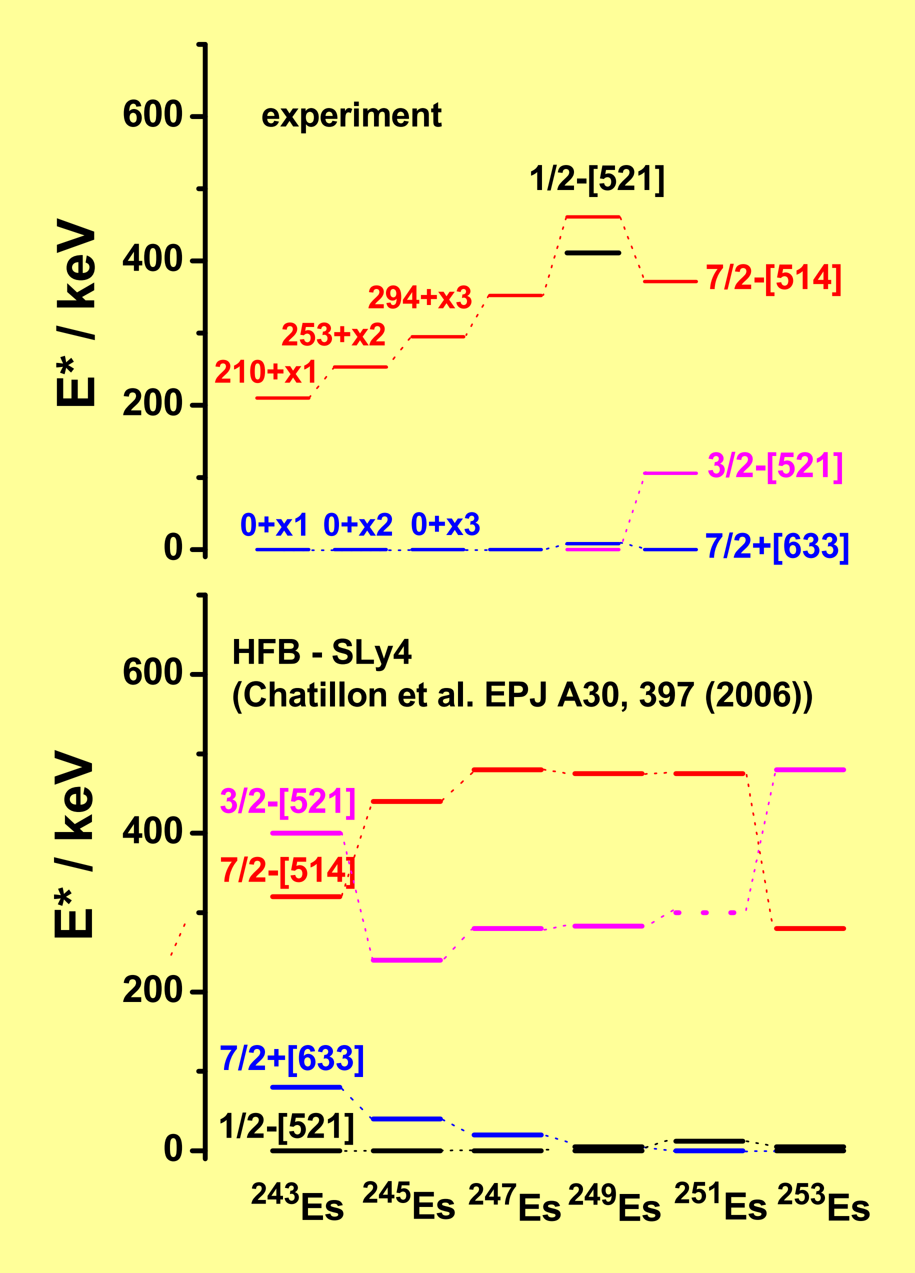
<u>The Strong Force</u>

One of the four basic interactions, playing among others an essential role for

→ Quark – Gluon - Plasma
→ Formation and development of stars
→ Development of the universe
→ Synthesis of the chemical elements
→ <u>Structure of the atomic nuclei</u>

The Strong Force





Physics Motivation for Synthesis and Nuclear Structure Investigations of SHE

Why synthesis and nuclear structure investigations ?

→Atomic nucleus is quantum mechanical ensemble of nucleons (p, n)

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

→Understanding decay properties and structure of nuclei is thus essential for understanding ‚fundamental' interactions

→Superheavy nuclei (SHE) are a specific class of exotic nuclei
- → ensembles of ‚extremely' large numbers of protons and neutrons
- → despite of high density of nuclear levels ‚gaps' between single particle states occur at certain numbers of Z and N indicating ‚shell closures'
- → no macroscopic (‚collective') fission barrier any more, stability against prompt disruption due to ‚shell effects'; B_f depends on single particle levels
- → shell structure determines nuclear mass excess → determines Q-values for α- and β- decay

Physics Motivation for Synthesis and Nuclear Structure Investigations of SHE

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

i.e. the ´limits of our world´

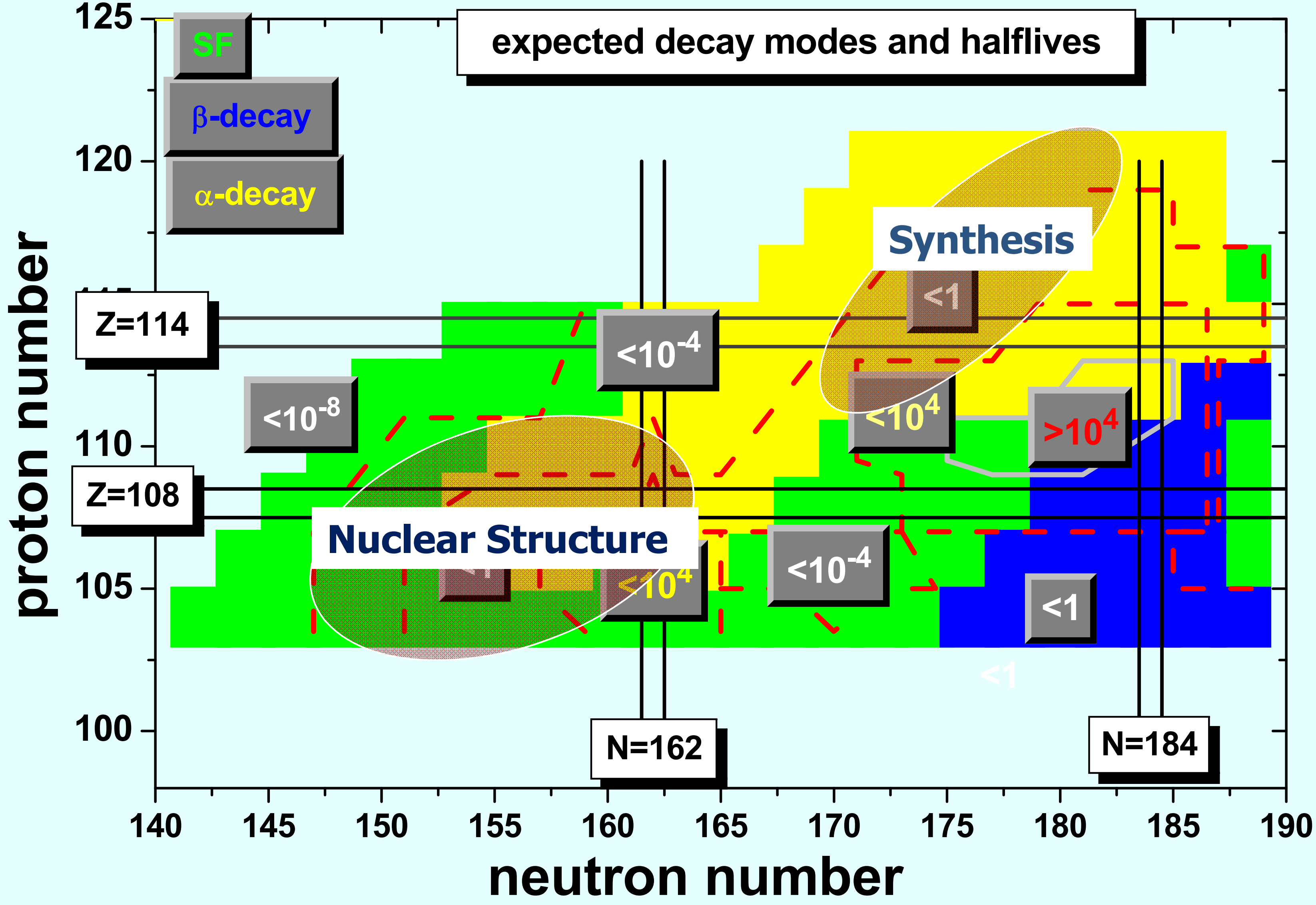
Topic Questions

→ Are there proton and neutron shells at all ?

→ How strong are they ?

→Where are they located ?

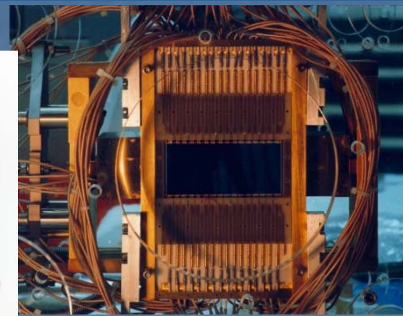
Expected Decay Modes and Halflives of SHE

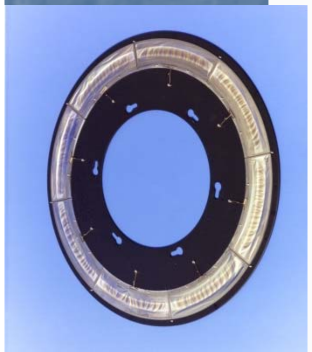


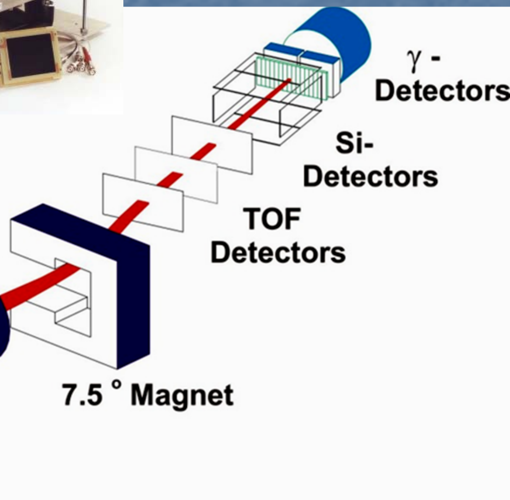
Velocity separator SHIP

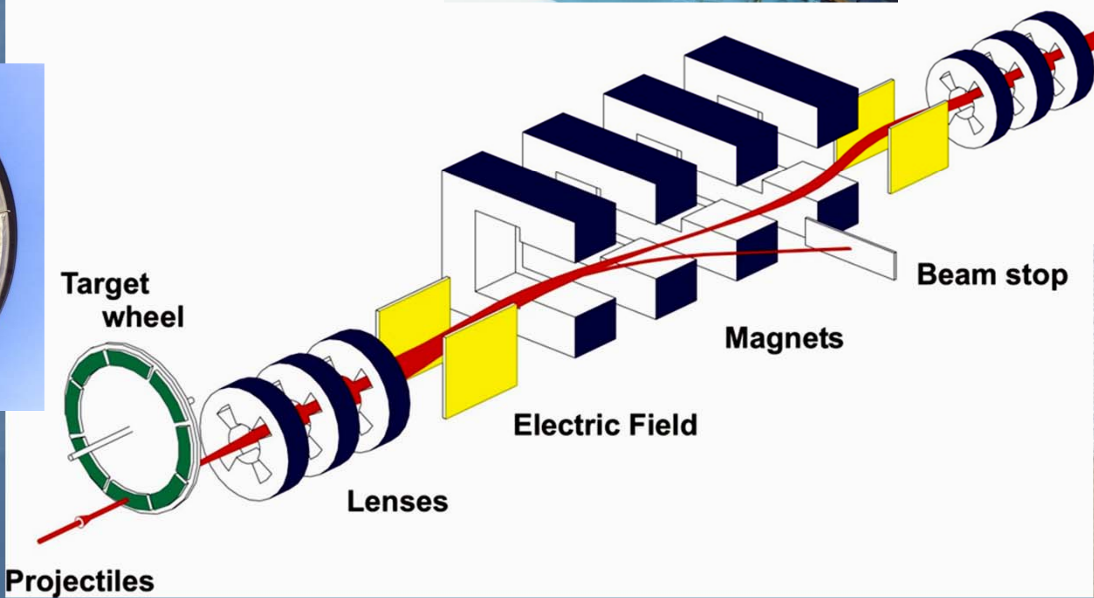
SHIP

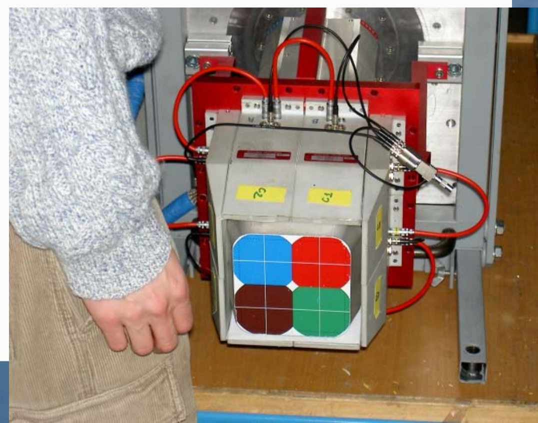
Separation time:	1 – 2 µs
Transmission:	20 – 50 %
Background:	10 – 50 Hz
Det. E. resolution:	18 – 25 keV
Det. Pos. resolution:	150 µm
Dead time:	25 µs











Decay Spectroscopy of SHE

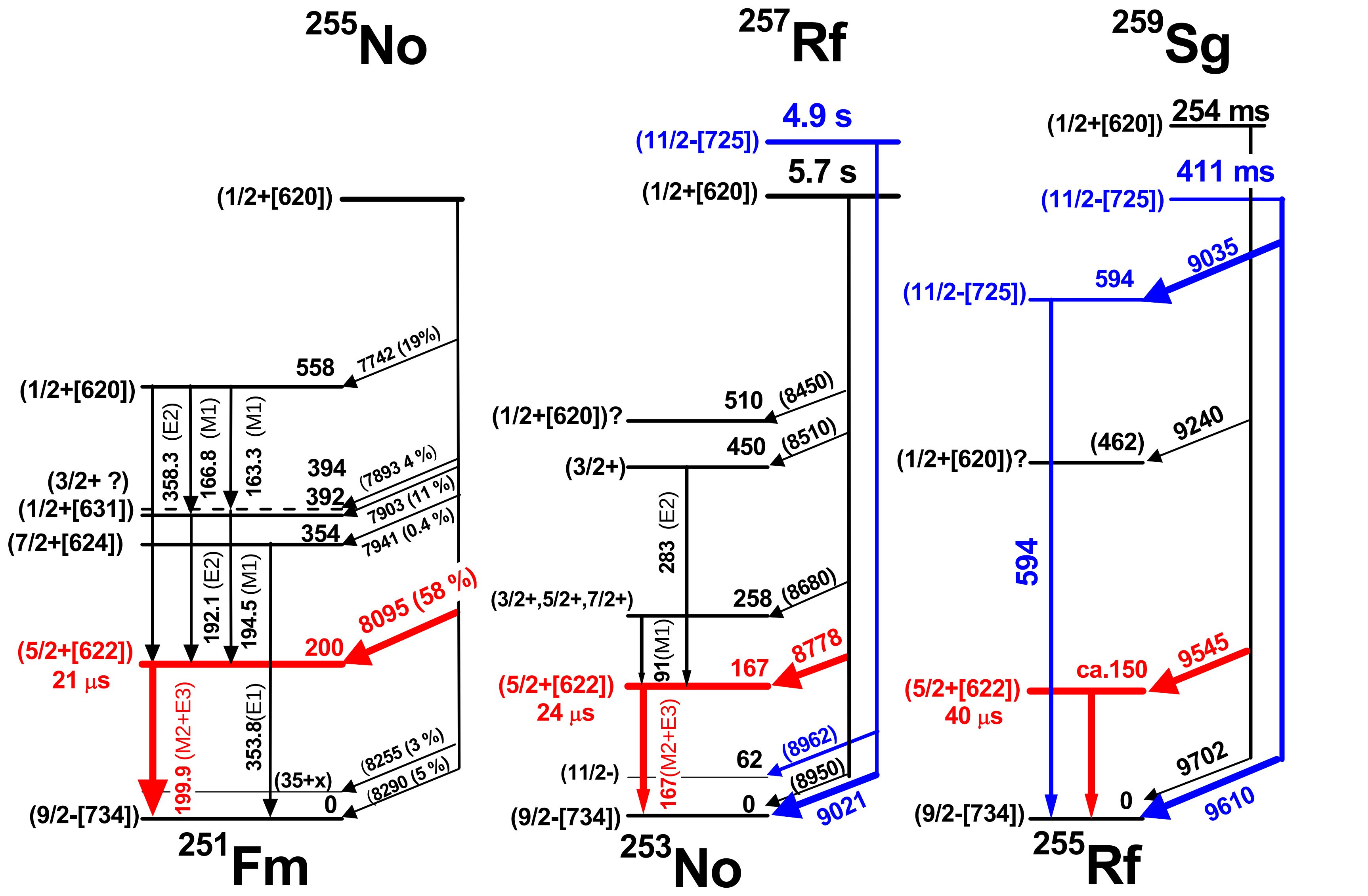
Nuclear structure investigations require a large amount of events, but production rates of SHE are low (ca. 240 /d/nb)

→ Nuclear structure of odd-A even Z nuclei is similar along isotone line

→ Nuclear structure of odd-A even Z nuclei is similar along isotope line

→ Study of systematics of (low lying) Nilsson levels in odd A nuclei

Decay schemes of the N=153 Isotones ^{255}No, ^{257}Rf, ^{259}Sg

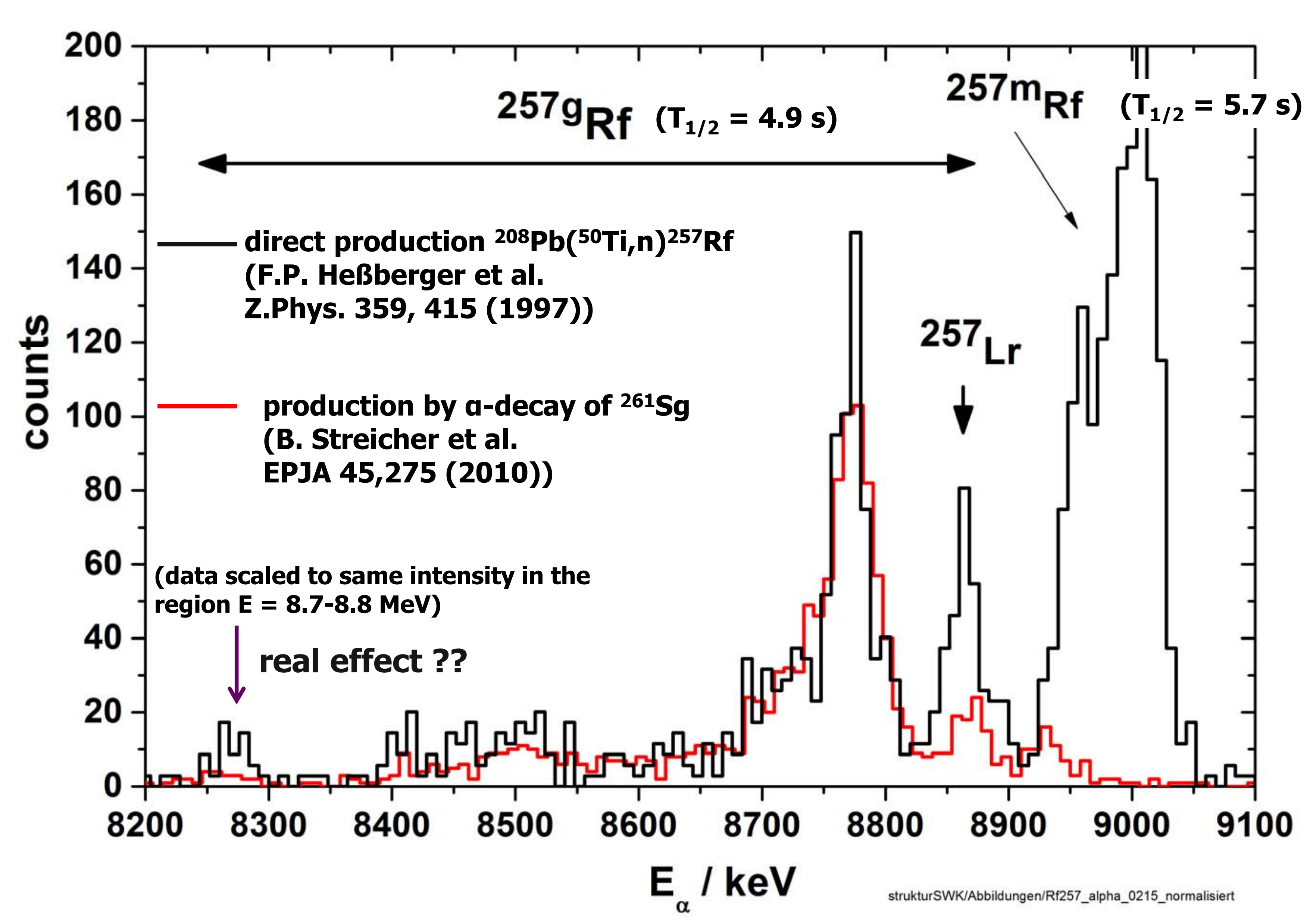


F.P. Heßberger et al. EPJ A29,165 (2006)

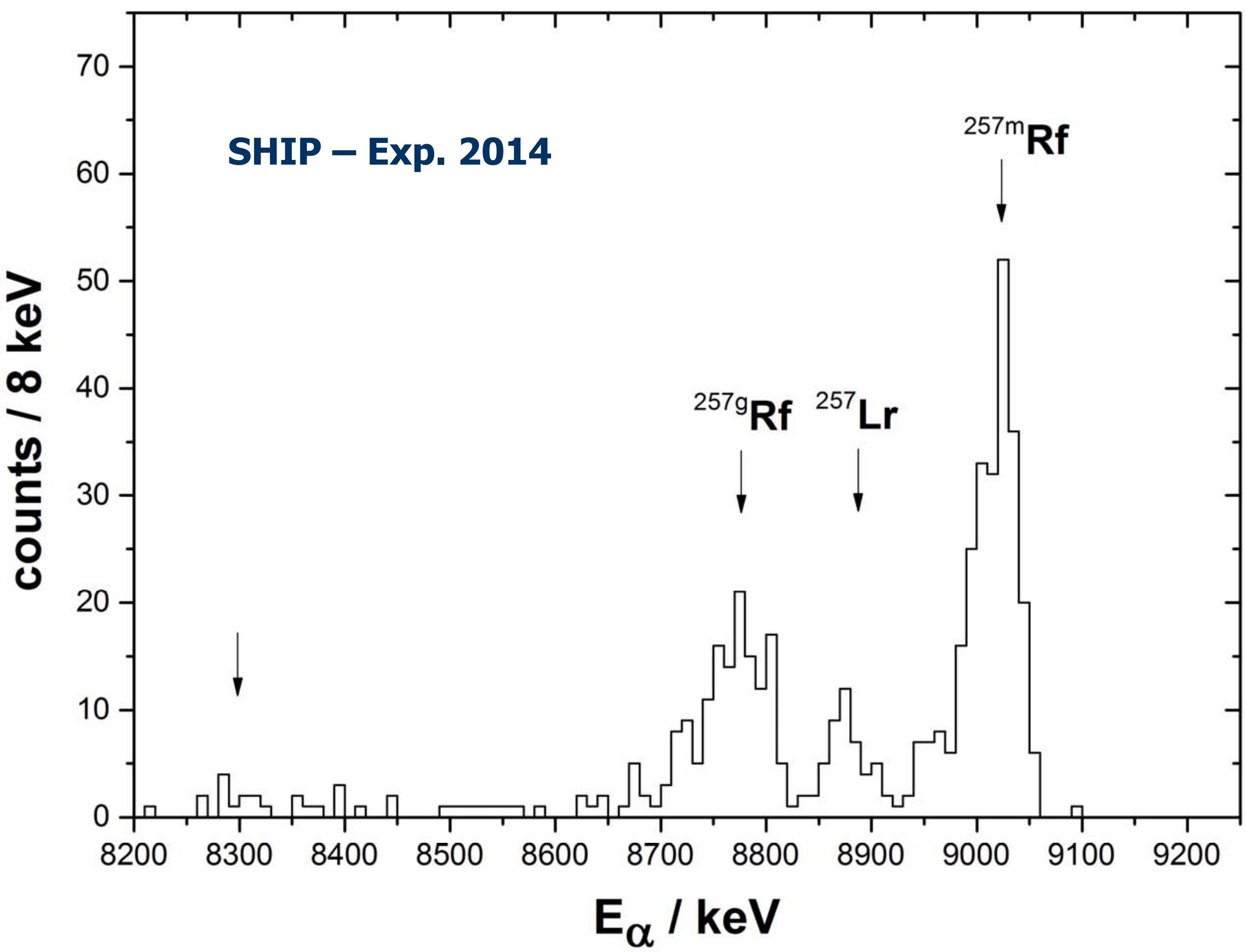
F.P. Heßberger et al. Z.Phys. A 359,415 (1997)
B. Streicher et al. EPJ A 45, 275 (2010)

S. Antalic et al. EPJ A 51:41 (2015)

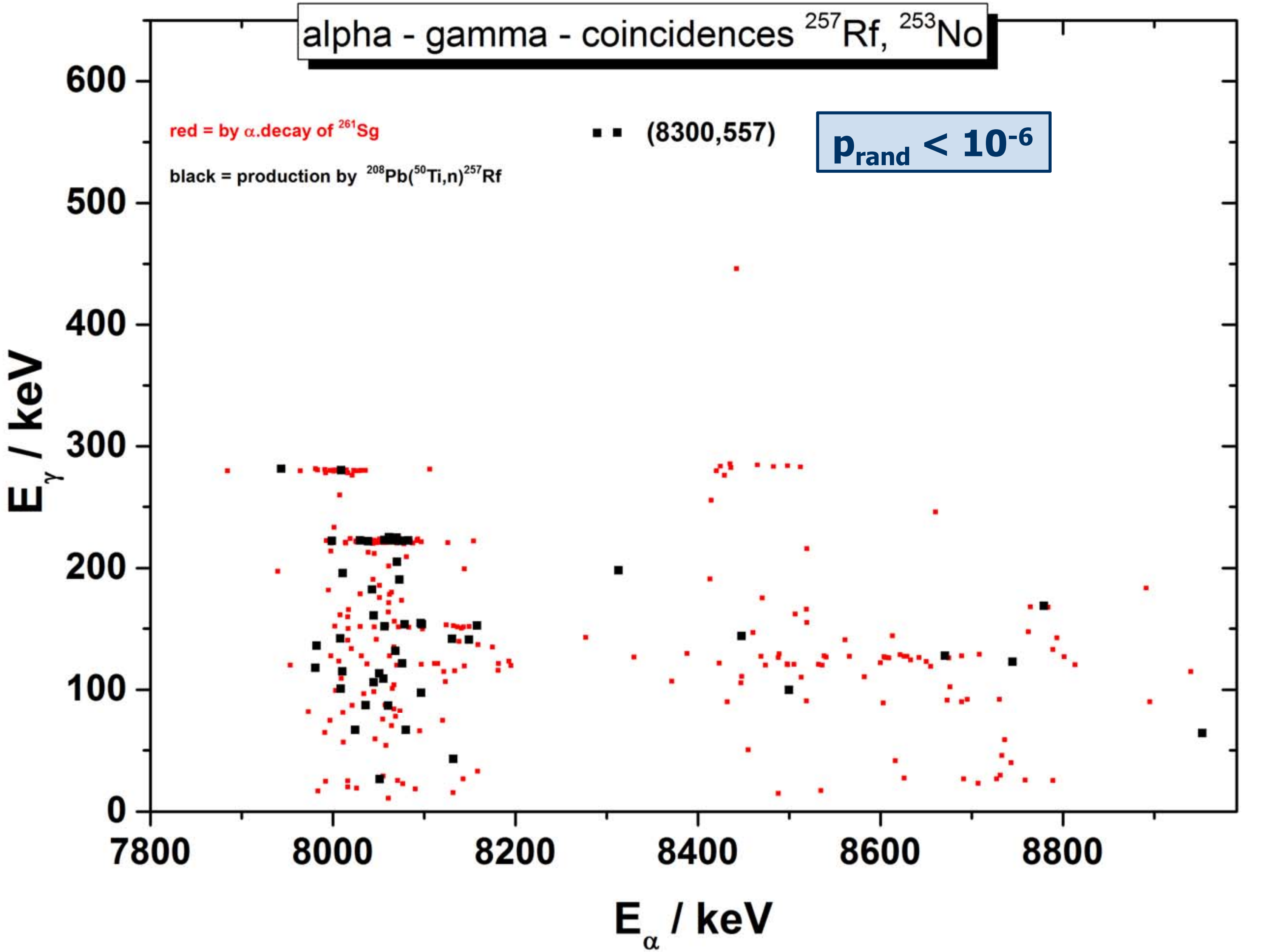
Decay Study of ^{257}Rf



Decay Study of ^{257}Rf



Decay Study of ^{257}Rf



Decay Study of ^{257}Rf

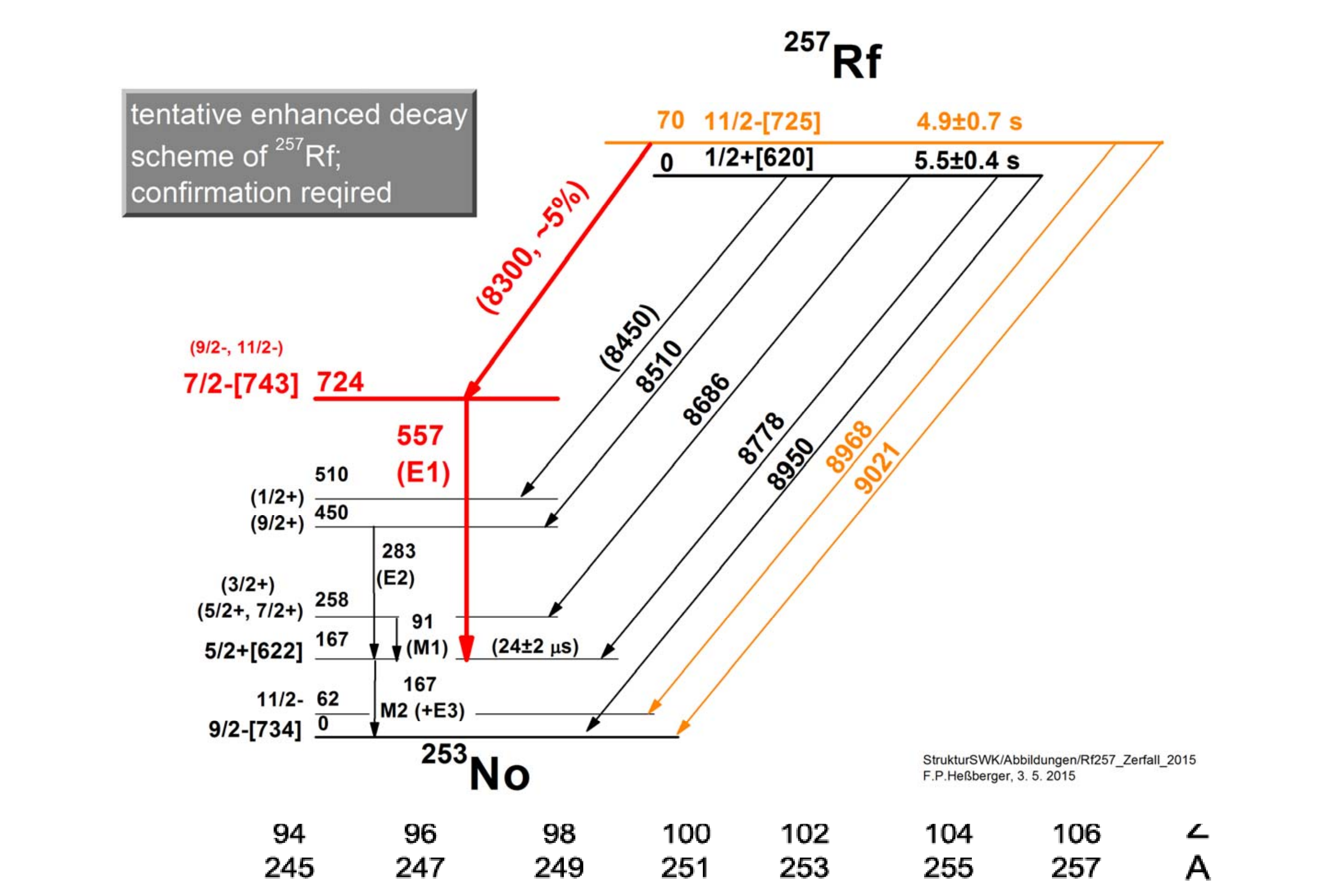
→ coincidence not observed in production by α-decay of ^{261}Sg

→ assignment to ^{257}Lr unlikely due to α-α-correlation to ^{253}No

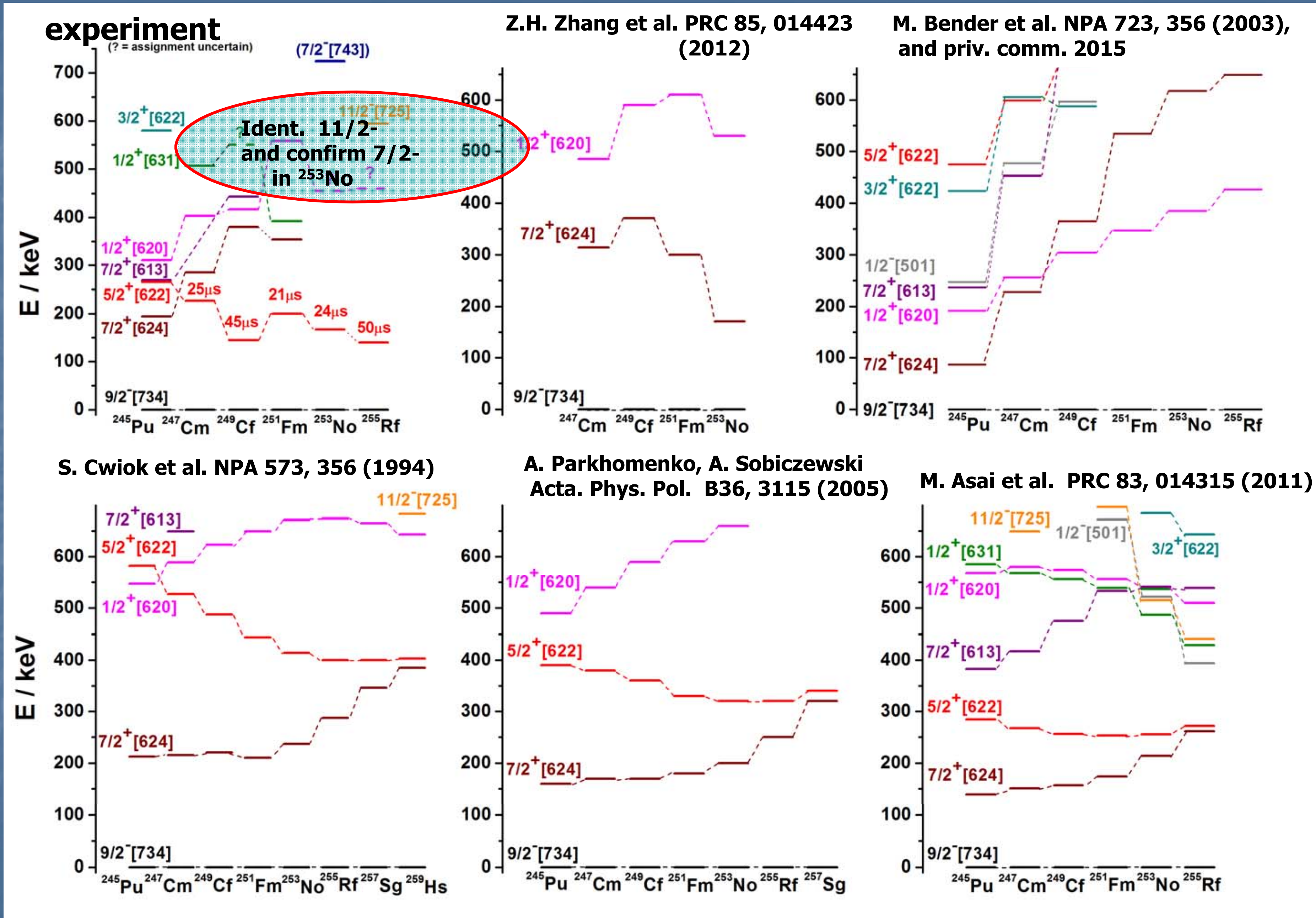
→ certainly related to decay of ^{257m}Rf

→ $E_\alpha + E_\gamma$ = 8.86 MeV, but $E_\alpha(^{257m}Rf)$ = 9.03 MeV
→ suggests population of a level at E* ≈ 170 keV (5/2+ isomer !!!)
→ cannot be 11/2-(^{257m}Rf) → 11/2-(^{253}No) transition; prefers M1 transition to 9/2- gs. and not E3 transition to 5/2+ isomer
→ α-transition only slightly hindered (HF ≈5-10); no parity change, no spin-flip

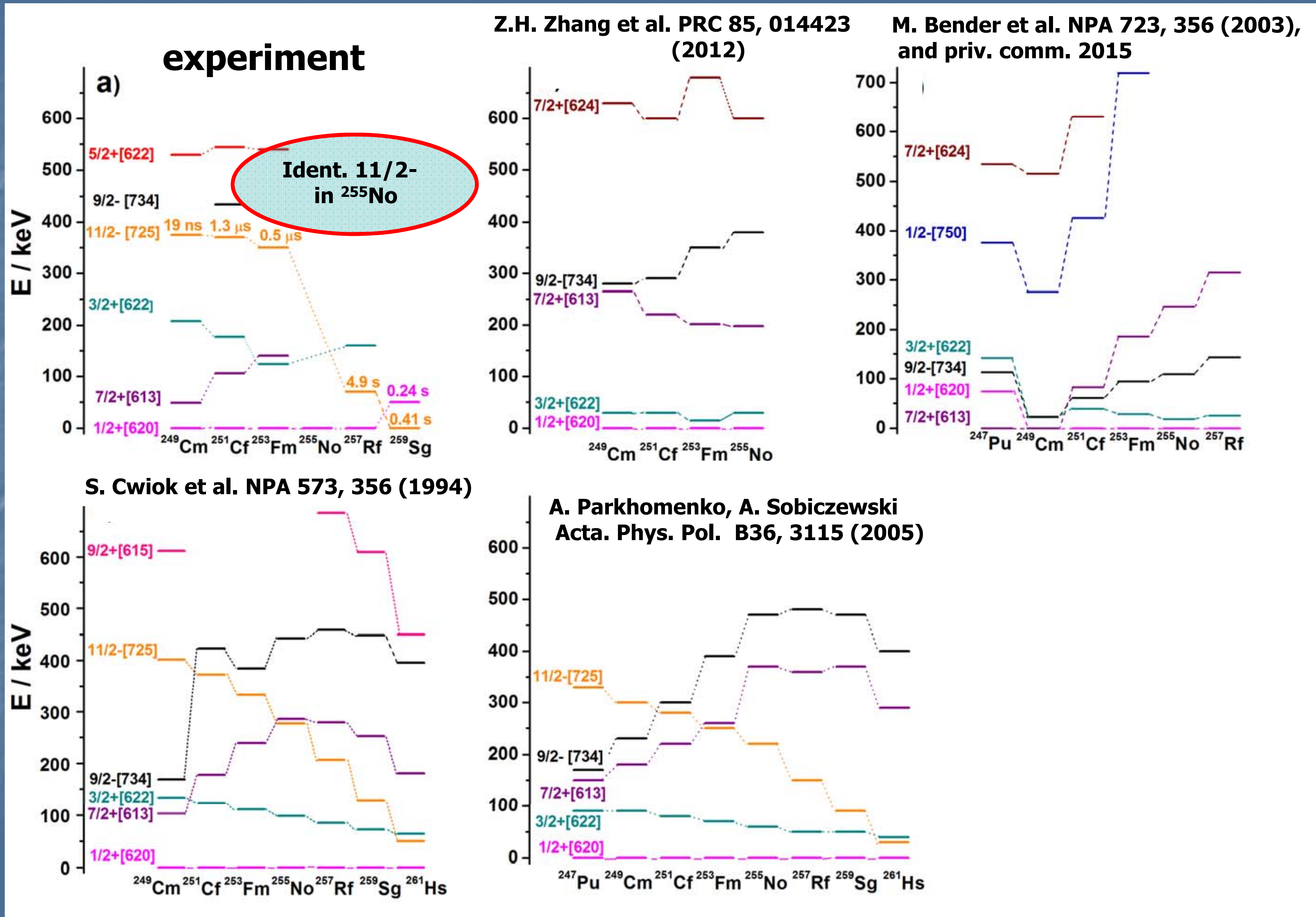
Decay Study of ^{257}Rf – expected levels in ^{253}No



Nilsson-Levels in N=151 Isotones



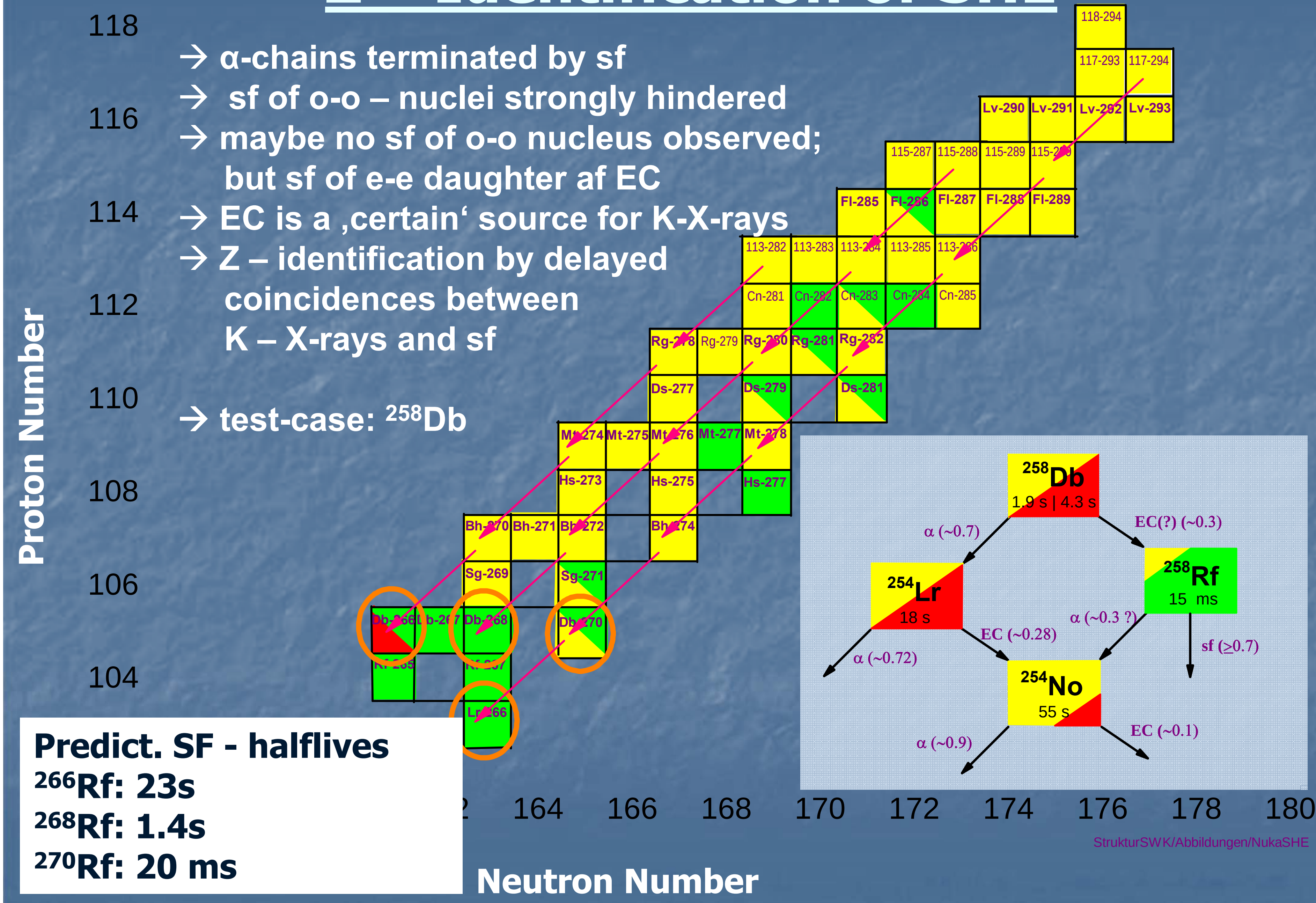
Nilsson-Levels in N=153 Isotones



Z – Identification of SHE

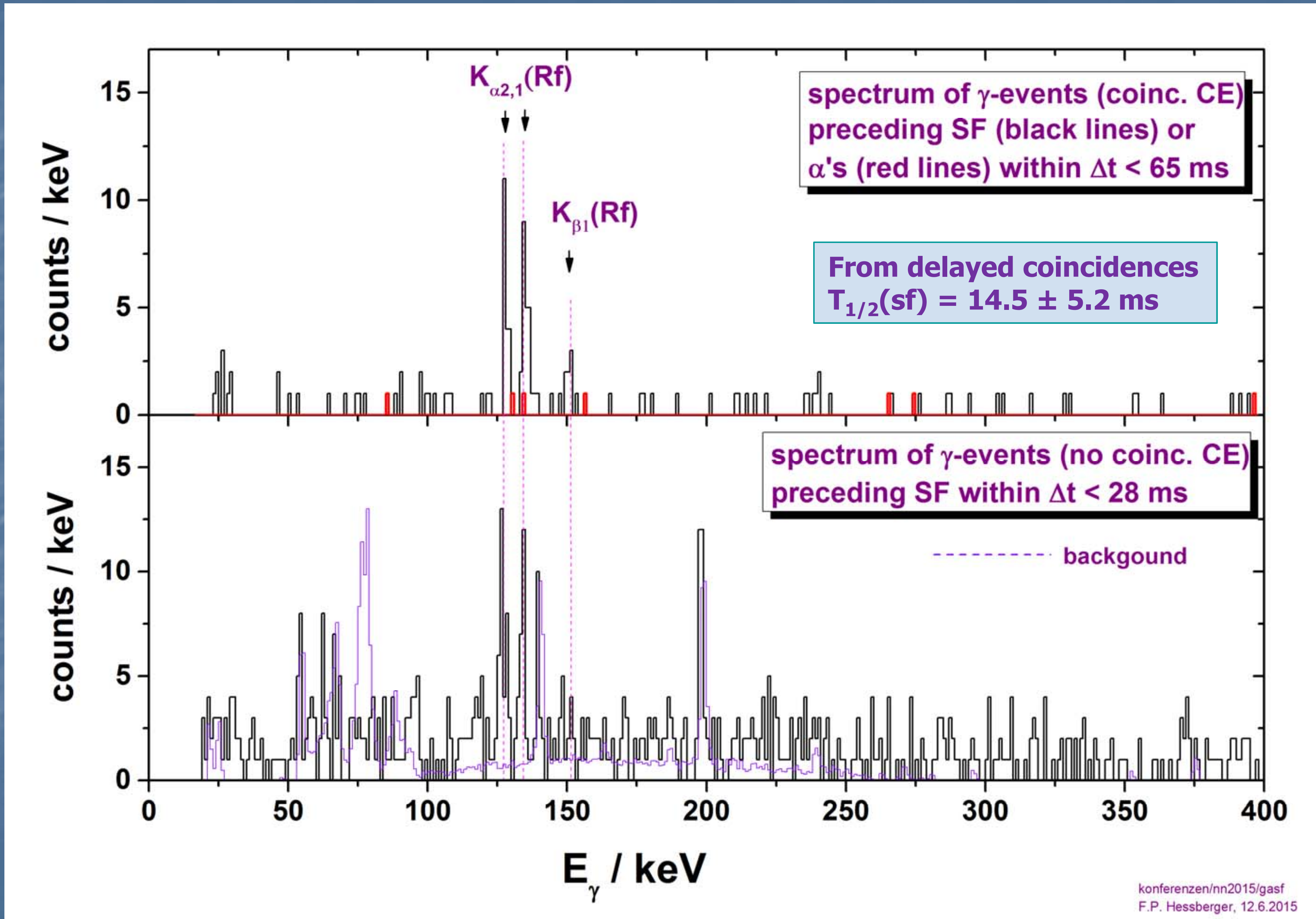
→ α-chains terminated by sf
→ sf of o-o – nuclei strongly hindered
→ maybe no sf of o-o nucleus observed; but sf of e-e daughter af EC
→ EC is a ‚certain‘ source for K-X-rays
→ Z – identification by delayed coincidences between K – X-rays and sf

→ test-case: ^{258}Db



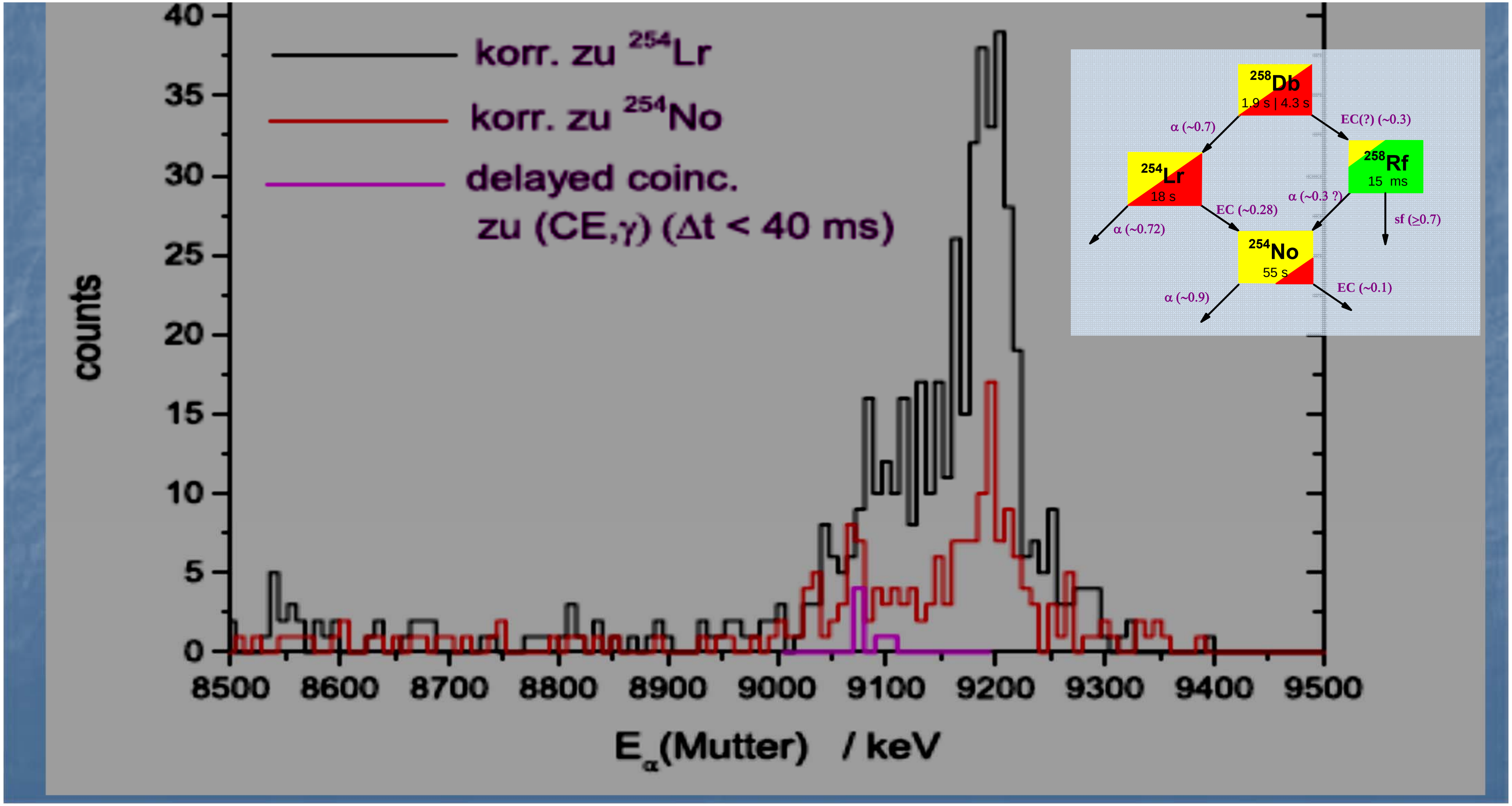
Predict. SF - halflives
^{266}Rf: 23s
^{268}Rf: 1.4s
^{270}Rf: 20 ms

Direct Prove of EC of ^{258}Db

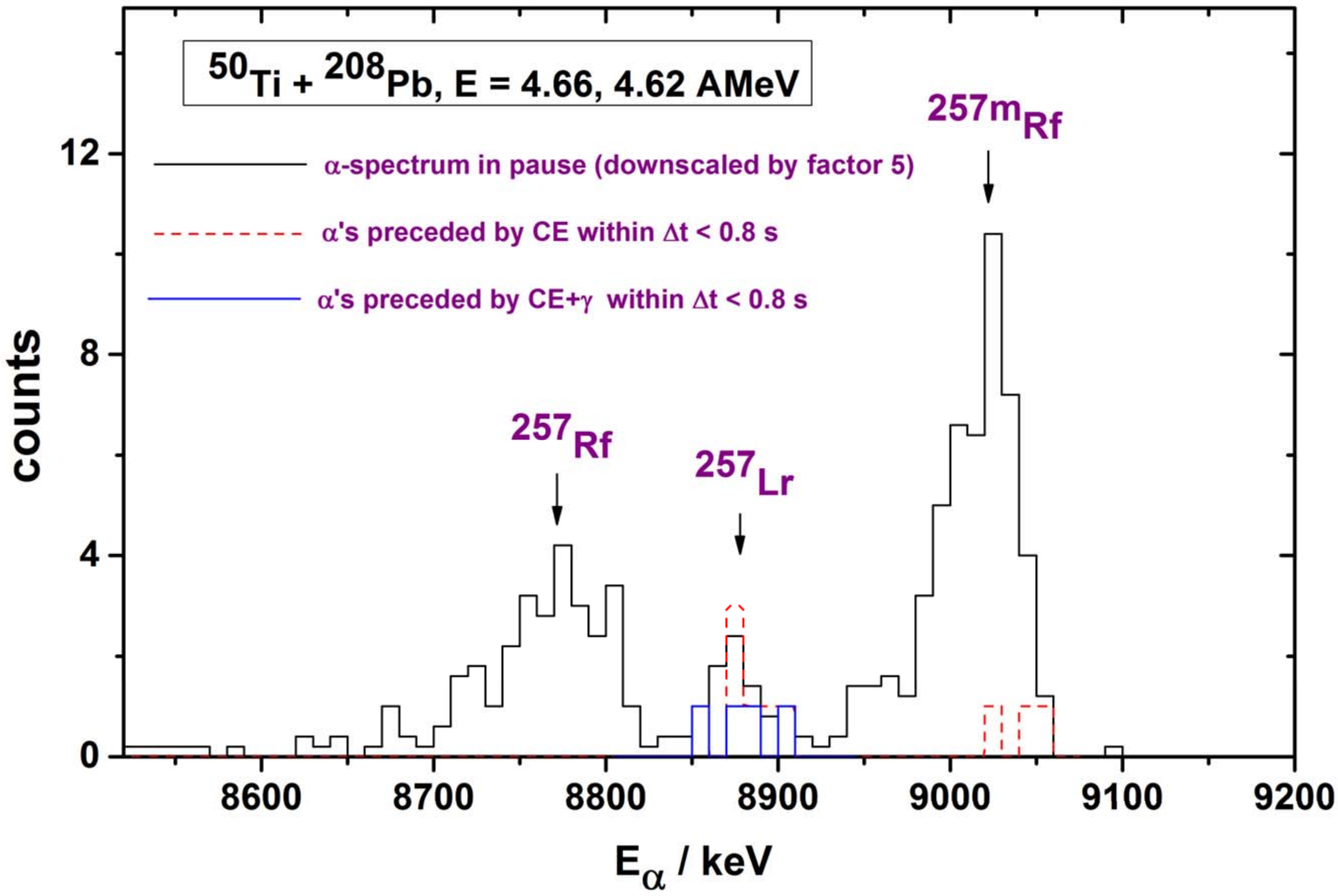


Alpha – decay branch ^{258}Rf

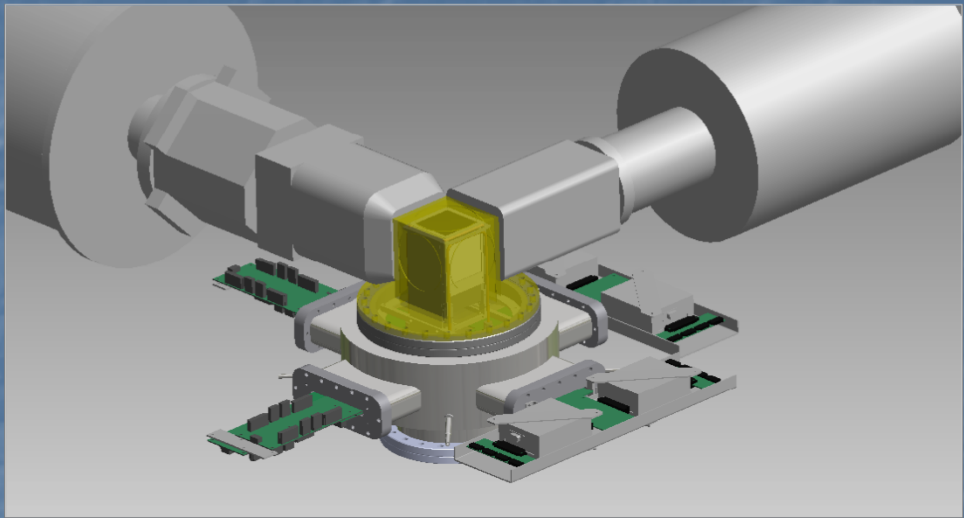
^{258}Rf: E_α = 9.05±0.03 MeV, b_α = 0.31 ± 0.11 (J. Gates et al. PRC 77, 034603 (2008))
E_α = 9.07±0.02 MeV, b_α = (0.07 +0.08/-0.04, preliminary) (this work)

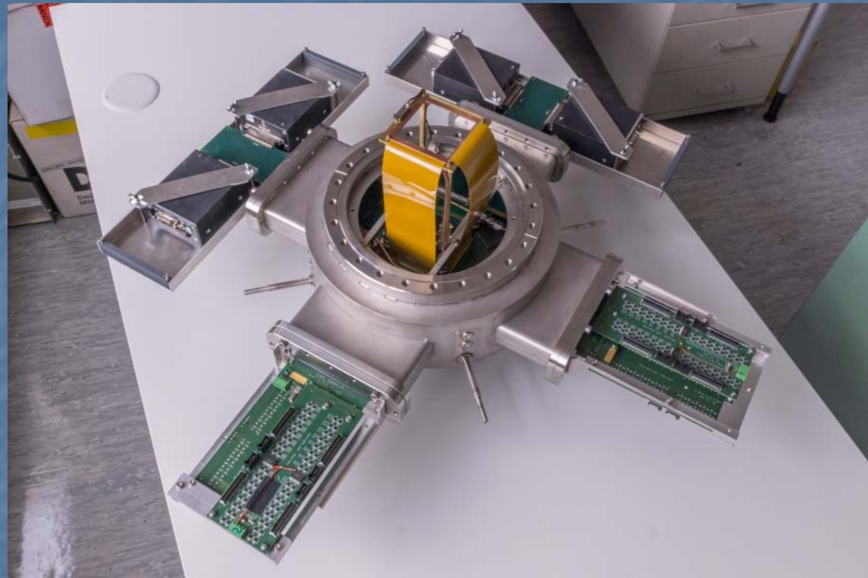


Proof of EC Decay of ^{257}Rf



Enhanced Focal Plane Detector Set-up for SHE Spectroscopy





configuration

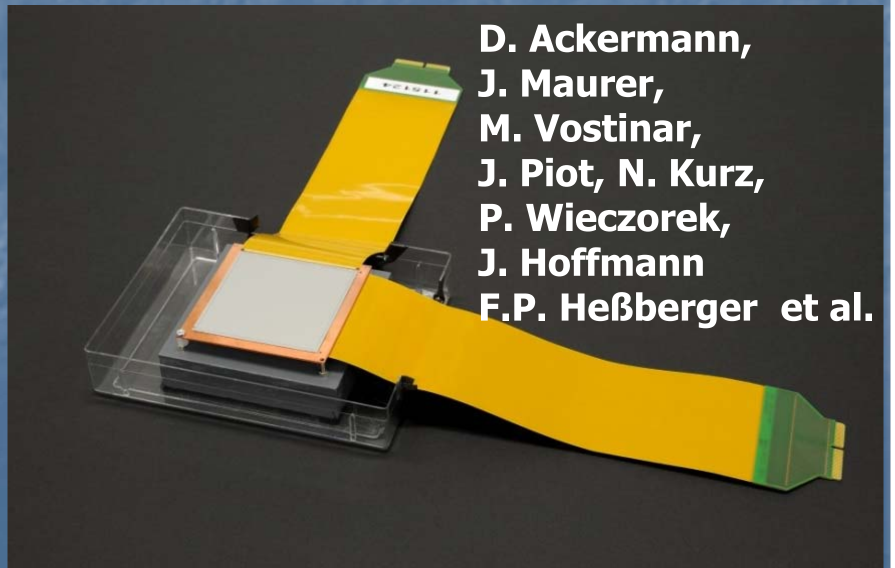
- *stop detector: 1 × DSSD (60×60 strips)*
- *box detectors: 4 × SSSD (32 strips)*
- *overall particle - γ-efficiency ≈ 40%*

chamber

- *compact (overall length 35 cm)*
- *Al-cap with thin γ window (1,5 mm)*
- *compatible due to 150 mm standard flange*
- *electronics partly integrated (vacuum)*

DSSD

- *integrated cooling (Cu-frame) and connection (flex-PCB)*
- *60×60 strips/mm (pitch 1 mm)*
- *300 µm*



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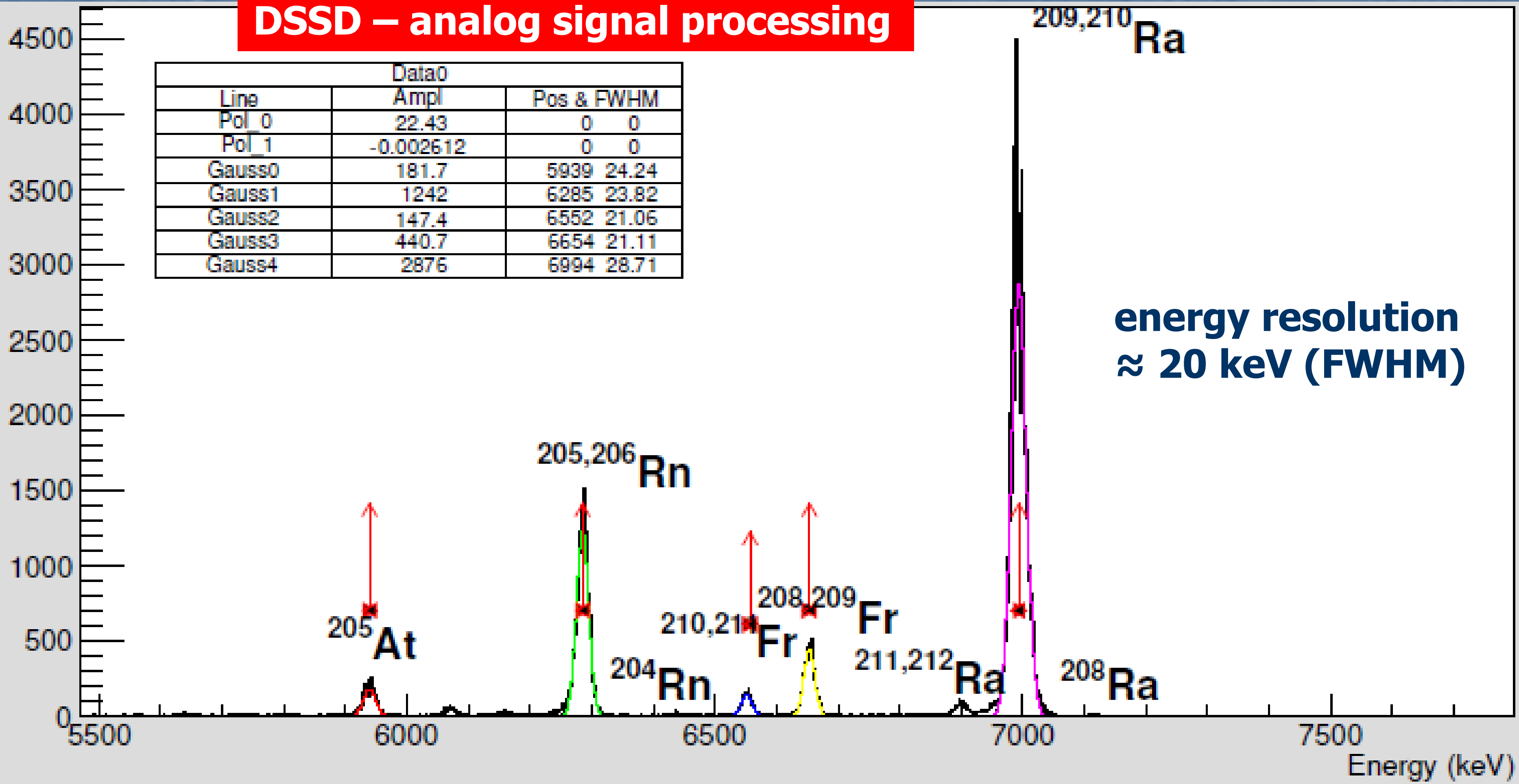
F.P. Heßberger et al.

Enhanced Focal Plane Detector Set-up for SHE Spectroscopy

First on-line test at LISE – Wienfilter GANIL, november 2014

^{40}Ar (4.66 AMeV) + ^{174}Yb → $^{209,210}Ra$

DSSD – analog signal processing

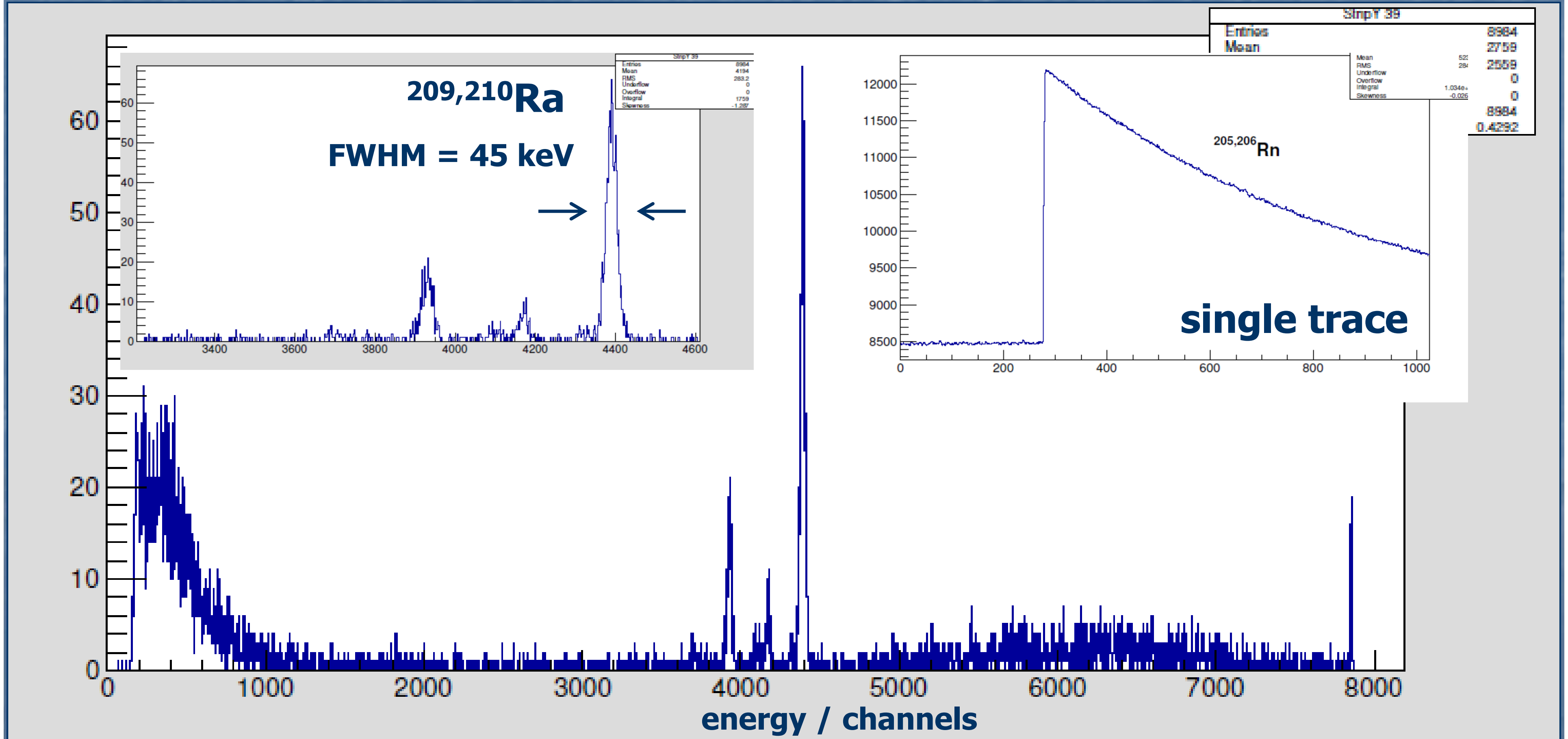


Data0		
Line	Ampl	Pos & FWHM
Pol_0	22.43	0 0
Pol_1	-0.002612	0 0
Gauss0	181.7	5939 24.24
Gauss1	1242	6285 23.82
Gauss2	147.4	6552 21.06
Gauss3	440.7	6654 21.11
Gauss4	2876	6994 28.71

energy resolution ≈ 20 keV (FWHM)

Enhanced Focal Plane Detector Set-up for SHE Spectroscopy

Digital signal processing → FEBEX + conventional PA
DSSD, Ge-detectors, ...
• fast timing • deadtime free • pulse shape analysis options



Conclusions

→ Decay spectroscopy and ground state mass measurement are powerful tools to investigate nuclear structure of SHE in terms of
  → ordering of nuclear levels
  → energy systematics of Nilsson levels
  → identification of neutron (and proton) shell
  → determination of shell strenghts
  → the stability of (multi) quasi-particle states

→ Measuring X-rays from EC in delayed coincidence with the decay (α, sf) is probably an alternative method for Z – identification of SHN.
→ population of excited levels in daughter nuclei by EC decay is an additional source for nuclear structure information

Future Goals:
→ identification of ‚missing' levels relevant for strength and location of the ‚SHE – shells' at $Z \leq 106$
→ detailed nuclear structure investigations at $Z > 106$
→ ‚more' detailed study of K – isomers at Z = 100 - 110

SHIP – SHE Nuclear Structure Collaboration (Spokesman: F.P. Heßberger)

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