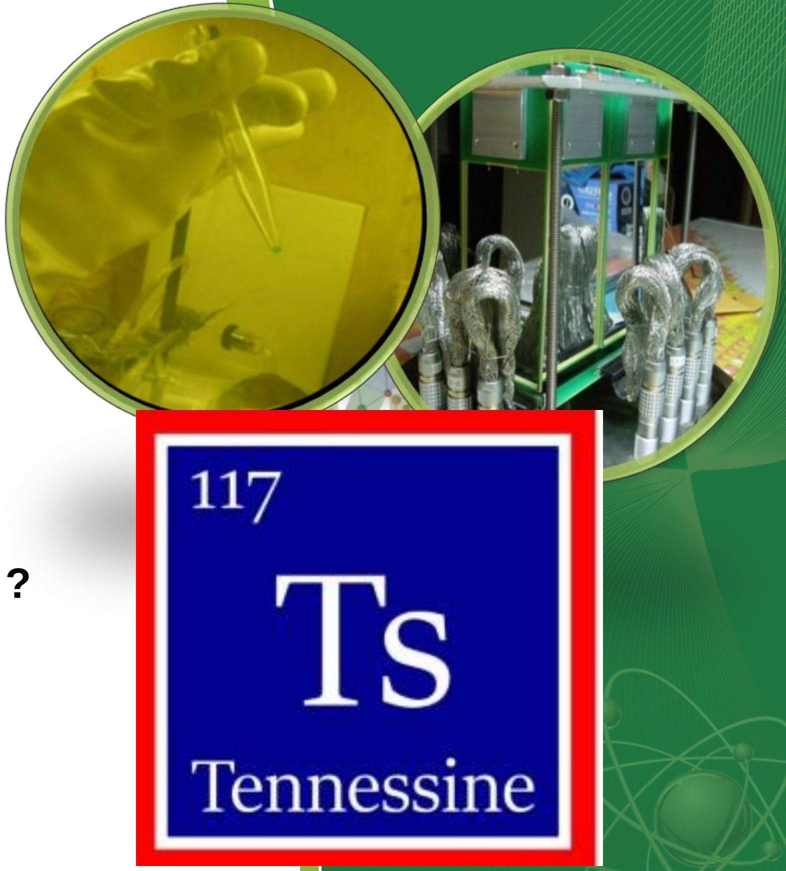
SHE - experimental opportunities for HIL ?

→ badania SHE w “doinwestowanym SLCJ” ?

K.P. Rykaczewski (ORNL)



- Super heavy elements and nuclei – experimental status
- SHE research directions in next ~ 5-10 years
- What is needed at upgraded HIL to contribute to the SHE research ?

Warszawa, SLCJ, styczeń 2019

OAK RIDGE
National Laboratory

Long term goals – including potential programs for HIL

New Heaviest Elements and Nuclei

- how many protons and neutrons a nucleus can hold → new super heavy elements and nuclei
- unified description of nuclear properties across varying proton and neutron numbers (collaboration with polish theory teams)
- new energy gaps, magic numbers and the extend of Island of Stability,

  or rather "enhanced stability without shell gaps and magic numbers" ? (as above)
- understanding fission process competing with other decay modes in compound and gs nuclei (upgraded ICAR and Eagle+ ?) /see studies by Katsuhisa Nishio et al, Tokai, Japan/
- structure beyond ground-state properties of super heavy nuclei - ISOMERS (separator, chemistry?)

Understanding production mechanism of the heaviest (very heavy) nuclei (upgraded/new ICAR, Eagle+ ??)

- hot and cold fusion reactions with stable and radioactive nuclei /see exps at ANL Canberra, by Hinde et al./
- multi-nucleon transfer between very heavy nuclei */I'm skeptical, but it is a growing field/*

Expansion of Periodic Table of Elements

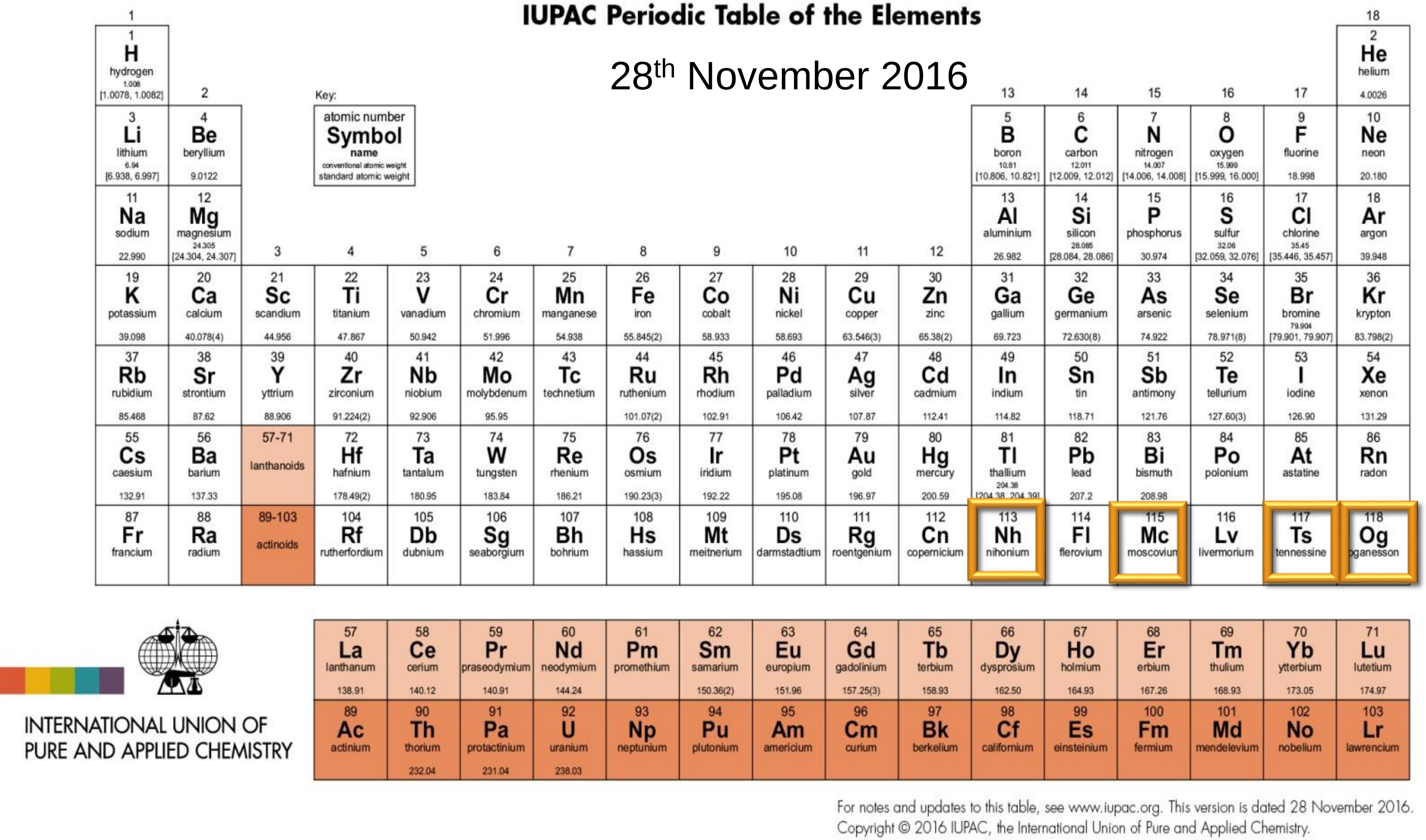
- relativistic effects in chemical properties of atoms (radius, ionization, compounds, bonding length)
- super heavy atoms in the Universe
- end of the Periodic Table: too short-lived nuclei to form an atom

Discoveries of new elements create a very positive response from the society.

Example: a joint visit of German and Polish Presidents to GSI for the celebration of naming element 112 “Copernicium”.

SHE studies at HIL would require a collaboration with Dubna, GSI and GANIL

Gov. Bill Haslam (left) speaks with Wigner Lecturer Yuri Oganessian



28th November 2016

IUPAC Periodic Table of the Elements

Key:
atomic number
Symbol
name
conventional atomic weight
standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H hydrogen 1.008 [1.0078, 1.0082]																	2 He helium 4.0026
3 Li lithium 6.94 [6.938, 6.997]	4 Be beryllium 9.0122											5 B boron 10.81 [10.806, 10.821]	6 C carbon 12.011 [12.009, 12.012]	7 N nitrogen 14.007 [14.006, 14.008]	8 O oxygen 15.999 [15.999, 16.000]	9 F fluorine 18.998	10 Ne neon 20.180
11 Na sodium 22.990	12 Mg magnesium 24.305 [24.304, 24.307]											13 Al aluminium 26.982	14 Si silicon 28.085 [28.084, 28.086]	15 P phosphorus 30.974	16 S sulfur 32.06 [32.059, 32.076]	17 Cl chlorine 35.45 [35.446, 35.457]	18 Ar argon 39.948
19 K potassium 39.098	20 Ca calcium 40.078(4)	21 Sc scandium 44.956	22 Ti titanium 47.867	23 V vanadium 50.942	24 Cr chromium 51.996	25 Mn manganese 54.938	26 Fe iron 55.845(2)	27 Co cobalt 58.933	28 Ni nickel 58.693	29 Cu copper 63.546(3)	30 Zn zinc 65.38(2)	31 Ga gallium 69.723	32 Ge germanium 72.630(8)	33 As arsenic 74.922	34 Se selenium 78.971(8)	35 Br bromine 79.904 [79.901, 79.907]	36 Kr krypton 83.798(2)
37 Rb rubidium 85.468	38 Sr strontium 87.62	39 Y yttrium 88.906	40 Zr zirconium 91.224(2)	41 Nb niobium 92.906	42 Mo molybdenum 95.95	43 Tc technetium	44 Ru ruthenium 101.07(2)	45 Rh rhodium 102.91	46 Pd palladium 106.42	47 Ag silver 107.87	48 Cd cadmium 112.41	49 In indium 114.82	50 Sn tin 118.71	51 Sb antimony 121.76	52 Te tellurium 127.60(3)	53 I iodine 126.90	54 Xe xenon 131.29
55 Cs caesium 132.91	56 Ba barium 137.33	57-71 lanthanoids	72 Hf hafnium 178.49(2)	73 Ta tantalum 180.95	74 W tungsten 183.84	75 Re rhenium 186.21	76 Os osmium 190.23(3)	77 Ir iridium 192.22	78 Pt platinum 195.08	79 Au gold 196.97	80 Hg mercury 200.59	81 Tl thallium 204.38 [204.38, 204.39]	82 Pb lead 207.2	83 Bi bismuth 208.98	84 Po polonium	85 At astatine	86 Rn radon
87 Fr francium	88 Ra radium	89-103 actinoids	104 Rf rutherfordium	105 Db dubnium	106 Sg seaborgium	107 Bh bohrium	108 Hs hassium	109 Mt meitnerium	110 Ds darmstadtium	111 Rg roentgenium	112 Cn copernicium	113 Nh nihonium	114 Fl flerovium	115 Mc moscovium	116 Lv livermorium	117 Ts tennessine	118 Og oganesson

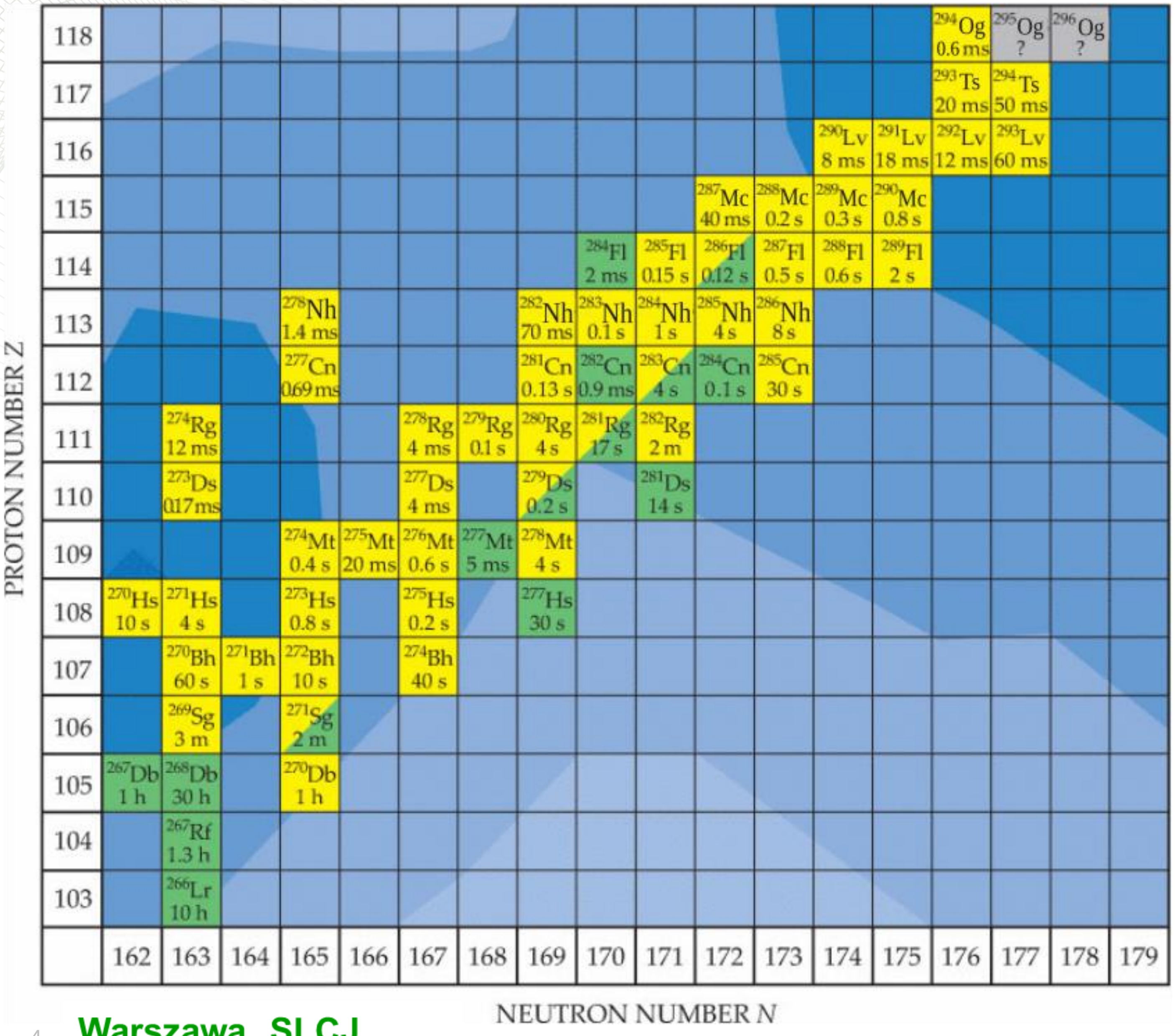
57 La lanthanum 138.91	58 Ce cerium 140.12	59 Pr praseodymium 140.91	60 Nd neodymium 144.24	61 Pm promethium	62 Sm samarium 150.36(2)	63 Eu europium 151.96	64 Gd gadolinium 157.25(3)	65 Tb terbium 158.93	66 Dy dysprosium 162.50	67 Ho holmium 164.93	68 Er erbium 167.26	69 Tm thulium 168.93	70 Yb ytterbium 173.05	71 Lu lutetium 174.97
89 Ac actinium	90 Th thorium 232.04	91 Pa protactinium 231.04	92 U uranium 238.03	93 Np neptunium	94 Pu plutonium	95 Am americium	96 Cm curium	97 Bk berkelium	98 Cf californium	99 Es einsteinium	100 Fm fermium	101 Md mendelevium	102 No nobelium	103 Lr lawrencium

INTERNATIONAL UNION OF
PURE AND APPLIED CHEMISTRY

For notes and updates to this table, see www.iupac.org. This version is dated 28 November 2016.

March 2017, TN Senate and House

Chart of Super Heavy Nuclei



118															^{294}Og 0.6 ms	^{295}Og ?	^{296}Og ?	
117															^{293}Ts 20 ms	^{294}Ts 50 ms		
116													^{290}Lv 8 ms	^{291}Lv 18 ms	^{292}Lv 12 ms	^{293}Lv 60 ms		
115											^{287}Mc 40 ms	^{288}Mc 0.2 s	^{289}Mc 0.3 s	^{290}Mc 0.8 s				
114									^{284}Fl 2 ms	^{285}Fl 0.15 s	^{286}Fl 0.12 s	^{287}Fl 0.5 s	^{288}Fl 0.6 s	^{289}Fl 2 s				
113				^{278}Nh 1.4 ms				^{282}Nh 70 ms	^{283}Nh 0.1 s	^{284}Nh 1 s	^{285}Nh 4 s	^{286}Nh 8 s						
112				^{277}Cn 0.69 ms				^{281}Cn 0.13 s	^{282}Cn 0.9 ms	^{283}Cn 4 s	^{284}Cn 0.1 s	^{285}Cn 30 s						
111		^{274}Rg 12 ms				^{278}Rg 4 ms	^{279}Rg 0.1 s	^{280}Rg 4 s	^{281}Rg 17 s	^{282}Rg 2 m								
110		^{273}Ds 0.17 ms				^{277}Ds 4 ms		^{279}Ds 0.2 s		^{281}Ds 14 s								
109				^{274}Mt 0.4 s	^{275}Mt 20 ms	^{276}Mt 0.6 s	^{277}Mt 5 ms	^{278}Mt 4 s										
108	^{270}Hs 10 s	^{271}Hs 4 s		^{273}Hs 0.8 s		^{275}Hs 0.2 s		^{277}Hs 30 s										
107		^{270}Bh 60 s	^{271}Bh 1 s	^{272}Bh 10 s		^{274}Bh 40 s												
106		^{269}Sg 3 m		^{271}Sg 2 m														
105	^{267}Db 1 h	^{268}Db 30 h		^{270}Db 1 h														
104		^{267}Rf 1.3 h																
103		^{266}Lr 10 h																
	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179

Experiments on new elements made at the 1+ picobarn cross section level are already done.

Discoveries of next new elements require the experimental sensitivity at the level of 10 femtobarns (10^{-8} microbarn). Such experiments require irradiations lasting many months to year(s).

Discovery of new isotope of known element :

- Cross section about 0.1 -1 picobarn,
- Intense heavy-ion beam ~ part*μA
- Radioactive actinide target
- Efficient He (H_2) filled electromagnetic separator
- Set of up-to-date detectors and digital data acquisition

- **Team of physicist with permanent positions (~3+), focused on performing SHE-related studies at "upgraded HIL"**

- **Collaboration with Dubna, GSI, GANIL and other SHE labs would be a part of this program, but not the main part.**

Necessary conditions to perform SHE experiments at HIL

1. High current heavy-ion accelerator, e.g., DS-280 type

- high-current means **shielded as required by the radiation protection** and having an **efficient ion source**

- **beams** of neutron-rich 36S, 44Ca, 48Ca, 51V, 54Cr, 58Fe, 64Ni are most important for SHE physics, but good experiments can be still performed with 18O, 22Ne, 26Mg, 30Si **/engineers/technicians/physicists/**

- SHE studies are now performed mostly with **radioactive actinide targets** which means **the respective licenses are required for receiving, making targets and irradiating such materials**

2. High transmission ^{4}He gas-filled separator for fusion products providing dramatically reduced background of a scattered primary beam (better than 10^{-10}), see DGFRS-II, GARIS-III, AGFA, S3, RITU – Darek's talk

- **The price tag** of GARIS-III at RIKEN is about 1 M$ (2018, likely without power supplies) – compare AGFA at Argonne (Darek Seweryniak)

- **Design of such separator** is by far not trivial (see Darek's AGFA). Perhaps a copy of new DGFRS-II??

3. Detector array with **dispensable implantation DSSDs and digital data ACQ.** **Scintillators, TPC ??**

4. Group of local physicists fully engaged in the SHE research program

Example of detector array (~ $ 100 K) and digital ACQ (~ $ 300 K) used in joint Russia-US SHE experiments at Dubnej since 2014

MICRON detectors

128 x48 mm,1 mm strips, 300 μm thick **DSSD BB-17**

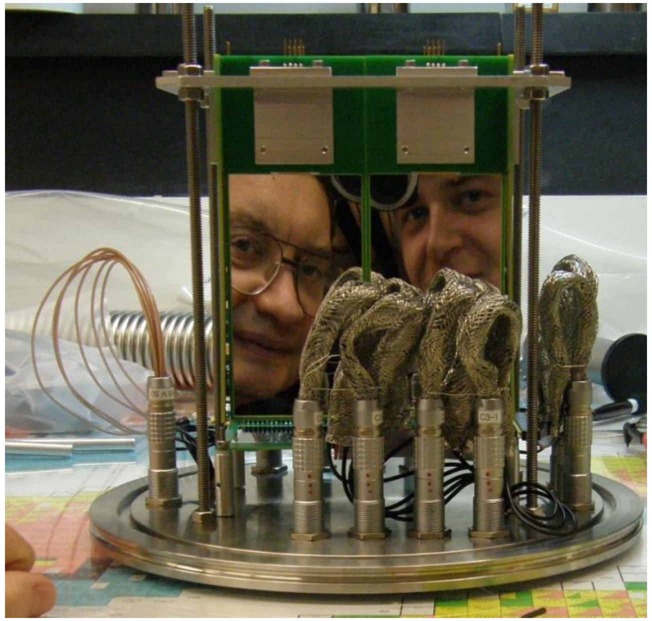
500 μm single **Si-veto** matching DSSD design

six 120 x 65 mm single Si 300 μm **Si-box**

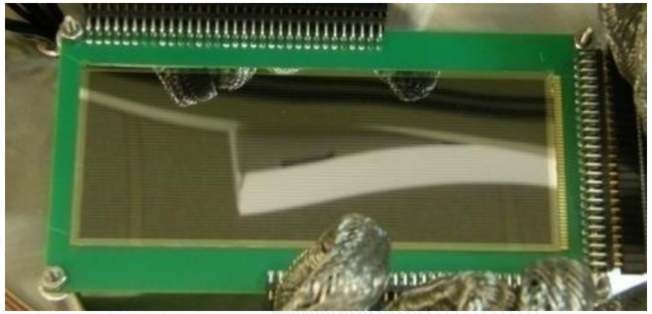
100 MHz XIA Pixie16 rev D (208 channels)

Parallel operation with Dubna's analog DAQ

Several ZSJ+HIL physicist were contributing to the development and using this universal digital ACQ



Dubna collaborators Y. Tsyganov, A. Polyakow and A. Voinov with **Krzysztof Miernik** at ORNL



DSSD BB-17, 1 mm^2 pixel

SHE vs other scientific programs at the "upgraded HIL"

SHE studies require long irradiations to battle very low cross sections ~ picobarn and below.

It means using the most of the available beam time per year, i.e., **SHEs becoming the main scientific program of HIL.**

However, the development of intense beams is usually staged. The construction and commissioning of the separator also takes time. At the early phase (might be a long phase) **other scientific programs might profit a lot** from a variety of heavy ion beams at the tens of part* nanoAmps level, before ~ part*microAmp is reached.

Know-how at HIL on in-beam spectroscopy (Eagle) and reaction studies (ICAR).

Gas-filled separator is a powerful facility for experiments other than SHEs – see AGFA (Darek Seweryniak)

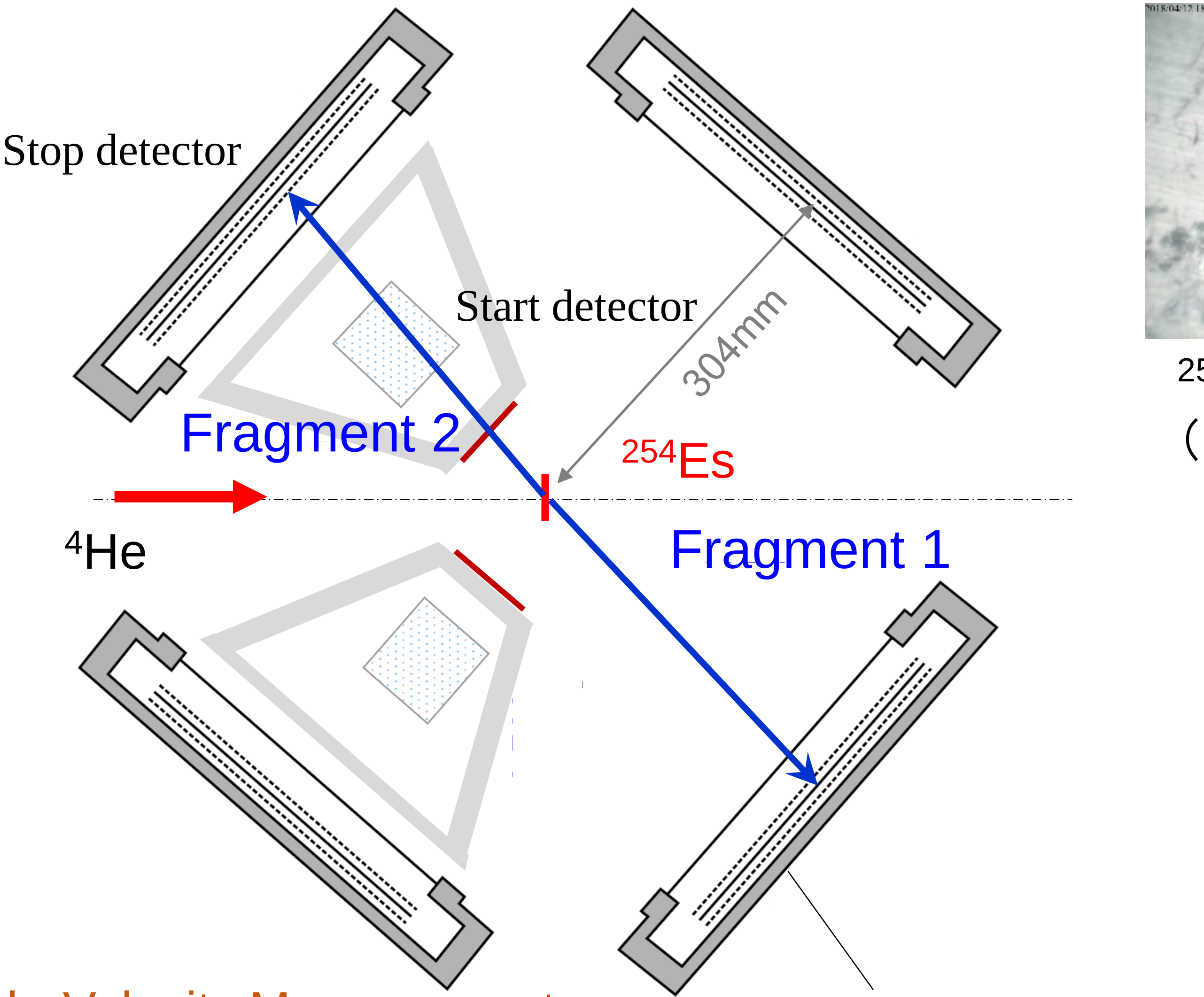
Digital data ACQ is a very powerful, versatile, universal system, can be used in many (all) other experiments at HIL (and other labs).

There are still experiments contributing to the general SHE program, which are less beam-time hungry, like several weeks of running. But it is not the search for new SHE nuclei.

Example: **studies of fission mechanism in a function of excitation energy.** Such program is run at the Tandem Laboratory at JAEA Tokai, by Katsuhisa Nishio group. **Microgram and nanogram amounts of actinide** targets are used, which reduces the licenses requirements due to much lower radioactivity.

In-beam fission measurement in ^{4}He + ^{254}Es = ^{258}Md*

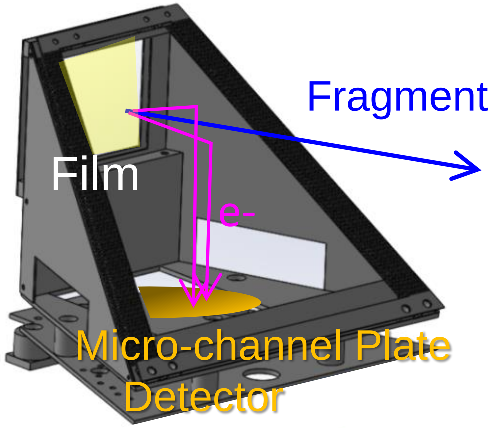
Katsuhisa Nishio et al., research program at JAEA ASRC Tandem Laboratory

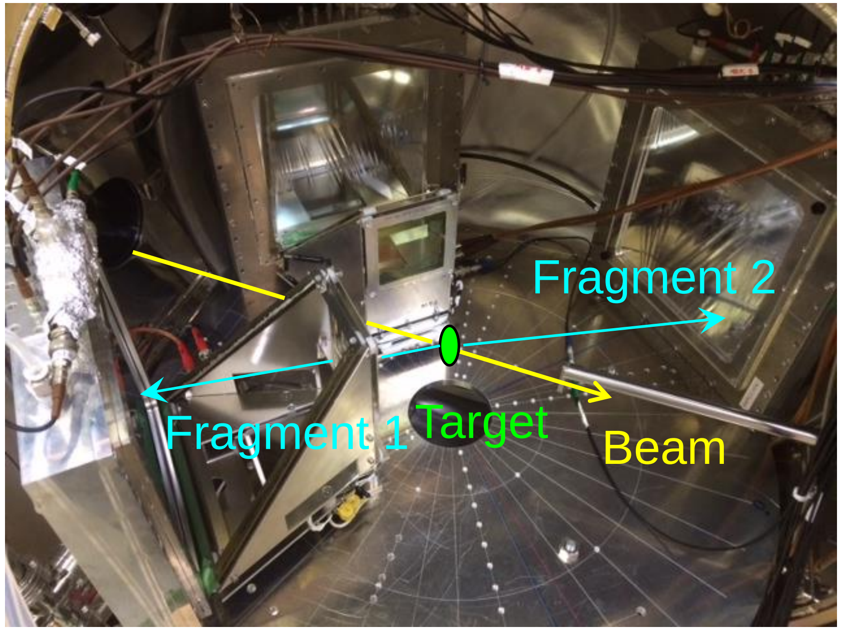


Double-Velocity Measurement

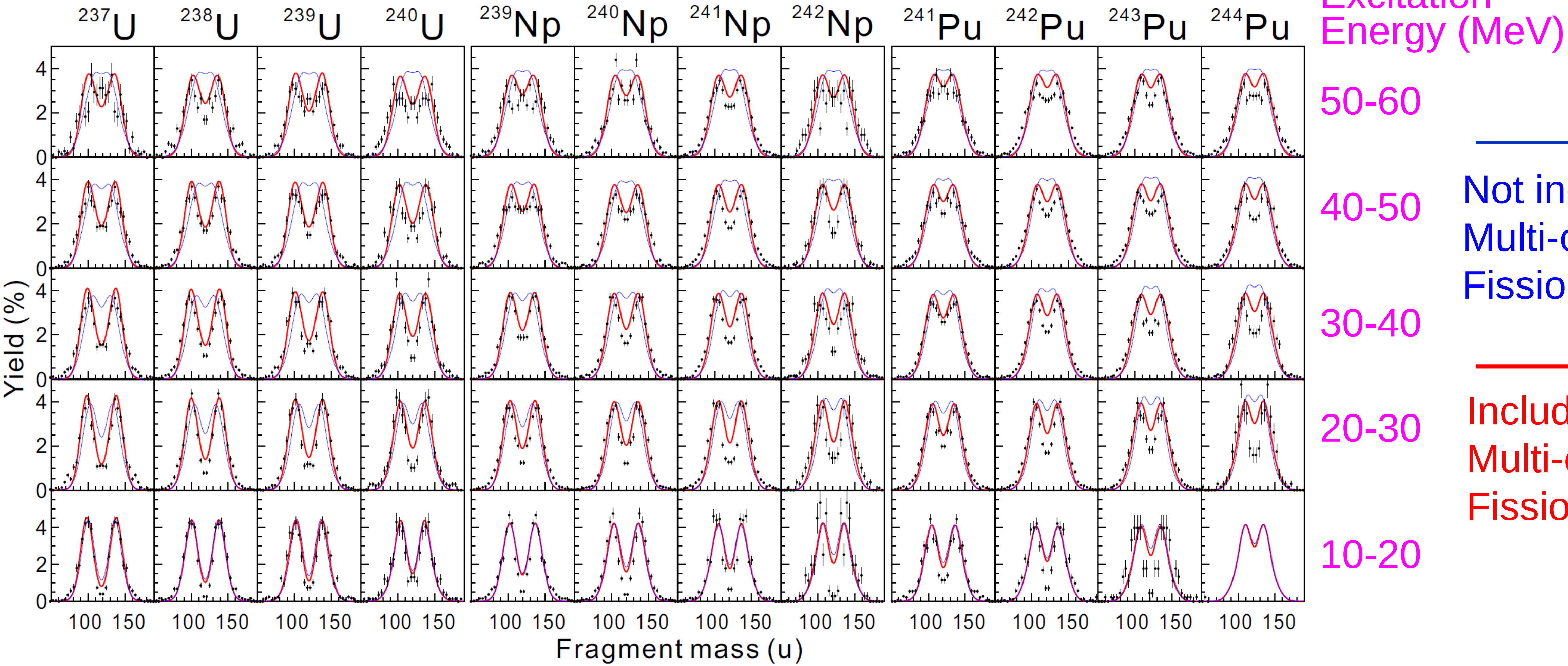
Warszawa, SLCJ

^{254}Es Target
（10 ng on Φ2mm）





Experimental Data Comparison with Langevin Calculation (Katsuhisa Nishio)



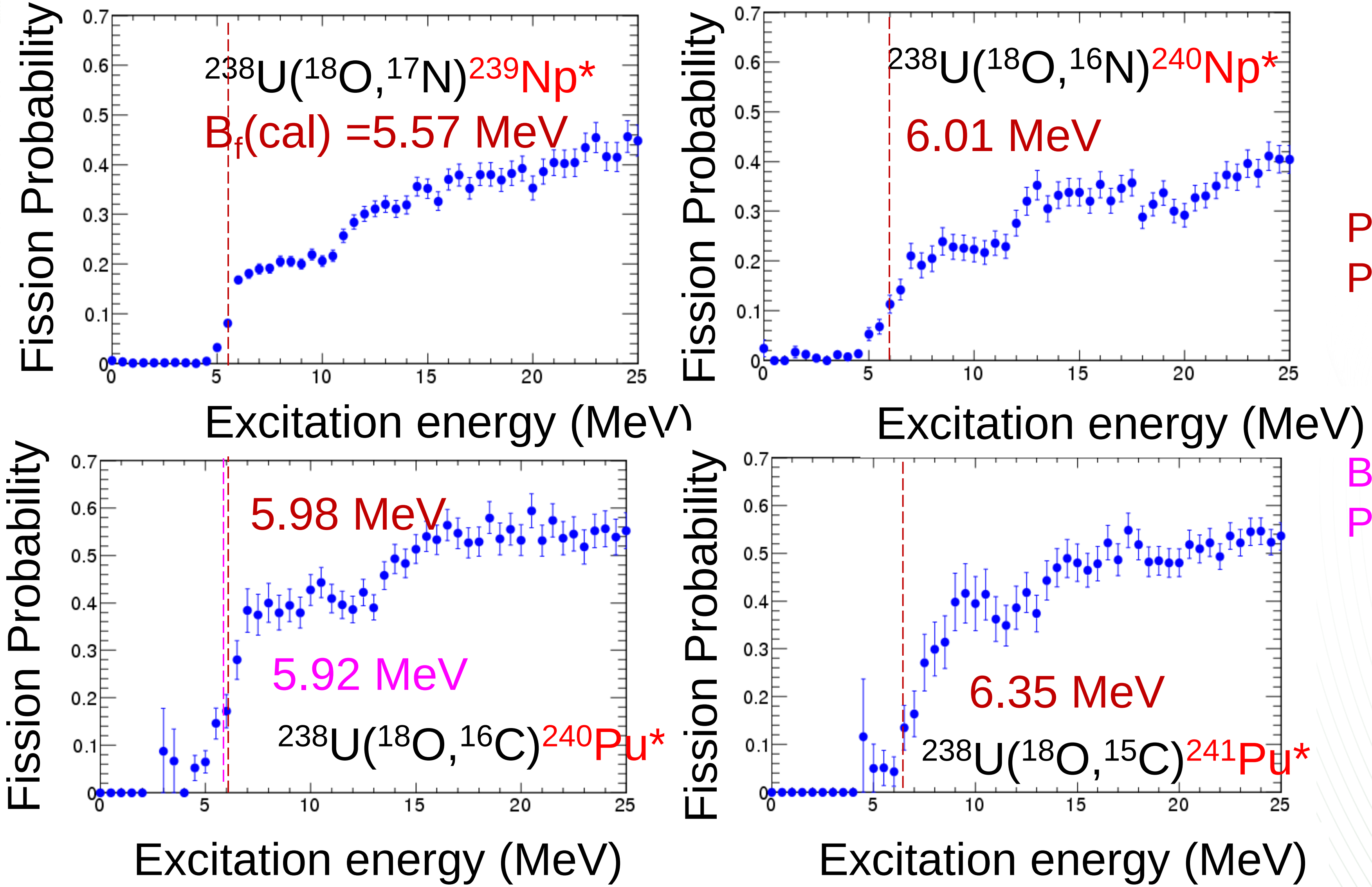
Not included Multi-chance Fission

Including Multi-chance Fission

"Role of multi-chance fission for description of fission fragment distributions at high energies"
K. Hirose et al., Phys. Rev. Lett. **119**, 222501 (2017).

Warszawa, SLCJ

Fission Probability and Fission Barrier Height (Katsuhisa Nishio)



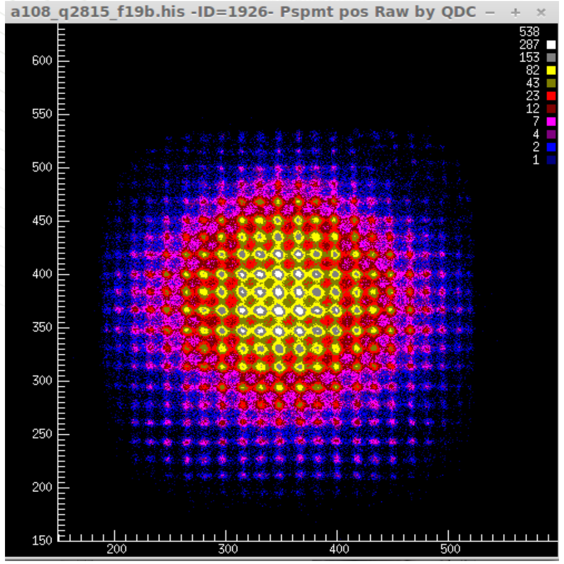
P. Moller et al.,
PRC 79, 064304 (2009)

B.N. Lu et al.,
PRC 89, 014323 (2014)

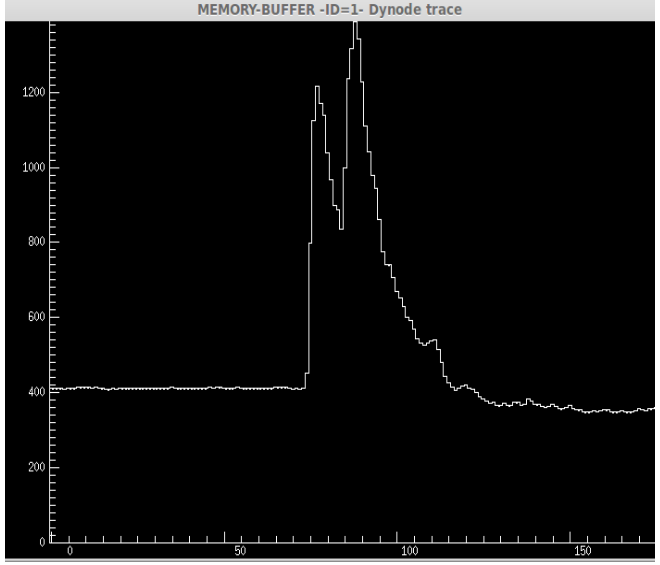
Interesting option for the detector array, so far not used for SHE studies.

ORNL/UTK digital detection system implemented at JAEA Tandem Laboratory at Tokai ~ 2011

UTK’s Robert **Grzywacz** Digital Pulse Processing Laboratory

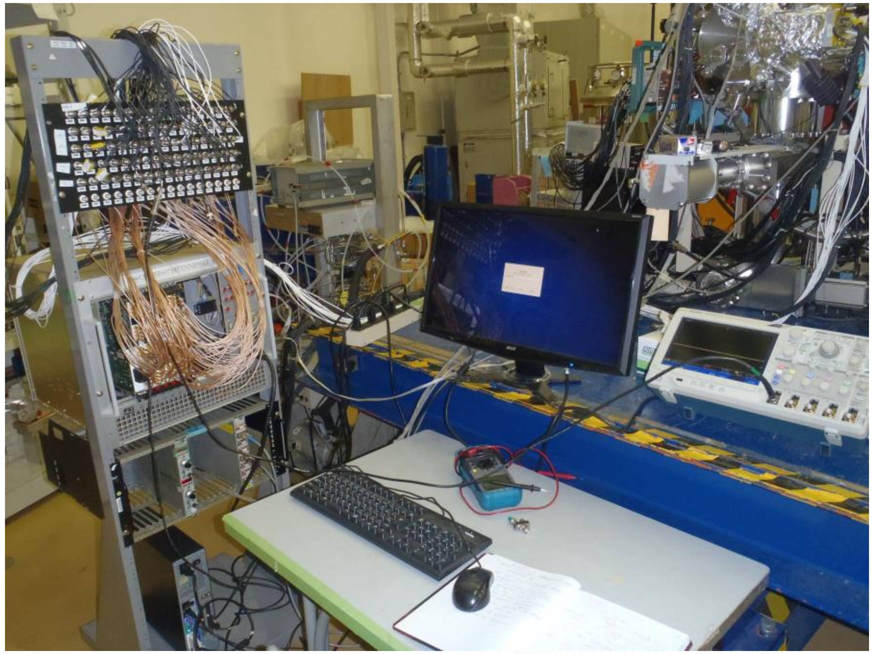


Spatial resolution
of YAP scintillator
(mass 109 ions)



Time resolution for two alpha
Signals, here 40 ns apart

RMS at JAEA Tokai

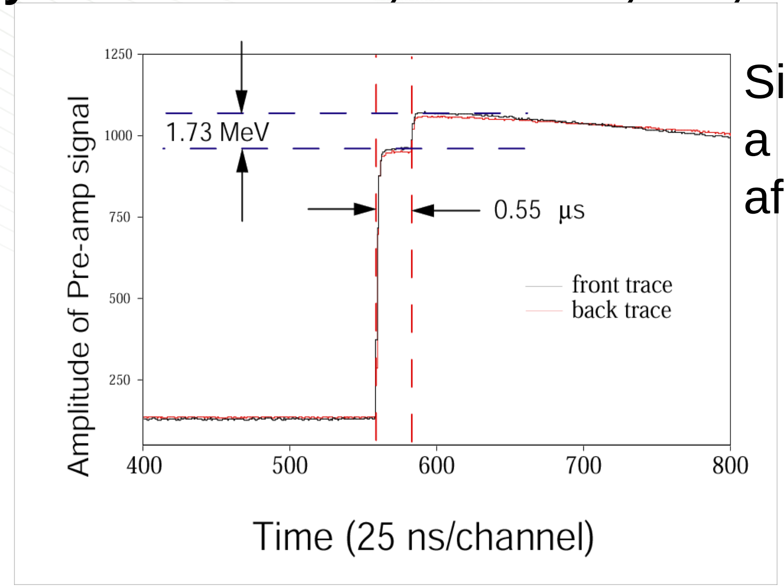


One can first consider for HIL the development and commissioning of new SHE detection techniques,
as an important contribution to the SHE physics.
In collaboration with other interested SHE labs, with an on-line testing using α-decays of heavy nuclei,
after a construction of a gas-separator on-line to the “upgraded accelerator”.

Examples of polish contributions
the modern detector and data acq systems

Digital pulse processing was required to detect (sub)-μs proton emitters at the HRIBF Recoil Mass Separator - first measurements with digital electronics were made in a Fall 1999.

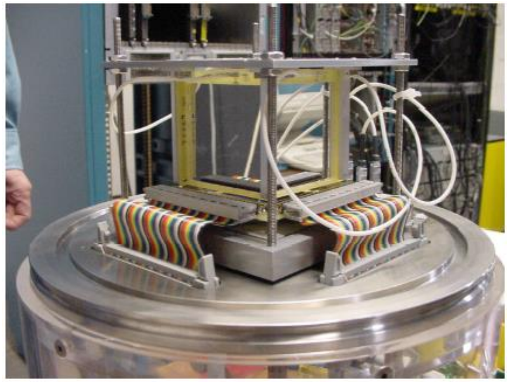
Rykaczewski et al., APP B 32, 971, 2000



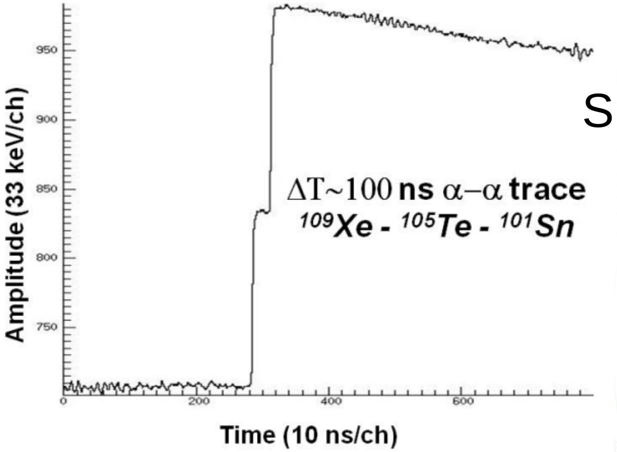
Signal trace showing a proton 550 ns after the ^{145}Tm recoil

In 2000, we have discovered fine structure in proton emission from 3-μs activity of ^{145}Tm, by taking digital traces of detector signals.

Marek Karny et al., PRL 2003



DSSD-Si-box-Si(Li) veto
at the HRIBF RMS



Signal trace showing two alpha signals detected within 100 ns

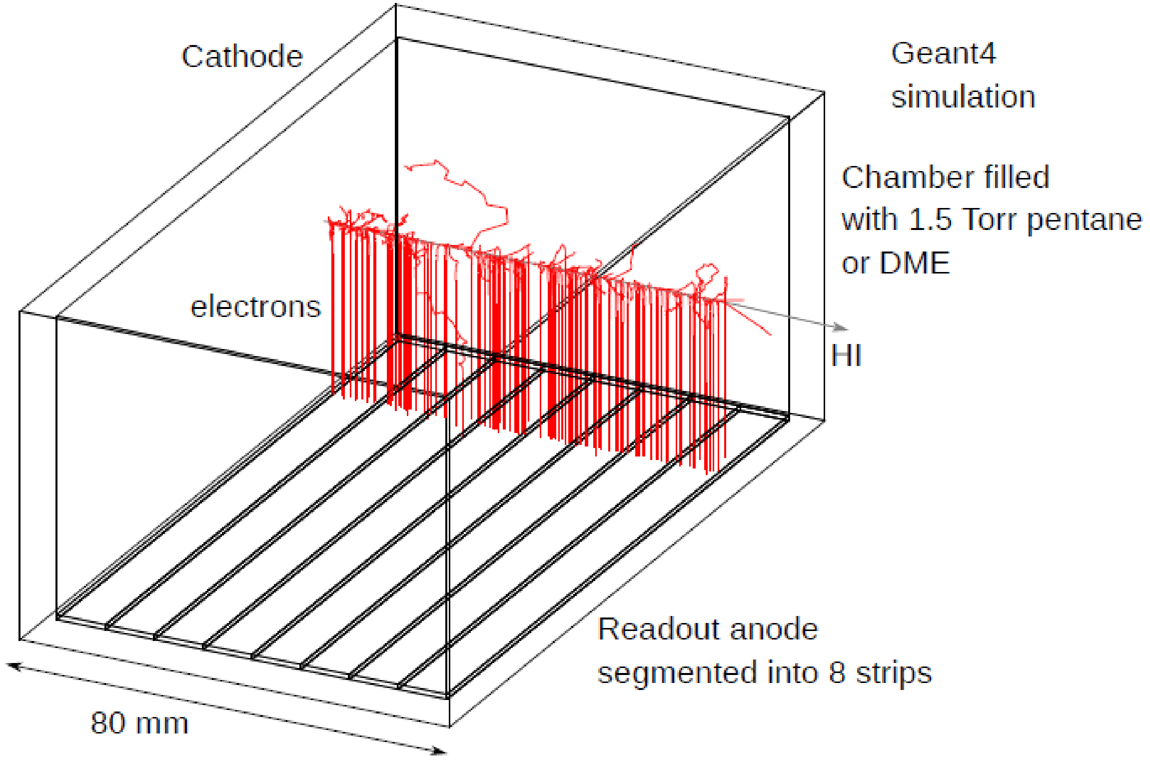
Grzywacz et al., NIM B261,1103, 2007
(+ two PRLs)

UTK Digital Pulse Processing Laboratory

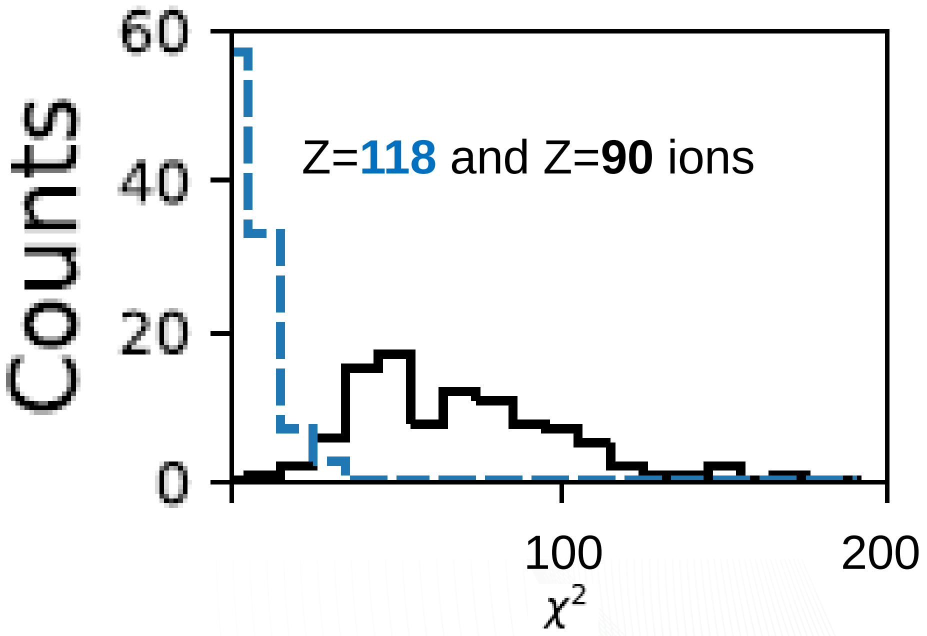
New Time Projection Chamber for the SHE Factory allowing Z-discrimination between target-like products (Z~ 90) and SHEs (Z~ 118)

important SHE detector still to be built and commissioned

TPC design



Amplification and second drift section is not shown for simplicity.

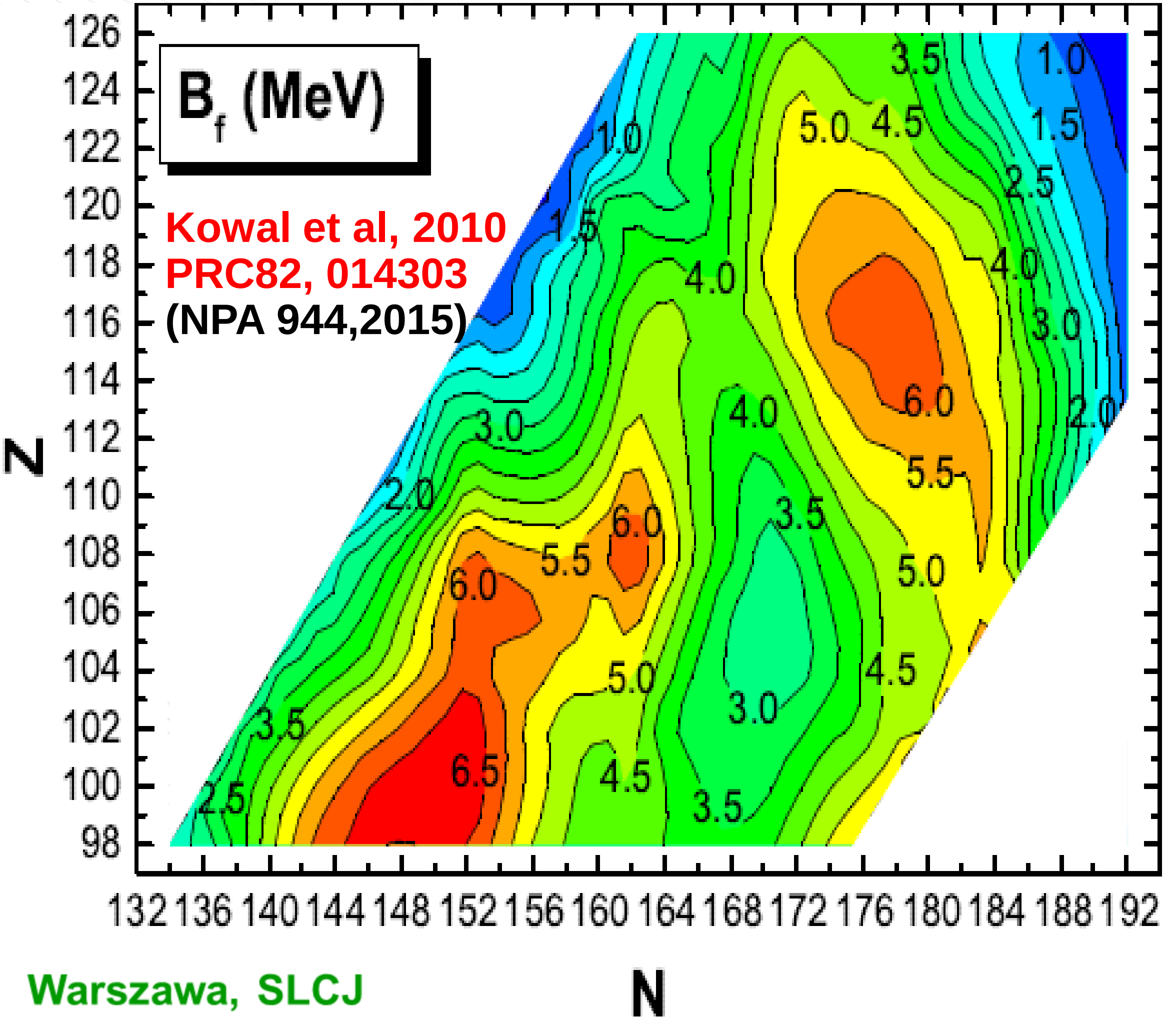


Discrimination through the analysis of ion tracks for Z=118 compared to Z=90

Krzysztof Miernik at SHE Symposium 2017, Oak Ridge – Warsaw – Dubna collaboration, ~ 200-300 k$

Connecting the Hot Fusion Island to Mainland

So far, we do not have a decay chain connecting the Island of Stability to the Mainland.
It is the effect of “fission corridor” aka “fission death valley” between the Island and Mainland.



Kowal et al, 2010
PRC82, 014303
(NPA 944,2015)

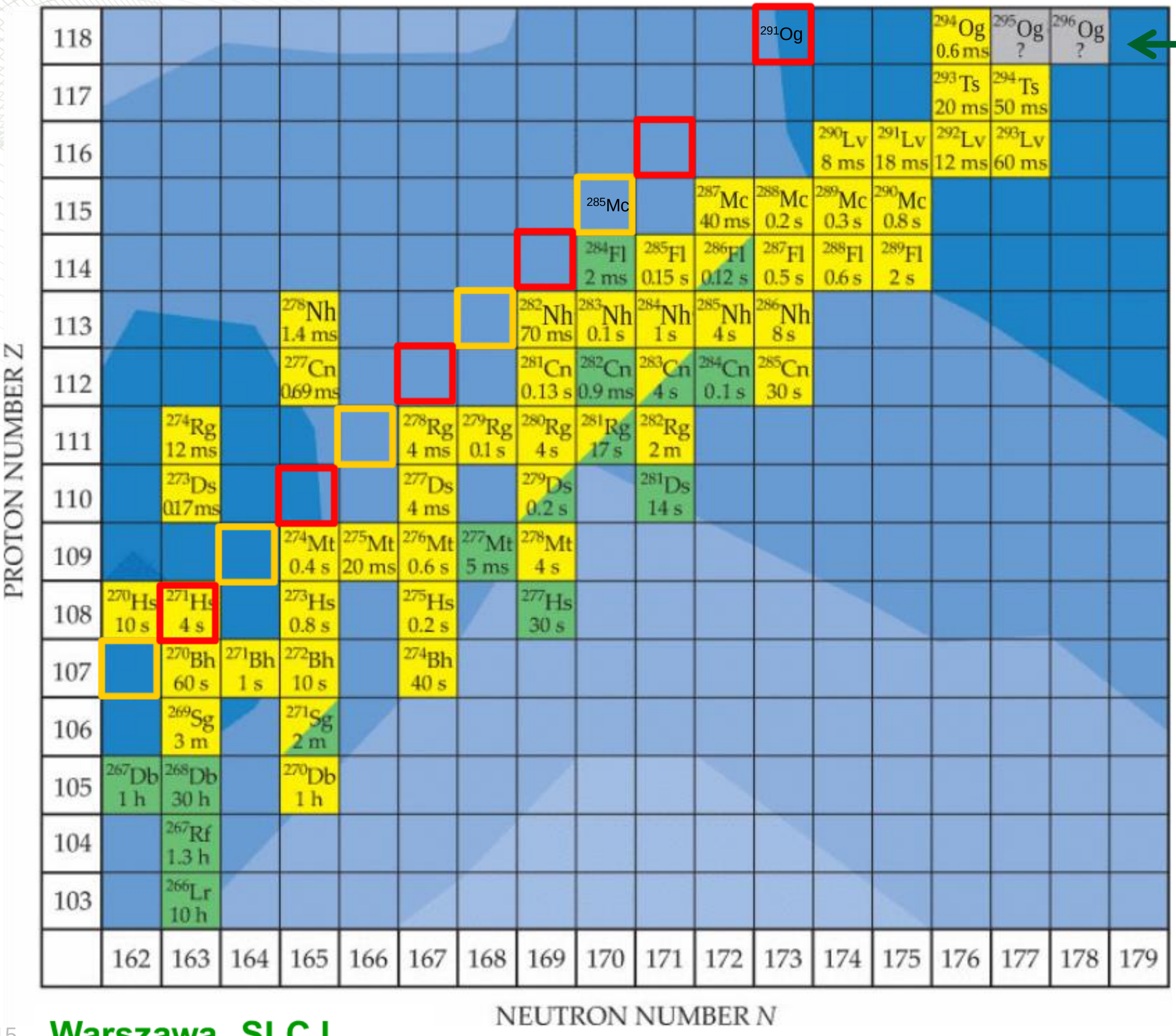
Part of the original motivation behind the attempt to observe such chain was related to the confirmation of the isotope assignment at the Island. However, now the identification of the elements and isotopes at the Island are officially adopted, and at least one mass number for ^{288}Mc is confirmed.

Still, the chains crossing “fission death valley” would offer unique data on the fission/alpha competition, important in general to analyze the structure and decay processes of super heavy nuclei.

Potential reactions aiming in a decay chain crossing the valley should address the production of odd-odd or at least odd-mass nuclei, to reduce fission competition.

Warszawa, SLCJ

Connecting the Hot Fusion Island to Mainland



	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179
118												^{291}Og			^{294}Og 0.6 ms	^{295}Og ?	^{296}Og ?	
117															^{293}Ts 20 ms	^{294}Ts 50 ms		
116													^{290}Lv 8 ms	^{291}Lv 18 ms	^{292}Lv 12 ms	^{293}Lv 60 ms		
115									^{285}Mc		^{287}Mc 40 ms	^{288}Mc 0.2 s	^{289}Mc 0.3 s	^{290}Mc 0.8 s				
114									^{284}Fl 2 ms	^{285}Fl 0.15 s	^{286}Fl 0.12 s	^{287}Fl 0.5 s	^{288}Fl 0.6 s	^{289}Fl 2 s				
113				^{278}Nh 1.4 ms				^{282}Nh 70 ms	^{283}Nh 0.1 s	^{284}Nh 1 s	^{285}Nh 4 s	^{286}Nh 8 s						
112				^{277}Cn 0.69 ms				^{281}Cn 0.13 s	^{282}Cn 0.9 ms	^{283}Cn 4 s	^{284}Cn 0.1 s	^{285}Cn 30 s						
111		^{274}Rg 12 ms				^{278}Rg 4 ms	^{279}Rg 0.1 s	^{280}Rg 4 s	^{281}Rg 17 s	^{282}Rg 2 m								
110		^{273}Ds 0.17 ms				^{277}Ds 4 ms		^{279}Ds 0.2 s		^{281}Ds 14 s								
109				^{274}Mt 0.4 s	^{275}Mt 20 ms	^{276}Mt 0.6 s	^{277}Mt 5 ms	^{278}Mt 4 s										
108	^{270}Hs 10 s	^{271}Hs 4 s		^{273}Hs 0.8 s		^{275}Hs 0.2 s		^{277}Hs 30 s										
107		^{270}Bh 60 s	^{271}Bh 1 s	^{272}Bh 10 s		^{274}Bh 40 s												
106		^{269}Sg 3 m		^{271}Sg 2 m														
105	^{267}Db 1 h	^{268}Db 30 h		^{270}Db 1 h														
104		^{267}Rf 1.3 h																
103		^{266}Lr 10 h																

mixed-Cf+^{48}Ca

Among the reactions to be considered are:

- **^{241}Am+^{48}Ca reaction**

leading to new lighter isotopes of Z=115 Mc like **^{285}Mc** made in 4n channel

The reaction ^{241}Am+^{50}Ti looks even more attractive, but X-section/$T_{1/2}$ might be too low)

^{241}Am is at the inventory at REDC/ORNL

^{244}Cm + ^{50}Ti → **^{291}Og** in 3n channel

77% enriched ^{244}Cm is at the inventory at REDC/ORNL

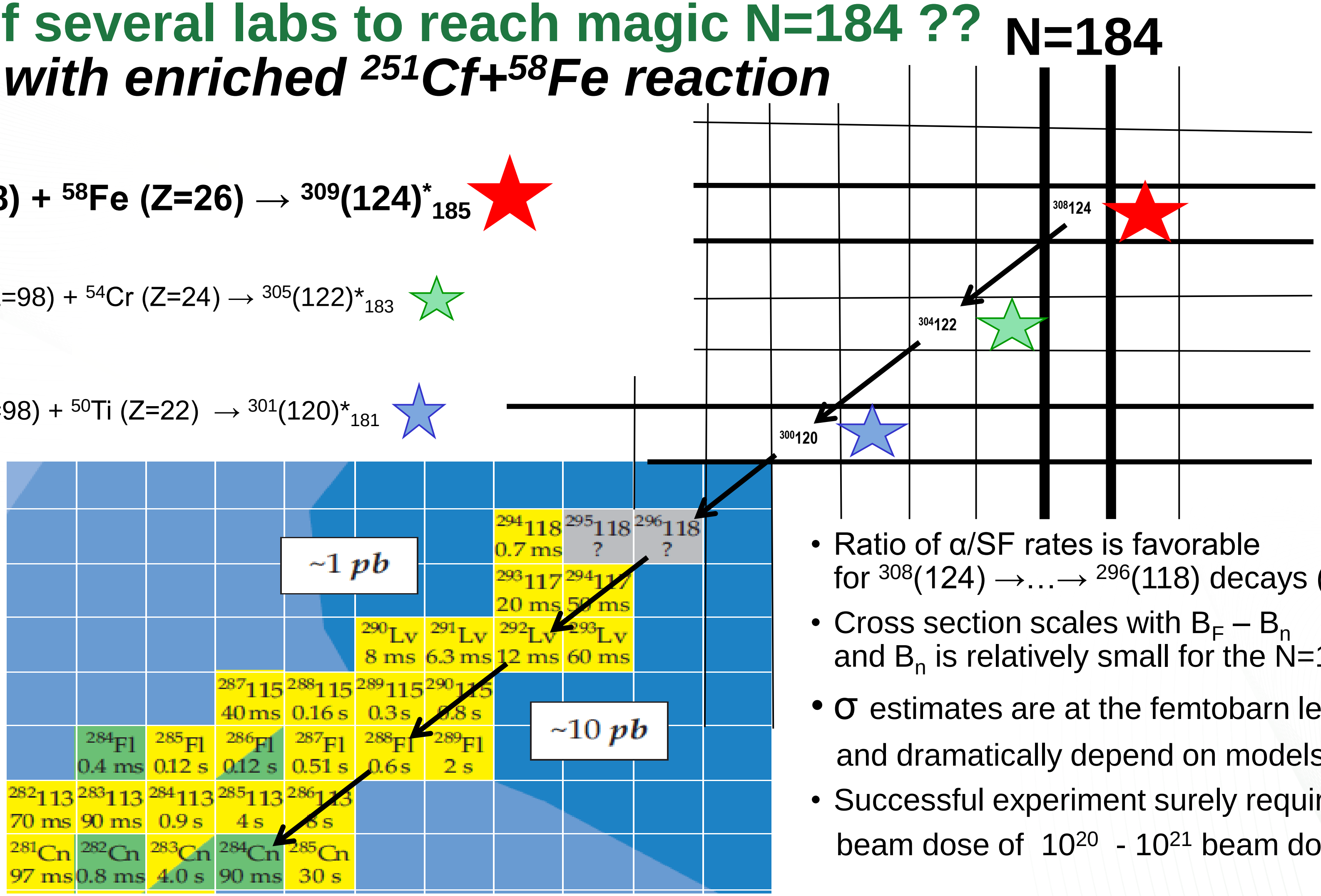
Collaboration of several labs to reach magic N=184 ??

towards N=184 with enriched ^{251}Cf+^{58}Fe reaction

^{251}Cf (Z=98) + ^{58}Fe (Z=26) → $^{309}(124)^{*}_{185}$ ★

^{251}Cf (Z=98) + ^{54}Cr (Z=24) → $^{305}(122)^{*}_{183}$ ☆

^{251}Cf (Z=98) + ^{50}Ti (Z=22) → $^{301}(120)^{*}_{181}$ ☆



- Ratio of α/SF rates is favorable for $^{308}(124)$ →…→ $^{296}(118)$ decays (both HFB and Mic-Mac)
- Cross section scales with $B_F - B_n$ and B_n is relatively small for the N=185 (184+1) nucleus
- σ estimates are at the femtobarn level for $B_f \sim 4.5$ MeV and dramatically depend on models (Wilczynska 2017)
- Successful experiment surely requires beam dose of 10^{20} - 10^{21} beam dose

Actinide mass separator would make the experiment about three times more probable.

35% ^{251}Cf now → over 95 % ^{251}Cf after enrichment

^{251}Cf has 900 years half-life → enrichment creates a safe target, which is allowed to be used in many laboratories!!

Rykaczewski et al., NOBEL SYMPOSIUM NS 160 - EPJ Web of Conferences, Vol. 131, 05005, 2016

Fission barriers and probabilities of spontaneous fission for elements with Z≥100

Nucl. Phys. A 944, 442, 2015, “SHE” Issue

A. Baran[1], M. Kowal[b], P.-G. Reinhard[d], L.M. Robledo[c], A. Staszczak[1], M. Warda[1]

even-even nuclei

N~185

$^{309}(124)^*$

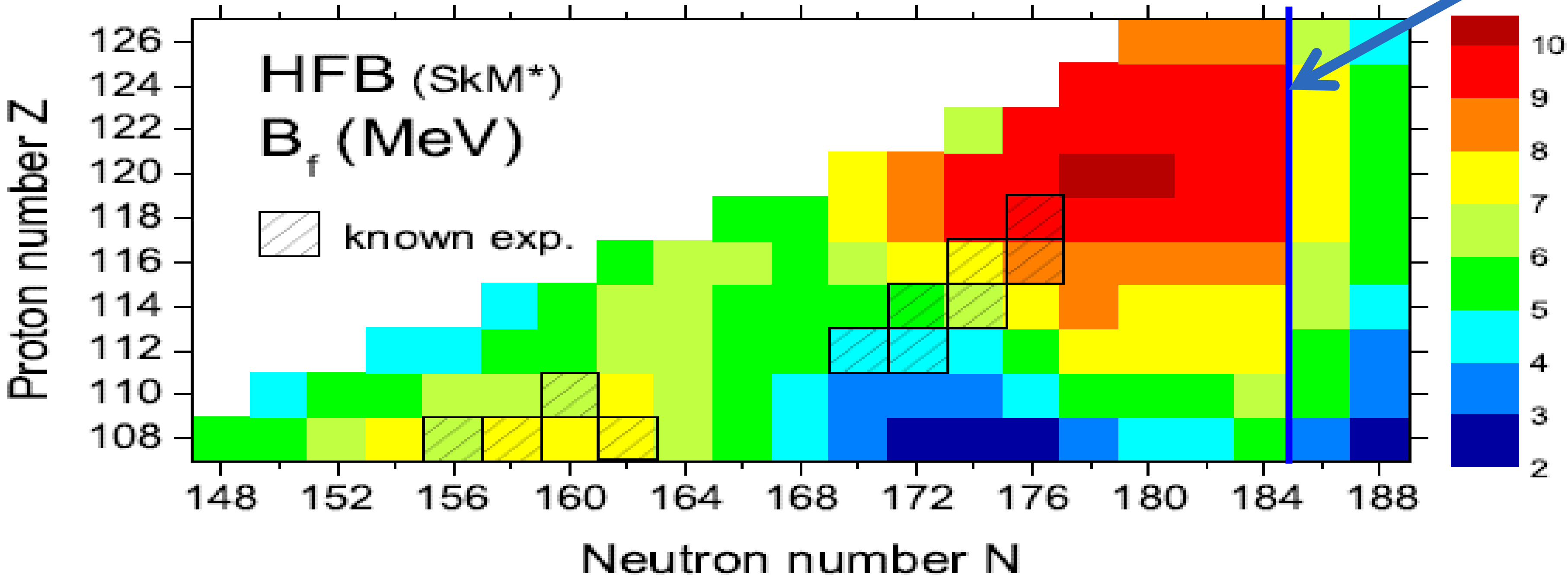


Figure 3: First fission barrier (MeV) of SH nuclei in HFB SkM* model. Cross-hatched squares represent observed nuclei.

Neutron separation energy values are around ~ 6-7 MeV

so for $^{309}(124)^*$ $B_f - B_n \sim 0$ MeV

Summary - with some options for HIL

Every real contribution to the SHE research requires a group of local experienced physicists dedicated to the success of their SHE program

Experimental contribution to SHE studies is expensive and requires state-of-the art equipment. Starting from **the accelerator performing very well over many months, with intense heavy ion beams,** efficient **separator** (Darek) and modern **detectors and ACQ** system.

Experiments with high beam intensity and radioactive targets requires appropriate **shielding and licensing**.

New accelerator offering many heavy-ion beams with a fusion products separator can attract **new users** coming with advanced detector systems and good proposals (not only SHEs).

Euro-competition/collaboration: JINR Dubna, GANIL, GSI, Jyvaskyla (RIKEN, HIAS, KORea, Tokai, Canberra)

“In-beam” studies contributing to the research on heavy nuclei requiring lower beam currents, and do not require a separator (but separator helps, see AGFA and others).
Know-how available at HIL

Studies of fusion mechanism (HIL) for very heavy nuclei and few nucleon transfer reactions applied to the fission mechanism studies
also can be performed at lower beam currents and without a separator (see Nishio et al)

Multinucleon transfer reactions towards heavy nuclei ?