"Super Heavy Elements and Nuclei"

Krzysztof P. Rykaczewski
Physics Division, Oak Ridge National Laboratory

This presentation is mostly about the heaviest elements and nuclei at the Island of (enhanced) Stability

Russia-US
JINR Dubna - ORNL Oak Ridge - LLNL Livermore UT Knoxville - RIAR Dmitrovgrad - Vanderbilt Nashville

Germany and the rest of the World
Darmstadt-Mainz-Lund-Oak Ridge-Berkeley et al

US
LBNL Berkeley-UC-LLNL-GSI-Mainz-Lund-Oregon

Japan
RIKEN- Uni. Kyushu and other Japanese labs

U.S. DEPARTMENT OF ENERGY

EBSS 2016, July 2016, MSU

Rose Boll and Shelley Van Cleve purifying ^{249}Bk (~40 Ci) at ORNL

Yuri Oganessian and V. Utyonkov correcting Z=117 Letter at Dubna

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

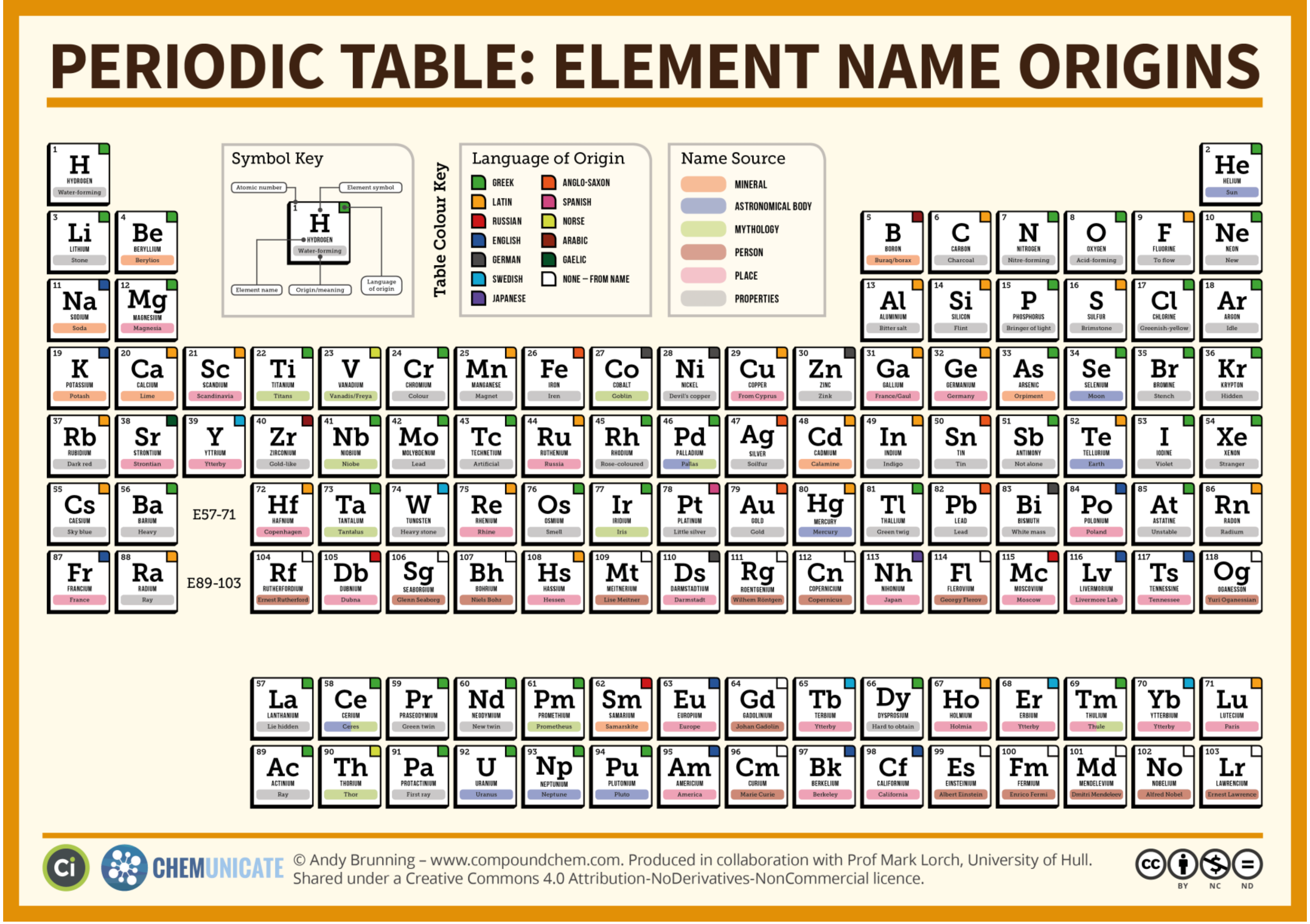
Mantra
for today's talk,
EBSS and our
research

Why we are studying *(decays of)* exotic nuclei far from beta-stability path ?

effects not present or weak in stable nuclei are often appearing or getting enhanced in nuclei far from β-stability, in nuclei with "unusual" proton-to-neutron content

".. decay data offer last verification points for theory before extrapolating into unknown …"

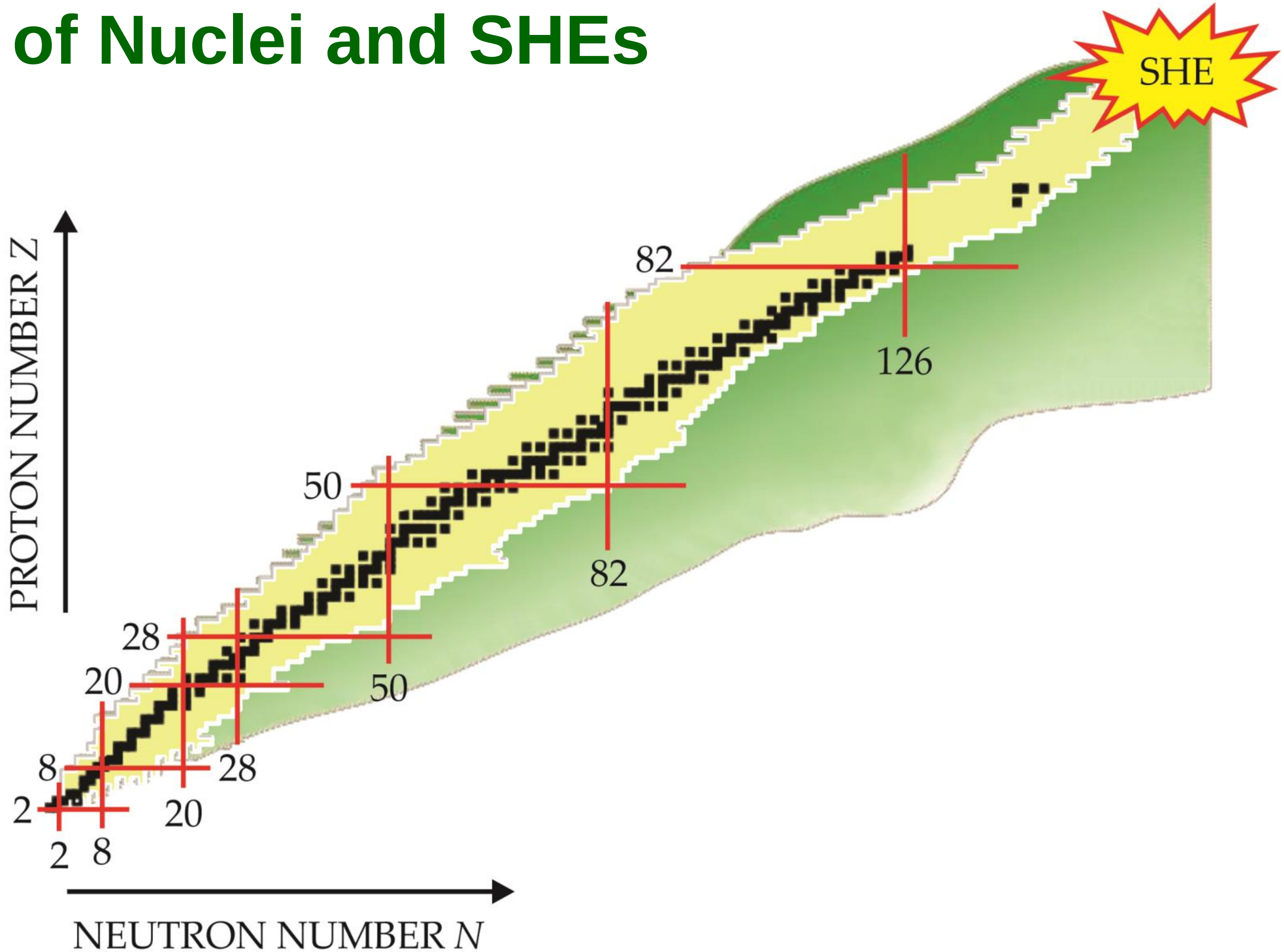
… and our goal is to understand the origin of structure and processes involving atomic nuclei



Four provisional names accepted/announced by IUPAC/IUPAP, with symbols Nh for 113, Mc for 115, Ts for 117 and Og for 118, are included

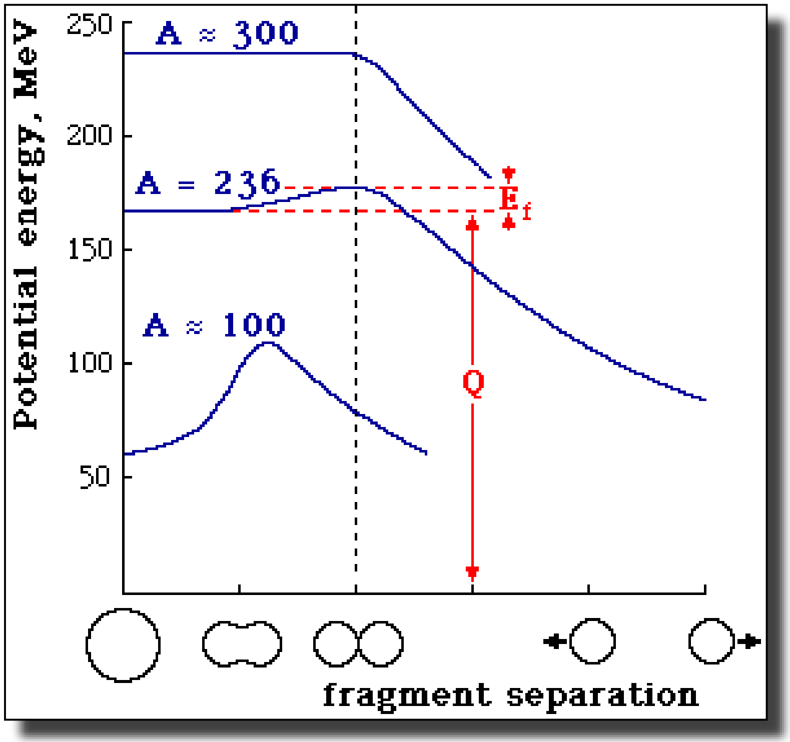
OAK RIDGE
National Laboratory

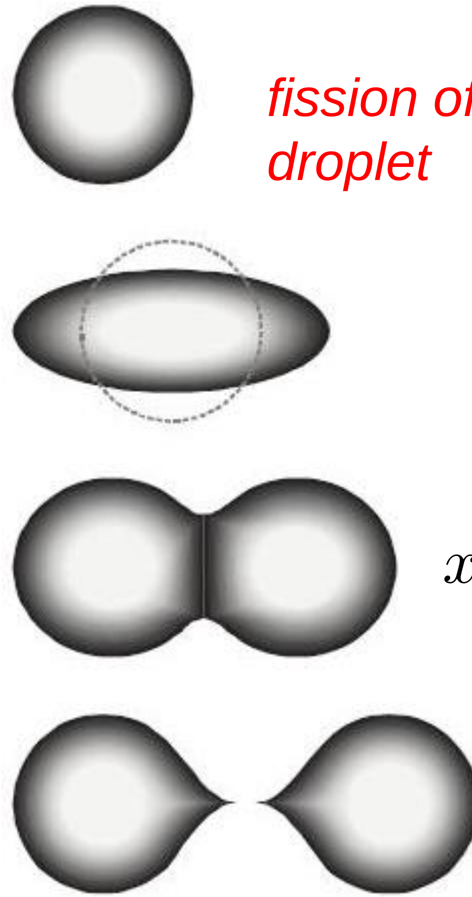
Segre Chart of Nuclei and SHEs



The definitions of SHE vary, from giving atomic number limit like Z>100, to the "true SHEs", namely atoms of nuclei stabilized against fission by nuclear structure effects like a shell correction to the binding energy.

Fission of charged nuclear droplet





fission of nuclear droplet

fissility parameter x:

$$x = \frac{E_{\mathrm{Coul}}}{2E_{\mathrm{surf}}} \approx \frac{Z^2}{50A}$$

The nuclear droplet stays stable and spherical for x<1.
For x>1, it fissions immediately. For ^{238}U, x=0.71, for ^{294}118 x=0.95.
Fissility x is not an universal measure of stability against fission since nuclei are (usually) not spherical.

from Witek Nazarewicz

PRL 102, 192501 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

Fission Barriers of Compound Superheavy Nuclei

J. C. Pei,[1,2,3] W. Nazarewicz,[2,3,4] J. A. Sheikh,[2,3] and A. K. Kerman[2,3,5]

Fission barrier in the excited state !

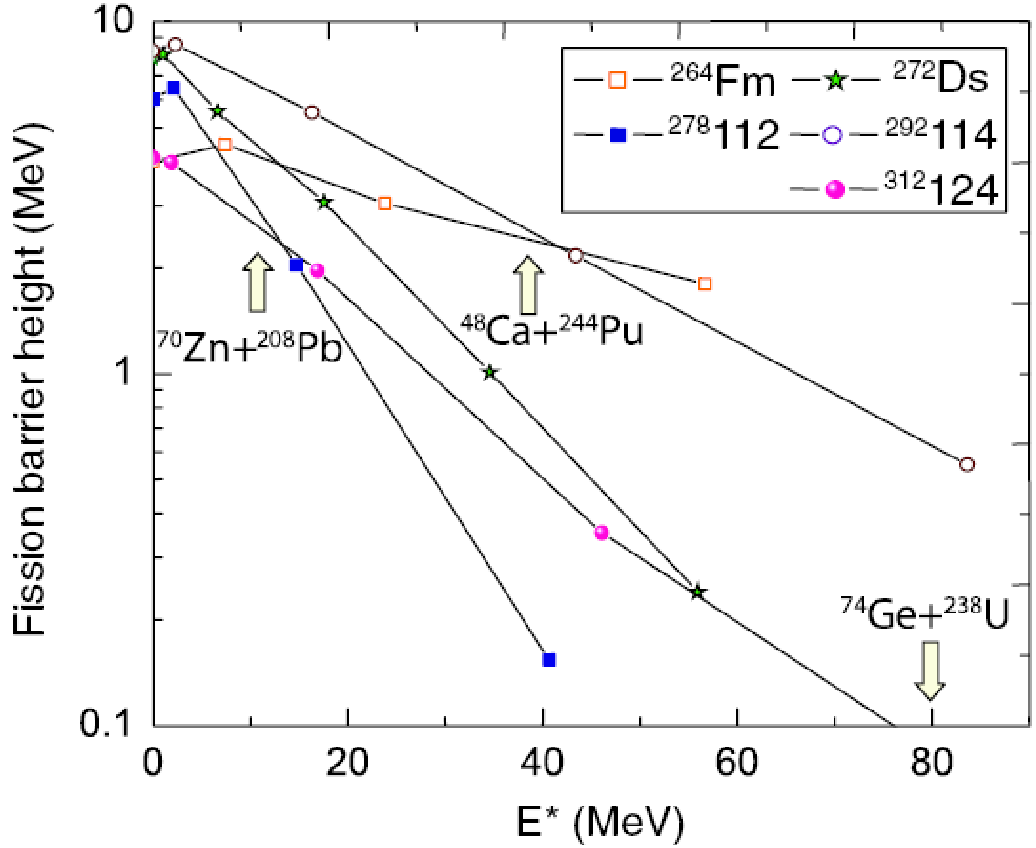
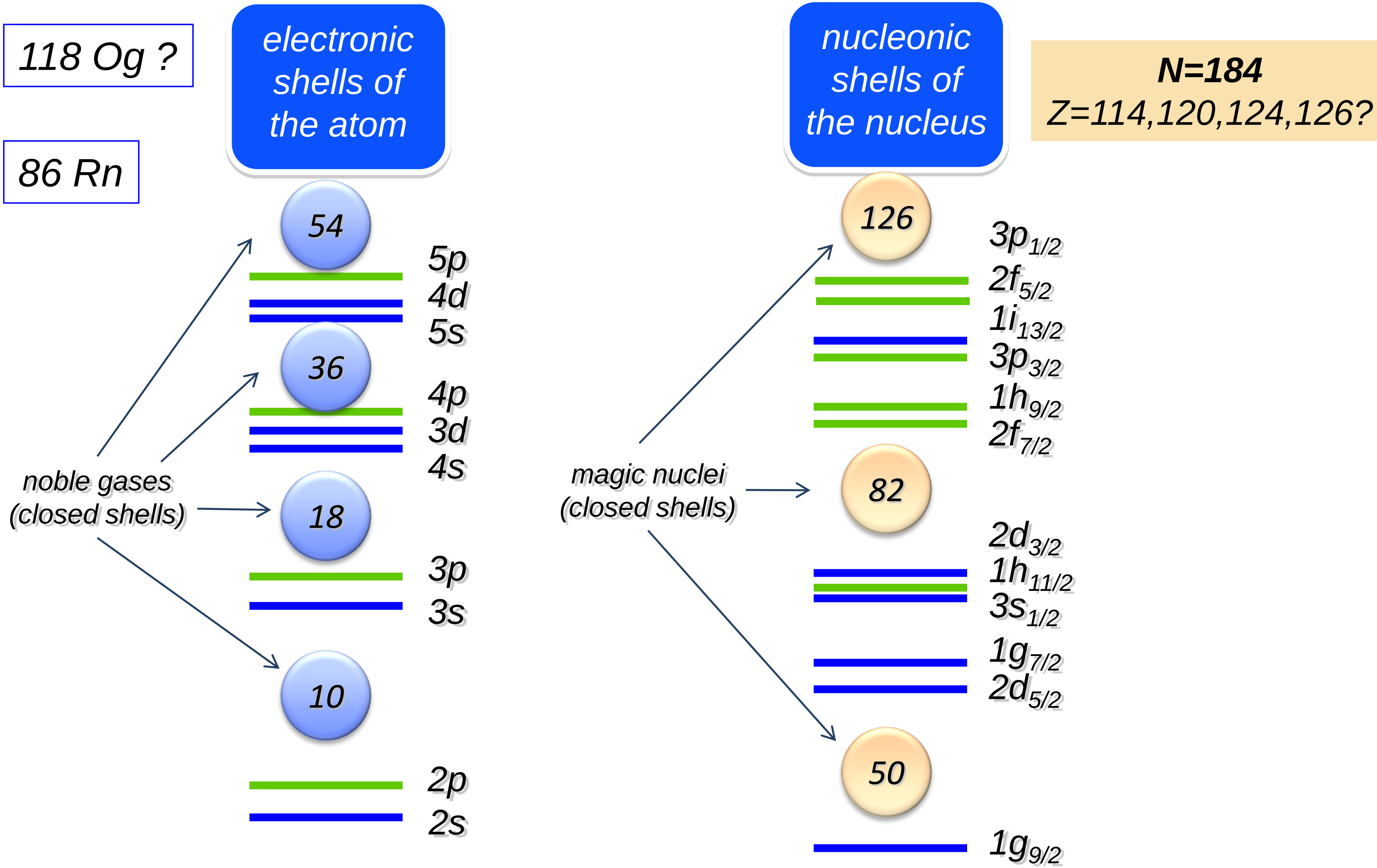


FIG. 4 (color online). The height of the inner fission barrier in ^{264}Fm, ^{272}Ds, ^{278}112, ^{292}114, and ^{312}124 as a function of excitation energy E^*. The effect of triaxiality on the fission barrier has been included. The experimental values of E^* corresponding to CN formed in the reactions indicated are marked by arrows.

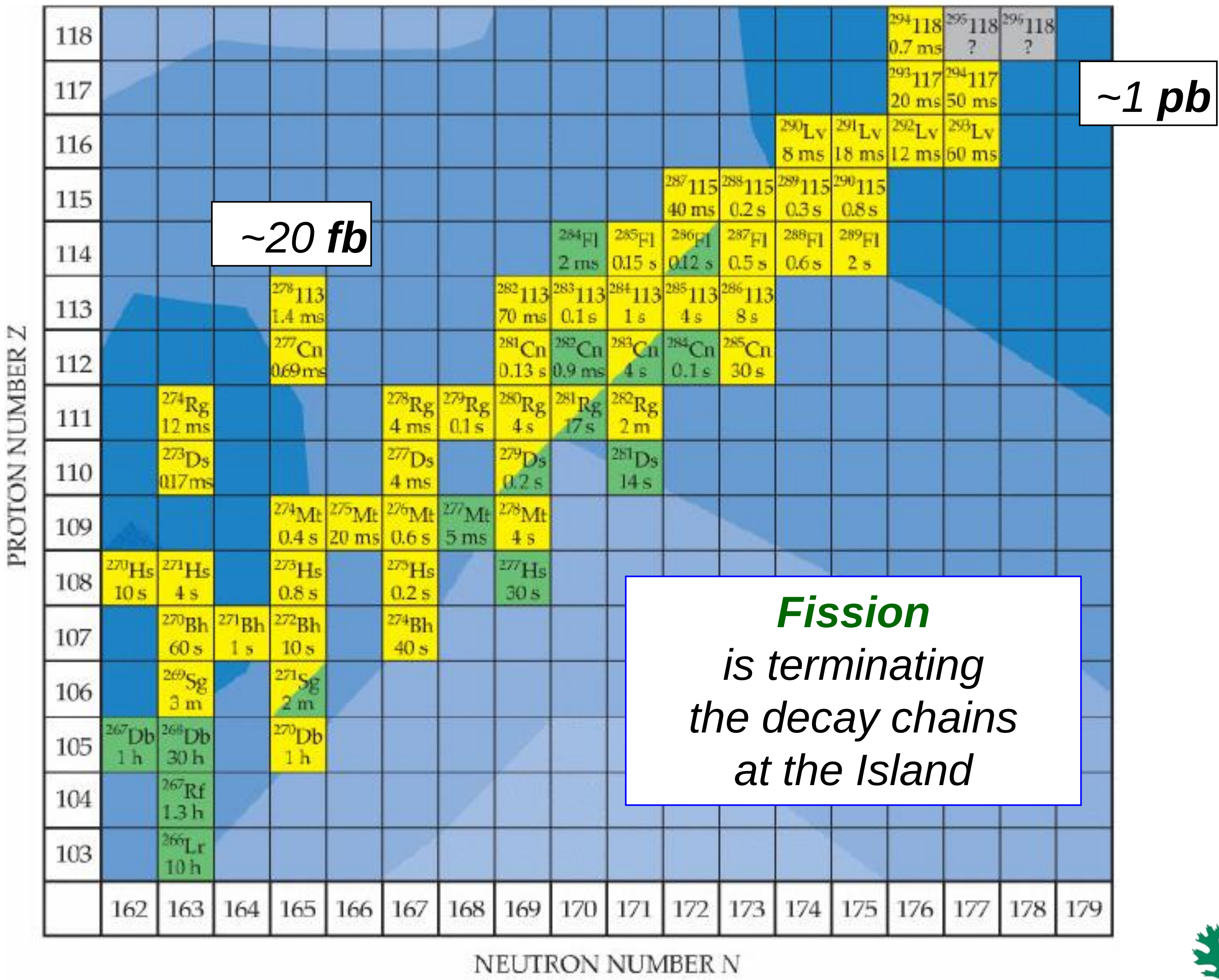
Shell effects come to the rescue of nucleus against fission



from Witek Nazarewicz

The Island of Stability of Super Heavy Nuclei

aka "Hot Fusion Island " of over 50 nuclei produced in ^{48}Ca+actinides targets reactions



from Yuri Oganessian and KR, Physics Today, Aug.2015

Long term goals – science drivers for SHE research

- **New Heaviest Elements and Nuclei**

  - *how many protons and neutrons a nucleus can hold ?*
  - *unified description of nuclear properties across varying proton and neutron numbers*
  - *new energy gaps, magic numbers and Island of Stability*
    or rather enhanced stability without shell gaps and magic numbers
  - *understanding fission process competing with other decay modes (α, EC)*
  - *structure beyond ground-state properties of super heavy nuclei*

- **Understanding production mechanism of the heaviest nuclei**

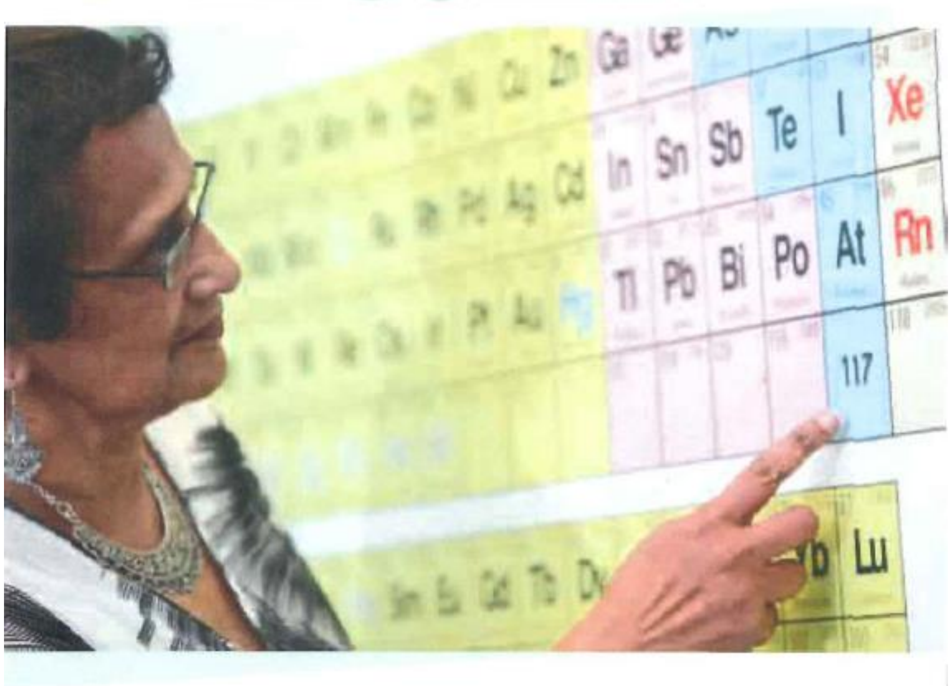
  - *hot and cold fusion reactions with stable and radioactive nuclei*
  - *multi-nucleon transfer between very heavy nuclei*

- **Expansion of Periodic Table of Elements**

  - *relativistic effects in chemical properties of atoms (radius, ionization, compounds)*
  - *super heavy atoms in the Universe*

The element name will stay forever in the Periodic Table

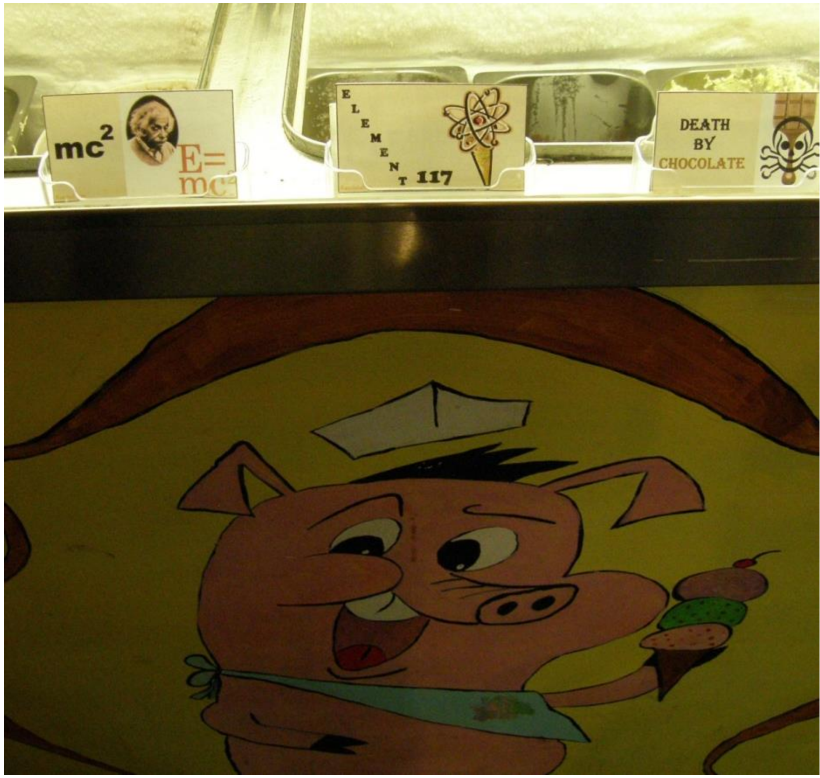
Oak Ridge High School, April 2010



International team discovers element 117

Now tennessine Ts

"Element 117" *ice cream*
Razzleberry Ice Cream Lab
Oak Ridge

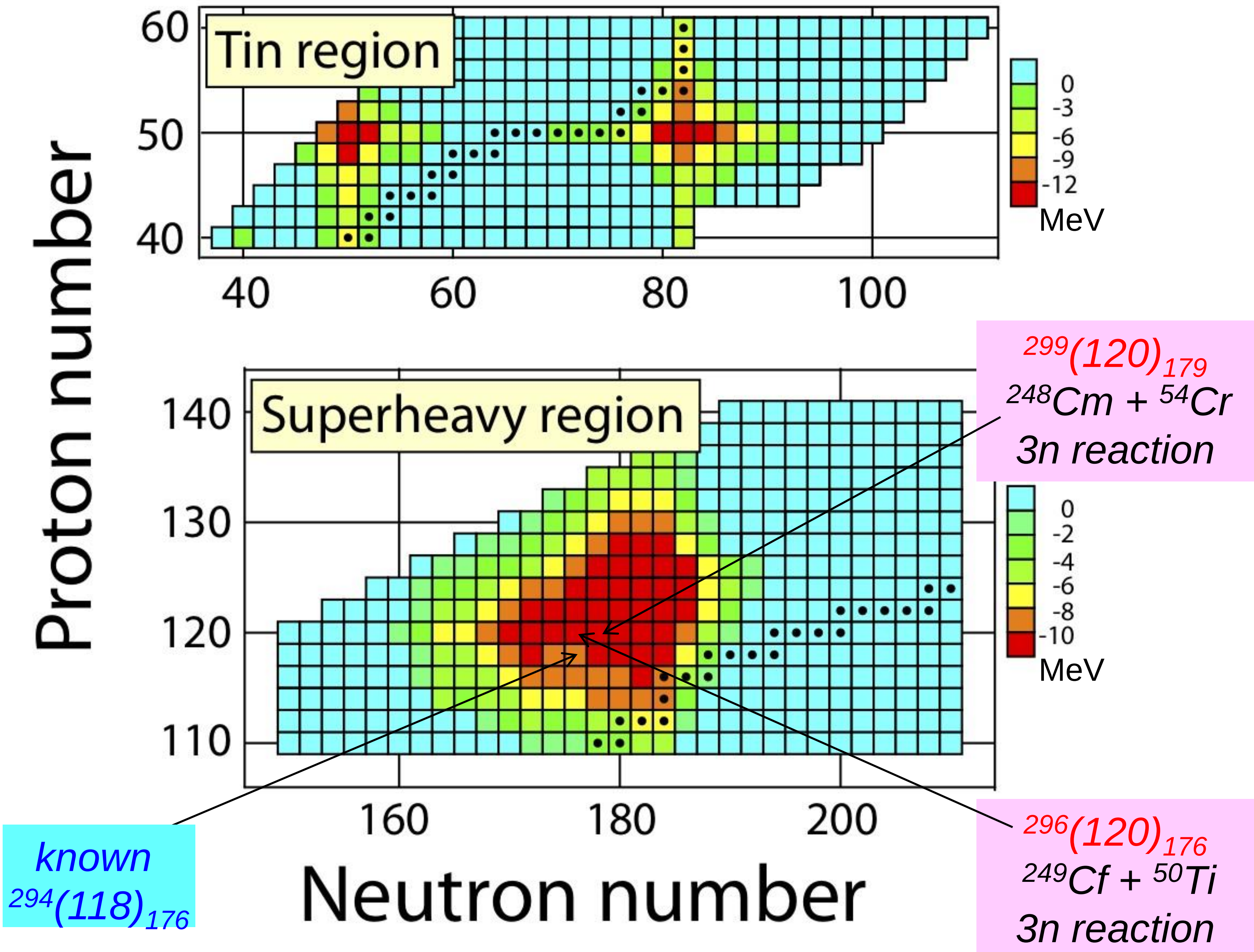


IUPAC/IUPAP press release on 8th June 2016,
where element 117 was provisionally named ***tennessine*** *(**Ts**),*
might trigger a development of a new brand of
Jack Daniels Whisky "No.117"

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY

M. Bender, W. Nazarewicz, P.-G. Reinhard , Phys. Lett. B 515, 42, 2001

"Shell stabilization of super- and hyper-heavy nuclei without magic gaps"

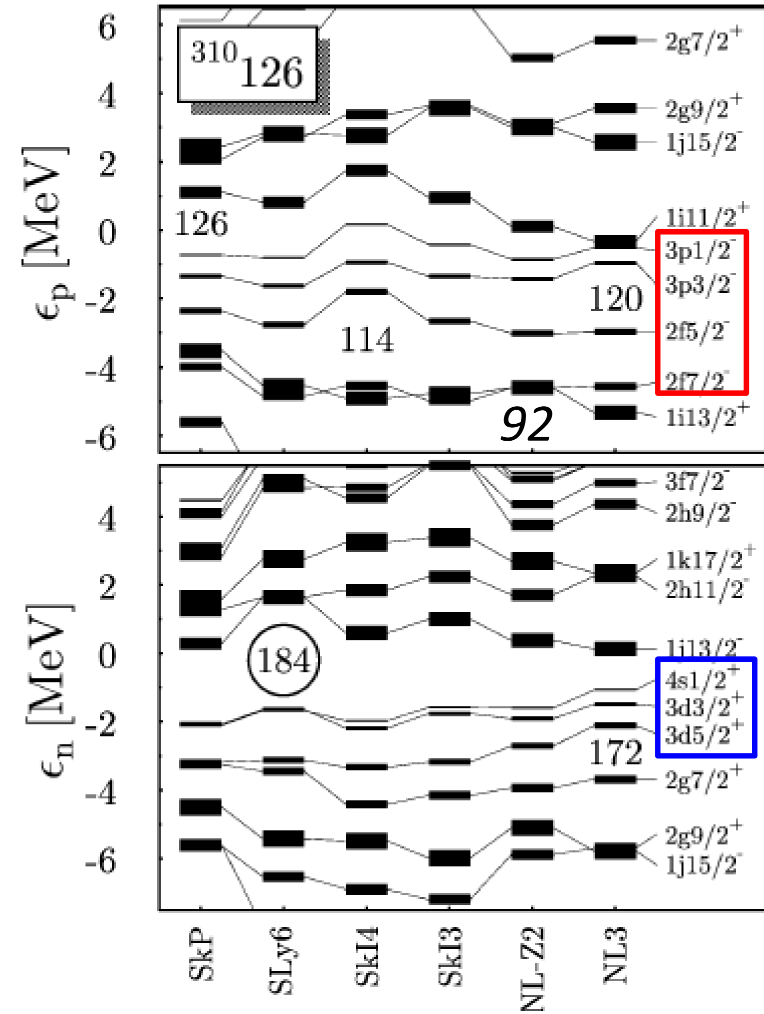


Single-particle levels in the region of super heavy nuclei

M. Bender, W. Nazarewicz, P.- G. Reinhard, PL B 515, 42, 2001

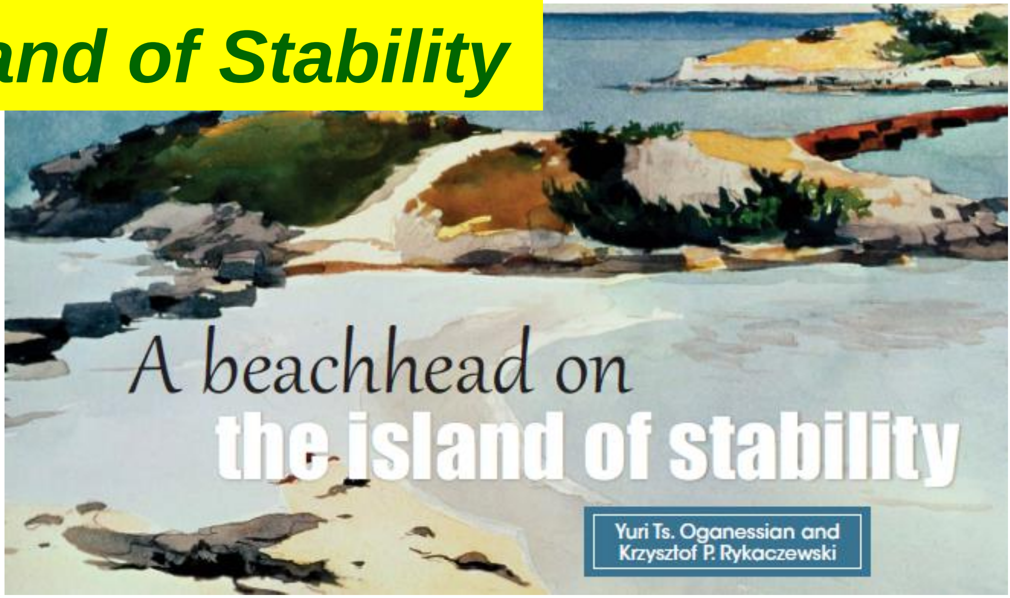
protons

neutrons

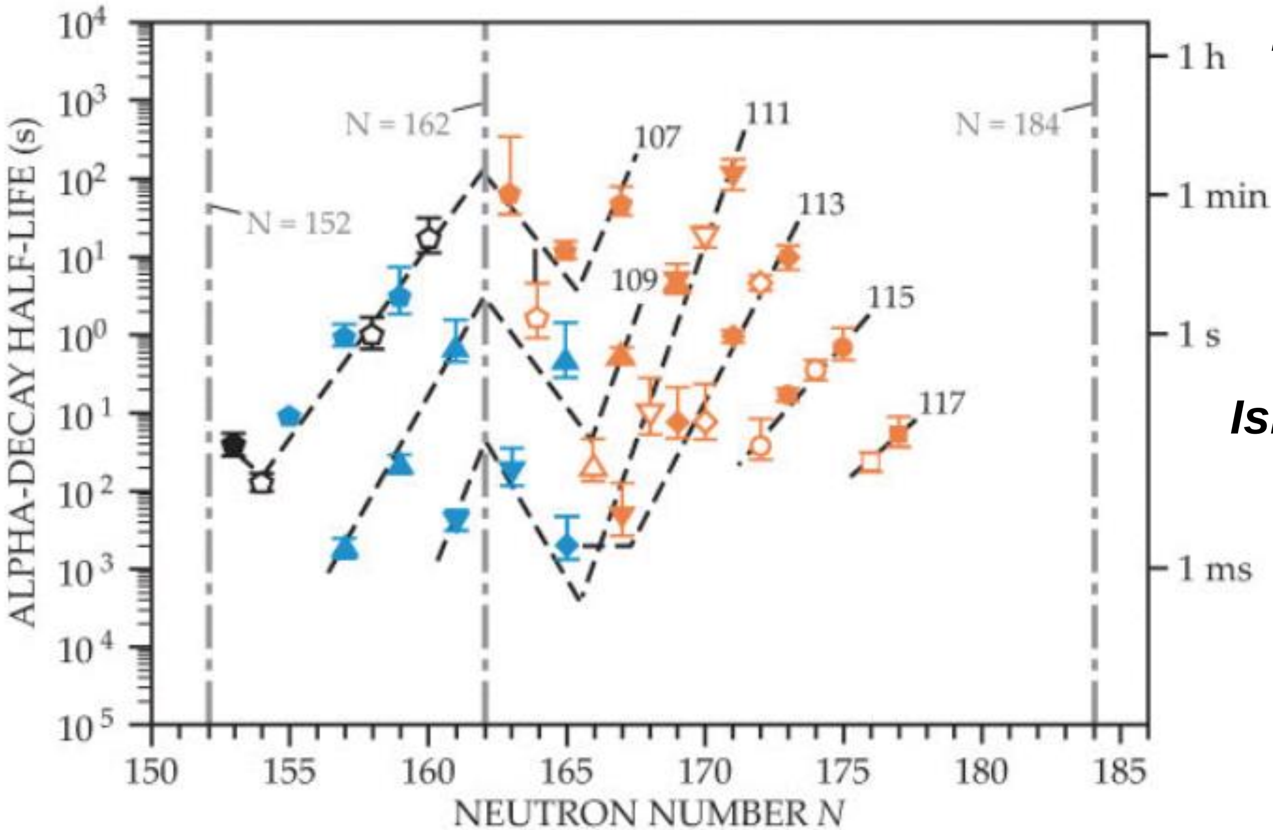


2016 - 50 Years of the Island of Stability

The concept of an island of stability has dominated the physics of superheavy nuclei since middle sixties,
see, e.g.
Myers-Świątecki 1966
Sobiczewski-Gareev-Kalinkin 1966
Viola-Seaborg 1966



Phys. Today, 68(8), 32, 2015



Indeed, we have reached a shore of the Island of (enhanced) Stability!

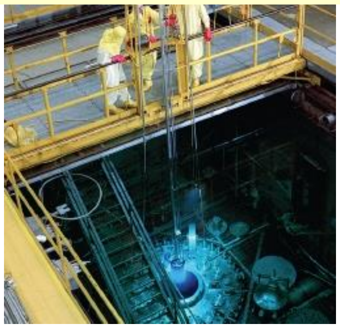
UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY

2009-2010: Synthesis of a New Element with Atomic Number Z=117 (Ts)

Dubna-Oak Ridge-Nashville-Livermore-Dmitrovgrad-Las Vegas

The identification of a new element Z=117 among the products of the $^{249}Bk+^{48}Ca$ reaction was enabled by the close collaboration and unique capabilities of the US and Russia laboratories, neither country could achieve it alone. The 327 days half-life of radioactive ^{249}Bk required a coordination of two years neutron irradiation and chemical separation at Oak Ridge followed by a target production at Dimitrovgrad and six months experiment with an intense ^{48}Ca beam at Dubna.

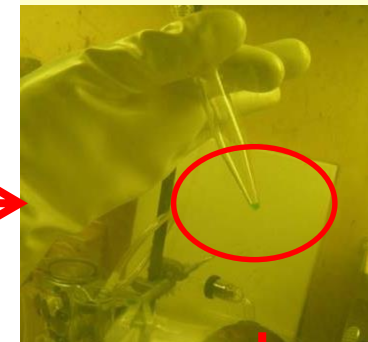
High Flux Isotope Reactor ORNL, Oak Ridge



25-ton Q-ball transporting irradiated Am/Cm seed material

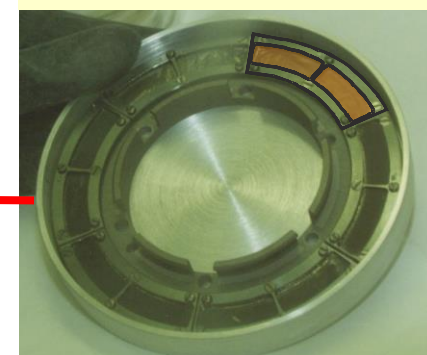
Chemical separation in hot cell REDC, ORNL, Oak Ridge

Pure 22 mg of ^{249}Bk



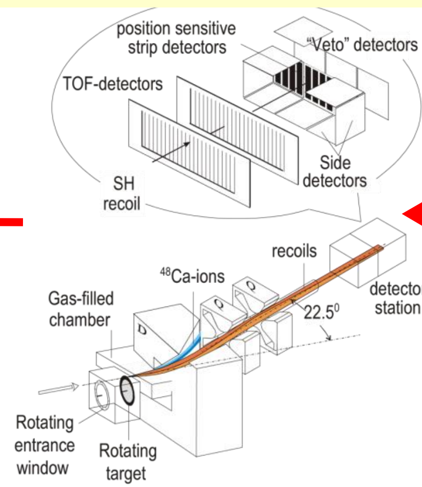
5 flights

^{249}Bk target wheel made at RIAR Dimitrovgrad

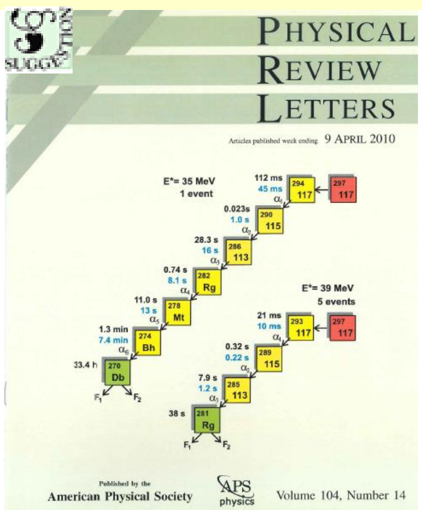


U-400 cyclotron at JINR Dubna

Dubna Gas Filled Recoil Separator



Decay chains of $^{294}(117)$ and $^{293}(117)$



UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY

Actinide production by irradiation of Am/Cm targets in HFIR

Targets specially designed for reactor conditions

- Composition controls fission and gamma heating (and decay heat)
- Irradiated targets typically remain in the reactor for 3 to 6 24-day cycles (up to 7 cycles/year)

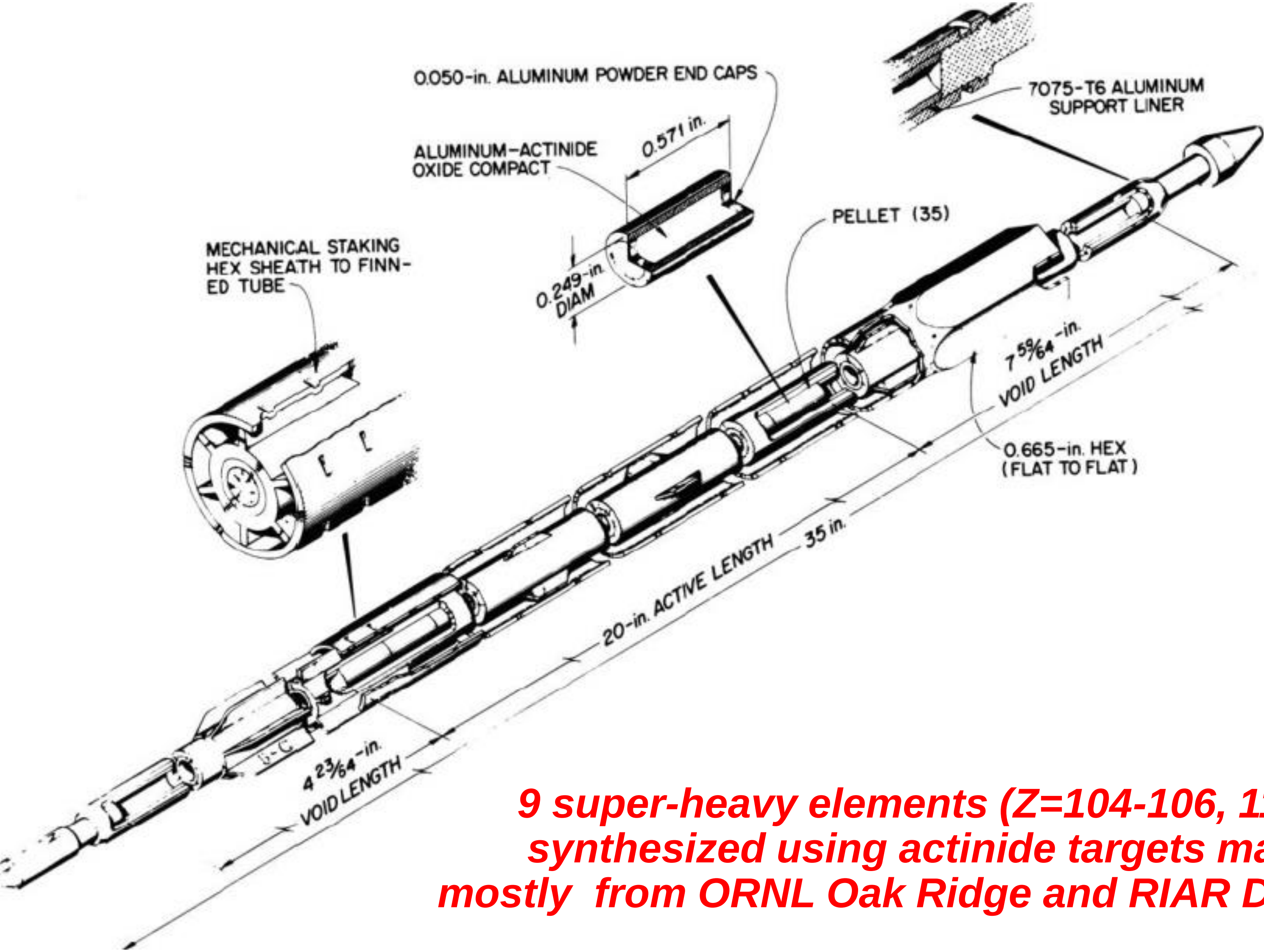
Irradiation in the HFIR flux trap

- Intense thermal neutron flux (2.5×10^{15} neutrons/cm^2·s)
- 31 target positions (6-8 targets typical for Cf production)
- Typical campaign now: up to 100 mg ^{252}Cf, **10 mg ^{249}Bk**, ~1 µg ^{254}Es

Target positions in the flux trap of HFIR fuel assembly

J. Roberto, SHE Symposium 2015

J.B. Roberto et al., Nucl. Phys. A 944, 99 (2015)

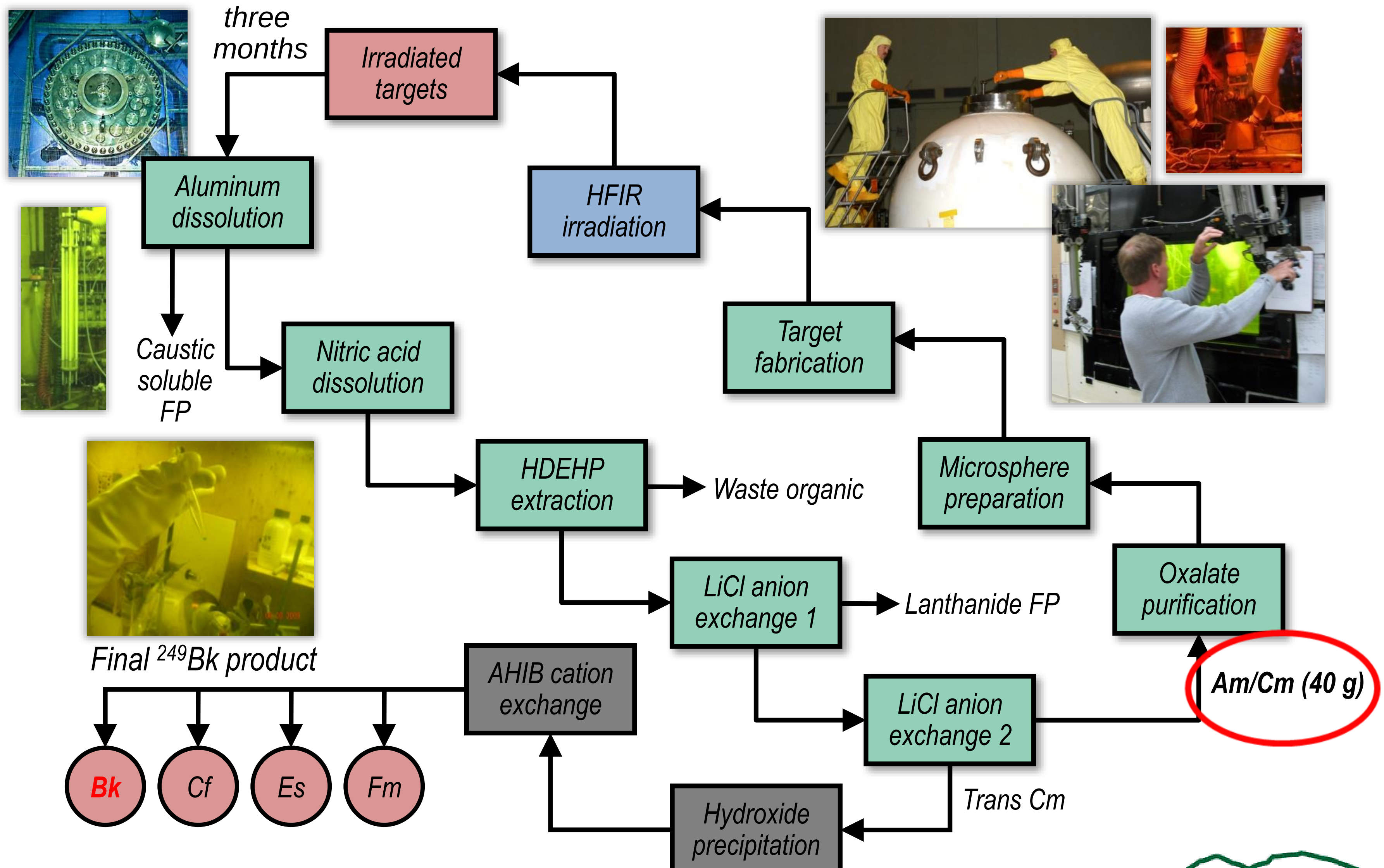


9 super-heavy elements (Z=104-106, 113-118) synthesized using actinide targets materials mostly from ORNL Oak Ridge and RIAR Dmitrovgrad

UT-BATTELLE OAK RIDGE NATIONAL LABORATORY

Z=97 ^{249}Bk production/separation cycle at ORNL

24 months ^{252}Cf/^{249}Bk



~22 mg ($T_{1/2}$~327 d)

The "voyage" of ^{249}Bk material started June 6th, 2009 at Oak Ridge

Oak Ridge - Knoxville - Jamaica (!) - JFK NY - SVO Moscow - JFK NY - SVO Moscow - JFK NY – SVO Moscow (frequent flyer miles for Bk + my grey hair)

The barrels with ^{249}Bk were kept for a week at Sheremetyevo airport custom clearance station. Since no radiation was detected outside the package, the crate was open and containers got unpacked till the Geiger's counters went REALLY HIGH !

Around 1st July 2009 ^{249}Bk reached target makers at Dmitrovgrad (400 miles from Moscow/Dubna)

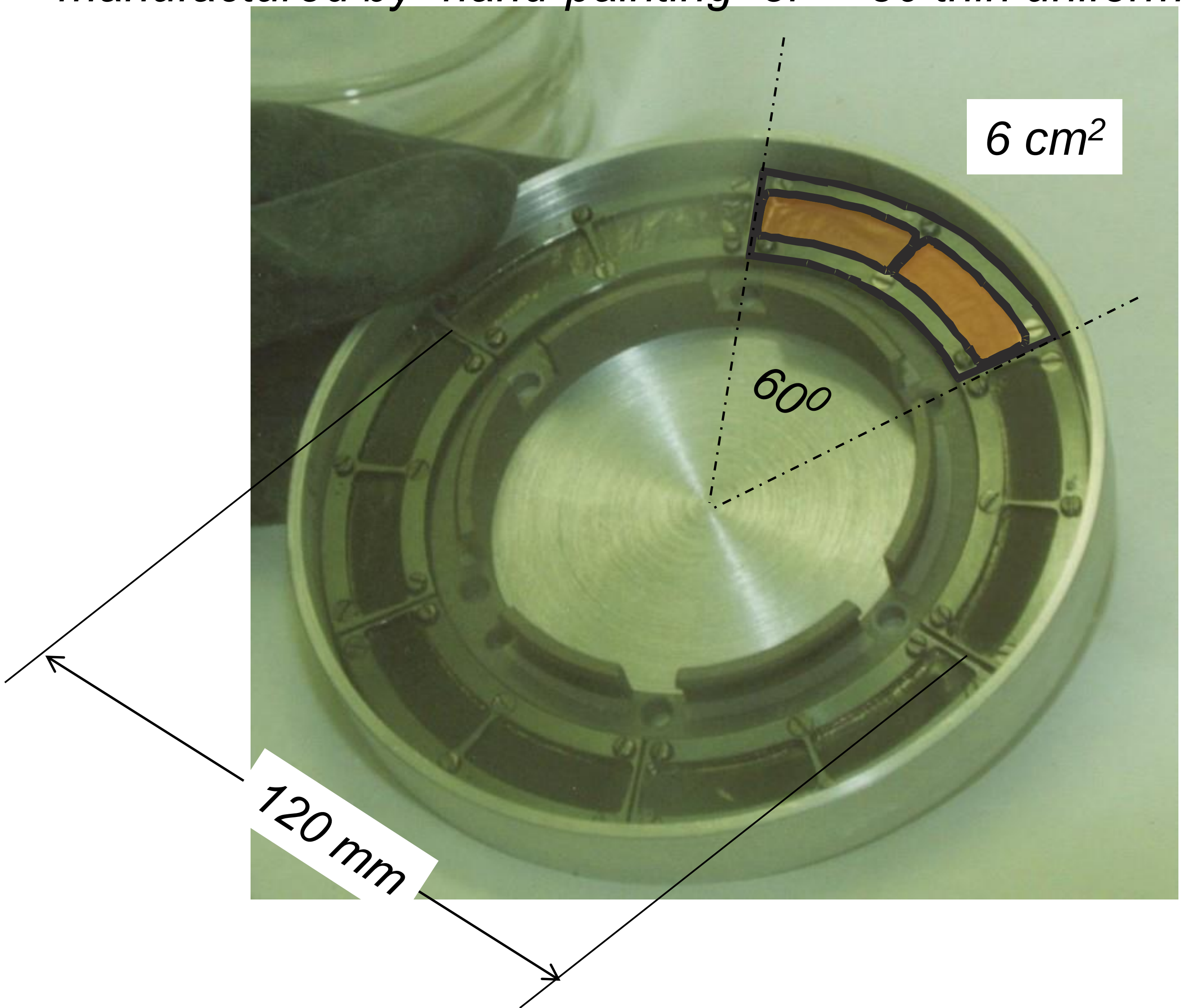
It was the fastest transfer of actinide target material from US to Dubna !!

OAK RIDGE National Laboratory

^{249}Bk target wheel manufactured at RIAR Dimitrovgrad

(M. A. Ryabinin et al.)

The originally planned electro-deposition of ^{249}Bk didn't work very well. Finally, the target sectors with 0.31mg/cm^2 ^{249}Bk on 0.74 mg/cm^2 Ti foils were manufactured by "hand-painting" of ~ 30 thin uniform layers

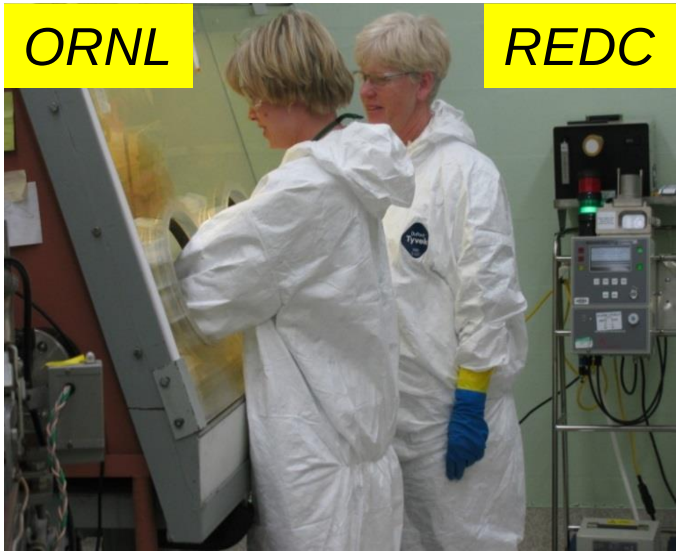


ω = 1700 rpm

Cf isotopic distribution following production and after several decades decay

Isotope	Atomic % (as produced)	Half-life (y)
^{249}Cf	3.41	**351**
^{250}Cf	8.7	13.08
^{251}Cf	2.60	**898**
^{252}Cf	**85.27**	2.645
^{253}Cf	0.004	0.049
^{254}Cf	0.010	0.166

Shelley Mc Cleve and Rose Boll



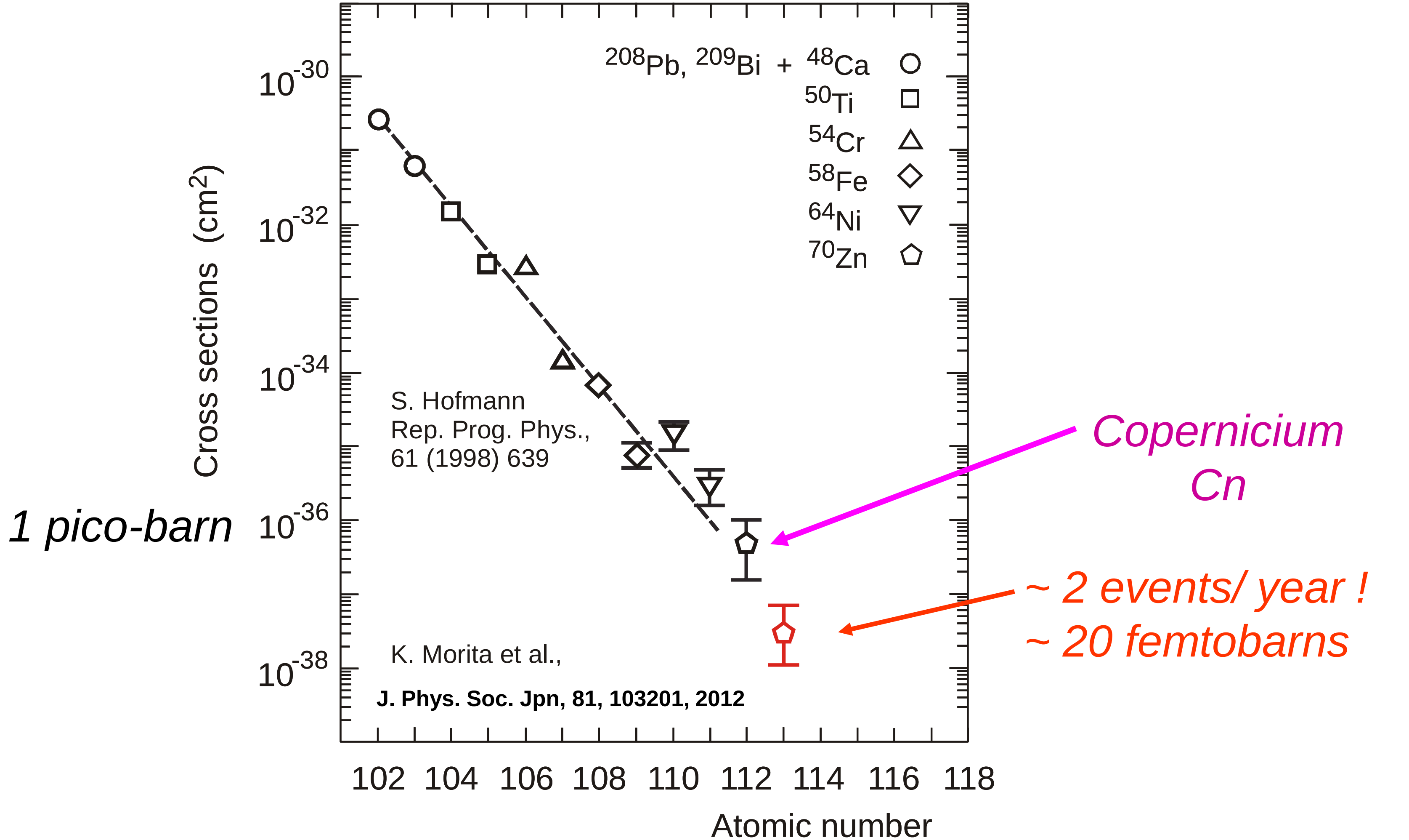
- *After several decades, ^{252}Cf substantially decays (15 half-lives→ factor 30,000 down)*
- *Remaining Cf a mixture of $^{249, 250, 251}$Cf, ~35% ^{251}Cf (heaviest SHE target material)*
- *Mixed target must be handled in a shielded glove box due primarily to ^{250}Cf content*
- *Possibility of producing two new heaviest isotopes of element 118, A=295 and 296*

Cf recovered from decayed sources				
Cf-249 (mg)	Cf-250 (mg)	Cf-251 (mg)	Cf-252 (mg)	Total Cf mg
7.6	2.5	5.7	0.003	15.8
48.1%	15.6%	36.3%	0.02%	**$3*10^7$ n/s**

Oak Ridge National Laboratory

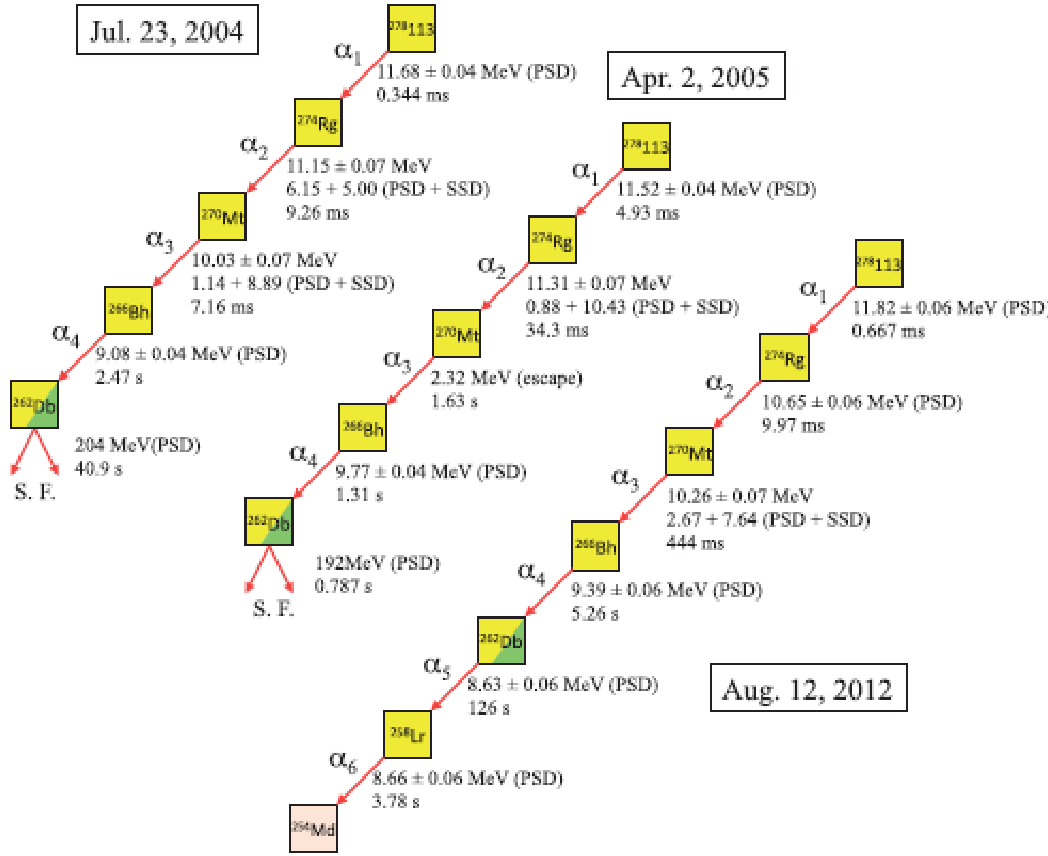
Cross section for formation of SHE nuclei in cold fusion

Cold Fusion *with magic ^{208}Pb,^{209}Bi targets and n-rich stable beams up to ^{70}Zn*
→ small E ~ 10 - 14 MeV barely allowing for ~ 1n emission*



Kosuke Morita and his RIKEN team

$^{70}Zn+^{209}Bi \rightarrow ^{279}113^* \xrightarrow{1n} ^{278}113$



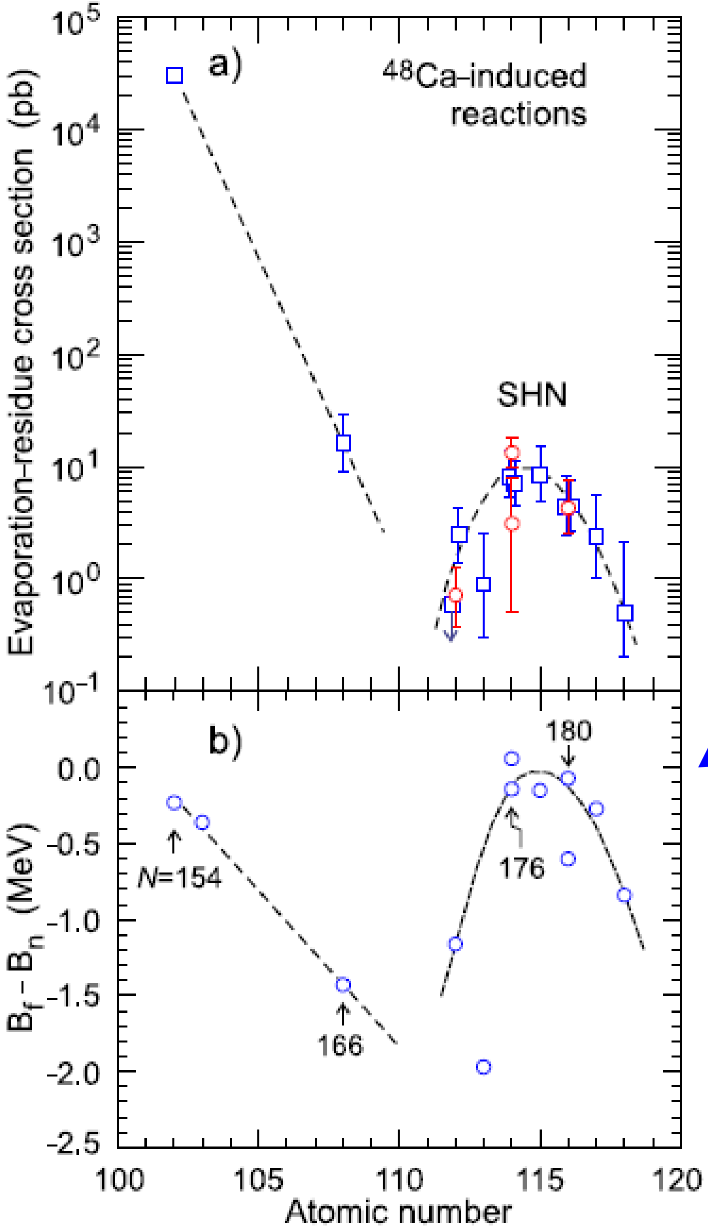
Nearly 600 days of irradiations→ 3 events, 22 (+20,-13) fb cross section

and Z=113 Nihonium Nh

OAK RIDGE National Laboratory

Cross sections in hot fusion experiments with actinide targets

“ a real breakthrough “ *Ben Mottelson, June 2016*



Yu.Ts. Oganessian and V. K. Utyonkov
Nucl. Phys. A 944, 62, 2015

CN survival ~ exp (B_f - B_n)
B_f - B_n ~ 0 MeV
at the maximum !

B_f and B_n values *from*
M. Kowal et al., Phys. Rev. C 82,2010,014303.
M. Kowal et al. arXiv:1203.5013, 2012.
K. Siwek-Wilczyńska et al., Phys. Rev. C 86,2012,014611.

Separator and detectors

Dubna Gas-Filled Recoil Separator
DGFRS

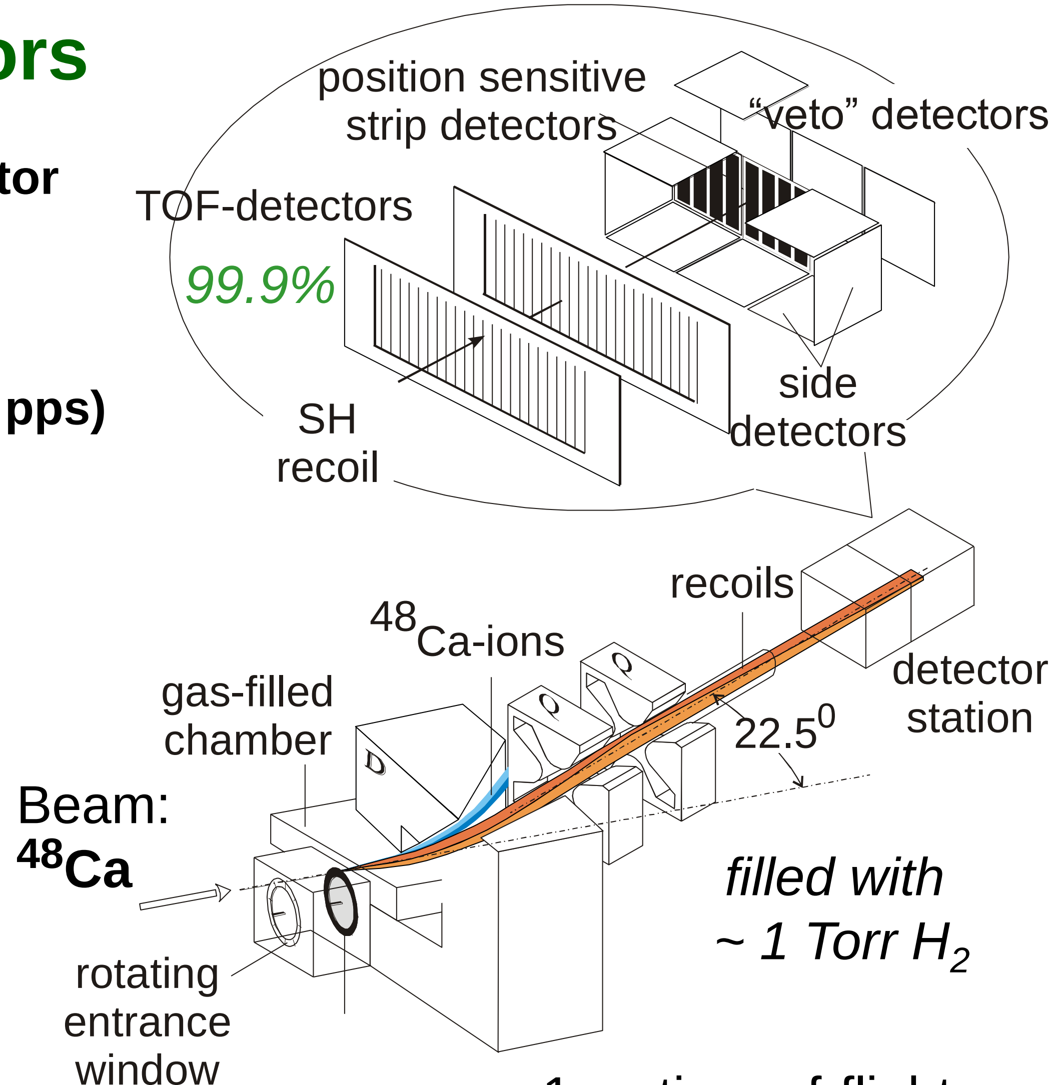
Z=117 experiment with
over 1 part×μA ^{48}Ca beam (7×10^{12} pps)
for 150 days

Transmission for:

evaporation residues 35 %
target-like products 10^{-4}-10^{-7}
projectile-like 10^{-15}-10^{-17}

Detection efficiency:

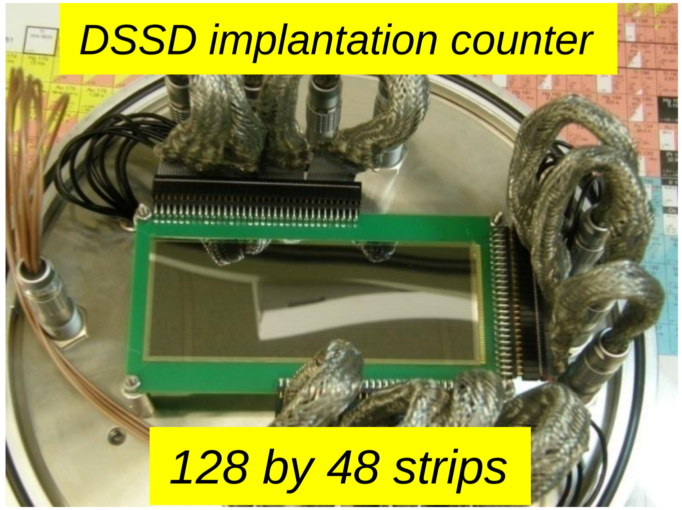
for α-particles 87%
for SF :
one fragment ~ 100%
two fragments ≈ 40%

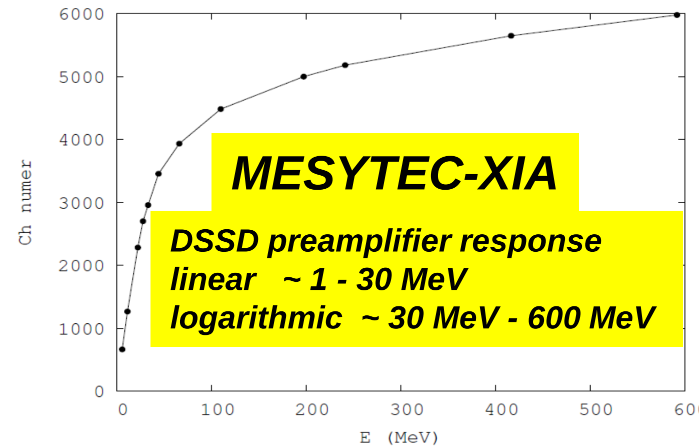


~ 1 μs time-of-flight
between target and detectors

Position-Time-Energy correlations !!!

ORNL-UTK 8-detector and digital data acquisition system operating at the Dubna Gas Filled Recoil Separator (DGFRS)

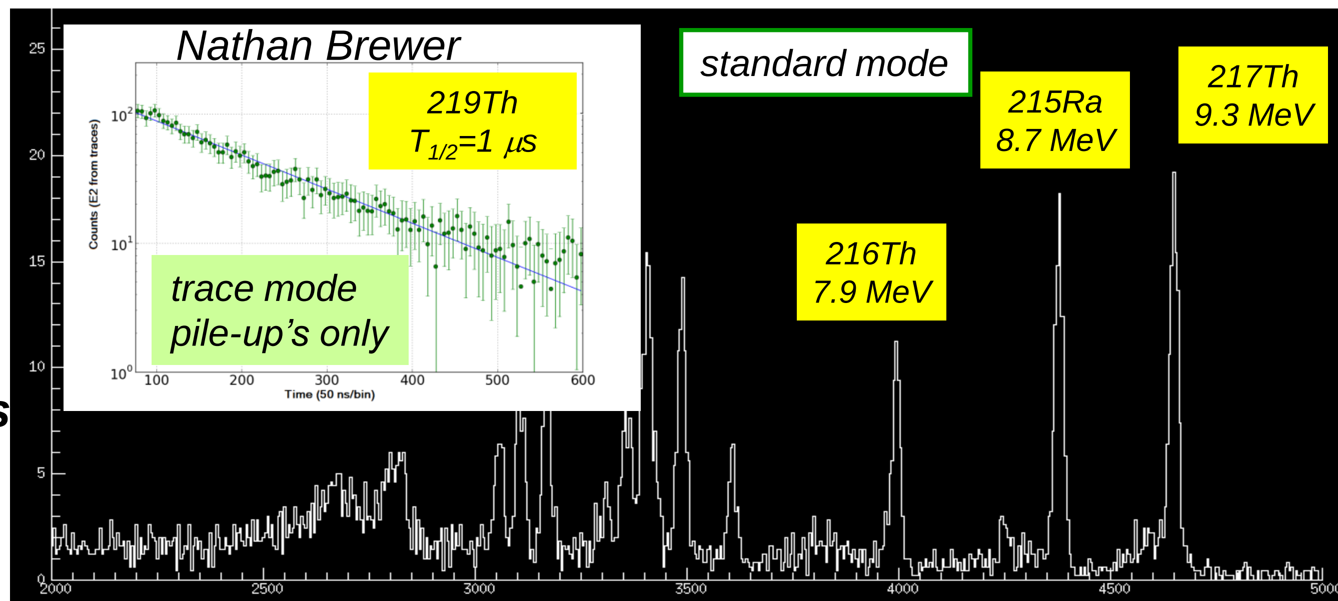




(now linear preamps)

***α*-emitters including 1 μs activity of ^{219}Th studied at the DGFRS during ^{48}Ca+^{nat}Yb run Nov.-Dec. 2013.**

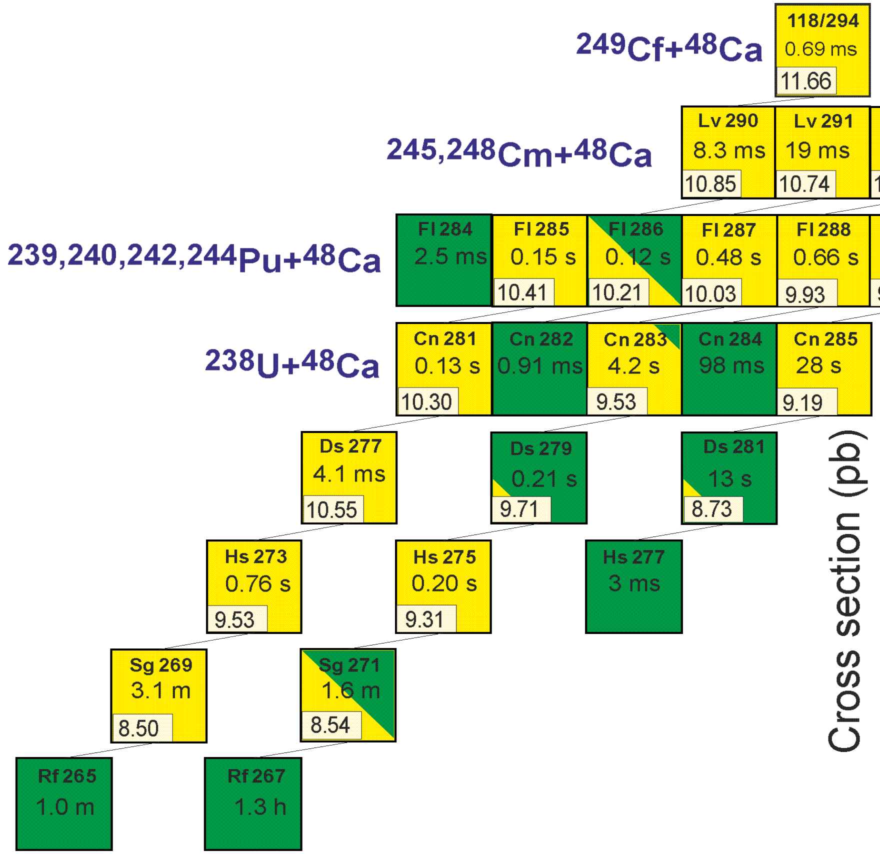
Search for new isotopes of element Z=114 (Fl) with $^{239, 240}$Pu targets Dec. 2013 – June 2015



energy of α-particles

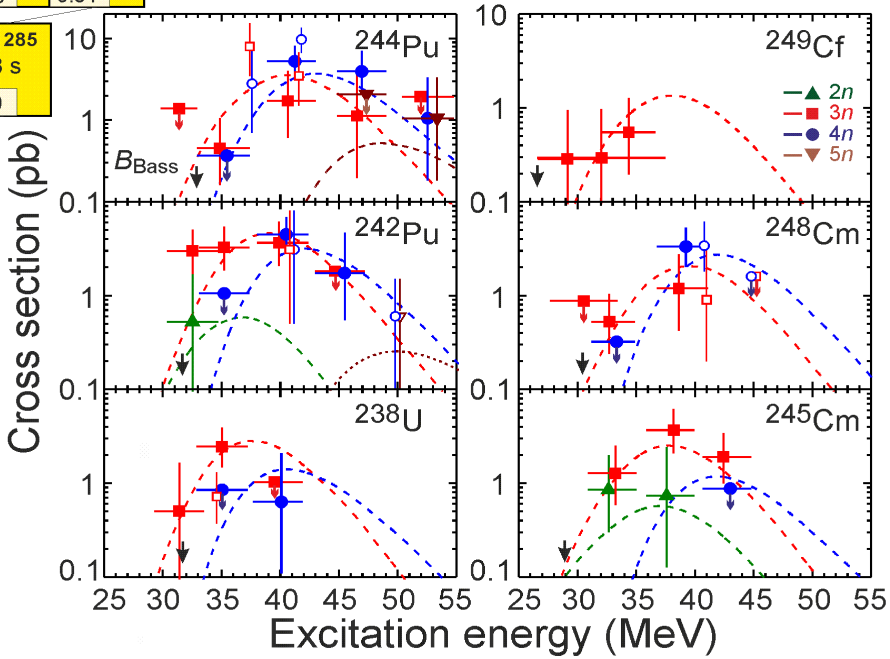
Oak Ridge National Laboratory

RESULTS (Russia-US): even-Z nuclei



116 -also GSI and RIKEN

114- also GSI and LBNL



cross bombardment ,
reproducibility,
and decay patterns

similarity of excitation functions

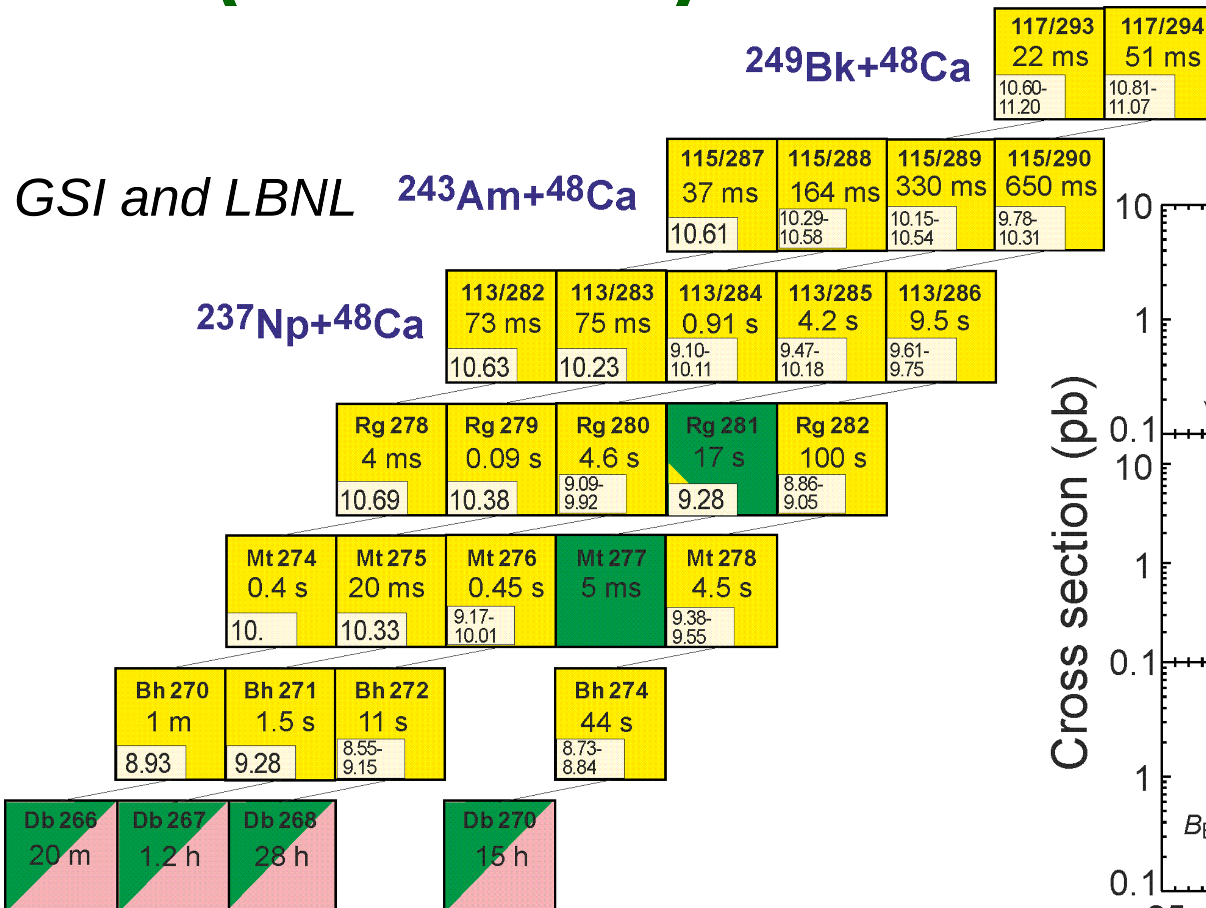
Utyonkov et al., Nobel Symposium, Scania, Sweden, June 2016

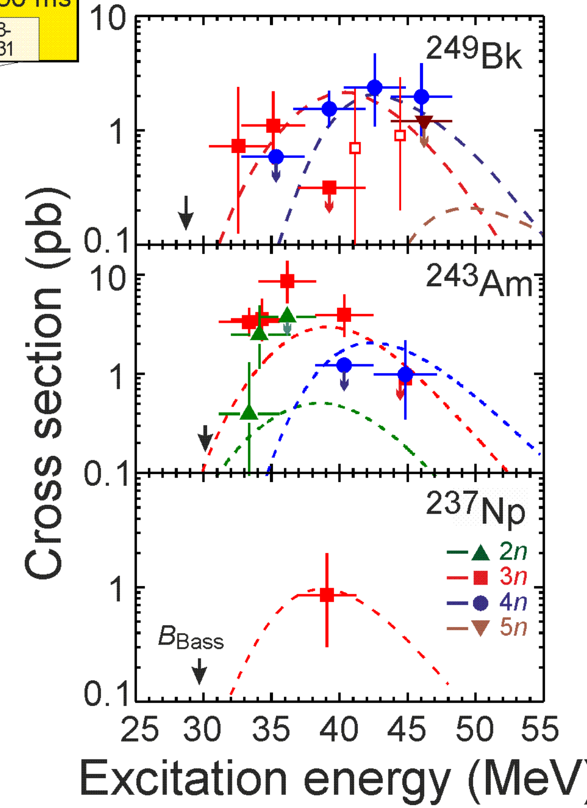
Oak Ridge National Laboratory

RESULTS (Russia-US): odd-Z nuclei

117-also GSI

115-also GSI and LBNL



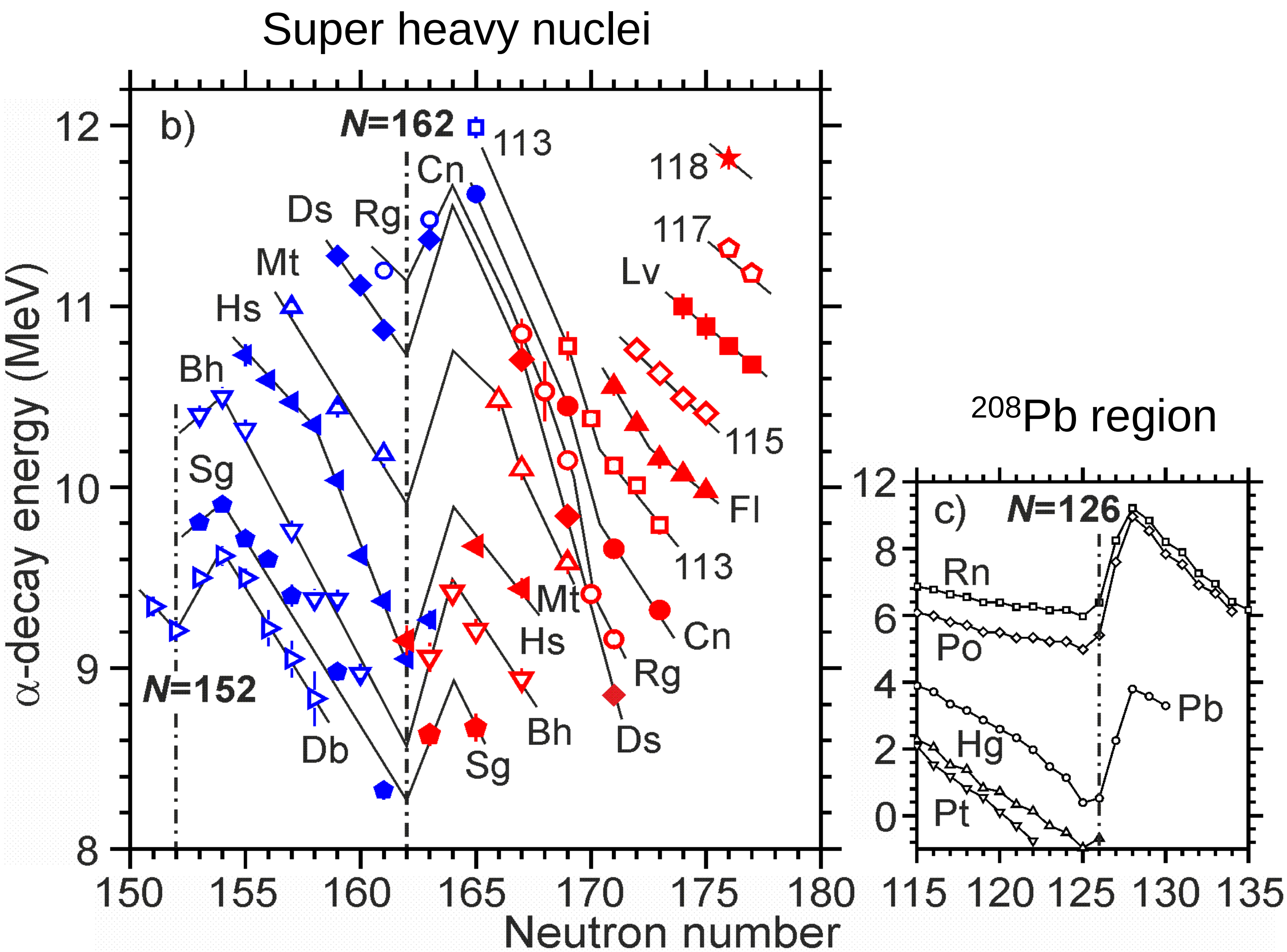


cross bombardment
reproducibility
and decay patterns

similarity of excitation function
2n,3n,4n evaporation

Utyonkov et al., Nobel Symposium, Scania, Sweden, June 2016

Shell effects in alpha-energy pattern



Note that the alpha energies for isotopes of given element do not cross

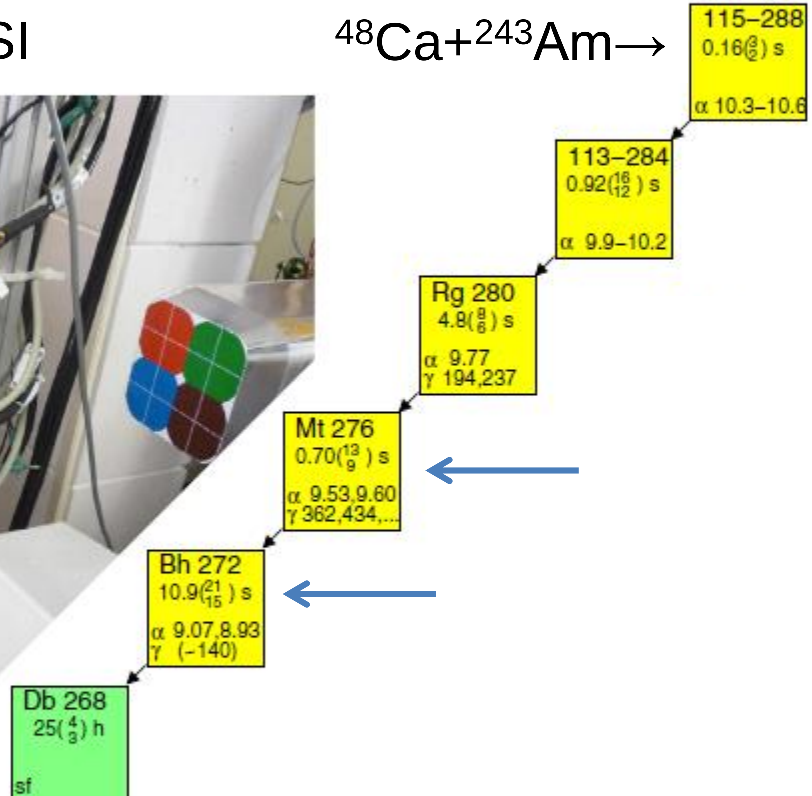
Beyond ground-states properties of SHE

D. Rudolph et al., Phys. Rev. Lett. 111, 112502, 2013.

Goal: direct determination of atomic number Z for the element at the Island of Stability

TASISpec at GSI

$^{48}Ca + ^{243}Am \rightarrow$



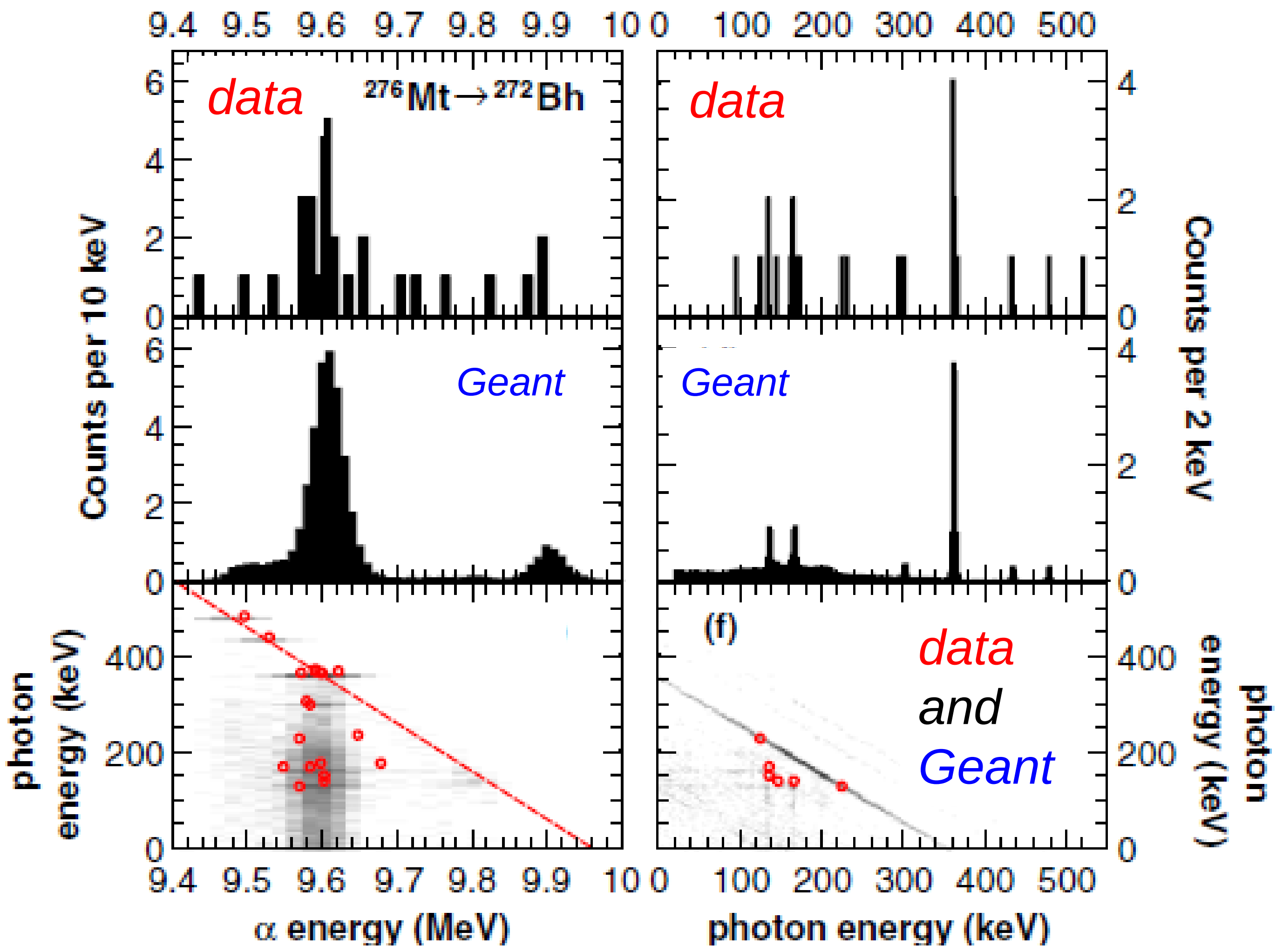
Method of identifying atomic number of heavy element through alpha- Xray observation pioneered by Bemis et al. at Oak Ridge, PRL 31, 647, 1973 (!!)

$^{249}Cf + ^{12}C \rightarrow ^{261}Rf^* \rightarrow 4n + ^{257}Rf \rightarrow ^{253}No^* \rightarrow ^{253}No + \gamma$ and characteristic X-rays

OAK RIDGE National Laboratory

Beyond ground-states properties of SHE

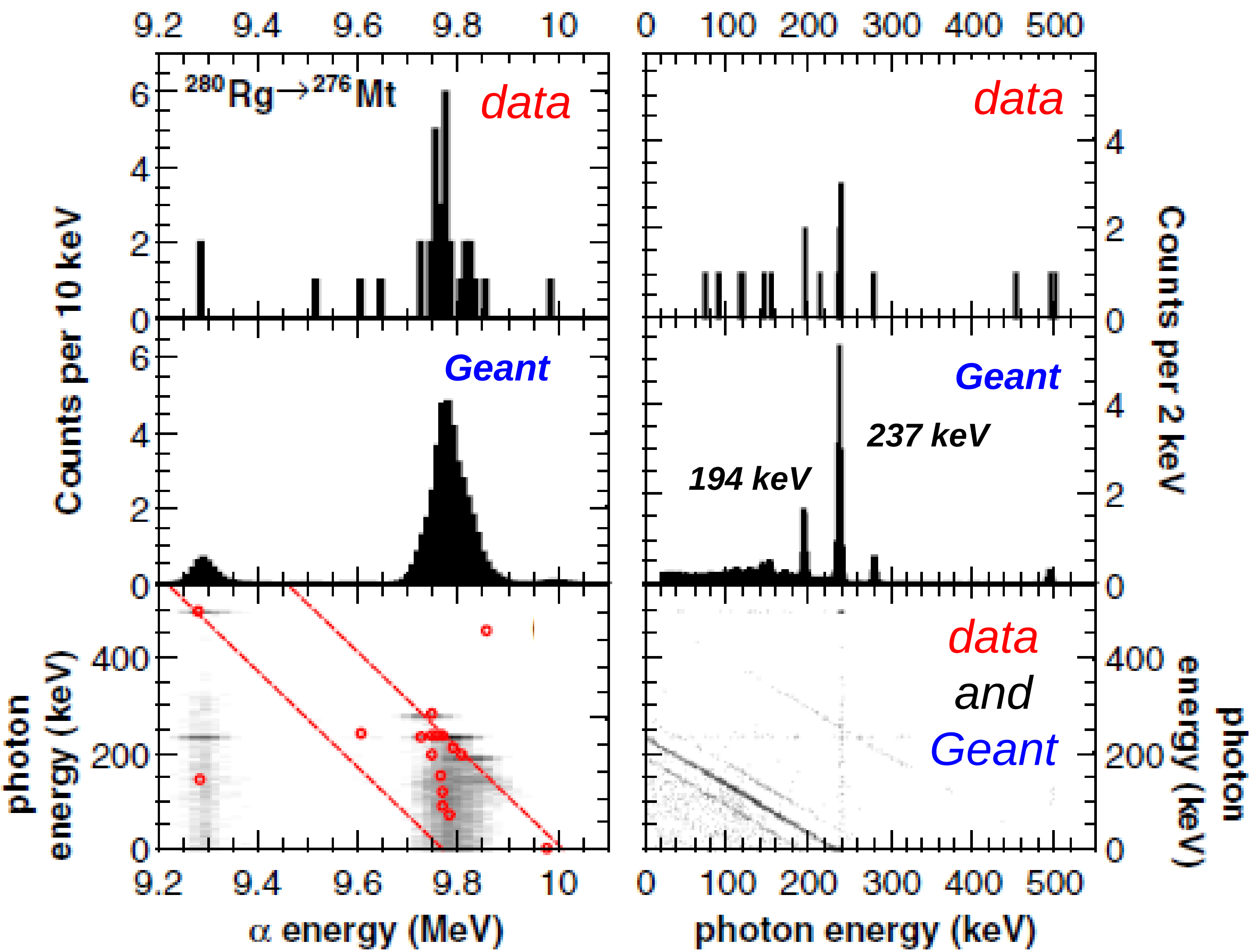
combined TASISpec and BGS+C3 data



J. Gates et al., Phys. Rev. C 92, 021301 (R), 2015
Berkeley Gas-filled Separator (BGS) + corner-cube-clover (C3)

OAK RIDGE National Laboratory

Beyond ground-states properties of SHE

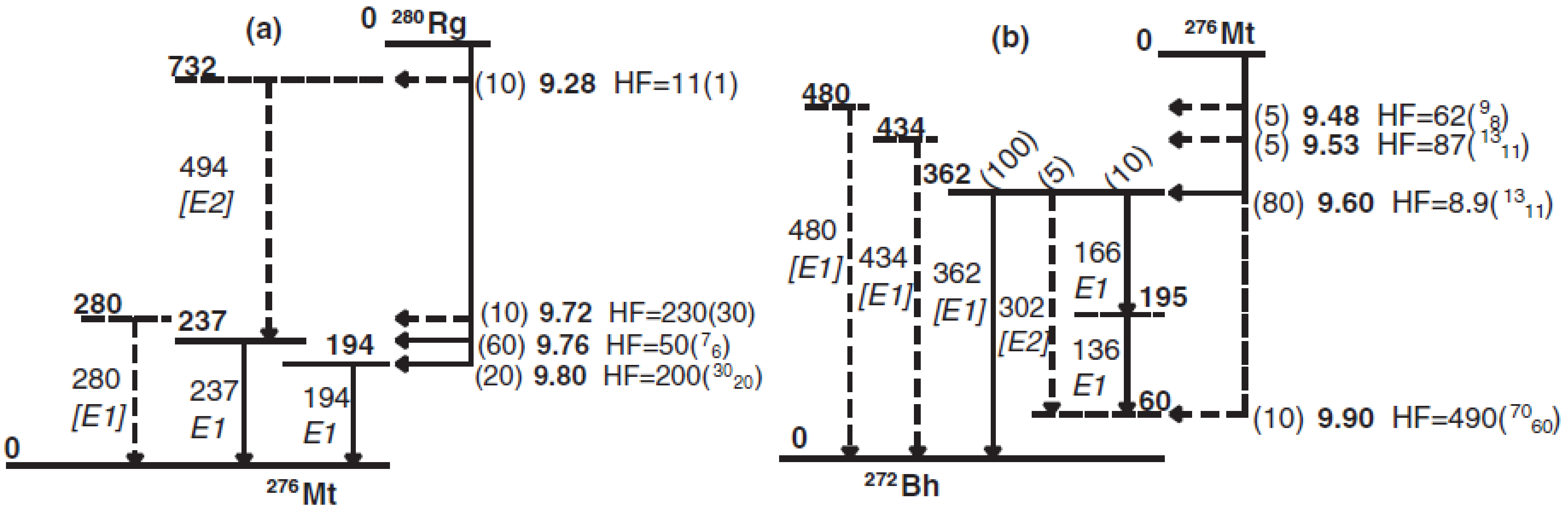


J. Gates et al., Phys. Rev. C 92, 021301 (R), 2015

Berkeley Gas-filled Separator (BGS) + corner-cube-clover (C3)

combined TASISpec and BGS+C3 results

First level schemes of superheavy nuclei at the Island of (enhanced) Stability



The presence of E1, parity-changing γ-transitions in ^{276}Mt and ^{272}Bh already constrains theoretical modeling, see Shi et al., Phys. Rev. C 90, 014308 ,2014

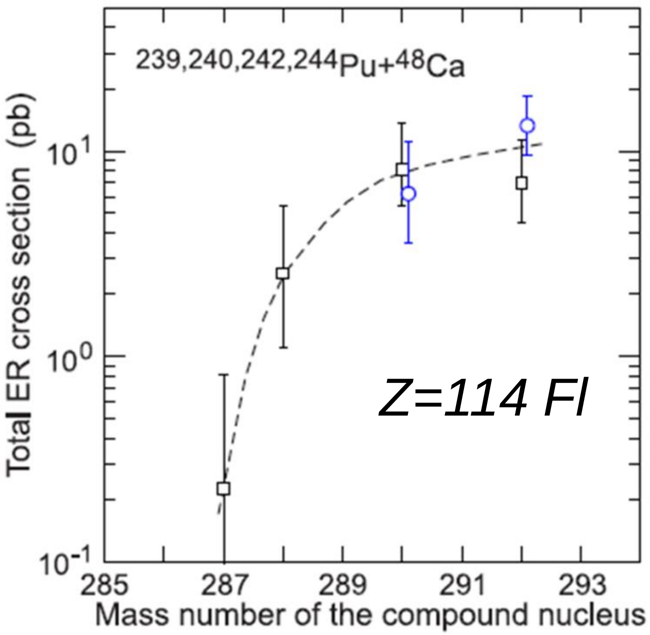
Way to go … to go for much better statistics !

What we have learned so far about super heavies ?

1. We reached element 118 (^{294}Og) and neutron number 177 (^{294}Ts and ^{293}Lv) and about 50 other nuclei produced with ^{48}Ca beam and radioactive actinides

2. The pattern of alpha decay energies and half-lives indicates that we have reached a beachhead at the Island of (enhanced) Stability. The shell effects make α-decay winning against fission, as was roughly predicted 50 years ago

3. For Z=114 Fl we even know where the shore of the Island dives into the sea of fission instability



The total xn cross section drops by a factor ~50 between ^{244}Pu and ^{239}Pu targets. It follows the predicted drop of fission barrier in respective Fl compound nuclei. The west shore of the Island of Stability for Z=114 was identified.

Utyonkov, Brewer et al., PR C92, 034609, 2015.

OAK RIDGE National Laboratory

4. *We have identified excited states in two odd-odd nuclei at the Island , even with limited statistics we got some guidance about single particle states.*
5. *Fission corridor exists between the Island and Mainland (hard to cross)*
6. *All nuclei at the Island were produced with 48Ca beam.We almost run out of new actinide targets. The end of Nuclear Chart and Periodic Table ?*

Periodic Table 1-172

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Orbitals
1	1 H																	2 He	1s
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	2s2p
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	3s3p
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	4s3d4p
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	5s4d5p
6	55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	6s5d6p
7	87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113	114	115	116	117	118	7s6d7p
8	119	120	121-	156	157	158	159	160	161	162	163	164	139	140	169	170	171	172	8s7d8p
9	165	166											167	168					9s9p

6	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	4f
7	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	5f
8	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	6f

8	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	5g

P. Pyykkö: *"A suggested Periodic Table up to Z ≤ 172"*
Phys. Chem. Chem. Phys. 13, 161-168 (2011)

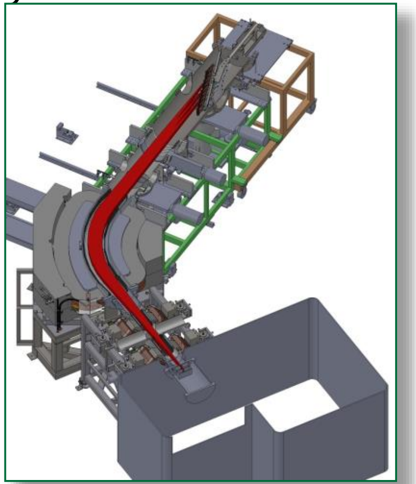
The limits of existence for atomic nuclei was not included in the analysis.

OAK RIDGE National Laboratory

Reestablishing isotope enrichment capability at ORNL

Electromagnetic Isotope Separator (EMIS)

- *Designed and built by ORNL (B. Eagle et al.,)*
- *Sponsored by DOE Office of Nuclear Physics*



Separated beams of molybdenum isotopes by new EMIS

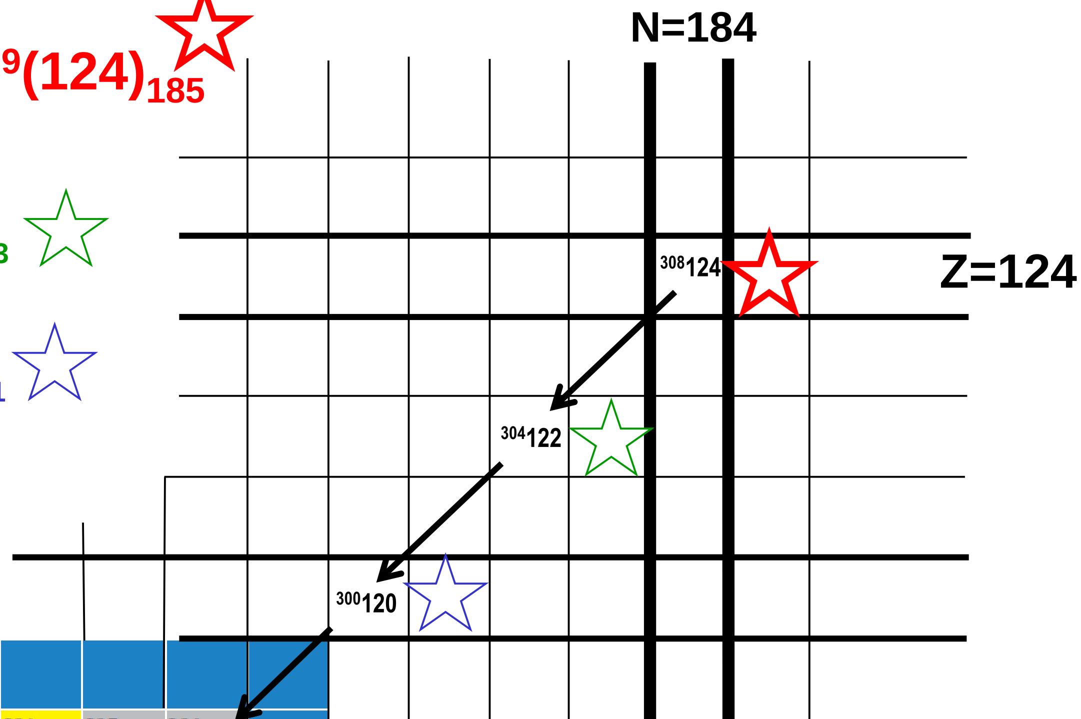
- *Currently capable of producing mg to gram quantities of >98% enriched stable isotopes*
- *Combined with gaseous centrifuge to increase throughput*
- ***Proposed radioactive EMIS for actinides ($$$)***

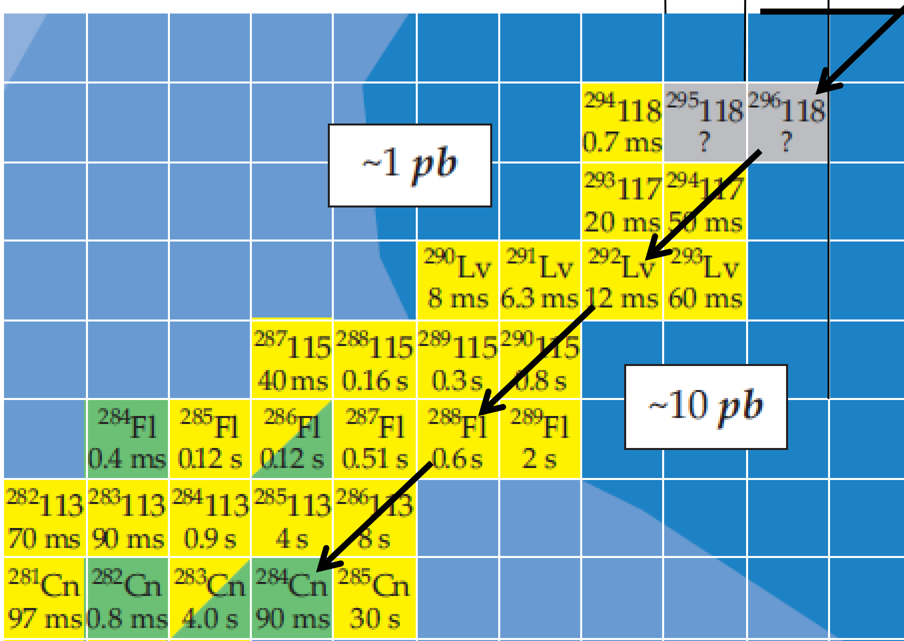
→ enriched ^{251}Cf safe target

^{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 predicted as 10^{12} to 10^{6} for $^{308}(124)$ → ..→ $^{296}(118)$ decays

Cross section ??? (~femtobarns ?)

Cross section scales with $B_F - B_n$

B_n is relatively small for N=185=(184+1) nucleus

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]

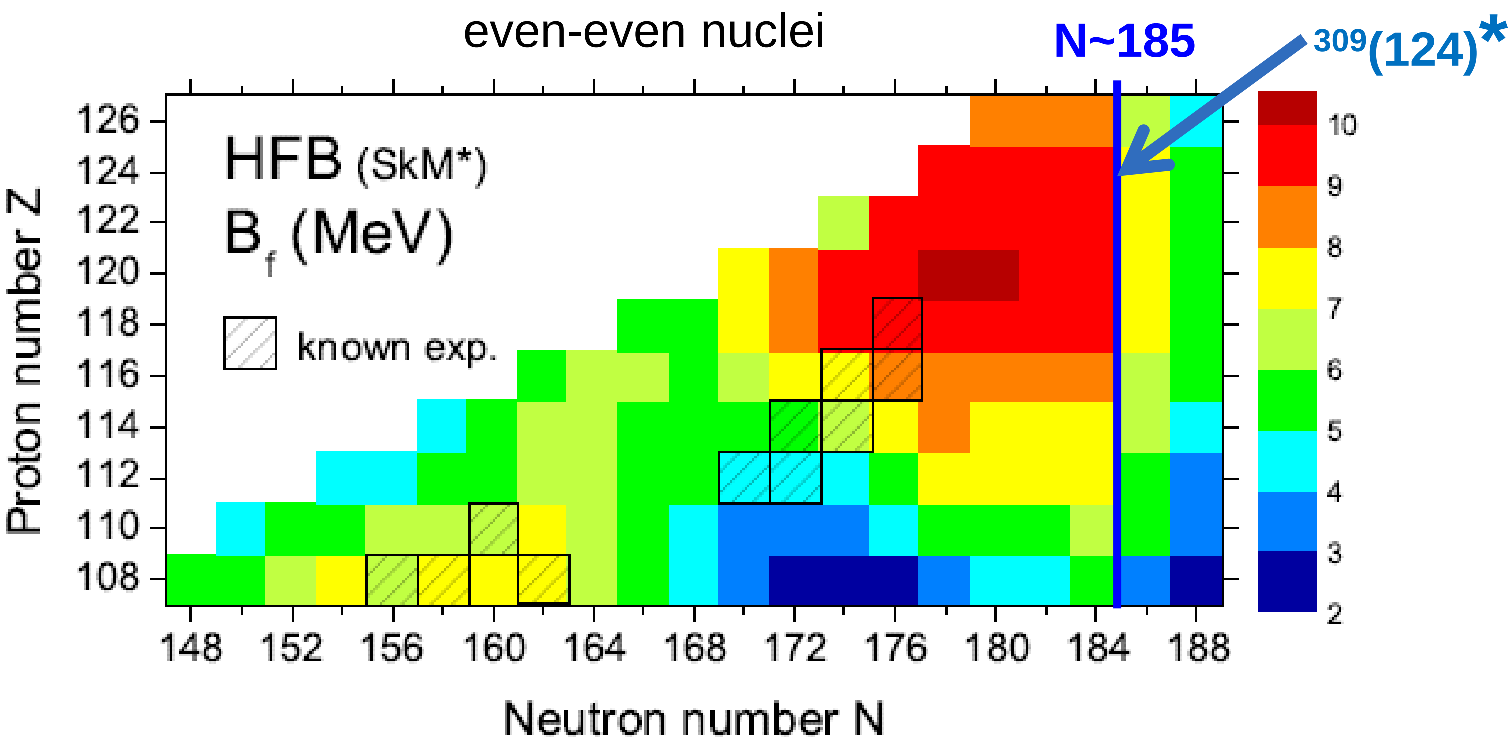


Figure 3: First fission barrier (MeV) of SH nuclei in HFB SkM* model. Cross-hatched squares represent observed nuclei.

Neutron separation energy values are around ~ 6-7 MeV

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

“Parameter study” from Krystyna Wilczyńska for a cold/hot fusion of ^{251}Cf and ^{58}Fe

T. Cap, K. Wilczyńska, M. Kowal, J. Wilczyński, PR C88, 037603, 2013

Mic-Mac Fission Barriers (Kowal *et al*) → σ (xn) ~ **0**

“a deal” on barrier height:

2* B_f (Mic-Mac 3 MeV) ~ ½ * B_f (HFB 12 MeV) ~ 6 MeV

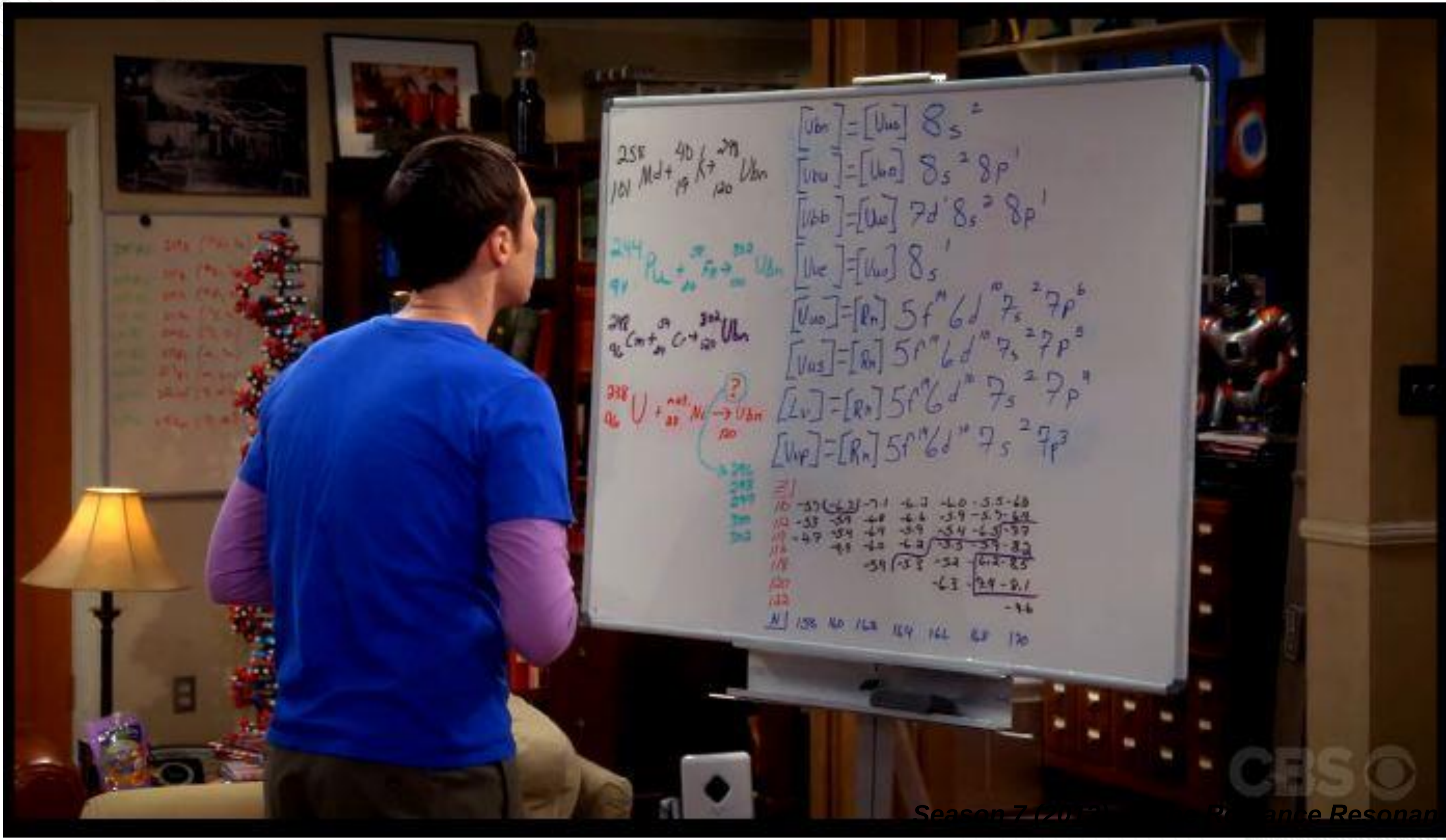
B_f ~ 6 MeV → σ (xn) ~ 20 - 40 picobarn (!!!!)

(maximum for 2n, 3n channels)

Too good to be true, but we expect measurable cross with fission barrier parameter slightly below 5 MeV

Such study should be doable at ~ 10^{20} - 10^{21} beam dose and worth to try providing ^{251}Cf target is available from ORNL

One episode of The Big Bang Theory had Sheldon theoretically discovering a stable SHE



From Mark Stoyer ***Season 7 (2013) – “The Romance Resonance”***

Decays of $^{294}117$!

The Big Bang Theory, Season 9 Episode 15: The Valentino Submergence

From Mark Stoyer

OAK RIDGE National Laboratory

Summary – what comes next ?

- HFIR/REDC complex at ORNL shall operate for next 25-40 years. New developments in accelerator technology should be complemented by target materials

- New detection techniques including digital signal processing should allow us to reach shorter-lived, heavier nuclei and get data beyond ground-state properties.

- There is no clear theoretical guidance where the Chart of Nuclei and Periodic Table end. Fission barrier and reaction mechanism analysis are critical.

- Experiments with intense beams heavier than ^{48}Ca, and with ^{251}Cf target (^{248}Cm, ^{249}Bk, ^{249}Cf) from ORNL, may help to reach the vicinity of predicted N=184 shell closure and create new elements up to Z=124.

The studies of super heavy elements and nuclei will continue at new or upgraded laboratories with the GFRS/SHELS/Masha at Dubna, GARIS 2 at RIKEN, BGS+C3/FIONA at LBNL, AGFA at ANL, at S3 at GANIL/SPIRAL2 and TASCA/SHIP at new LINAC at GSI.