“Synteza najcięższych jąder atomowych”

Krzysztof P. Rykaczewski
Physics Division, Oak Ridge National Laboratory
Robert Grzywacz (UTK/ORNL),
Krzysztof Miernik (ORNL→UW)
David Miller (UTK→TRIUMF)
Nathan Brewer (UTK→ORNL)

wyniki z lat 2011-2013 otrzymane we współpracach

Rosja i USA
JINR Dubna - ORNL Oak Ridge - LLNL Livermore
UT Knoxville - RIAR Dmitrovgrad - Vanderbilt Nashville
i Uniwersytet Warszawski (!)

Niemcy i reszta świata
Darmstadt-Mainz-Lund-Oak Ridge-Berkeley
i inne laboratoria (Warszawa)

Rose Boll and Shelley Van Cleve przygotowujące próbke ^{249}Bk (~40 Ci)

Vladimir Utyonkov analizujacy dane ^{48}Ca+^{239}Pu

U.S. DEPARTMENT OF ENERGY

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

Warszawa, 16 stycznia 2014

Long term research goals

- **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*
  - *super heavy atoms in the Universe*

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Oak Ridge High School, April 2010

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

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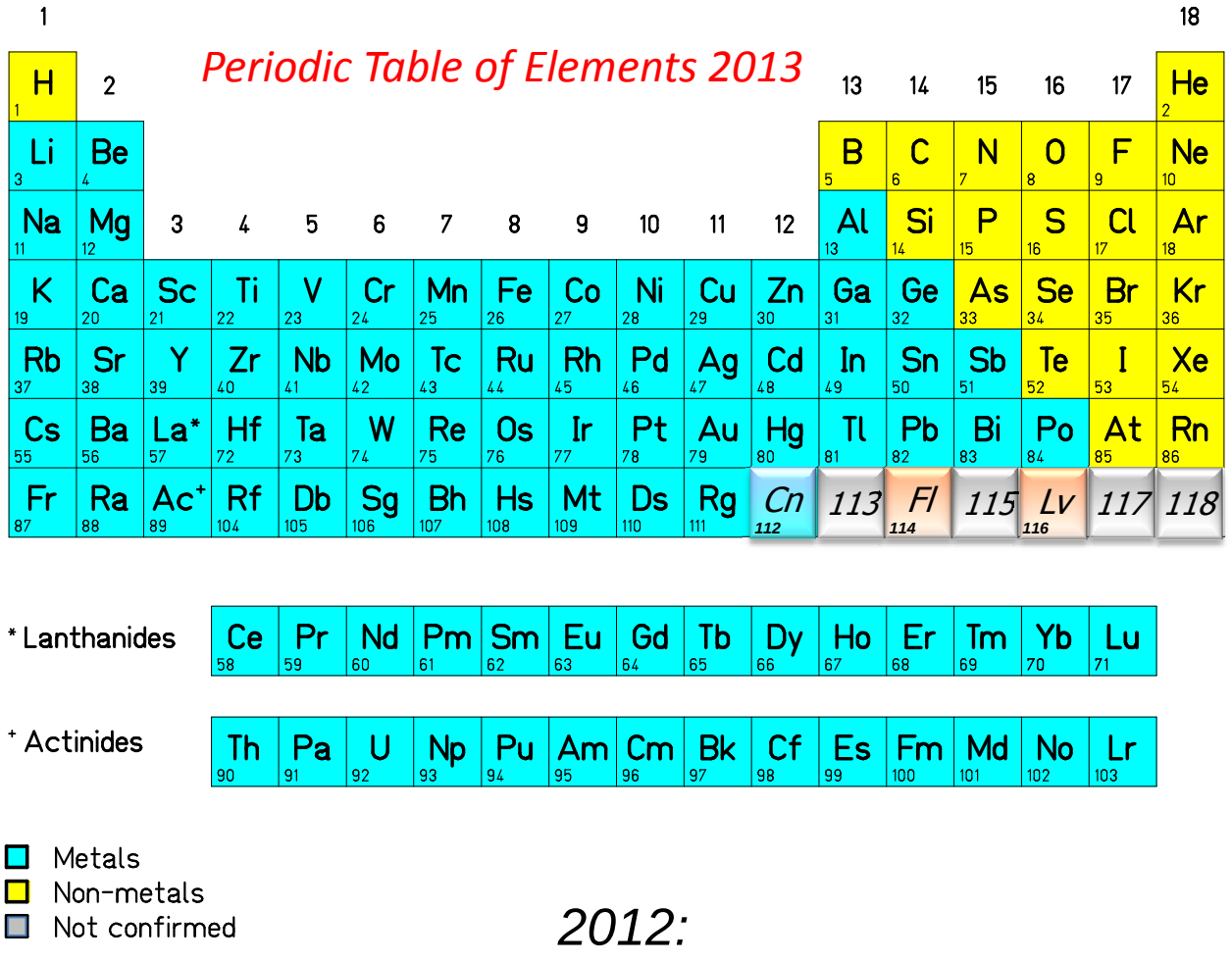

2012:

~ 150 days search for Z=119 in ^{249}Bk+^{50}Ti reaction, TASCA, GSI, $\sigma < 70$ fb

~ 34 days search for Z=120 in ^{248}Cm+^{54}Cr reaction, SHIP, GSI, $\sigma < 600$ fb

(??!!)

discovery of Z=121 can start a group of next 18 elements...

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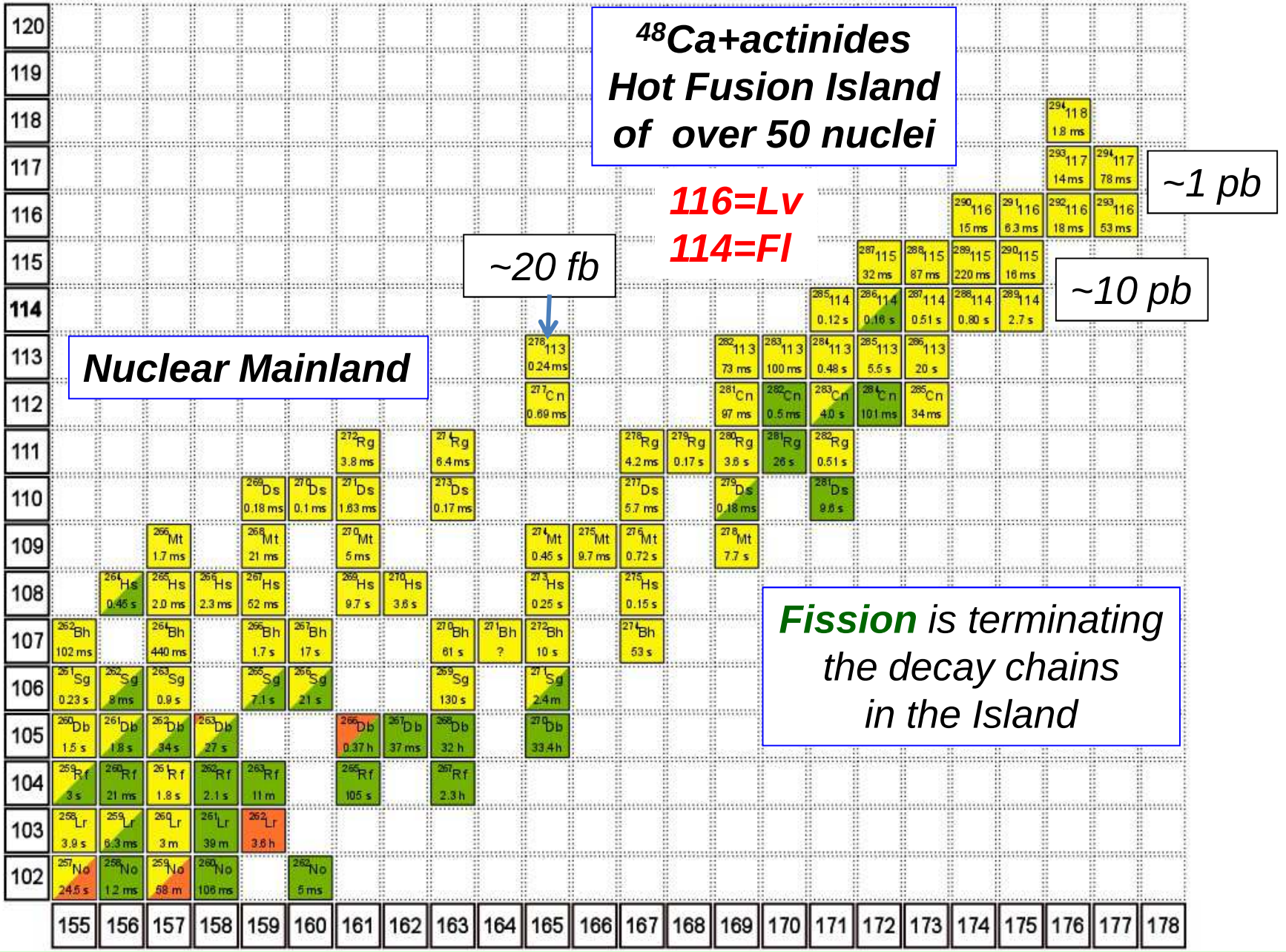
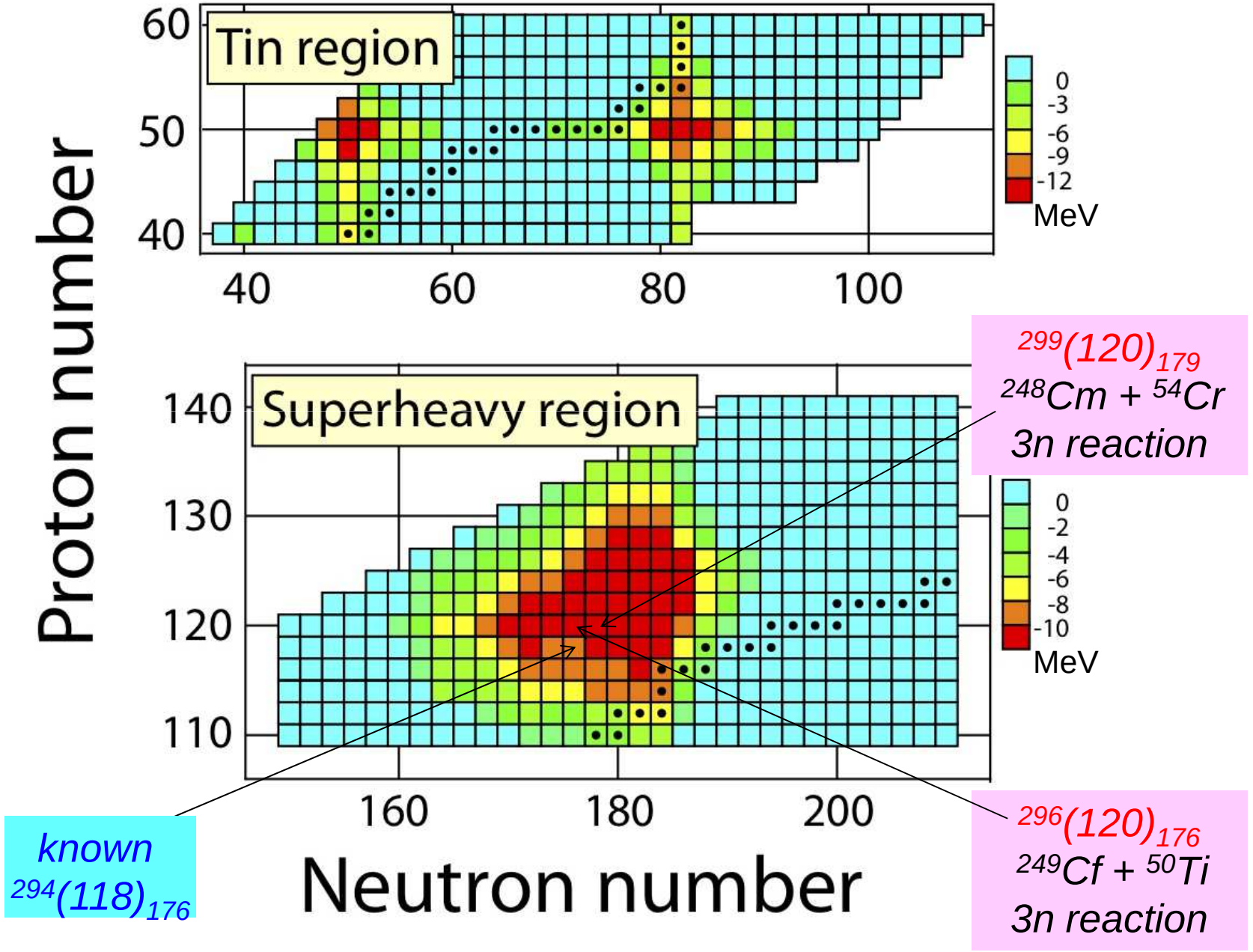


All nuclei from the Island were created using ^{48}Ca beam, attempts to use ^{64}Ni, ^{58}Fe, ^{54}Cr, ^{50}Ti + actinides were so far not successful

M. Bender, W. Nazarewicz, P.-G. Reinhard , Phys. Lett. B 515, 42, 2001
"Shell stabilization of super- and hyper-heavy nuclei without magic gaps"

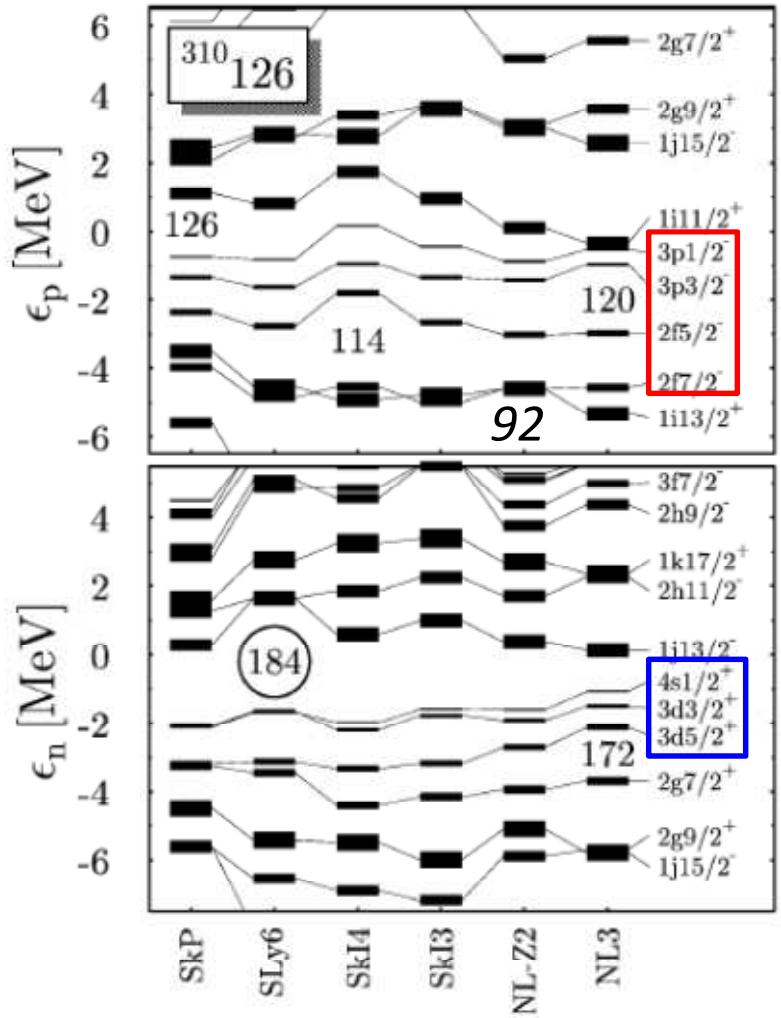


Single-particle levels in the region of super heavy nuclei

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

protons

neutrons



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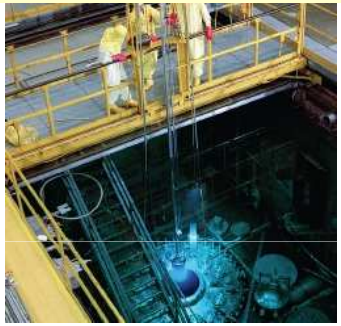
2009-2010: Synthesis of a New Element with Atomic Number Z=117

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

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 330 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.

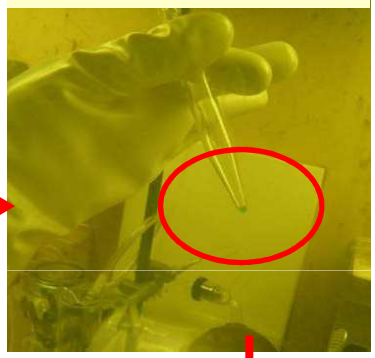
High Flux Isotope Reactor ORNL, Oak Ridge



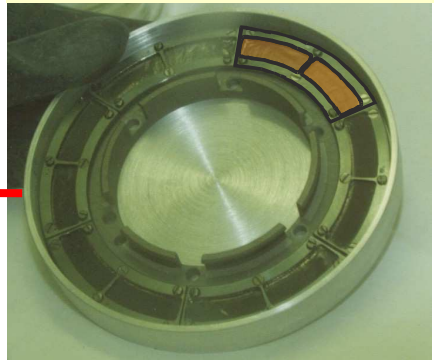
25-ton Q-ball transporting irradiated Am/Cm seed material

Chemical separation in hot cell REDC, ORNL,Oak Ridge

Pure 22 mg of ^{249}Bk

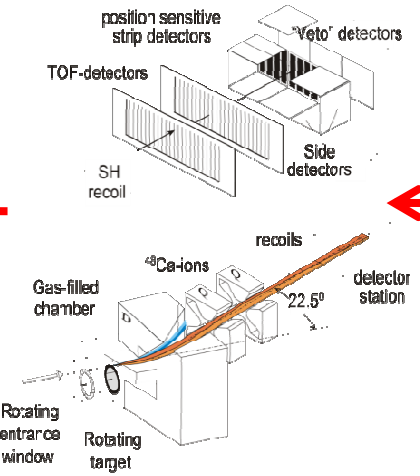


^{249}Bk target wheel made at RIAR Dimitrovgrad

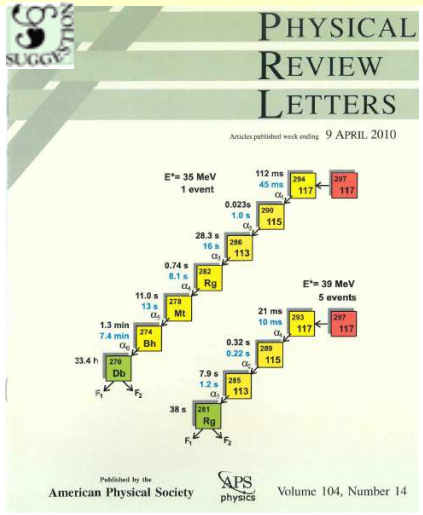


U-400 cyclotron at JINR Dubna

Dubna Gas Filled Recoil Separator



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



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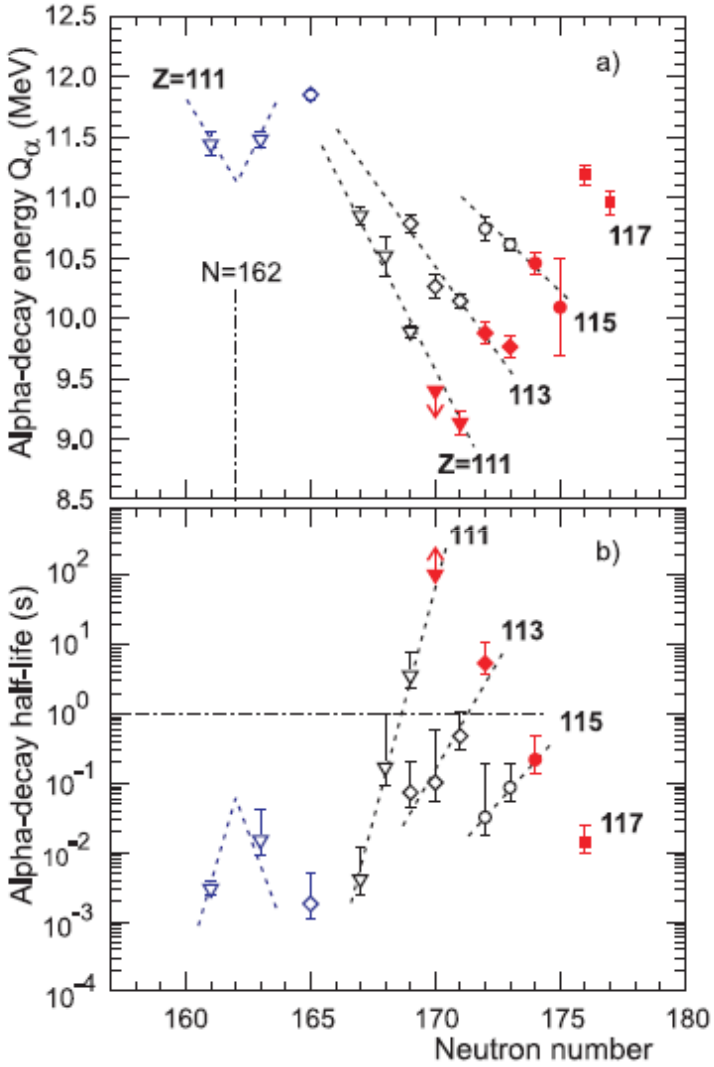
Towards the Island of (enhanced) Stability

Oganessian et al., PRL 104, 142502, 2010 and PR C83, 054315, 2011



Indeed we observe an increased stability with larger neutron number N, but alpha half-lives are getting shorter with increased atomic number Z (indicating a need for fast detection in a next generation of SHE studies!)

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new experiments at the DGFRS (JINR Dubna)

- $^{243}Am+^{48}Ca$, *November 1st, 2010 - February 27th, 2012, beam dose* ***3.3*10^19***

- ***verification of 2003-2004 results on Z=115, 113, and "mass production"***

- *α-decay properties (fine structure ?)*

- *excitation function*

- $^{289}115$ *from* ***2n*** *reaction channel - **"cross bombardment"** for* $^{293}117$

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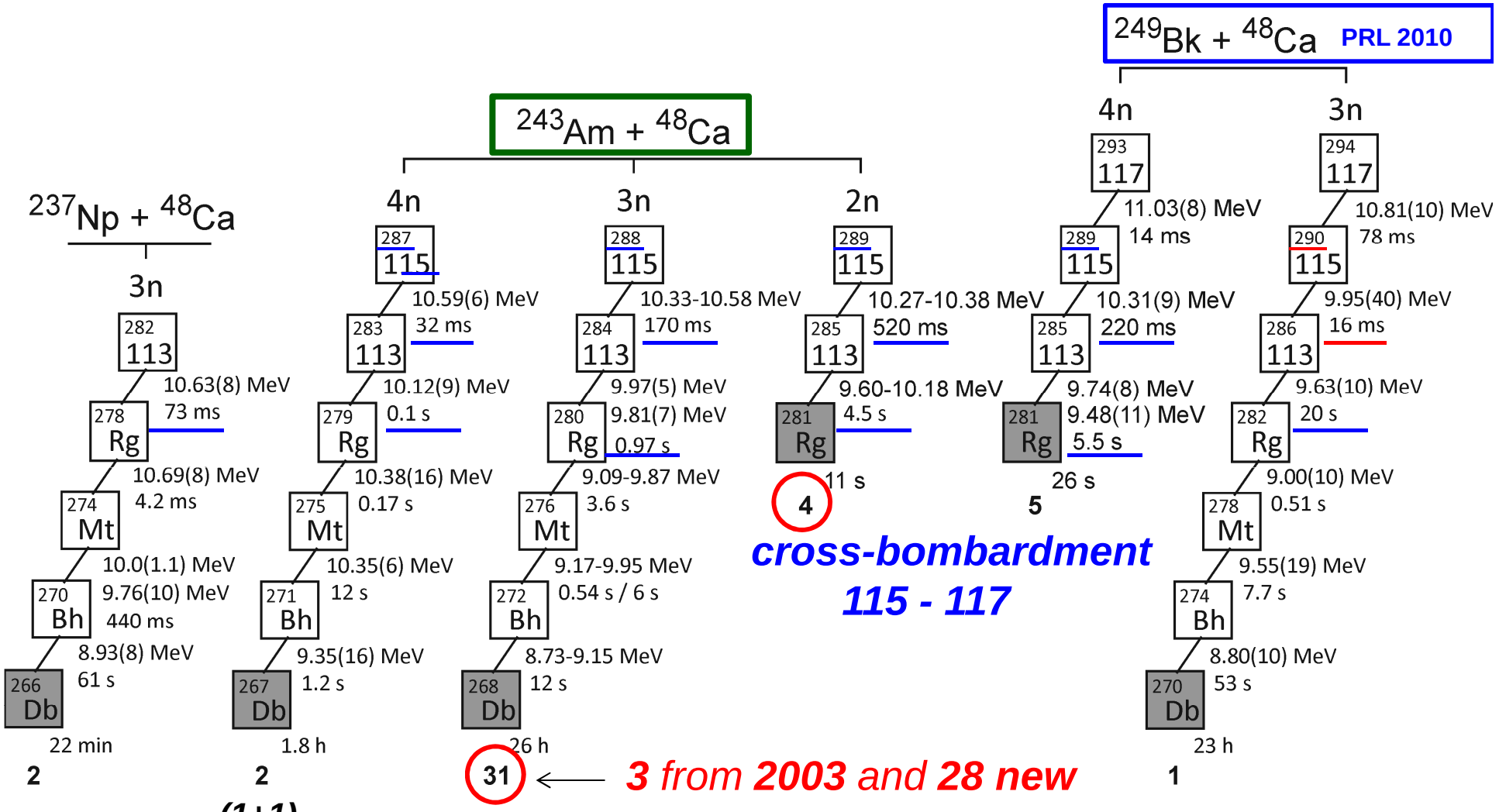
New study of Z=115 decay chains



total number of observed decay chains (**2003, 2010 - 2012**) is listed at the end of the chain

Oganessian et al., PRL 108, 022502, 2012, PRC87, 014302, 2013

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new experiments at the DGFRS (JINR Dubna)

- ^{249}***Bk+^{48}Ca,*** *from April 23rd, 2012 till October 23rd, 2012, beam dose ~* ***4.6*10^{19}***

  - *α-decay properties, in particular of* ***^{294}117*** *chain (only 1 event detected earlier)*

  - *new isotope Z=109* ***^{277}Mt and its very fast fission !***

  - *excitation function (search for ^{295}117 produced in 2n reaction channel)*

  - *evidence for* ***^{294}(118)*** *decay chain*

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New studies of super heavy nuclei
with Z=97 ^{249}Bk and Z=98 ^{249}Cf target materials at Dubna (2012)

11 *new events of* ^{293}*(117)*

ER	# 9 9.91 MeV	# 23 13.23 MeV	# 12 11.76 MeV	# 25 11.00 MeV	# 7 9.36 MeV
293 117	10.90$_{10}$ MeV [a] 7.525 ms	11.142$_{65}$ MeV 3.305 ms	11.114$_{89}$ MeV [a] 153.948 ms	10.914$_{68}$ MeV 10.547 ms	10.598$_{49}$ MeV 109.878 ms
289 115	10.37$_{28}$ MeV [b] 0.2665 s	**10.310$_{65}$ MeV** **0.1719 s**	missing α	**10.198$_{68}$ MeV** **1.4348 s**	**10.217$_{49}$ MeV** **0.1510 s**
285 113	9.857$_{40}$ MeV 1.5155 s	**missing α**	9.631$_{67}$ MeV *19.0456 s*	**9.36$_{30}$ MeV [b]** **1.3153 s**	**9.683$_{49}$ MeV** **18.3997 s**
281 Rg	204.0 MeV [c] 9.4192 s	**222.0 MeV [c]** ***7.4538 s***	212.8 MeV [c] 1.4809 s	**162.9 MeV [c]** **103.406 s**	**150.8 MeV** **42.1349 s**

3 *new events of* ^{294}*(117)*

ER	# 16 12.64 MeV	# 8 13.11 MeV
294 117	10.960$_{70}$ MeV 100.72 ms	10.967$_{73}$ MeV 3.986 ms
290 115	**10.28$_{12}$ MeV [a]** **0.3010 s**	**9.775$_{73}$ MeV** **0.6976 s**
286 113	**9.61$_{11}$ MeV [a]** **5.7895 s**	**9.750$_{11}$ MeV [a]** **3.6525 s**
282 Rg	**9.18$_{30}$ MeV [b]** **145.34 s**	**9.04$_{11}$ MeV [a]** **29.202 s**
278 Mt	**9.396$_{70}$ MeV** **4.1713 s**	**9.382$_{73}$ MeV** **7.2154 s**
274 Bh	8.791$_{70}$ MeV 102.58 s	**8.69$_{30}$ MeV [b]** **55.722 s**
270 Db	142.4 MeV 37.49 h	195.9 MeV [c] 23.49 h

^{249}Cf + ^{48}Ca

ER	# 23 11.63 MeV	
294 118	11.65$_{6}$ MeV $0.89^{+1.07}_{-0.31}$ ms	11.679$_{65}$ MeV 0.135 ms
290 Lv	10.84$_{8}$ MeV $7.1^{+3.2}_{-1.7}$ ms	10.848$_{65}$ MeV 29.437 ms
286 Fl	10.19$_{6}$ MeV 129^{+39}_{-24} ms	**219.3 MeV [c]** **3.486 ms**
282 Cn	$0.82^{+0.30}_{-0.18}$ ms	

new event of ^{294}*(118)*

Z=97 ^{249}*Bk → Z=98* ^{249}*Cf*

$T_{1/2}$*=330 days*

E(*^{297}*118) ~ 31 MeV*

consistent data on Z=117 and Z=118 production and decay

Oganessian et al., ***PRL 109, 162501, 2012*** *and* ***PRC 87, 054621, 2013***

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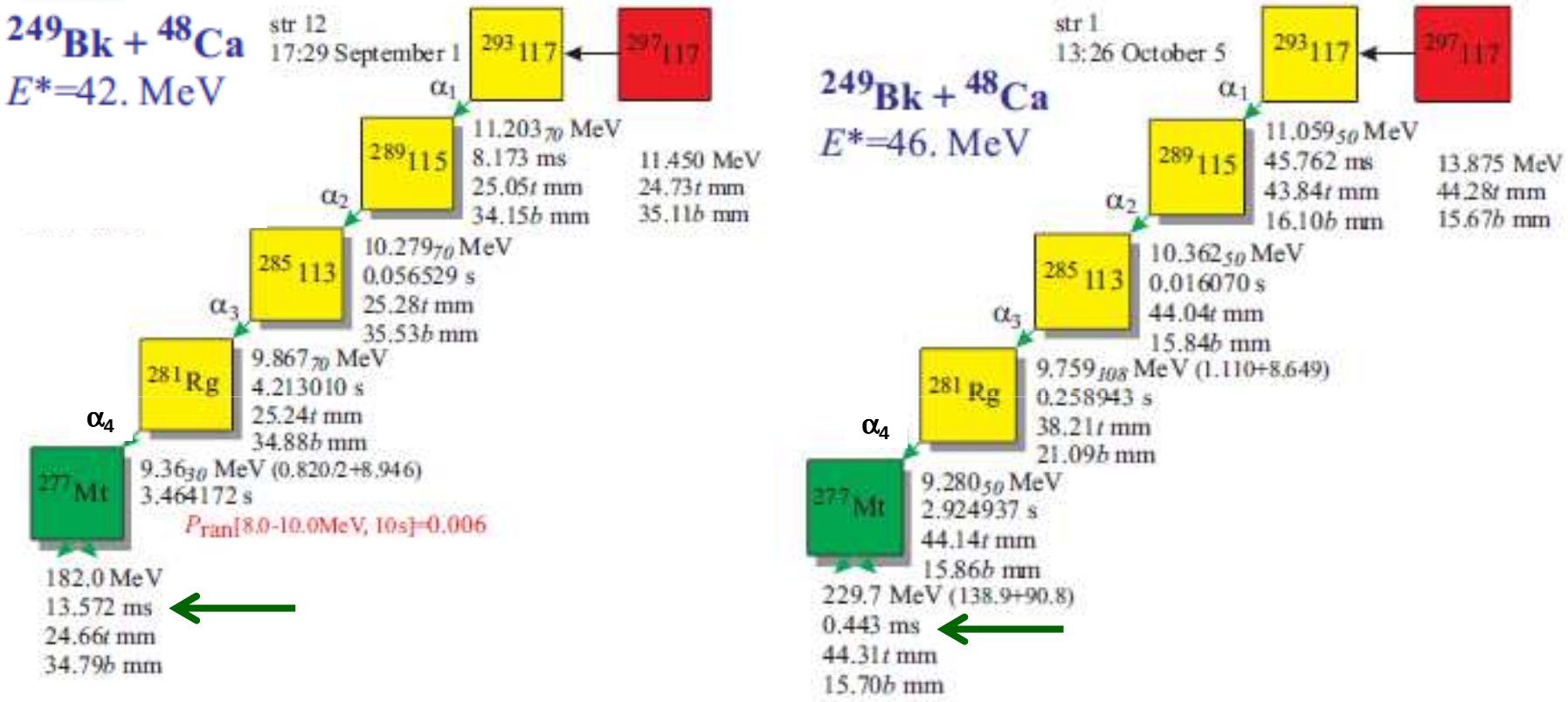
First observation of ^{281}Rg α-decay and fast fission of new isotope ^{277}Mt



*Z=111 ^{281}Rg SF ~ **20 s** (α ~ 10%)*

*Z=109 ^{277}Mt SF ~ **5 (+9,-2) ms** **"fission corridor"***

nuclear structure dramatically influences fission probability

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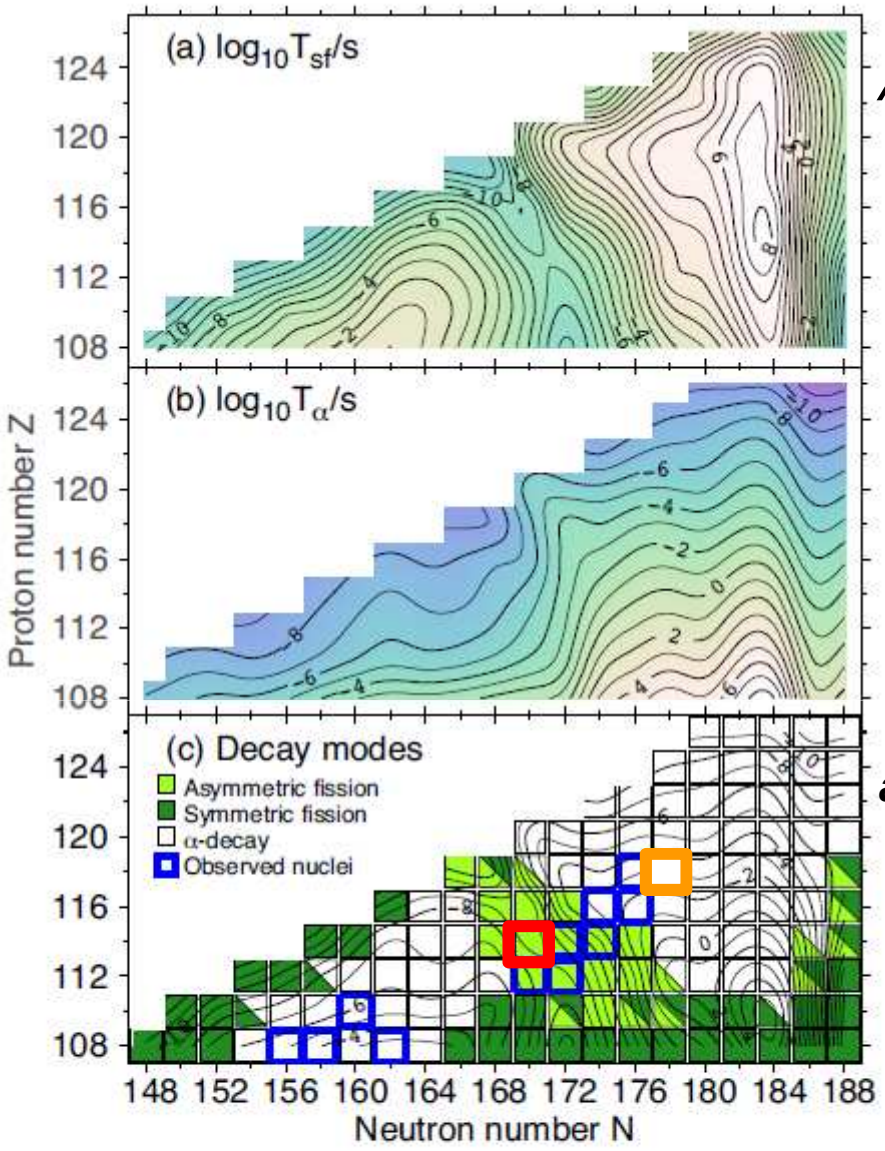

FIG. 4. (Color online) Summary of our SkM* results for decay modes of SH nuclei. (a) SF half-lives $\log_{10} T_{sf}$ (in seconds). (b) α-decay half-lives $\log_{10} T_{\alpha}$ (in seconds). (c) Dominant decay modes. If two modes compete, this is marked by coexisting triangles.

A.Staszczak, A. Baran and W.Nazarewicz
Phys. Rev. C 87, 024320, 2013
EVEN-EVEN SHE nuclei
advanced analysis of shapes and symmetric vs asymmetric fission modes affecting SHE lifetimes

Pretty good agreement for $T_{1/2}$'s of even-even alpha emitters, but the SF mode at the end of "Dubna Island" decay chains appears to be much too fast in the calculations.
However, the large gradient of SF life-time is indeed observed in experiment.

^{284}Fl (now searched for)
^{239,240}Pu+^{48}Ca, 3,4n channel

^{296}118 (to be searched for)
^{251}Cf+^{48}Ca, 3n channel

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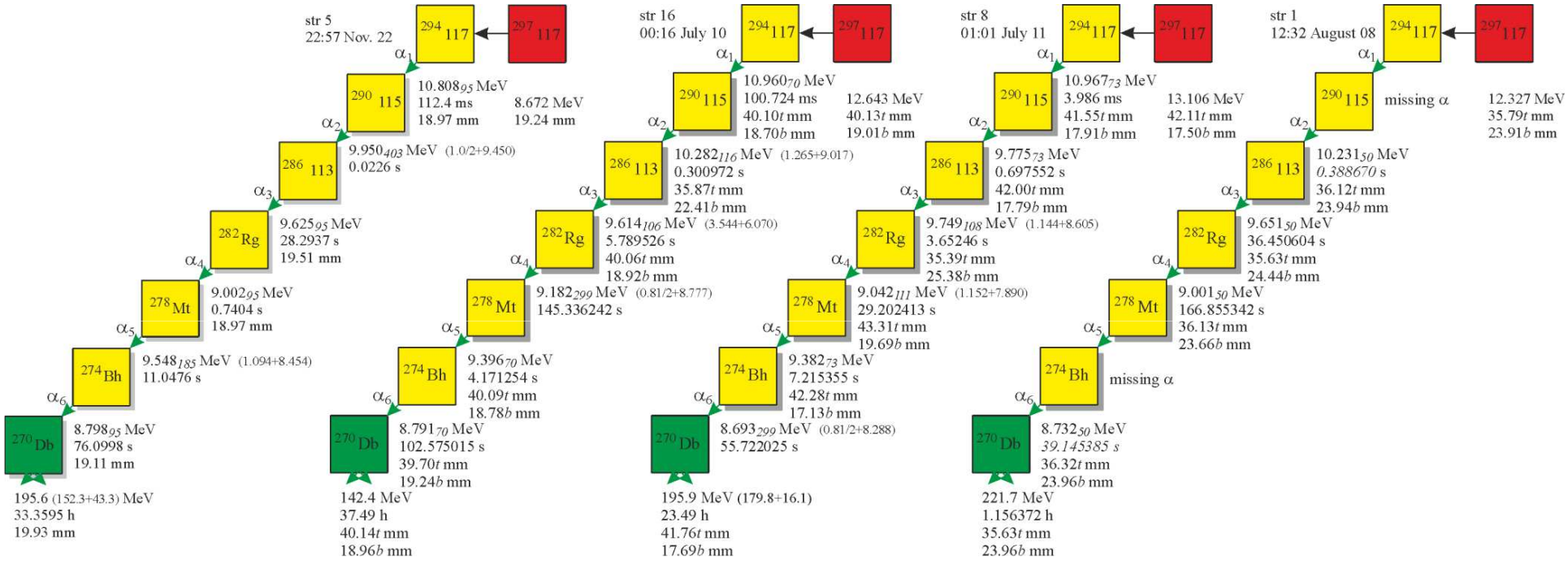
Total of four $^{294}117_{177}$ decay chains found at Dubna (3n channel of $^{249}Bk+^{48}Ca$ reaction)

2009, E~ 35 MeV* *2012: E*~ 35 MeV* *E*~ 32.6 MeV*



all decay chains ended with SF of Z=105 ^{270}Db, $T_{1/2}$(SF)~ 17 h

E~ 35 MeV denotes E*(^{297}117) ranging from 32.8 MeV to 37.5 MeV*

Oganessian et al., ***PRL 109, 162501, 2012,*** ***PRC 87, 054621, 2013***

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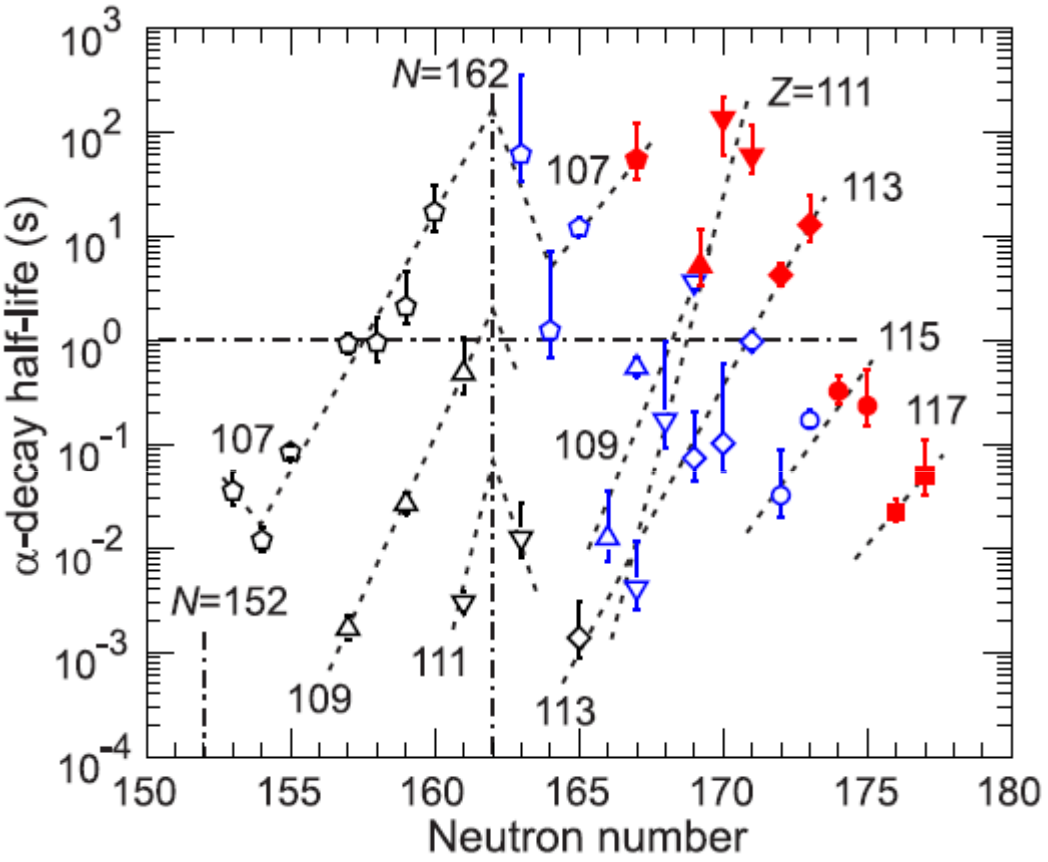
Towards the Island of (enhanced) Stability 2013



Better statistics on Z=117 and Z=115 decay chains confirms enhanced stability with increasing neutron number

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experiments at TASCA (GSI Darmstadt)

- ^{249}**Bk+^{50}Ti,** *TASCA, April – September 2012, beam dose* **~ 3.6 *10^{19}**
  - *search for isotopes of new element Z=119,* ^{295,296}**(119)**$_{174,175}$
  - *cross section limit of about* ***70 femtobarn*** *reached*

- ^{249}**Bk+^{48}Ca,** *TASCA, September - October 2012, beam dose* **~ 1.1 *10^{19}**
  - *search for isotopes of element Z=117,* ^{293,294}**(117)** ***/GSI-ORNL scientific agreement/***

12.7 mg ^{249}Bk from ORNL
impressive production of ^{249}Bk target at Mainz
(Klaus Eberhardt, Norbert Trautmann,
Jörg Runke and their collaborators)

*Rotating target survived ~ 4 part * microAmps*
*i.e., 2.4 * 10^{13} ^{50}Ti projectiles per 0.25 second*
over several months of irradiations

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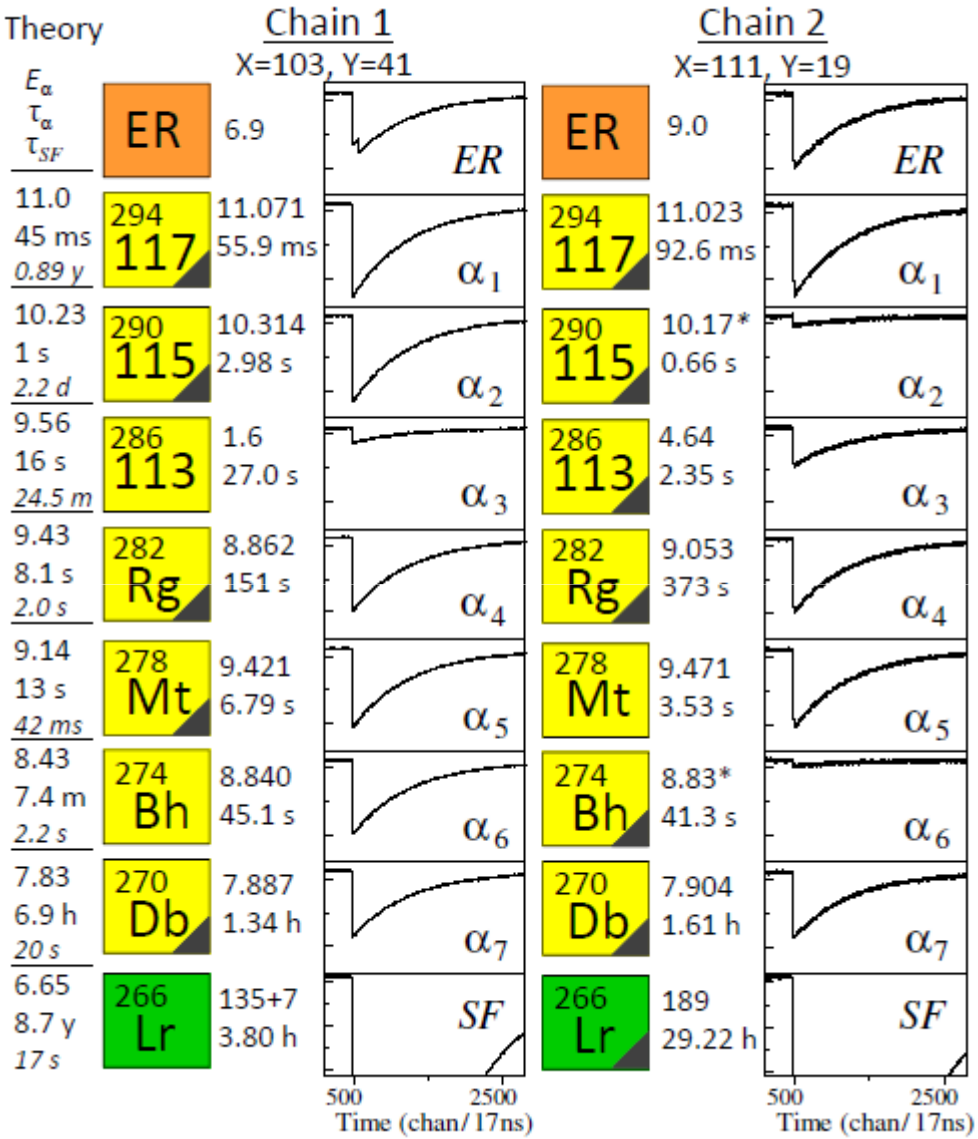
Element 117 independently confirmed at TASCA !



Jadambaa Khuyagbaatar et al.,
→ PRL 2014

among coauthors:
K. Miernik
M. Węgrzecki (ITME)

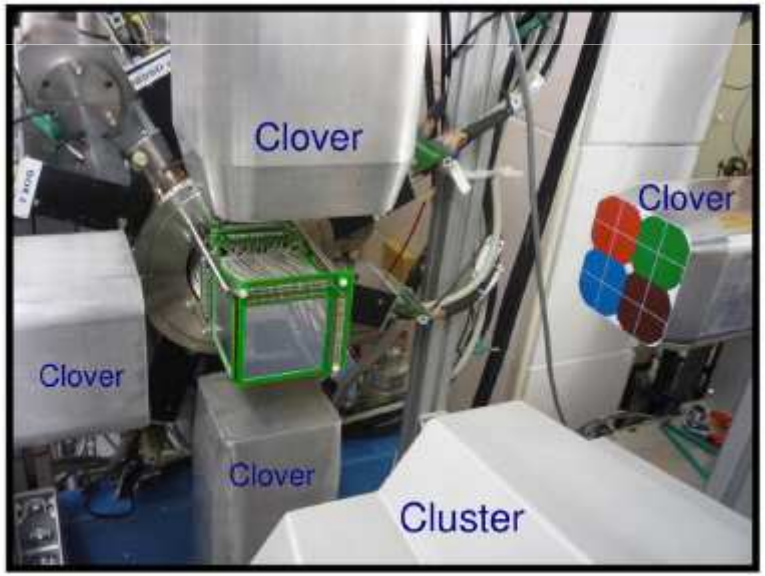
NEW:
α-decay of ^{270}Db
and new SF isotope ^{266}Lr

GSI Darmstadt D. Rudolph et al., PRL 111, 112502, 2013

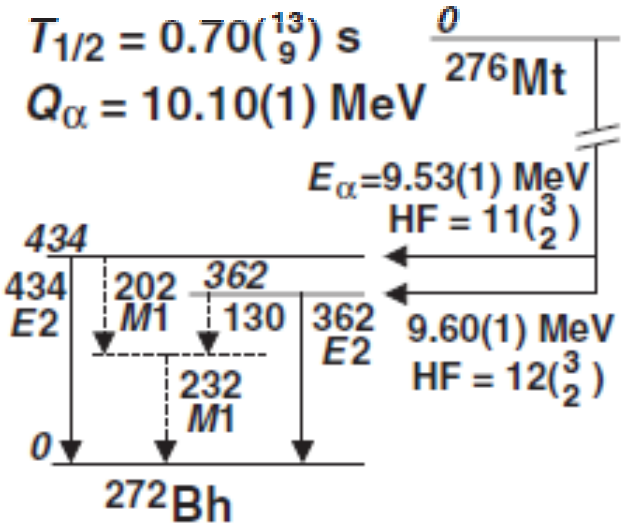
- **^{243}Am+^{48}Ca,** ***TASCA-TASISpec, ^{243}Am (ORNL), 0.8 mg/cm^2 target (Mainz)***

  3 weeks *in Nov. 2012, beam dose ~* ***7*10^{18}***

  - *study of known isotopes of element Z=115 , e.g., ^{288}(115)*
  - ***independent confirmation of 2003-2004 and 2010-2012 Dubna data on Z=115,113,...***
  - ***attempt to directly measure atomic number Z through α - X ray correlation***
  - ***30 decay chains*** *of Z=115 isotopes observed* ***in three weeks*** *!*



~ 40 % efficiency at KX-ray region



first γ-spectroscopy at Hot Fusion Island

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Results – $^{288}115$ (3n-chain)

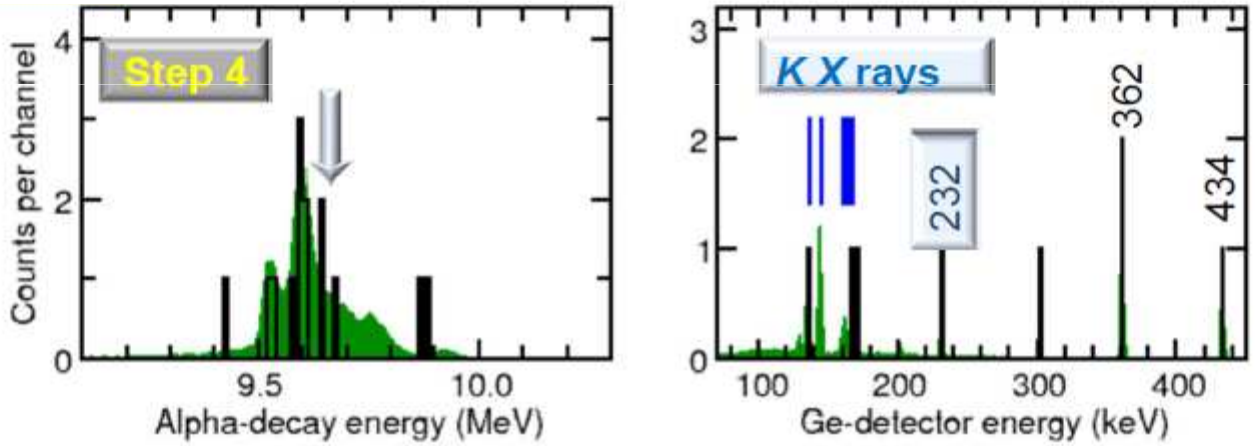
X-ray Case?

$^{276}Mt \rightarrow {}^{272}Bh$

Chain 5 : E_α = 9.65(1) MeV
E_{ph} = 232(1) keV

cascade (of 2 *K X* rays?)

8x α-photon coincidences

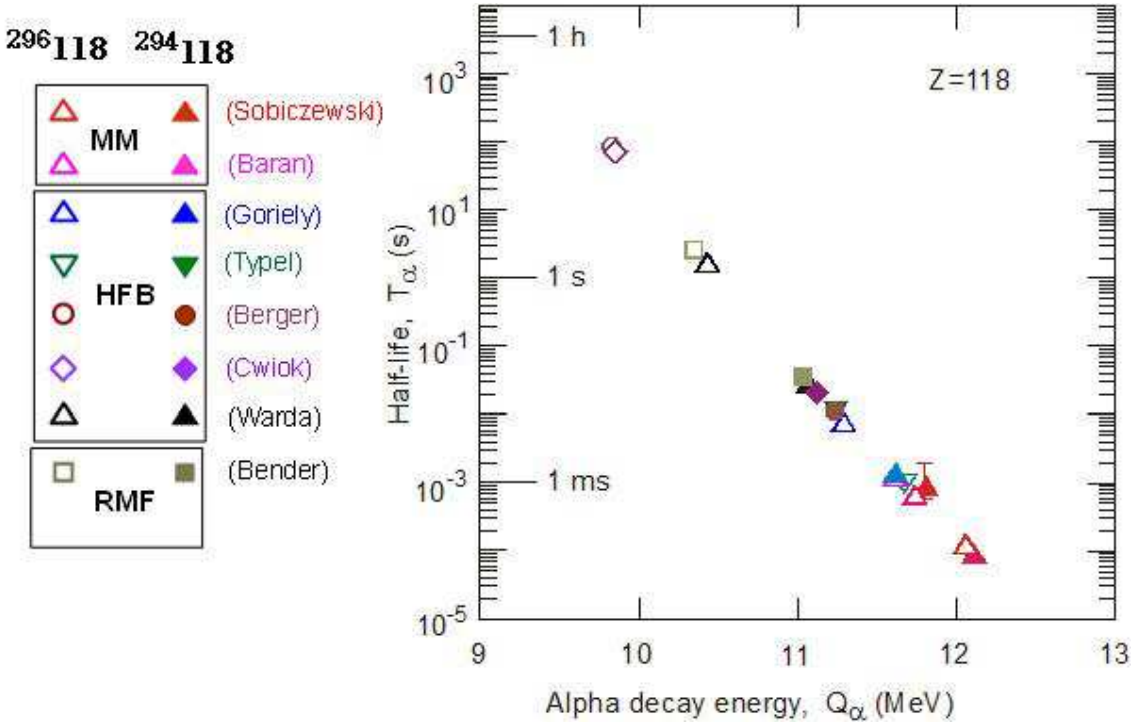


GEANT4 simulations: 100000 decays, normalized to number of α's

D. Rudolph et al., PRL 111, 112502, 2013

Plans for 2014-2015: search for Z=118 isotopes

Models do not agree about the decay properties of $^{294}118$ and $^{296}118$



exp data on $^{294}118$ α-decay:
E_α=11.7 MeV , $T_{1/2}$ ~ 0.7 ms

Staszczak, Baran, Nazarewicz
Phys. Rev. C 87, 024320, 2013

$^{294}118$: E_α=11.8 MeV , $T_{1/2}$=0.66 ms
$^{296}118$: E_α=11.7 MeV , $T_{1/2}$= 1 ms

long experiment with a mixed-Cf target from ORNL and ^{48}Ca beam has a potential to identify new isotopes ***$^{293}118$, $^{295}118$ and $^{296}118$***

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Mixed-Cf target ORNL 2013-2014

Radiochemical Engineering Development Center REDC

~ 40 years old Cf-sources processed at REDC to obtain mixed-Cf material

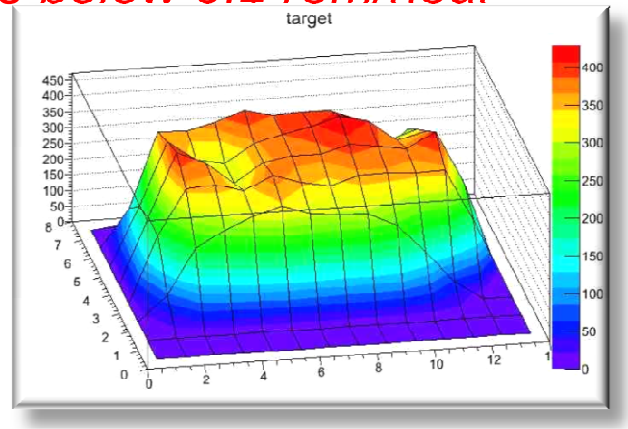
^{249}Cf (351 y)	^{250}Cf (13 y)	^{251}Cf (898 y)	^{252}Cf (2.65 y)
7.6 mg	2.5 mg	**5.7 mg**	0.007 mg
48.1%	15.6%	**30.3%**	0.04%

~ 3* 10^{7} n/s**, *unshielded dose in 6" ~* ***1 rem/hour

polyethylene shield reduces the radiation dose below 0.1 rem/hour

work on mixed-Cf at REDC

first target sector ready in Dec. 2013



radiographic image of Sm test target

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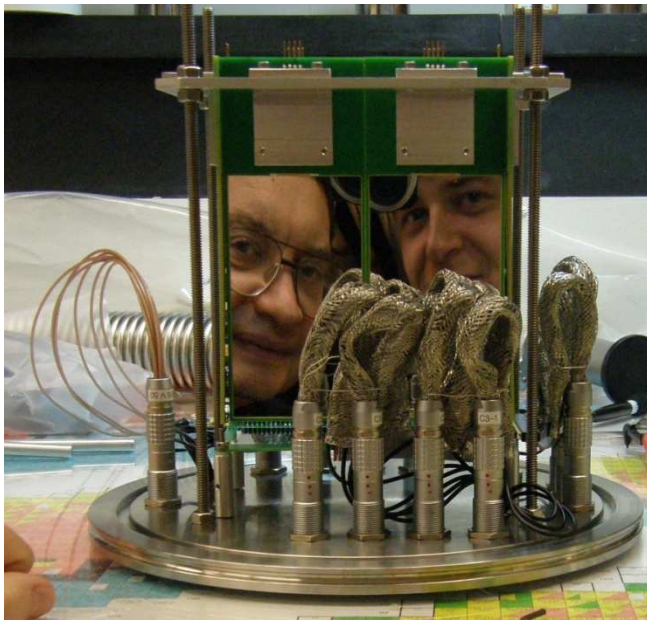
New ORNL-UTK detectors and digital data acquisition system

(similar DAQ at SHIP Z=120 exp was serving PSSD+Si-box+MCPs)

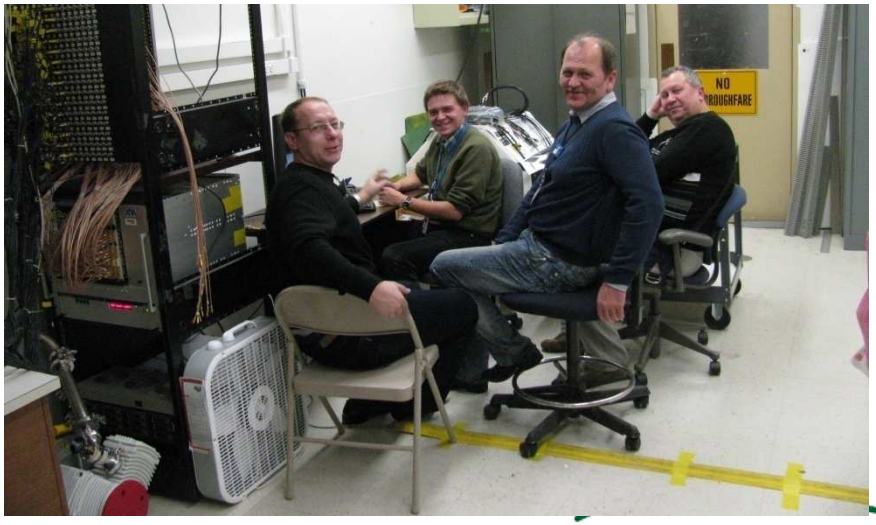
MICRON

128 x48 mm
1 mm wide strips DSSD
and
matching Si-veto detector

six 120 x 65 mm single Si
forming Si-box

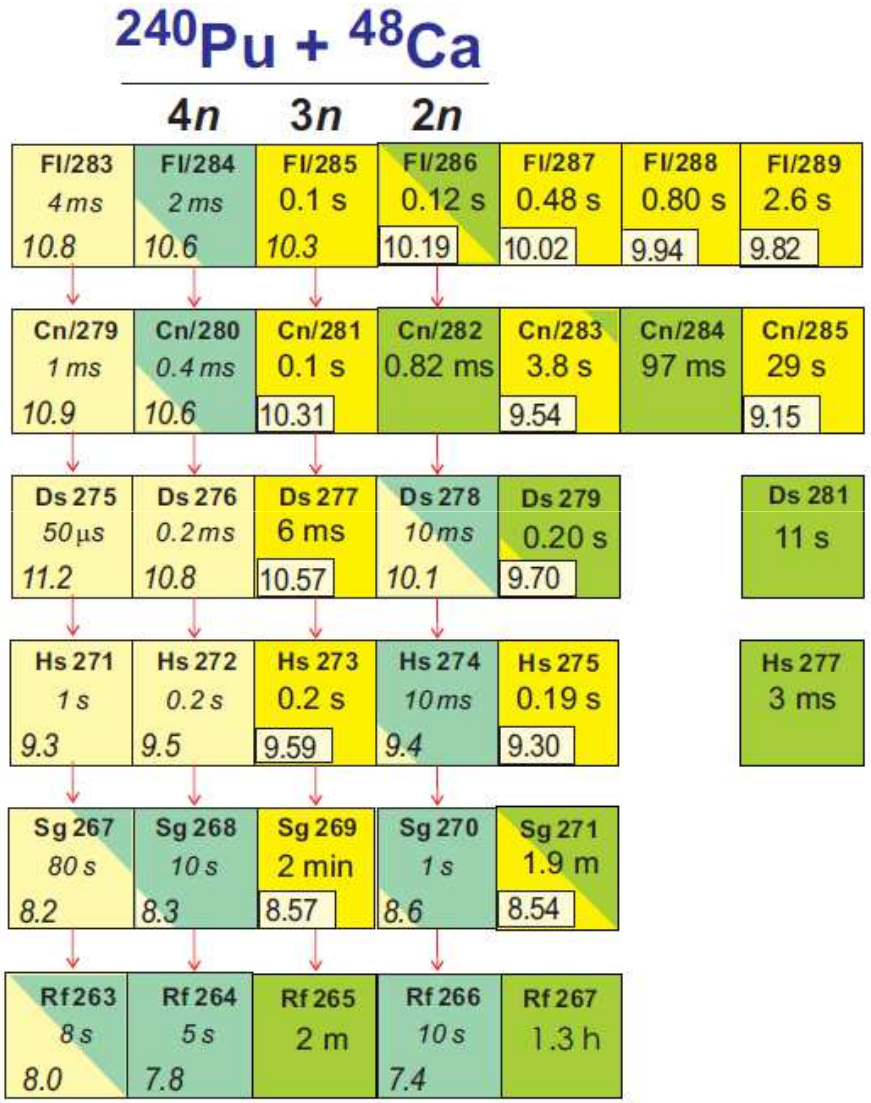


MESYTEC
lin-log preamps
XIA Pixie16 rev D
(208 channels)
Dell Power Edge



Connecting Hot Fusion Island with Nuclear Mainland

search for new Z=114 Flerovium isotopes and their decay products



^{240}Pu material from Oak Ridge delivered to Dubna on 27thDec. 2013 (after 51 weeks of paperwork)

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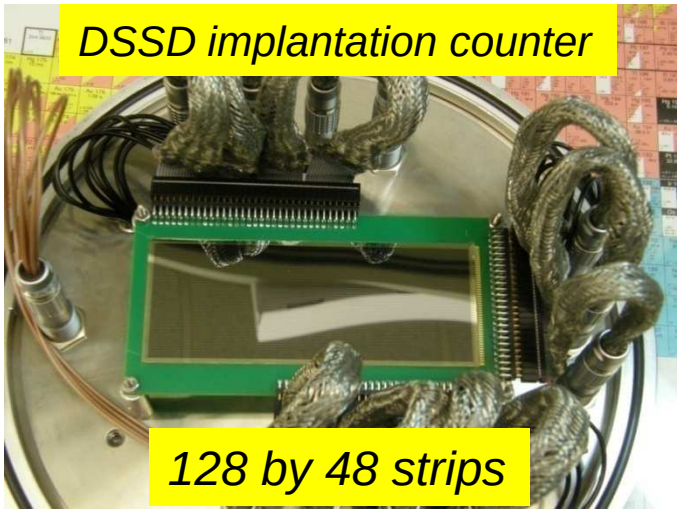
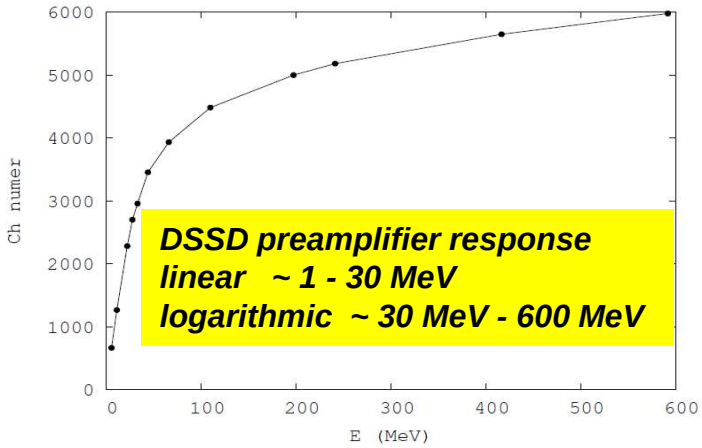
ORNL-UTK 8-detector and digital data acquisition system operating at the Dubna Gas Filled Recoil Separator (DGFRS)

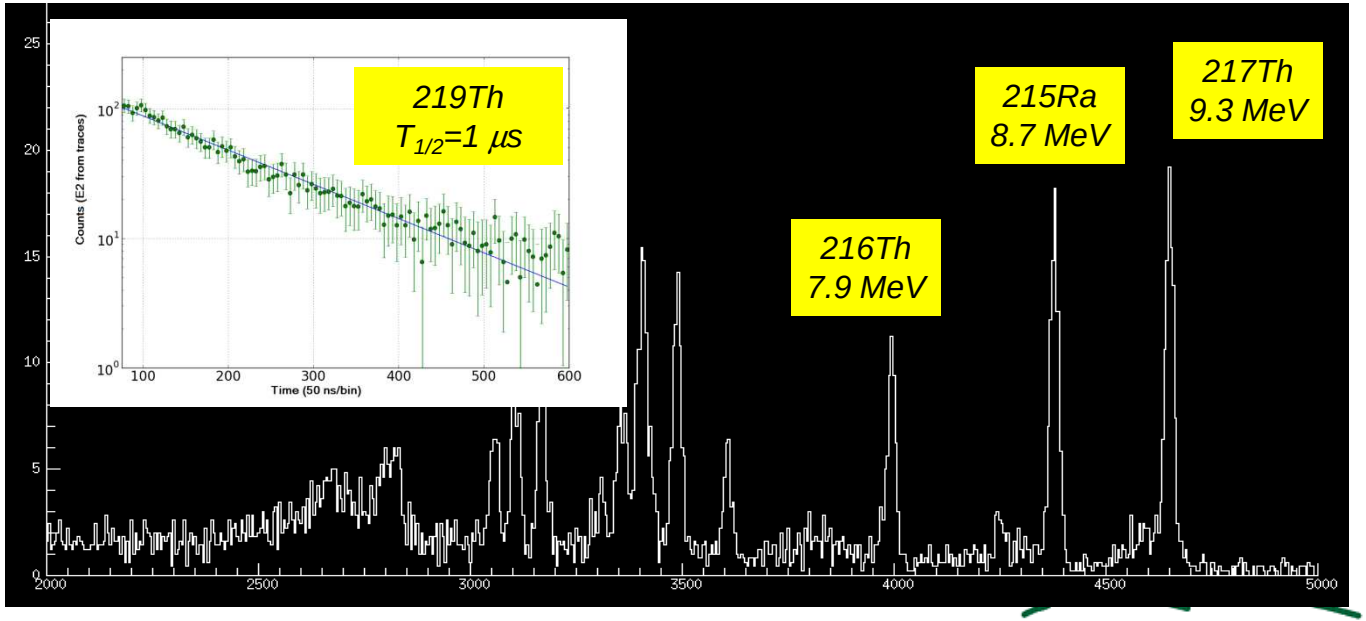
Si-detector stack





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 started on 6th Dec. 2013



energy of α-particles

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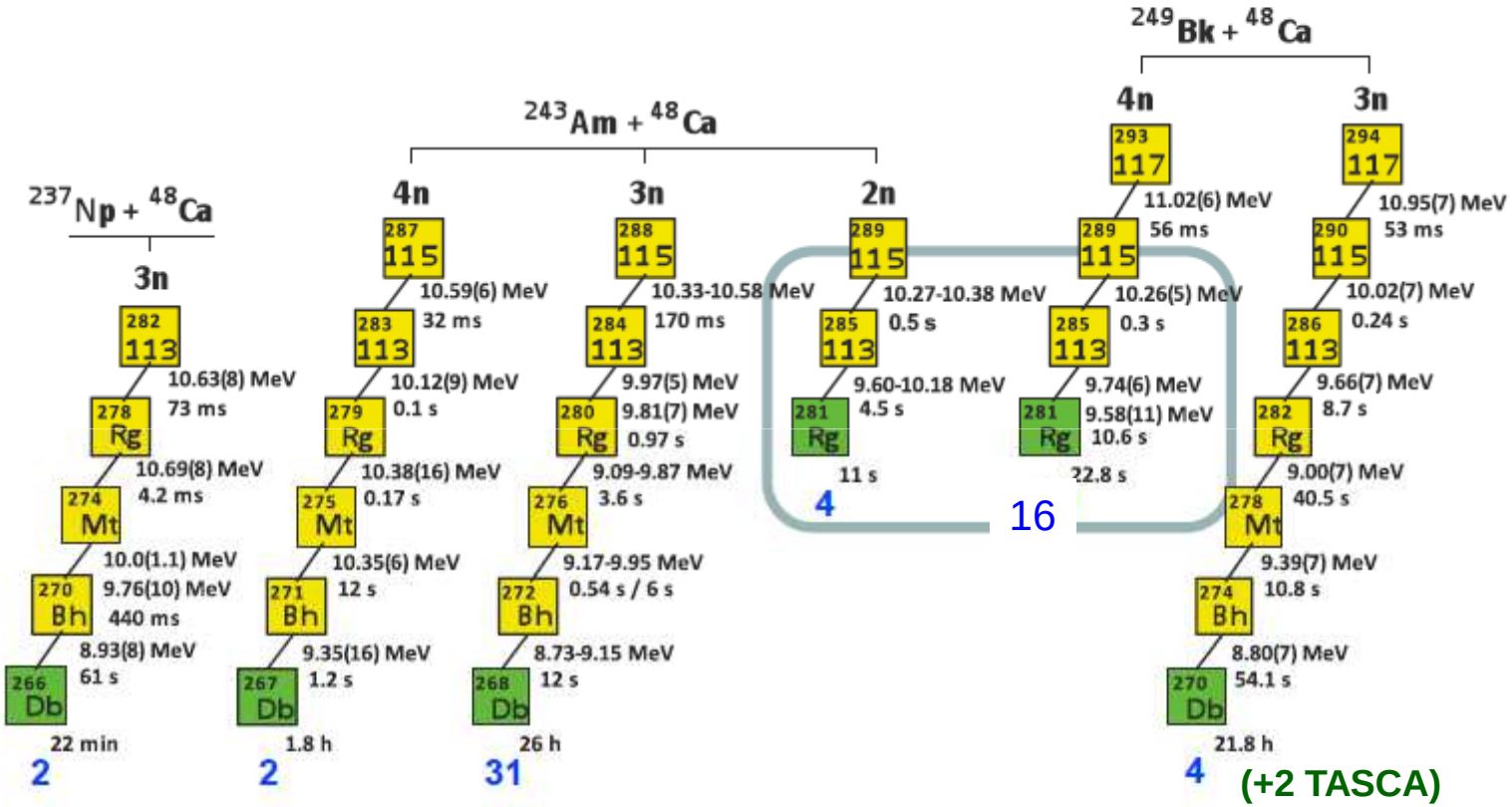
Summary

2003-2013

odd Z nuclei produced in ^{48}Ca-induced reactions



number of the detected chains

(+30 TASCA + ~ 40 BGS)

Yu.Ts. Oganessian et al.,
*PRL **104**, 142501, 2010, PRL **108**, 022502, 2012, PRL **109**, 162501, 2012.*

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Summary

- *new data consistent with earlier results on Z=117, 115 , 113 and 118*

- *Dubna discoveries of elements 115 and 113 (2003-2004) and of 117 (2010) independently confirmed at TASCA (GSI)*

- *"cross bombardment" achieved in ^{48}Ca-induced reactions: 4n (^{249}Bk target, ^{293}117) and 2n (^{243}Am, ^{289}115) reaction channels*

- *nearly "mass production" of Z=115 isotopes , σ_{MAX} ~ 9 pb*

- *total of ~ 100 decay events of ^{288}115 and 16 events of ^{293}117 and ^{294}117 (4 +2 events) help to determine the decay properties (new isotope ^{266}Lr)*

- *an evidence for fine structure in α-spectra and α-KX-ray events*

- *new isotope ^{277}Mt (~ 5 ms SF !) ending the ^{293}117 decay chain*

- *σ(117) ~ 2-3 pb, ^{294}118 observed with ingrown ^{249}Cf target component*

- ***new SHE experiments with important ORNL/UTK contributions at Dubna***

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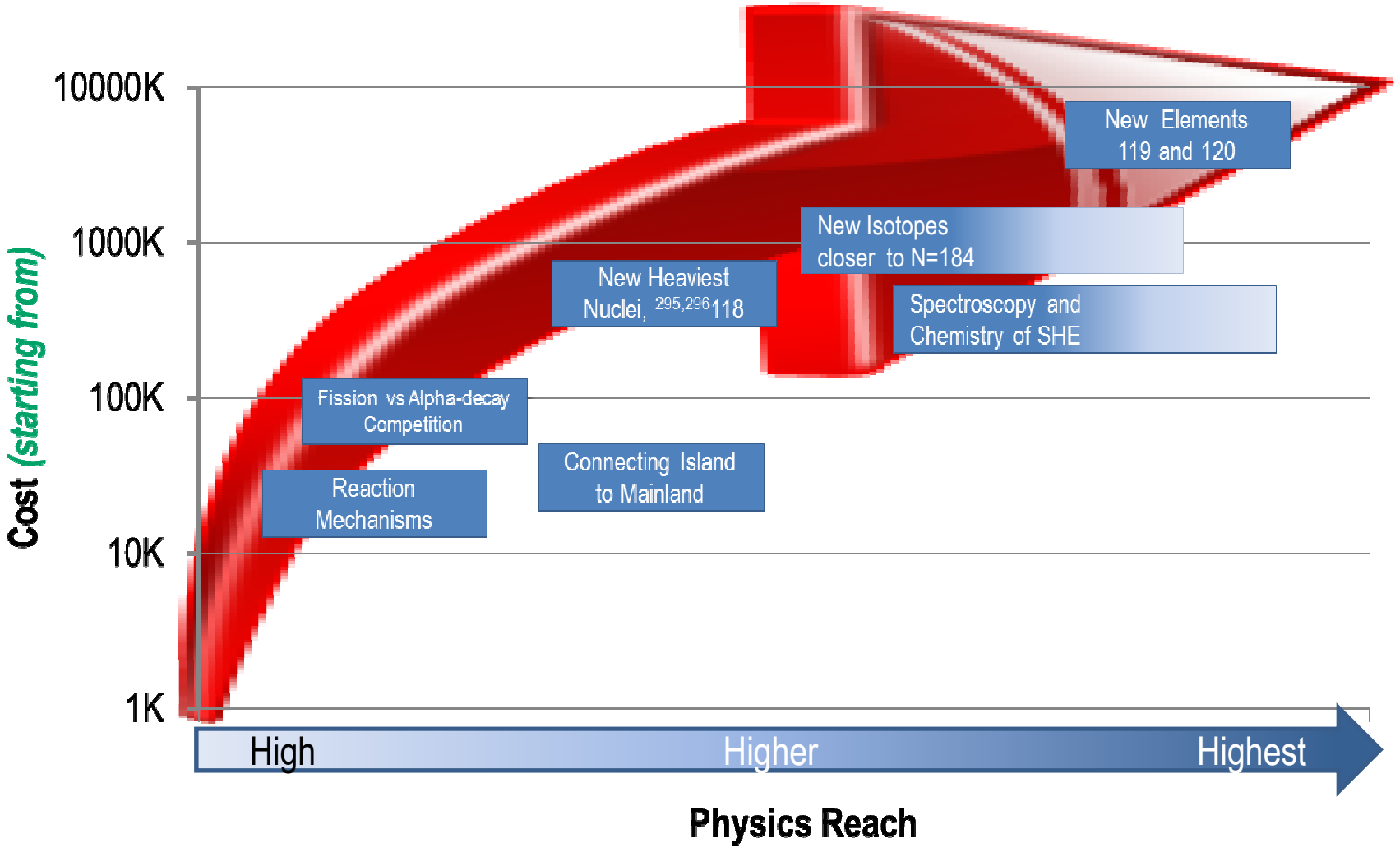
Approach to Highest Value Experiments
(e.g., at Dubna SHE Factory)



Timeline of SHE Experiments (Dubna-ORNL)