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Quest for Superheavy Elements

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Helmholtz Institut Mainz

Ecole Joliot-Curie "Nucleus through the looking glass – High intensity stable and ISOL beam frontier"

La Villa Clythia – Fréjus – France – September 30-October 05, 2012

What's on the menu this week?

Lesson 1:

-Discovery of the transuranium elements: Z=93 - 112

-Stability of superheavy elements I

Lesson 2:

-Discovery of the transuranium elements: Z=113- …

-Stability of superheavy elements II

Lesson 3:

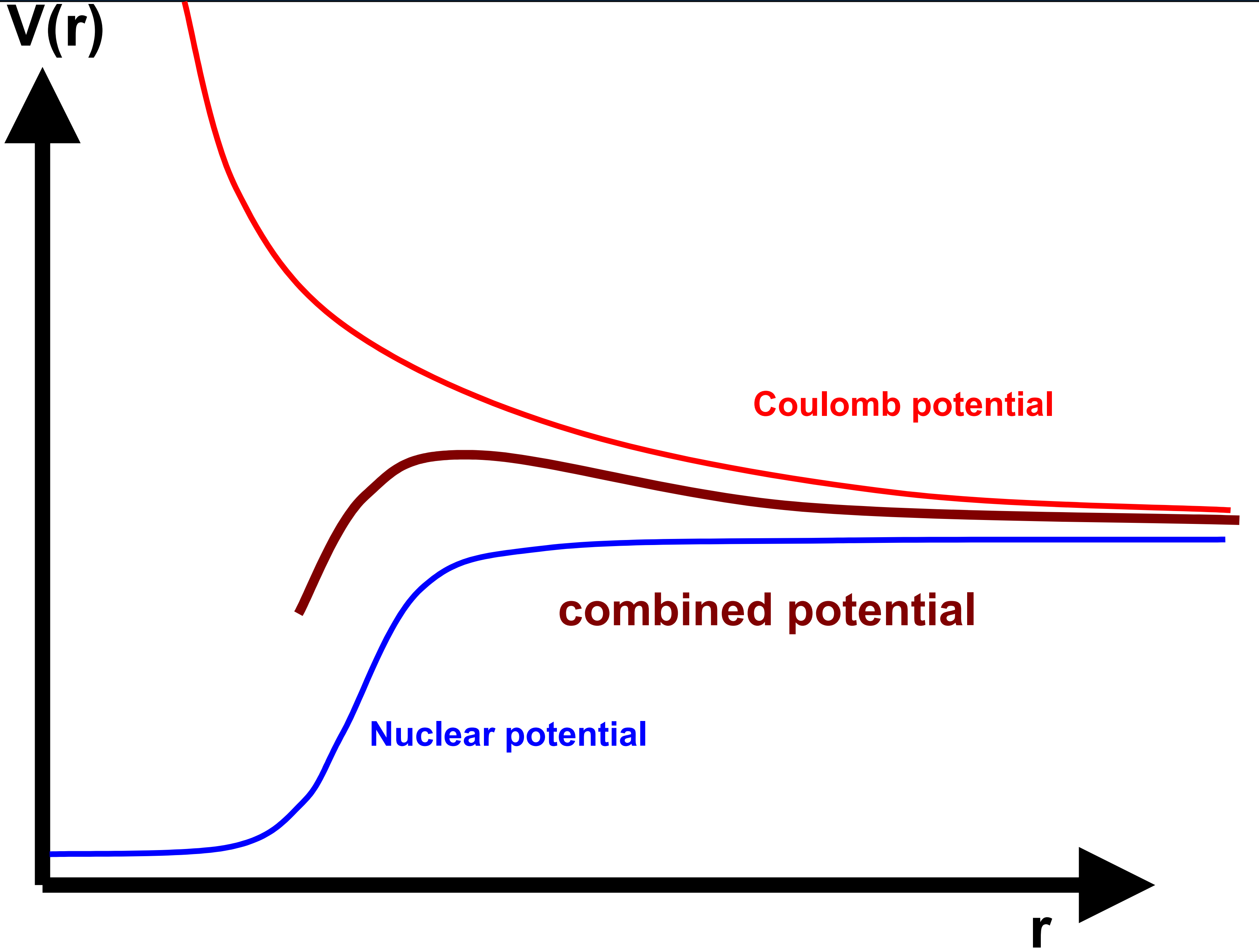
-Reactions: synthesis of SHE

-Search for new elements at GSI

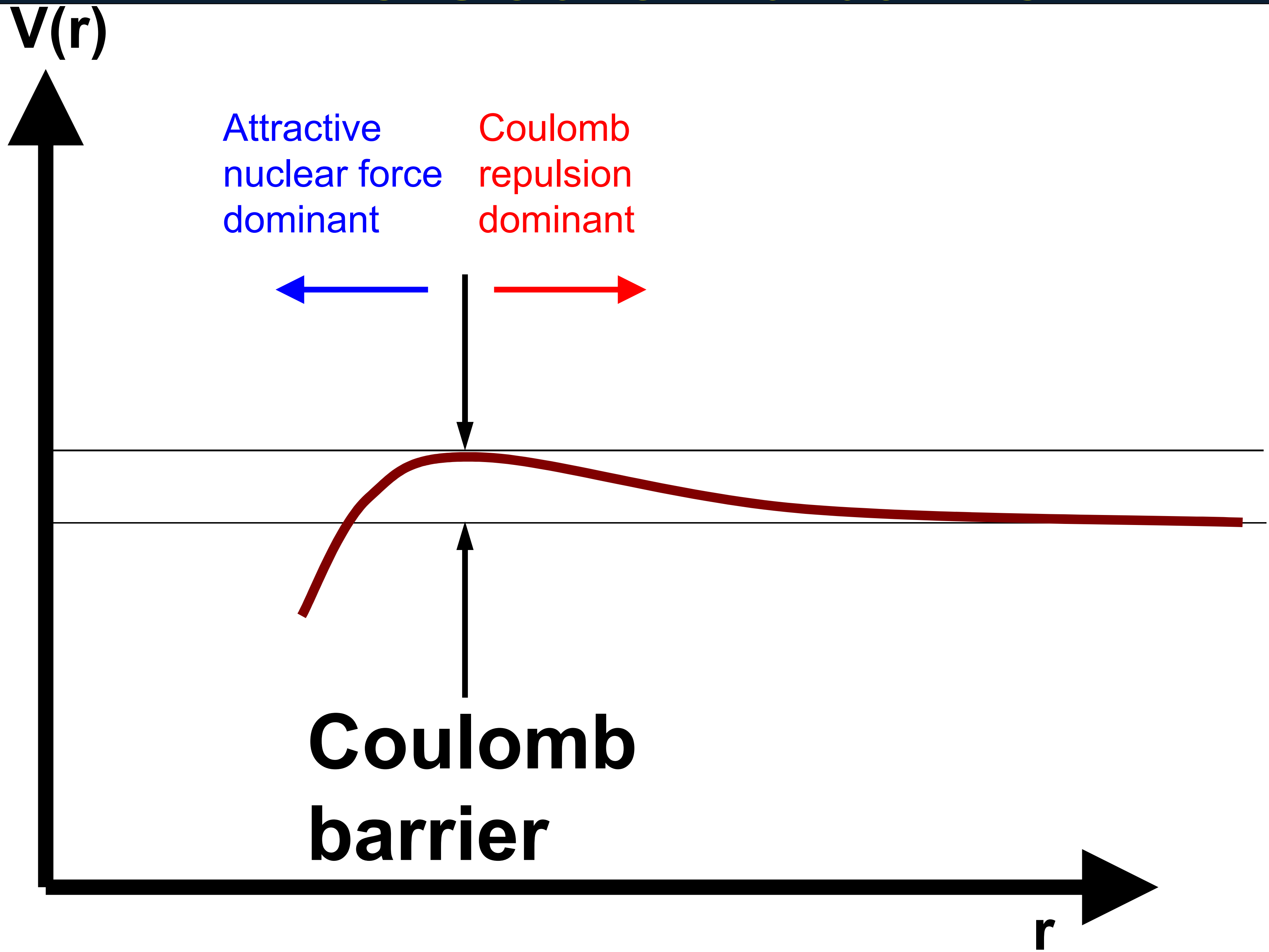
Synthesis of SHE

It's all about the cross section…

The Coulomb barrier



The Coulomb barrier



Energetics of the reactions

Analog to α decay.

Example: **$^{24}Mg + ^{242}Cm \rightarrow ^{266}Hs^*$**

$\Delta(^{242}Cm) + \Delta(^{24}Mg) = \Delta(^{266}Hs) + Q$

Therefore:

$Q = \Delta(^{242}Cm) + \Delta(^{24}Mg) - \Delta(^{266}Hs)$

Using mass excess values from "Atomic Mass Evaluation 2003"
(A.H. Wapstra et al., Nucl. Phys. A 729 (2003) 337) yields:

$Q = 54.81\ MeV + (-13.93\ MeV) - 121.19\ MeV = -80.31\ MeV$

Excitation energies at the Coulomb barrier

An important property of a heavy-ion induced fusion reaction is the excitation energy of the compound nucleus if the beam energy corresponds to the Coulomb barrier height

Generally: $E^* = V_C(\text{c.m.}) + Q$

Excitation energies at the Bass barrier for different reactions:

Hot Fusion

$^{24}Mg + ^{242}Cm$	$\rightarrow$	$^{266}Hs^*$	B_{Bass} = 127.8 MeV	E^*_{min} = 47.5 MeV
$^{32}S + ^{234}U$	$\rightarrow$	$^{266}Hs^*$	B_{Bass} = 161.4 MeV	E^*_{min} = 52.3 MeV
$^{58}Fe + ^{208}Pb$	$\rightarrow$	$^{266}Hs^*$	B_{Bass} = 226.7 MeV	E^*_{min} = 21.6 MeV
$^{86}Kr + ^{180}Hf$	$\rightarrow$	$^{266}Hs^*$	B_{Bass} = 270.8 MeV	E^*_{min} = 16.6 MeV
$^{132}Xe + ^{134}Xe$	$\rightarrow$	$^{266}Hs^*$	B_{Bass} = 301.7 MeV	E^*_{min} = 3.1 MeV

Cold Fusion

Cross Section for EVR Formation

$$\sigma(E) = CAPTURE \cdot p_{CN} \cdot SURVIVAL$$

Capture Diffusion Survival

Fusion (CN Formation)

CAPTURE: cross section to form a composite system inside the Coulomb barrier

p_{CN}: probability of the dinuclear system to evolve to a CN

SURVIVAL: statistical evaporation cascade of the CN

Cross Section for EVR Formation

$$\sigma(E) = CAPTURE \cdot p_{CN} \cdot SURVIVAL$$

Capture   Diffusion   Survival

CAPTUR

p_{CN}:

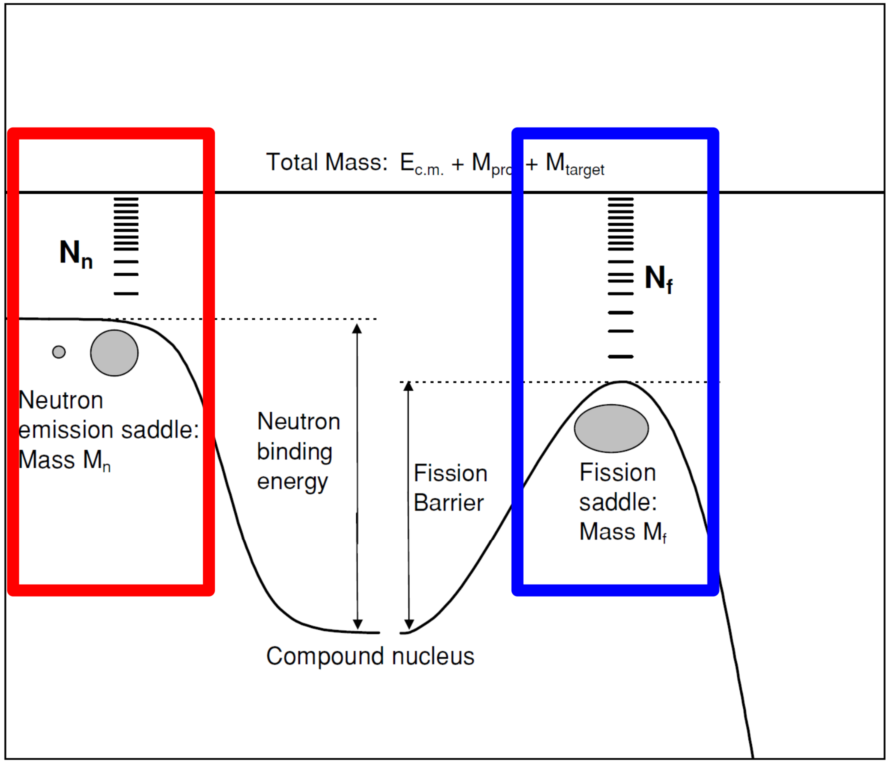
SURVIVA

Survival

$$\sigma(E) = \sigma_{fus} \cdot W\left[\prod_{i=1}^{i_{max}} \left(\frac{\Gamma_n}{\Gamma_{tot}}\right)_i, E^*\right]$$

E*:	Excitation energy
Γ_n:	Probability for evaporation of one neutron
Γ_{tot}:	Probability for all possible exit channels. $\Gamma_{tot}=\Gamma_n+\Gamma_p+\Gamma_\gamma+...$ $\Gamma_{tot} \sim \Gamma_f$ for the heaviest elements

The exit channel: Γ_n / Γ_{tot}



Spherical nuclei:

-Density of states above the neutron emission saddle point: very small.

-Density of states above (deformed) saddle point: very large.

⇒ Spherical nuclei hardly survive, but fission!

⇒ *Synthesis of magic (spherical) nuclei should be extremely difficult!*

For SHE: $\Gamma_{tot} \sim \Gamma_f$

CN survival probablility depends on number of states in the energy intervals between total energy (or: mass) and the masses of the neutron emission saddle point and the fission saddle point.

W. Swiatecki et al., PRC 71 (2005) 014602

Production of Heavy Elements in Complete Fusion Reactions

$$\sigma_{\mathrm{EVR}}(E_{\mathrm{c.m.}}) = \sum_{J=0}^{J_{\max}} \sigma_{\mathrm{CN}}(E_{\mathrm{c.m.}}, J) W_{\mathrm{sur}}(E_{\mathrm{c.m.}}, J),$$

where

$$\sigma_{\mathrm{CN}}(E_{\mathrm{c.m.}}) = \sum_{J=0}^{J_{\max}} \sigma_{\mathrm{capture}}(E_{\mathrm{c.m.}}, J) P_{\mathrm{CN}}(E_{\mathrm{c.m.}}, J),$$

- We need to know three spin-dependent quantities: (a) the capture cross section, (b) the fusion probability and (c) the survival probability, and their isospin dependence

Courtesy of W. Loveland, 2012

Capture cross sections:

- For the 50-150 "calibration" reactions, we know capture cross sections within 50%
- We know interaction barriers within 20%
- For the heavy element synthesis reactions, we know the capture cross sections within a factor of 2.
- The "coupled channels" calculations (such as Zagrebaev) do the best overall job of describing capture cross sections.

Courtesy of W. Loveland, 2012

CN cross sections

At ℓ_{crit} fission barrier damped to about 1/e of $\ell = 0$ height

With $\ell_{crit} = 15\hbar$: σ_{cap} about 10-100 mb.

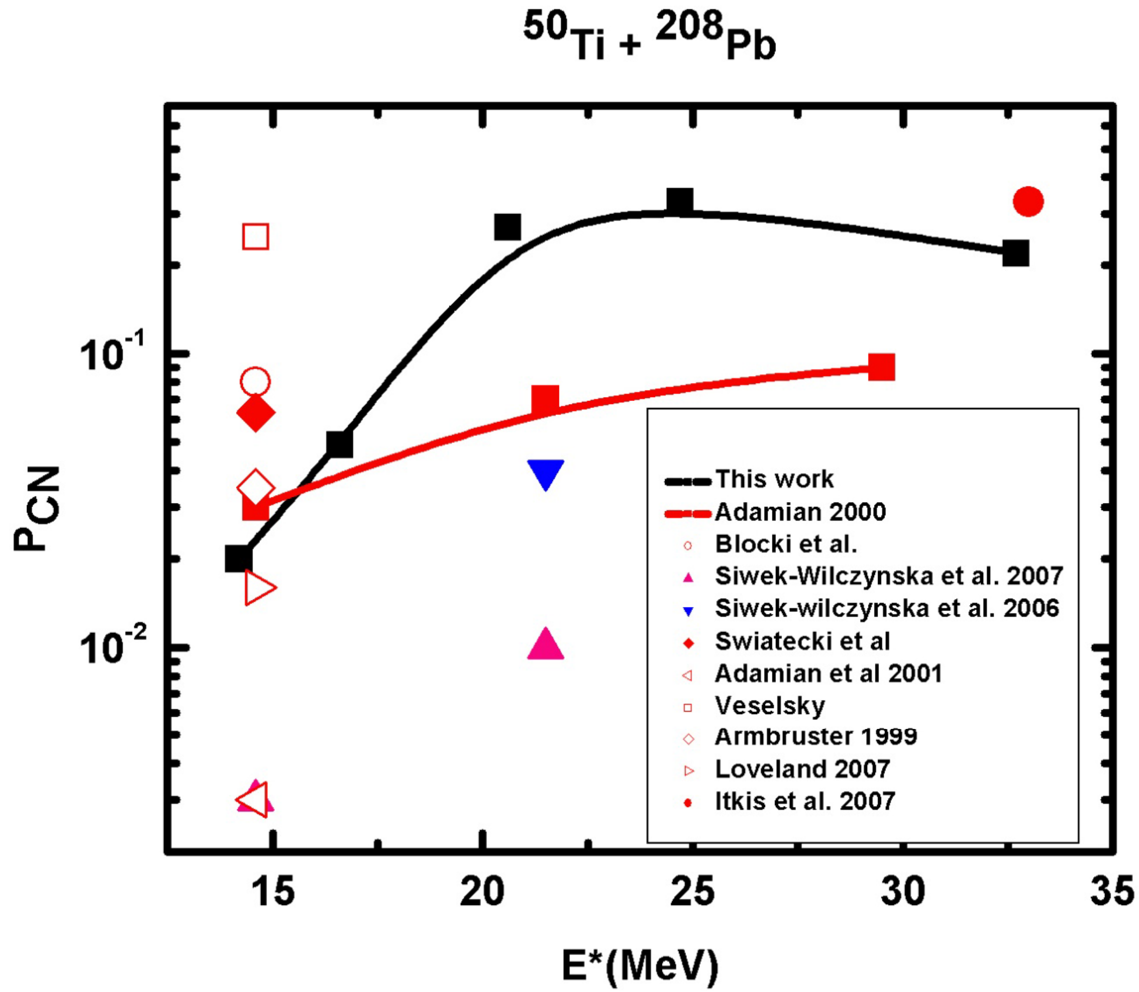
Cross section for Z=112: about 1 pb

$$\rightarrow p_{CN} \bullet W\left[\prod_{i=1}^{i_{max}}\left(\frac{\Gamma_n}{\Gamma_{tot}}\right)_i, E^*\right] \text{ist} \sim 10^{-10}$$

Physics of p_{CN} and of W largely different!
Experimentally, the measurement of the individual contributions is difficult. Only product is known pretty well.

→ Different theoretical models have drastically different values for p_{CN} and W, only the product of the two is identical (and thus allows for correct description of experimental cross sections)

P_{CN} results



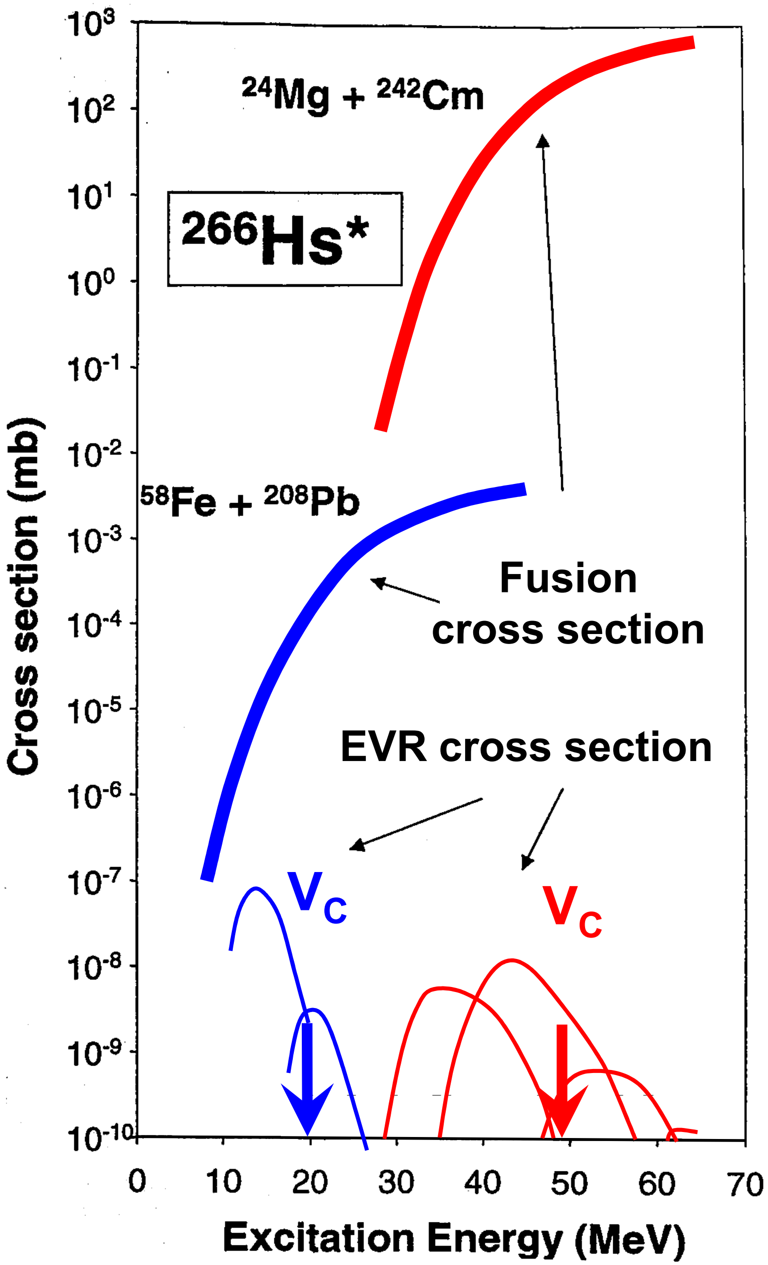
Courtesy of W. Loveland, 2012

How well can we calculate W_{sur}?

- We took a group (~75) heavy element synthesis reactions where $Z_1Z_2 < 1000$ (Z_{CN} =98-108) and compared the calculated and measured values of σ_{EVR}.
- The average ratio of (measured/calculated) cross sections was 6.5. We conclude that we know W_{sur} within a factor of 3.

Courtesy of W. Loveland, 2012

Production of heavy elements



Asymmetric reactions with actinide targets:

Small fusion hindrance

→ High fusion cross section

High excitation energy in CN

→ Hot fusion

→ Multiple neutron-evaporation steps

→ Big losses in exit channel

(More) symmetric reactions, Pb/Bi targets:

Considerable fusion hindrance

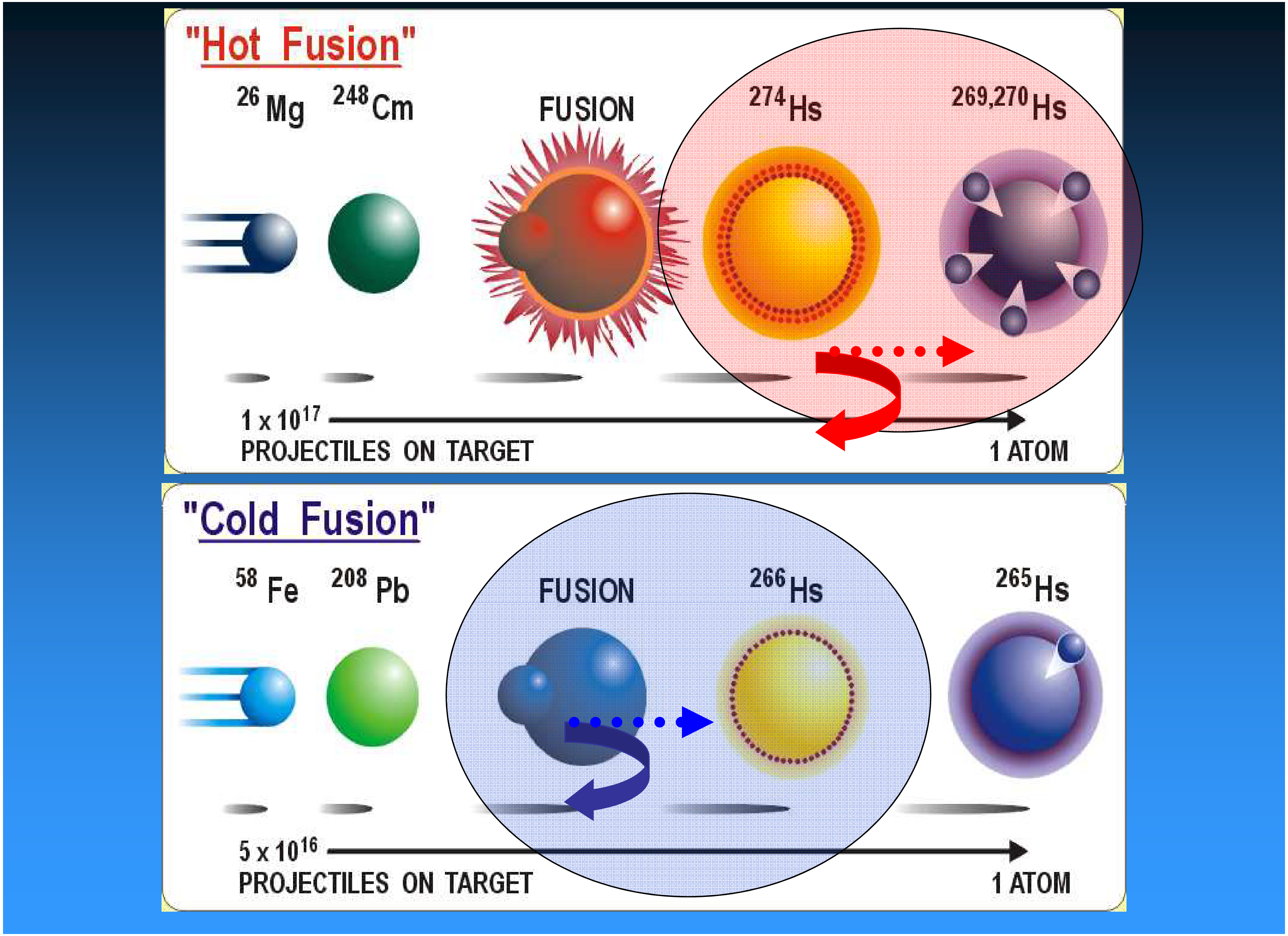
→ Small fusion cross section

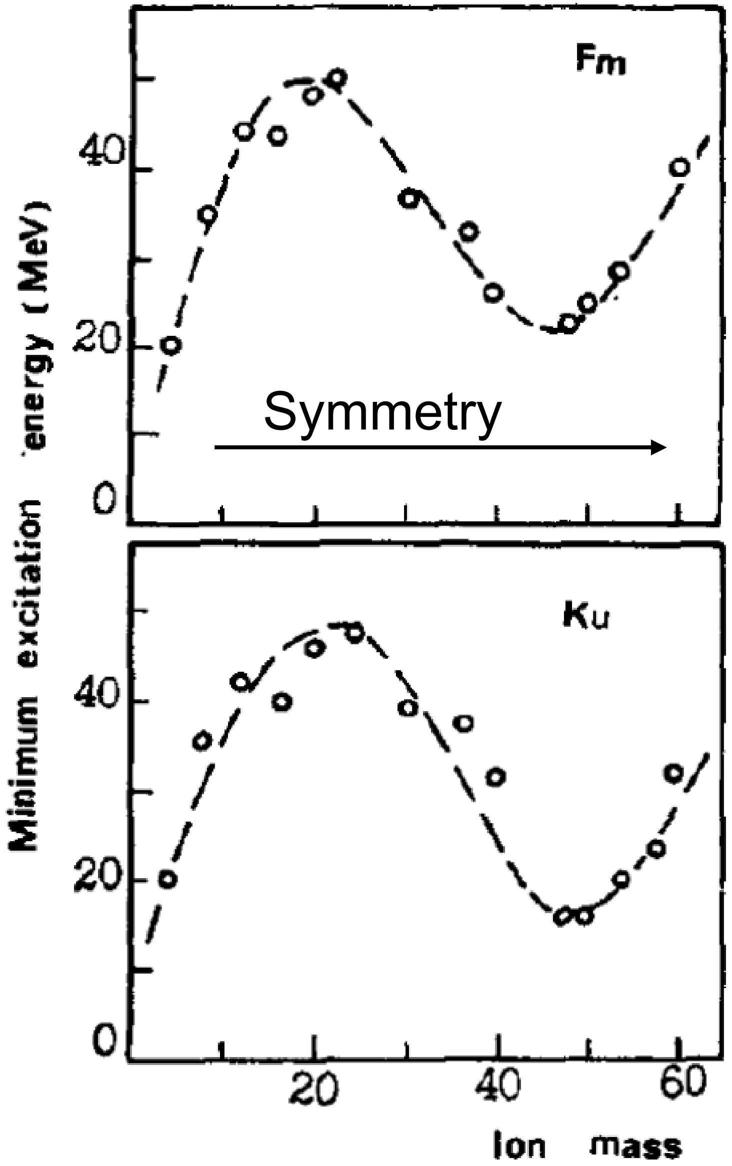
Low excitation energy in CN thanks to shell effects in the target

→ Cold fusion

→ Only ~1 neutron evaporation step

→ Small losses in exit channel


"Hot Fusion"
26 Mg
248 Cm
FUSION
274 Hs
269,270 Hs
1 x 10^17
PROJECTILES ON TARGET
1 ATOM
"Cold Fusion"
58 Fe
208 Pb
FUSION
266 Hs
265 Hs
5 x 10^16
PROJECTILES ON TARGET
1 ATOM



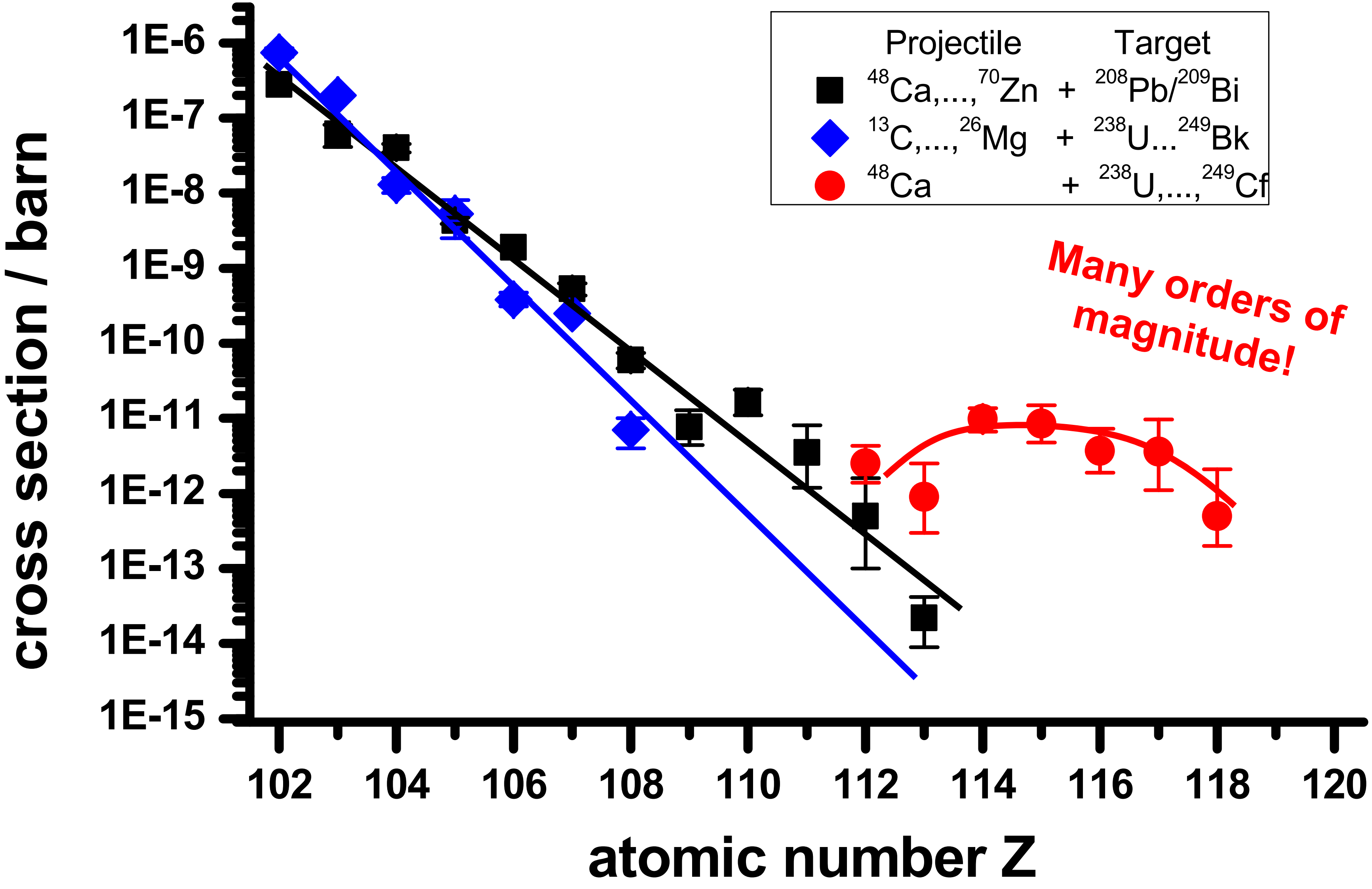
FLNR/GSI: Cold fusion

Shell effects around ^{208}Pb decrease excitation energy in CN
→ evaporation of fewer neutrons
→ loss in exit channel smaller
→ should enhance cross sections

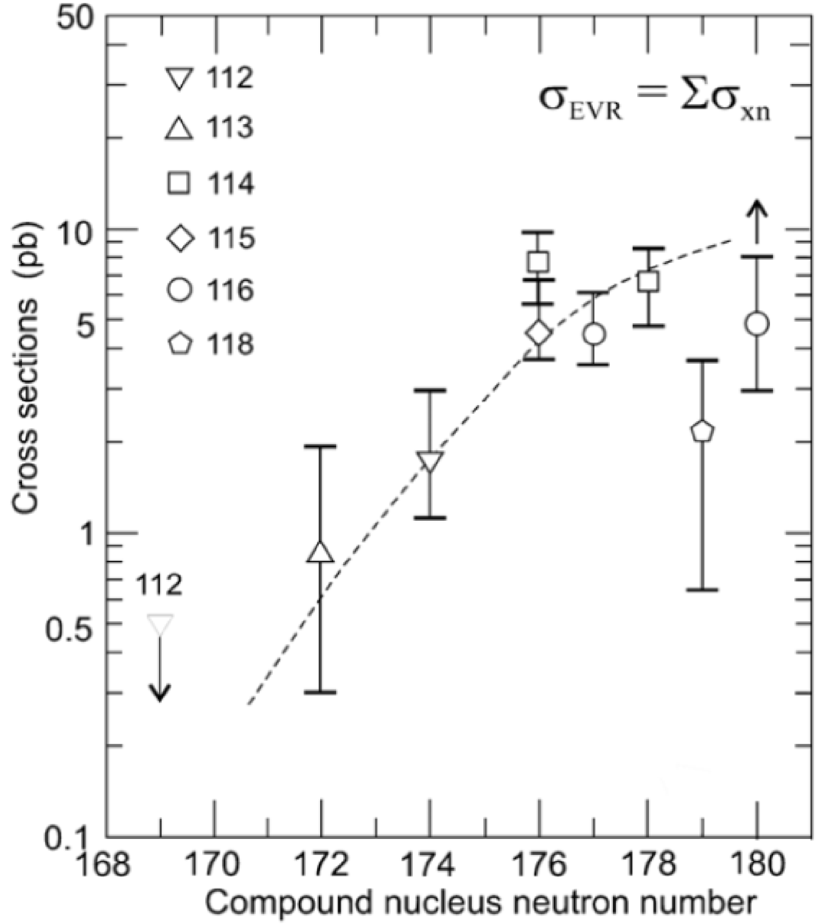
$^{207}Pb(^{40}Ar,3n)^{244}Fm$
$^{208}Pb(^{48}Ca,2n)^{254}No$
→ high cross sections measured at FLNR!

Fig. 5. Minimum excitation energy of the compound nuclei ^{248}Fm and ^{258}Ku formed in different target-projectile combinations. The dashed curves are drawn through the calculated E^*_{min} values shown by points.

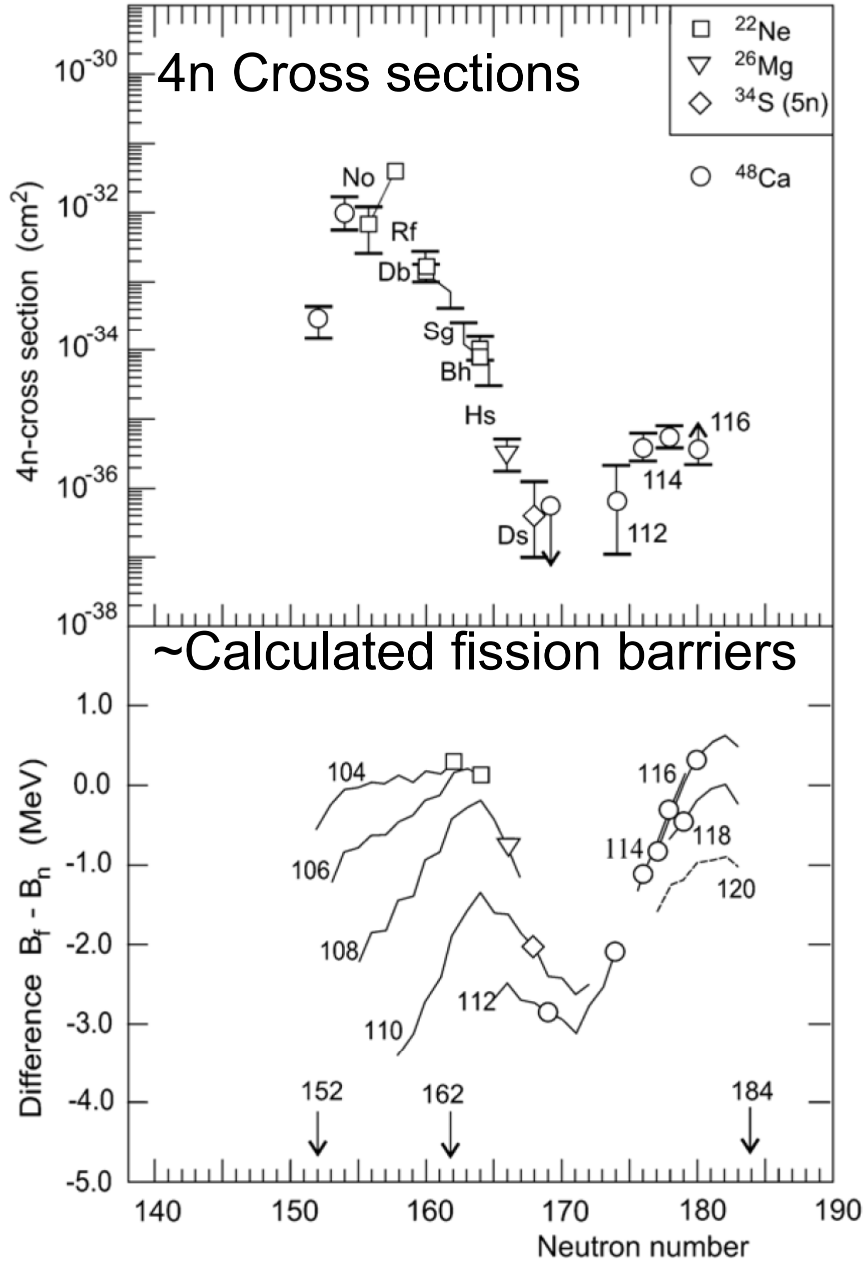
Cross Sections in Hot / Cold / ^{48}Ca Induced Fusion Reactions



Cross sections



Maximum 3n/4n cross sections
in ^{48}Ca-induced reactions



Yu.Ts. Oganessian, J. Phys. G 34 (2007) R165

"Influence" of the N=126-shell on σ

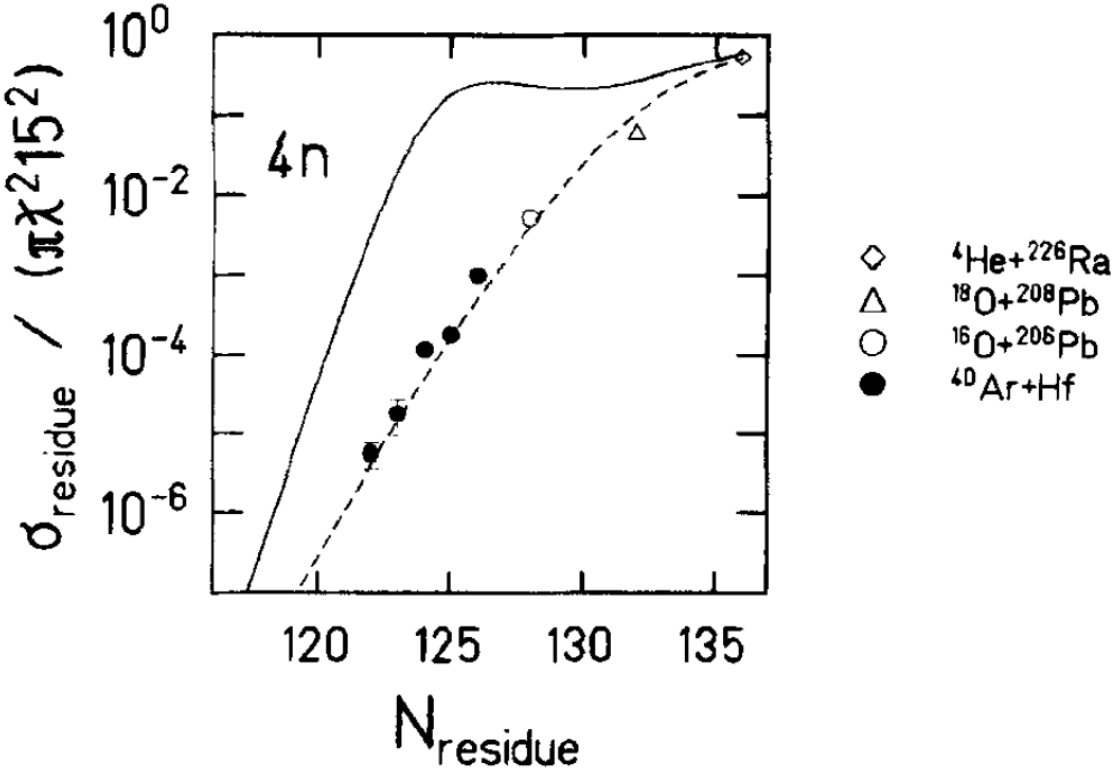


Fig. 6. Data points: Maxima of the $4n$ excitation-functions as a function of the neutron number for Th evaporation residues. The factor $1/(\pi \lambda^2 15^2)$ was applied in order to remove trivial entrance-channel effects for different target-projectile combinations and to make the ordinate scale approximately equal to the survival probability $\Pi(\Gamma_n/\Gamma_{tot})$ times the transmission coefficient of the fusion barrier for low angular momentum [9]. Lines: Calculated survival probability $\Pi(\Gamma_n/\Gamma_{tot})$ for zero angular momentum. Solid line: standard evaporation calculation. Dashed line: evaporation calculation without shell effects

Spherical nuclei do barely survive!

Γ_n/Γ_f worse by orders of magnitude compared to deformed nuclei!

Washing out of shell effects with increasing E*

→N=126 shell has basically no influence on σ

D. Vermeulen et al., Z. Phys. A 318 (1984) 157

A scenario by P. Armbruster

Eur. Phys. J. A **37**, 159–167 (2008)
DOI 10.1140/epja/i2008-10607-5

THE EUROPEAN
PHYSICAL JOURNAL A

Regular Article – Experim

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P. Armbruster[a]

GSI Darmstadt, Planckstr. 1,

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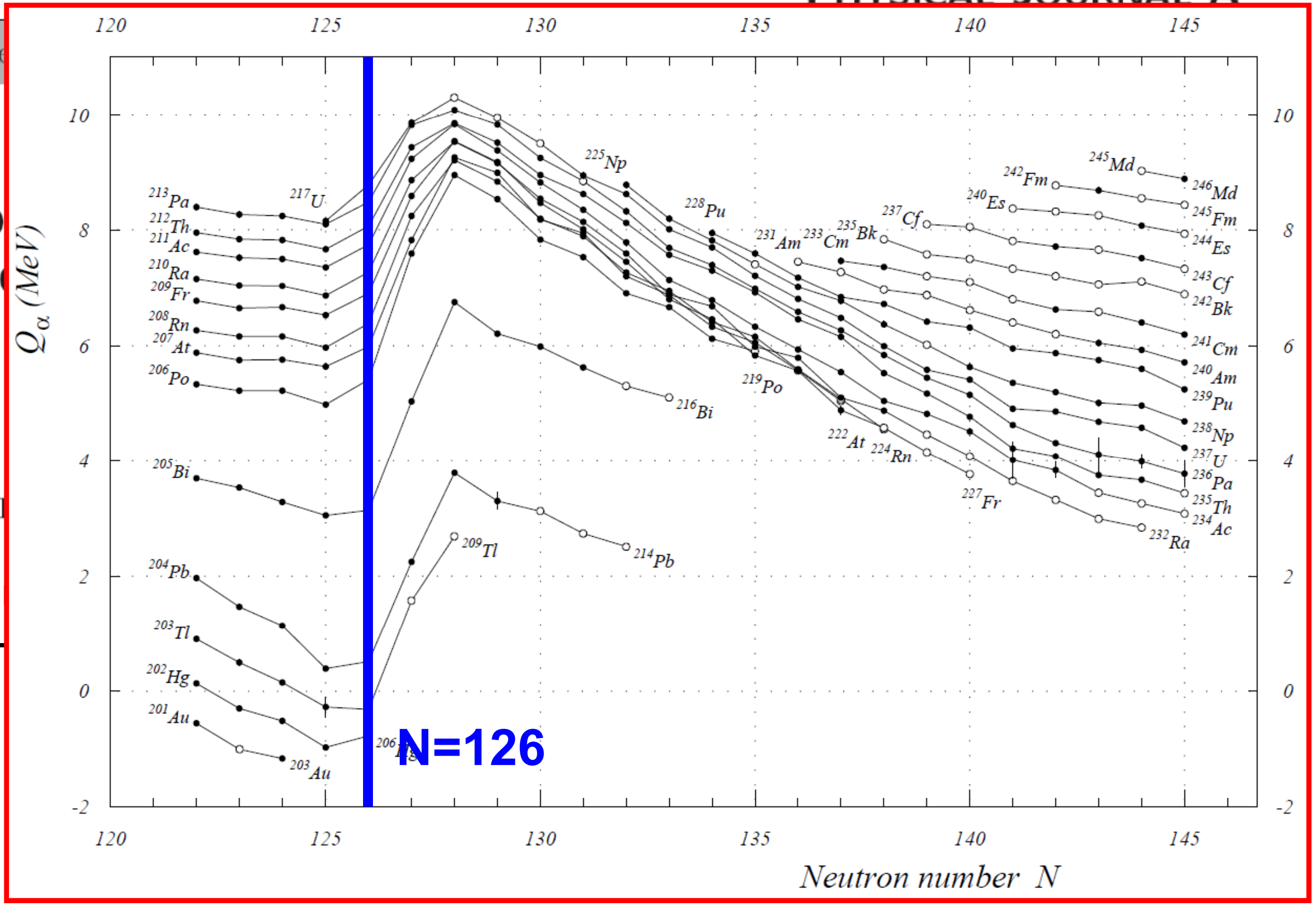

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THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Shifting the closed proton shell to Z = 122 —A possible scenario to understand the production of superheavy elements Z = 112–118

P. Armbruster[a]

GSI Darmstadt, Planckstr. 1, D-64291 Darmstadt, Germany

-Analysis of Q_α values: Z=114 not magic!

-Periodicities in chart of nuclei: next magic Z ~ 122
→ ALL so far found SHE are NOT spherical, but oblately DEFORMED

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Eur. Phys. J. A **37**, 159–167
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Regular Article – Experi

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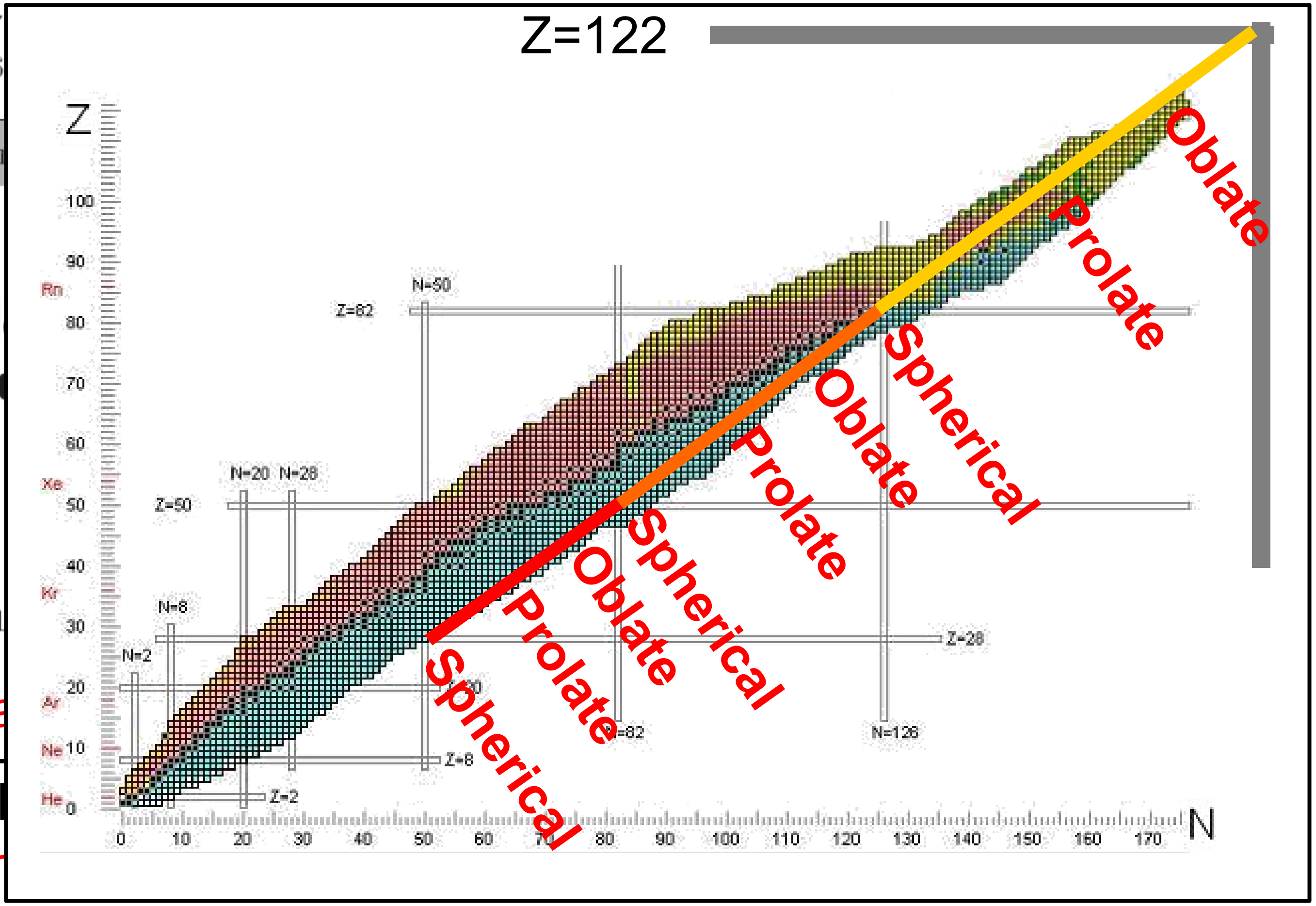

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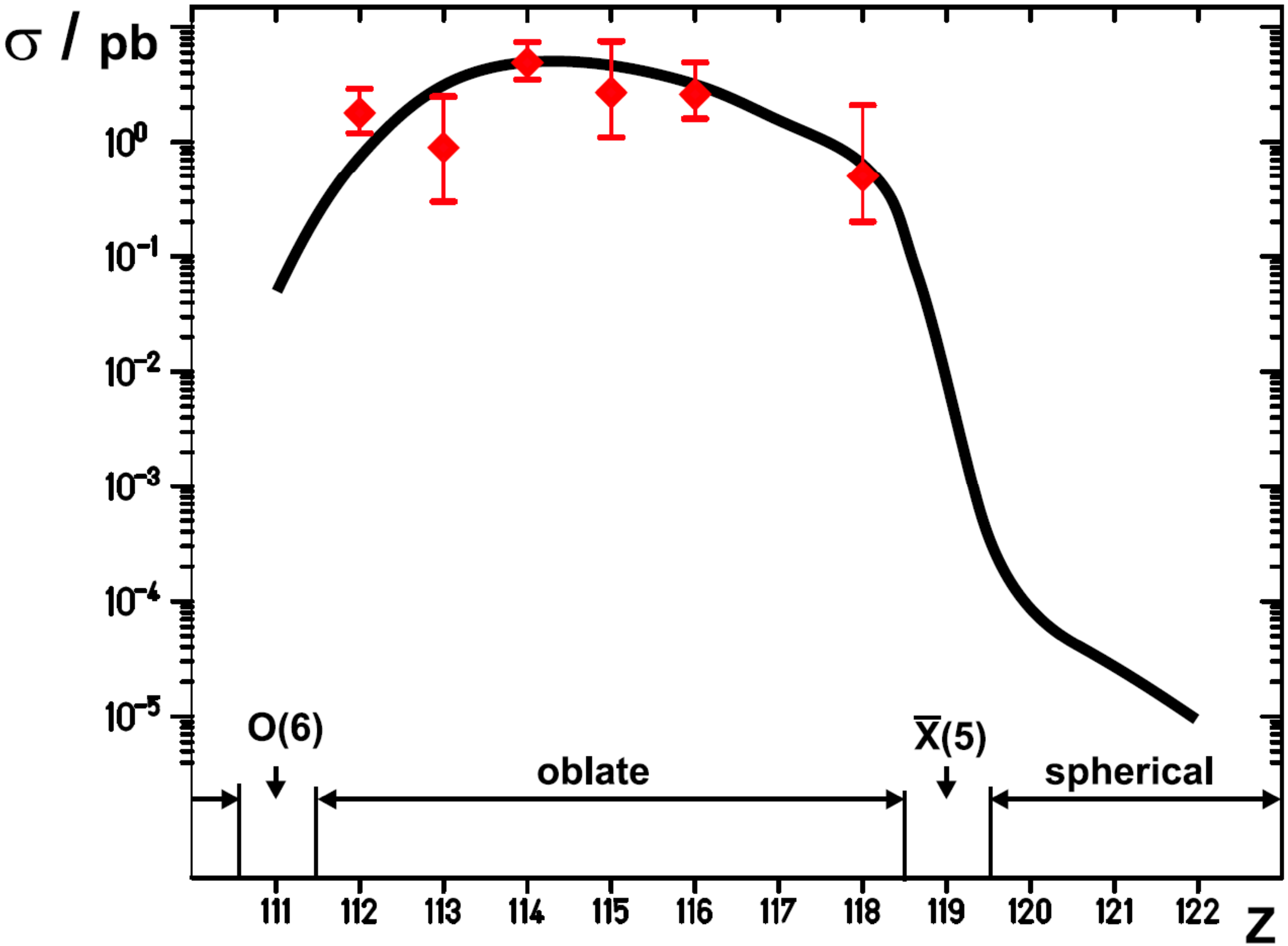
-Analysis of Q_α values: Z=114 not magic!

-Periodicities in chart of nuclei: next magic Z ~ 122
→ ALL so far found SHE are NOT spherical, but oblately DEFORMED

-Fission of oblate nuclei over prolate saddle point hindered → Γ_n/Γ_f favorable!
High cross sections due to strong effects in EXIT channel

(But: there are models with magic Z=114 @ N=184, where Z=114 is not magic at smaller N, in the region of nuclei accessible in ^{48}Ca+actinides)

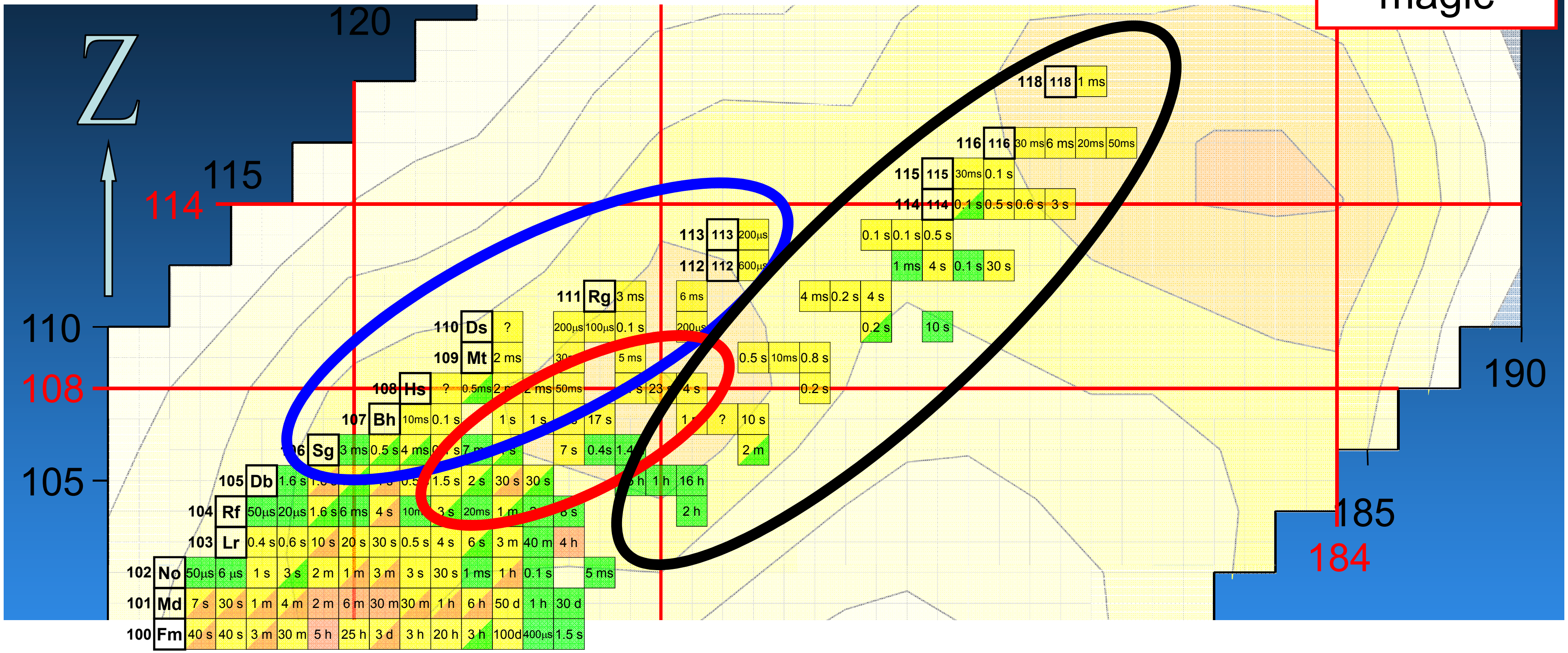
Armbruster's model: theory vs. experiment



P. Armbruster, Eur. Phys. J. A 37 (2008) 159

Landing points of heavy ion induced fusion reactions

Model w/ Z=114 magic



Pb/Bi targets; cold fusion (E*~10-15 MeV), n-poor isotopes

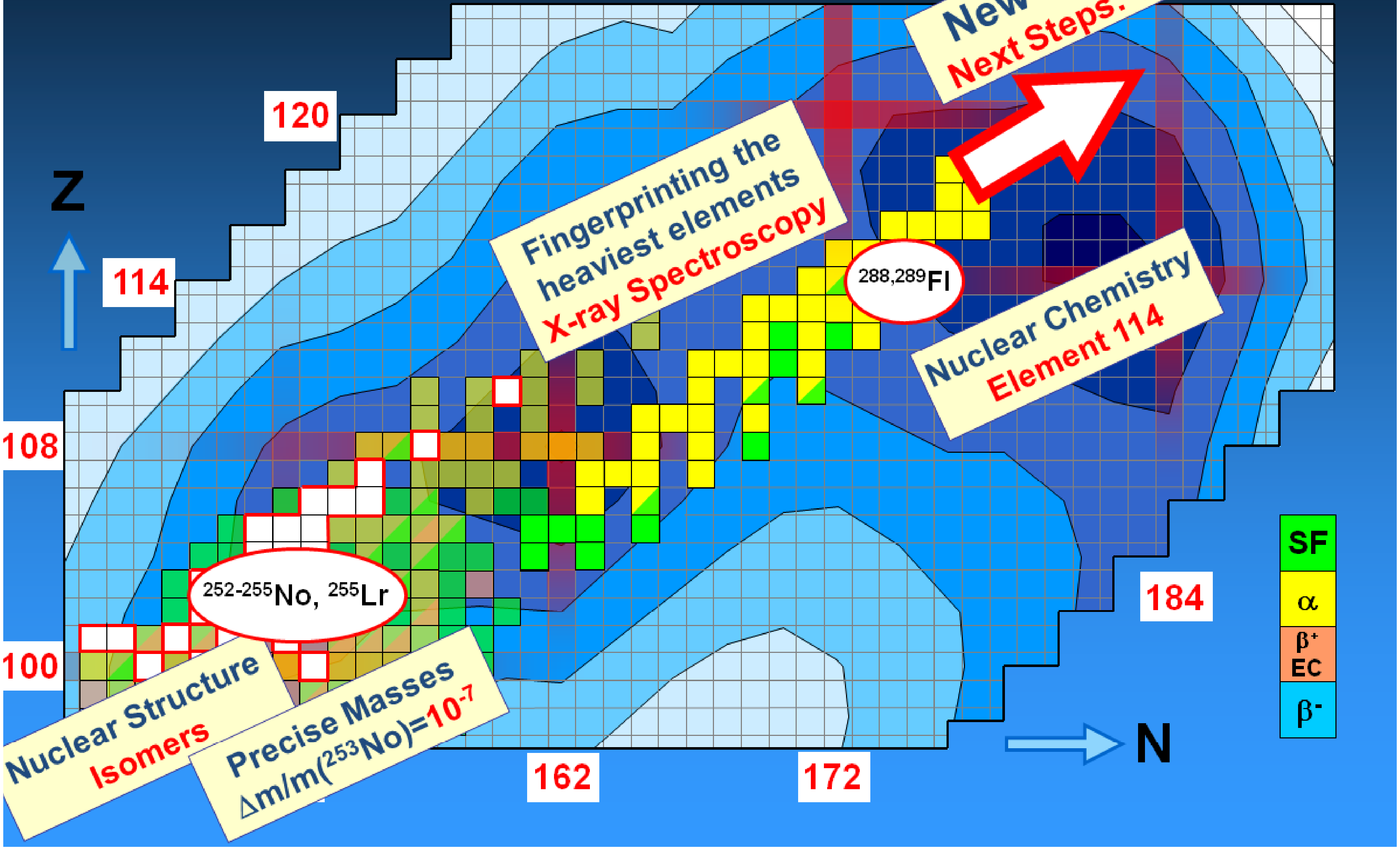
Light projectiles (^{12}C~^{30}Si)+actinide targets; hot fusion (E*~50 MeV), n-rich isotopes up to ~Z=108

^{48}Ca beam + actinide targets; warm/hot fusion (E*~30-50 MeV), n-rich isotopes

Search for new elements

Again: it's all about the cross section...

Superheavy Elements
– The hottest topics at GSI



Making elements 119 and 120

E119

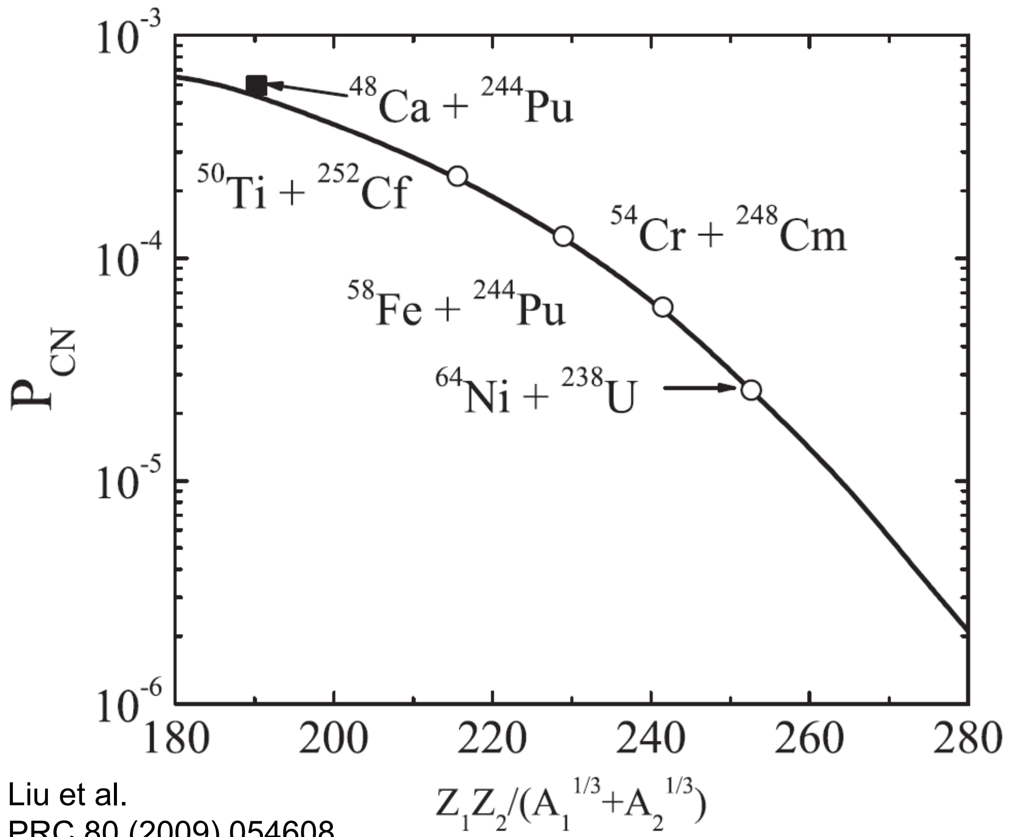
Z_{Beam}	Beam	Target	Asymmetry	$E^*@B_{Bass}$
21	^{45}Sc	^{249}Cf		41.7
22	^{50}Ti	^{249}Bk		32.4
23	^{51}V	^{248}Cm		36.8
24	^{54}Cr	^{243}Am		31.5
25	^{55}Mn	^{244}Pu		37.7
26	^{58}Fe	^{237}Np		29.9
27	^{59}Co	^{238}U		36.7

E120

Z_{Beam}	Beam	Target	Asymmetry	$E^*@B_{Bass}$
22	^{50}Ti	^{249}Cf		31.7
23	^{51}V	^{249}Bk		35.9
24	^{54}Cr	^{248}Cm		33.0
25	^{55}Mn	^{243}Am		34.5
26	^{58}Fe	^{244}Pu		33.9
27	^{59}Co	^{237}Np		32.9
28	^{64}Ni	^{238}U		27.3

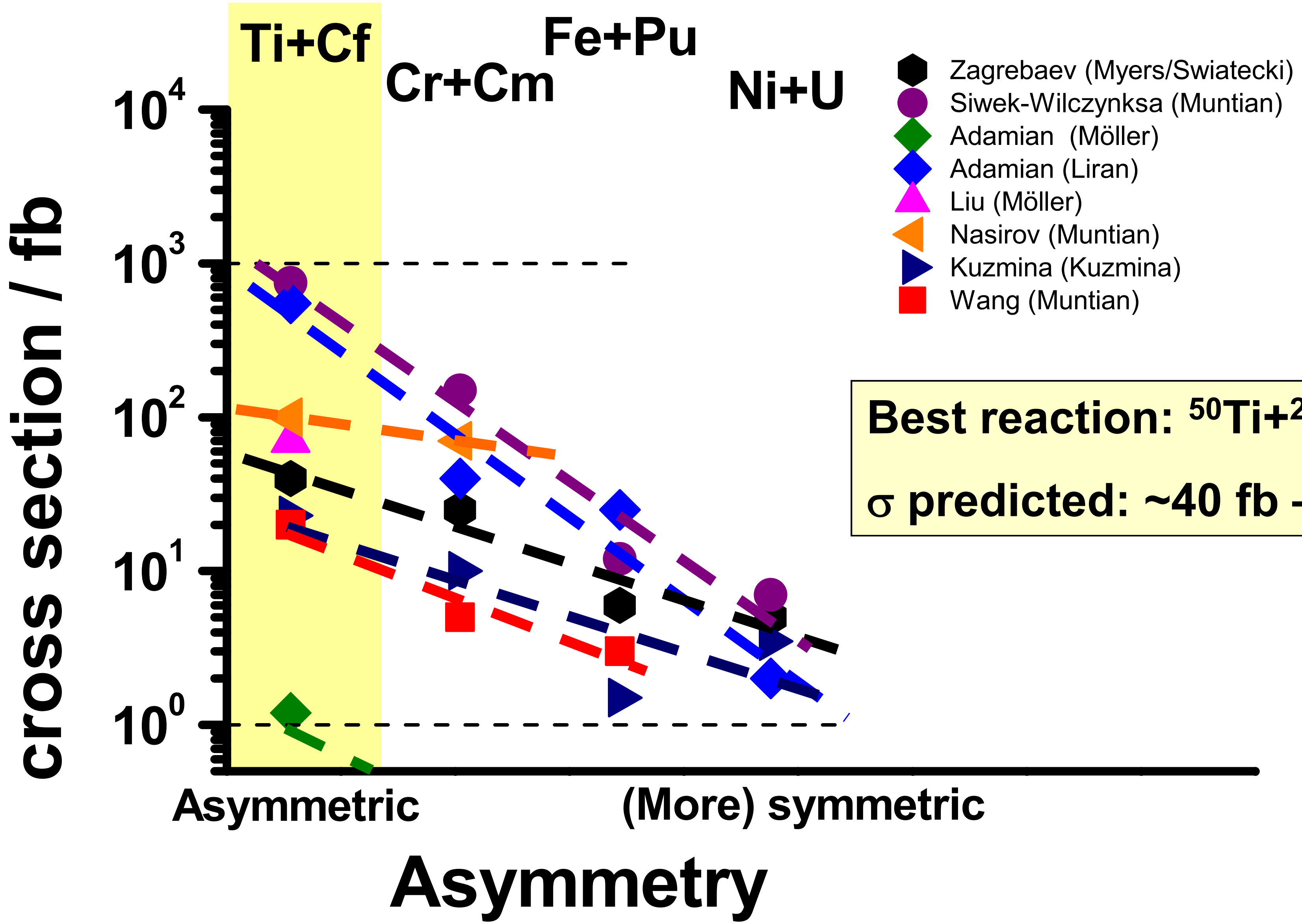
Cross Sections for Production of Element 120

$^{50}Ti + ^{249}Cf \Rightarrow ^{299}120$
$^{54}Cr + ^{248}Cm \Rightarrow ^{302}120$
$^{58}Fe + ^{244}Pu \Rightarrow ^{302}120$
$^{64}Ni + ^{238}U \Rightarrow ^{302}120$



Liu et al.
PRC 80 (2009) 054608

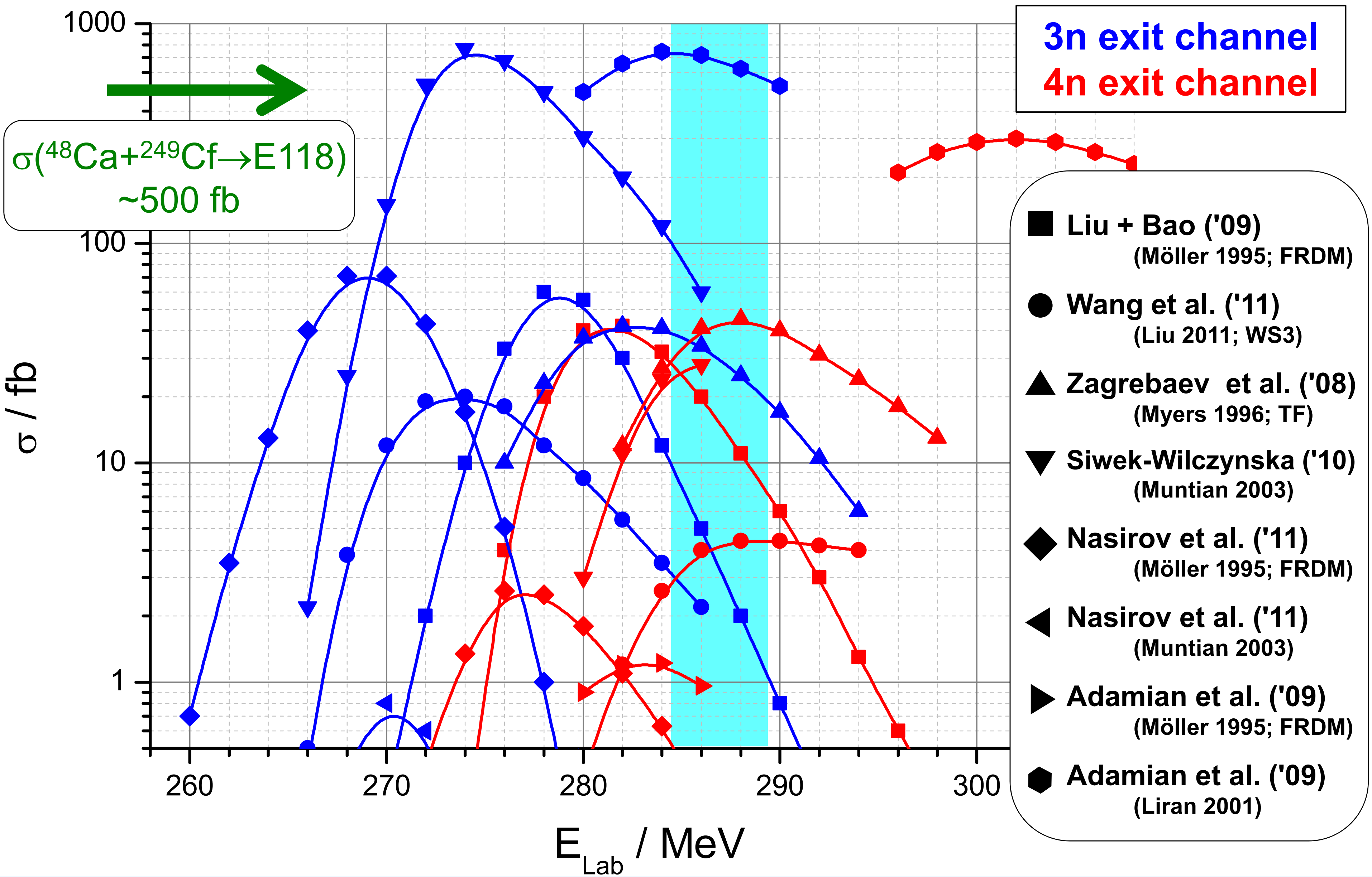
Cross sections: current predictions from theory



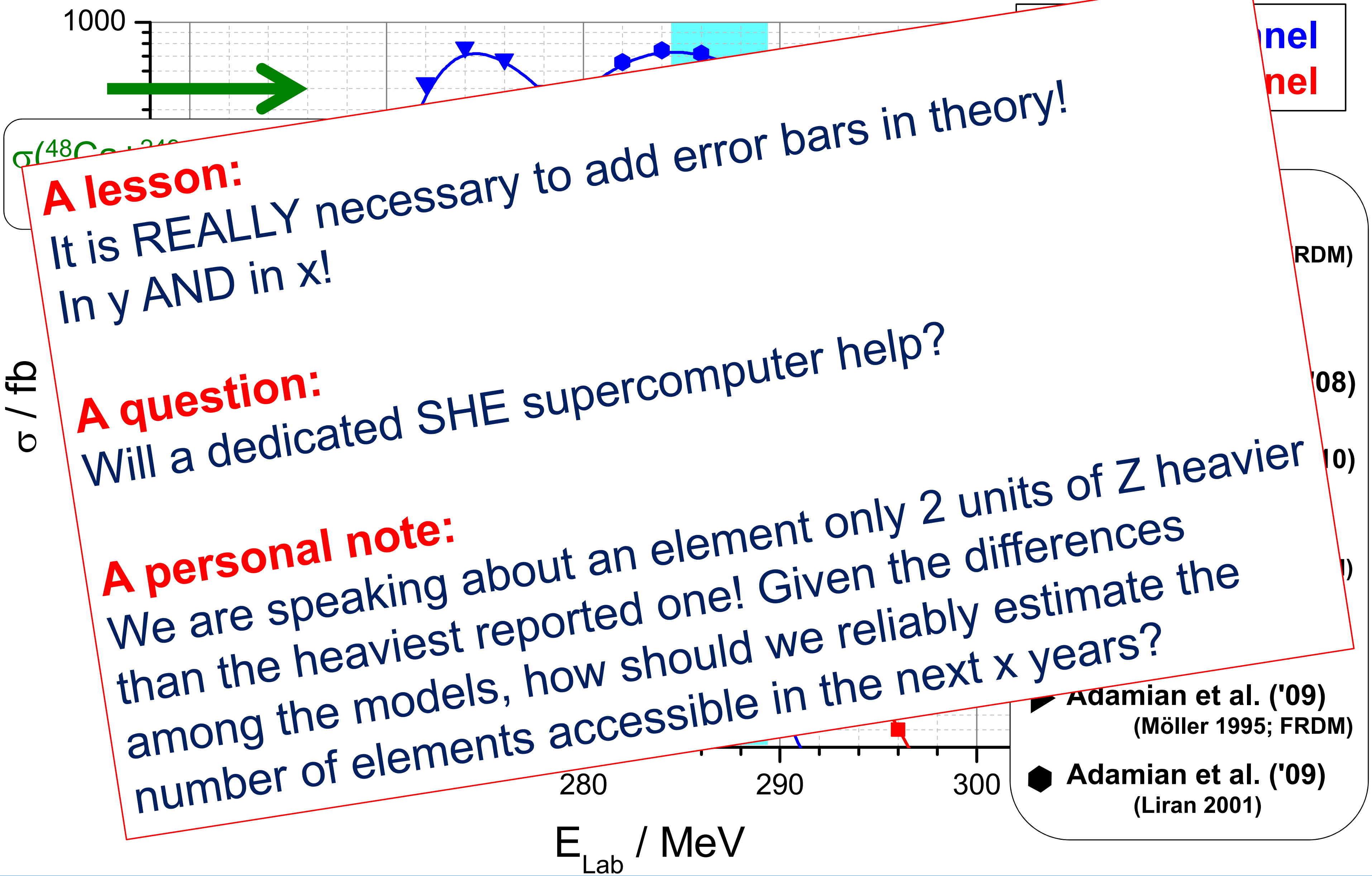
Best reaction: $^{50}Ti+^{249}Cf$

σ predicted: ~40 fb – 1 pb

$^{50}Ti + ^{249}Cf$ Excitation Function



$^{50}Ti+^{249}Cf$ Excitation Function



A lesson:
It is REALLY necessary to add error bars in theory!
In y AND in x!

A question:
Will a dedicated SHE supercomputer help?

A personal note:
We are speaking about an element only 2 units of Z heavier than the heaviest reported one! Given the differences among the models, how should we reliably estimate the number of elements accessible in the next x years?

NEWSFOCUS

Science 9 September 2011 | $10

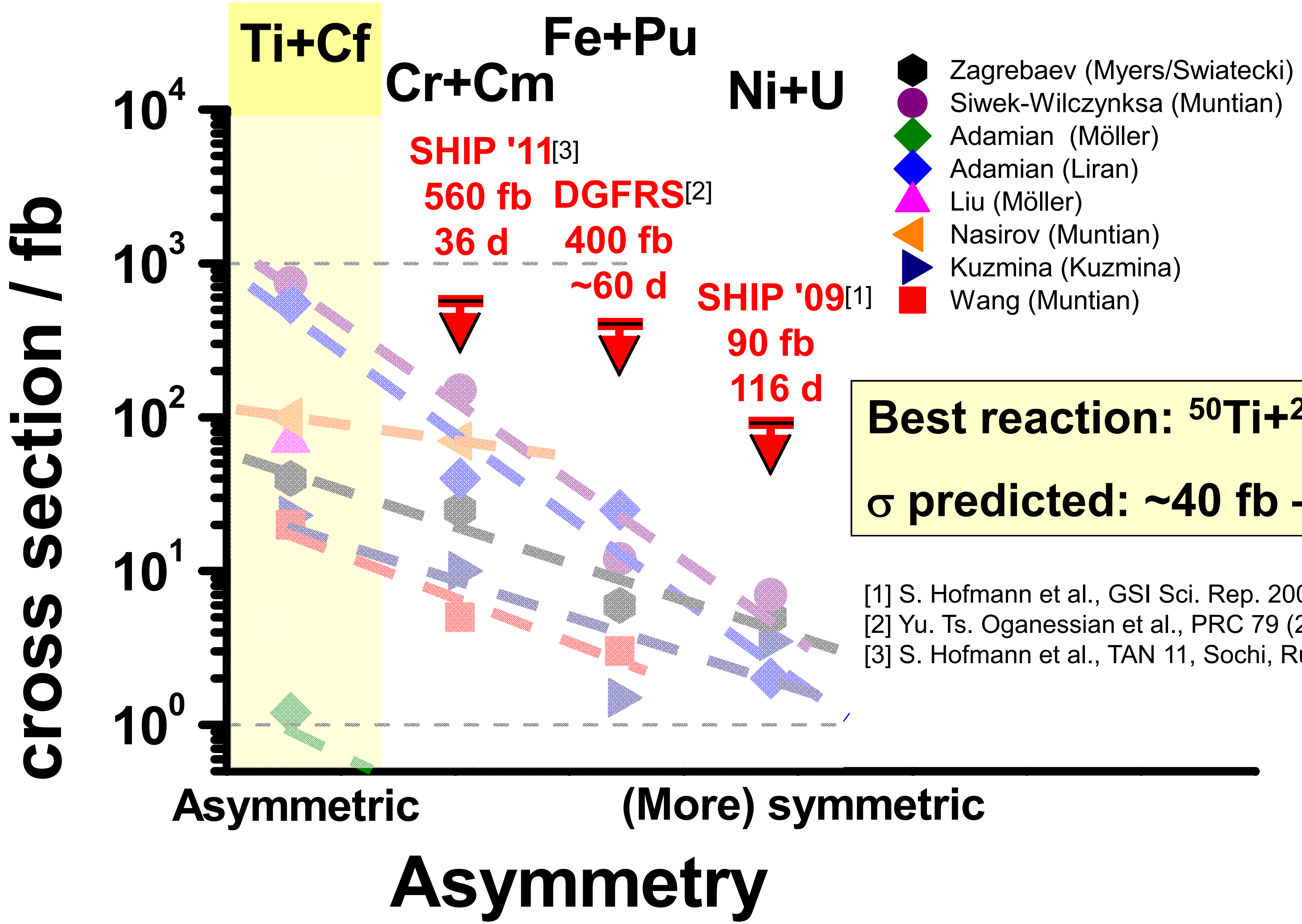
SUPERHEAVY ELEMENTS

Which Way to the Isla

Last month at the Helmholtz Centre for
Ion Research (GSI) in Darmstadt, Gern
team of physicists and chemists from
the globe began firing an intense be
titanium ions at a thin foil made of c
nium. They will continue to bombard
and night, until October.…

Science 333 (

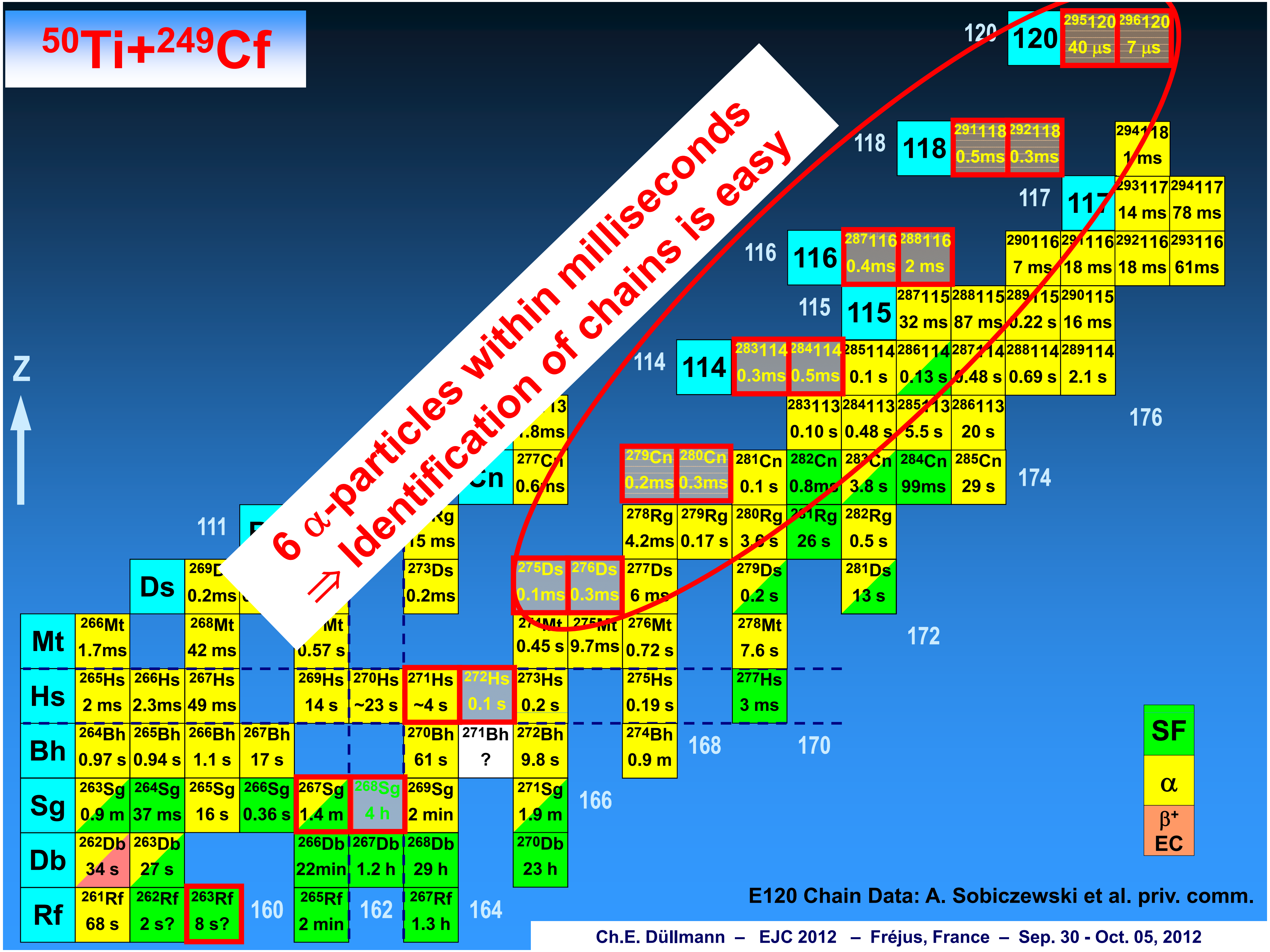
The Hunt for Element 120



Best reaction: $^{50}Ti+^{249}Cf$

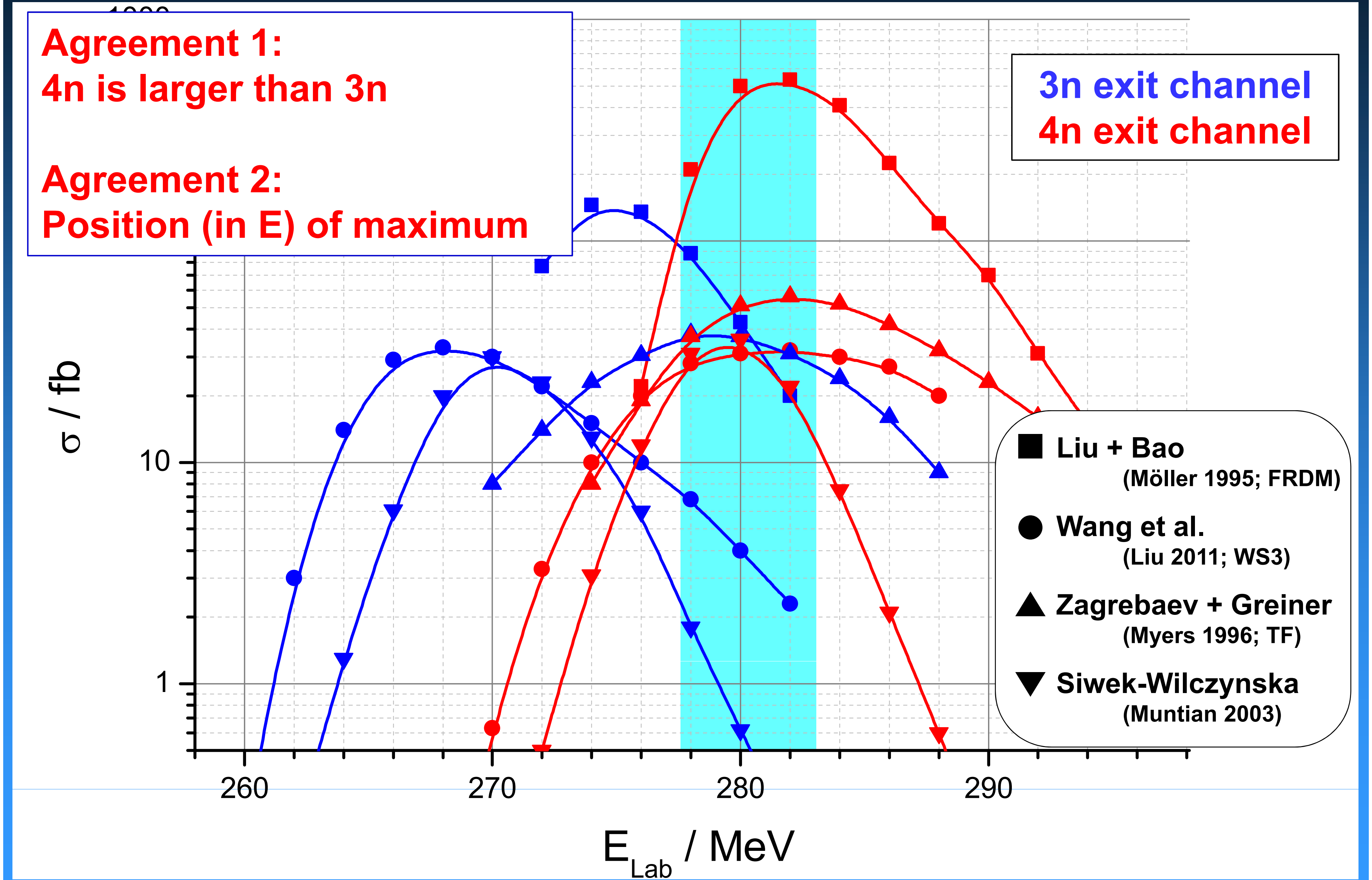
σ predicted: ~40 fb – 1 pb

[1] S. Hofmann et al., GSI Sci. Rep. 2008, p. 131
[2] Yu. Ts. Oganessian et al., PRC 79 (2009) 024603
[3] S. Hofmann et al., TAN 11, Sochi, Russia

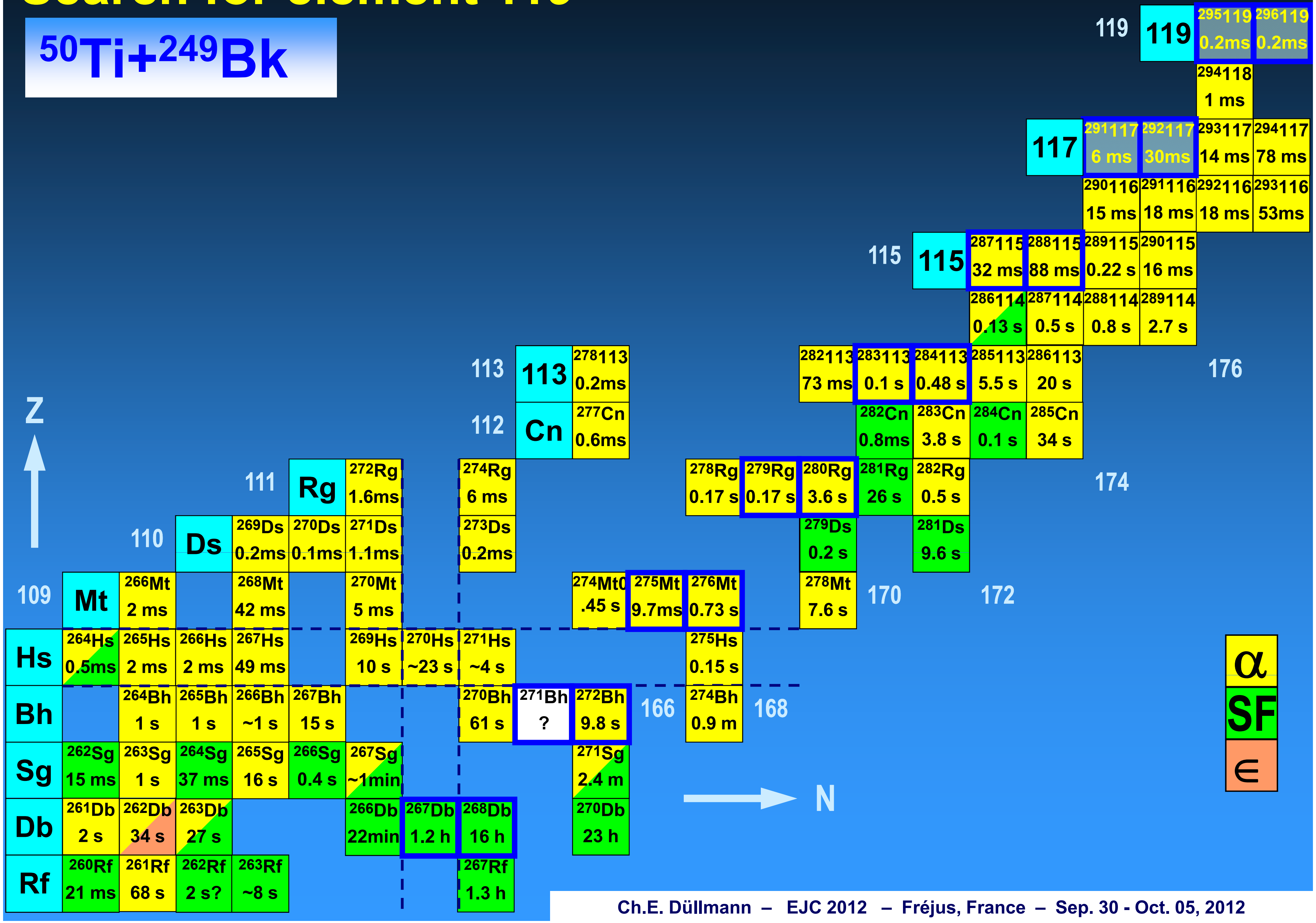


$^{50}Ti+^{249}Cf$
6 α-particles within milliseconds
⇒ Identification of chains is easy
Z
120
118
117
116
115
114
Ds
Mt
Hs
Bh
Sg
Db
Rf
SF
α
β+ EC
E120 Chain Data: A. Sobiczewski et al. priv. comm.

2012: $^{50}Ti+^{249}Bk$



Search for element 119

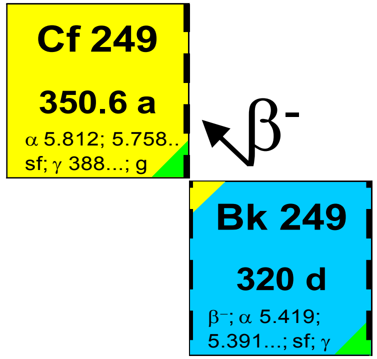


TASCA High Power Target Wheel used for E119 at GSI

Ø Target Wheel: 100 mm
Ø Beam Spot: 8 mm

Target wheel with Gd tested up to 2500 particle·nA

Wheel system: E. Jäger, T. Torres, J. Krier



March 6:
^{249}Bk arrives in Mainz

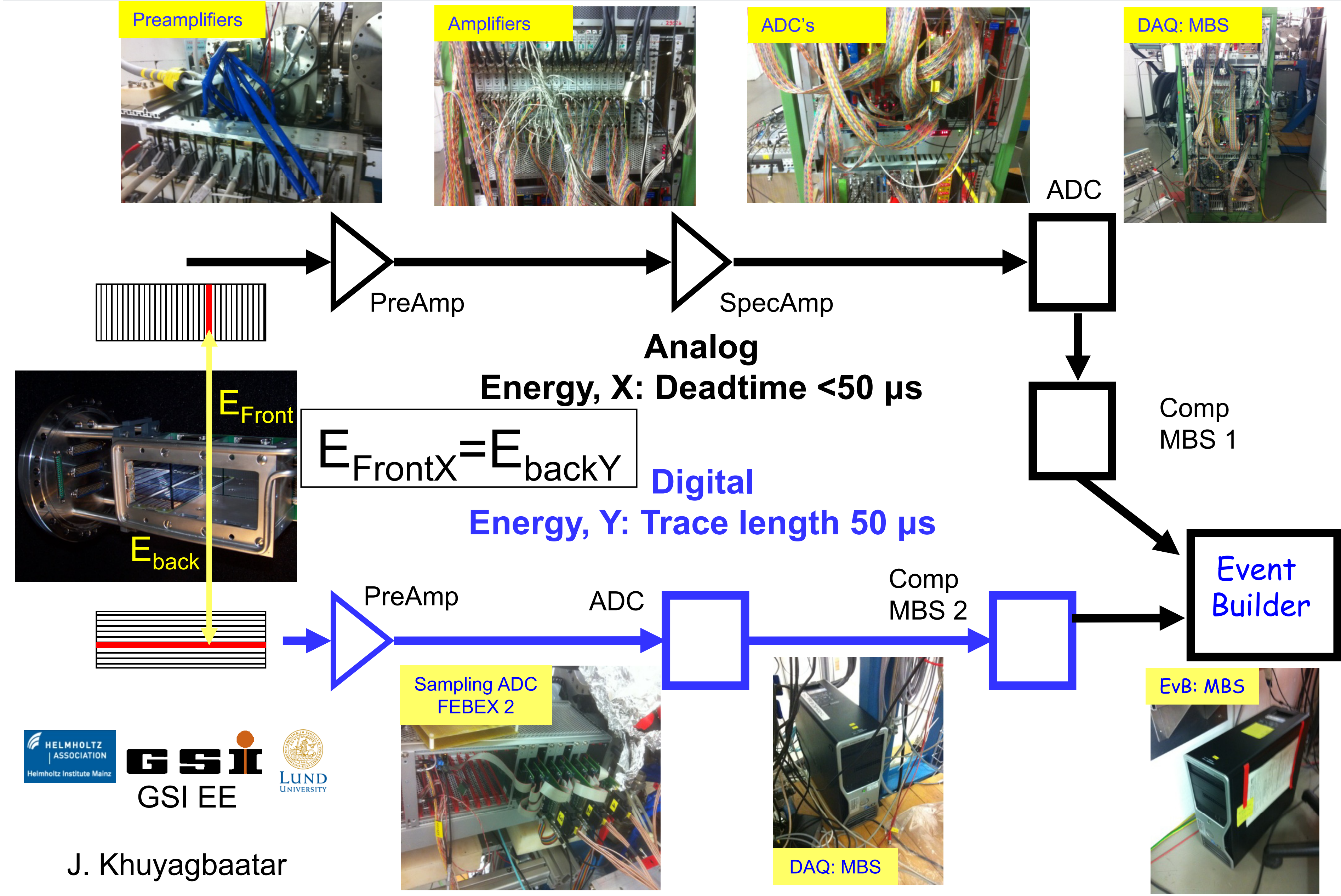
March 23:
Targets arrive at GSI

April 12:
Targets mounted in TASCA

April 14:
Begin Element 119 search

....still going on

A new ANalog/DIgital (ANDI) DAQ system for μs-isotopes



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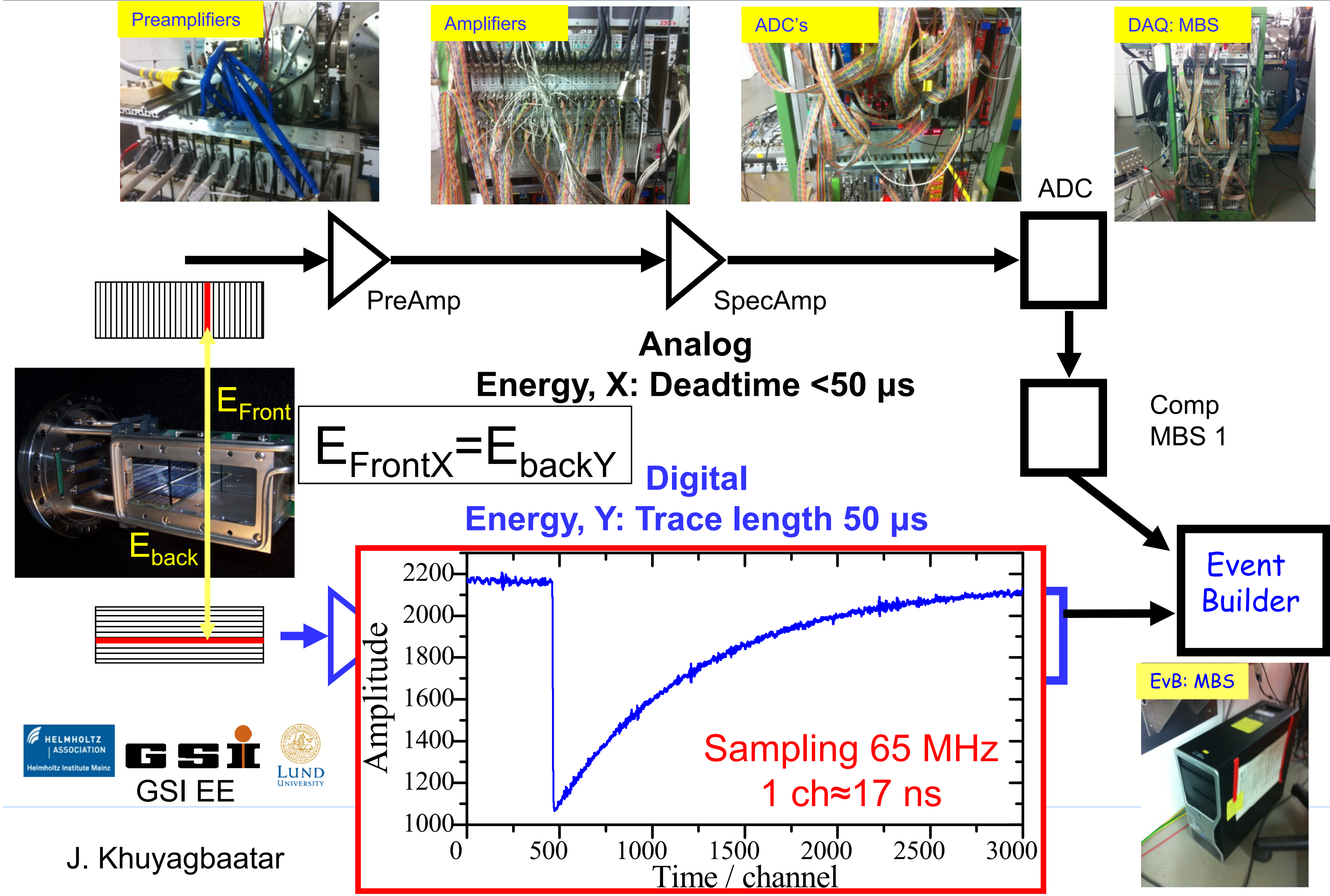
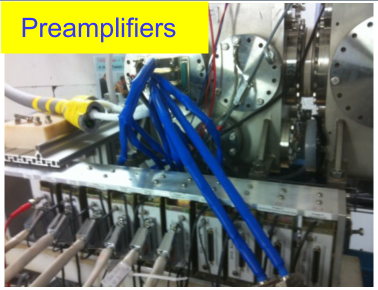
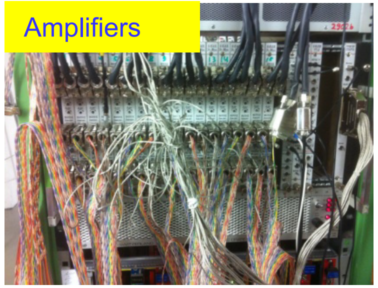
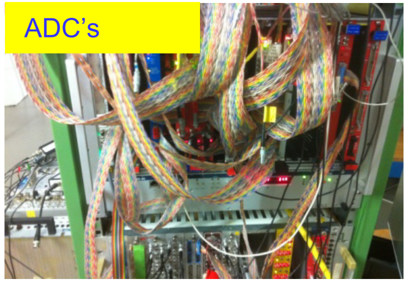


J. Khuyagbaatar

A new ANalog/DIgital (ANDI) DAQ system for μs-isotopes



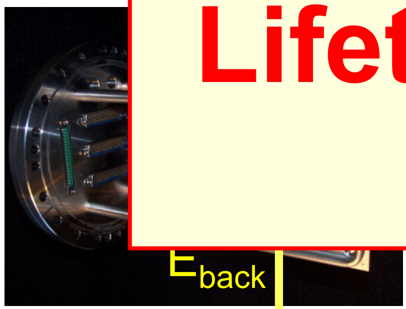


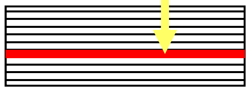


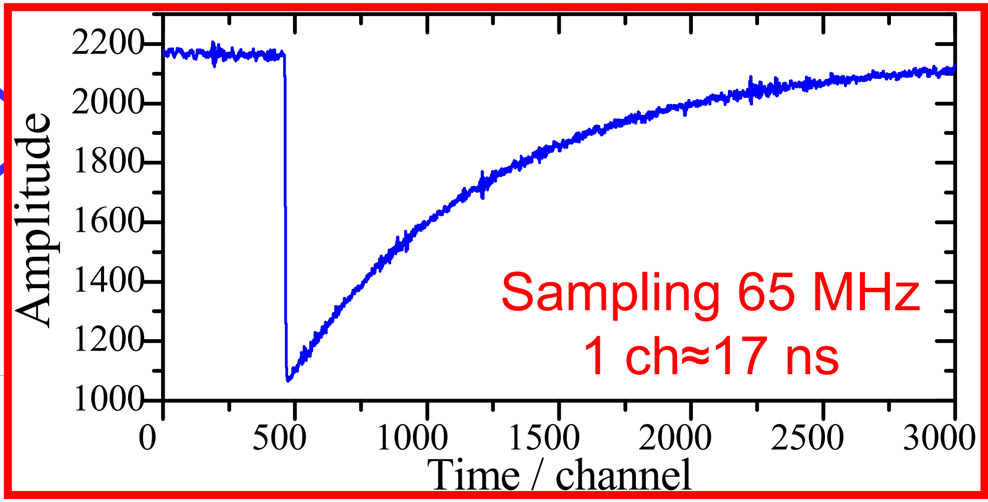
ADC

Dead-time free!

Lifetimes down to about 100 ns can be measured







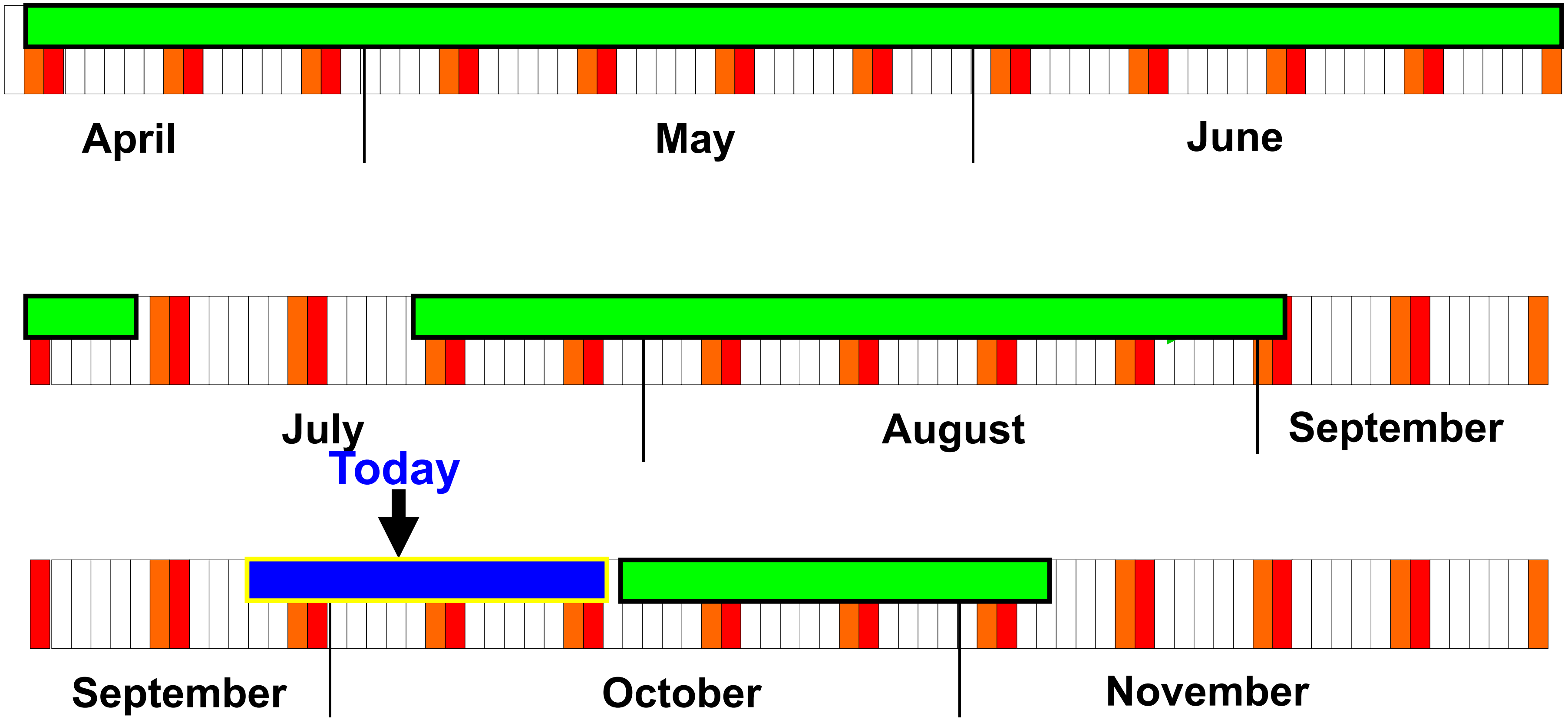
Event Builder

GSI EE

J. Khuyagbaatar

Current status of experiment

^{50}Ti beam 750 nA$_p$ and ^{249}Bk targets with initial thickness ≈0.44 mg/cm^2.



^{48}Ca+^{249}Bk⇒Element 117

^{50}Ti+^{249}Bk⇒Element 119

Conclusion

Superheavy elements are a cool research topic!

Elements up to 112 + 114 + 116 named.

All elements up to 118 claimed

Rich field:

- **-Synthesis**
- **-Structure**
- **-Decay properties**
- **-Mass measurements**
- **-Chemical properties**

GSI 2012: Element 119 search (^{50}Ti + ^{249}Bk) at *TASCA*

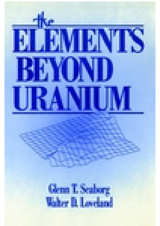
Superheavy elements are a really cool research topic!

You are a great student class!

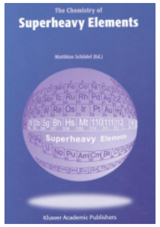
Thanks for listening AND discussing!

Literature: Recommended Books

Text books:

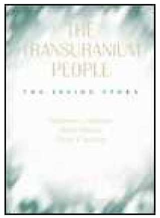


- G.T. Seaborg + W.D. Loveland
  The elements beyond uranium
  Wiley, New York, 1990
  ISBN 0-471-89062-6



- M. Schädel (Ed.)
  The Chemistry of Superheavy Elements
  Kluwer, Dordrecht, 2003
  ISBN 1-4020-1250-0

Historical reminiscies of three giants in SHE :



- D.C. Hoffman, A. Ghiorso, G.T. Seaborg
  The Transuranium People: The Inside Story
  Imperial College Press, London, 2000; ISBN 1-86094-087-0

Literature: Overview Articles

Discovery of the actinide elements (G.T. Seaborg, Radiochim. Acta 71/71 (1995) 69

Superheavy elements at GSI (Ch.E. Düllmann, Radiochim. Acta 100 (2012) 67)
(current overview article about GSI superheavy element research)

Radiochimica Acta **Special Issue "Heavy Elements"** on occasion of the "International Year of Chemistry: Volume 99 / Issue 7-8, 2011:
http://www.oldenbourg-link.com/toc/ract/99/7-8

(All articles available in open access, no subscription needed!)

Includes:

1) **Production and properties of transuranium elements** (Y. Nagame and M. Hirata)

2) **Theoretical description of superheavy nuclei** (A. Sobiczewski)

3) **Synthesis of superheavy elements by cold fusion** (S. Hofmann)

4) **Synthesis of the heaviest elements in ^{48}Ca-induced reactions** (Yu.Ts. Oganessian)

5) **Spectroscopy of actinide and transactinide nuclei** (R.-D. Herzberg and D. M. Cox)

6) **Superheavy element studies with preseparated isotopes** (Ch.E. Düllmann)

..and some further articles