Overview of the synthesis of the heaviest elements

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Cold and Hot Fusion

- Cold Fusion
- Pb or Bi Target
- Heavier Projectile (Ca-Kr)
- E* ~ 13 MeV (1n reaction, high survival)
- Significant fusion hindrance

- Hot (Warm) Fusion
- Actinide Target
- Lighter Projectiles (O-Ca)
- E* ~ 30 – 60 MeV (low survival)
- Small fusion hindrance

Criteria for the discovery of an element

- Harvey et al. Science 193, 1271 (1976)
- New Z, (chemistry, X-rays, genetic decay to known elements)
- Not good--SF, reaction systematics

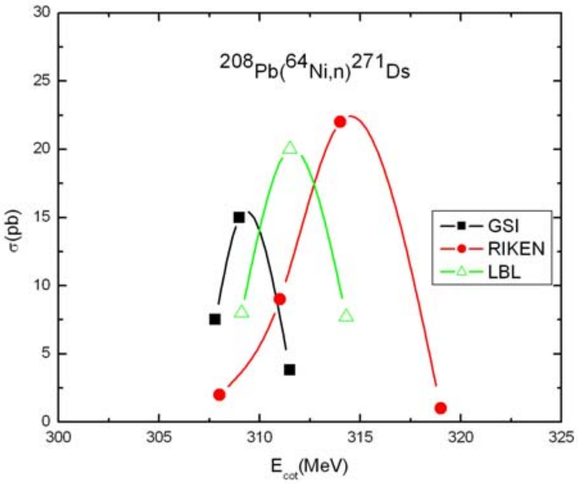
- Barber et al., Prog. Part. Nucl. Phys. 23, 454 (1992)
- Not clear cut, use combination of properties
- New Z
- Reproducibility
- Allows use of reaction systematics

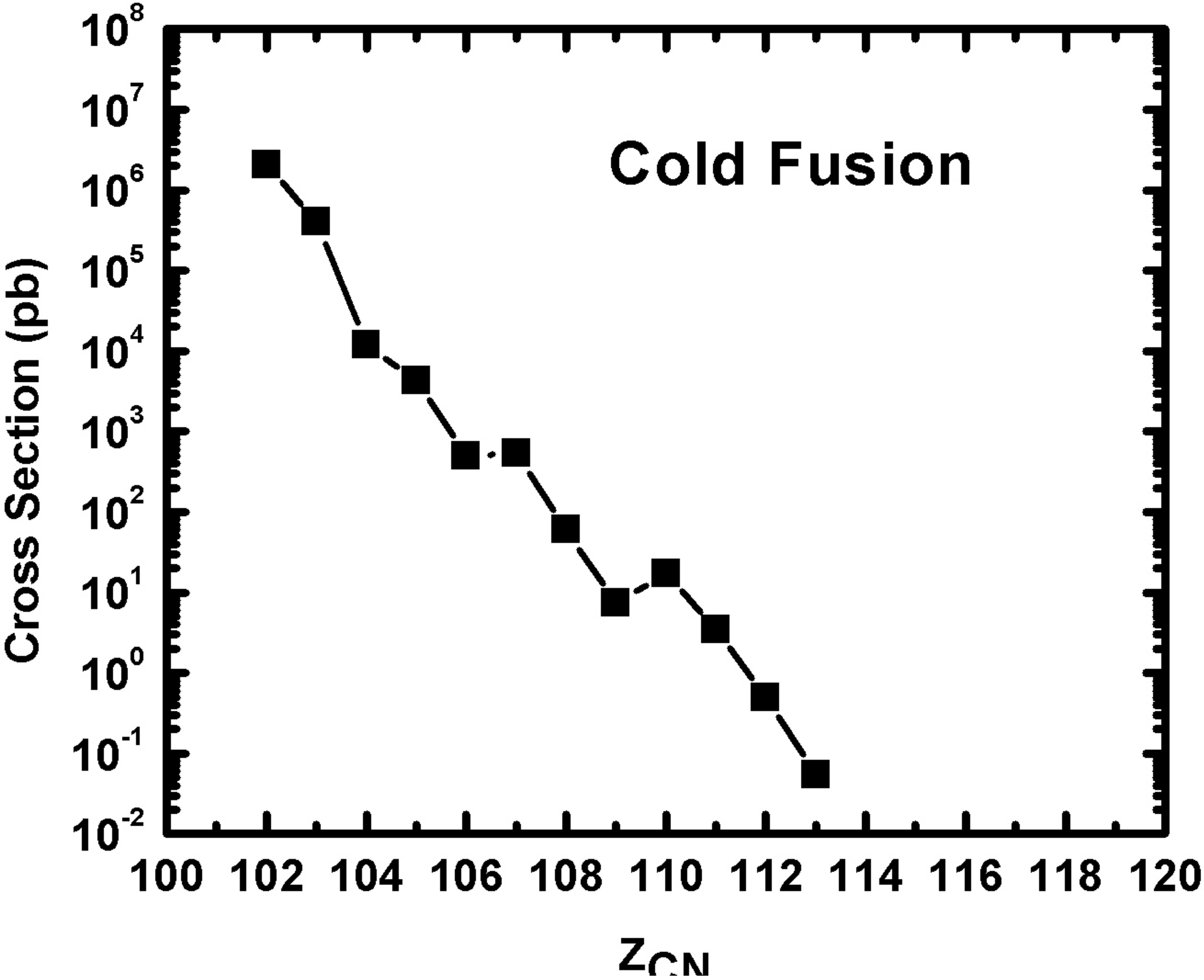
Cold Fusion

Z	*Reaction*	*E*(MeV)*	*# of Event*	*Cross section (pb)*	*Discovery?*
107(Bh)	**^{54}Cr+^{209}Bi**	**18**	**38**	**163±34**	**Yes**
108(Hs)	**^{58}Fe+^{208}Pb**	**13**	**30**	**60**	**Yes**
109(Mt)	**^{58}Fe+^{209}Bi**	**14**	**14**	**7.4±2.7**	**Yes**
110(Ds)	**^{64}Ni+^{208}Pb**	**12**	**19**	**13**	**Yes**
111(Rg)	**^{64}Ni+^{209}Bi**	**13**	**6**	**2.9±1.6**	**Yes**
112	**^{70}Zn+^{208}Pb**	**10**	**4**	**0.5**	**Yes**
113	**^{70}Zn+^{209}Bi**	**16**	**2**	**0.055**	**Z(Y), Repro(N)**

Cold Fusion--Comments

- Event 2--110 and Event 1--112 “spuriously created”
- Accelerator energies not well known




Cold Fusion
Cross Section (pb)
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
100
102
104
106
108
110
112
114
116
118
120
Z_{CN}

Hot fusion

Z	Reaction	E*(MeV)	# of Event	Cross Section (pb)	Discovery?
106(Sg)	$^{18}O+^{249}Cf$	43	82	300	Yes
107(Bh)	$^{22}Ne+^{249}Bk$	43	6	77	No
108(Hs)	$^{26}Mg+^{248}Cm$	49	5	6	No
110(Ds)	$^{48}Ca+^{232}Th$			3-5	No
112	$^{48}Ca+^{238}U$	35	18	2.5	No
113	Decay of 115		3		?*
114	$^{48}Ca+^{242}Pu$	35	38	4.5	?*
115	$^{48}Ca+^{243}Am$	40	3	3.7	?*
116	$^{48}Ca+^{245}Cm$	39	4	3.5	?*
118	$^{48}Ca+^{249}Cf$			2	No

Hot fusion--Comments

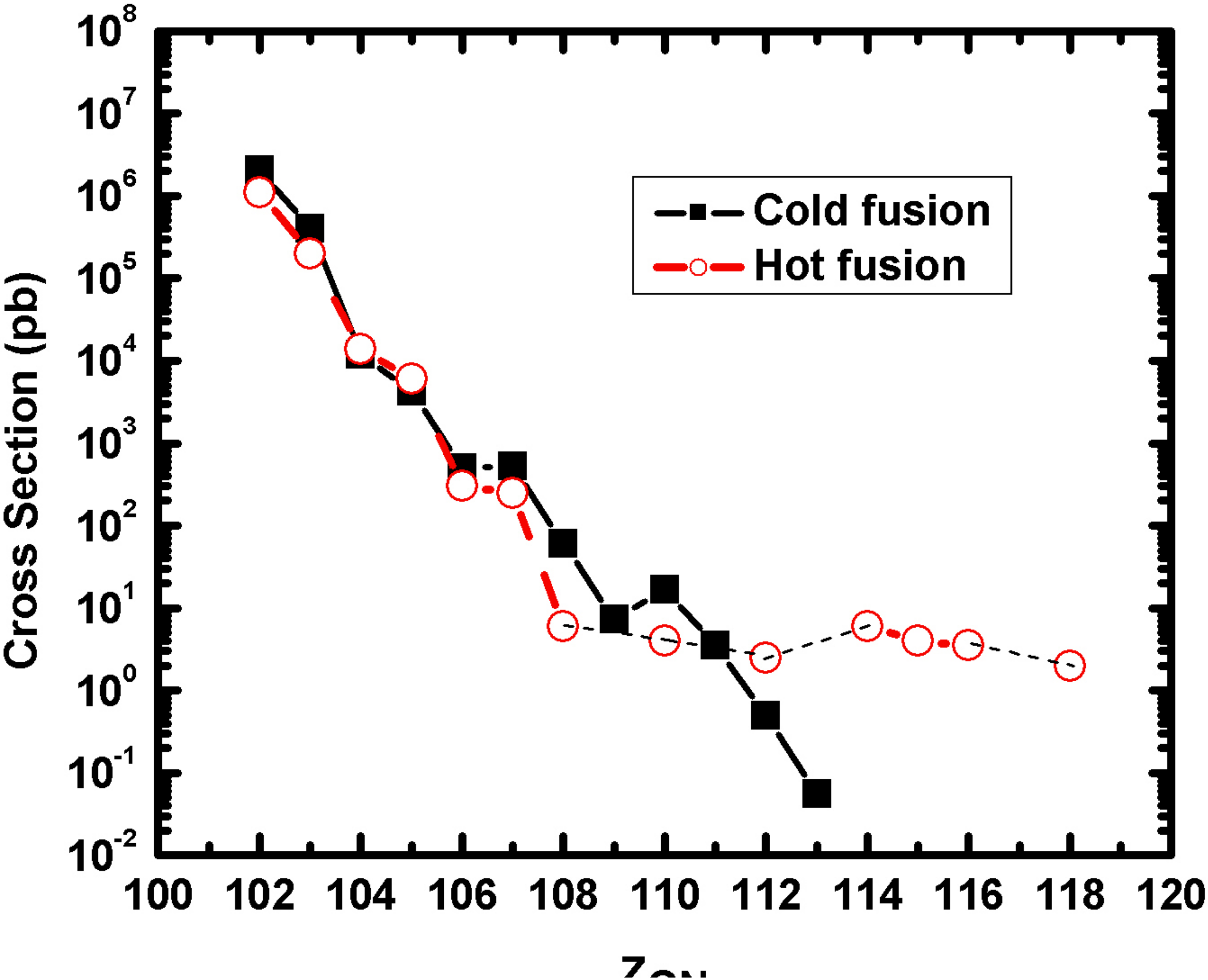
- All decay chains for the ^{48}Ca induced reactions end in SF and there is not genetic link to known nuclei.
- Z is inferred from reaction systematics
- Numerous groups (LBNL, GSI, PSI) have tried to reproduce the ^{238}U(^{48}Ca,3n)^{283}112 observations and have not been able to do so.

Establishing Z from Chemistry

- In the reaction $^{243}Am(^{48}Ca,3n)$ the decay chains terminated in a 16 h SF emitter assigned to ^{268}Db. Radiochemical separations were performed on irradiated targets to isolate group 4 and 5 elements, like Db. 15 atoms of SF activity were found in the group 4-5 fraction.

The most recent development

- In a study by the PSI group (Gaggeler, Eichler, et al.) working at Dubna, one attempted to chemically isolate element 112 (^{283}112) from the products of the ^{238}U(^{48}Ca,3n) reaction. ***No events were observed, σ_{upper} (2σ) ~ 1.3 pb.***
- The same group continued on to study the ^{242}Pu(^{48}Ca,3n)^{287}114 reaction. In their thermochromatography apparatus, they observed two events with 9.5 MeV α emitter decaying to an SF nucleus.**This is interpreted as ^{287}114 ($t_{1/2}$ ~ 0.5 s) decaying as it entered the apparatus, with the detection of the α-emitting ^{283}112 daughter ($t_{1/2}$ ~ 4s). (σ ~ 2 pb).** The chemical properties of ^{283}112 are between Hg and Rn.


Cross Section (pb)
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
100
102
104
106
108
110
112
114
116
118
120
ZCN
Cold fusion
Hot fusion

Can we understand this?

σ_{EVR} = "stick" x "diffuse" x "survive"

$$\sigma_{EVR} = \sigma_{CN} \bullet W_{sur}$$

$$\sigma_{CN} = \sum \sigma_{capture}(E_{cm},J) P_{CN}(E_{cm},J)$$

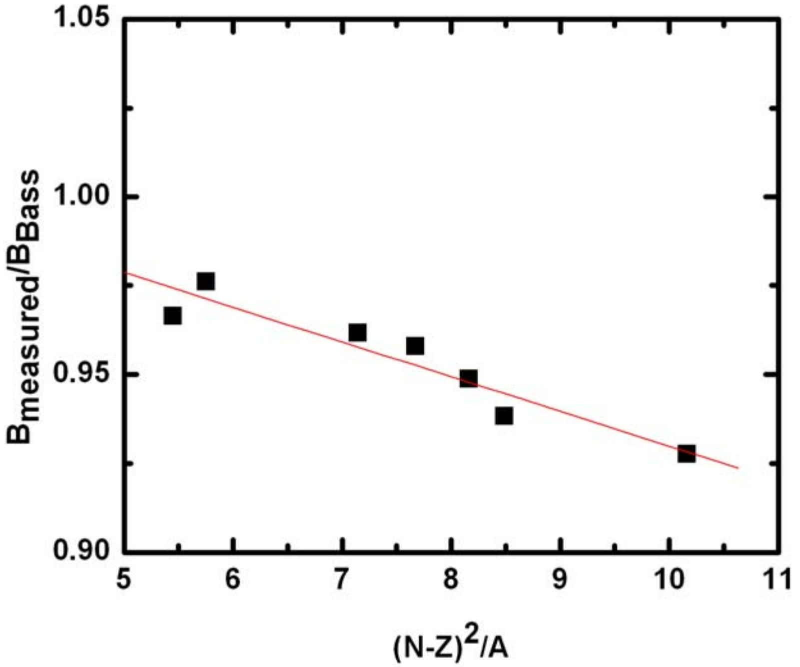
$\sigma_{capture}$ ↔ **Fusion with radioactive beams**

P_{CN} and W_{sur} ↔ How well do we understand heavy element synthesis?

Rules of the Game

- Try to understand the basic physics behind the evaporation residue cross sections.
- Use simple “textbook” expressions that make the physics transparent at the possible expense of getting detailed fits to the data.

$\sigma_{capture}$ taken from semi-empirical model
of Swiatecki, et al (PRC 71 014602 (2005)
with isospin dependence of barriers shown below



Fusion Hindrance—The P_{CN} factor

Armbruster has parameterized the data on P_{CN} in the form:

$$P_{CN}(E_{cm},J) \approx P_{CN}(E_{cm}) = 0.5 \exp\left[-c(x_{eff} - x_{thr})\right]$$

For “cold” fusion, $c = 140$, $x_{thr} = 0.79$

For “hot” fusion, $c = 106$, $x_{thr} = 0.72$

W_{sur} evaluated from Vandenbosch and Huizenga expression

$$W_{sur}(E^*_{CN},J) \approx P_{xn}(E^*_{CN},J)\prod_{i=1}^{x}\frac{\Gamma_n(E^*_i,J_i)}{\Gamma_n(E^*_i,J_i)+\Gamma_f(E^*_i,J_i)}$$

$$\frac{\Gamma_n(E^*_{CN})}{\Gamma_f(E^*_{CN})} = \frac{4A^{2/3}(E^*_{CN}-B_n)}{k\left\{2\left(a\left[E^*_{CN}-B_f\right]\right)^{1/2}-1\right\}}\exp(2a^{1/2}\left\{\left(E^*_{CN}-B_n\right)^{1/2}-\left(E^*_{CN}-B_f\right)^{1/2}\right\})$$

k=9.8   a=A/12

B_n, B_f from Möller et al., (ADNDT 39,213; 59, 185)

$$B_f(E^*_{CN}) = B_f^{LD} + B_f^{M}(E^*_{CN}=0)\exp\left[\frac{-E^*_{CN}}{E_D}\right]$$

Excitation energy dependence of B_f from Ignatyuk(Yad. Fiz 21, 185)

$$\delta U = \delta U_0 \exp(-\gamma E^*)$$

$$\gamma^{-1} = \frac{5.48A^{1/3}}{\left(1+1.3A^{-1/3}\right)}$$

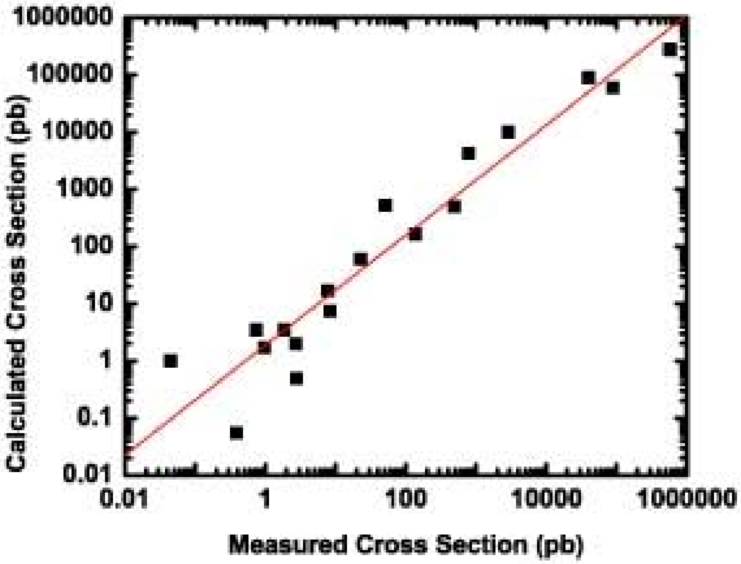
- Consider all hot fusion reactions with $x < 0.72$

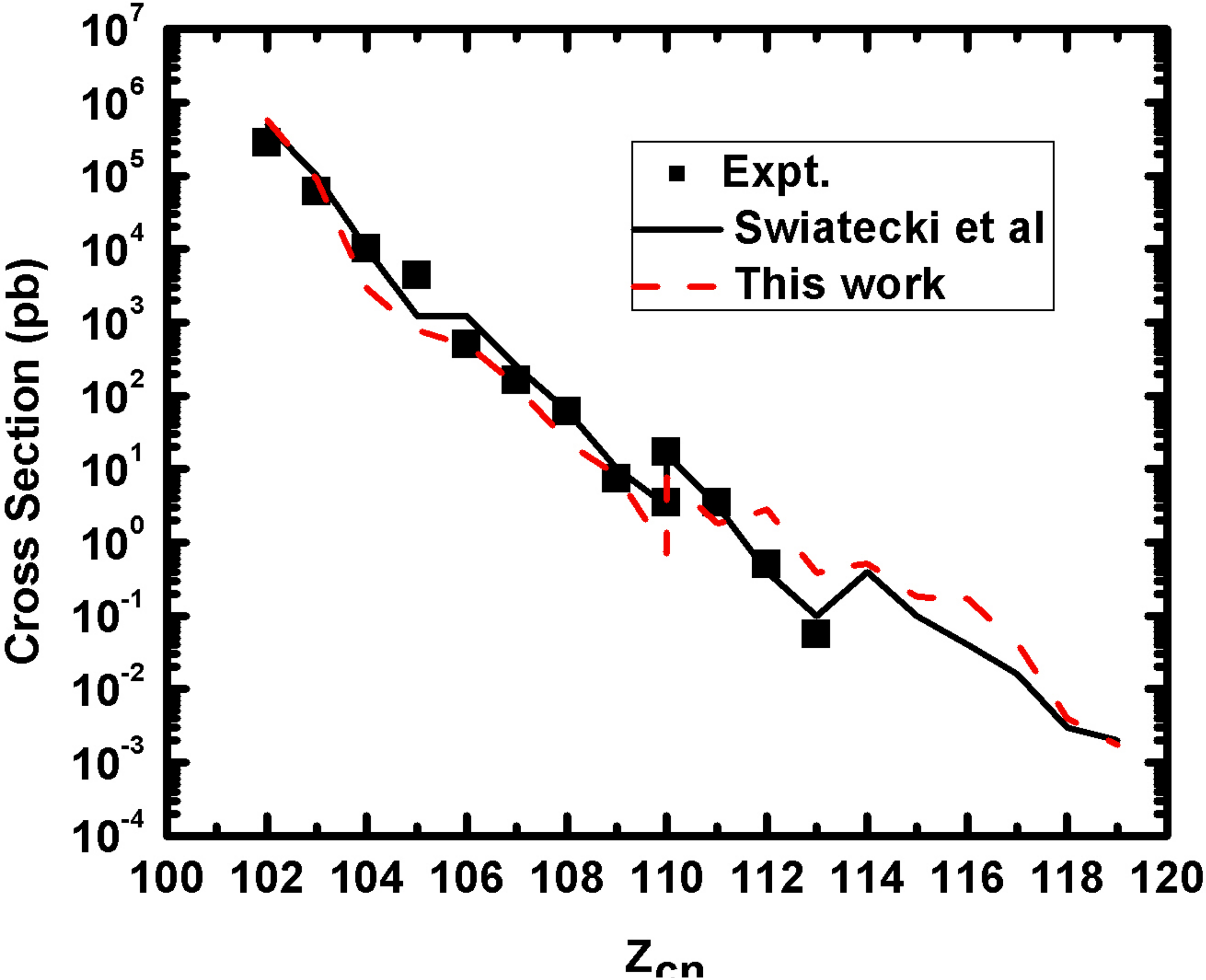
- Assume $P_{CN} = 1$

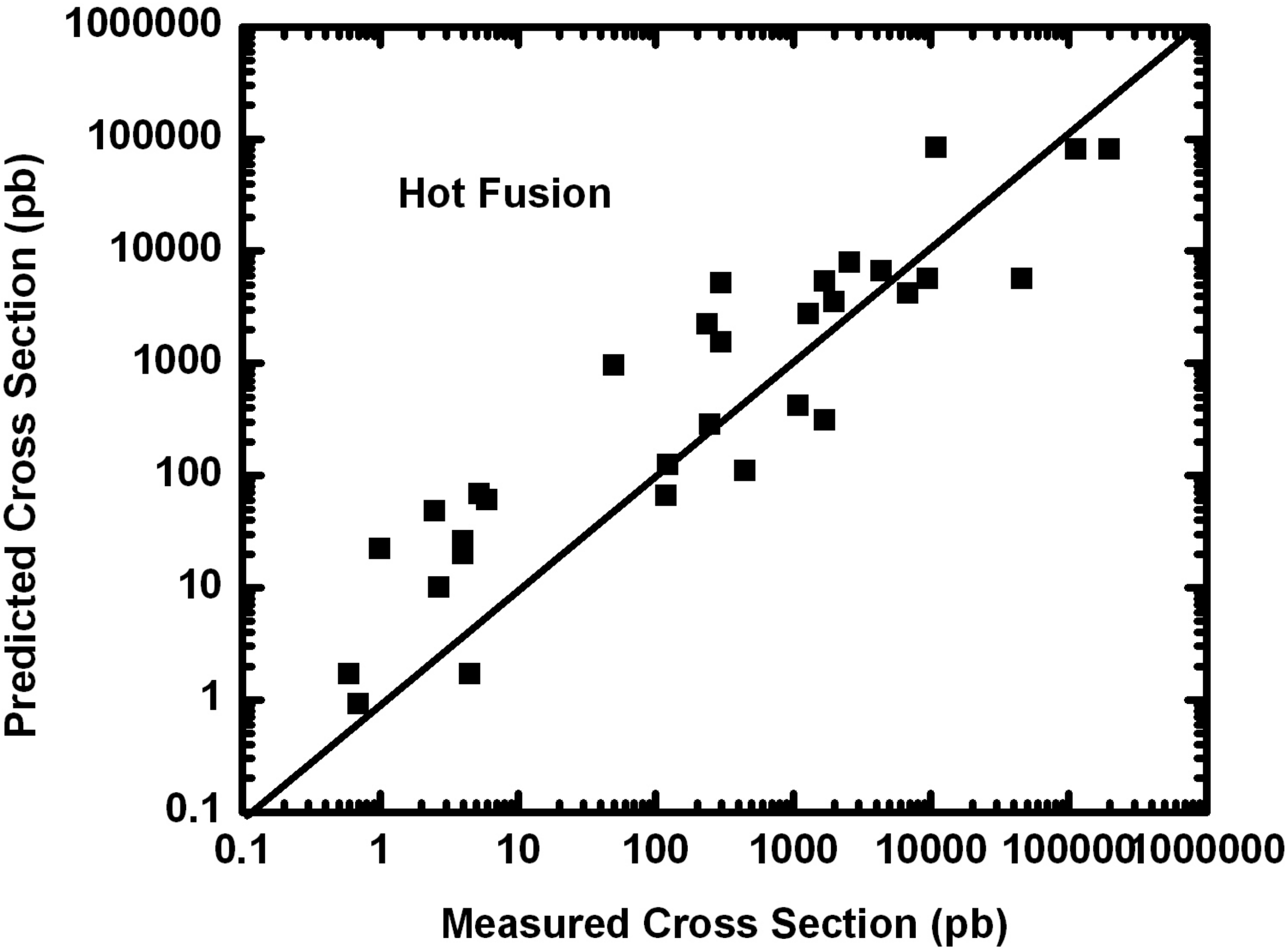
- $W_{sur} = \sigma_{EVR}/\sigma_{capture}$

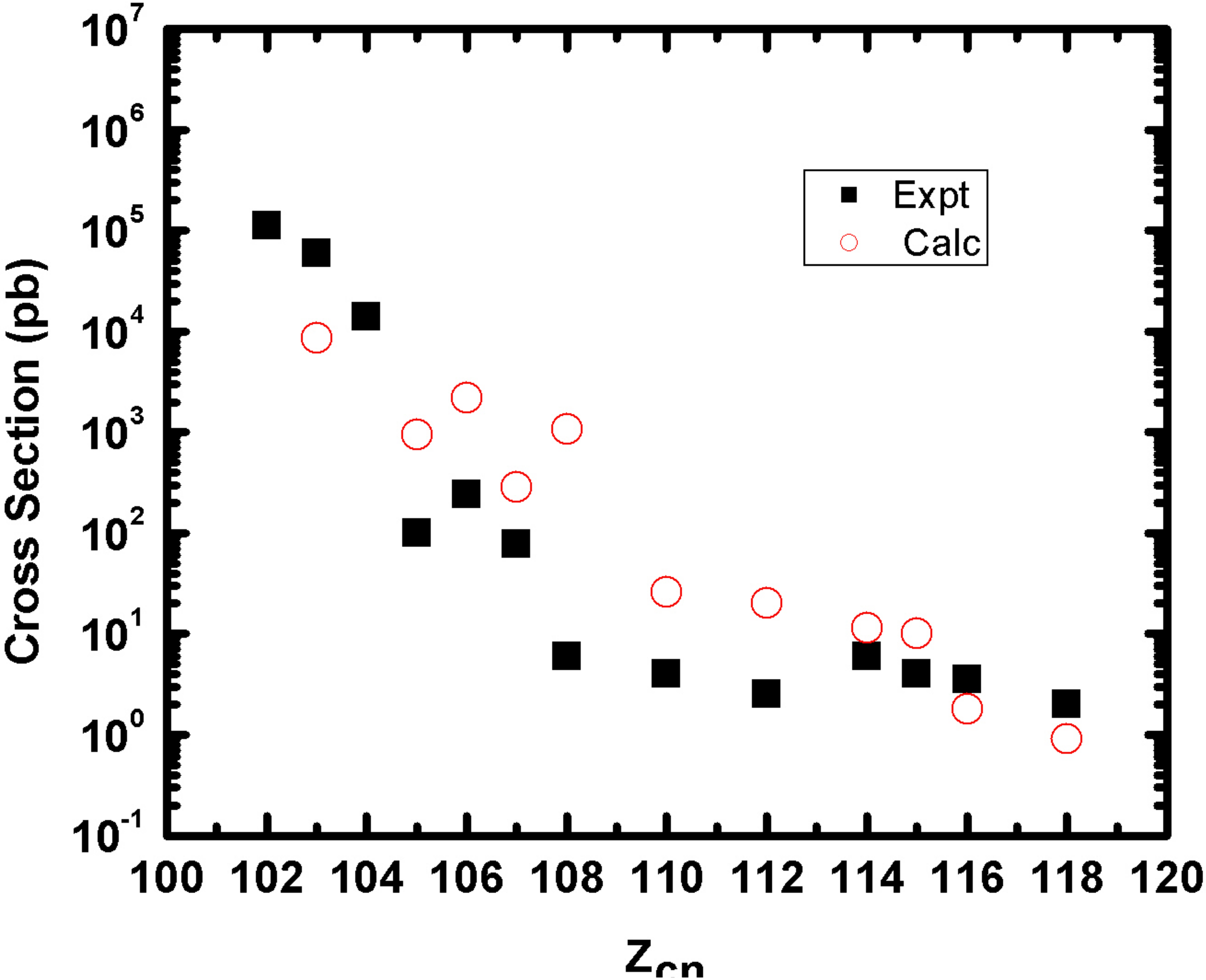
- For 20 cases, $(W_{sur})_{expt}/(W_{sur})_{model} = 0.86 +- 0.67$

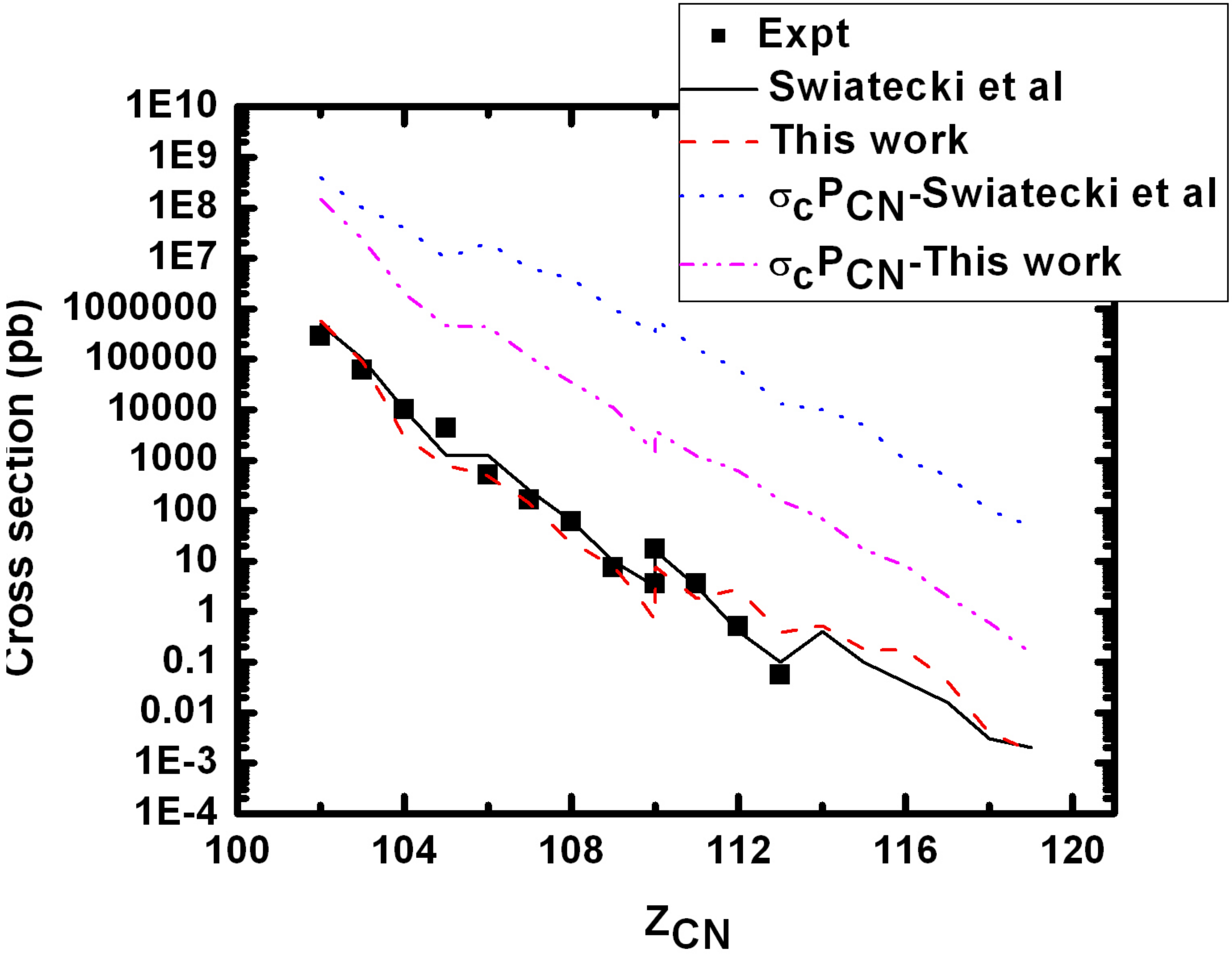
Stable Beam Cold Fusion Reactions




Cross Section (pb)
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
100
102
104
106
108
110
112
114
116
118
120
Z_{cn}
Expt.
Swiatecki et al
This work


Hot Fusion
Predicted Cross Section (pb)
Measured Cross Section (pb)
1000000
100000
10000
1000
100
10
1
0.1
0.1
1
10
100
1000
10000
100000
1000000


Cross Section (pb)
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
100
102
104
106
108
110
112
114
116
118
120
Z_{cn}
■ Expt
○ Calc


■ Expt
Swiatecki et al
This work
$\sigma_c P_{CN}$-Swiatecki et al
$\sigma_c P_{CN}$-This work
Cross section (pb)
1E10
1E9
1E8
1E7
1000000
100000
10000
1000
100
10
1
0.1
0.01
1E-3
1E-4
100
104
108
112
116
120
Z_{CN}

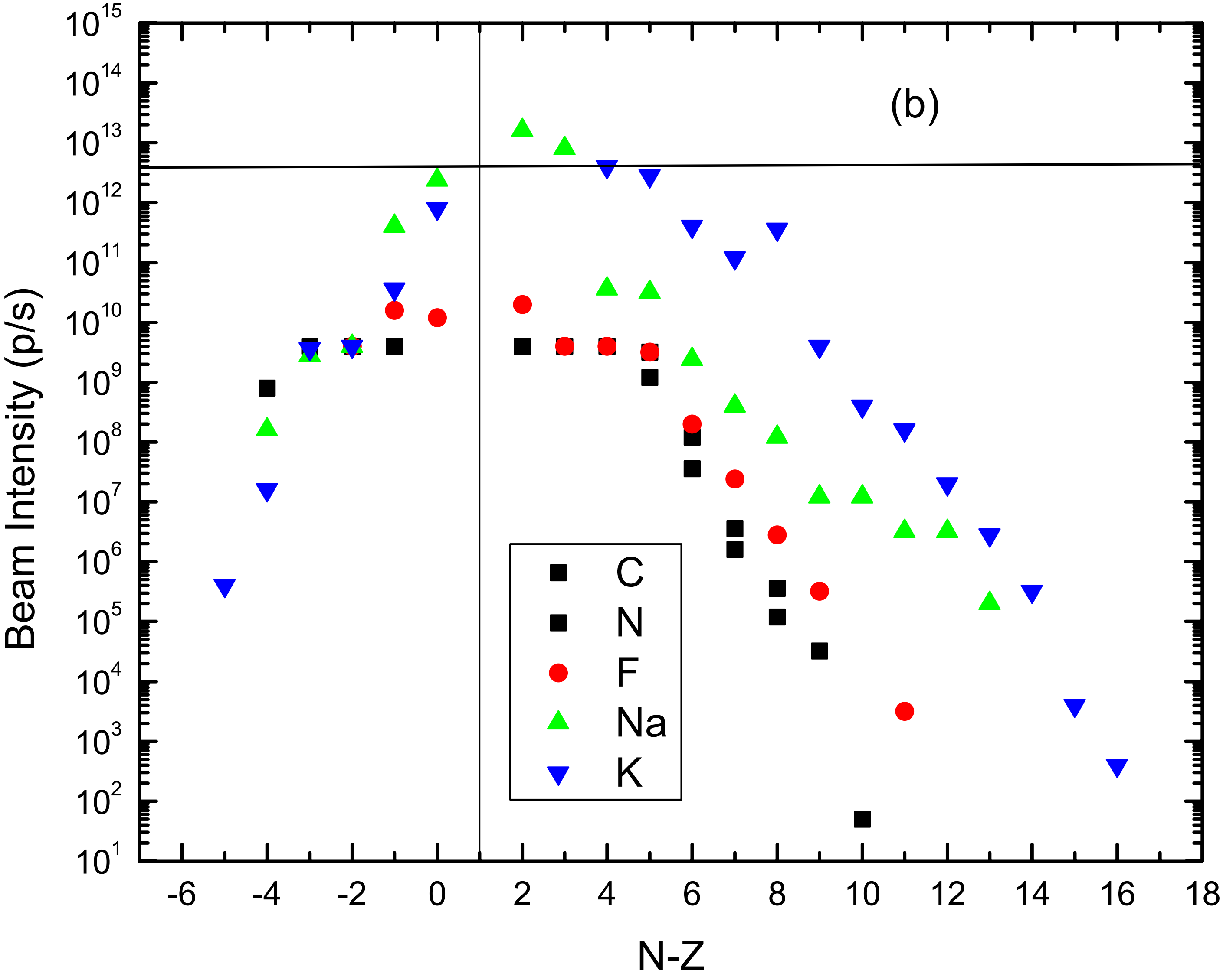
Calculational Model For RNB-Induced Reactions

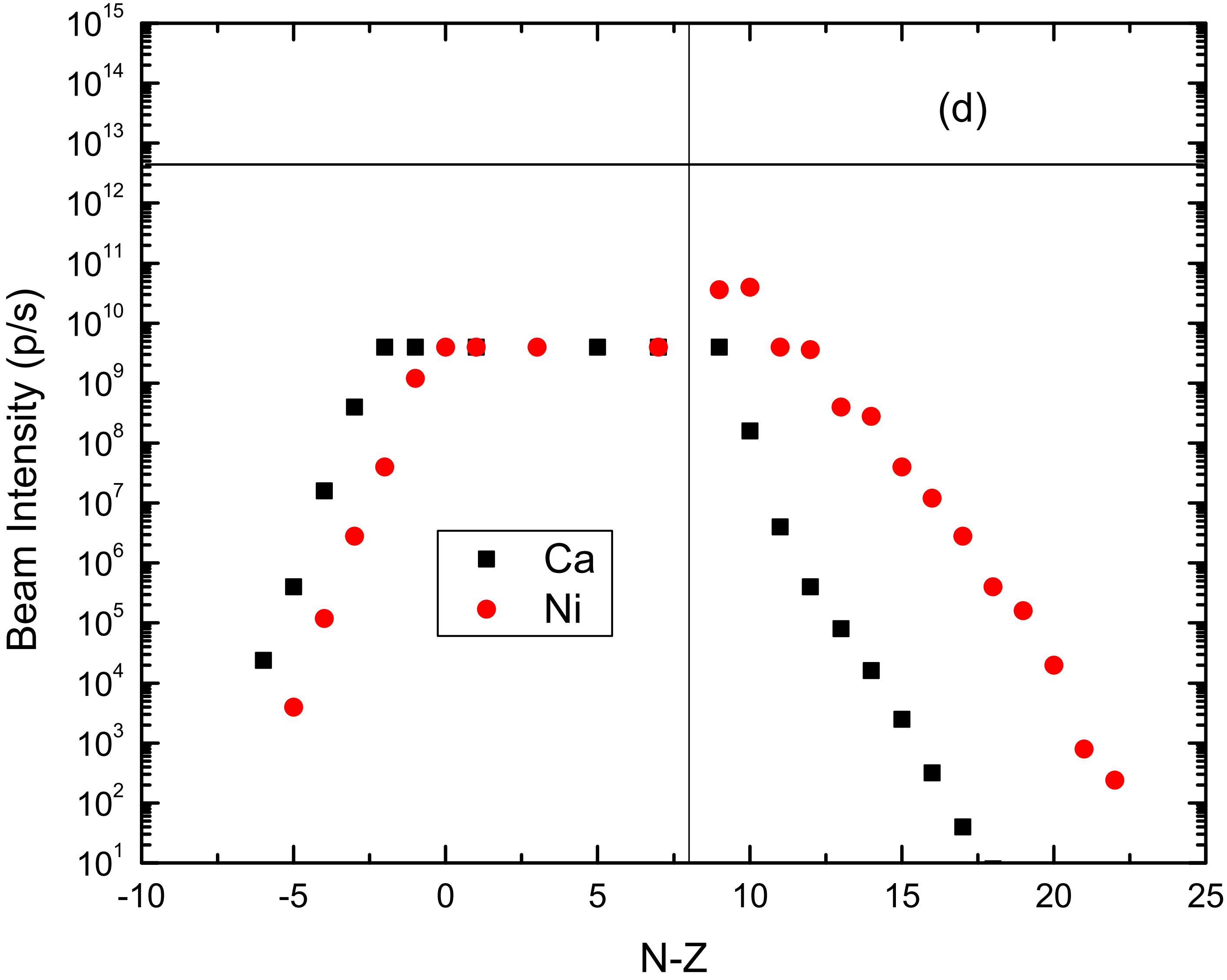
- RIA Beam List
- All “stable” targets

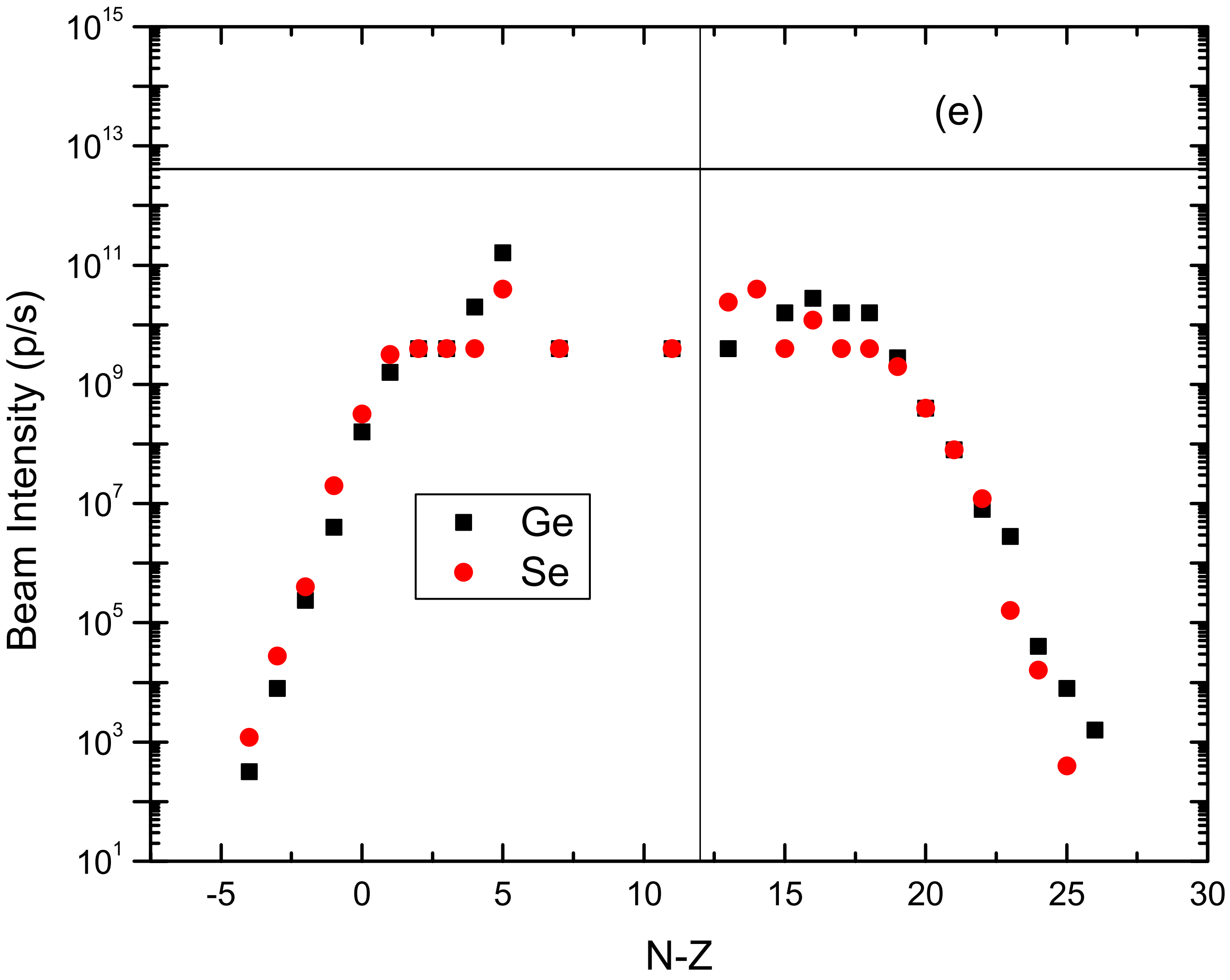
- Fusion Probability

- Survival Probability

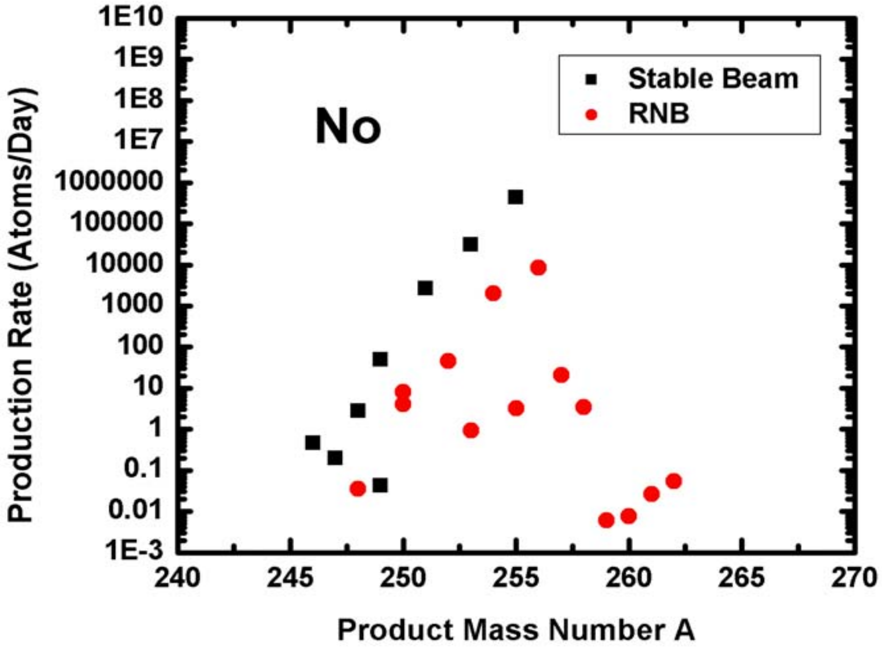
Yield in atoms/day

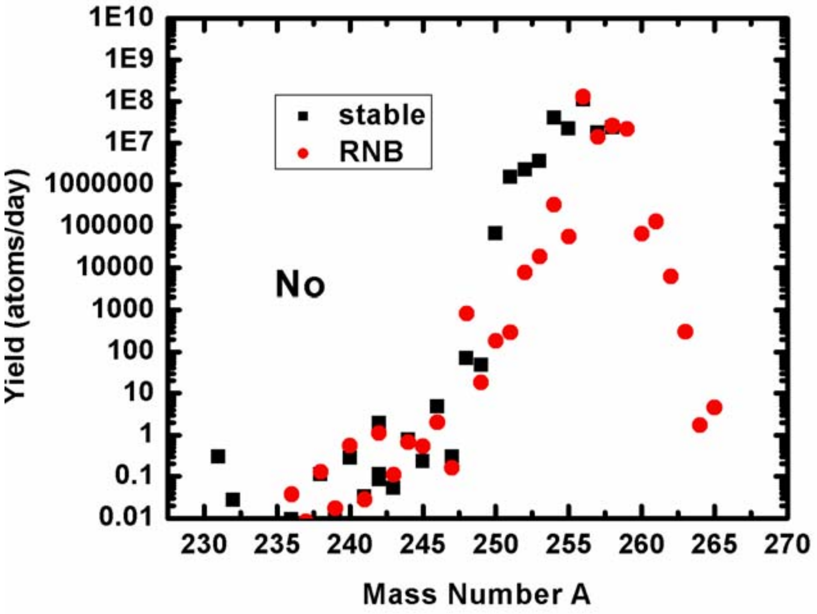

(b)
Beam Intensity (p/s)
N-Z
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
-6
-4
-2
0
2
4
6
8
10
12
14
16
18
■ C
■ N
● F
▲ Na
▼ K

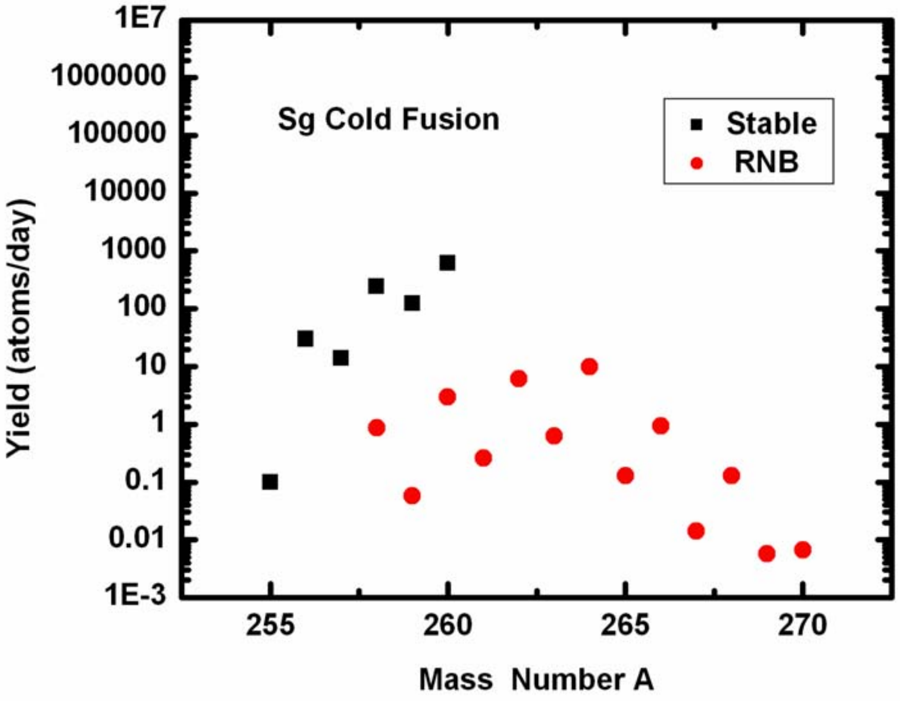

(d)
Beam Intensity (p/s)
N-Z
■ Ca
● Ni
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
-10
-5
0
5
10
15
20
25

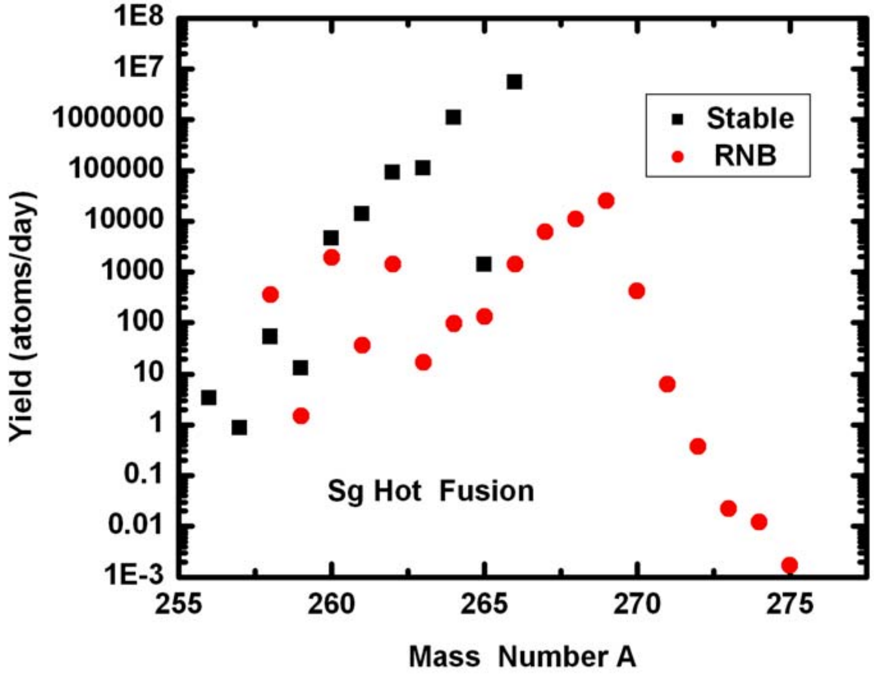


(e)
Ge
Se
Beam Intensity (p/s)
10^{15}
10^{13}
10^{11}
10^{9}
10^{7}
10^{5}
10^{3}
10^{1}
-5
0
5
10
15
20
25
30
N-Z


No
■ Stable Beam
● RNB
Production Rate (Atoms/Day)
1E10
1E9
1E8
1E7
1000000
100000
10000
1000
100
10
1
0.1
0.01
1E-3
240
245
250
255
260
265
270
Product Mass Number A

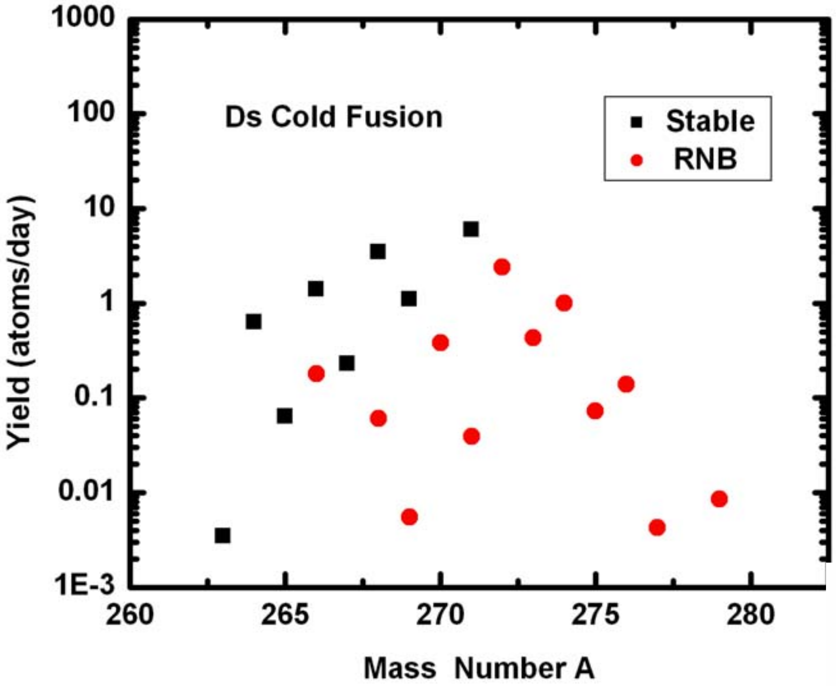

No
■ stable
● RNB
Yield (atoms/day)
1E10
1E9
1E8
1E7
1000000
100000
10000
1000
100
10
1
0.1
0.01
230
235
240
245
250
255
260
265
270
Mass Number A

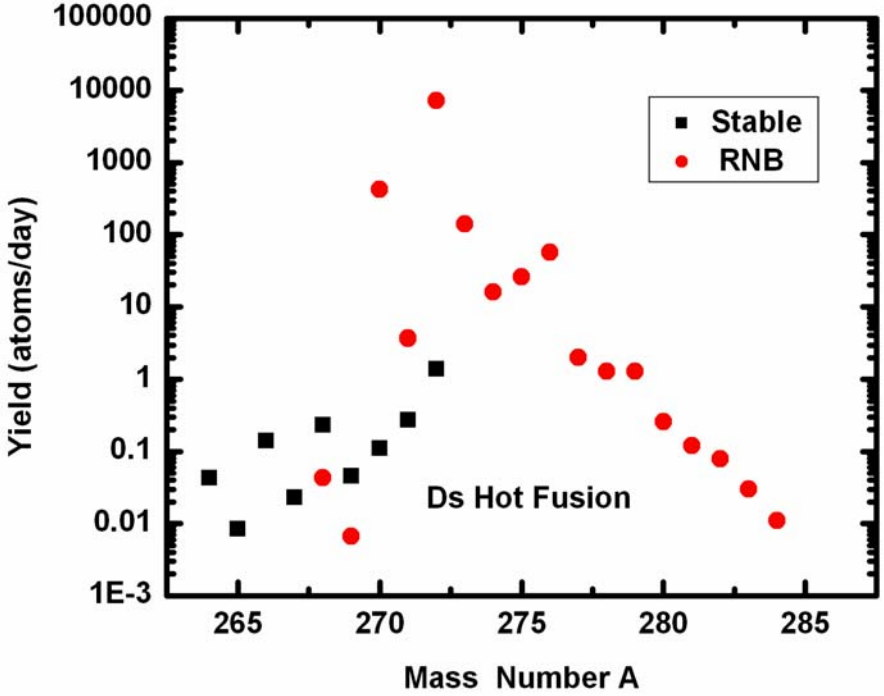

Sg Cold Fusion
■ Stable
● RNB
Yield (atoms/day)
1E7
1000000
100000
10000
1000
100
10
1
0.1
0.01
1E-3
255
260
265
270
Mass Number A

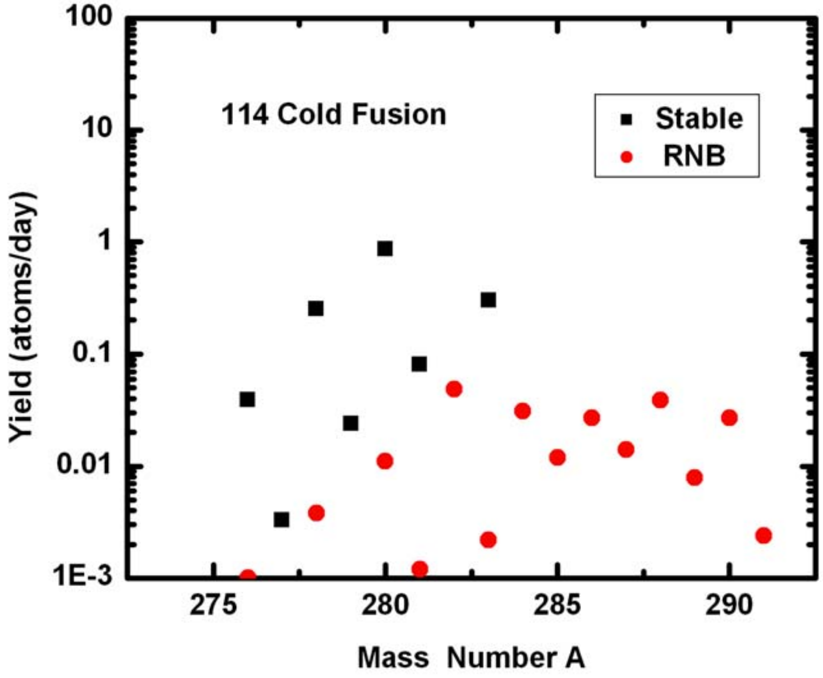

Sg Hot Fusion
■ Stable
● RNB
Yield (atoms/day)
1E8
1E7
1000000
100000
10000
1000
100
10
1
0.1
0.01
1E-3
255
260
265
270
275
Mass Number A

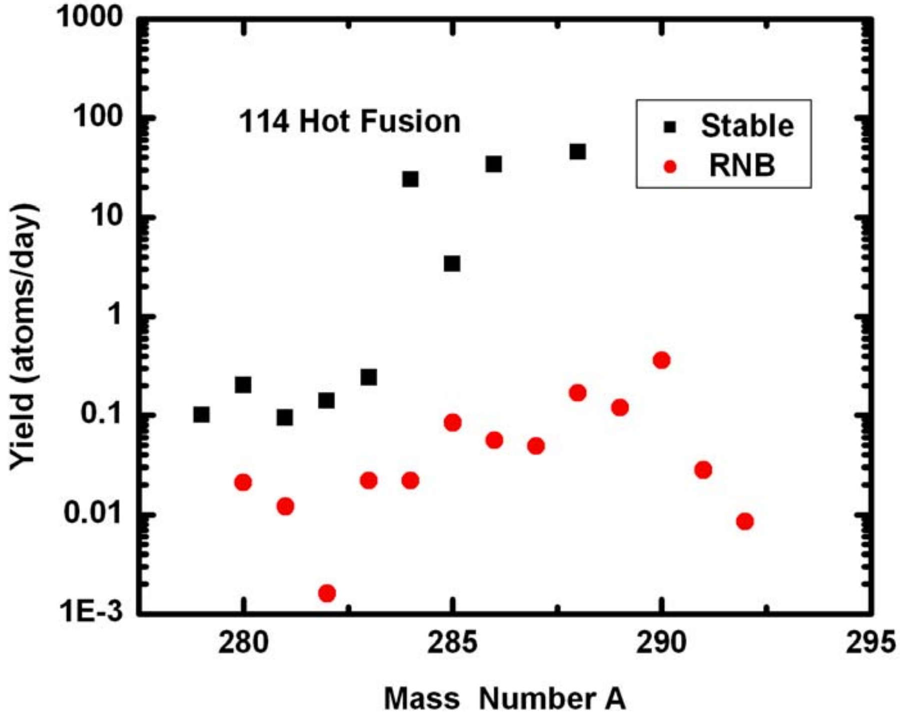
What kind of reactions with RNBs are used to form n-rich nuclei?

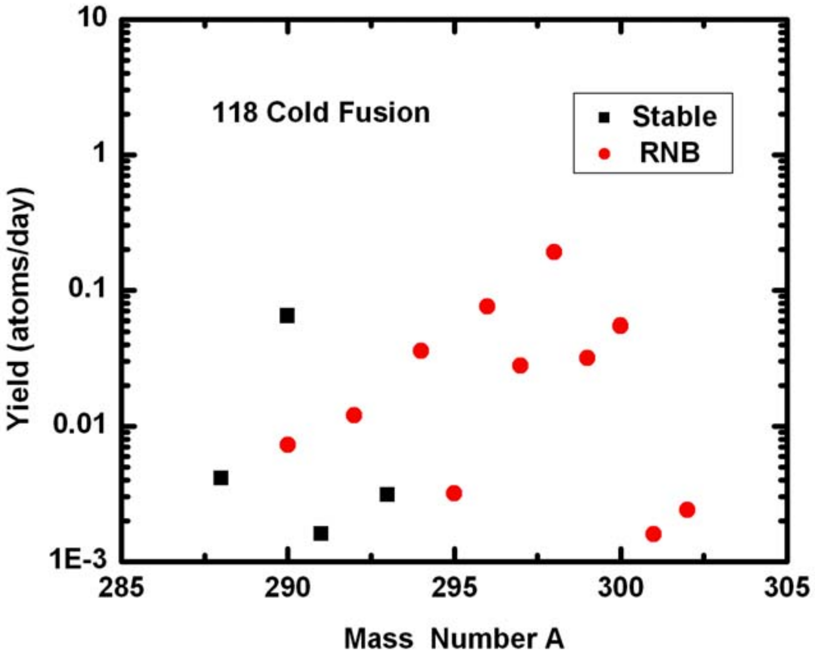
Reactants	Products	Beam Intensity (p/s)	Production Rate (atoms/day)
$^{23}O + {}^{252}Cf$	$^{271}Sg + 4n$	8×10^6	6
$^{30}Mg + {}^{244}Pu$	$^{270}Sg + 4n$	2.8×10^9	420
$^{21}O + {}^{252}Cf$	$^{269}Sg + 4n$	1.6×10^{10}	25000
$^{20}O + {}^{252}Cf$	$^{268}Sg + 4n$	4×10^9	11000
$^{25}Ne + {}^{246}Cm$	$^{267}Sg + 4n$	3.6×10^9	500

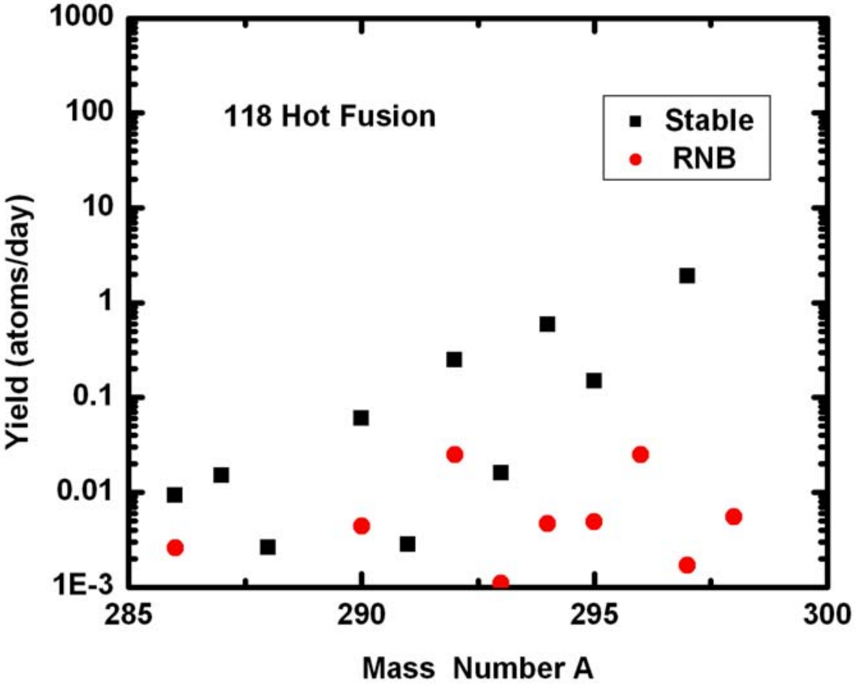

Ds Cold Fusion
Stable
RNB
Yield (atoms/day)
1000
100
10
1
0.1
0.01
1E-3
260
265
270
275
280
Mass Number A


Stable
RNB
Ds Hot Fusion
Yield (atoms/day)
100000
10000
1000
100
10
1
0.1
0.01
1E-3
265
270
275
280
285
Mass Number A


114 Cold Fusion
■ Stable
● RNB
Yield (atoms/day)
100
10
1
0.1
0.01
1E-3
275
280
285
290
Mass Number A


114 Hot Fusion
■ Stable
● RNB
Yield (atoms/day)
1000
100
10
1
0.1
0.01
1E-3
280
285
290
295
Mass Number A


118 Cold Fusion
■ Stable
● RNB
Yield (atoms/day)
10
1
0.1
0.01
1E-3
285
290
295
300
305
Mass Number A


118 Hot Fusion
■ Stable
● RNB
Yield (atoms/day)
1000
100
10
1
0.1
0.01
1E-3
285
290
295
300
Mass Number A

What about conventional “cold fusion” reactions?

- **The predicted cross sections are too low for the available beam intensities**.
- For example,

$^{208}\mathrm{Pb}(^{93}\mathrm{Kr},n)^{300}118$	5.5×10^{-37}	10^{12}
$^{209}\mathrm{Bi}(^{66}\mathrm{Cu},n)^{274}112$	5.0×10^{-36}	10^{11}
$^{208}\mathrm{Pb}(^{61}\mathrm{Fe},n)^{268}\mathrm{Hs}$	5.0×10^{-33}	10^{9}
$^{208}\mathrm{Pb}(^{59}\mathrm{Cr},n)^{266}\mathrm{Sg}$	3.7×10^{-32}	10^{8}

Atomic Physics and Chemistry of the Transactinides

>100 atom/day list

➢ $^{266}\mathrm{Rf}$	$^{248}\mathrm{Cm}(^{22}\mathrm{O},4n)$
➢ $^{268}\mathrm{Db}$	$^{248}\mathrm{Cm}(^{24}\mathrm{F},4n)$
➢ $^{270}\mathrm{Sg}$	$^{244}\mathrm{Pu}(^{30}\mathrm{Mg},4n)$
➢ $^{271}\mathrm{Bh}$	$^{248}\mathrm{Cm}(^{27}\mathrm{Na},4n)$
➢ $^{272}\mathrm{Hs}$	$^{253}\mathrm{Es}(^{23}\mathrm{F},4n)$
➢ $^{275}\mathrm{Mt}$	$^{252}\mathrm{Cf}(^{27}\mathrm{Na},4n)$