Production of Heavy Nuclei Using RNBs

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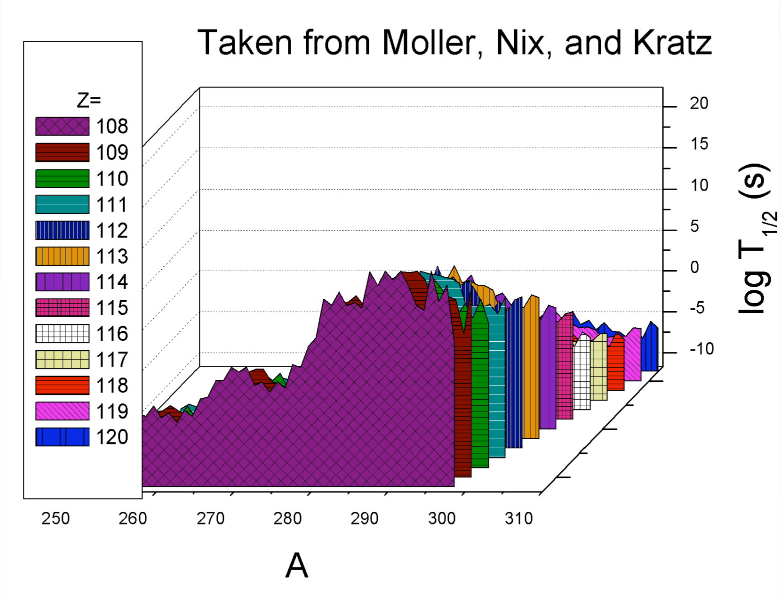
Why use RNBs for producing new heavy nuclei?

- **Longer half-lives of products enable more detailed atomic physics and chemical studies.**

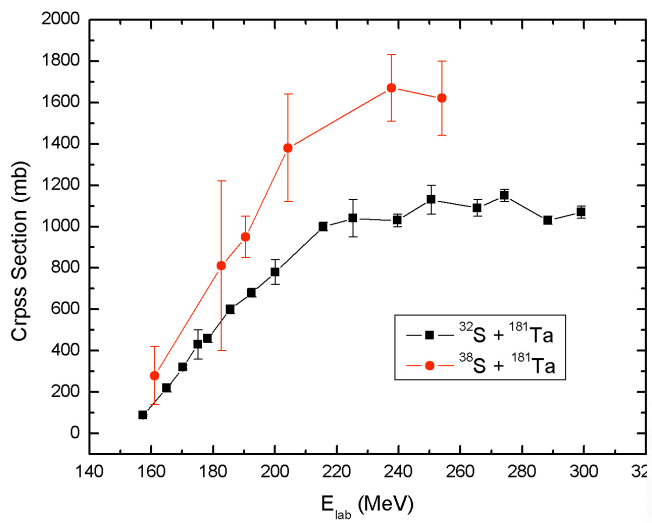


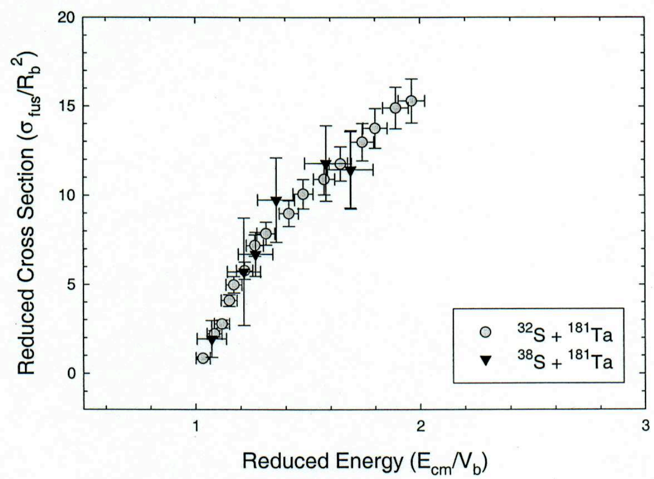
- **Lowered fusion barrier due to n-rich projectiles allows lower E^*.**

- **Higher survival probabilities for n-rich products.**

Fusion Enhancement—Type I

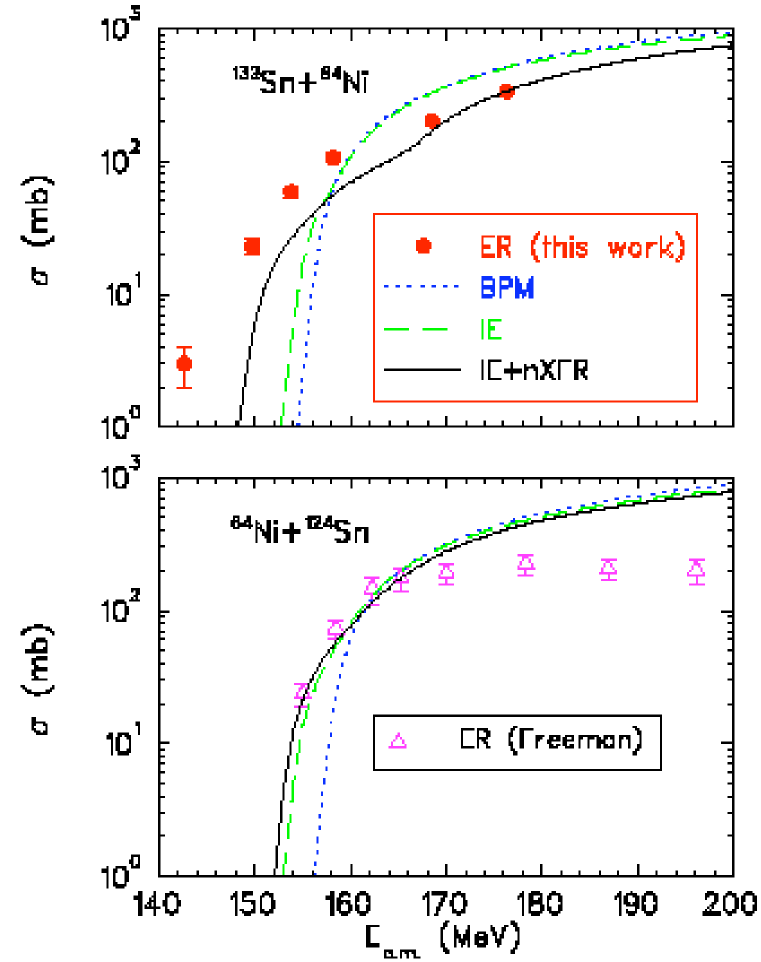
Simple shift of Fusion Barrier



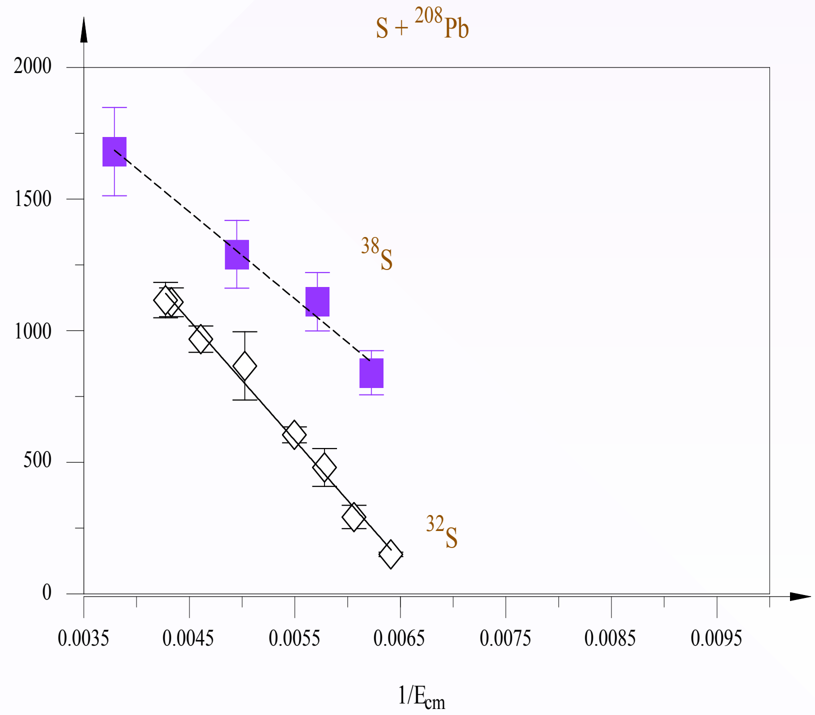


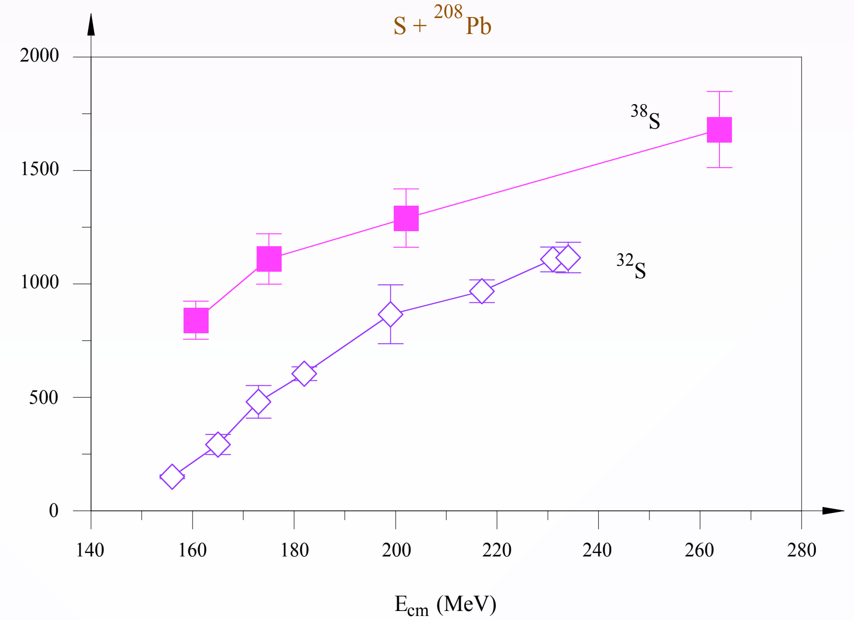
Fusion Enhancement—Type II

Enhancement beyond barrier shift



Fusion Enhancement—Type II





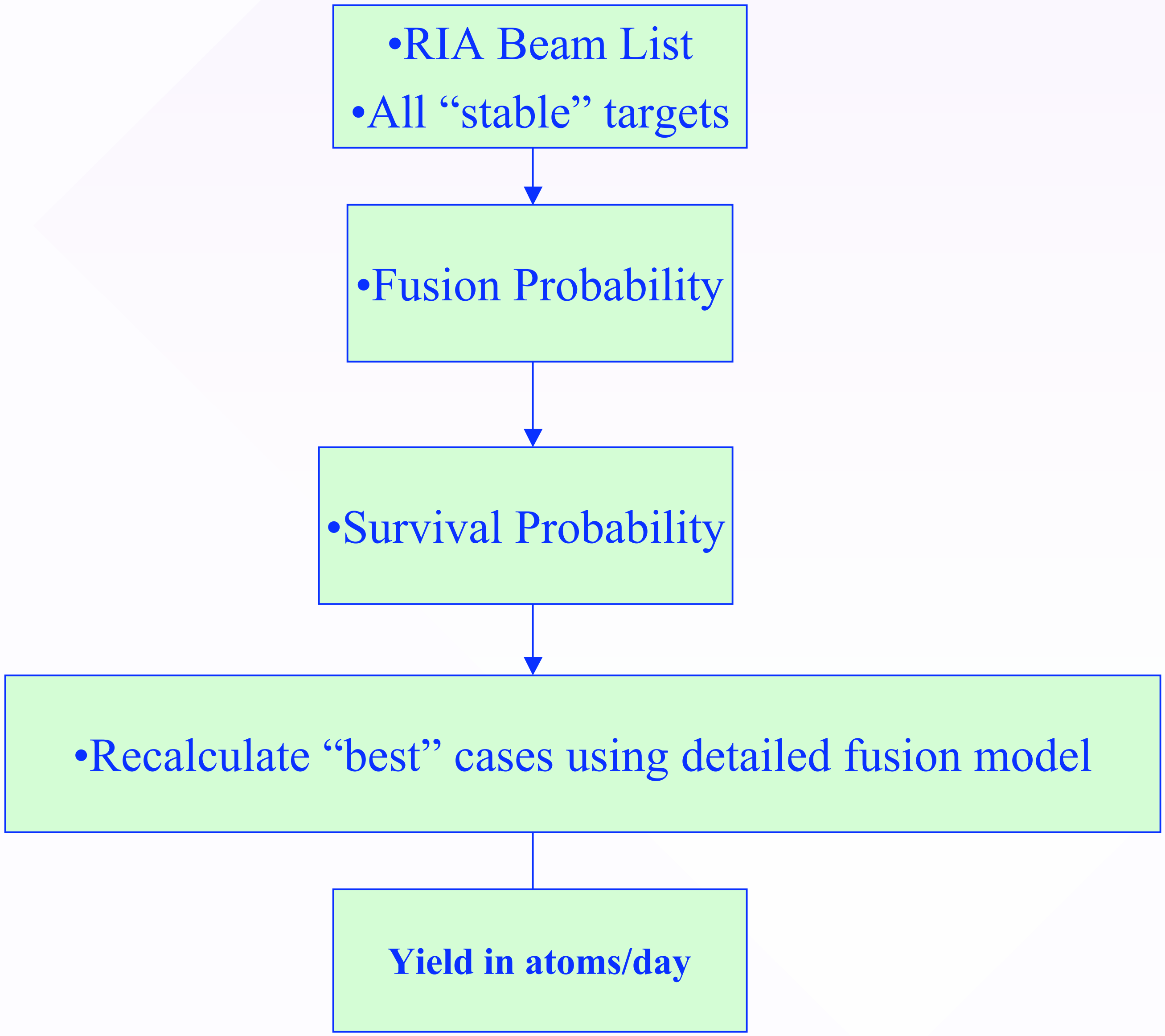
Effect of type II enhancement on heavy element production

- Enhancement shown in Liang et al experiment has the effect of lowering the excitation energy without lowering the production cross section. This effect appears to be a shift of about one neutron binding energy in E* for ^{132}Sn + ^{64}Ni.

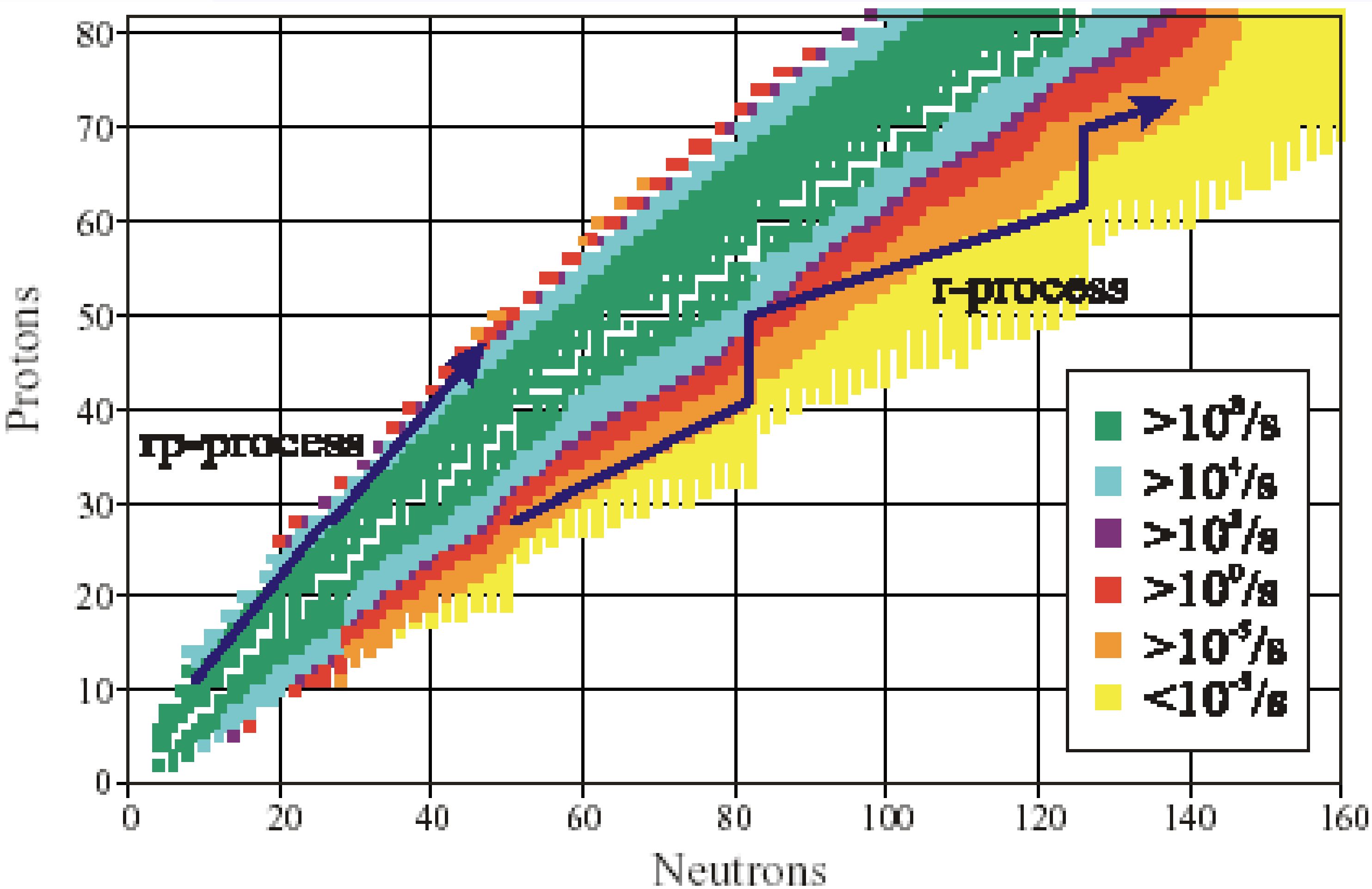
Effect of a shift of B_n on Survival Probability

Nucleus	E*(MeV)	Enhancement in Survival Probability
^{256}No	13	1.5
	45	1.1
^{270}Ds	13	5
	45	1.1
$^{282}118$	13	56
	45	1.15

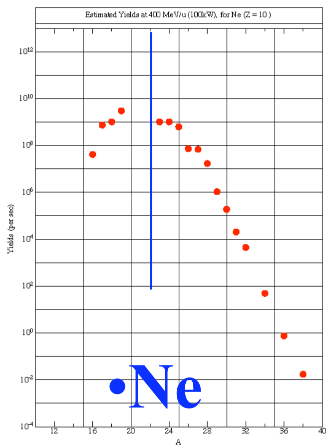
Calculational Model

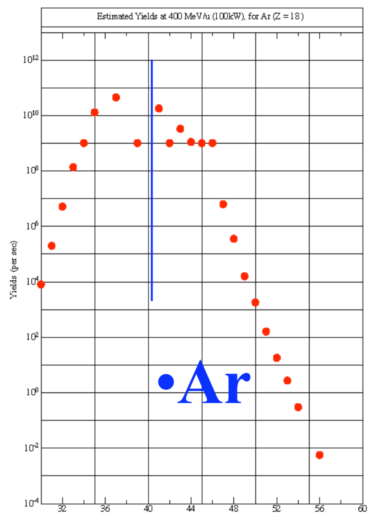


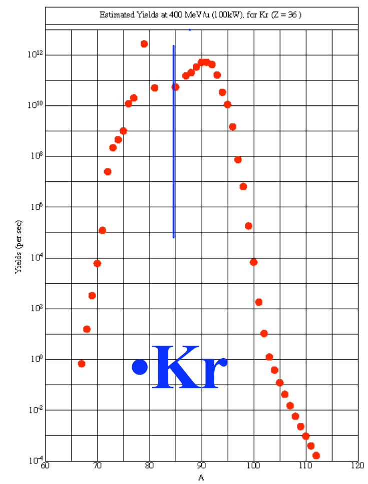
RIA Beam List

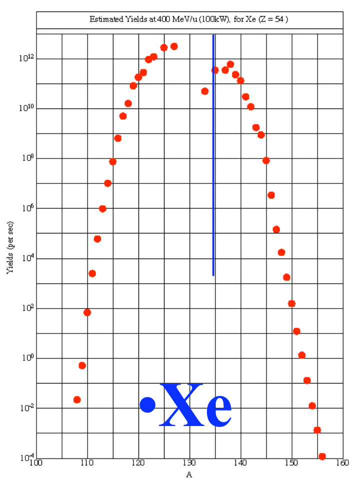


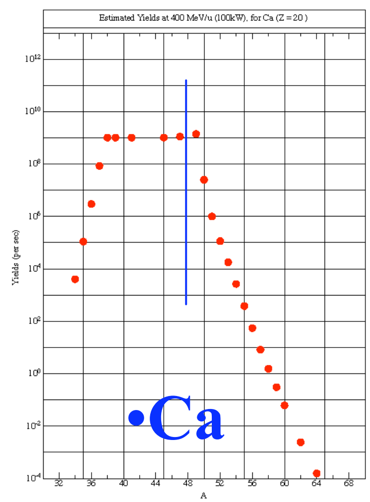
Details of RIA Yields

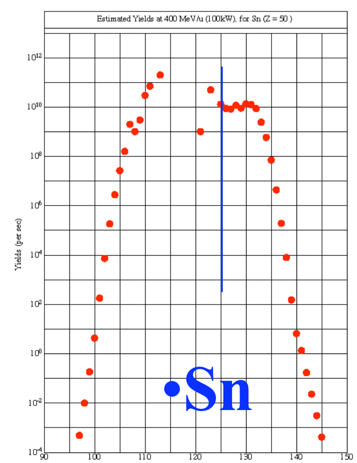






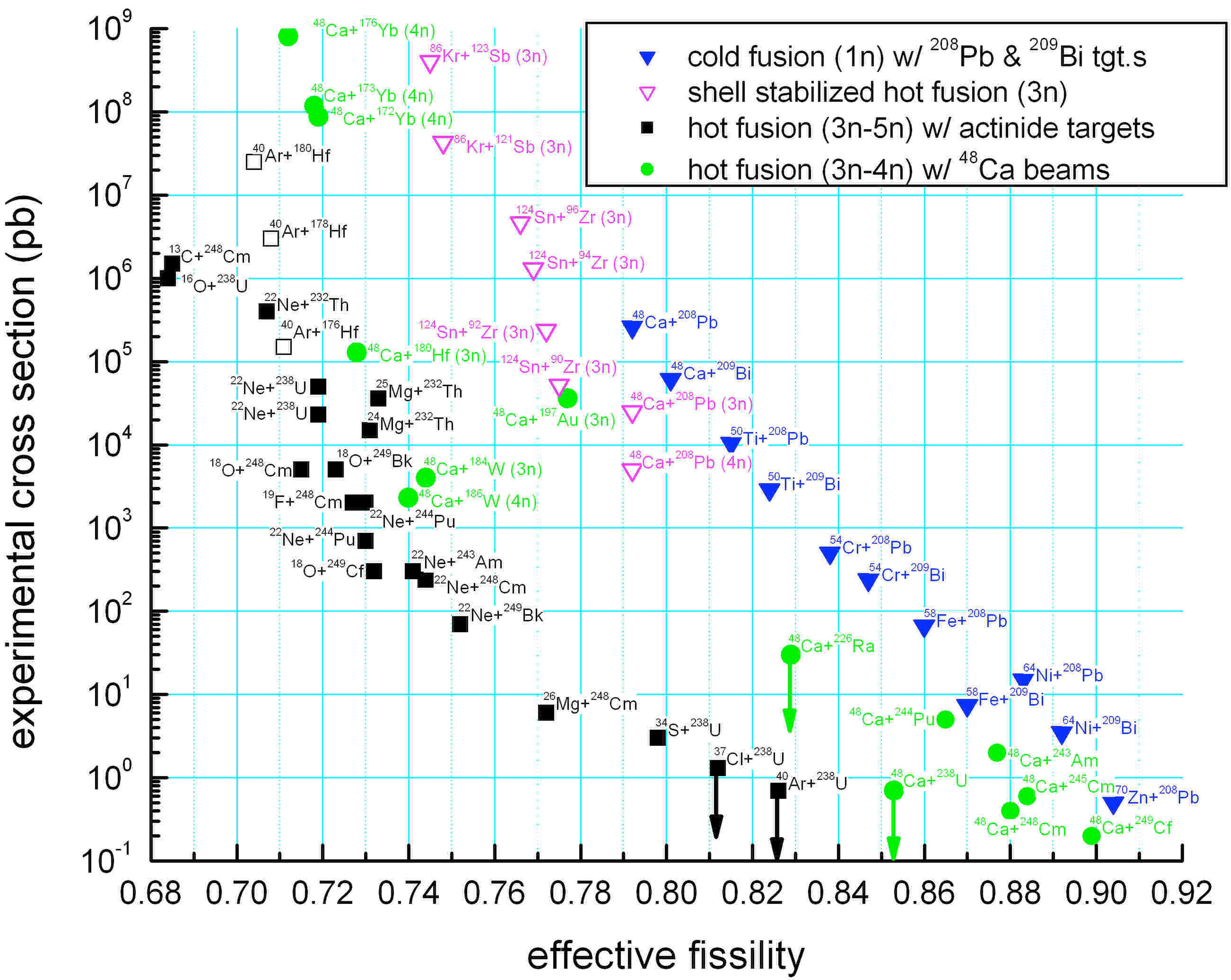






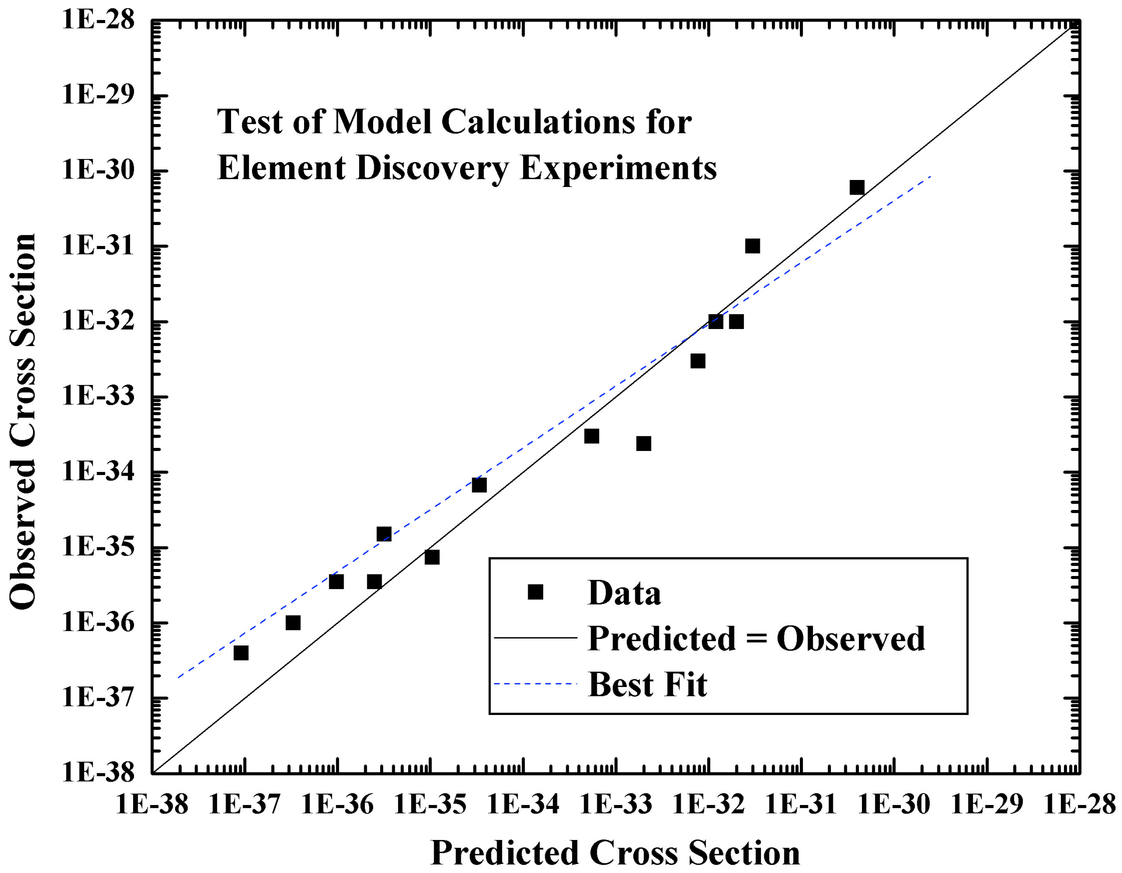
Details of Model

- Semiempirical fusion systematics (Armbruster, Ann. Rev. Nucl. Sci. 35, 135)
- □n/□f systematics (Vandenbosch and Huizenga)
- Detailed calculation of fusion probability using HIVAP
- No fusion enhancement except lowered fusion barrier for n-rich nuclei (Zyromski et al., 1997)

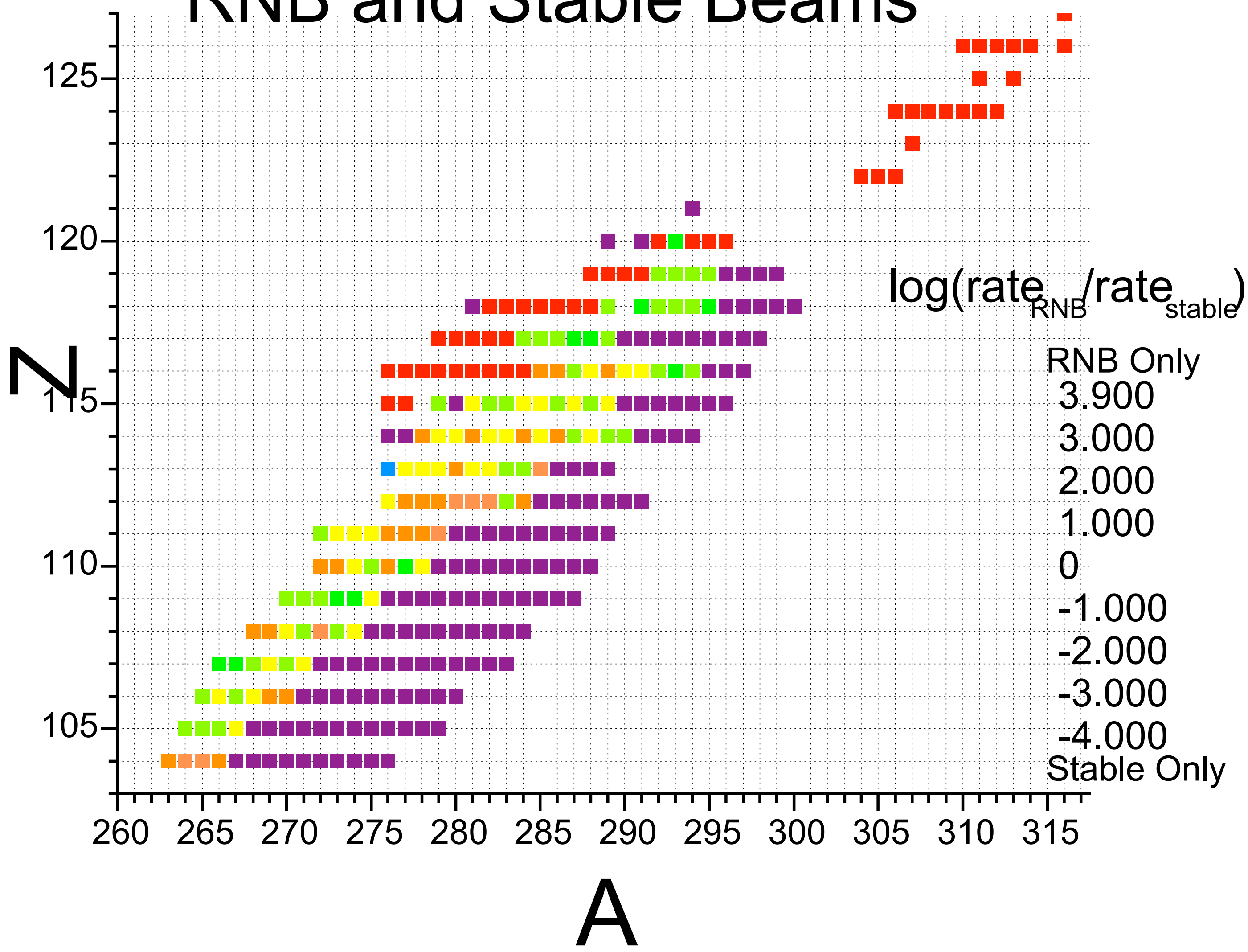


experimental cross section (pb)
effective fissility
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
0.68
0.70
0.72
0.74
0.76
0.78
0.80
0.82
0.84
0.86
0.88
0.90
0.92
cold fusion (1n) w/ 208Pb & 209Bi tgt.s
shell stabilized hot fusion (3n)
hot fusion (3n-5n) w/ actinide targets
hot fusion (3n-4n) w/ 48Ca beams
48Ca+176Yb (4n)
86Kr+123Sb (3n)
48Ca+173Yb (4n)
48Ca+172Yb (4n)
86Kr+121Sb (3n)
40Ar+180Hf
124Sn+96Zr (3n)
40Ar+178Hf
124Sn+94Zr (3n)
13C+248Cm
16O+238U
22Ne+232Th
40Ar+176Hf
124Sn+92Zr (3n)
48Ca+208Pb
48Ca+180Hf (3n)
124Sn+90Zr (3n)
48Ca+209Bi
22Ne+238U
25Mg+232Th
22Ne+238U
24Mg+232Th
48Ca+197Au (3n)
48Ca+208Pb (3n)
50Ti+208Pb
18O+248Cm
18O+249Bk
48Ca+184W (3n)
48Ca+208Pb (4n)
50Ti+209Bi
19F+248Cm
48Ca+186W (4n)
22Ne+244Pu
22Ne+244Pu
54Cr+208Pb
18O+249Cf
22Ne+243Am
54Cr+209Bi
22Ne+248Cm
22Ne+249Bk
58Fe+208Pb
48Ca+226Ra
64Ni+208Pb
26Mg+248Cm
58Fe+209Bi
48Ca+244Pu
34S+238U
64Ni+209Bi
37Cl+238U
48Ca+243Am
40Ar+238U
48Ca+238U
48Ca+245Cm
70Zn+208Pb
48Ca+248Cm
48Ca+249Cf

Success of Model



Heavy Element Production Rates for RNB and Stable Beams



Best Stable Beam Reactions for New Elements*

- ^{70}Zn + ^{209}Bi □ ^{278}113 + n □□ 0.1 pb
- ^{76}Ge + ^{208}Pb □ ^{283}114 + n □□ 0.04 pb
- ^{76}Ge + ^{200}Bi □ ^{284}115 + n □□ 0.01 pb
- ^{80}Se + ^{208}Pb □ ^{287}116 + n □□ 3.5 fb
- ^{81}Br + ^{208}Pb □ ^{288}117 + n □□ 0.9 fb

* Excludes radiative capture reactions

Nuclear Spectroscopy of n-rich Nuclei

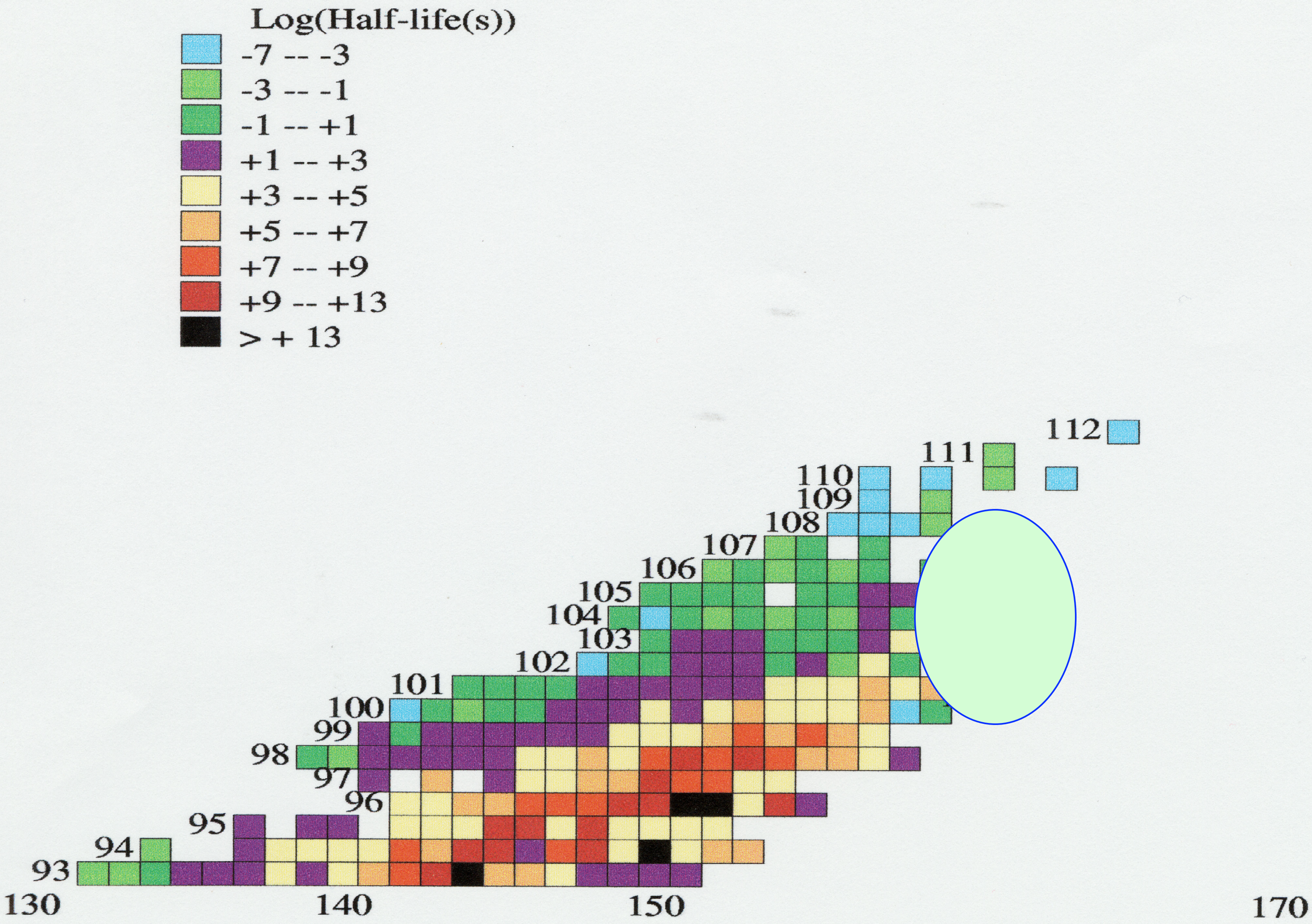
^{256}Fm	$^{244}Pu(^{16}C,4n)$	10^5 atoms/day
^{257}Fm	$^{244}Pu(^{17}C,4n)$	1800 atoms/day
^{257}Fm	$^{252}Cf(^{8}He,3n)$	10^5 atoms/day
^{258}Fm	$^{244}Pu(^{18}C,4n)$	500 atoms/day
^{259}Fm	$^{244}Pu(^{19}C,4n)$	100 atoms/day
^{260}Fm	$^{244}Pu(^{20}C,4n)$	25 atoms/day
^{261}Fm	$^{244}Pu(^{22}C,5n)$	1 atoms/day

Atomic Physics and Chemistry of the Heaviest Elements

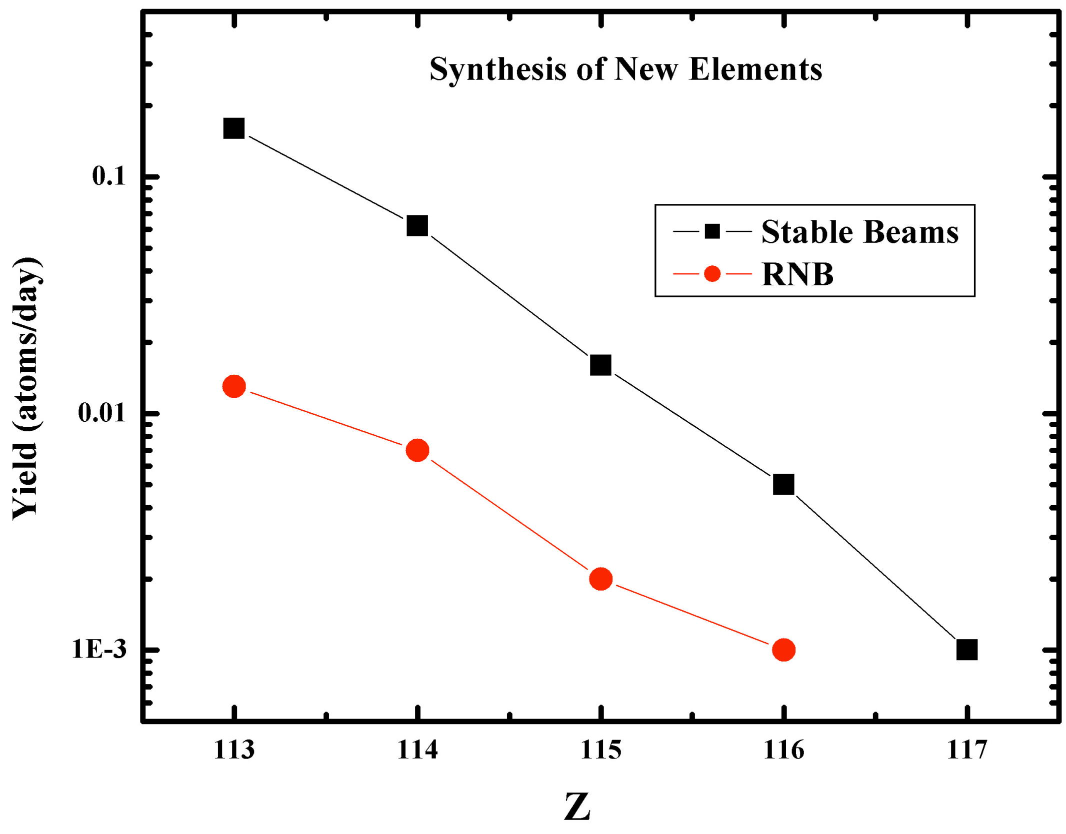
100 atom/day list

^{259}Fm (or lighter)	^{244}Pu(^{19}C,4n)	
^{260}Md	^{244}Pu(^{20}N,4n)	
^{261}No	^{244}Pu(^{21}O,4n)	
^{261}No	^{248}Cm(^{17}C,4n)	
^{262}Lr	^{252}Cf(^{14}B,4n)	
^{264}Rf	^{244}Pu(^{24}Ne,4n)	
^{265}Db	^{252}Cf(^{17}N,4n)	
^{268}Sg	^{252}Cf(^{20}O,4n)	
^{269}Ns	^{248}Cm(^{25}Na,4n)	20
^{270}Hs	^{249}Bk(^{25}Na, 4n)	1.4

Half-lives of Transuranium Nuclei



Impact of RIA on Synthesis of New Elements



What about conventional "cold fusion" reactions?

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

$^{196}Pt(^{88}Kr,n)^{283}114$	0.7×10^{-38}	10^{11}
$^{204}Hg(^{94}Kr,n)^{297}116$	1.1×10^{-38}	10^{10}
$^{209}Bi(^{66}Cu,n)^{274}112$	0.3×10^{-36}	10^{10}
$^{208}Pb(^{61}Fe,n)^{268}Hs$	4.6×10^{-35}	10^{9}
$^{208}Pb(^{59}Cr,n)^{266}Sg$	7.5×10^{-34}	10^{7}