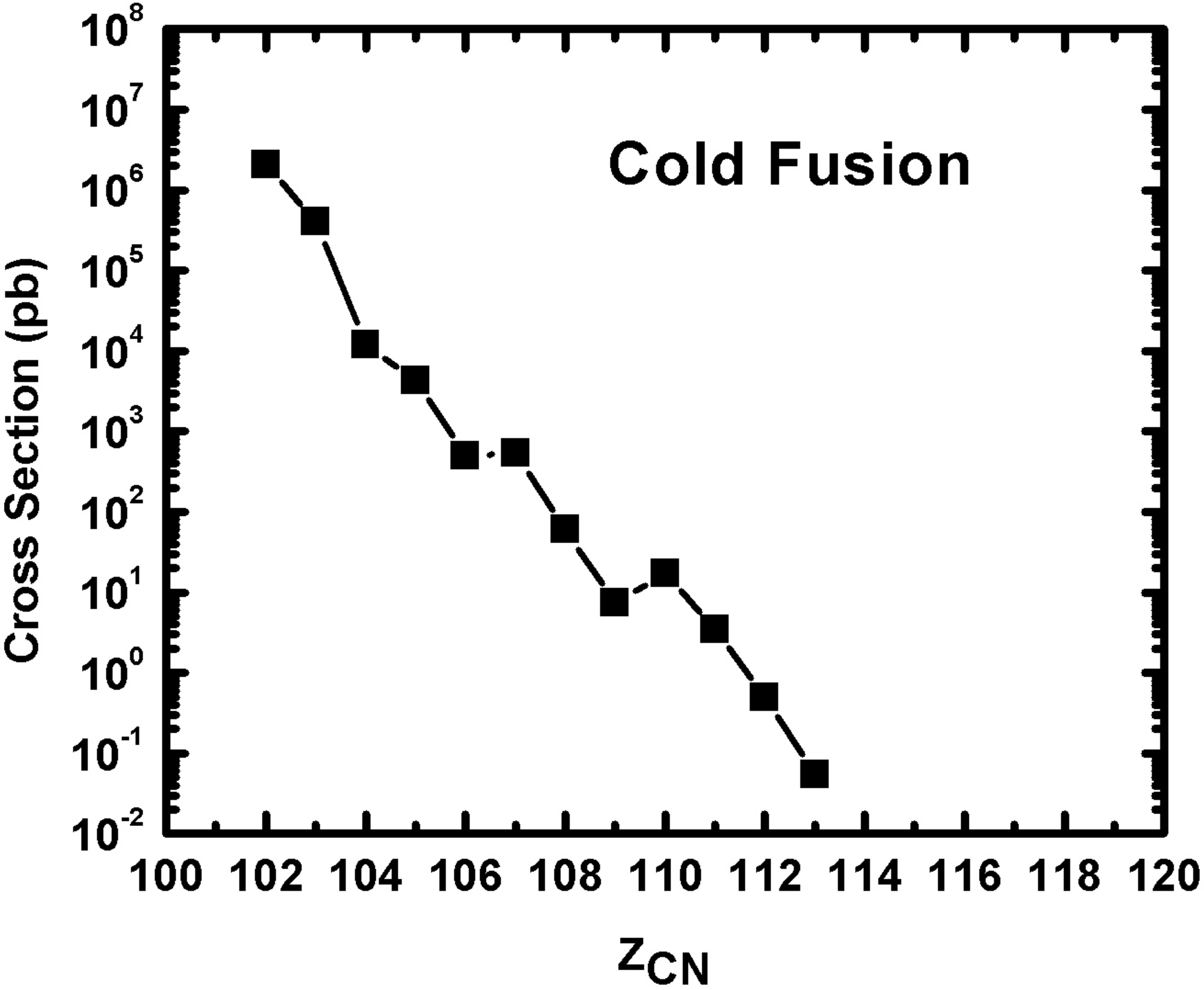
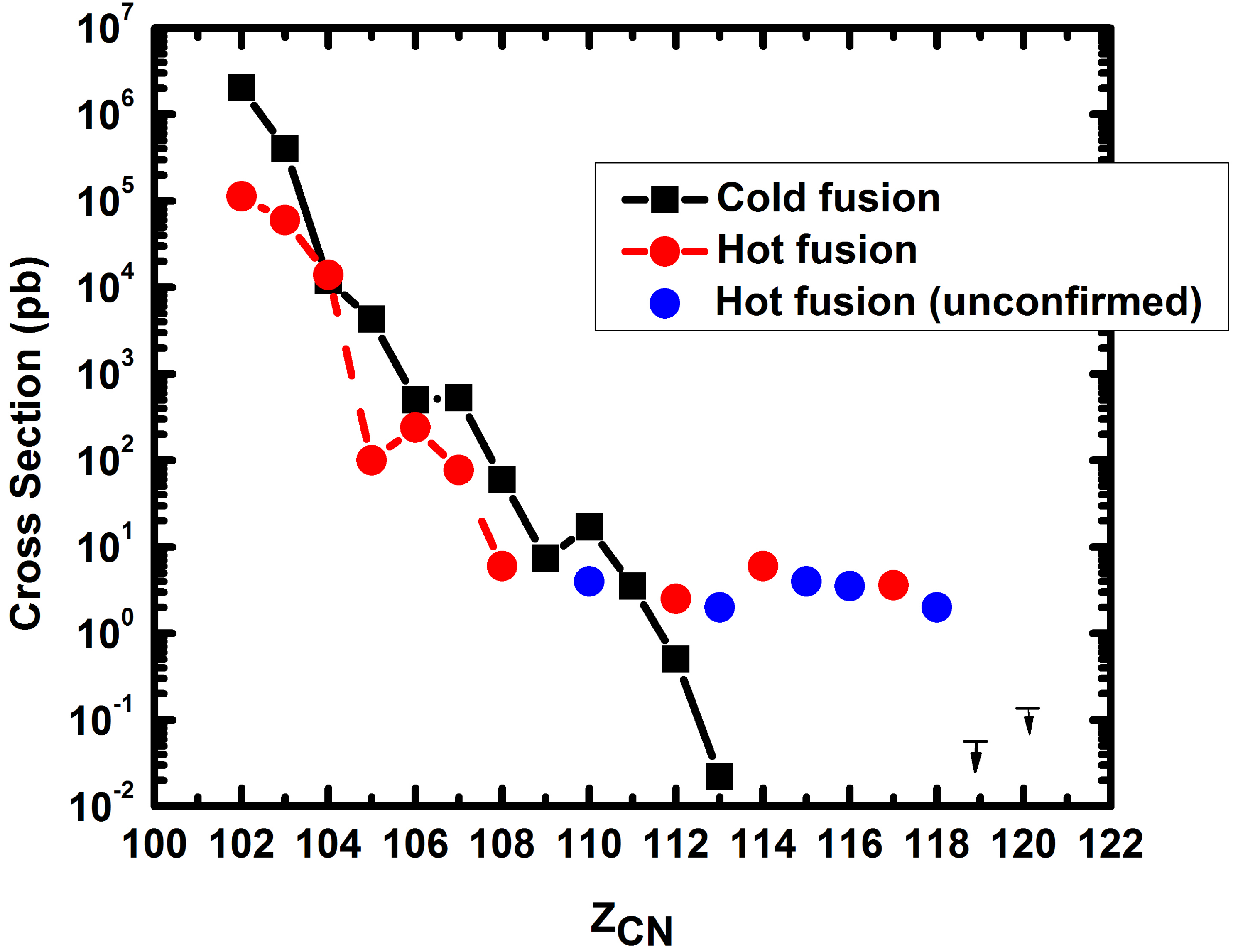
New synthetic paths to neutron rich heavy nuclei

W. Loveland
Oregon State University


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}

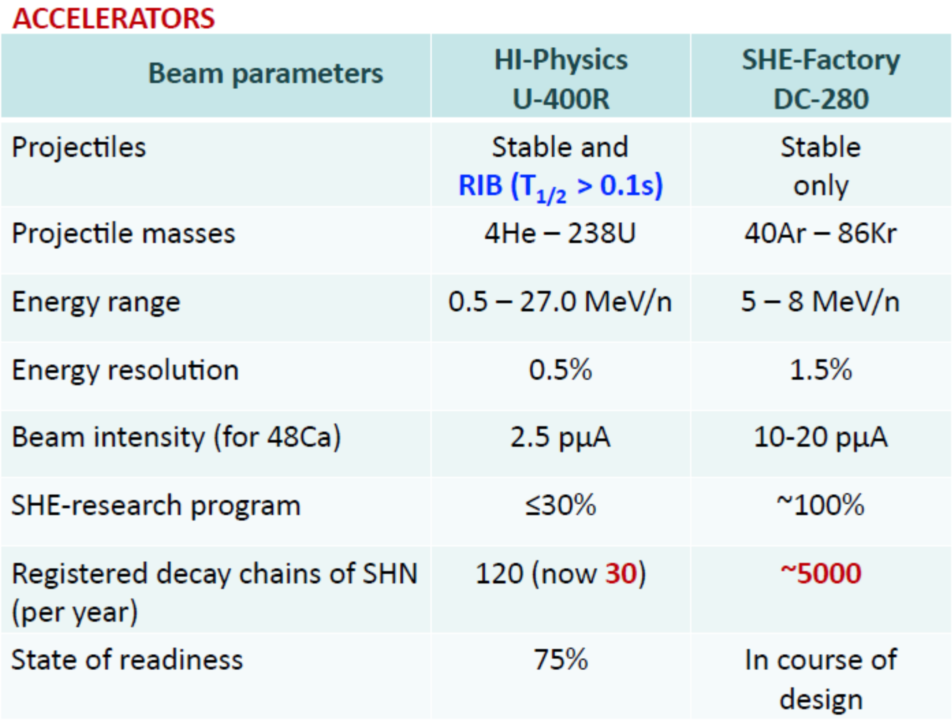

Cold fusion
Hot fusion
Hot fusion (unconfirmed)
Cross Section (pb)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
100
102
104
106
108
110
112
114
116
118
120
122
Z_{CN}

Hot fusion predictions

- $^{249}Bk(^{48}Ca,3n)^{294}117$ σ_{EVR}=1 pb.
- $^{249}Bk(^{50}Ti,4n)^{295}119$ σ_{EVR}=0.07 pb.
- $^{248}Cm(^{54}Cr,4n)^{302}120$ σ_{EVR}=0.02 pb.
- $^{244}Pu(^{58}Fe,4n)^{302}120$ σ_{EVR}=0.006 pb.
- $^{238}U(^{64}Ni,3n)^{302}120$ σ_{EVR}=0.004 pb.

Based upon MNMS masses

The SHEF at Dubna



ACCELERATORS

Beam parameters	HI-Physics U-400R	SHE-Factory DC-280
Projectiles	Stable and RIB ($T_{1/2} > 0.1s$)	Stable only
Projectile masses	4He – 238U	40Ar – 86Kr
Energy range	0.5 – 27.0 MeV/n	5 – 8 MeV/n
Energy resolution	0.5%	1.5%
Beam intensity (for 48Ca)	2.5 pμA	10-20 pμA
SHE-research program	≤30%	~100%
Registered decay chains of SHN (per year)	120 (now 30)	~5000
State of readiness	75%	In course of design

150 times more SHE!

Significant new opportunities for study of the heaviest elements will exist

The Way Forward

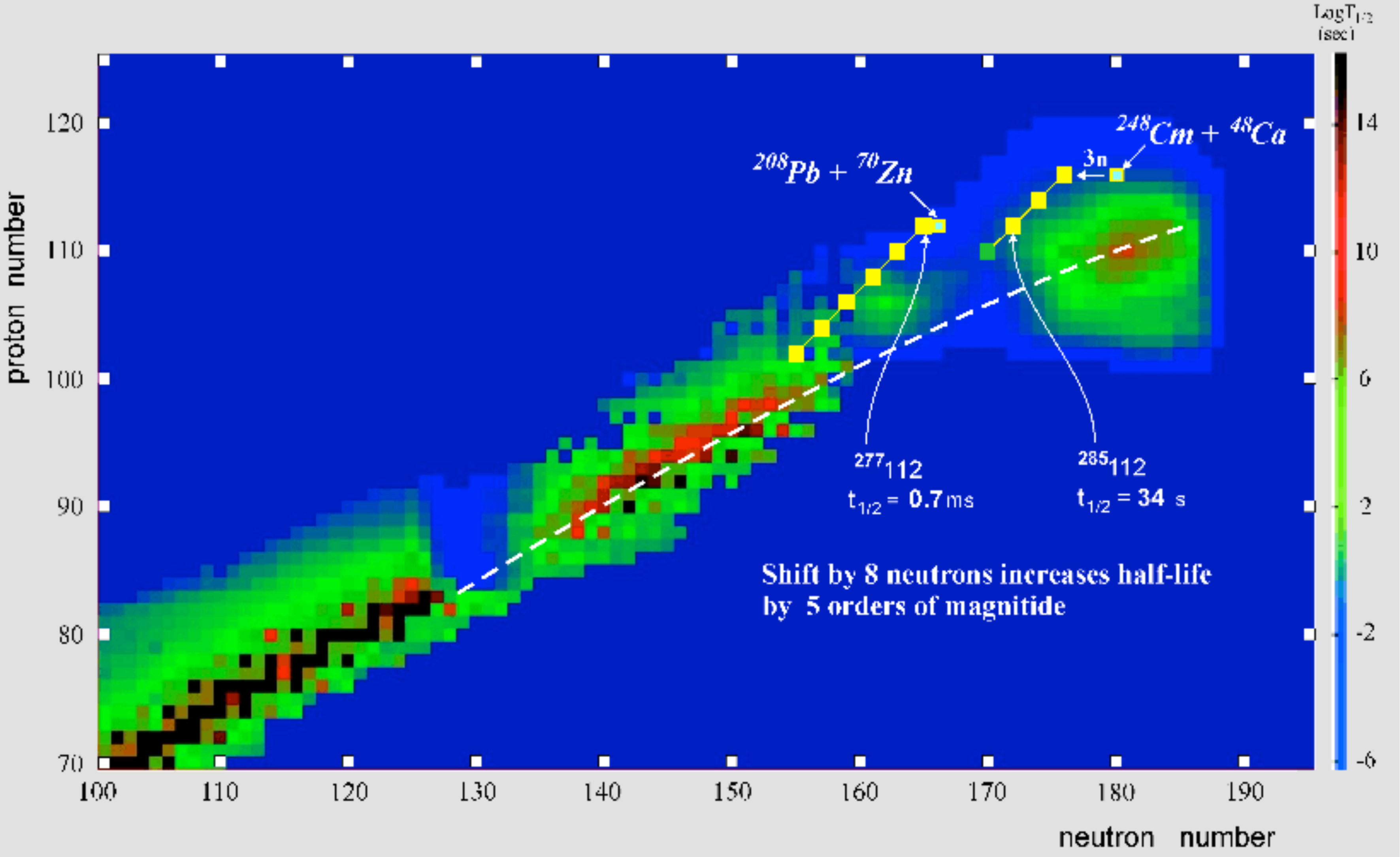
- **Synthesis of new neutron-rich nuclei**

Damped Collisions

Multi-nucleon transfer reactions

Reactions with radioactive beams (Fusion and Multi-nucleon transfer)

We are still far from the line of stability

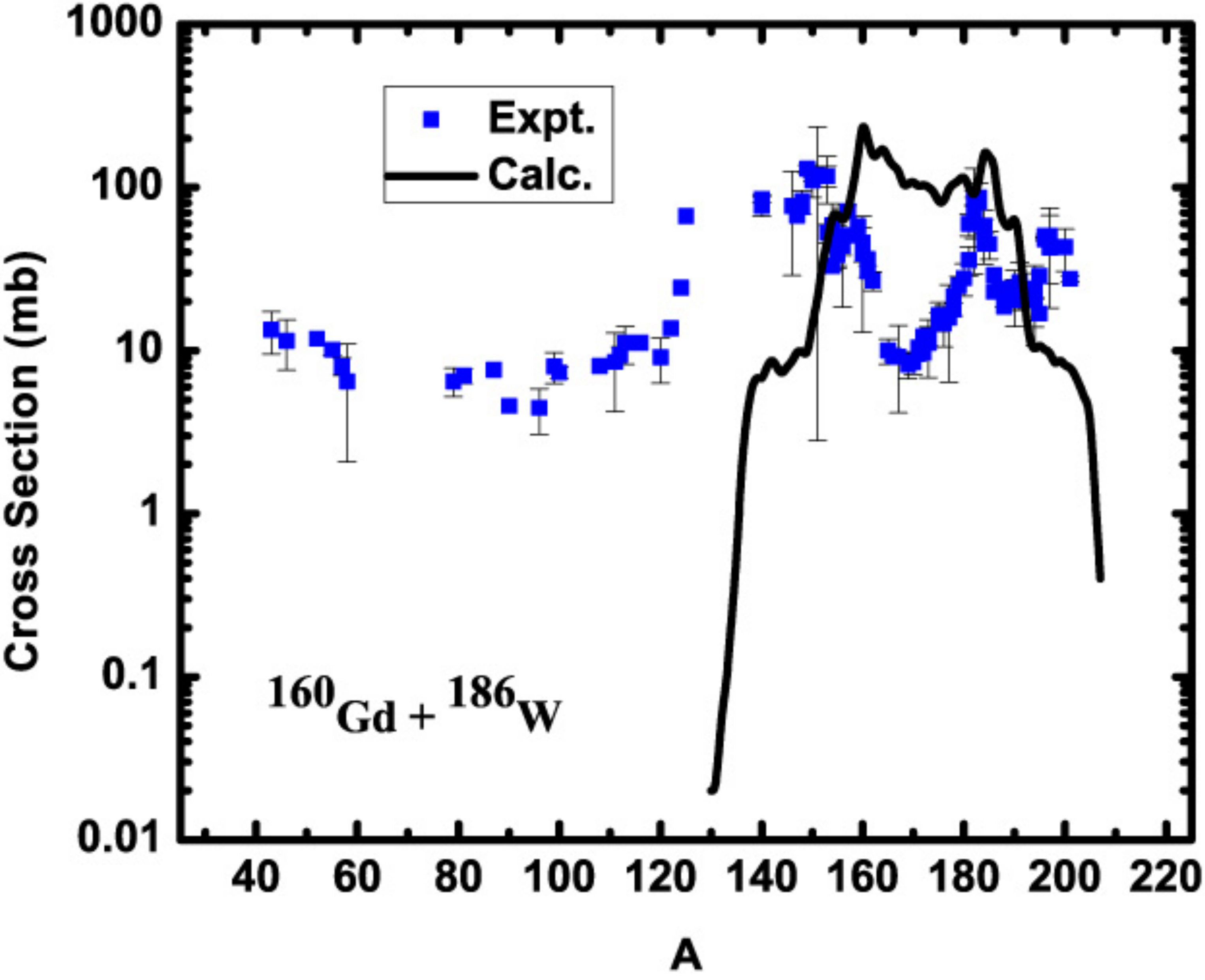


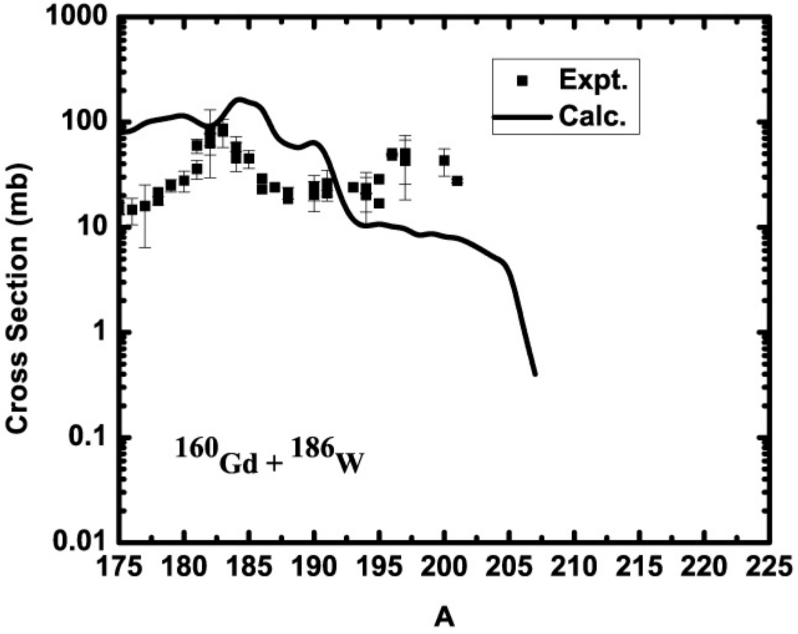
Shift by 8 neutrons increases half-life by 5 orders of magnitide

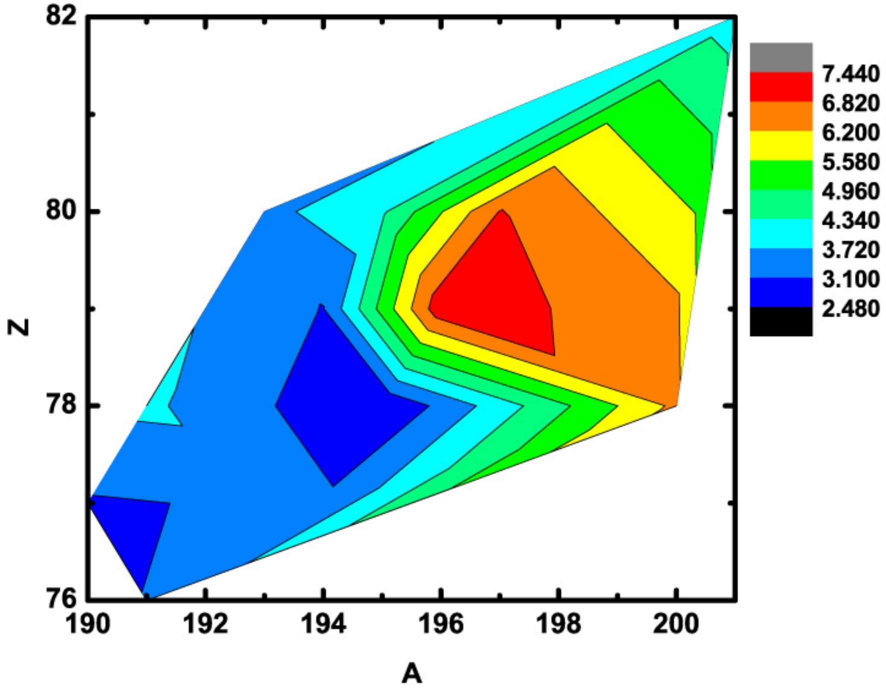
Zagrebaev and Greiner, IRIS 10

Damped Collisions—*A* new path to the superheavy nuclei?

- **Zagrebaev and Greiner have predicted that damped collisions (such as ^{232}Th + ^{250}*Cf*, ^{238}U+^{238}U, ^{238}U +^{248}Cm) might produce new n-rich isotopes of *Cn*.**
- **Surrogate for this reaction is ^{160}Gd + ^{184}W. Because of difficulties in studying the damped collisions of the heaviest nuclei, it has been suggested to study this surrogate reaction.**


Cross Section (mb)
1000
100
10
1
0.1
0.01
40
60
80
100
120
140
160
180
200
220
A
Expt.
Calc.
^{160}Gd + ^{186}W


Expt.
Calc.
Cross Section (mb)
1000
100
10
1
0.1
0.01
175
180
185
190
195
200
205
210
215
220
225
A
^{160}Gd + ^{186}W

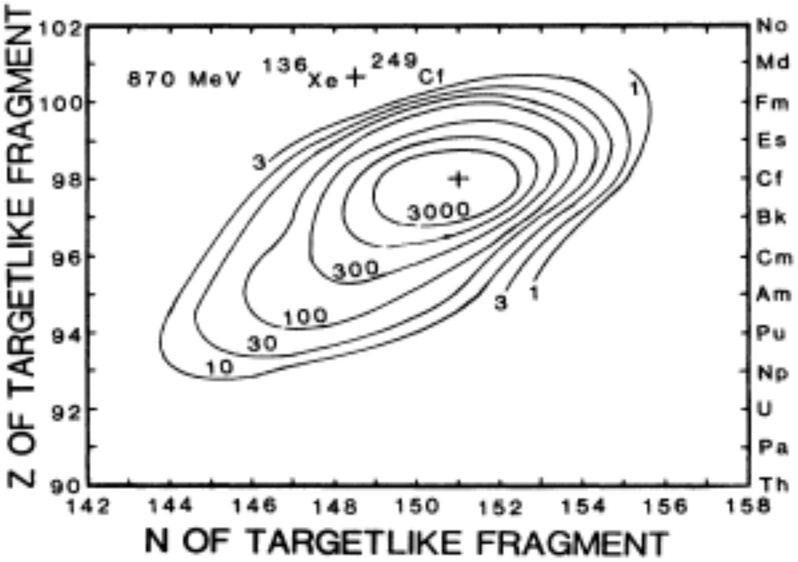

82
80
78
76
Z
190
192
194
196
198
200
A
7.440
6.820
6.200
5.580
4.960
4.340
3.720
3.100
2.480

Multi-nucleon transfer reactions (Pollarolo, IRIS10) Phenomenology of MNT

- The system does not reach charge equilibration. The population in the (N,Z) plane is dictated by the $\mathbf{Q}_{\mathbf{opt}}$
- For each transferred neutron the cross section drops by a constant factor (3.5) **(sequential transfer)**
- The ONE-neutron transfer channel is much larger than the ONE-proton transfer channel
- The pure TWO-proton transfer is as large as the ONE-proton transfer **(pair-transfer mode)**

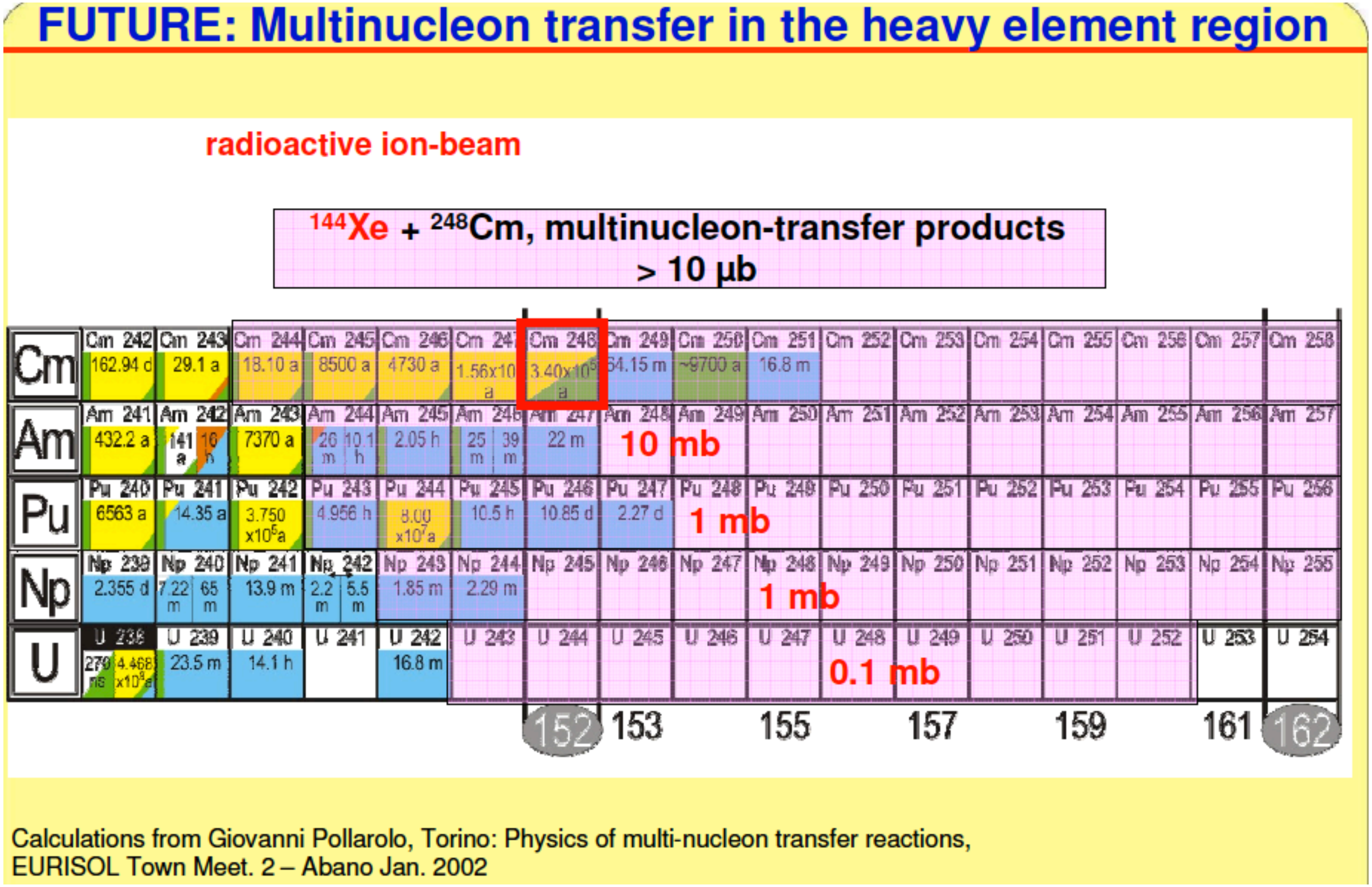
MNT for the Actinides

- Conventional wisdom based on experiment is that you only make nuclei with $Z < Z_{tgt}$.



Gregorich et al. PRC 35, 2117 (1985)

An Example of Interest



FUTURE: Multinucleon transfer in the heavy element region

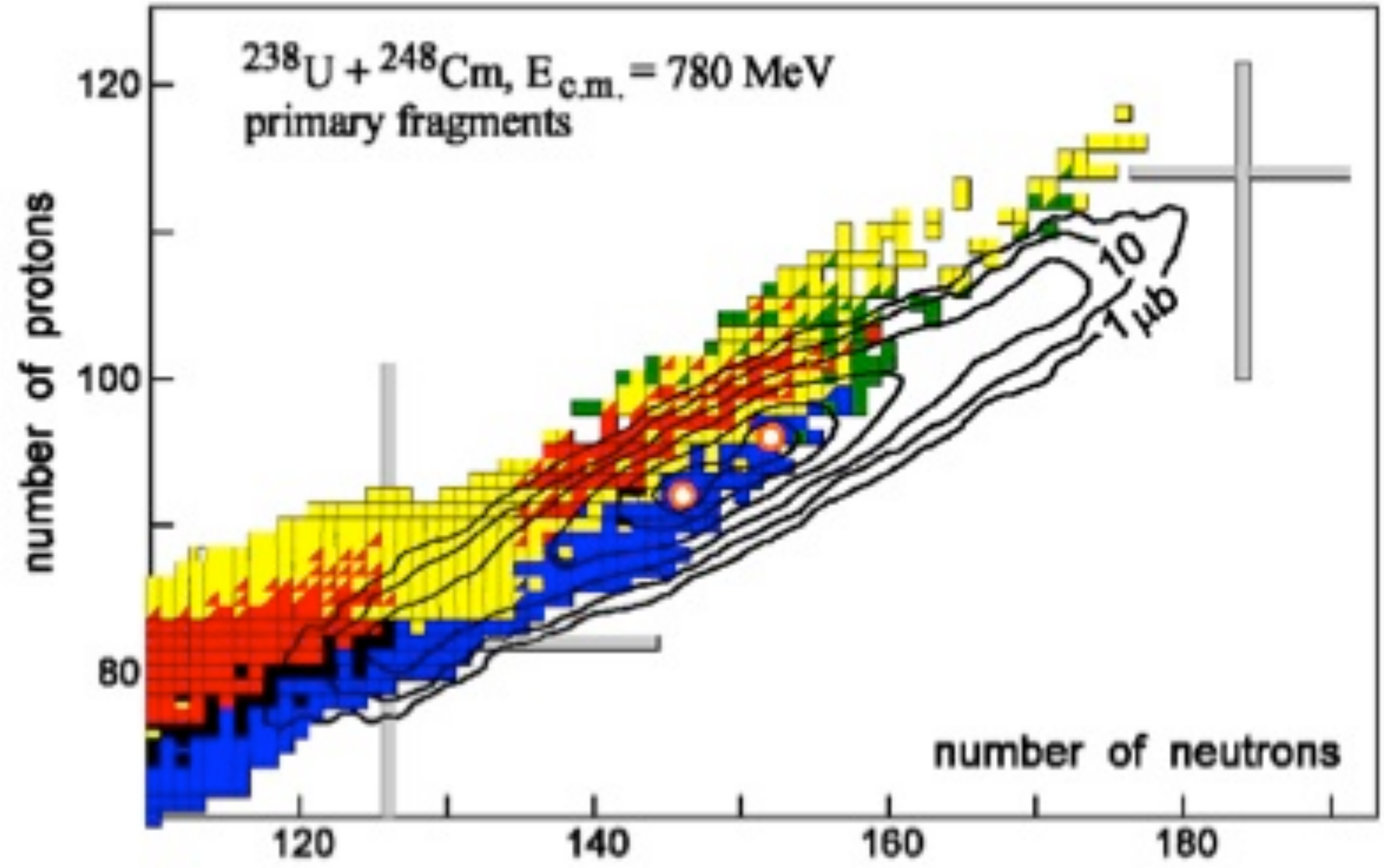
radioactive ion-beam

^{144}Xe + ^{248}Cm, multinucleon-transfer products > 10 µb

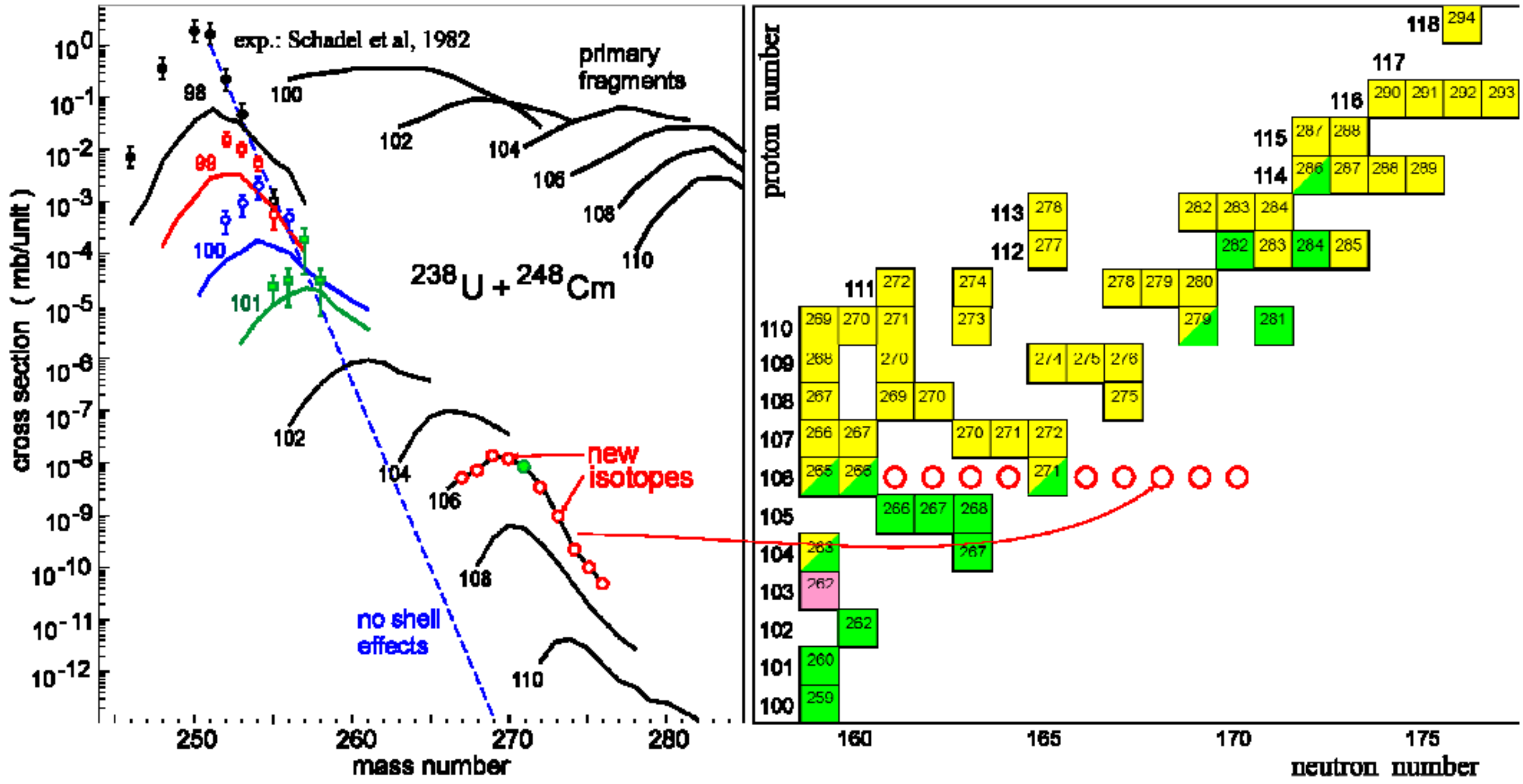
Cm	Cm 242 162.94 d	Cm 243 29.1 a	Cm 244 18.10 a	Cm 245 8500 a	Cm 246 4730 a	Cm 247 1.56x10 a	Cm 248 3.40×10^5 a	Cm 249 64.15 m	Cm 250 ~9700 a	Cm 251 16.8 m	Cm 252	Cm 253	Cm 254	Cm 255	Cm 256	Cm 257	Cm 258
Am	Am 241 432.2 a	Am 242 141 a 16 h	Am 243 7370 a	Am 244 26 m 10.1 h	Am 245 2.05 h	Am 246 25 m 39 m	Am 247 22 m	Am 248 10 mb	Am 249	Am 250	Am 251	Am 252	Am 253	Am 254	Am 255	Am 256	Am 257
Pu	Pu 240 6563 a	Pu 241 14.35 a	Pu 242 3.750 $\times10^5$a	Pu 243 4.956 h	Pu 244 8.00 $\times10^7$a	Pu 245 10.5 h	Pu 246 10.85 d	Pu 247 2.27 d	Pu 248 1 mb	Pu 249	Pu 250	Pu 251	Pu 252	Pu 253	Pu 254	Pu 255	Pu 256
Np	Np 239 2.355 d	Np 240 7.22 m 65 m	Np 241 13.9 m	Np 242 2.2 m 5.5 m	Np 243 1.85 m	Np 244 2.29 m	Np 245	Np 246	Np 247	Np 248 1 mb	Np 249	Np 250	Np 251	Np 252	Np 253	Np 254	Np 255
U	U 238 270 ns 4.468 $\times10^9$a	U 239 23.5 m	U 240 14.1 h	U 241	U 242 16.8 m	U 243	U 244	U 245	U 246	U 247	U 248 0.1 mb	U 249	U 250	U 251	U 252	U 253	U 254
							152	153		155		157		159		161	162

Calculations from Giovanni Pollarolo, Torino: Physics of multi-nucleon transfer reactions,
EURISOL Town Meet. 2 – Abano Jan. 2002

What’s New?



Zagrebaev and Greiner

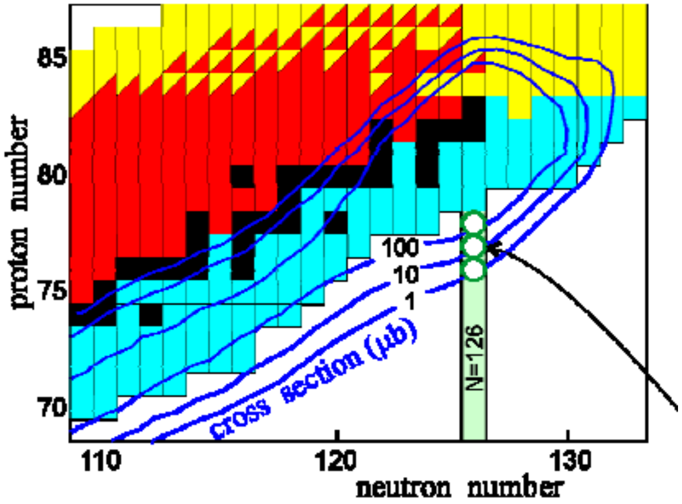


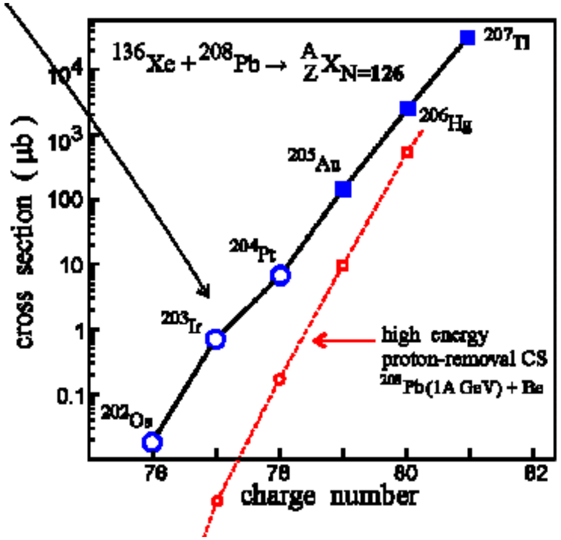
Zagrebaev and Greiner

^{136}Xe + ^{208}Pb

A Surrogate that is Important for Several Reasons

- N=126 r-process waiting point

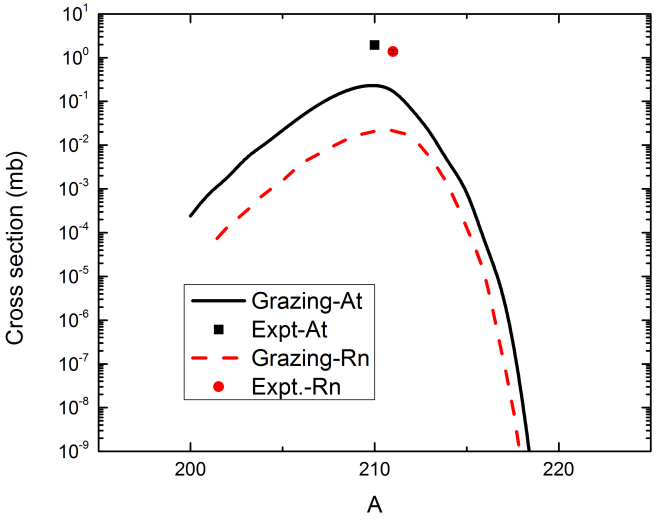




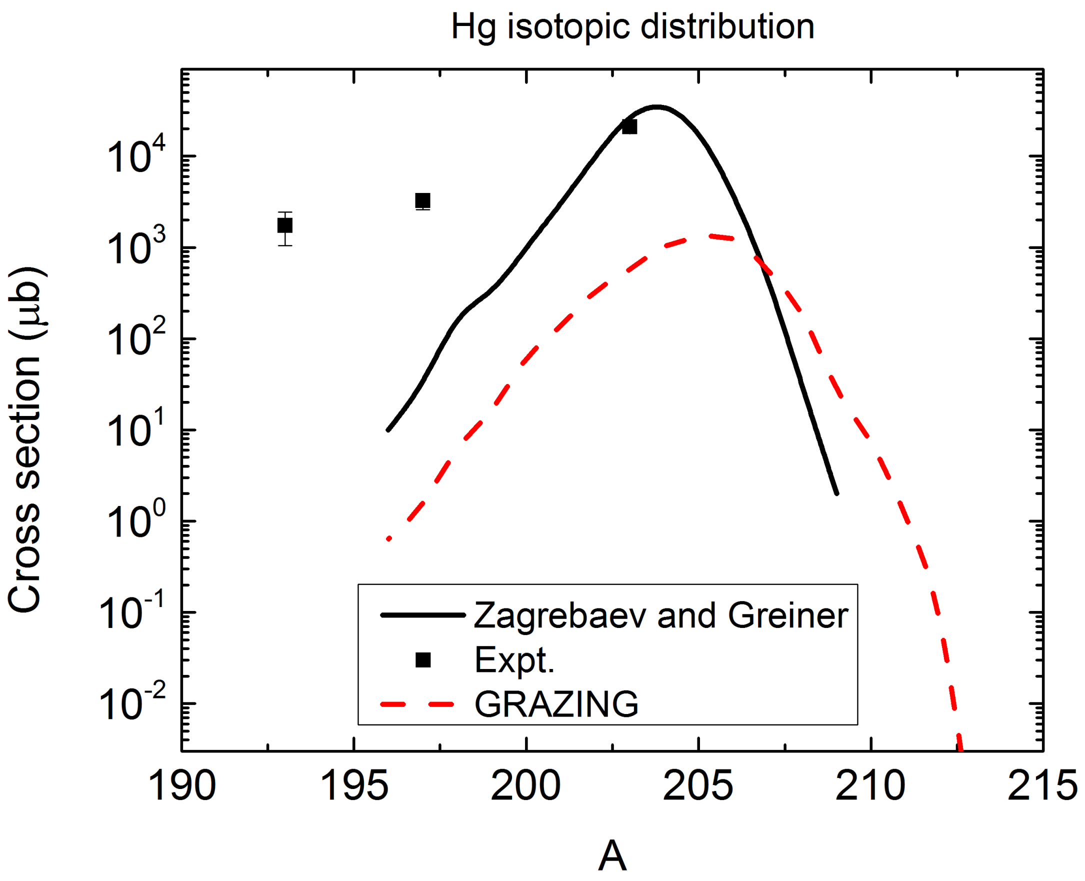
J.S. Grell, et al. (OSU) have studied this reaction at ATLAS using radiochemistry

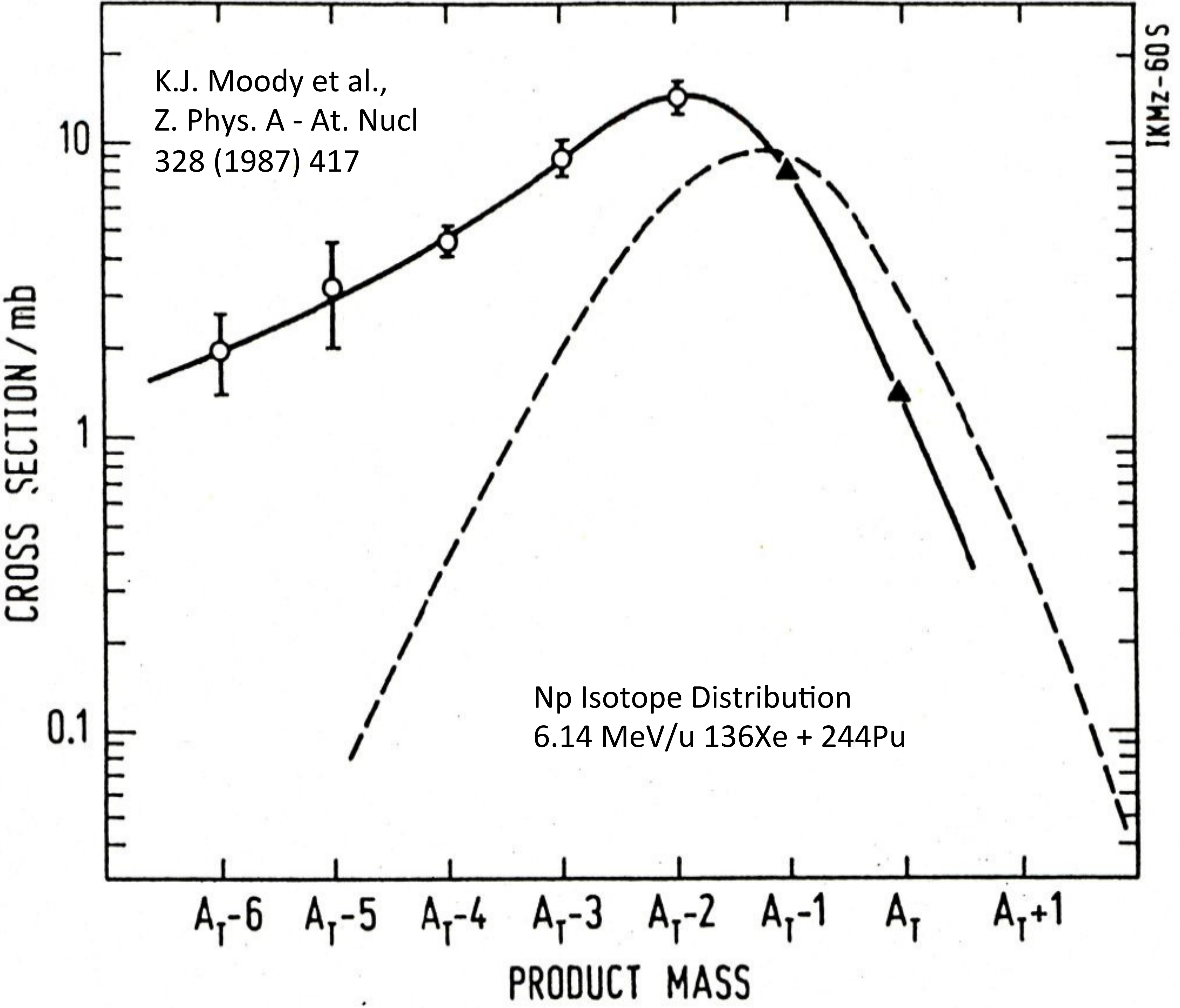
Magnitude of Trans-Target Transfer Cross Sections

N	Product	ΔZ	ΔN	σ(mb)	E_{cm}(MeV)
125	^{210}At	+3	-1	0.078	470
125	^{210}At	+3	-1	1.93	500
125	^{211}Rn	+4	-1	1.37	500



Hg (Z= 80) isotopic distributions

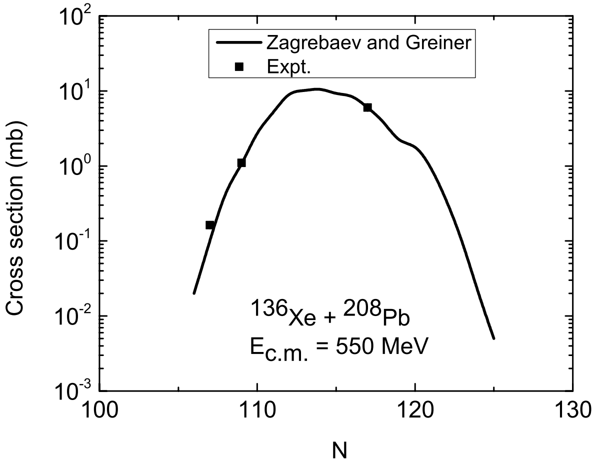


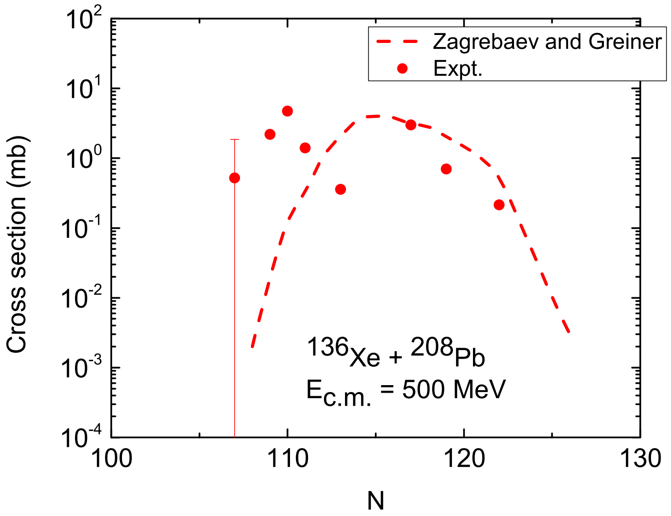


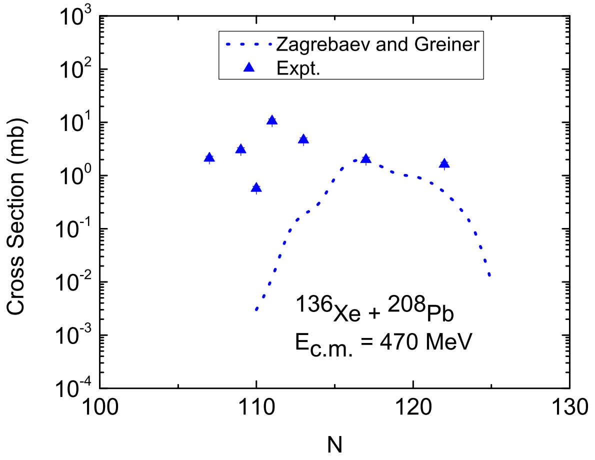
K.J. Moody et al.,
Z. Phys. A - At. Nucl
328 (1987) 417

Np Isotope Distribution
6.14 MeV/u 136Xe + 244Pu

Pt (Z= 76) isotopic distributions







Applying what we know about the synthesis of the heaviest nuclei to the problem of making new heavy nuclei with radioactive nuclear beams using complete fusion reactions

Calculational Model For RIB-Induced Reactions

RIA/SPIRAL2/FRIB…Beam List

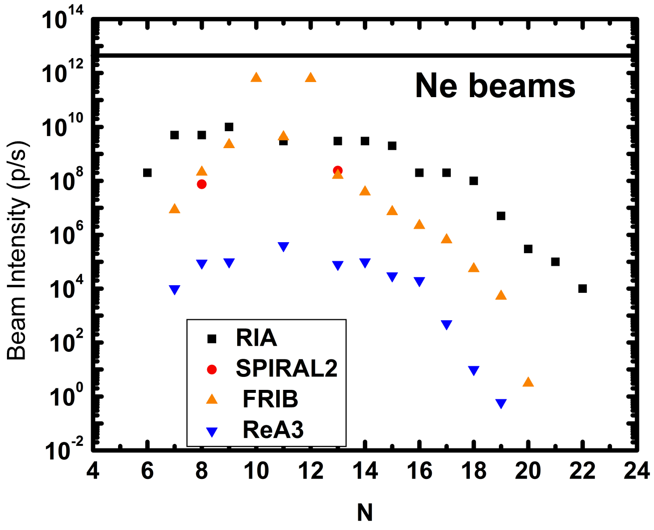
- All "stable" targets

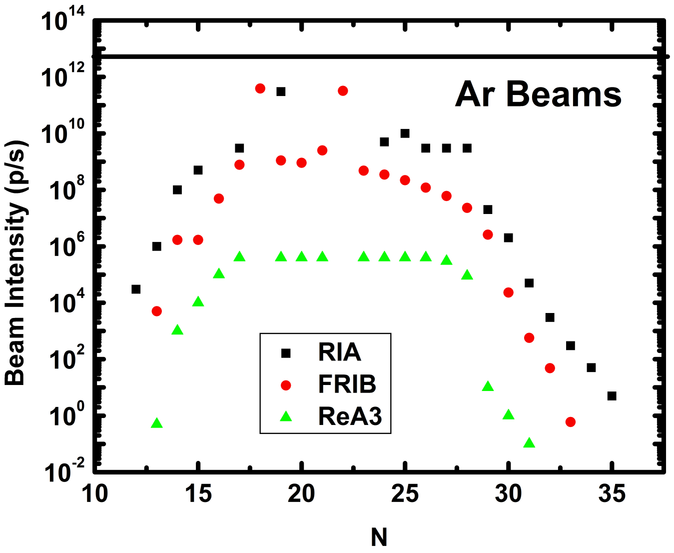
- Fusion Probability

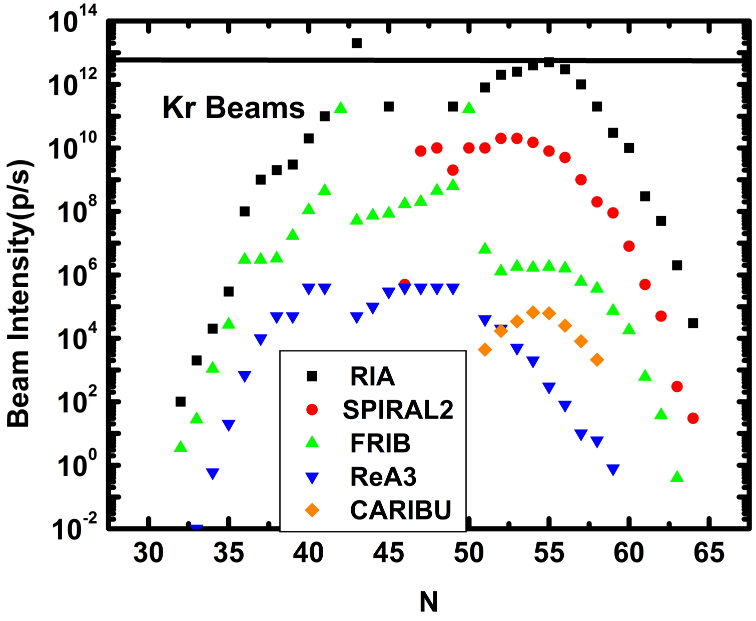
- Survival Probability

Yield in atoms/day

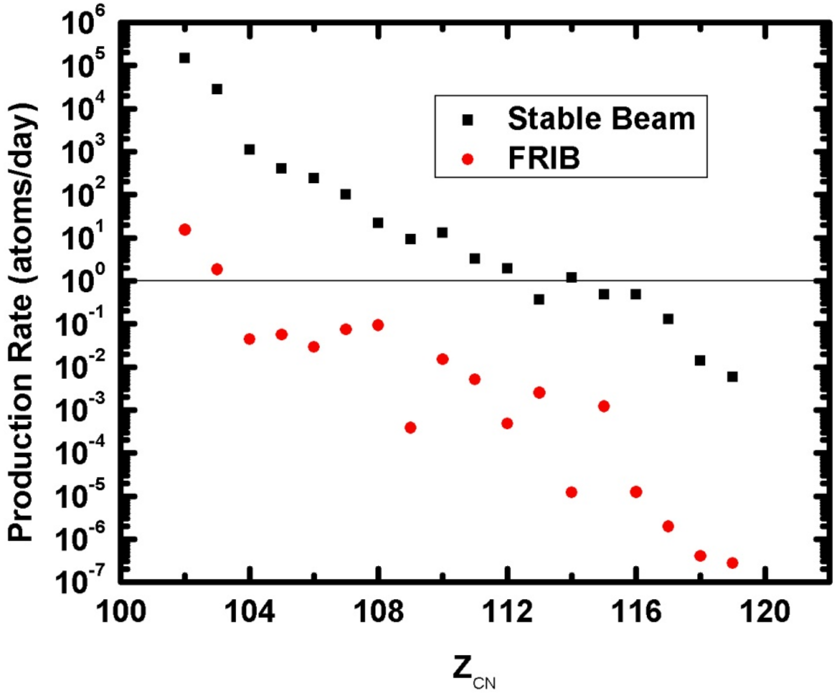
What RIBs are likely to be most useful in the short term?



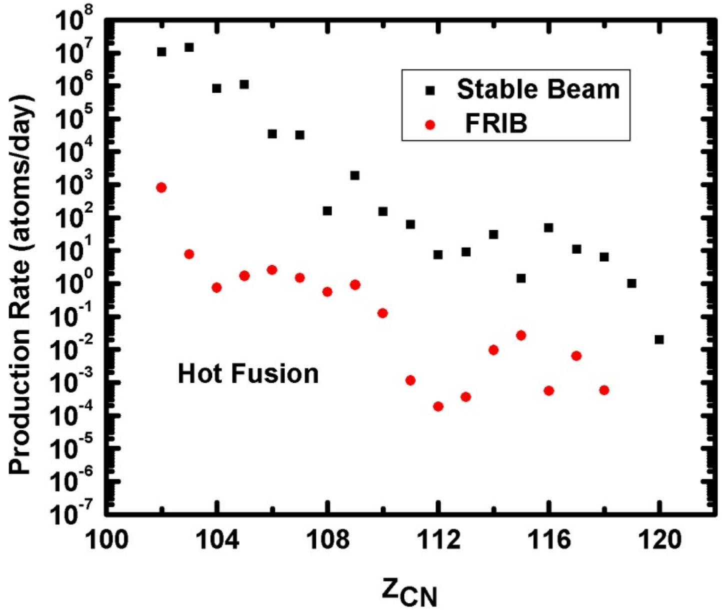




Cold fusion



New elements will NOT be produced at RIB facilities



Atomic Physics and Chemistry of the Transactinides

>5 atom/day list

➢ ^{264}Rf	^{252}Cf(^{16}C,4n)
➢ ^{265}Db	^{249}Bk(^{20}O,4n)
➢ ^{268}Sg	^{252}Cf(^{20}O,4n)
➢ ^{267}Bh	^{252}Cf(^{21}F,6n)

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

Reactants	Products	FRIB Beam Intensity (p/s)	Production Rate (atoms/ day)
^{26}Ne + ^{248}Cm	^{271}Sg + 4n	2.2×10^6	0.004
^{30}Mg + ^{244}Pu	^{270}Sg + 4n	7.1×10^6	1
^{29}Mg + ^{244}Pu	^{269}Sg + 4n	3.6×10^7	0.2
^{20}O + ^{252}Cf	^{268}Sg + 4n	1.5×10^8	5
^{23}Ne + ^{248}Cm	^{267}Sg + 4n	1.6×10^8	1

Beta stability is at ^{276}Sg

Targeted Radioactive Beams

- Special opportunities may exist if RNB facilities focus on producing a beam of particular interest.
- Example: ^{46}Ar (from ^{48}Ca fragmentation)

FRIB "fast beam rate" 1.1×10^{10}

FRIB "reaccelerated beam rate" 2.3×10^{7}

Reaction	Beam Intensity (p/s)	Cross Section (pb)	Atoms/day
^{238}U(^{48}Ca, 3n)^{283}Cn	3×10^{12}	0.7	0.5
^{244}Pu(^{46}Ar, 4n)^{286}Cn	1.1×10^{10}	250	0.6
^{244}Pu(^{46}Ar, 3n)^{287}Cn	1.1×10^{10}	140	0.3

The Take-Away

- There are credible ways to make new n-rich heavy nuclei that will produce longer lived nuclei of importance to atomic physics and chemistry.
- It is very difficult to approach N=184.