Lecture 2:

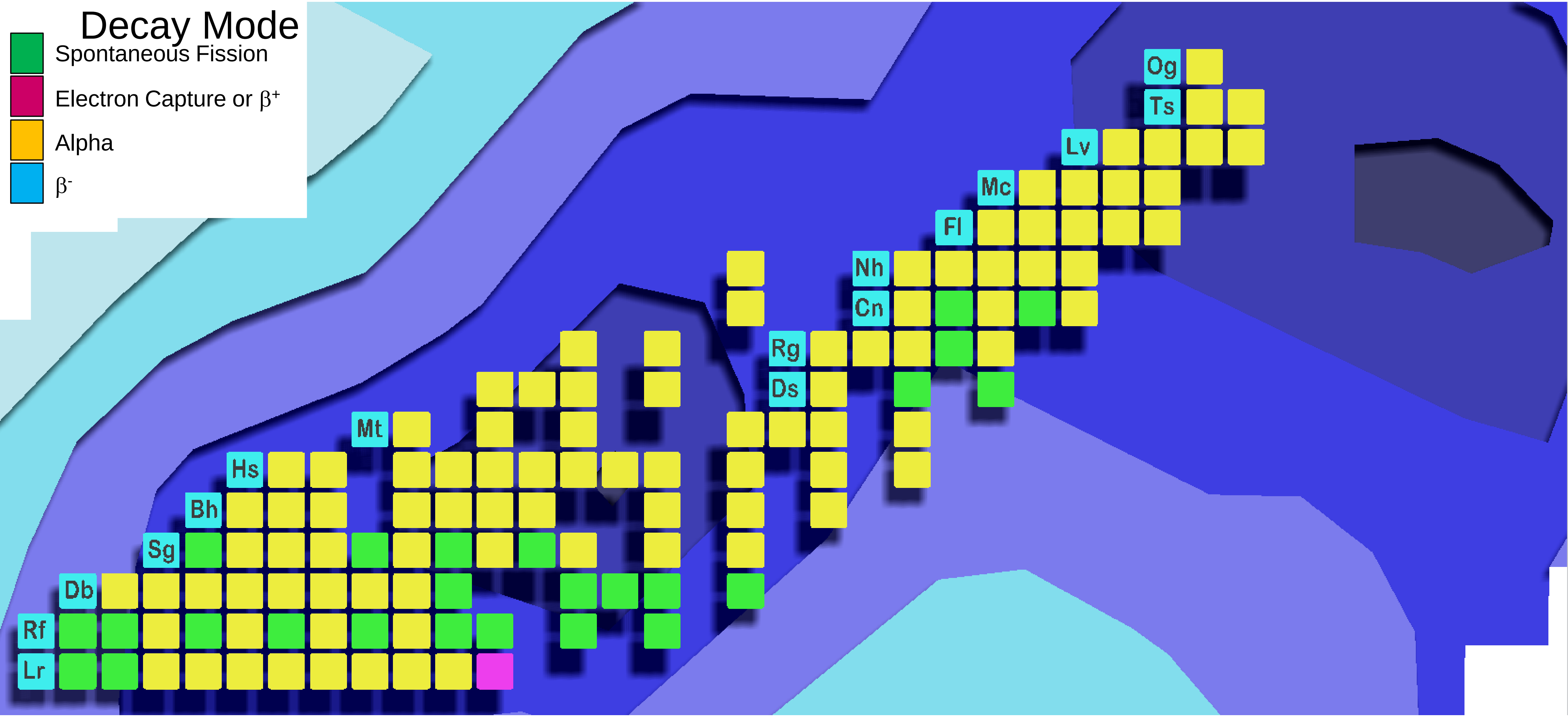
How to Make the Heaviest Elements

Periodic Table

1 1IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 **H** Hydrogen 1.008																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012											5 **B** Boron 10.811	6 **C** Carbon 12.011	7 **N** Nitrogen 14.007	8 **O** Oxygen 15.999	9 **F** Fluorine 18.998	10 **Ne** Neon 20.180
11 **Na** Sodium 22.99	12 **Mg** Magnesium 24.305											13 **Al** Aluminum 26.982	14 **Si** Silicon 28.086	15 **P** Phosphorus 30.974	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.453	18 **Ar** Argon 39.948
19 **K** Potassium 39.098	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.956	22 **Ti** Titanium 47.867	23 **V** Vanadium 50.942	24 **Cr** Chromium 51.996	25 **Mn** Manganese 54.938	26 **Fe** Iron 55.845	27 **Co** Cobalt 58.933	28 **Ni** Nickel 58.693	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.38	31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.631	33 **As** Arsenic 74.922	34 **Se** Selenium 78.971	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.789
37 **Rb** Rubidium 85.468	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.906	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.906	42 **Mo** Molybdenum 95.95	43 **Tc** Technetium 98.907	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.906	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.868	48 **Cd** Cadmium 112.414	49 **In** Indium 114.818	50 **Sn** Tin 118.711	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.6	53 **I** Iodine 126.904	54 **Xe** Xenon 131.294
55 **Cs** Cesium 132.905	56 **Ba** Barium 137.328	57-71	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.948	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217	78 **Pt** Platinum 195.085	79 **Au** Gold 196.967	80 **Hg** Mercury 200.592	81 **Tl** Thallium 204.383	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.980	84 **Po** Polonium [208.982]	85 **At** Astatine 209.987	86 **Rn** Radon 222.018
87 **Fr** Francium 223.020	88 **Ra** Radium 226.025	89-103	104 **Rf** Rutherfordium [261]	105 **Db** Dubnium [262]	106 **Sg** Seaborgium [266]	107 **Bh** Bohrium [264]	108 **Hs** Hassium [269]	109 **Mt** Meitnerium [278]	110 **Ds** Darmstadtium [281]	111 **Rg** Roentgenium [280]	112 **Cn** Copernicium [285]	113 **Nh** Nihonium [286]	114 **Fl** Flerovium [289]	115 **Mc** Moscovium [286]	116 **Lv** Livermorium [293]	117 **Ts** Tennessine [294]	118 **Og** Oganesson [294]

Lanthanide Series	57 **La** Lanthanum 138.905	58 **Ce** Cerium 140.116	59 **Pr** Praseodymium 140.908	60 **Nd** Neodymium 144.243	61 **Pm** Promethium 144.913	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.964	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.925	66 **Dy** Dysprosium 162.500	67 **Ho** Holmium 164.930	68 **Er** Erbium 167.259	69 **Tm** Thulium 168.934	70 **Yb** Ytterbium 173.055	71 **Lu** Lutetium 174.967
Actinide Series	89 **Ac** Actinium 227.028	90 **Th** Thorium 232.038	91 **Pa** Protactinium 231.036	92 **U** Uranium 238.029	93 **Np** Neptunium 237.048	94 **Pu** Plutonium 244.064	95 **Am** Americium 243.061	96 **Cm** Curium 247.070	97 **Bk** Berkelium 247.070	98 **Cf** Californium 251.080	99 **Es** Einsteinium [254]	100 **Fm** Fermium 257.095	101 **Md** Mendelevium 258.1	102 **No** Nobelium 259.101	103 **Lr** Lawrencium [262]

Chart of the Nuclides: 2019

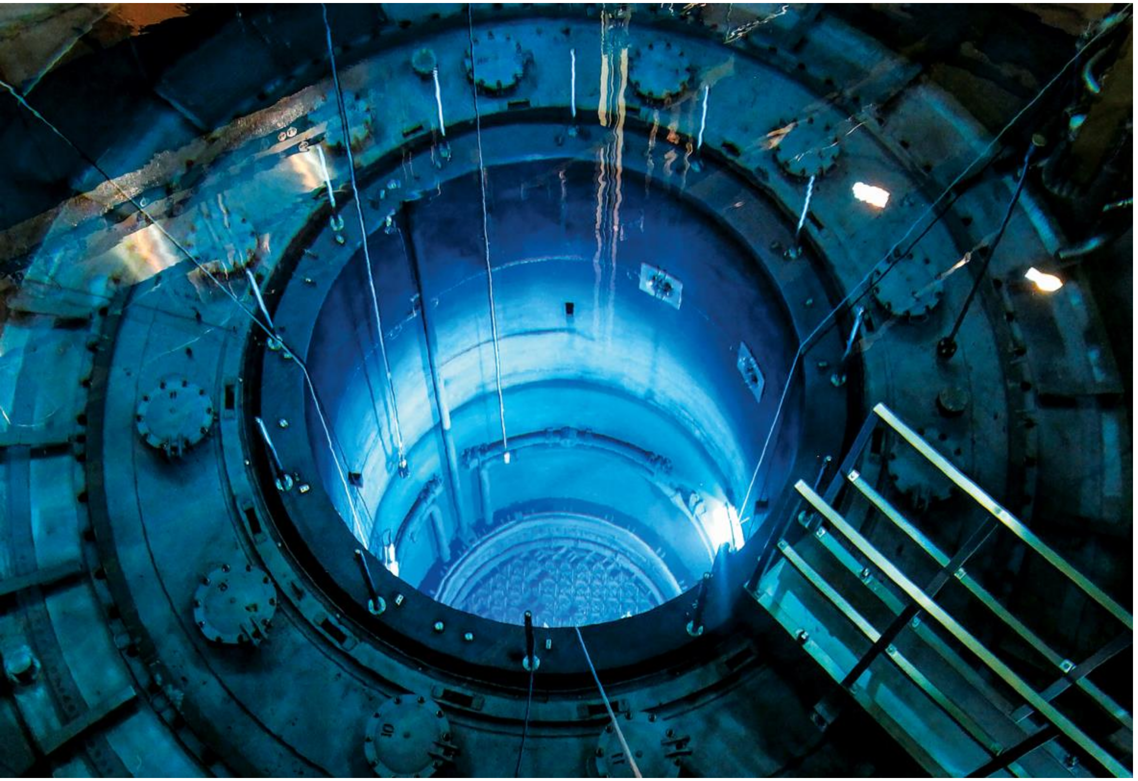


Question: How are new elements made?

Three techniques for making elements

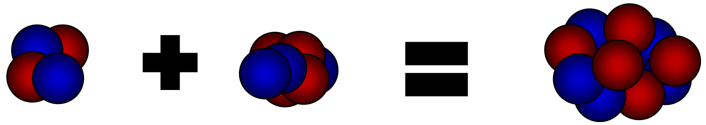
Sequential neutron capture and beta decay

- Oldest (and natural) methods for production of new elements
- Used beginning 1940

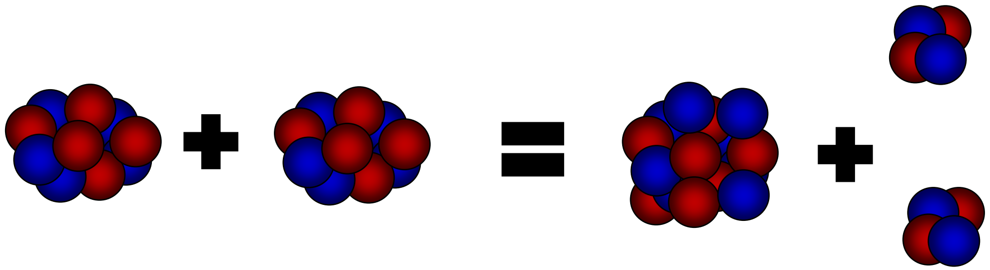


Compound Nucleus Reactions

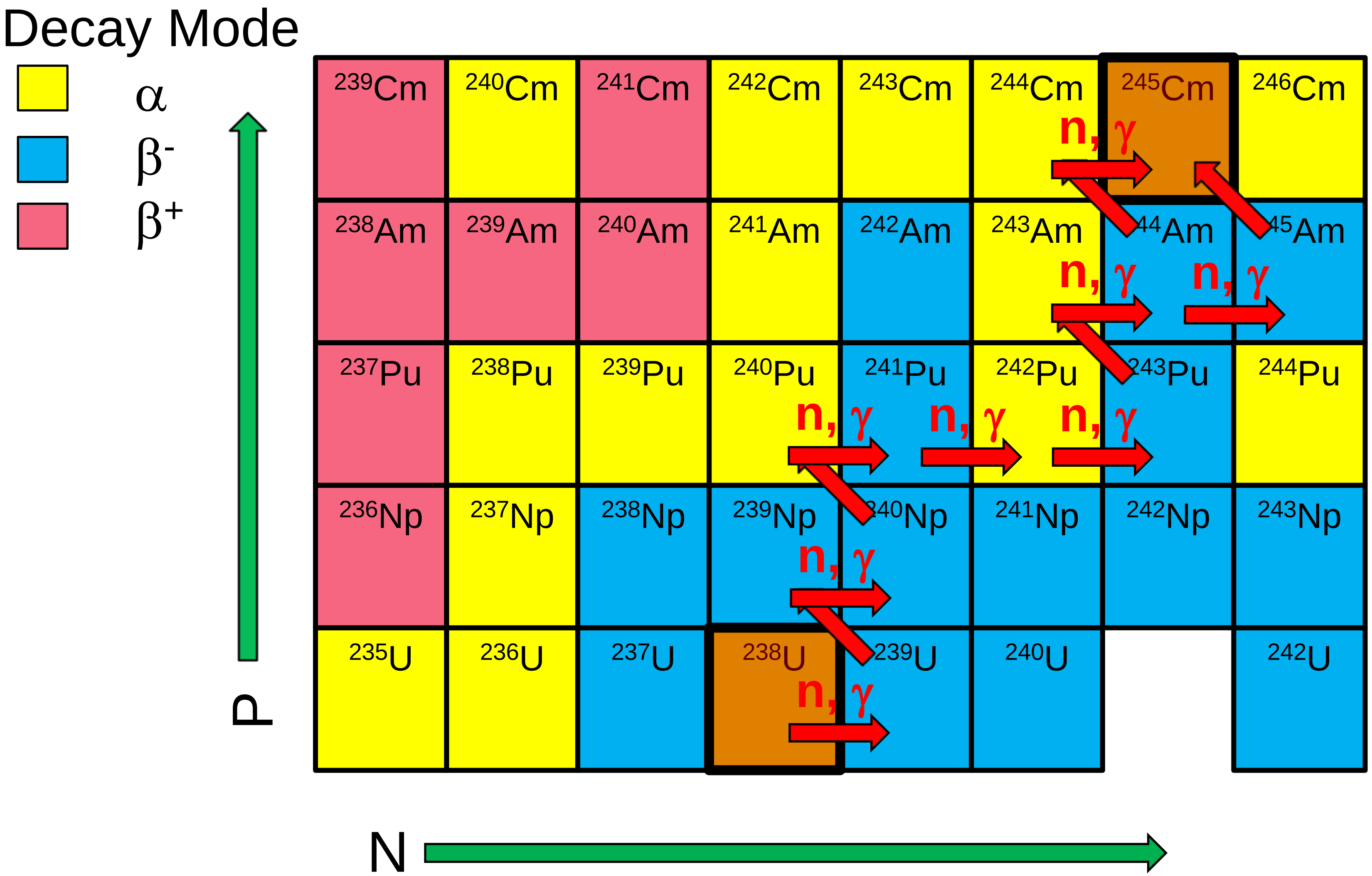
- Add two nuclei together!



Multi-nucleon Transfer Reactions



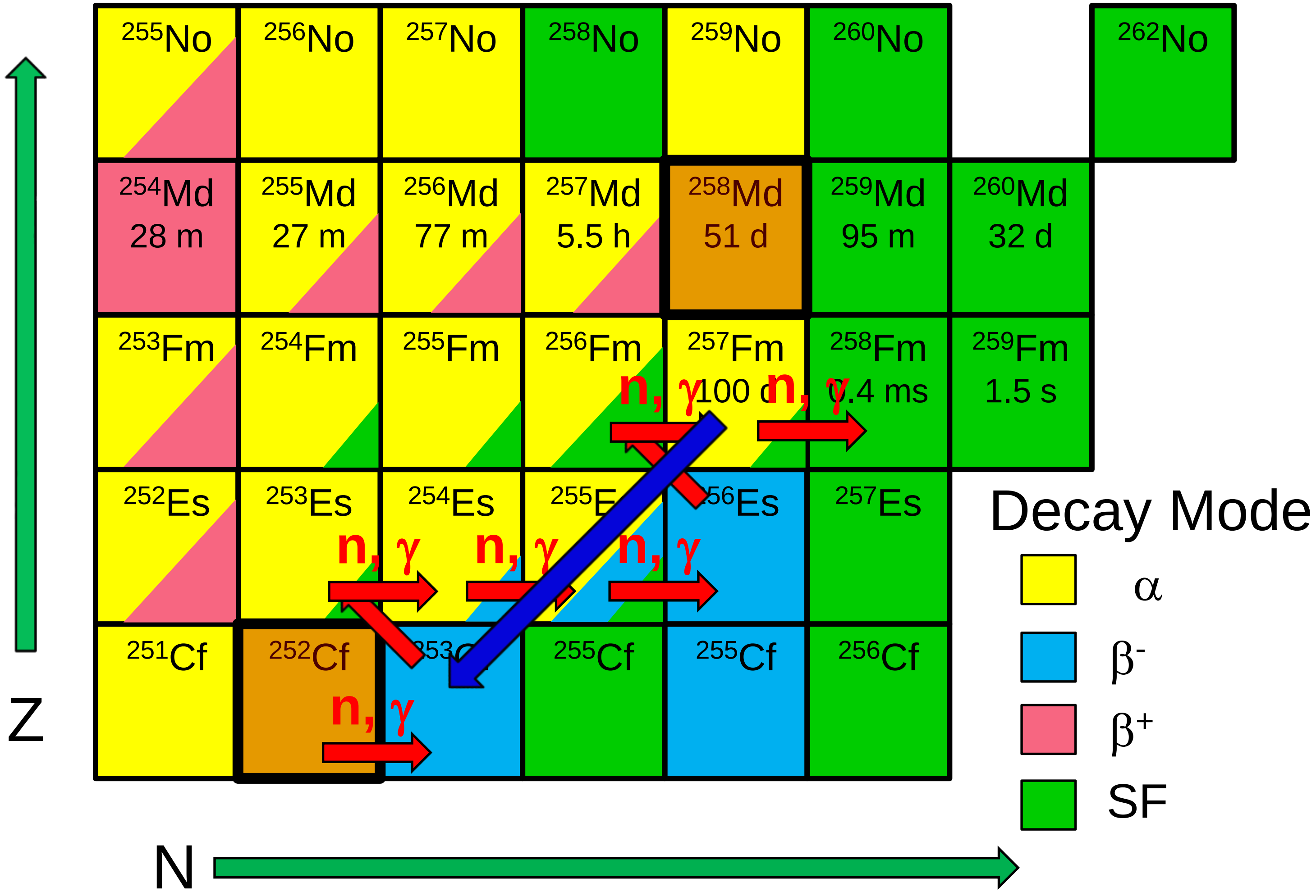
How to make heavy elements – Nuclear Reactors



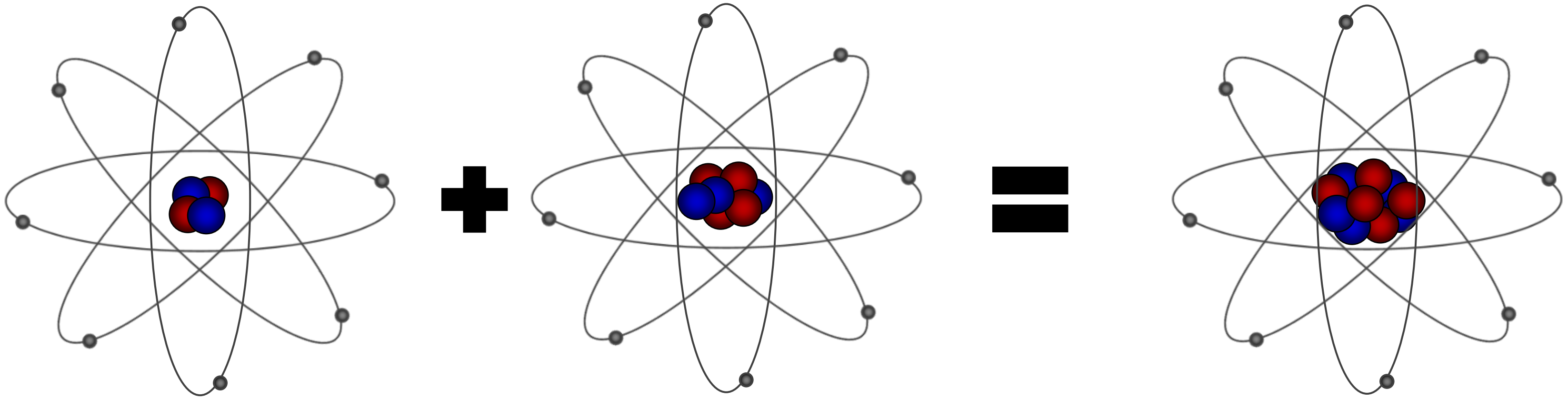
Making Transactinides: Problems Arise

Fermium gap

- Consists of short-lived, SF/alpha decaying Fm isotopes
- Impedes formation of nuclei with Z>100 in nuclear reactors
- Nuclear and supernova explosions have higher neutron fluences ➔ gap may be bypassed in nature



Pushing Beyond Mendelevium: Compound Nucleus Reactions



$^{48}_{20}Ca$ $^{243}_{95}Am$ $^{291}_{115}Mc$

Fuse two lighter nuclei to make heavier ones

- What are compound nucleus reactions
- How to experimentally make/study
- Types of compound nucleus reactions

Compound Nucleus Reactions: Theory

Process of SHE formation modeled by three-step process

Production cross section

$$\sigma_{EVR}(E_{c.m.}) = \sum_J \sigma_{cap}(E_{c.m}, J) P_{CN}(E_{c.m}, J) W_{sur}(E_{c.m}, J)$$

Capture cross section

Fusion Probability

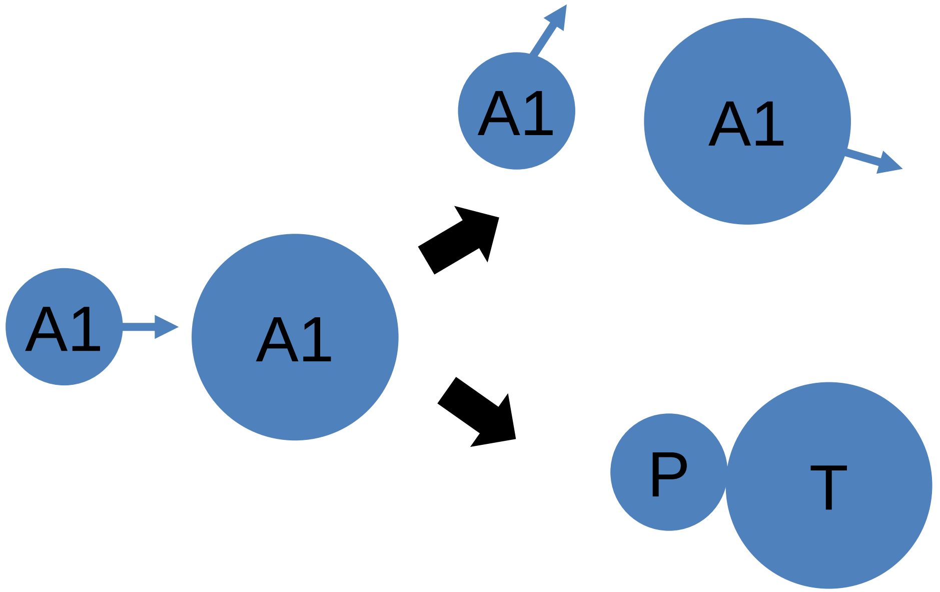
Survival

Fusion = (sticking) x (diffusion) x (survival)

Process of SHE formation modeled by three-step process

$$\sigma_{EVR}(E_{c.m.}) = \sum_J \sigma_{cap}(E_{c.m},J)P_{CN}(E_{c.m},J)W_{sur}(E_{c.m},J)$$

Capture



Step 1: Capture

- Probability of colliding nuclei to overcome the Coulomb barrier and come in close contact with overlapped nuclear surfaces
- Competes with elastic and quasi-elastic scattering, few nucleon transfers
- Strongly depends on collision energy and impact parameter

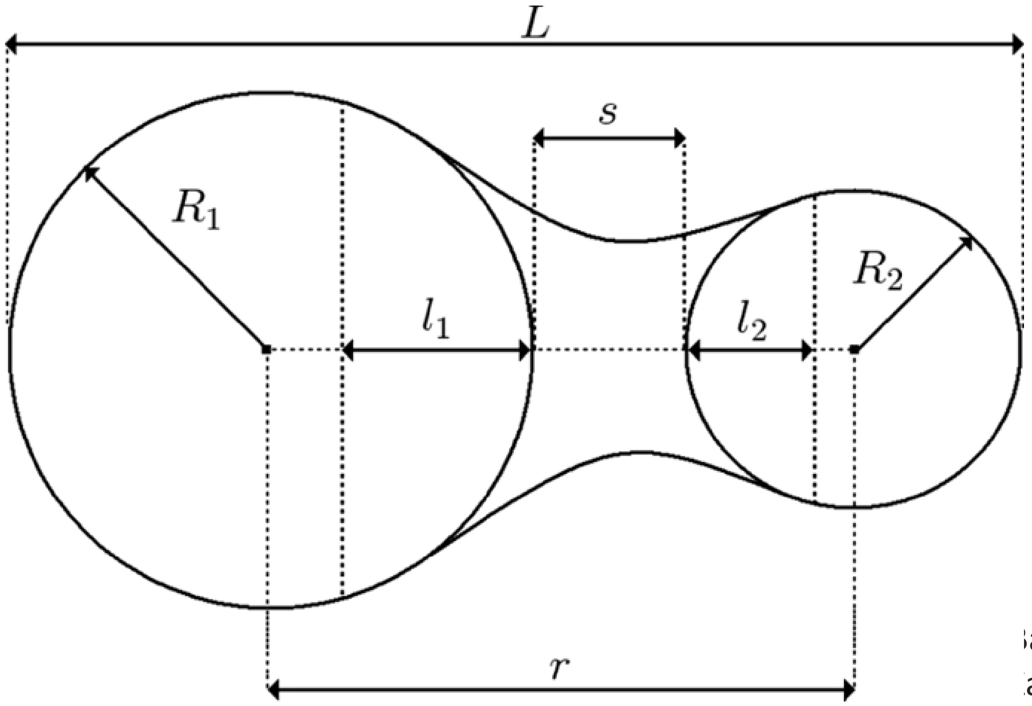
Bau, XJ: Front. Phys., 28 (2020): https://doi.org/10.3389/fphy.2020.00014
Zagrebaev, VI: Nucl. Phys. A, **944** (2015), 257: https://doi.org/10.1016/j.nuclphysa.2015.02.010
Cap, T: Euro. Phys. J. A, **58** (2022) 231: https://doi.org/10.1140/epja/s10050-022-00891-8

Compound Nucleus Reactions: Theory

Process of SHE formation modeled by three-step process

$$\sigma_{EVR}(E_{c.m.}) = \sum_J \sigma_{cap}(E_{c.m},J)P_{CN}(E_{c.m},J)W_{sur}(E_{c.m},J)$$

Fusion



Step 2: Compound Nucleus Formation

- Accounts for probability of two (nearly) touching spheres to fuse

ːau, XJ: Front. Phys., 28 (2020): https://doi.org/10.3389/fphy.2020.00014
ːagrebaev, VI: Nucl. Phys. A, **944** (2015), 257: https://doi.org/10.1016/j.nuclphysa.2015.02.010
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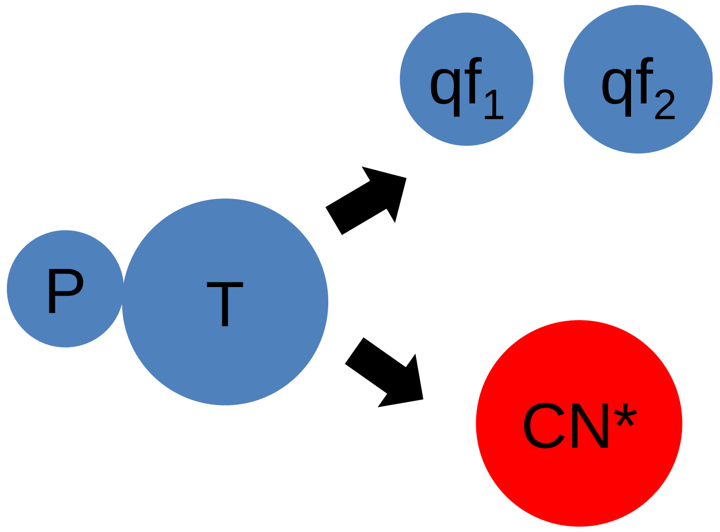
Compound Nucleus Reactions: Theory

Process of SHE formation modeled by three-step process

$$\sigma_{EVR}(E_{c.m.}) = \sum_{J} \sigma_{cap}(E_{c.m},J) P_{CN}(E_{c.m},J) W_{sur}(E_{c.m},J)$$

Fusion



Step 2: Compound Nucleus Formation

- two touching nuclei is transformed into more or less spherical configuration of compound nucleus (CN)
- Competes with quasifission
- CN formed in excited state ➔ has excitation energy and angular momentum

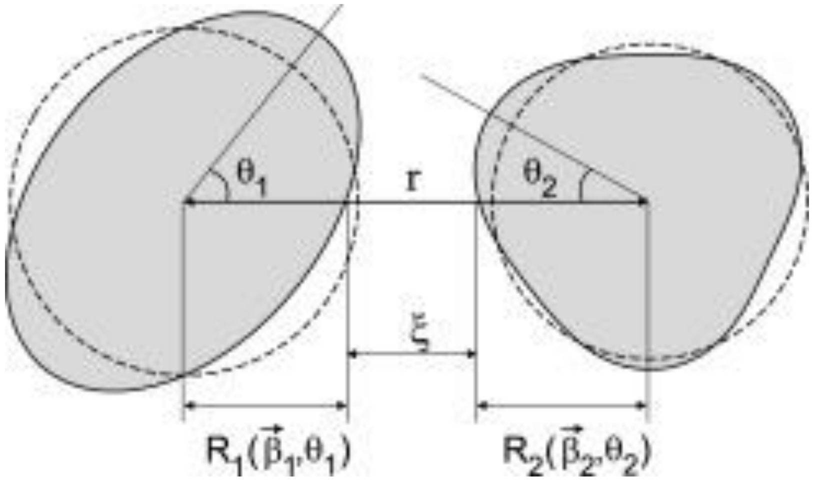
Bau, XJ: Front. Phys., 28 (2020): https://doi.org/10.3389/fphy.2020.00014
Zagrebaev, VI: Nucl. Phys. A, **944** (2015), 257: https://doi.org/10.1016/j.nuclphysa.2015.02.010
Cap, T: Euro. Phys. J. A, **58** (2022) 231: https://doi.org/10.1140/epja/s10050-022-00891-8

Compound Nucleus Reactions: Theory

Process of SHE formation modeled by three-step process

$$\sigma_{EVR}(E_{c.m.}) = \sum_J \sigma_{cap}(E_{c.m}, J) P_{CN}(E_{c.m}, J) W_{sur}(E_{c.m}, J)$$

Fusion



Step 2: Compound Nucleus Formation

- Accounts for probability of two (nearly) touching spheres to fuse
- Or deformed nuclei

Bau, XJ: Front. Phys., 28 (2020): https://doi.org/10.3389/fphy.2020.00014

Zagrebaev, VI: Nucl. Phys. A, **944** (2015), 257: https://doi.org/10.1016/j.nuclphysa.2015.02.010

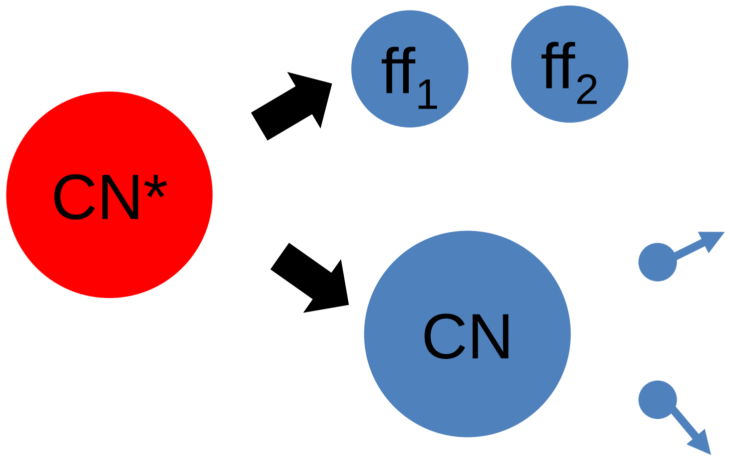
Cap, T: Euro. Phys. J. A, **58** (2022) 231: https://doi.org/10.1140/epja/s10050-022-00891-8

Compound Nucleus Reactions: Theory

Process of SHE formation modeled by three-step process

$$\sigma_{EVR}(E_{c.m.}) = \sum_J \sigma_{cap}(E_{c.m},J)P_{CN}(E_{c.m},J)W_{sur}(E_{c.m},J)$$

Survival



Step 3: Survival

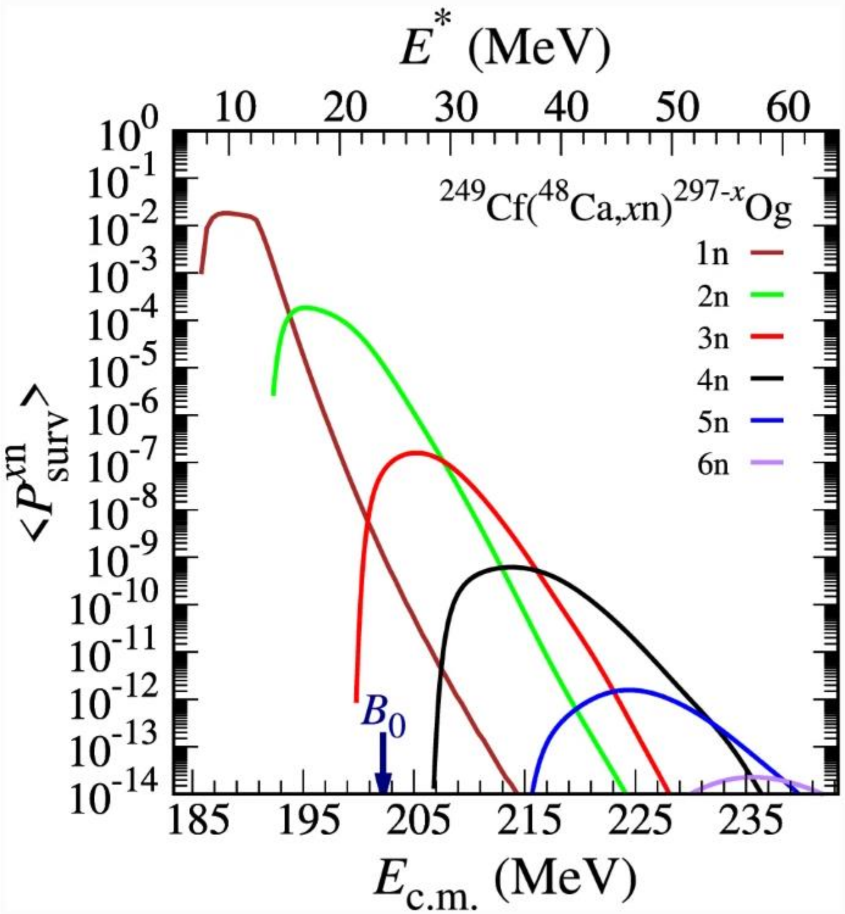
- CN formed in excited state ➔ has excitation energy and angular momentum
- Deexcitation via neutron and gamma emission competes with fission

Bau, XJ: Front. Phys., 28 (2020): https://doi.org/10.3389/fphy.2020.00014
Zagrebaev, VI: Nucl. Phys. A, **944** (2015), 257: https://doi.org/10.1016/j.nuclphysa.2015.02.010
Cap, T: Euro. Phys. J. A, **58** (2022) 231: https://doi.org/10.1140/epja/s10050-022-00891-8

Process of SHE formation modeled by three-step process

$$\sigma_{EVR}(E_{c.m.}) = \sum_J \sigma_{cap}(E_{c.m},J)P_{CN}(E_{c.m},J)W_{sur}(E_{c.m},J)$$

Survival



Step 3: Survival

- Survival probability decreases with each additional neutron emission

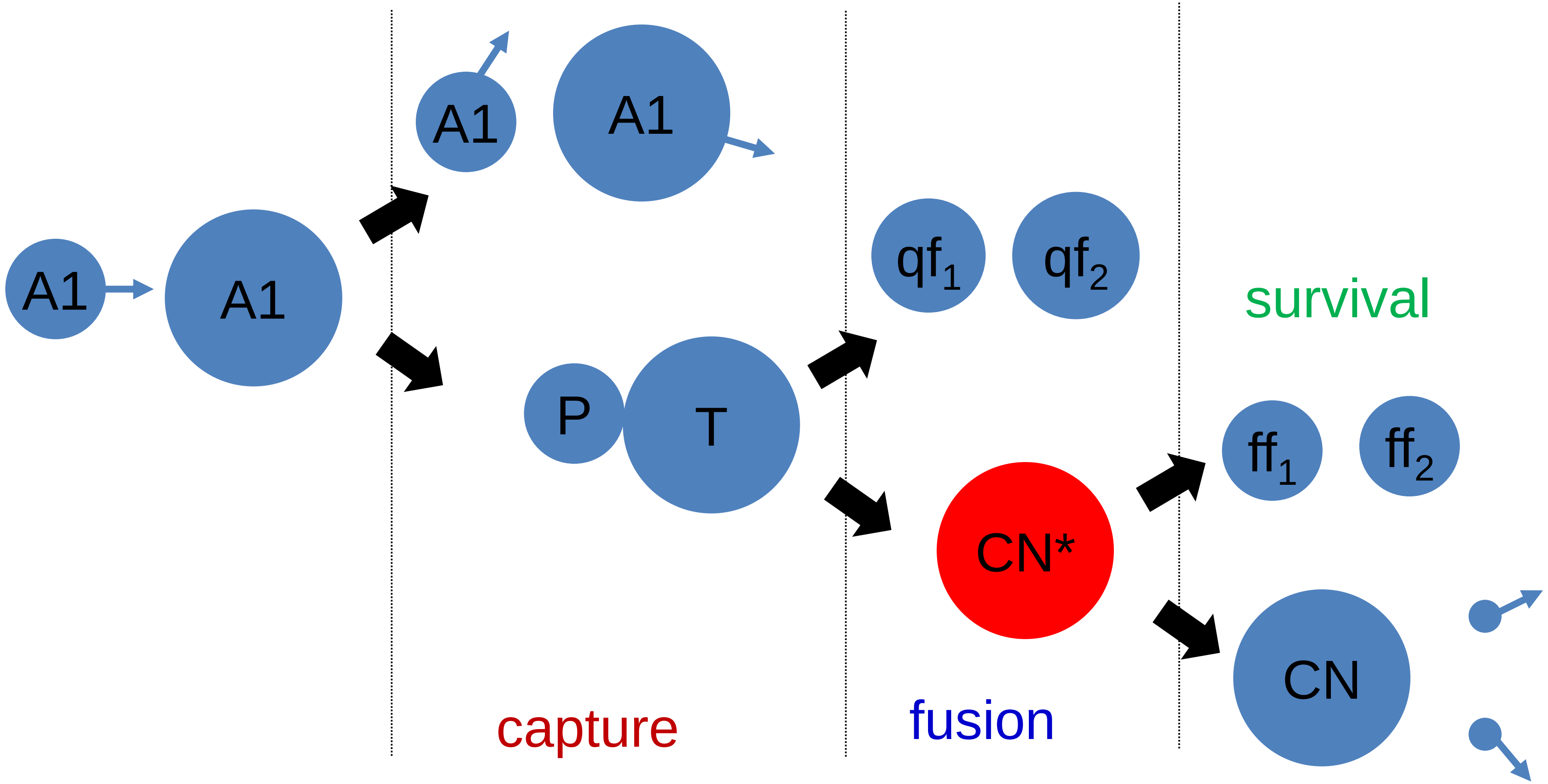
Bau, XJ: Front. Phys., 28 (2020): https://doi.org/10.3389/fphy.2020.00014

Zagrebaev, VI: Nucl. Phys. A, **944** (2015), 257: https://doi.org/10.1016/j.nuclphysa.2015.02.010

Cap, T: Euro. Phys. J. A, **58** (2022) 231: https://doi.org/10.1140/epja/s10050-022-00891-8

Compound Nucleus Reactions: Theory

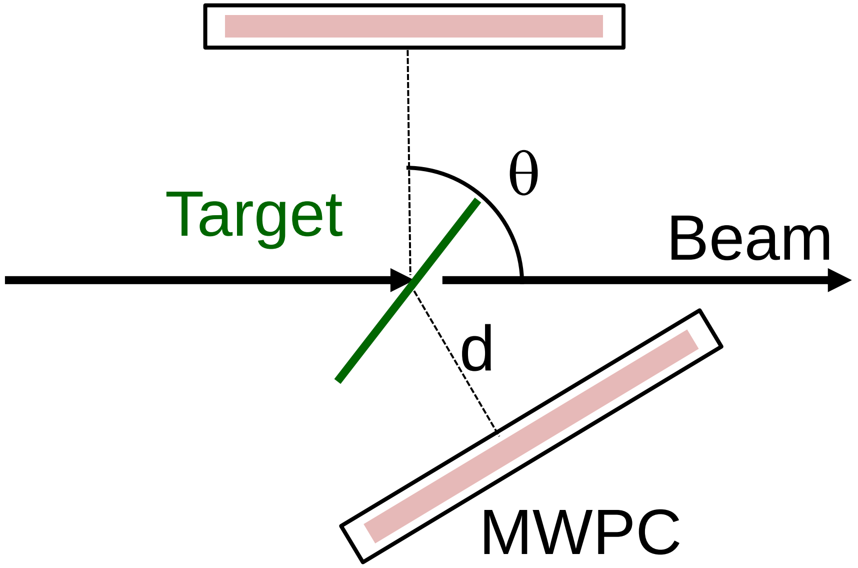
$$\sigma_{EVR}(E_{c.m.}) = \sum_J \sigma_{cap}(E_{c.m}, J) P_{CN}(E_{c.m}, J) W_{sur}(E_{c.m}, J)$$

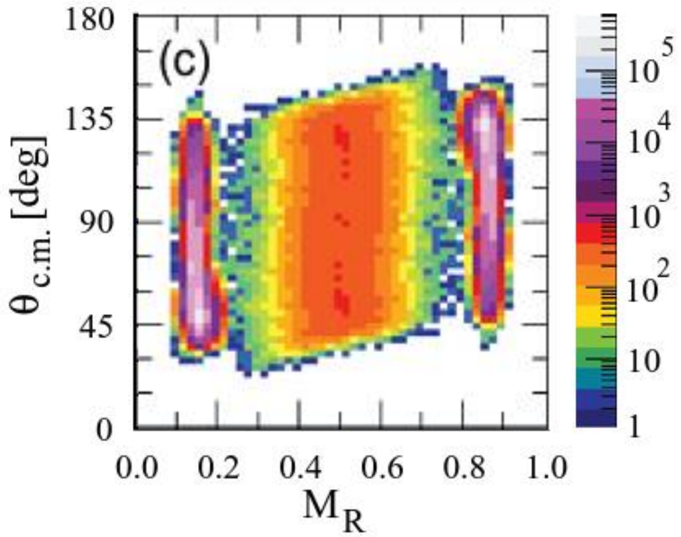


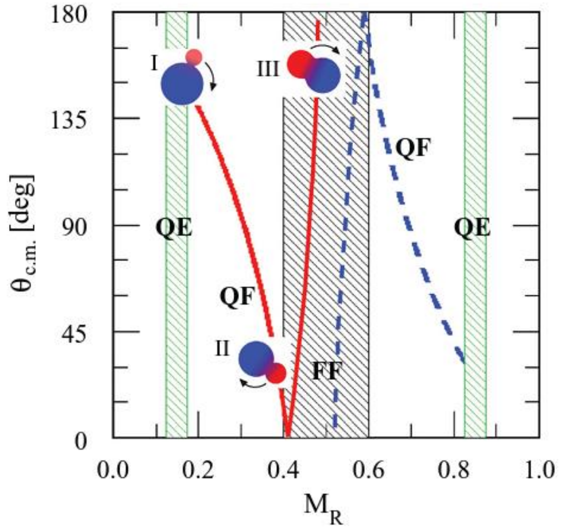
How can we test portions of this theory?

How to Measure

Position-sensitive MWPCs can measure position, angle, mass and total kinetic energy (TKE) of reaction products

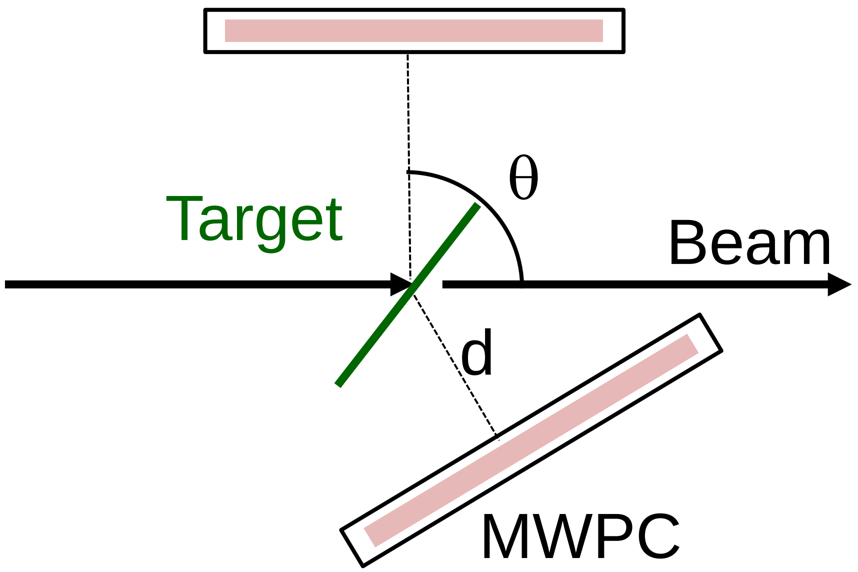


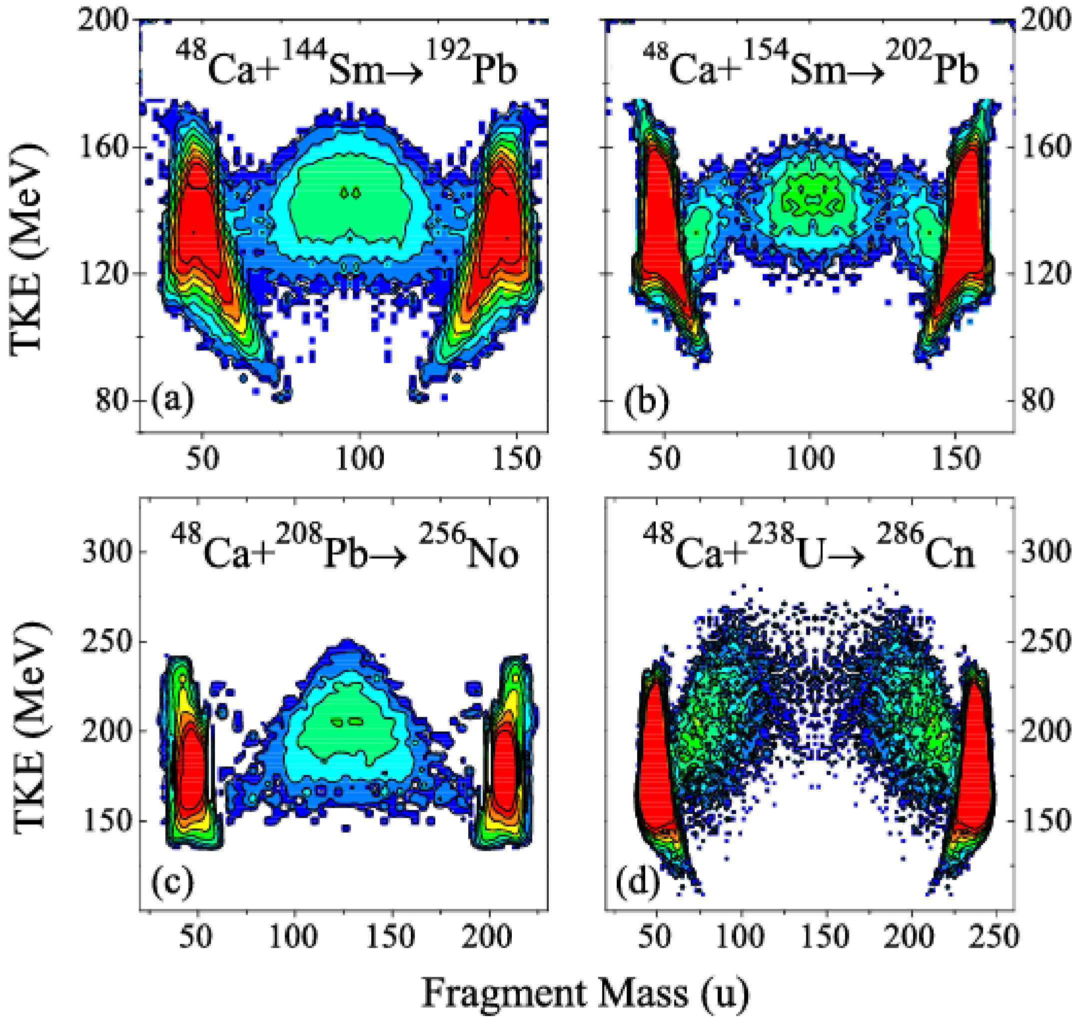




Banerjee, K., Phys. Rev. Lett **122** (2019) 232503: https://doi.org/10.1103/PhysRevLett.122.232503
du Rietz, R., Phys. Rev. C **88** (2013) 054618: https://doi.org/10.1103/PhysRevC.88.054618

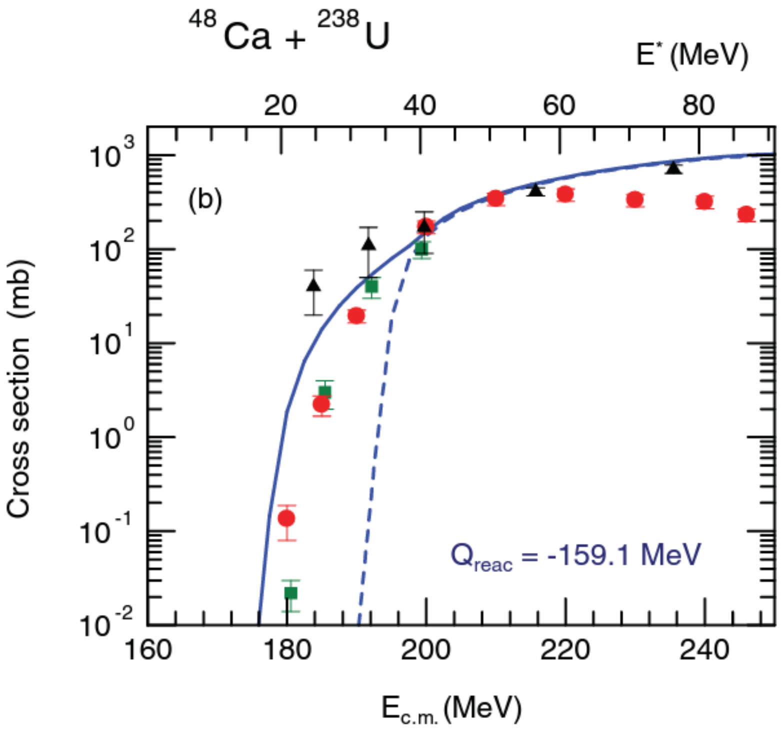
Mass-energy distributions for reaction fragments

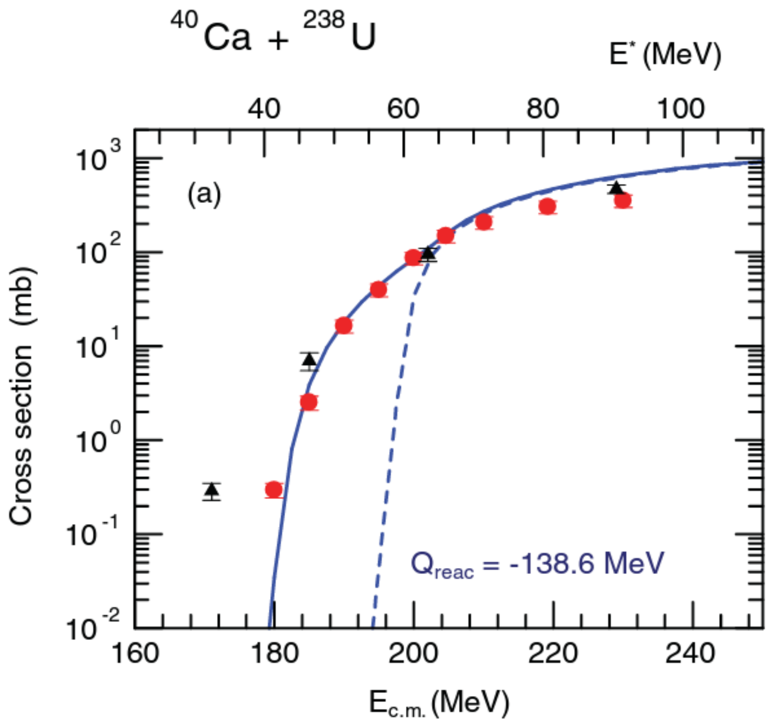




Kozulin, E.M., Phys. Rev. C **90** (2014) 054608: https://doi.org/10.1103/PhysRevC.90.054608

Experiment vs Theory: Capture Cross Sections



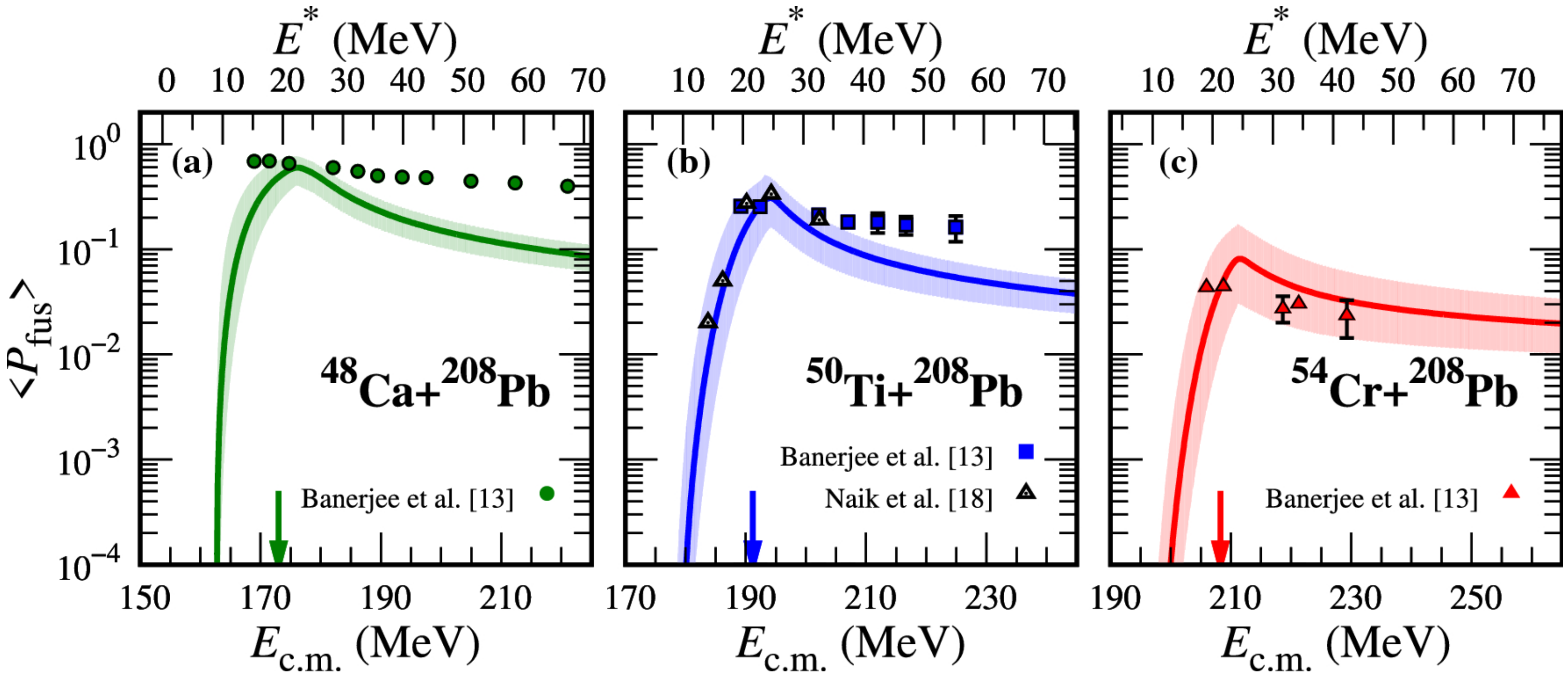


Comparison with Experiment

- Limited experimental calculations of capture cross sections in SHE production
- Triangles, circles, squares = experimental data
- Solid line = model w/ deformation
- Dash line = model w/o deformation

Nishio, K: Phys. Rev. C, **86** (2012): https://doi.org/10.1103/PhysRevC.86.034608

Experiment vs Theory: Fusion Probability

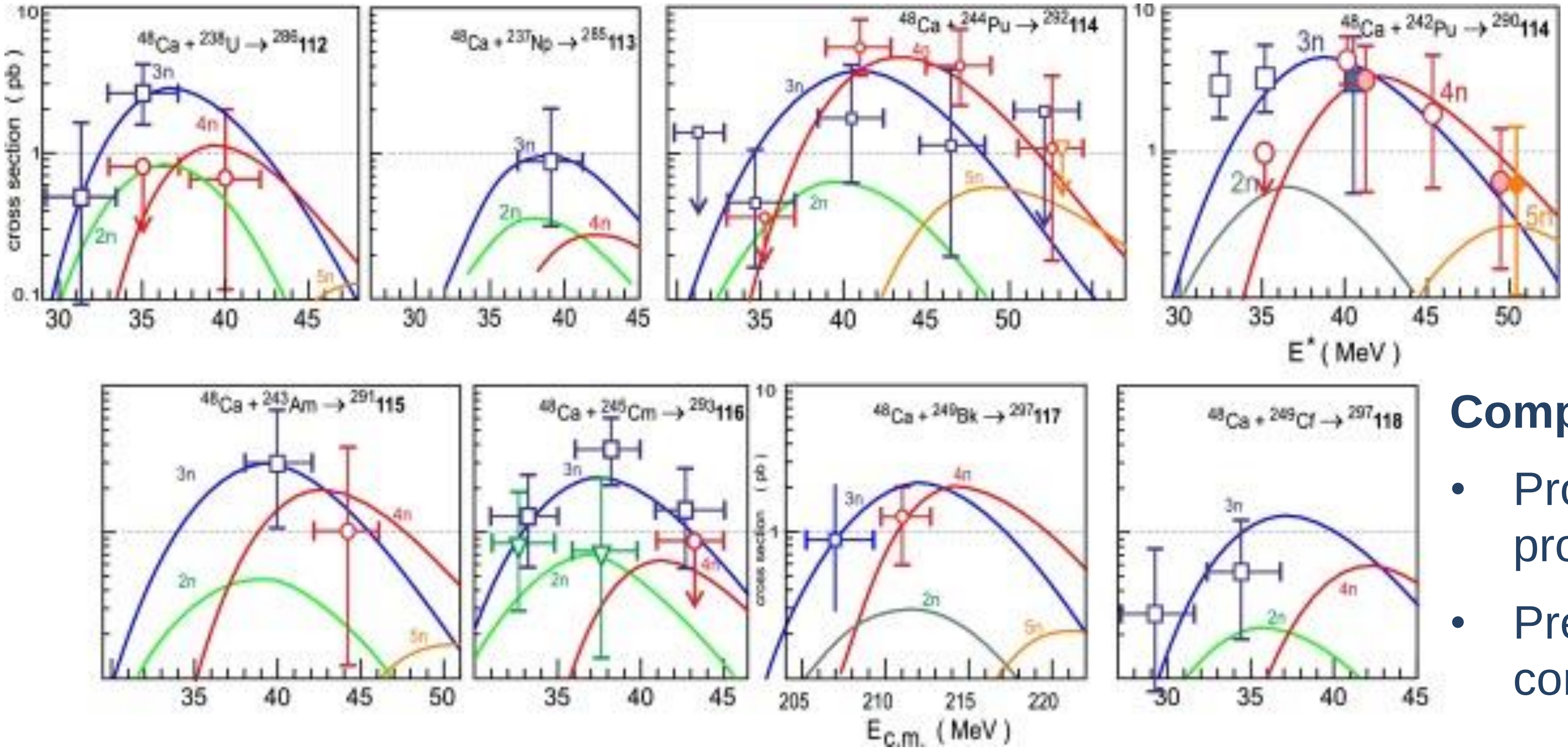


Comparison with Experiment

- Limited experimental calculations of fusion probability in SHE production
- Triangles, circles, squares = experimental data
- Solid line = model with error bars

Cap, T: Euro. Phys. J. A, **58** (2022) 231: https://doi.org/10.1140/epja/s10050-022-00891-8

Experiment vs Theory: Survival

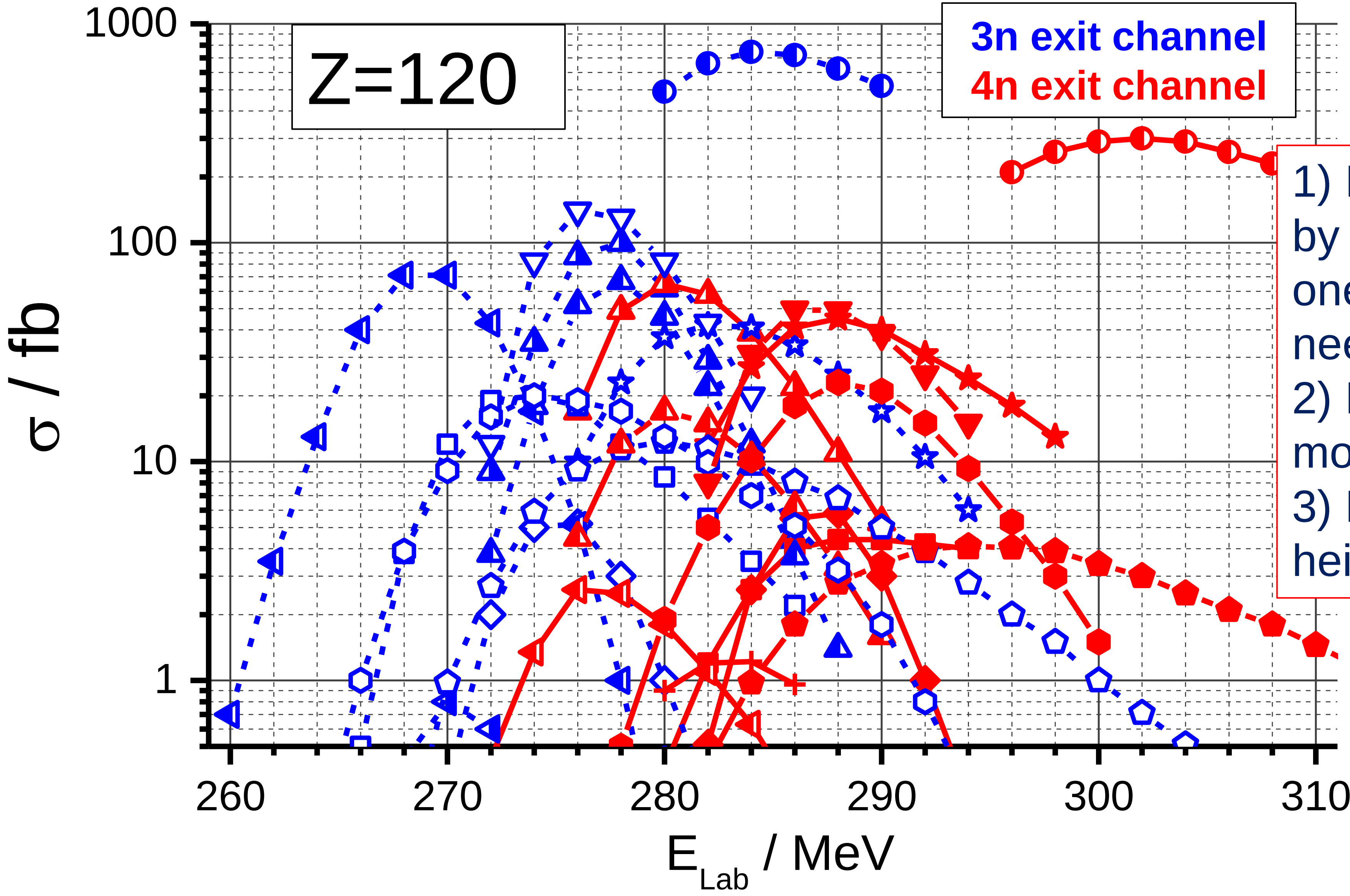


Comparison with Experiment

- Probed indirectly by comparing production cross sections
- Predictions seem to converge on correct solution ***after*** experiments

Zagrebaev, VI: Nucl. Phys. A, **944** (2015), 257: https://doi.org/10.1016/j.nuclphysa.2015.02.010

Predictions for $^{50}Ti + ^{249}Cf$ ➔ E120 Excitation Function



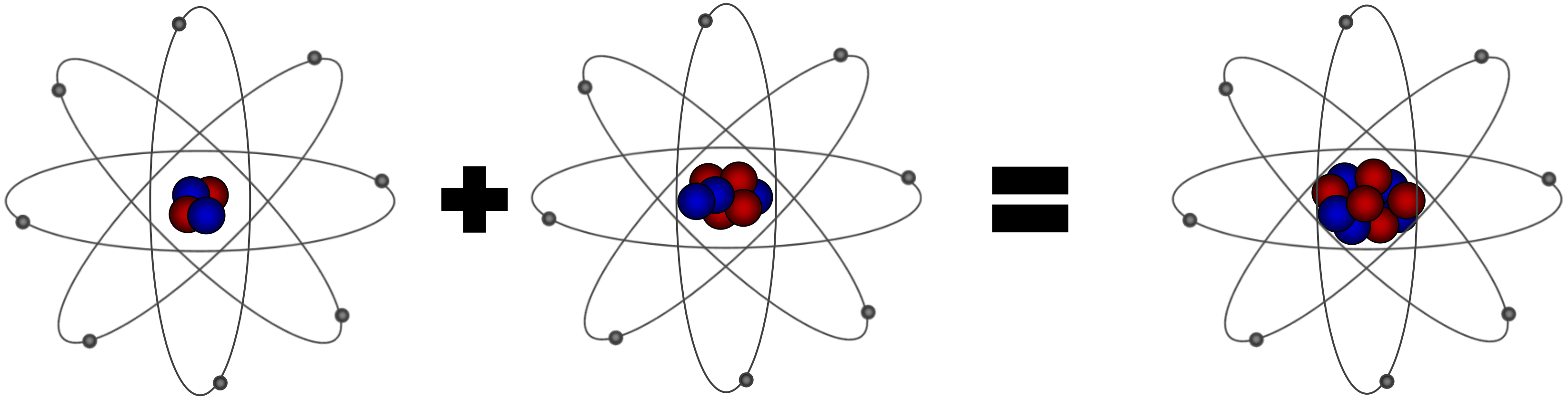
1) Experimenters more worried by E_{Lab} uncertainties than σ_{EVR} ones! → Error bars (in x!) are needed!
2) No need for YAM (yet another model). Need ways to test them!
3) Measure(!) the fusion barrier height

Slide from Ch. E. Duellmann

Theory is difficult

Lets try experiment

How to make new elements

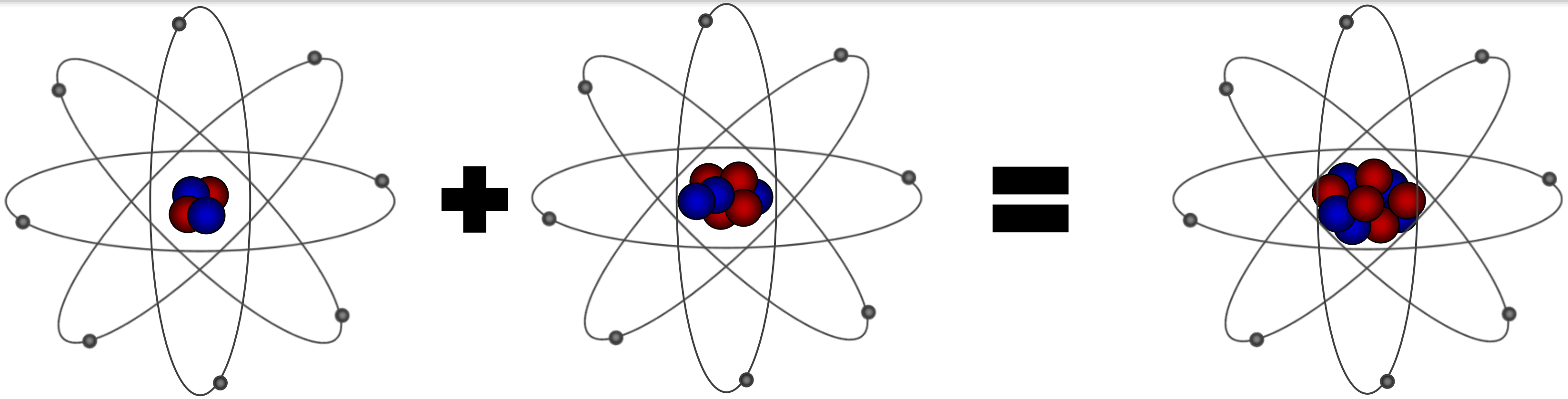


$^{48}_{20}Ca$ $^{243}_{95}Am$ $^{291}_{115}Mc$

Fuse two lighter nuclei to make heavier ones

Step 1: Chose beam/target combination
Step 2: Create and accelerate ions
Step 3: Bombard target
Step 4: Be lucky
Step 5: Separation
Step 6: Detection and Science!

How New Elements are Discovered



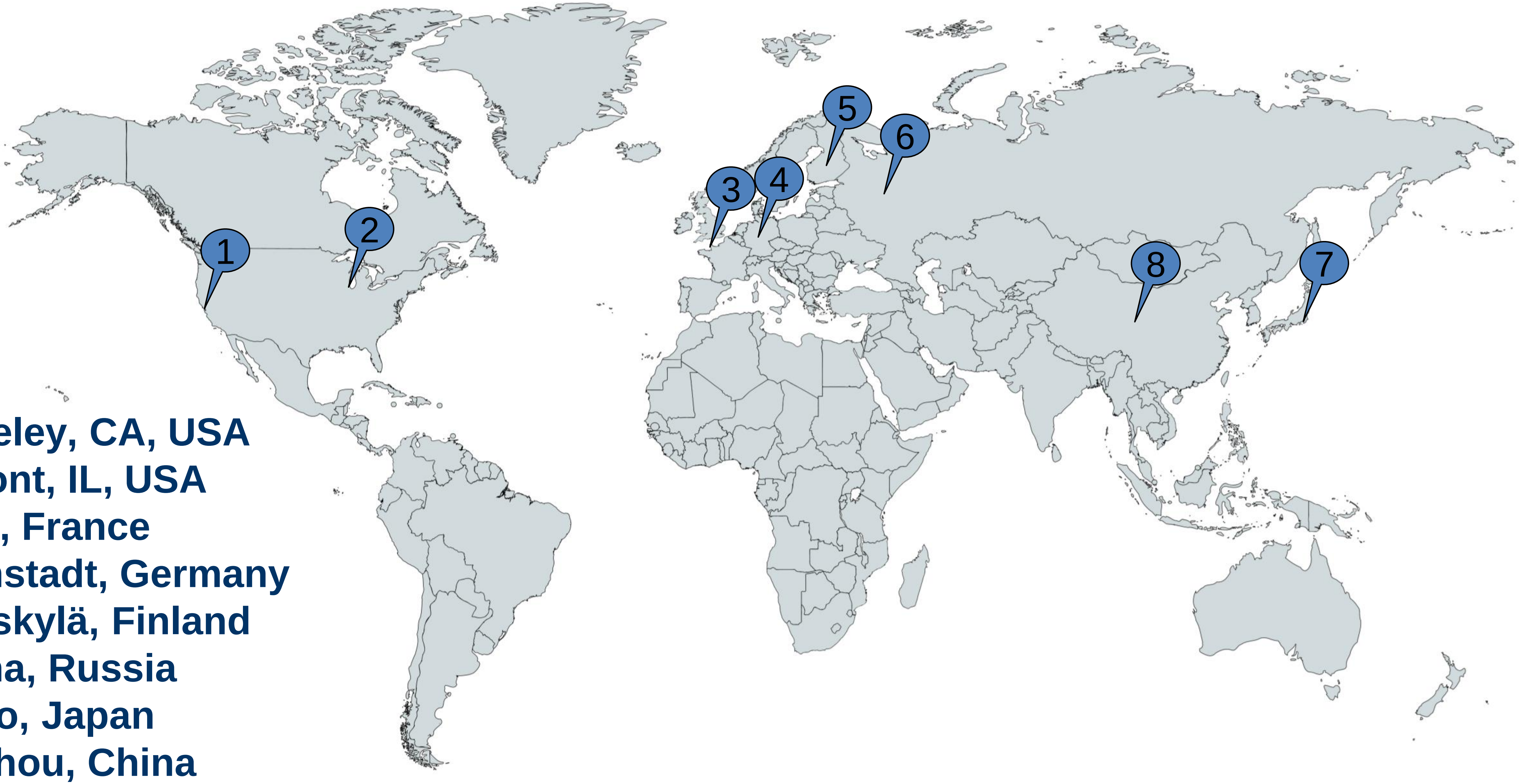
$^{48}_{20}Ca$ $^{243}_{95}Am$ $^{291}_{115}Mc$

Fuse two lighter nuclei to make heavier ones

Challenges

1. **Finding two nuclei:**
   Nuclei are small compared to atoms ➔ ~10^{-15} m vs 10^{-10} m
   Atoms are mostly empty space
1. **Fusing them together**
   Nuclei are positively charged ➔ repel each other

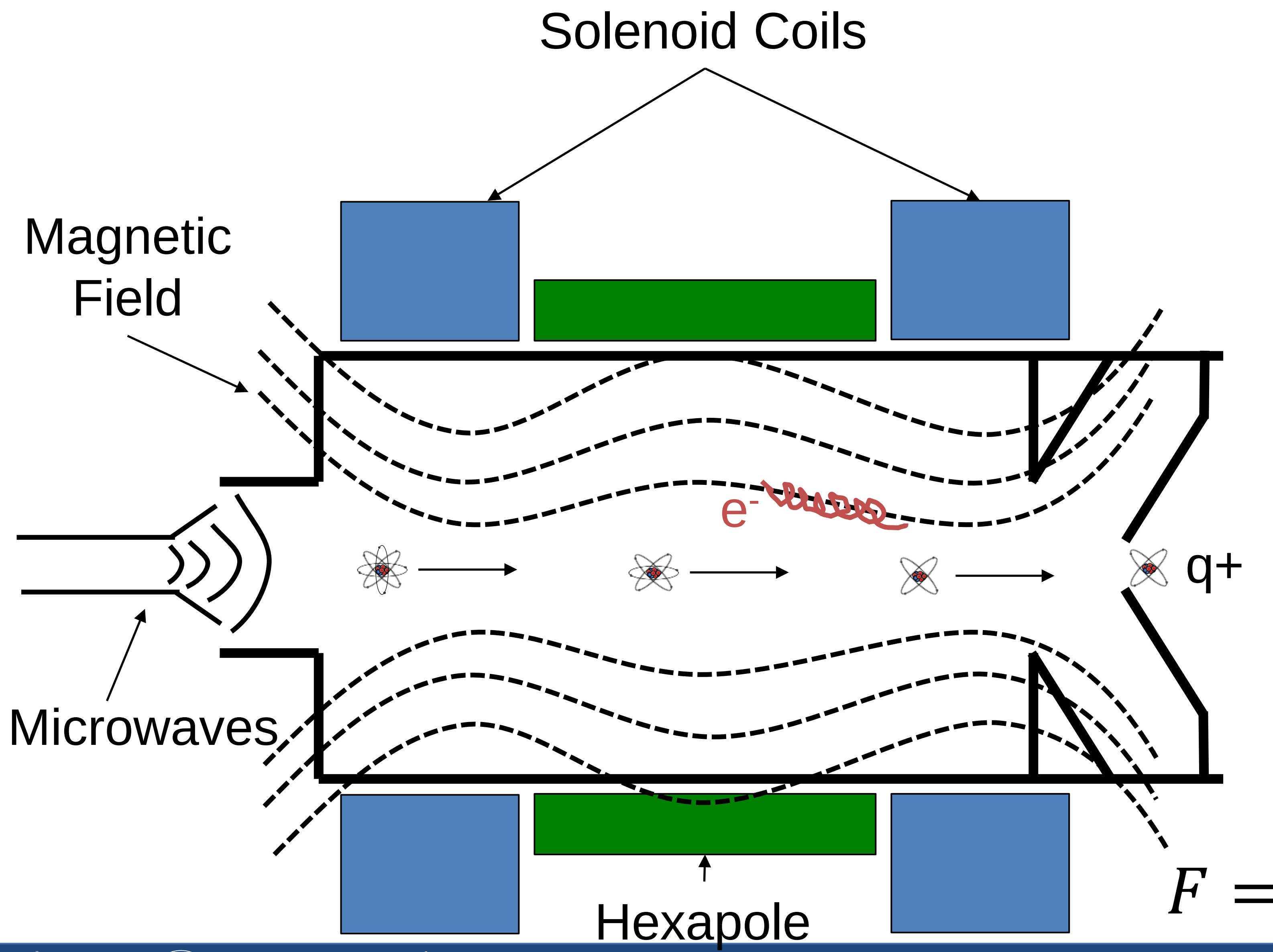
Places capable of producing the heaviest elements

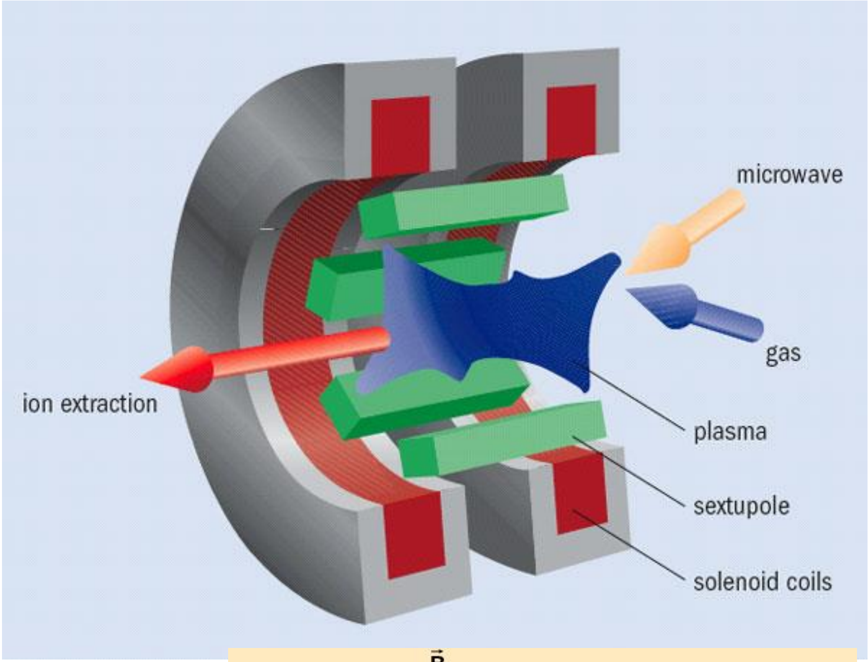


1. **Berkeley, CA, USA**
2. **Lemont, IL, USA**
3. **Caen, France**
4. **Darmstadt, Germany**
5. **Jyväskylä, Finland**
6. **Dubna, Russia**
7. **Tokyo, Japan**
8. **Lanzhou, China**

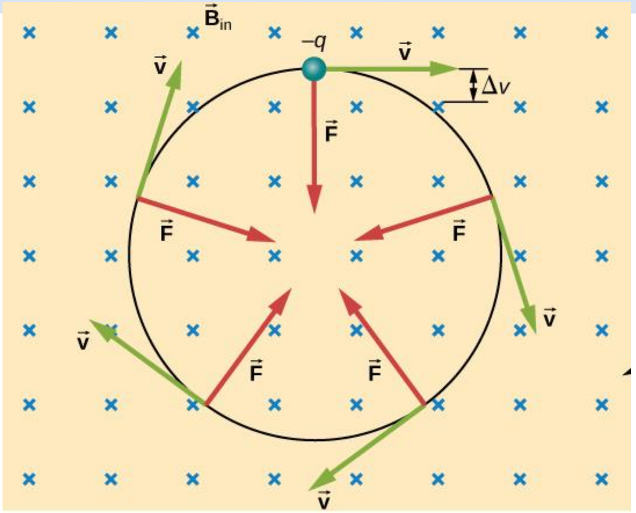
How do you accelerate atoms to 10% the speed of light?

Steps 1: Accelerate – Turn Atoms into Ions



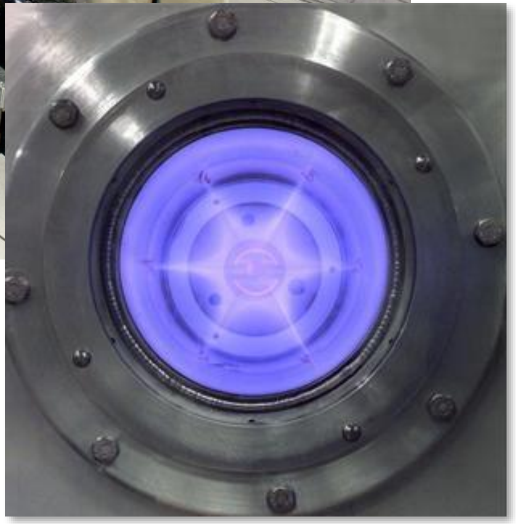


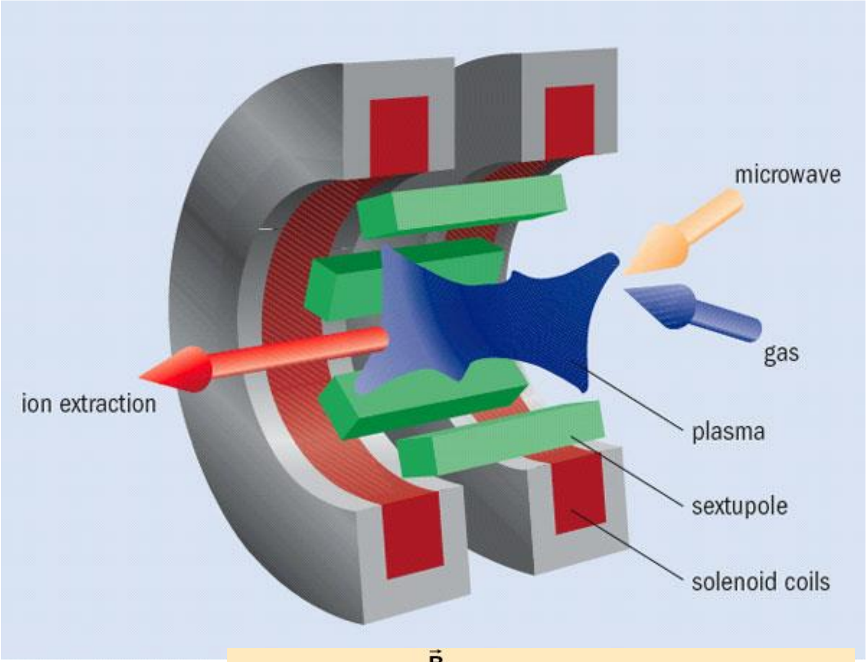
$$F = qv \; x \; B$$

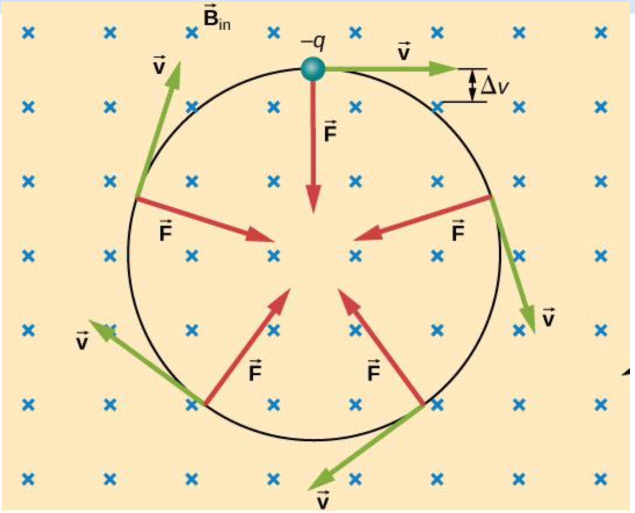


Steps 1: Accelerate – Turn Atoms into Ions

VENUS Ion source

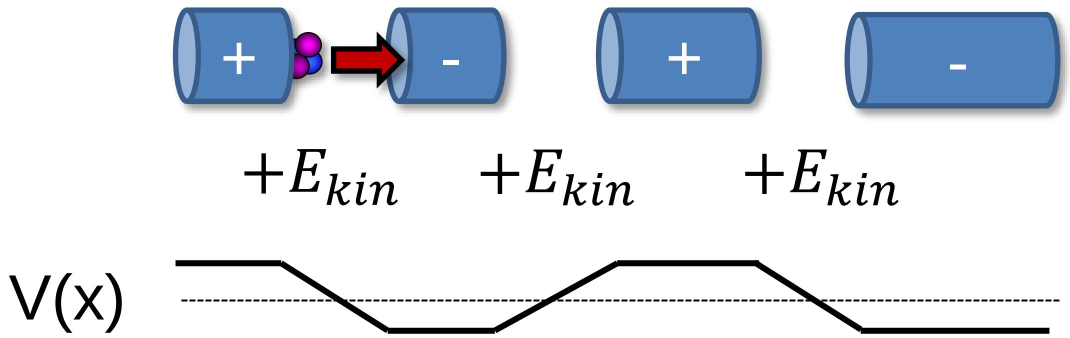






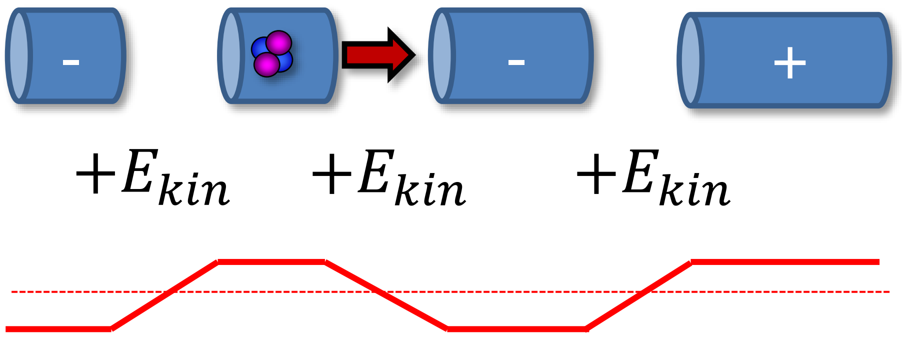
$$F = qv\ x\ B$$

Steps 1: Accelerate – Use electric fields to accelerate ions



$$E_{kin} = qV$$

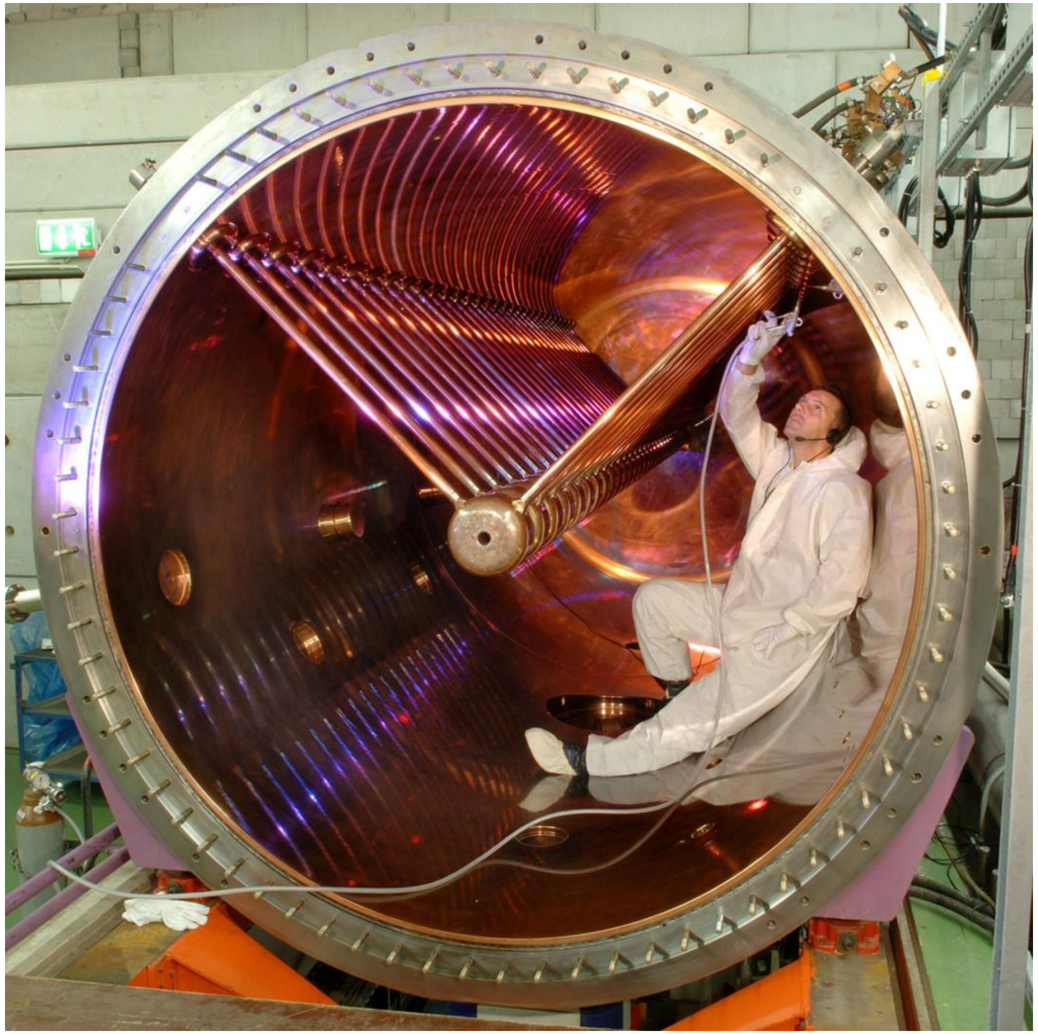
Step 1: Accelerate Ions



$+E_{kin}$ $+E_{kin}$ $+E_{kin}$

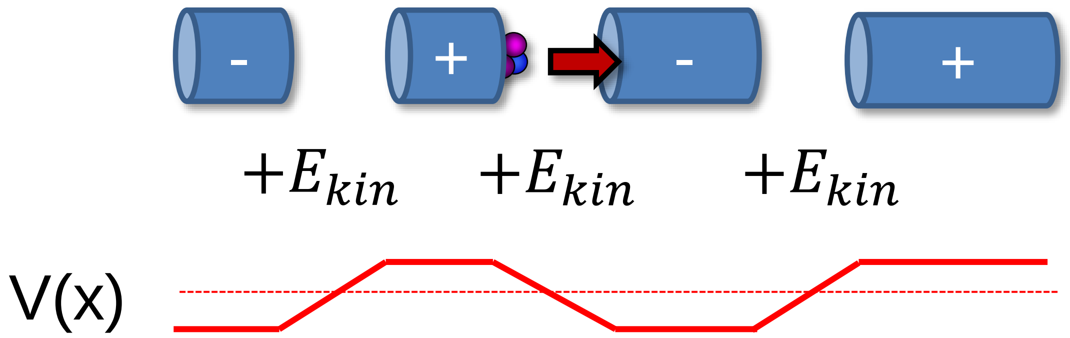
V(x)

$$E_{kin} = qV$$



GSI UNILAC (universal linear accelerator)

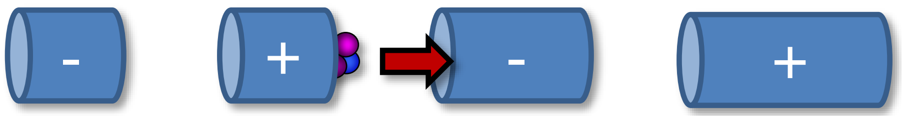
Step 1: Accelerate Ions



$$E_{kin} = qV$$

What if you want to reach high velocities, but don't have a lot of space?

Step 1: Accelerate Ions

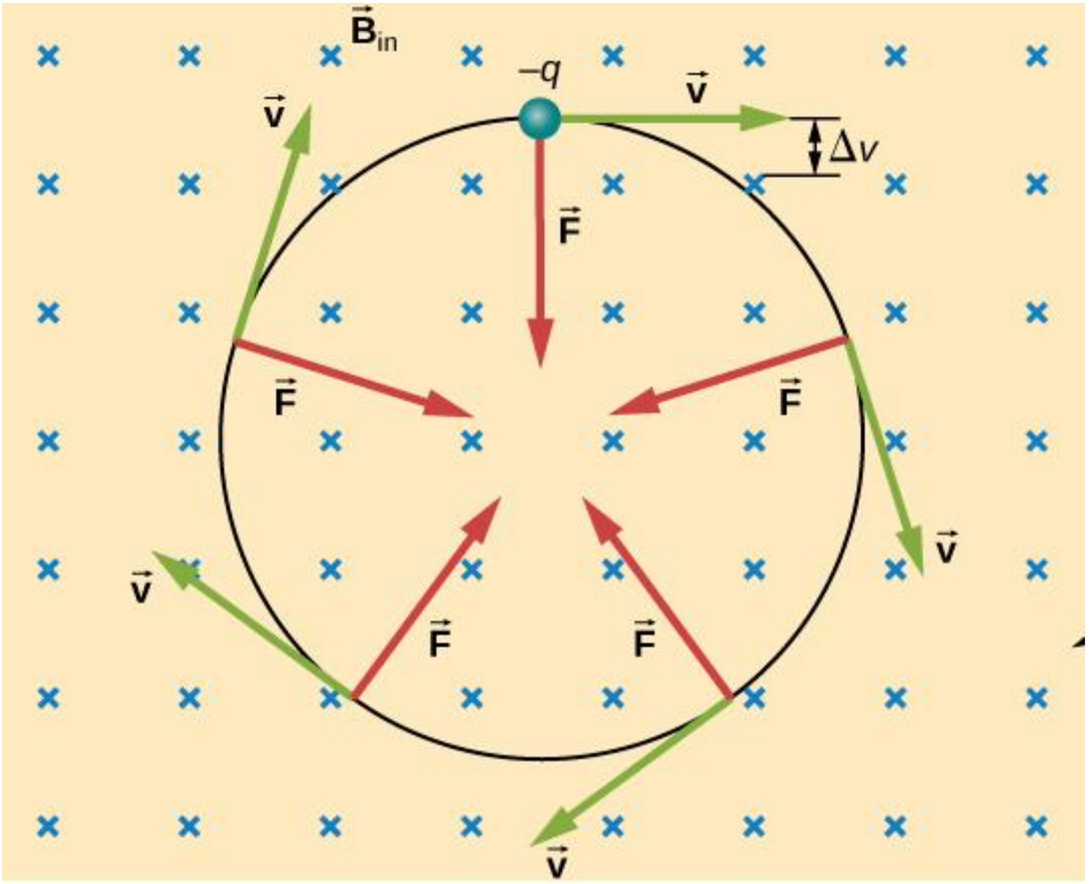


$+E_{kin}$ $+E_{kin}$ $+E_{kin}$

$E_{kin} = qV$

What if you want to reach high velocities, but don't have a lot of space?

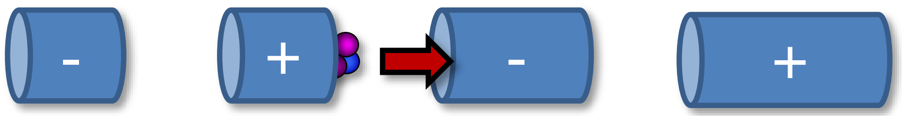
Add a magnetic field!



Centripetal Force: $Fc = mv^2/r$
Magnetic Force: $F = qvB$
Radius of curvature: $r = mv/qB$

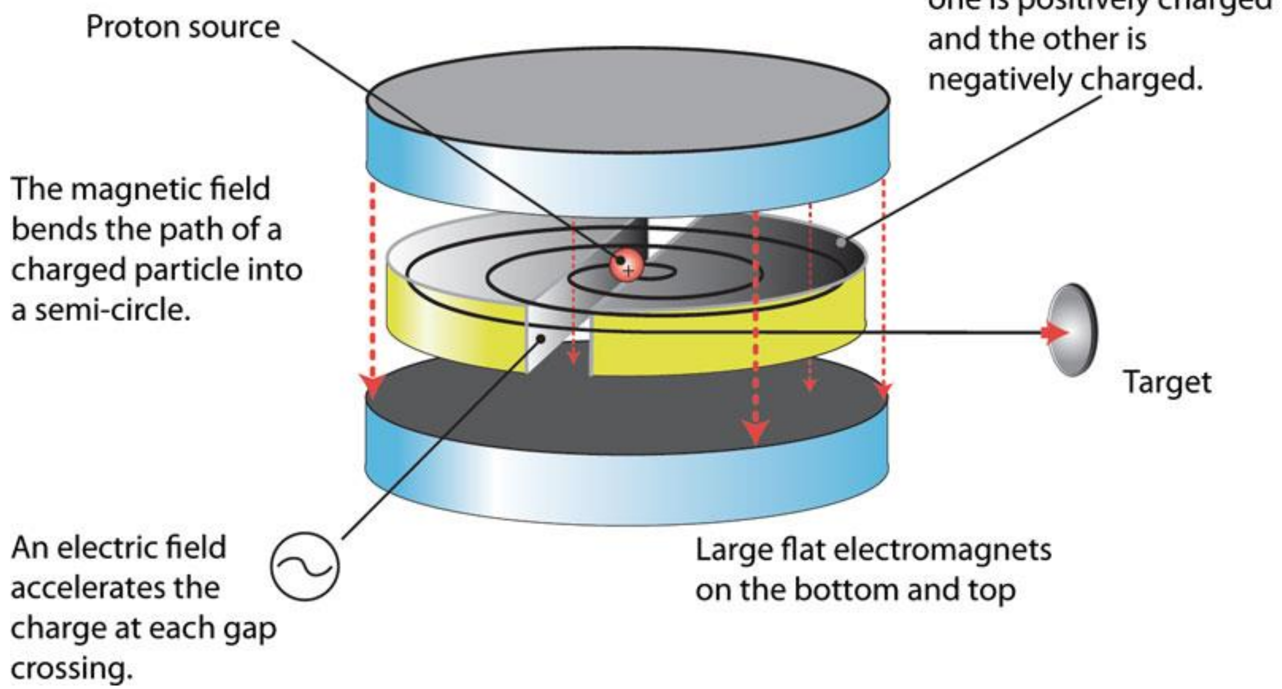
m=mass v=velocity r=radius
q=charge state B=magnetic field

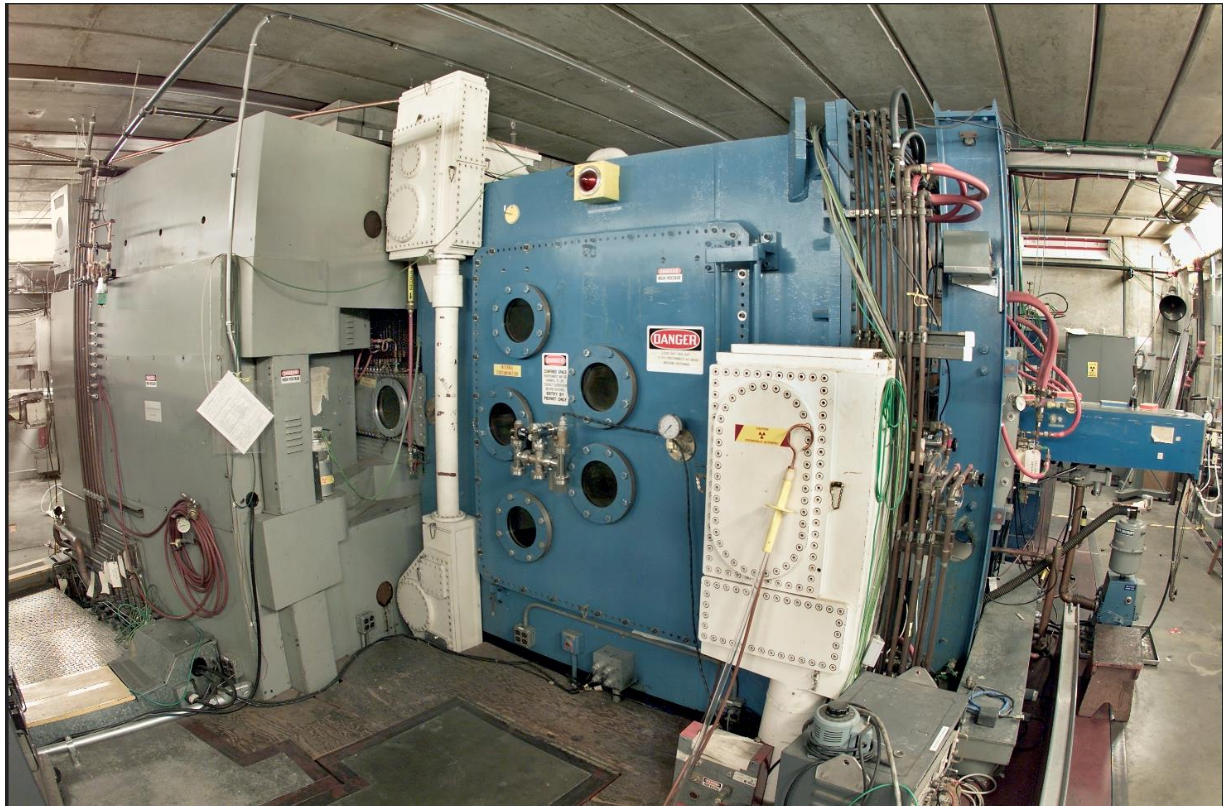
Step 1: Accelerate Ions



$+E_{kin}$ $+E_{kin}$ $+E_{kin}$

$$E_{kin} = qV$$

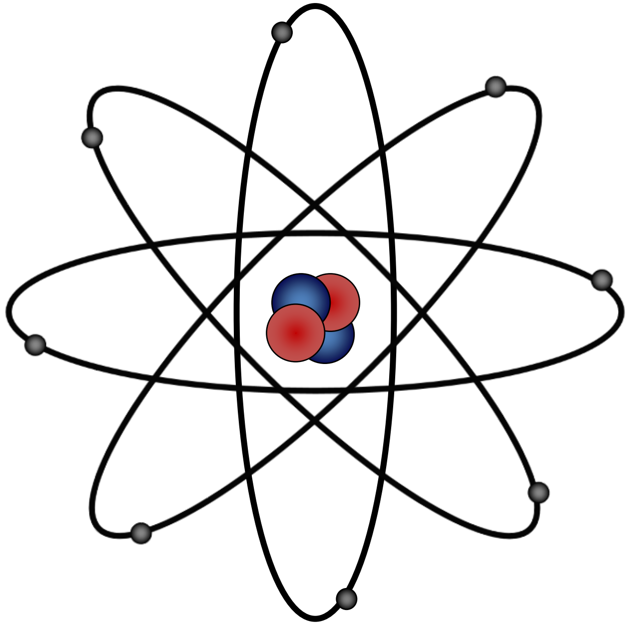




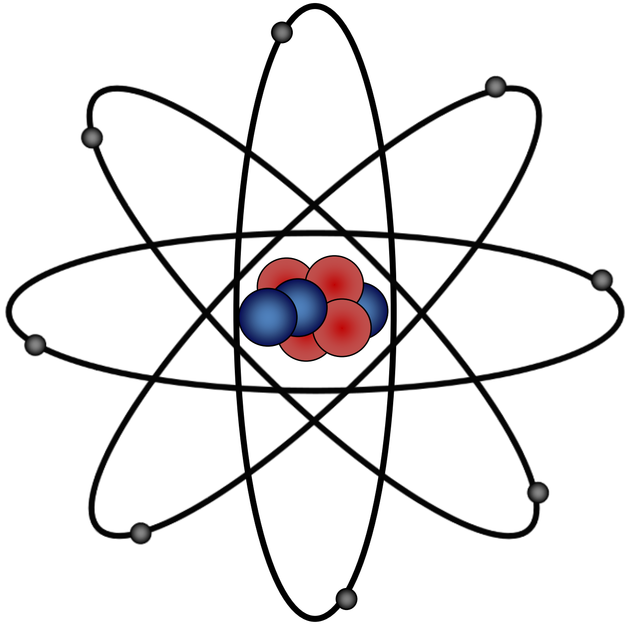
88-Inch Cyclotron

$$r = mv/qB$$

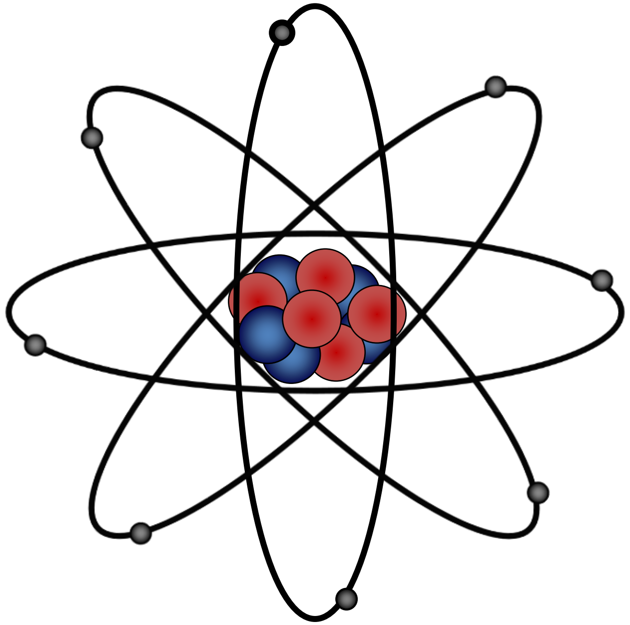
How to Make New Elements



Beam



Target



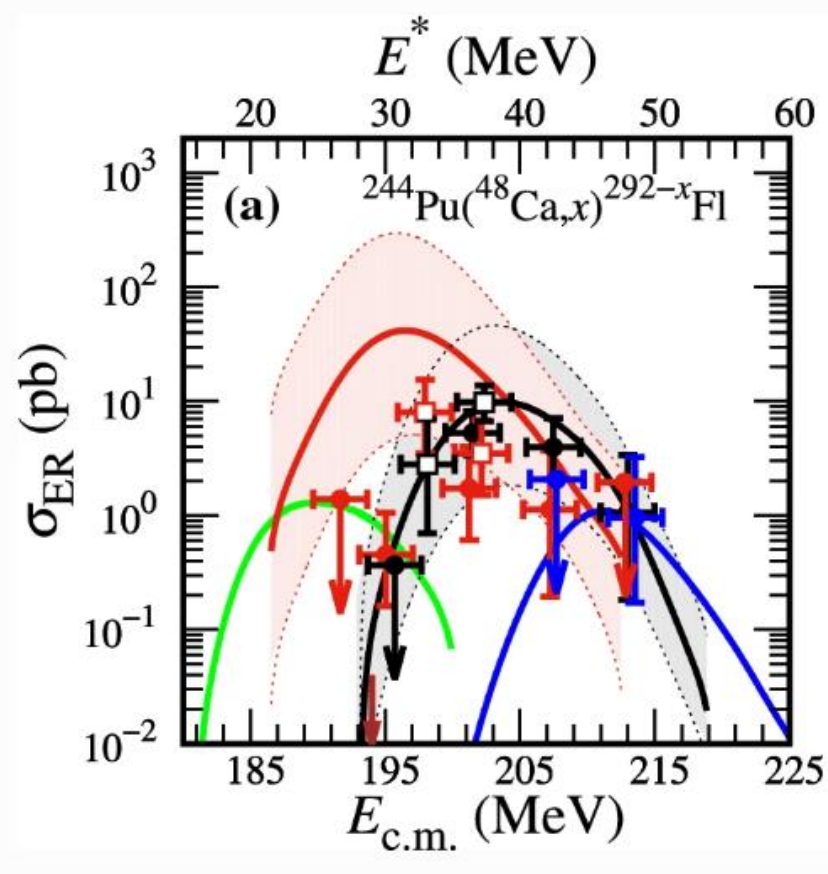
Product

How Thick Should Our Targets Be?

Step 2: Targets

Things to consider:

- Energy loss ➔ width of excitation function, heating of the target



Energy loss of ^{48}Ca in ^{238}U

Energy (MeV)	dE/dx (MeV/mg/cm^2)	Range (um)
200	7.485	14.46
210	7.396	15.16
220	7.307	15.87
230	7.220	16.60
240	7.134	17.33
250	7.048	18.06
260	6.965	18.81

Step 2: Targets

Things to consider:

- Energy loss → width of excitation function, heating of the target
- How to detect a SHE after it has been made

^{254}No
55 s

^{276}Mt
0.54 s

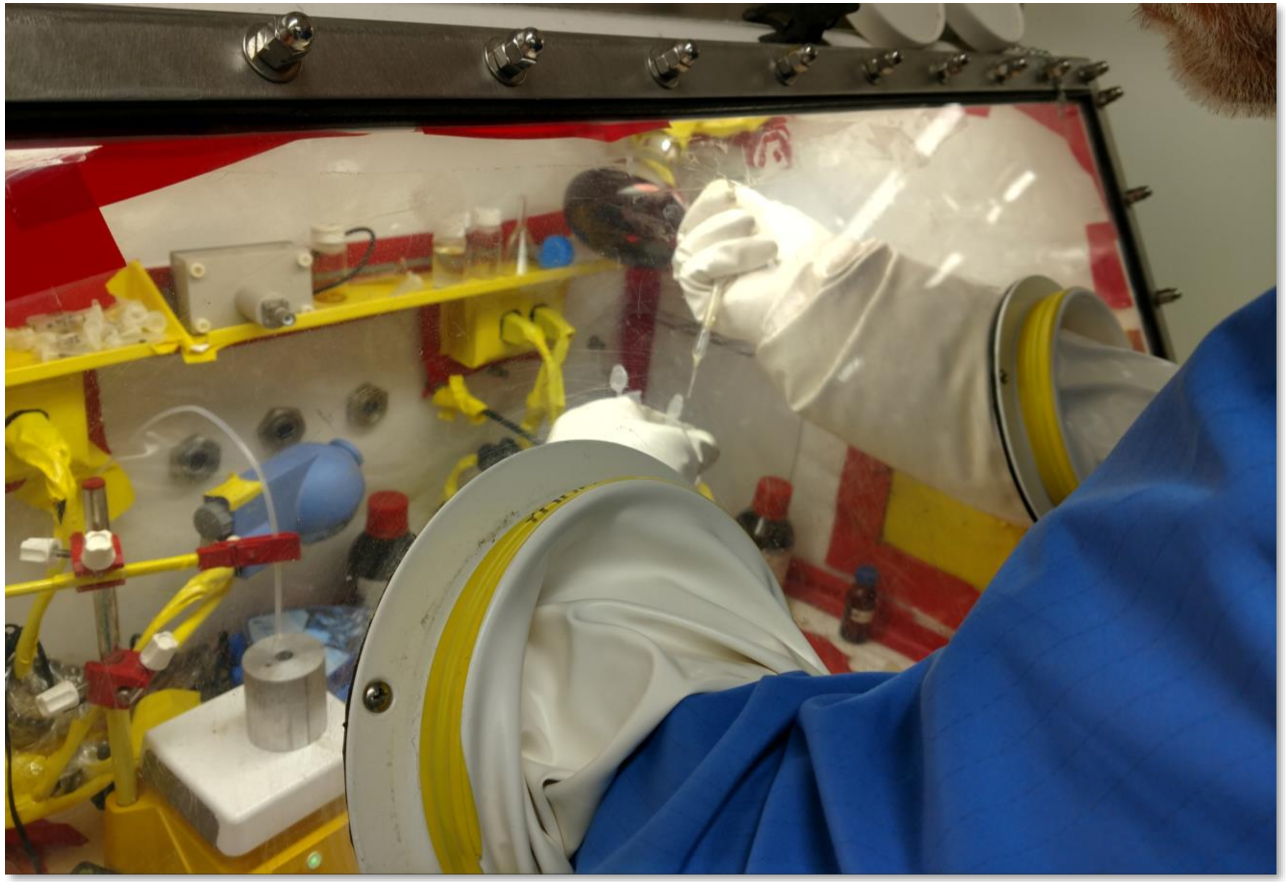
^{258}Db
4 s

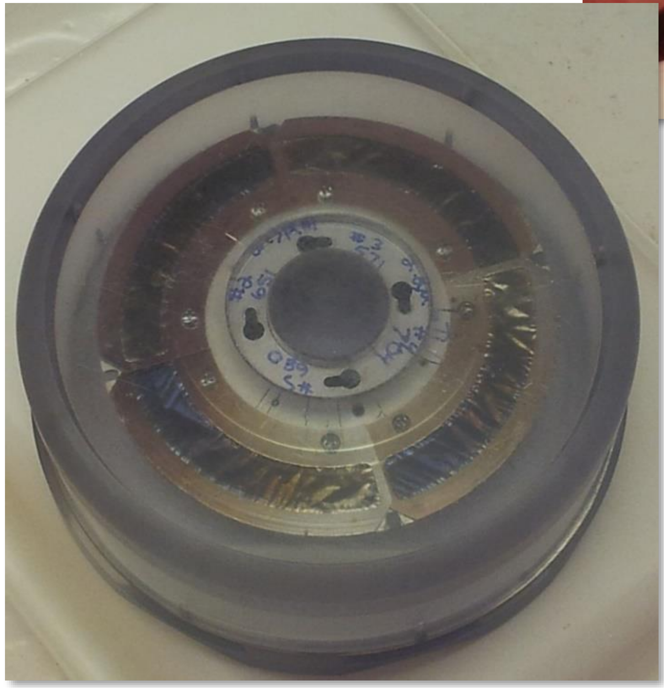
^{288}Mc
171 ms

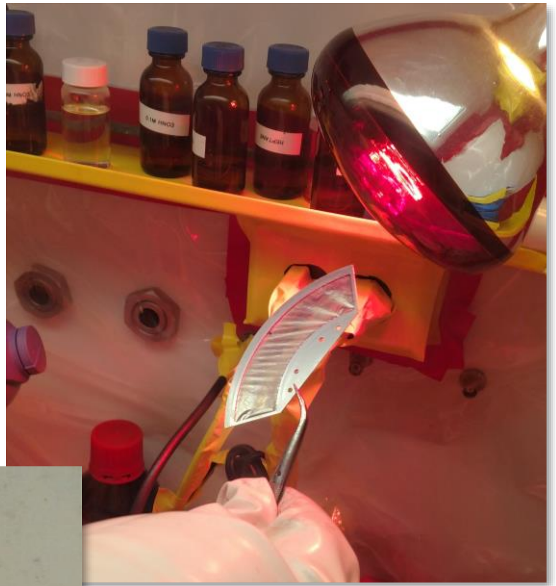
Steps 2: Bombard Targets

Thin targets ➔ 0.25 – 0.8 mg/cm^2

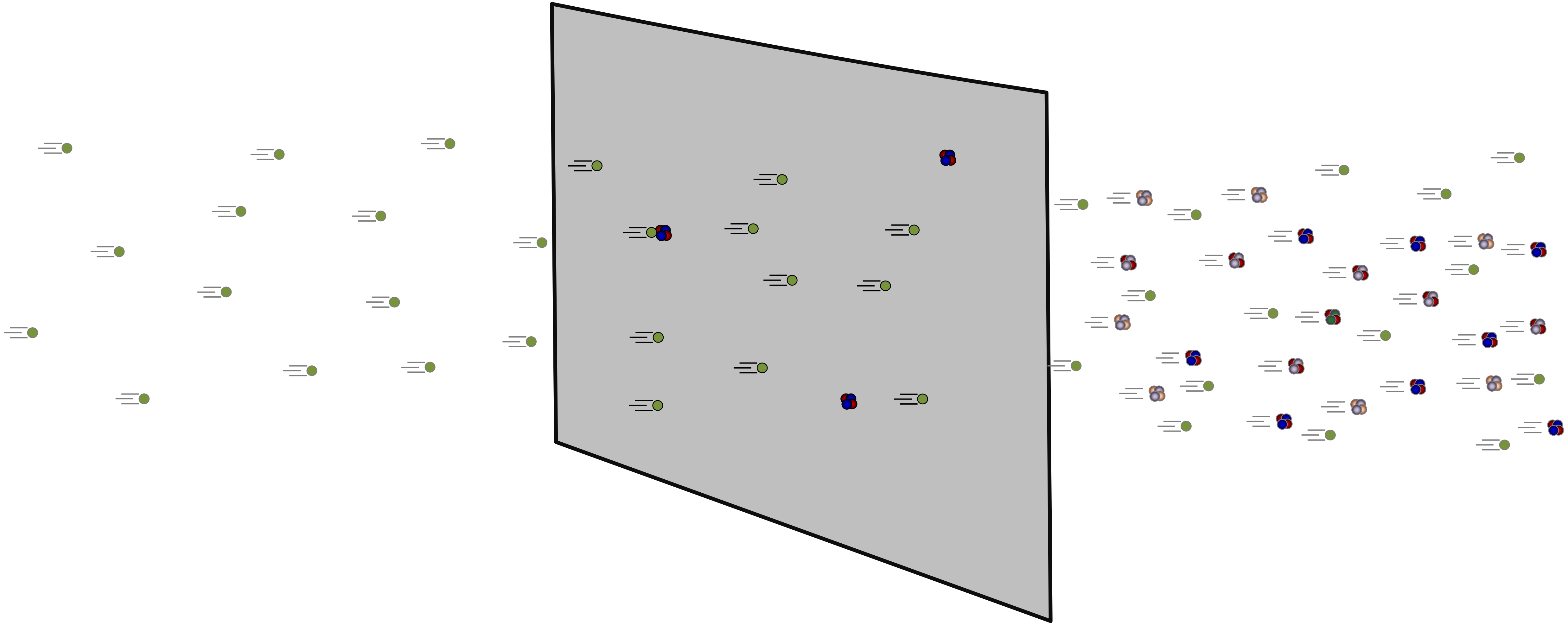
0.2 – 0.7 um







Step 3: Be Lucky



Zoomed in target

Step 4: Separation

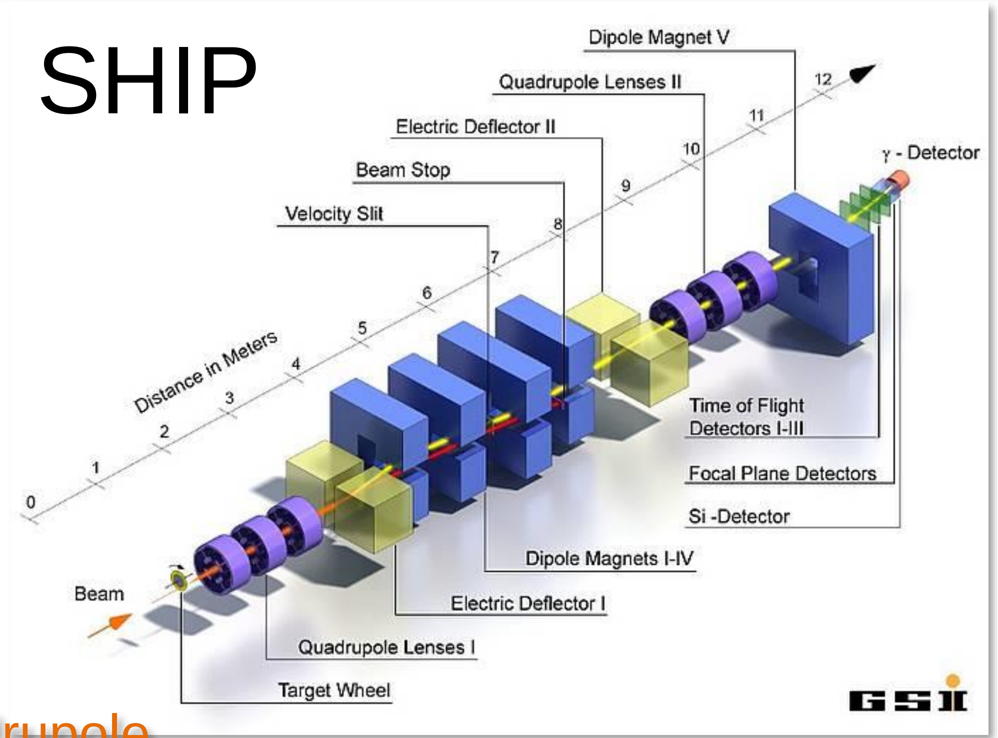
102	103	104	105	109	115
^{254}No	^{255}Lr	^{257}Rf	^{258}Db	^{276}Mt	^{288}Mc
55 s	22 s	4.7 s	4 s	0.54 s	171 ms
1/s	10/min	1/min	1/hr	1/wk	1/day

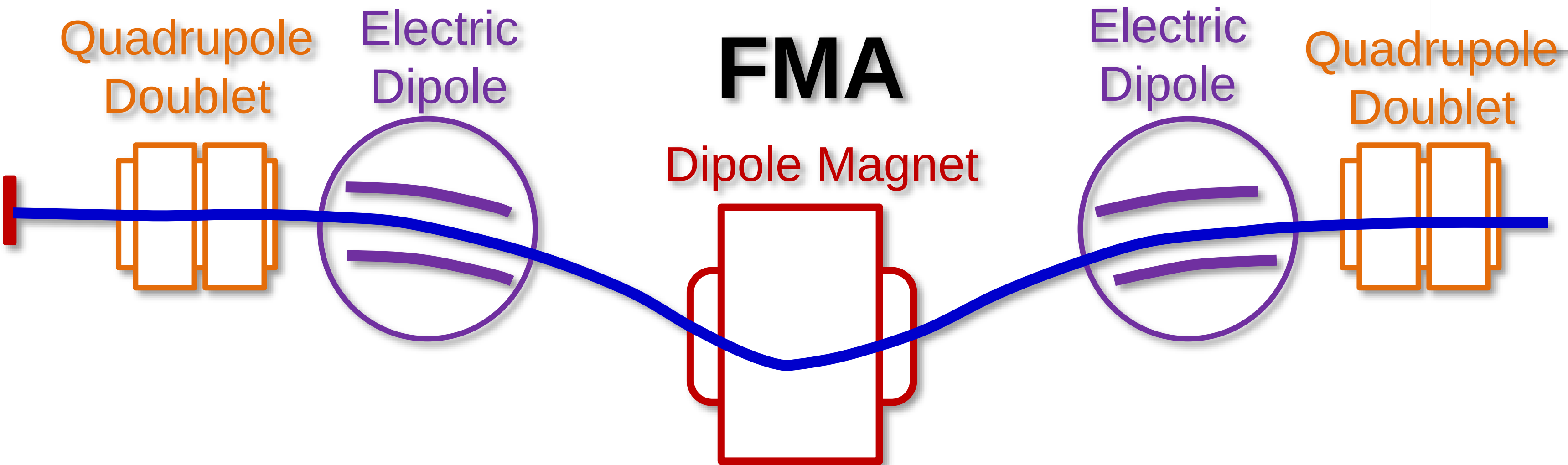
Two Types of Separators with *Complementary* Capabilities

Step 4: Separation: Vacuum Separators

Standard Configuration:
- Quadrupole doublet (or triplet)
- Electric Dipole
- Magnetic Dipole
- Electric Dipole
- Quadrupole doublet (or triplet)

Examples: FMA, SHIP, SHELLS

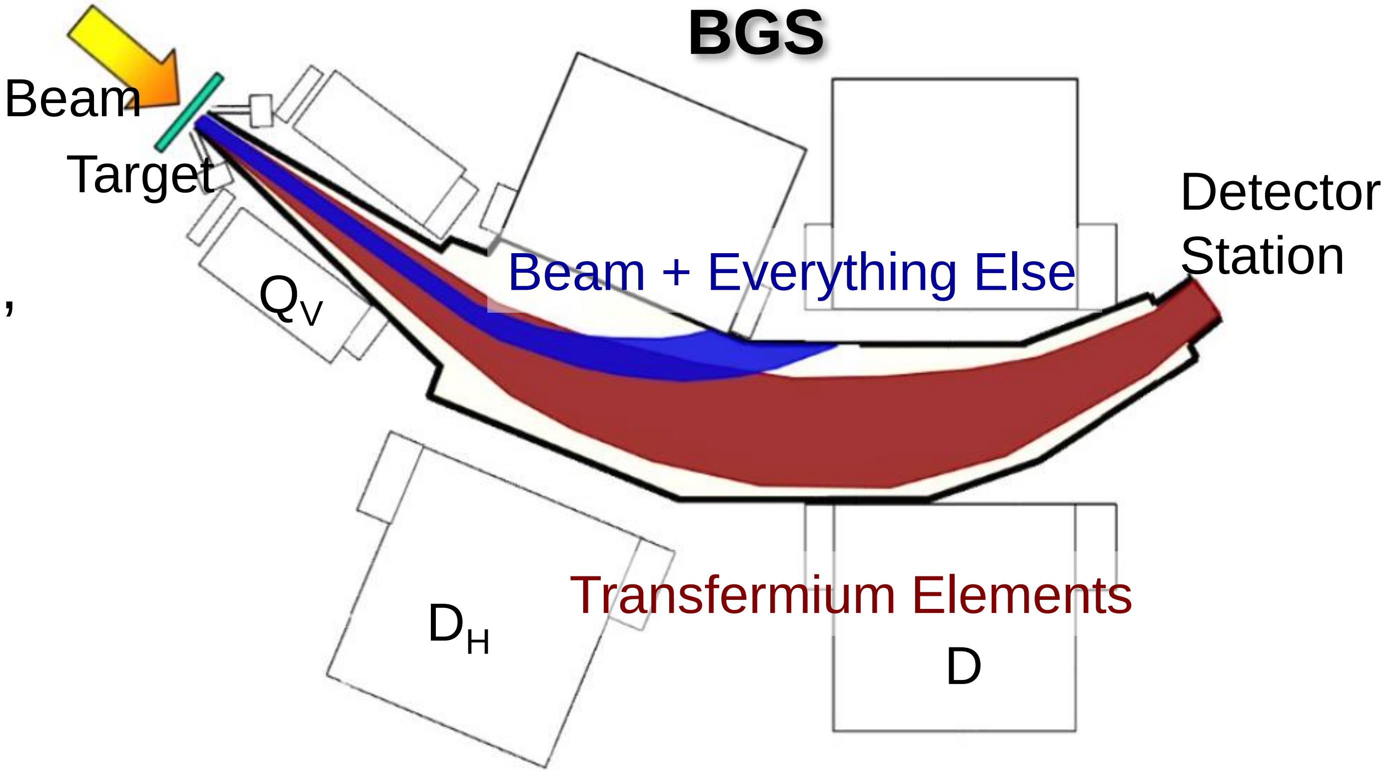


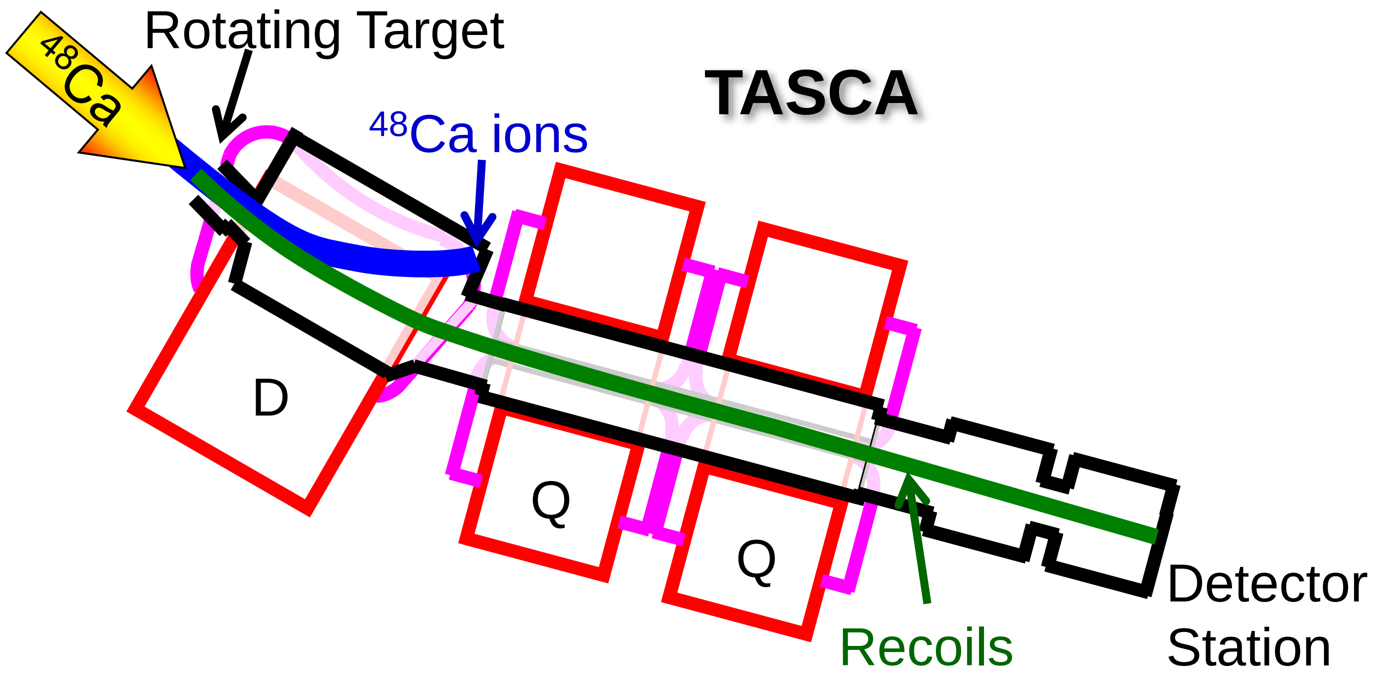


Step 4: Separation: Gas-filled Separators

Standard Configuration:
- Dipole
- Quadrupole doublet

Examples: DGFRS, GARIS(I-III), RITU, SASSY, TASCA

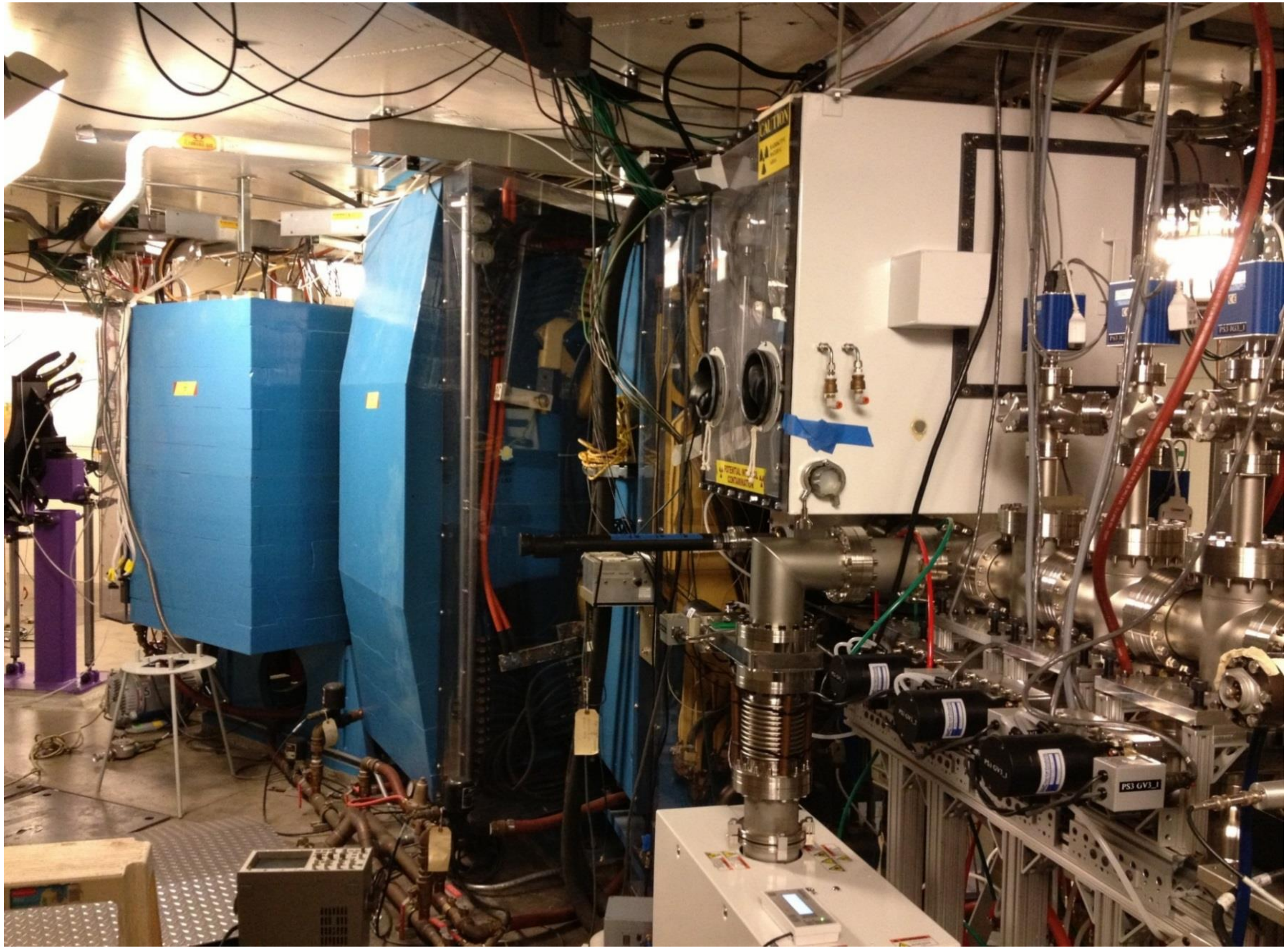




Other Configuration:
- Quadrupole
- Focusing dipole
- Dipole

Examples: BGS

Step 4: Separation



Step 4: Separation

Why two different types?

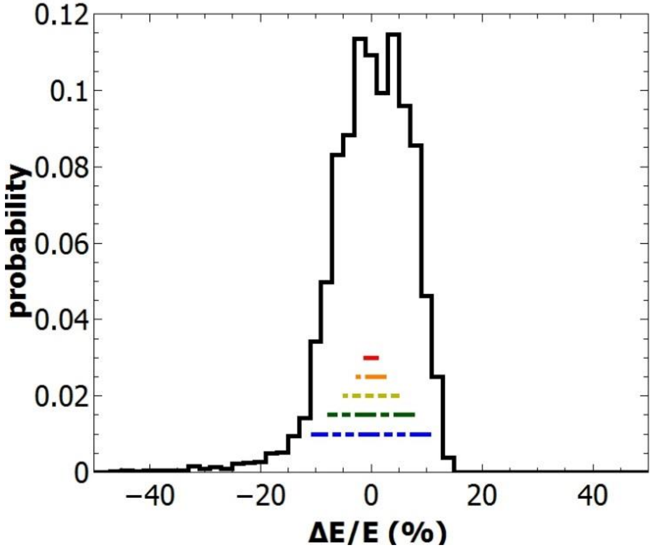
Step 4: Separation

Evaporation Residues leaving the target have a distributions in:

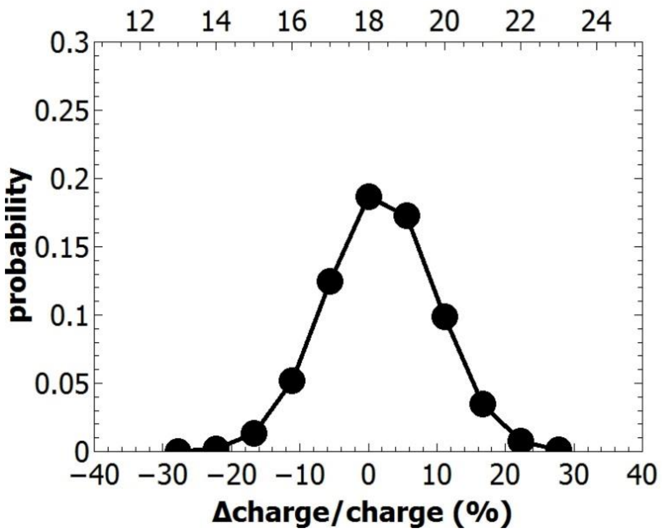
- Energy
- Charge State
- Angle

Example Distributions from:
$^{208}Pb(^{48}Ca,2n)^{254}No$

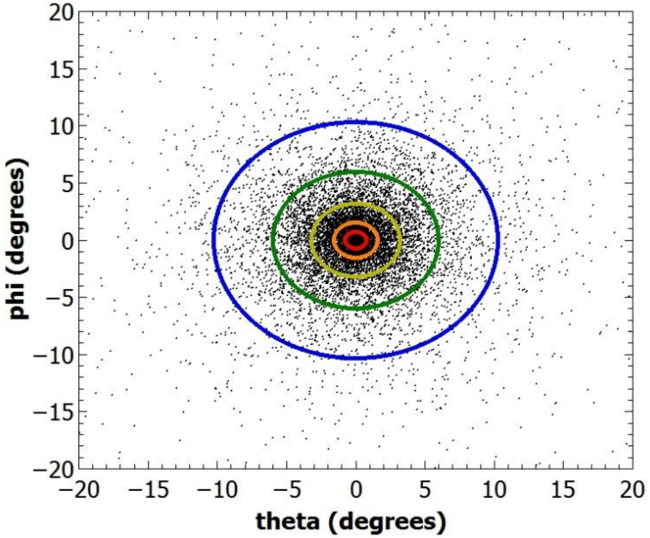
Energy



Charge State



Angle



Charged Particles in Electric/Magnetic Fields

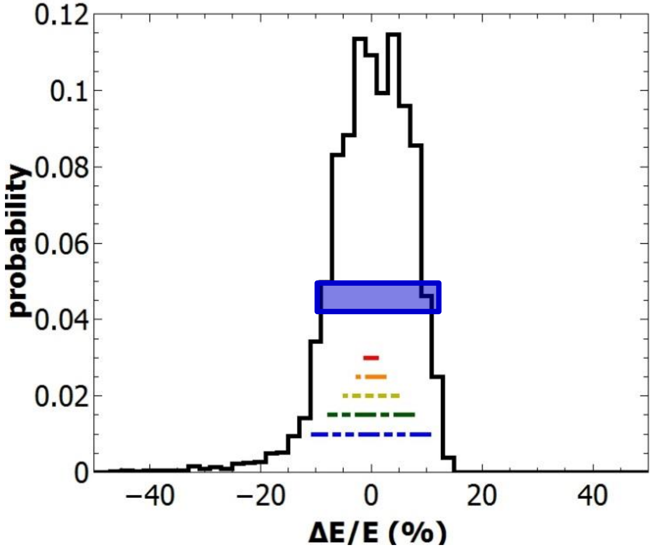
Different charges, velocities and masses will take different trajectories

Distributions in charge and energy limit transmission efficiency of vacuum separators

Vacuum Mode Separators

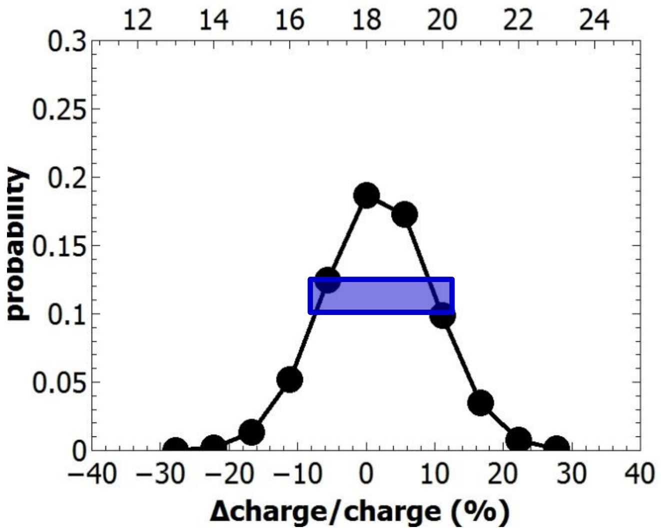
$^{48}Ca+^{208}Pb$
Hot Fusion

Energy



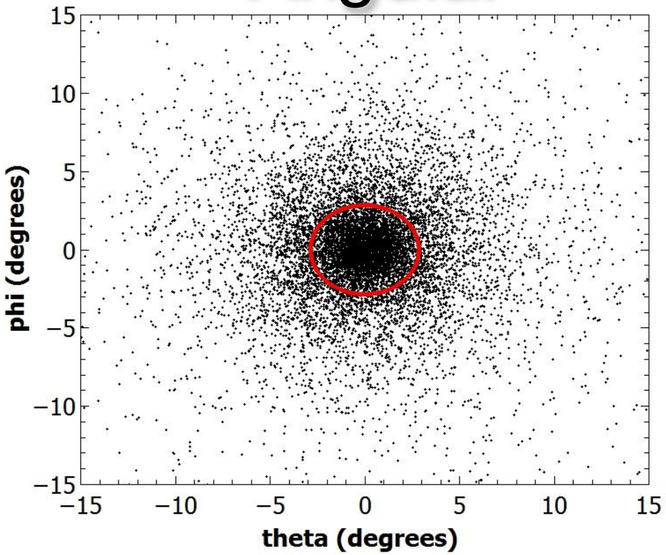
SHIP: ±10%
Acceptance ~90%

Charge State



SHIP: ±10%
Acceptance ~65%

Angular



SHIP
Acceptance: ±3° = ~45%

Limited by gap in electric deflector and acceptance in quadrupoles

Efficiency for $^{208}Pb(^{48}Ca,2n)^{254}No$ reaction:

SHIP: 30%

Gas-filled Separators

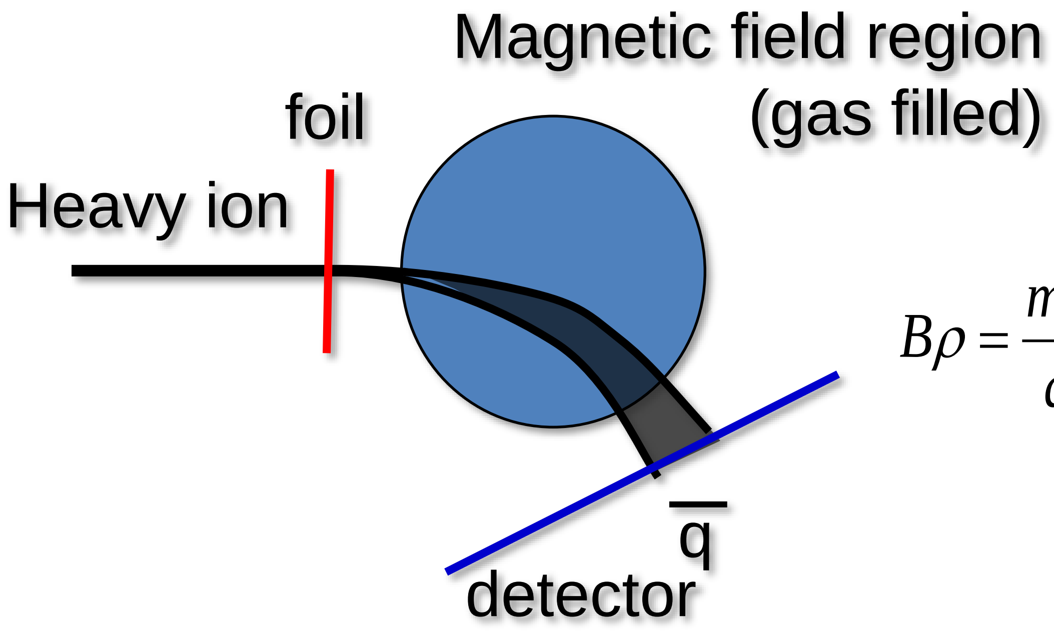
Recoils passing through He take on a well-defined average charge state.

(100% charge acceptance)

The average charge state is nearly proportional to velocity.

(large velocity/energy acceptance)

Efficiency of gas-filled separator can be ***double*** that of vacuum separator



$$B\rho = \frac{mv}{q}$$

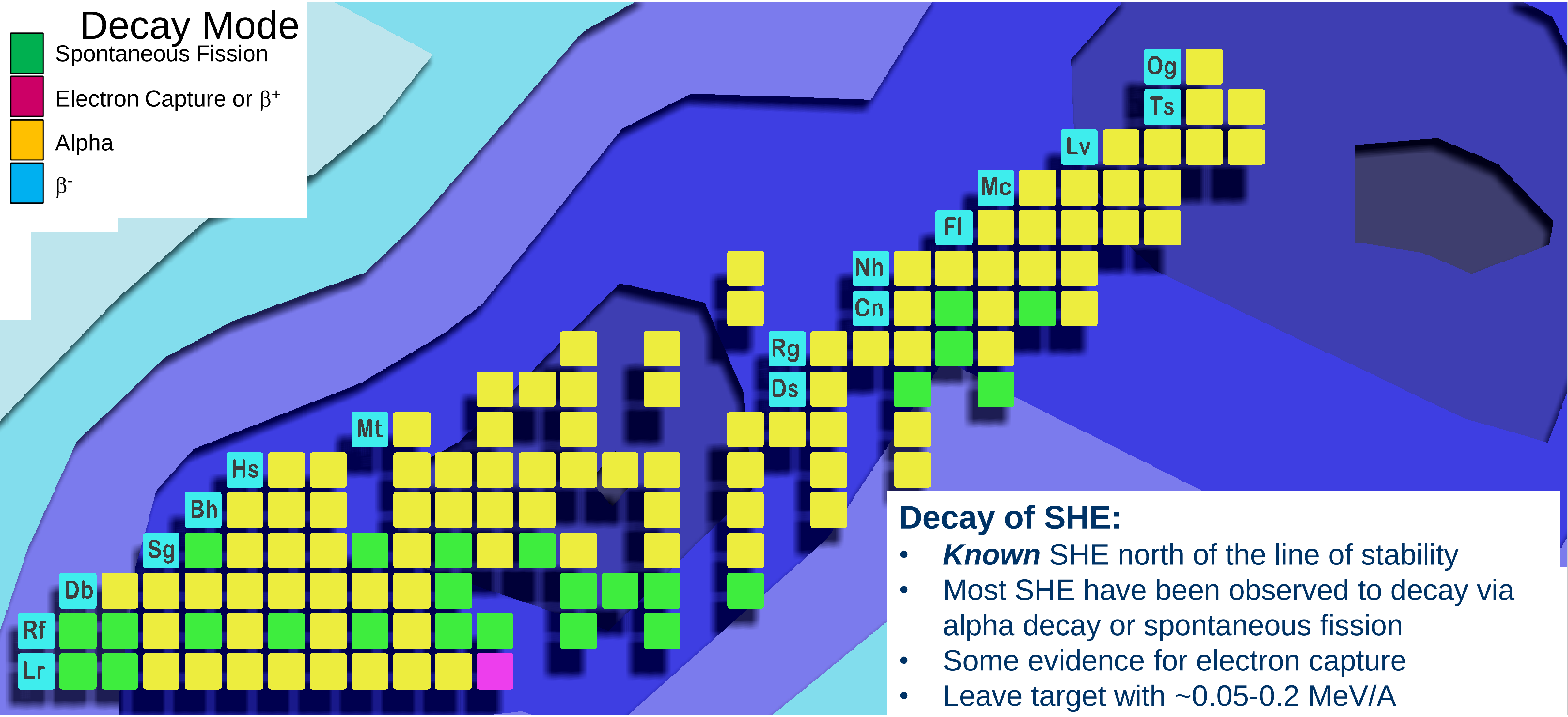
Step 4: Separation

Why would you choose a vacuum separator?

Two types of compound nucleus separators have *complementary* capabilities

	Vacuum Separators	Gas-filled Separators
Examples	FMA, SHIP, VASSILISSA, etc	BGS, DGFRS, GARIS, RITU, TASCA, etc
Angular acceptance	Moderate (up to 16 msr)	Large (up to 45 msr)
Velocity acceptance	Moderate (up to ±25%)	Large (up to 100%)
Charge acceptance	Moderate (up to ±7%)	Large (up to 100%)
Efficiency: $^{48}Ca+^{208}Pb$	**Up to 30%**	**Up to 70%**
Mass resolution	Good (M/ΔM>200)	Poor (M/ΔM <30)

Step 5: Detection



Decay of SHE:

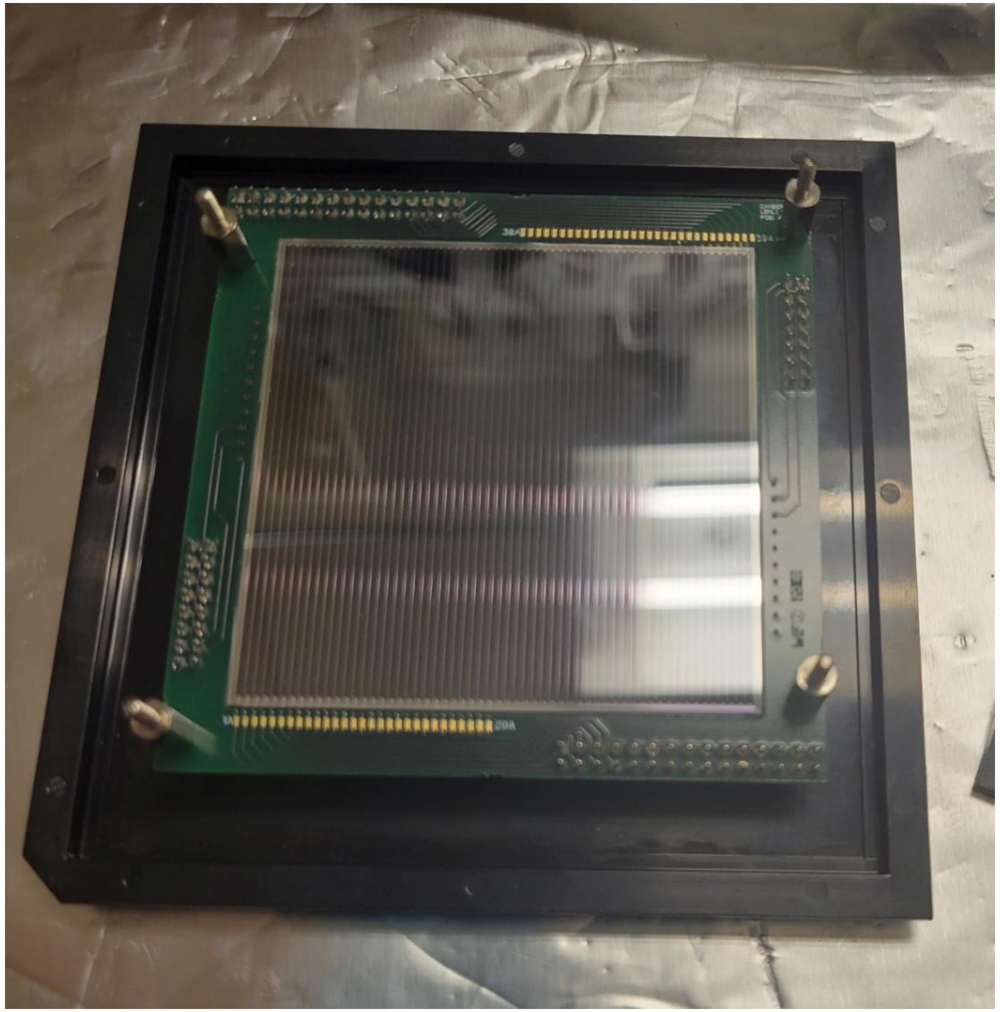
- ***Known*** SHE north of the line of stability
- Most SHE have been observed to decay via alpha decay or spontaneous fission
- Some evidence for electron capture
- Leave target with ~0.05-0.2 MeV/A

Step 5: Detection

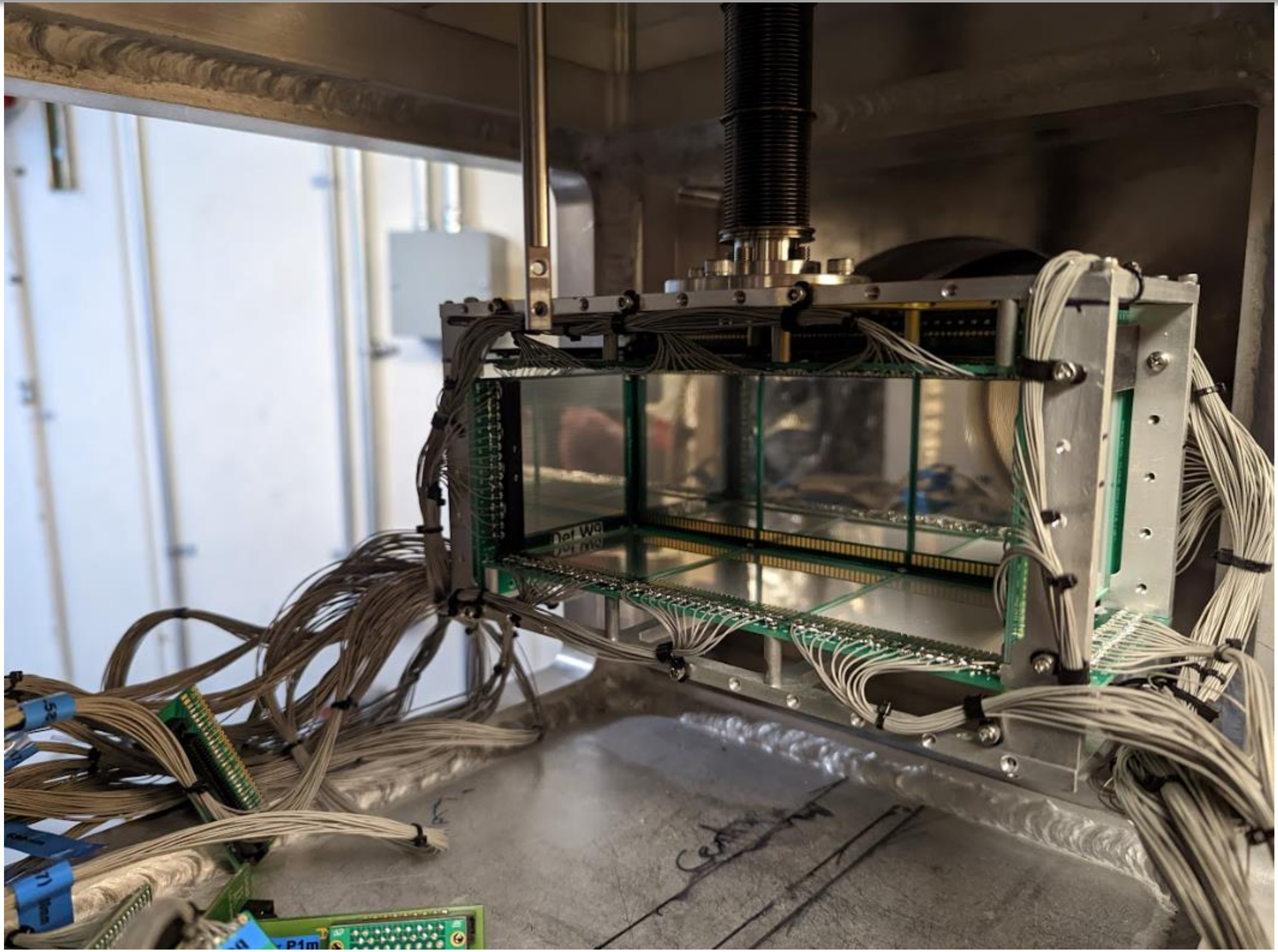
Decay of SHE:

- ***Known*** SHE north of the line of stability
- Most SHE have been observed to decay via alpha decay or spontaneous fission
- Some evidence for electron capture
- Leave target with ~ 0.05 – 0.2 MeV/A

Detectable with silicon detectors

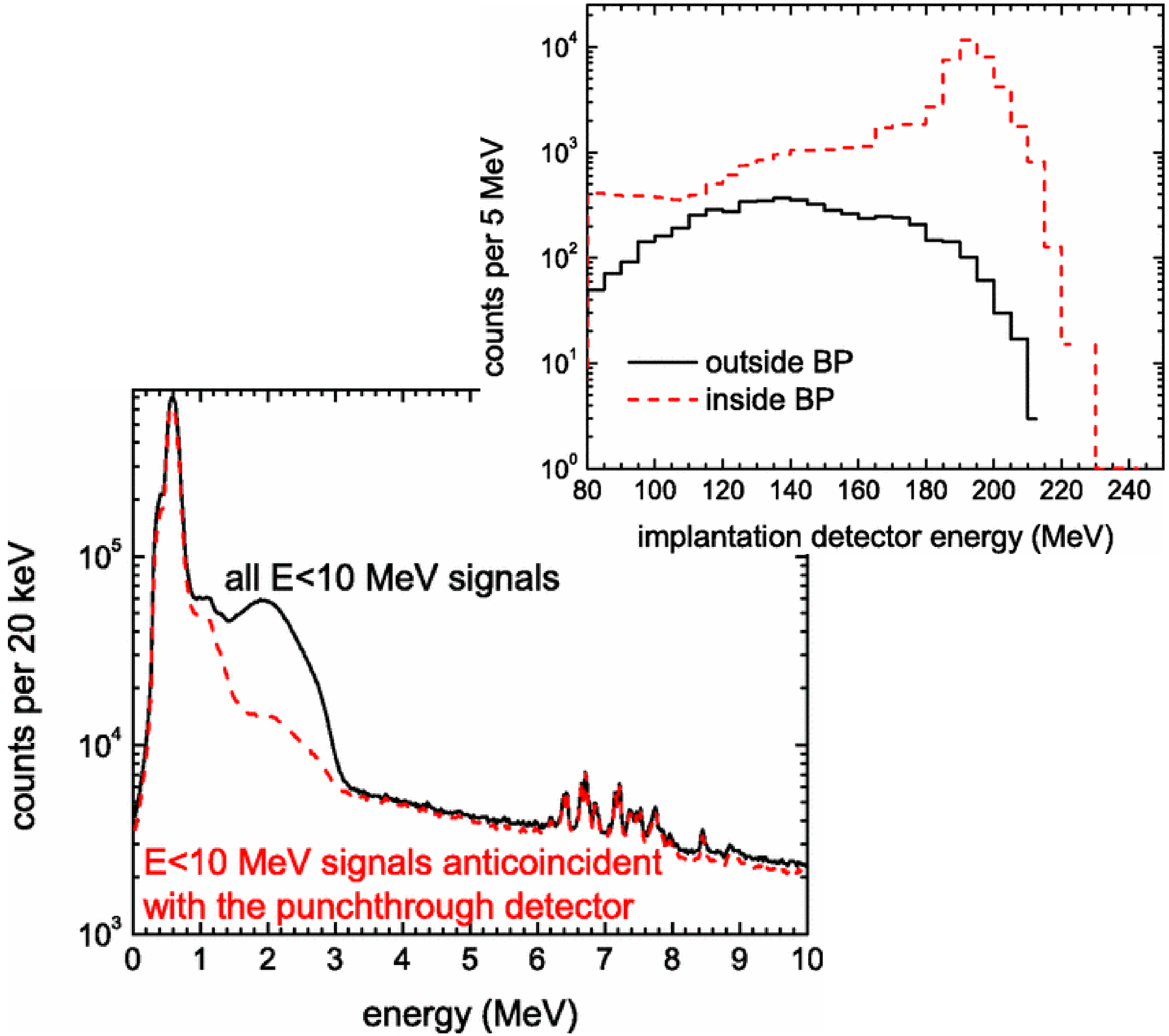


Step 5: Detection – BGS Focal Plane Detector



What hits the detector?

- Separators are great, but not perfect!
- Detectors behind separators operate at 1-2 kHz
  - Compton scattered photons
  - Elastically scattered He, H fill gas
  - Protons from beamstop
  - Deuterons
  - Scattered beam
  - Primary beam
  - Transfer reaction products
  - Decays (alpha, beta) from transfer reactions

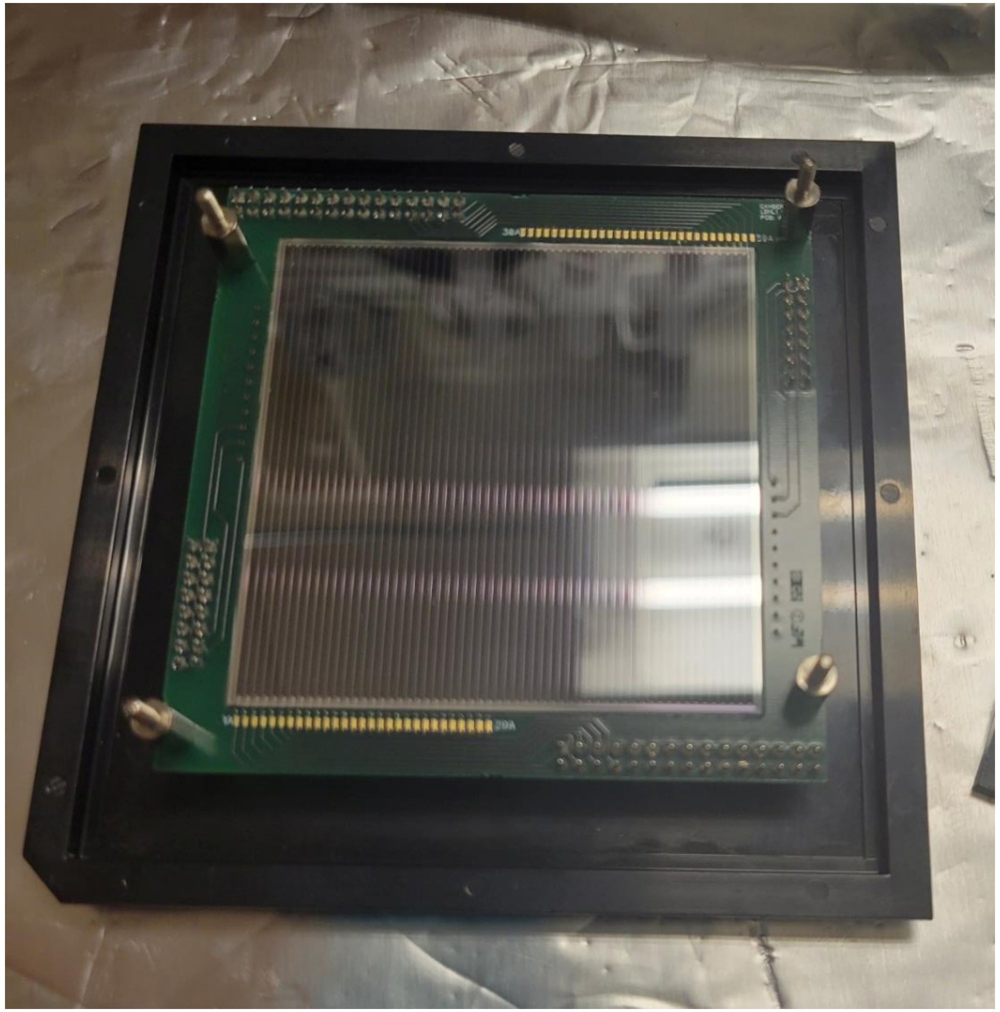


Question: How do you detect SHE implantation over background?

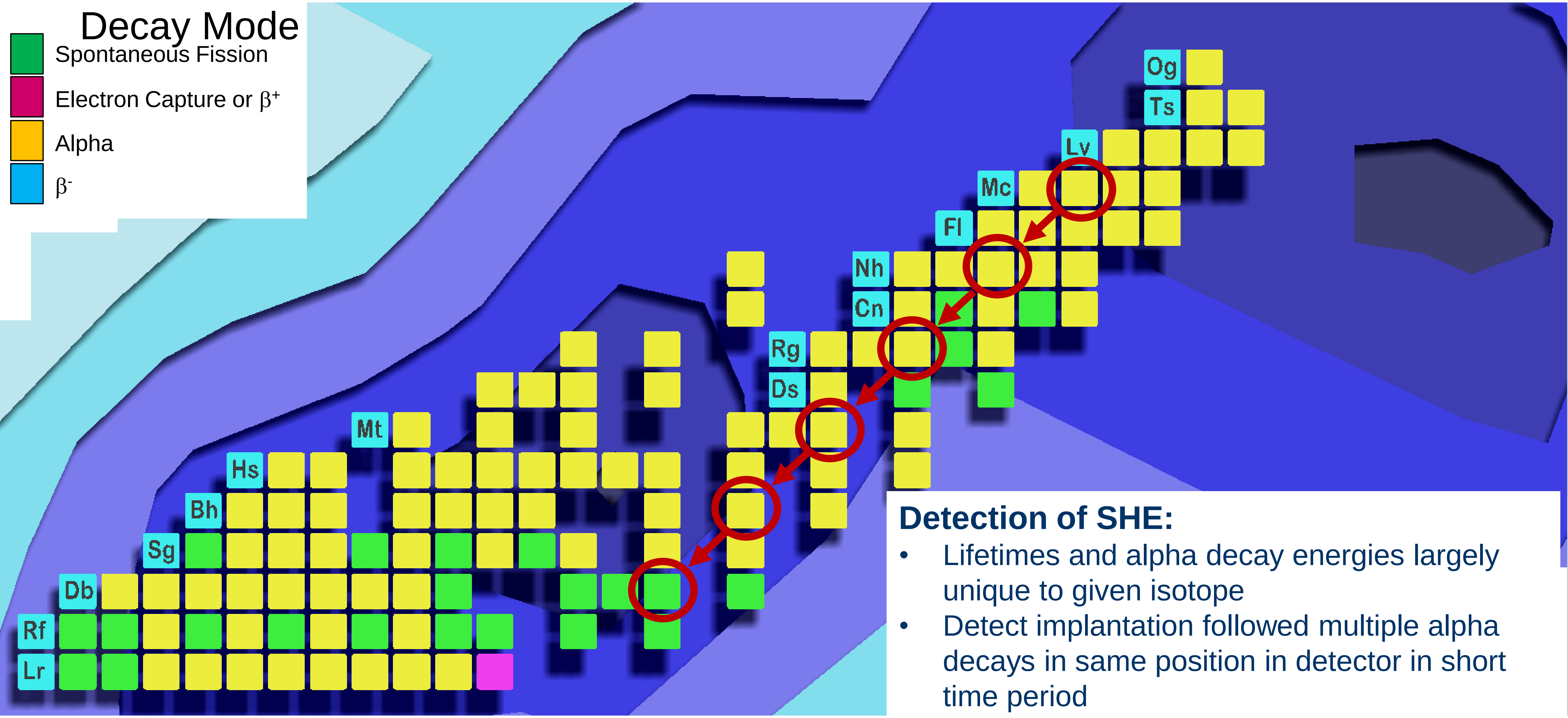
Step 5: Segmented Detectors

Silicon detectors are segment!

- EVR implants in specific location → know location w/in 1-2 mm (depending on detector)
- Decay happens in same location



Step 5: Detection – Genetic Correlations



Detection of SHE:

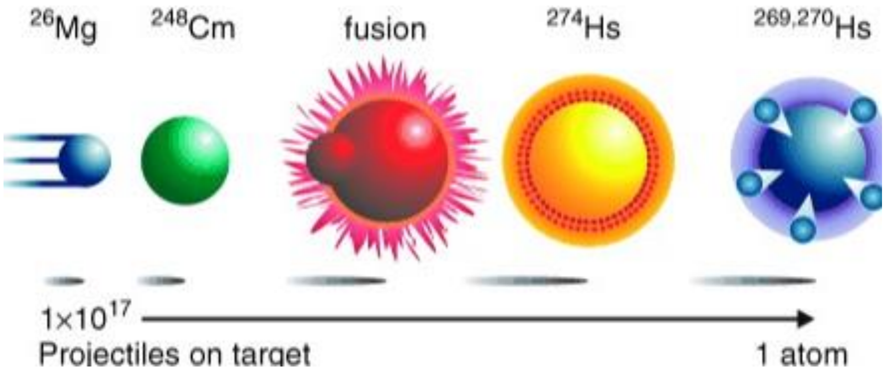
- Lifetimes and alpha decay energies largely unique to given isotope
- Detect implantation followed multiple alpha decays in same position in detector in short time period

Question: How do you pick beam/target combinations?

Types of Fusion Reactions

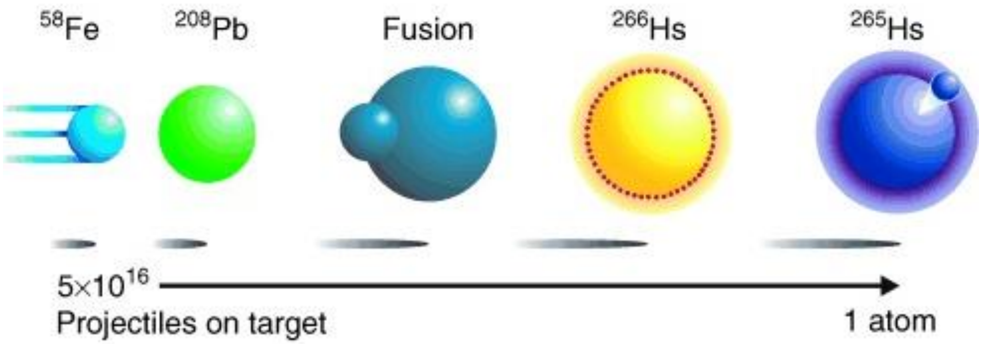
Hot Fusion

- Fusion of light ion beams (^{18}O, ^{22}Ne, ^{40}Ar, ^{48}Ca) with actinide targets



Cold Fusion

- Fusion of transition metals (^{48}Ca, ^{50}Ti, ^{54}Cr, etc) with Pb or Bi targets



Excitation energy for a reaction:

$$E^* = E_{cm} - (m_{beam} + m_{target} - m_{product})$$

Types of Fusion Reactions

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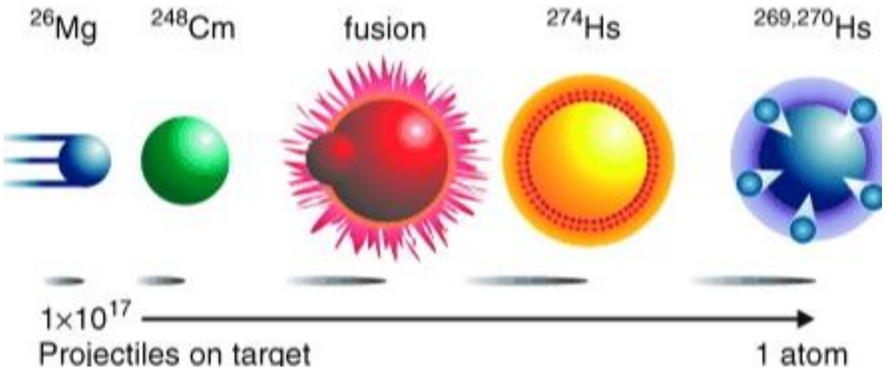
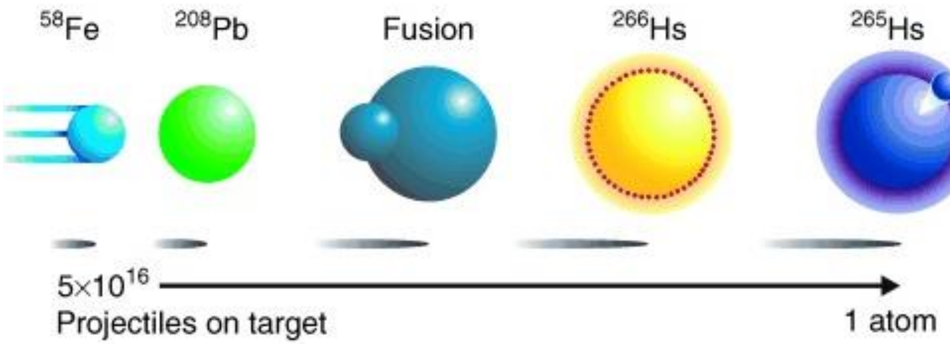


Bass barrier ≈ 125 MeV E_{cm}

$E^* \approx 40$ MeV

Cold Fusion

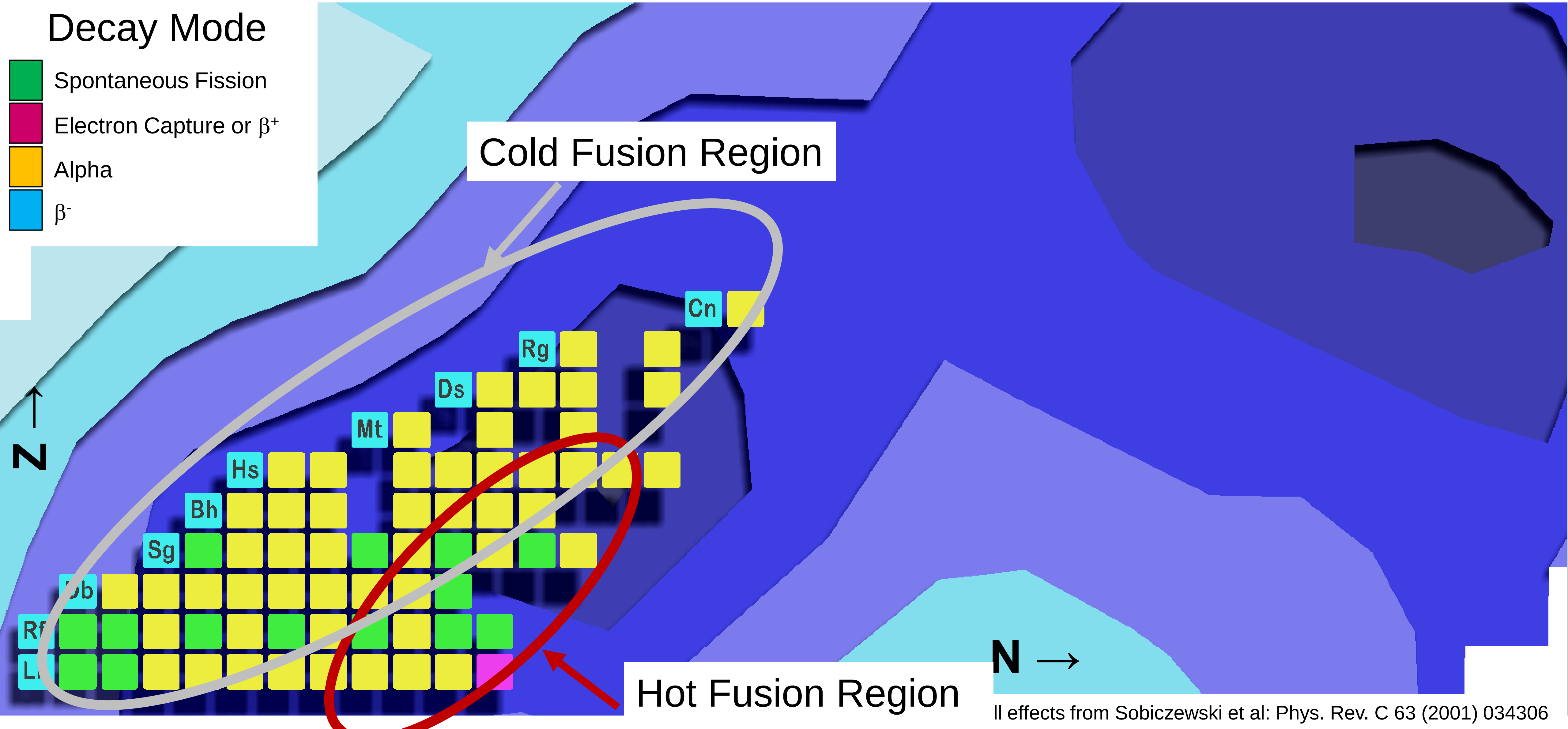
- Fusion of transition metals (^{48}Ca, ^{50}Ti, ^{54}Cr, etc) with Pb or Bi targets



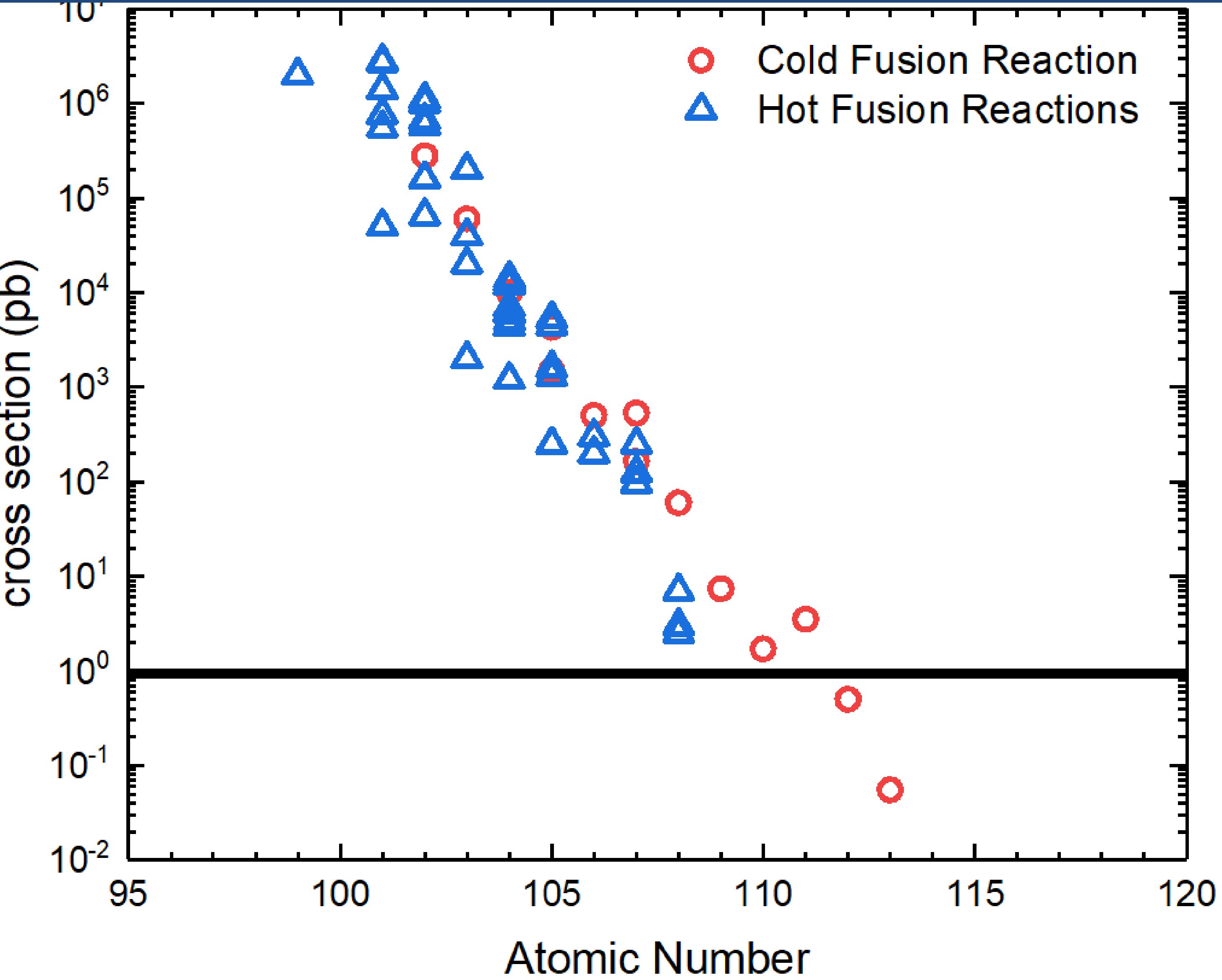
Bass barrier ≈ 225 MeV E_{cm}

$E^* \approx 10$ MeV

Chart of the Nuclides: 2000



Discovery of Elements: Pre 2000

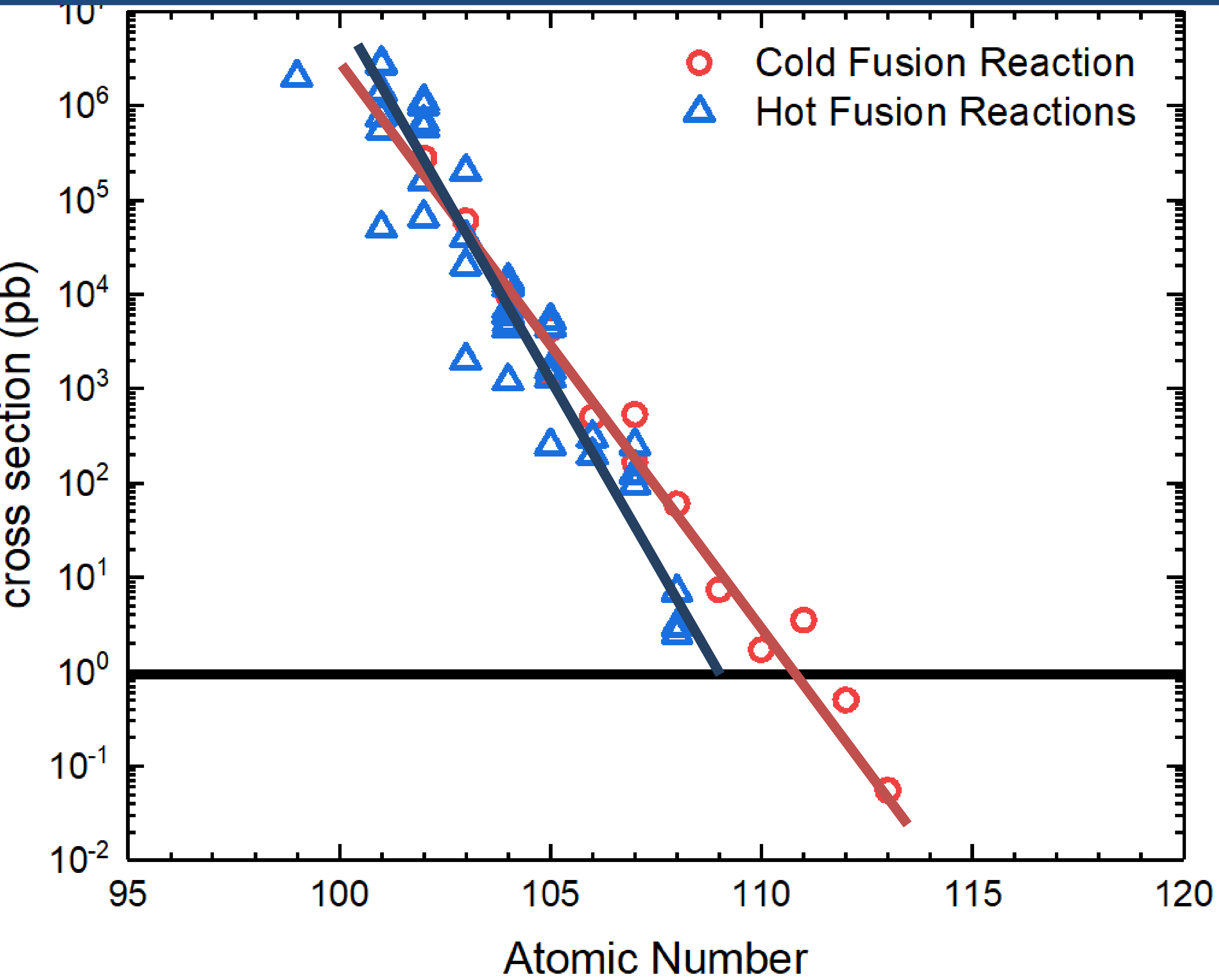


Two main types of reactions used for heavy element synthesis:

- Cold Fusion: transition metals (Ti-Zn) on Lead and Bismuth targets
- Hot Fusion: light ions (O-Ar) on actinide targets

One atom per week

Discovery of Elements: Pre 2000



Two main types of reactions used for heavy element synthesis:

- Cold Fusion: transition metals (Ti-Zn) on Lead and Bismuth targets
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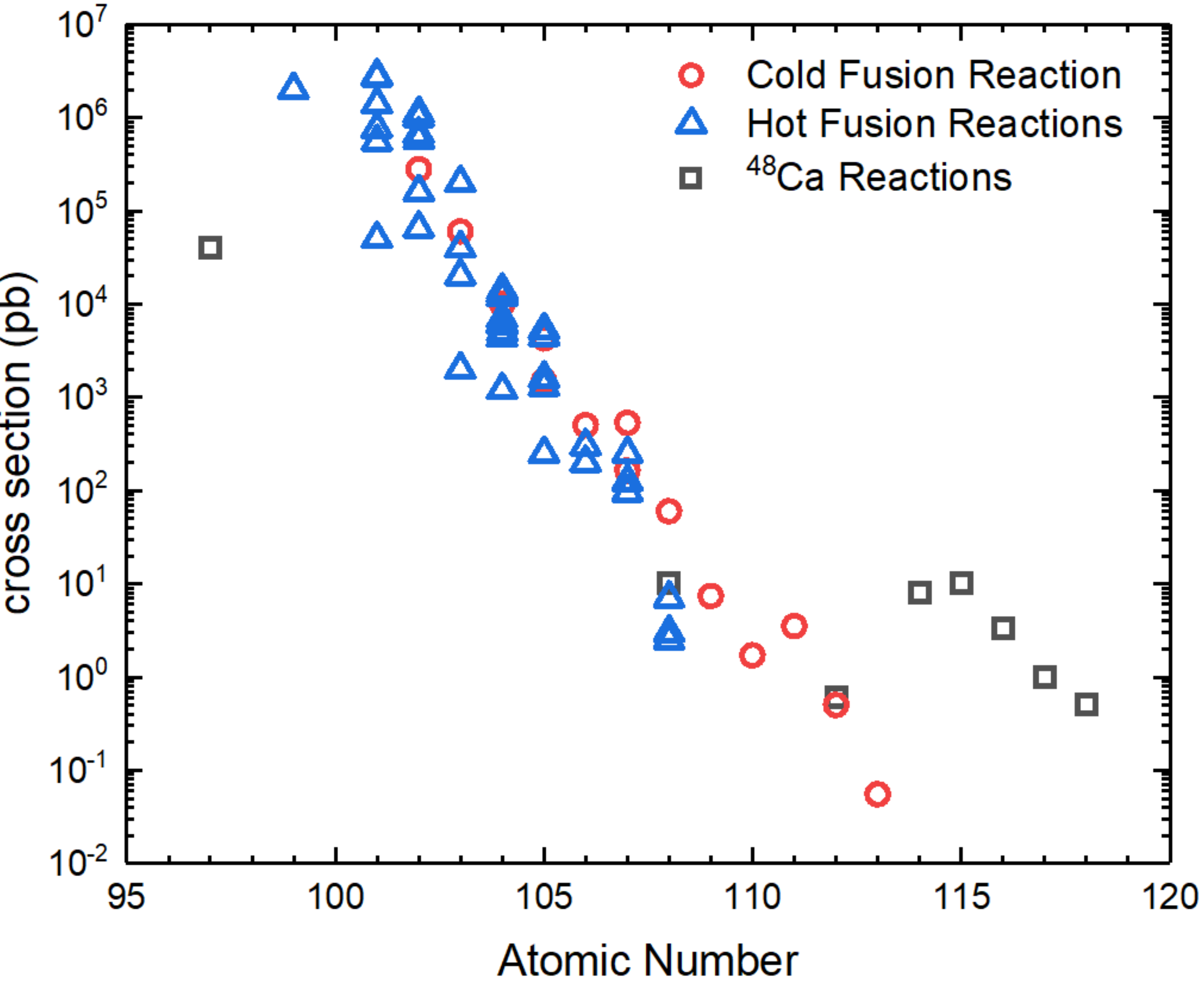
One atom per week

Extension of Chart of Nuclides

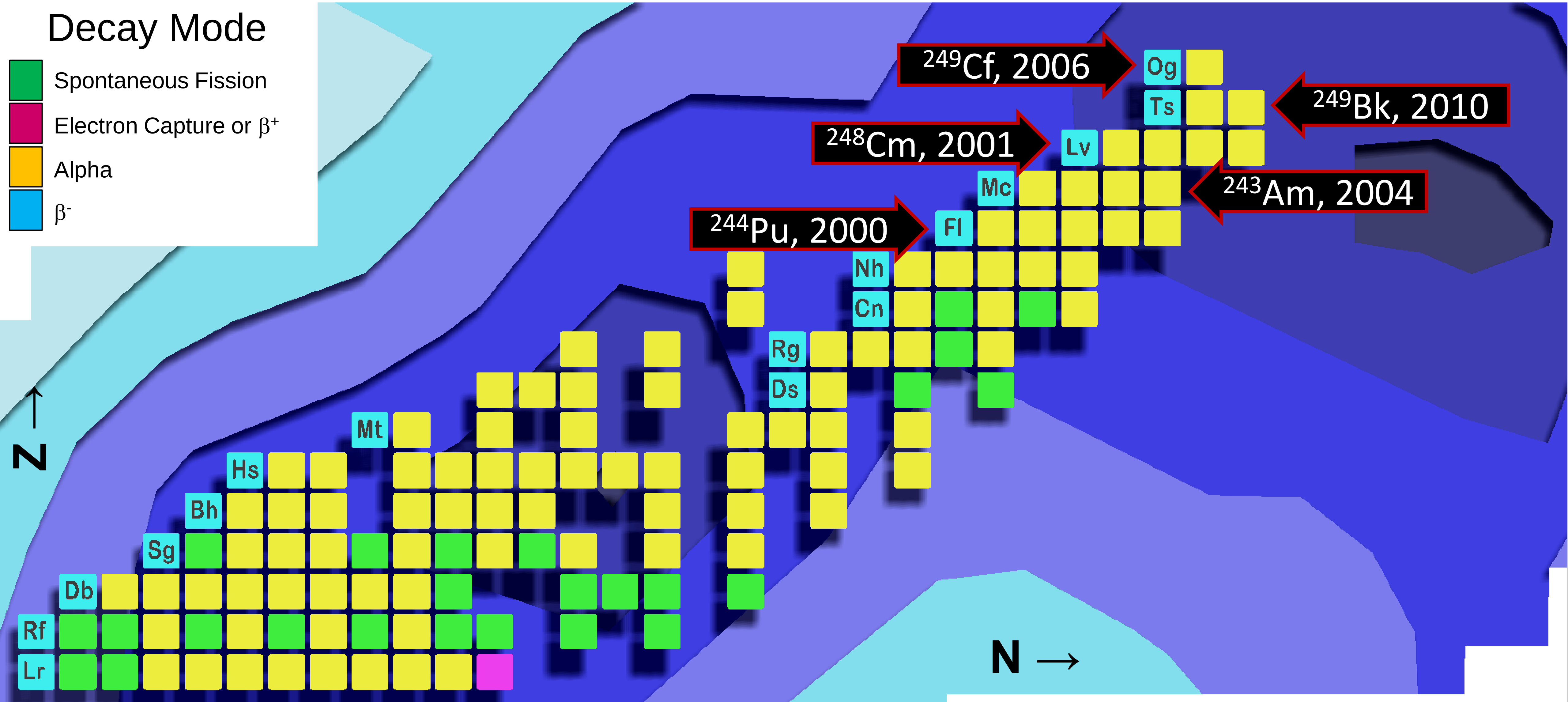
New reaction type (re)discovered: ^{48}Ca+Actinide targets



Superheavy Elements from ^{48}Ca+Actinide targets:

- Cross sections increase with E114>E112>E110
- Cross sections peaked Z~114-115

Chart of the Nuclides: 2019



Shell effects from Sobiczewski et al: Phys. Rev. C 63 (2001) 034306

Latest Elements Discovered

INTERNATIONAL UNION OF
PURE AND APPLIED CHEMISTRY

For Release 8 June 2016

IUPAC is naming the four new elements nihonium, moscovium, tennessine, and oganesson

Following earlier reports that the claims for discovery of these elements have been fulfilled [1, 2], the discoverers have been invited to propose names and the following are now disclosed for public review:

- Nihonium and symbol Nh, for the element 113,
- Moscovium and symbol Mc, for the element 115,
- Tennessine and symbol Ts, for the element 117, and
- Oganesson and symbol Og, for the element 118.

FLNR 2000
FLNR 2000
FLNR 2002

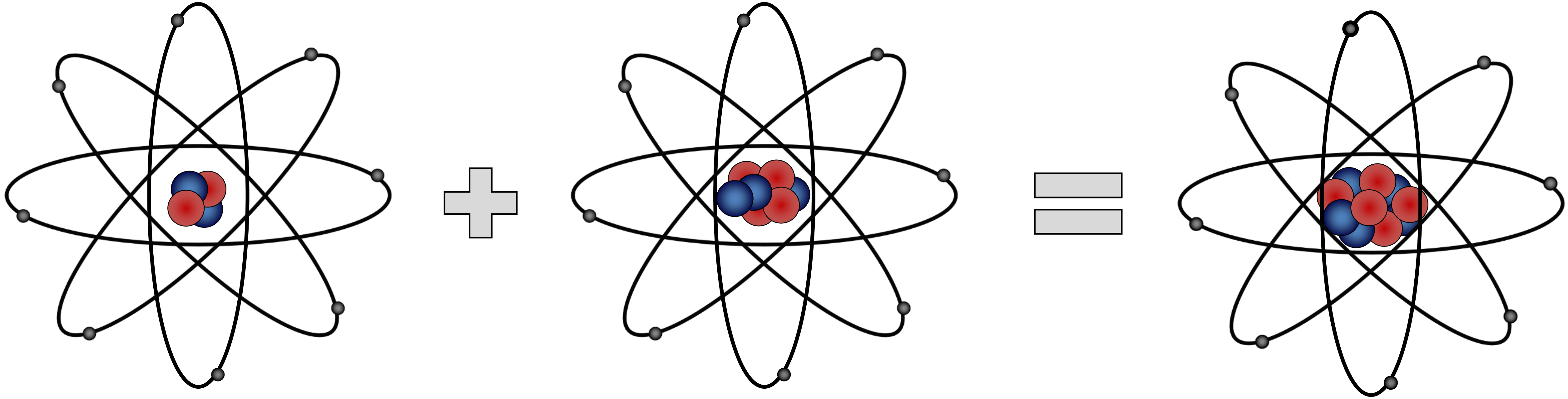
87	88	89-103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
Francium	Radium		Rutherfordium	Dubnium	Seaborgium	Bohrium	Hassium	Meitnerium	Darmstadtium	Roentgenium	Copernicium	Nihonium	Flerovium	Moscovium	Livermorium	Tennessine	Oganesson
223.020	226.025		[261]	[262]	[266]	[264]	[269]	[278]	[281]	[280]	[285]	[286]	[289]	[289]	[293]	[294]	[294]

Riken 2004
FLNR 2003
FLNR 2010

6 new elements discovered in the last 2 decades

We've reached the end of the road with ^{48}Ca+Actinide reactions

Heaviest target available = ^{248}Cf (Z=98)



^{48}Ca (Z=20) ^{248}Cf (Z=98) ^{296}Og* (Z=118)

Summary and Conclusions

How to make new elements:

- Actinides: neutron absorption → beta decay → high-flux nuclear reactors
- Z>100: Add 2 lighter nuclei together

Two reaction types:

- Hot fusion
- Cold fusion

Tomorrow:

- What do we know about SHE?
- How can we push towards even heavier elements?