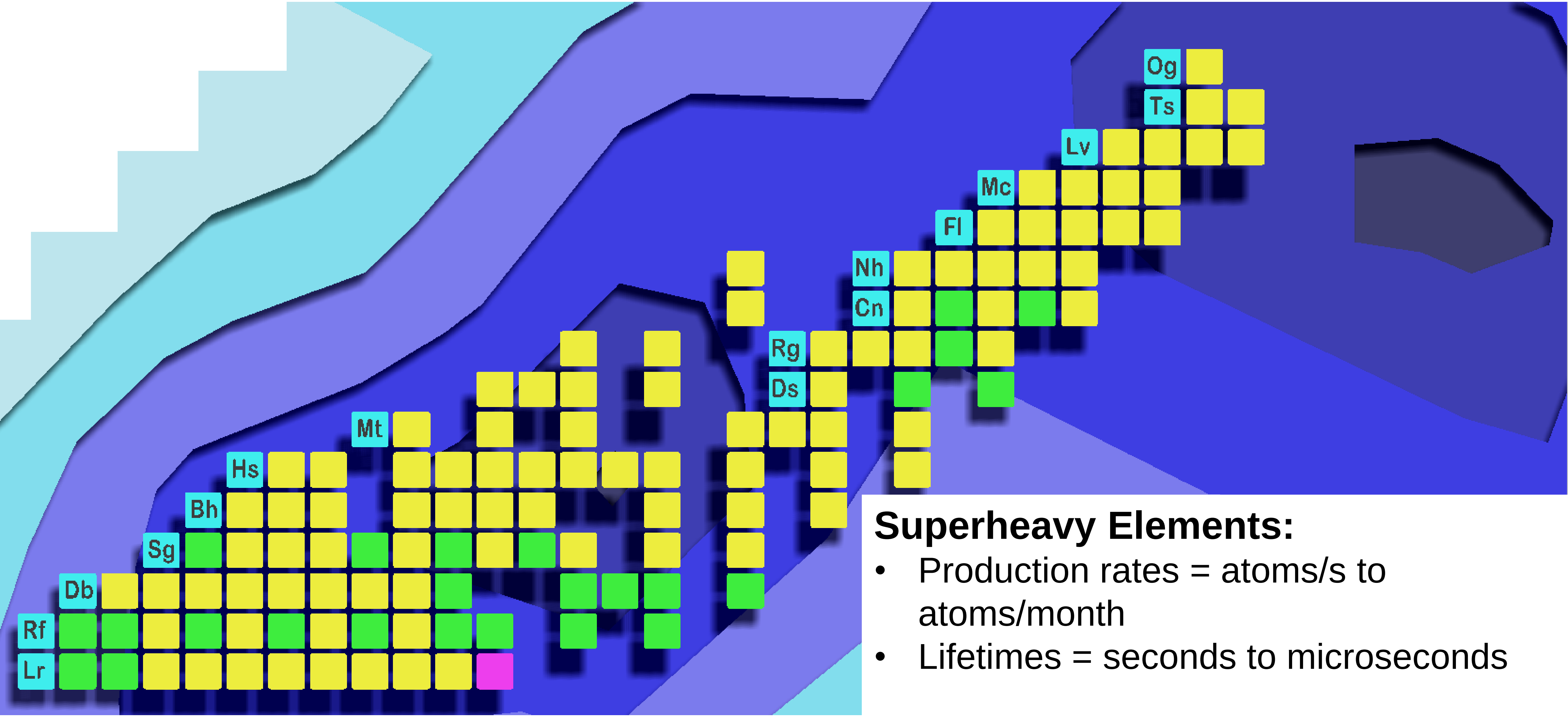
Lecture 3:

Properties of Superheavy Elements

Searching for New Elements

Chart of the Nuclides: 2019



Superheavy Elements:

- Production rates = atoms/s to atoms/month
- Lifetimes = seconds to microseconds

Unique Challenges With Transactinide Experiments

Challenges with heavy element chemistry:

- Only make one atom-at-a-time
- Atoms formed with the momentum of the beam → 36000 m/s
- Transactinides are short-lived with lifetimes of minutes or less

	^{254}No	^{255}Lr	^{257}Rf	^{258}Db	^{272}Bh	^{276}Mt	^{280}Rg	^{284}Nh	^{288}Mc
	55 s	22 s	4.7 s	4 s	12 s	0.54 s	3.6 s	0.97 s	171 ms
Z=	102	103	104	105	107	109	111	113	115
atoms*	1/s	10/min	1/min	6/hr	1/hr	10/wk	1/wk	1/wk	1/day

*rates observed at BGS focal plane in recent campaigns

What we can learn from decays of just a few atoms?

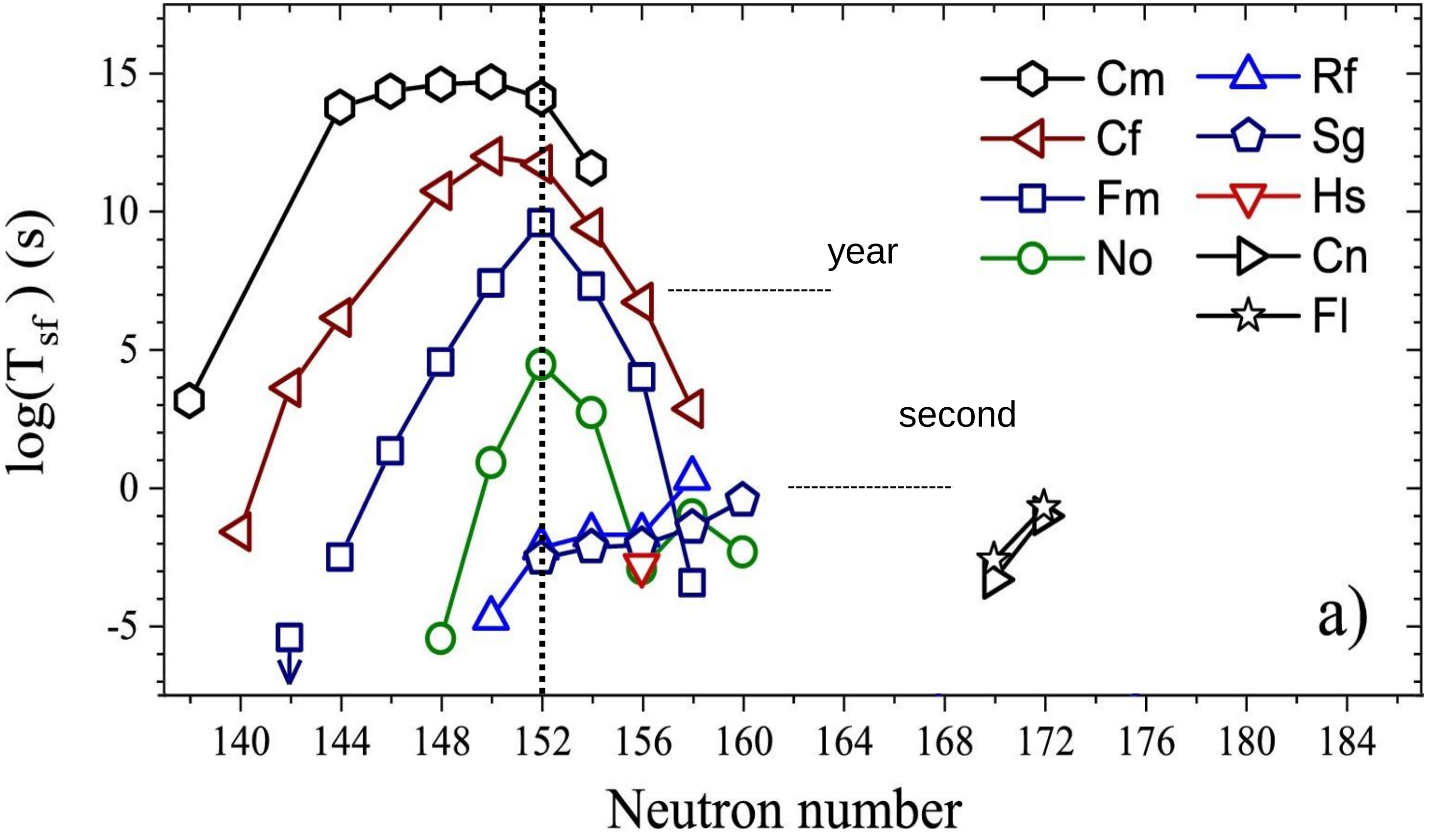
Can measure

- Decay mode
- Decay energy
- Decay lifetime
- Photons emitted during de-excitation
- (Some) chemistry
- High precision mass measurements (Z<=104)
- Energies of atomic levels (Z<=102)

Fission

Spontaneous Fission Lifetimes

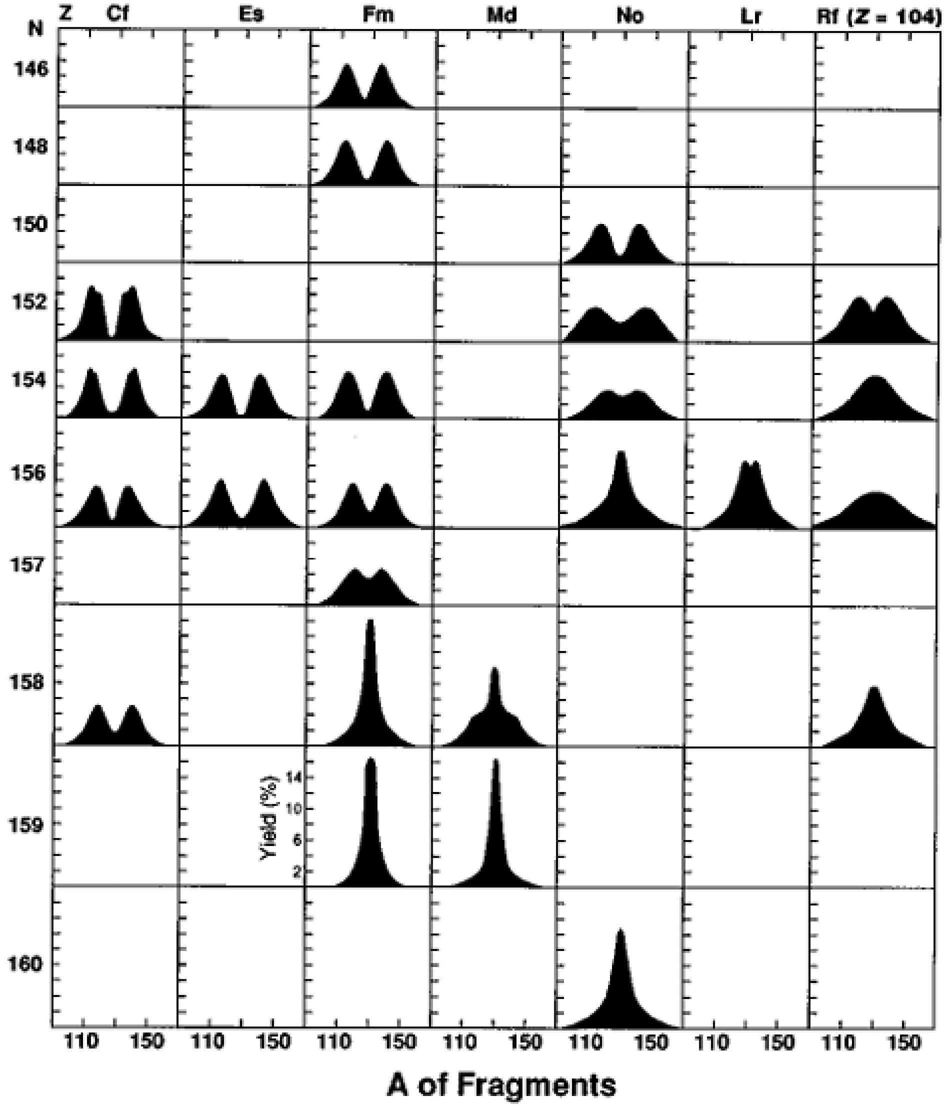
- **Plot of spontaneous fission partial half-lives for known fission emitters**
- **Strong *N*=152 shell in lighter isotopes**



Khuyagbaatar, J.: Nucl. Phys. A **1002** (2020) 121958: https://doi.org/10.1016/j.nuclphysa.2020.121958

Fission Fragment Masses

Can observe the evolution of fragment mass yields for actinide and transactinide isotopes

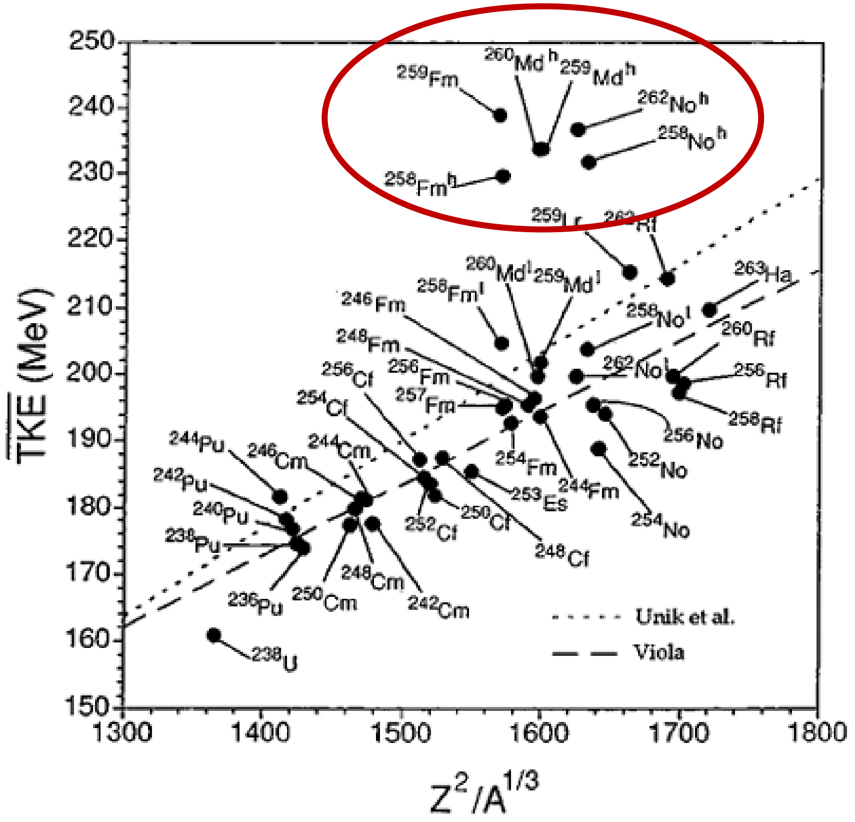


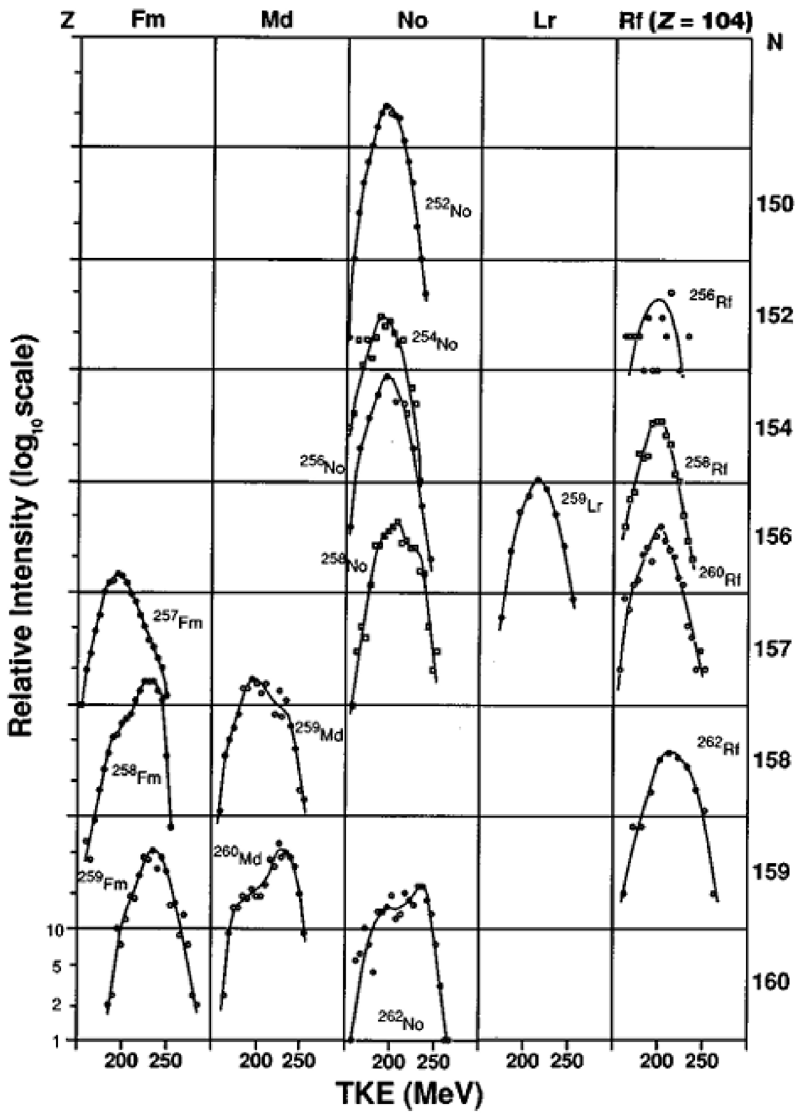
Lane, M.R. Phys. Rev. C **53** (1996) 2893: https://doi.org/10.1103/PhysRevC.53.2893

Total Kinetic Energy

TKE Distributions for actinide and transactinide nuclides

Symmetric fission



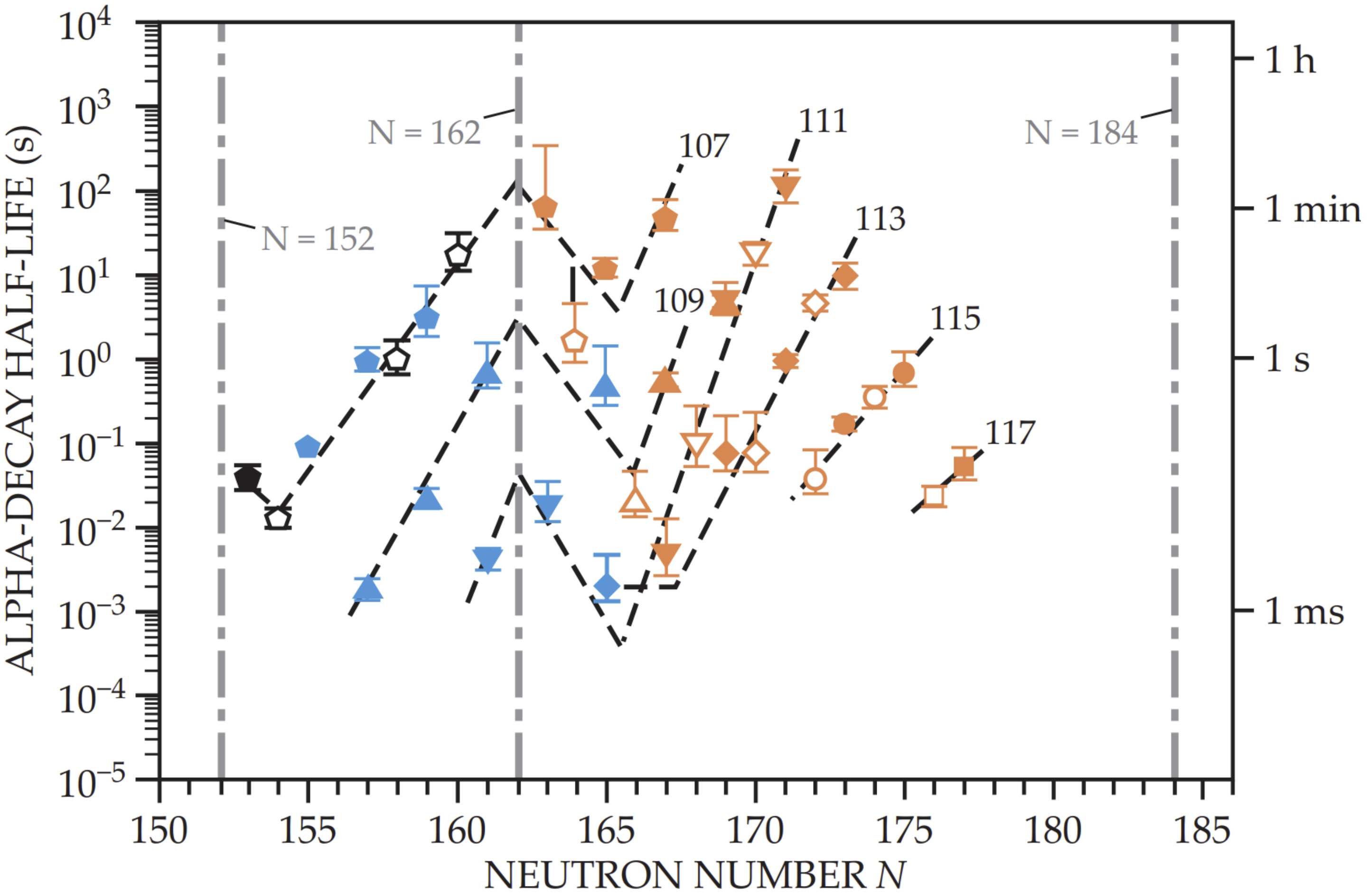


Lane, M.R. Phys. Rev. C **53** (1996) 2893: https://doi.org/10.1103/PhysRevC.53.2893

Alpha Decay

Alpha Decay Half-life

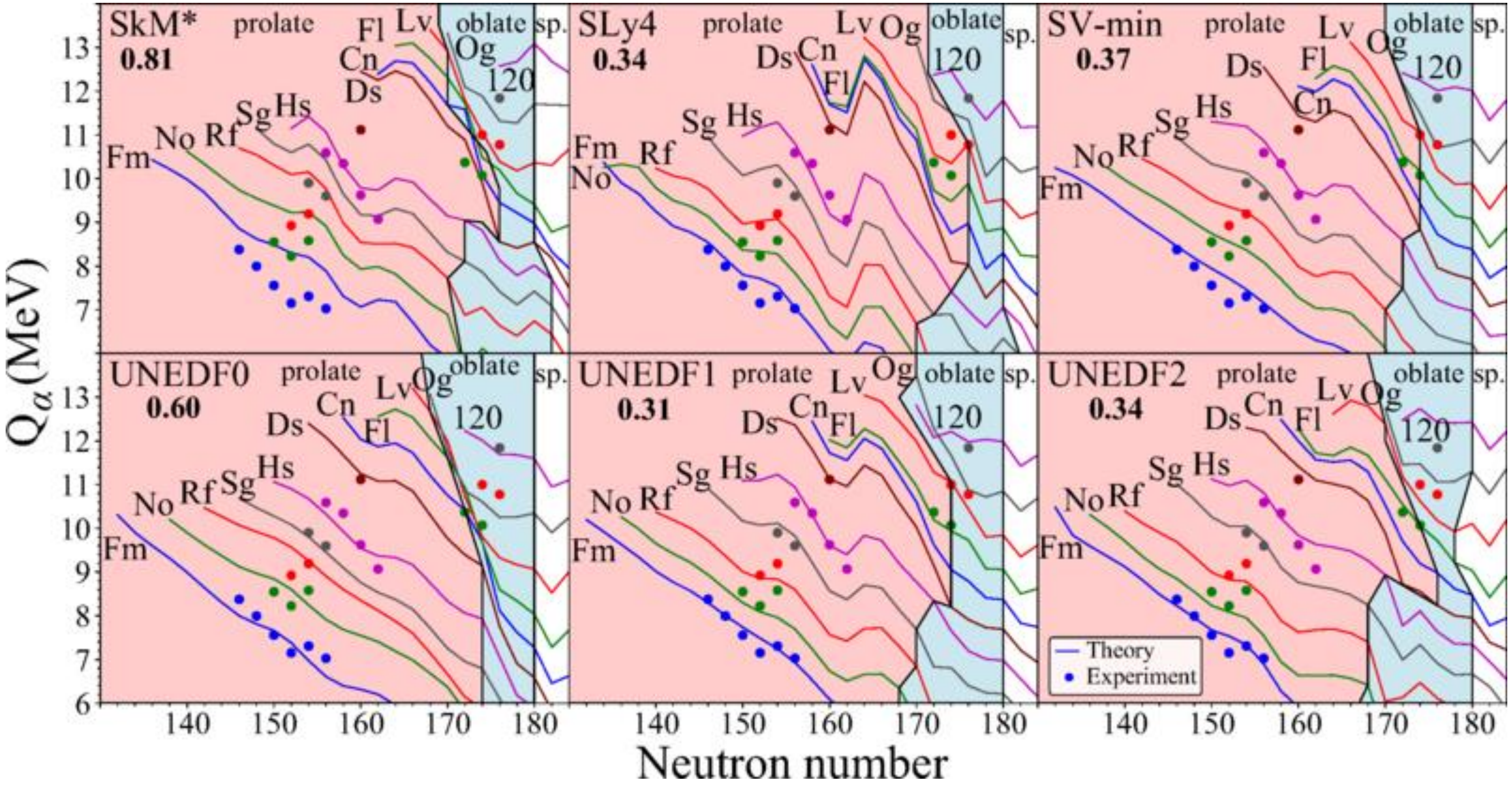
Can measure alpha decay energies and half-lives for all isotopes observed to decay via alpha



Oganessian, Yu.Ts., Phys. Today **68** (2015) 32: https://doi.org/10.1063/PT.3.2880

Alpha energy systematics

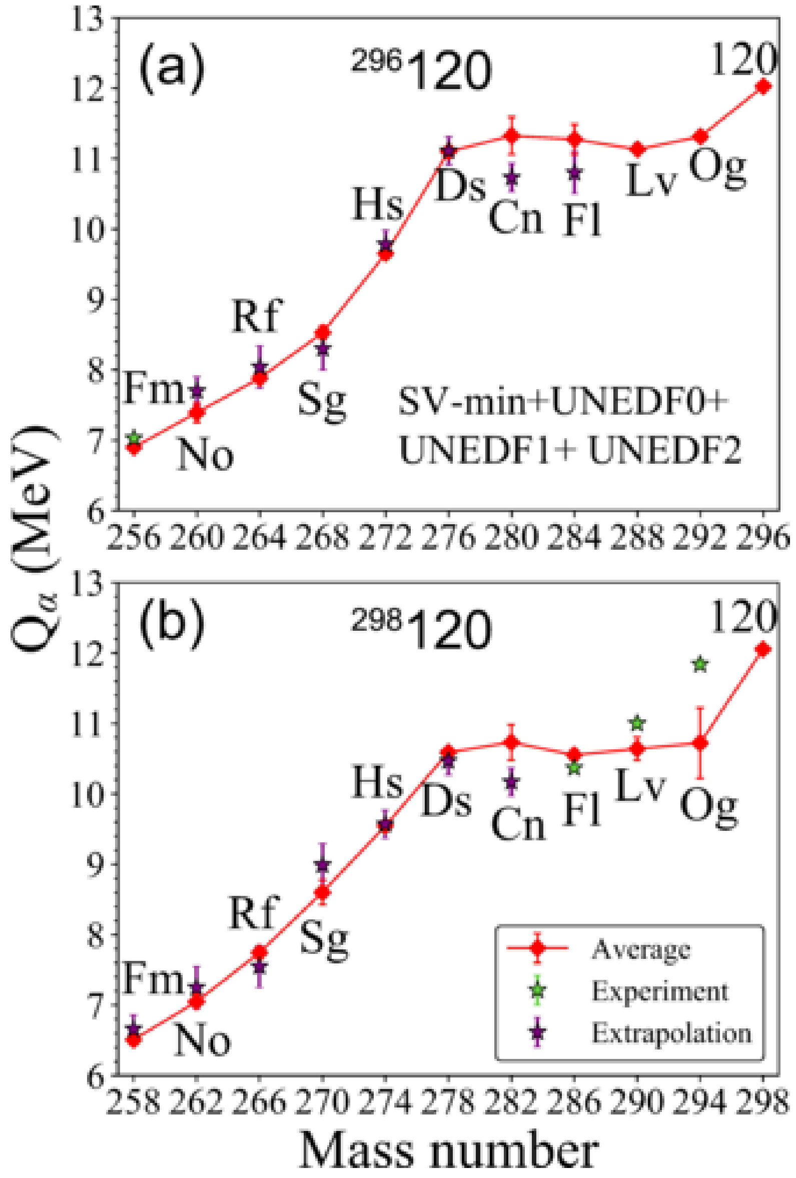
Can use known alpha decay energies to hone theories of nuclear stucture



Olsen, E., Phys. Rev. C **99** (2019) 014317: https://doi.org/10.1103/PhysRevC.99.014317

Alpha decay

Honing theories allows us to look and identify new isotopes through observations of isotopic chains and comparisons to theory

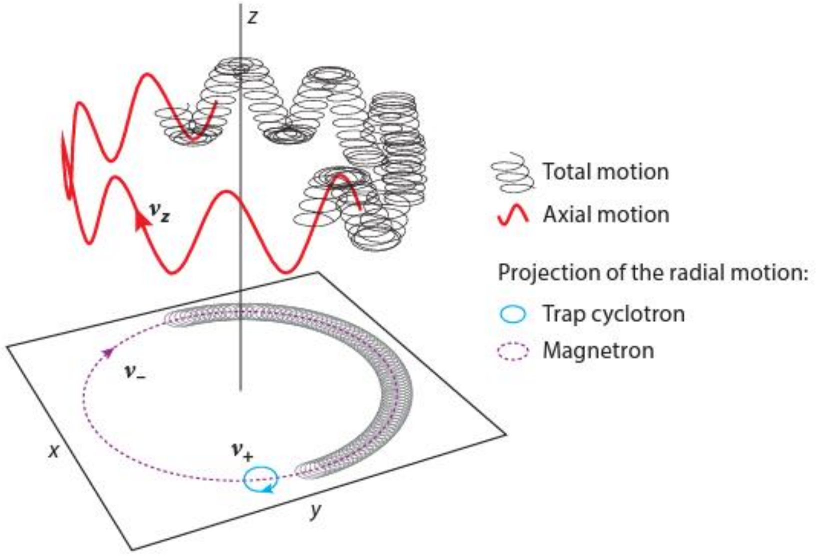


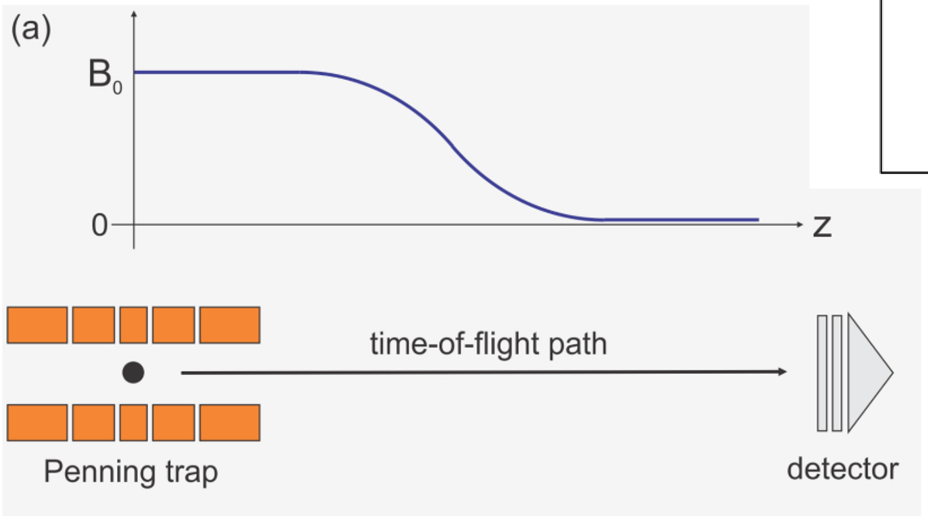
Olsen, E., Phys. Rev. C **99** (2019) 014317: https://doi.org/10.1103/PhysRevC.99.014317

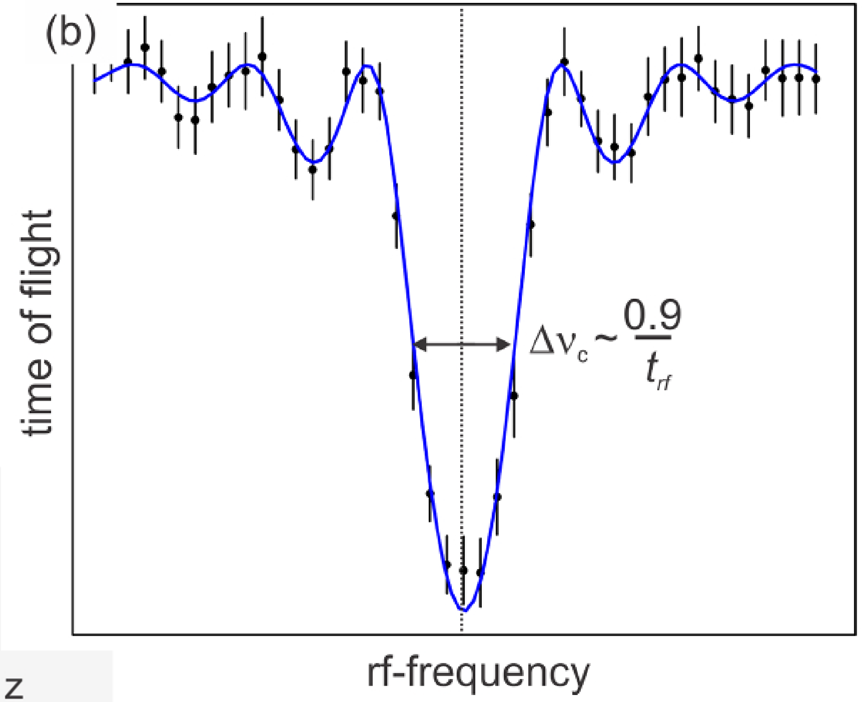
Atomic Masses

Atomic Masses – Penning Trap

Trap ion in: Superposition of a static strong uniform magnetic field (B) and a static three-dimensional quadrupole electric potential

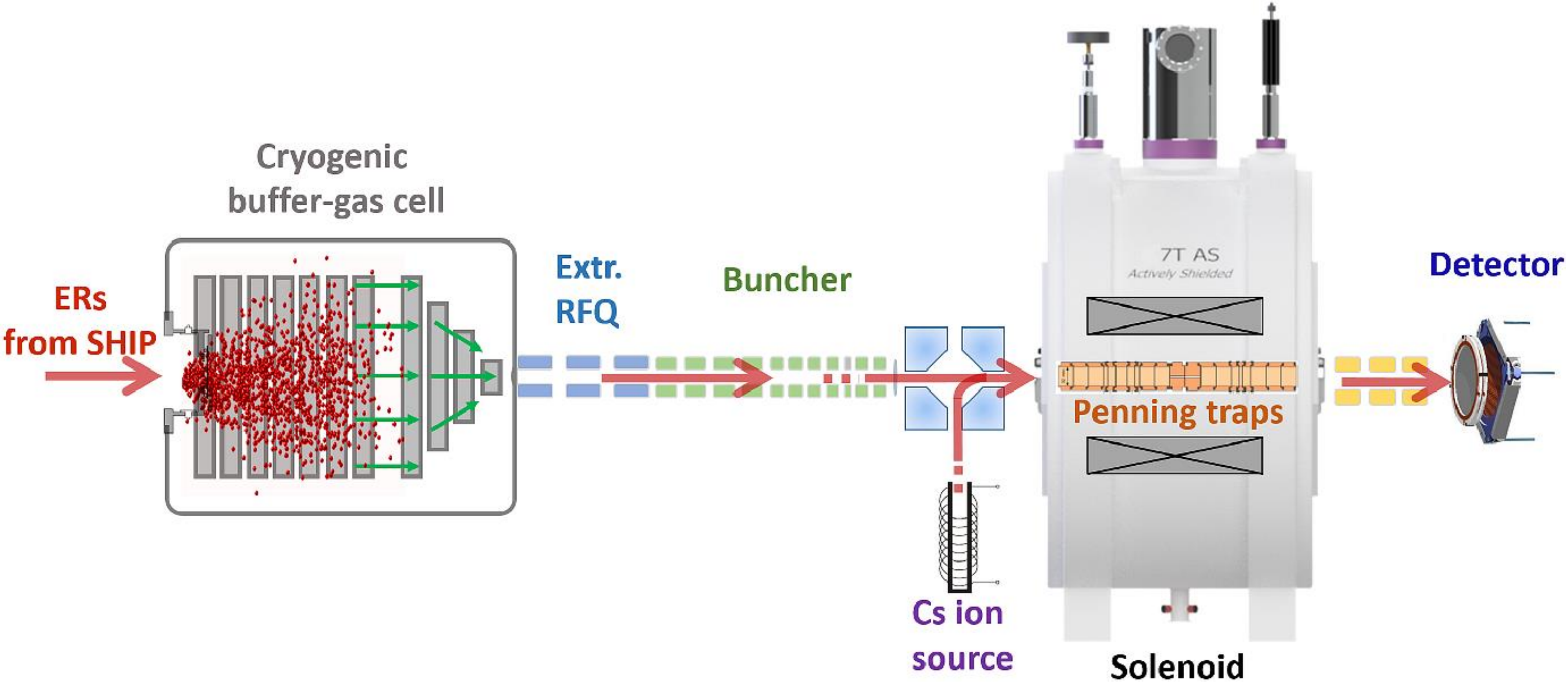






Eliseev, S., Euro. Phys. J. A, **59** (2023) 34: https://doi.org/10.1140/epja/s10050-023-00946-4
Dilling, J, Annul. Rev. Nucl. Part. Sci. **68** (2018) 45: https://doi.org/10.1146/annurev-nucl-102711-094939

Atomic Masses – Penning Trap



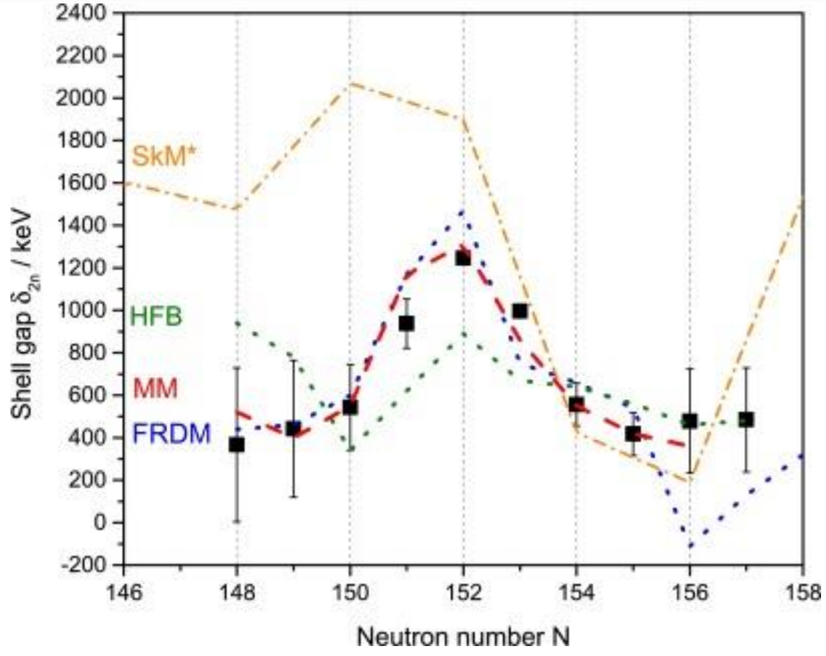
Block, M., Nucl. Phys. A, **944** (2015) 471: https://doi.org/10.1016/j.nuclphysa.2015.09.009
Block, M. La Rivista del Nuovo Cimento **45** (2022) 279: https://doi.org/10.1007/s40766-022-00030-5

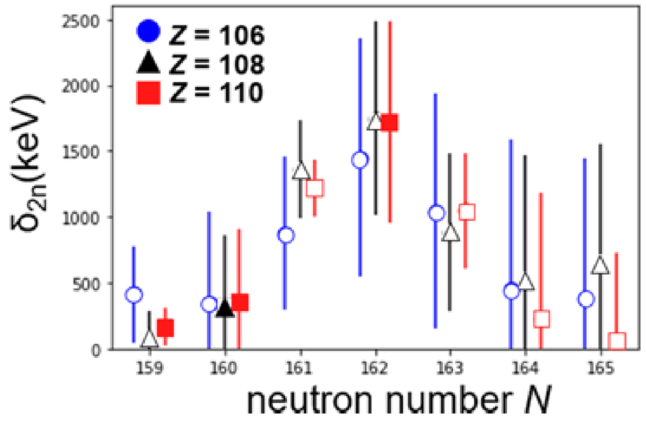
Atomic Masses – Penning Traps

Precise masses can be used to access evolution of neutron shell gaps at *N*=152 and *N*=162

Newer techniques such as PI-ICR can identify energies of isomeric states

Downside: Lots of ions required to make measurements ➔ limit to how high in *Z* measurements can go





Block, M., Nucl. Phys. A, **944** (2015) 471: https://doi.org/10.1016/j.nuclphysa.2015.09.009
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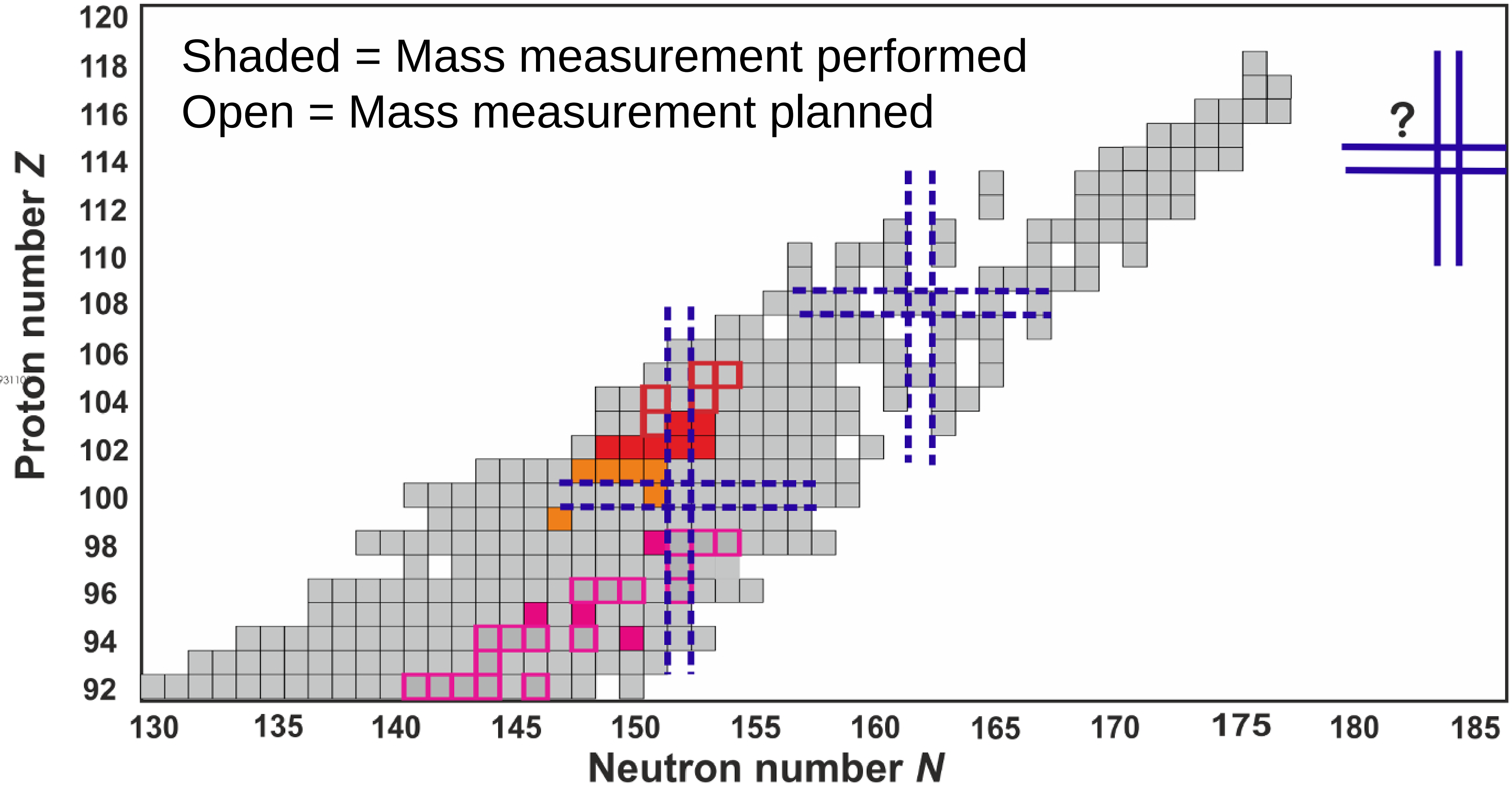
Atomic Masses – Penning Trap



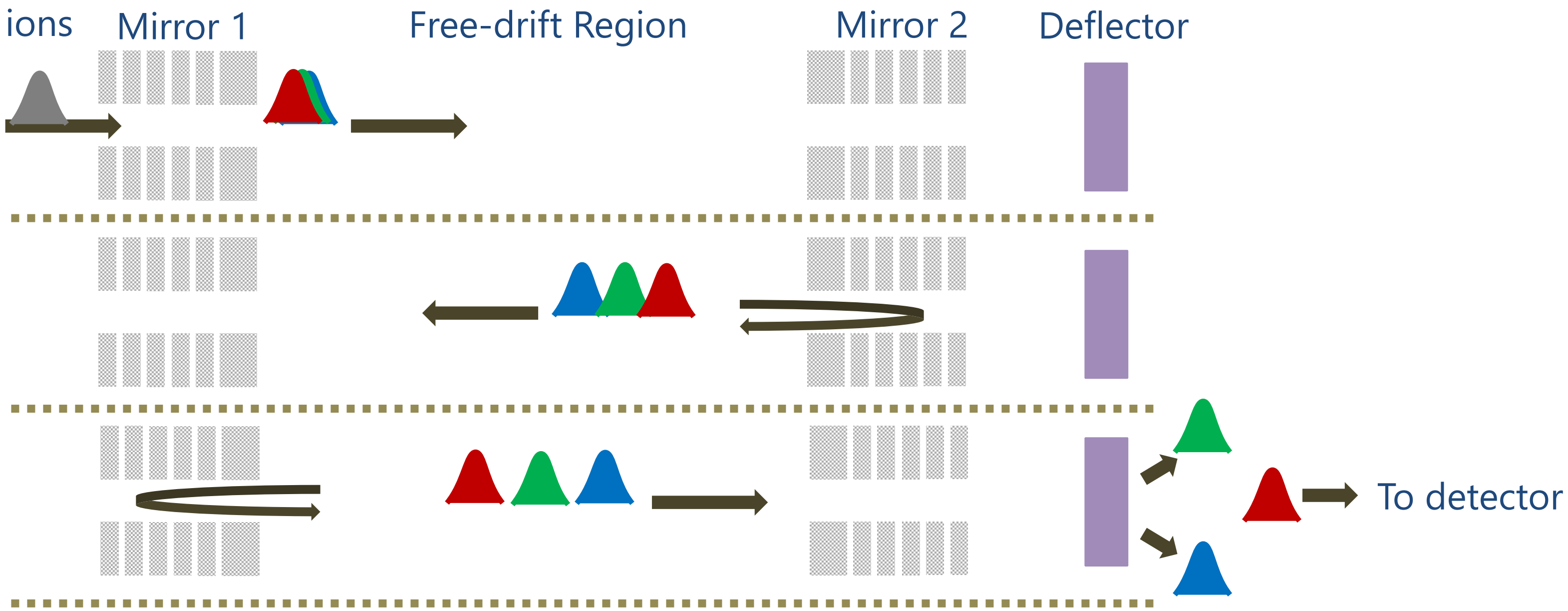
Block, M., Nucl. Phys. A, **944** (2015) 471: https://doi.org/10.1016/j.nuclphysa.2015.09.009
Block, M. La Rivista del Nuovo Cimento **45** (2022) 279: https://doi.org/10.1007/s40766-022-00030-5

Question: can we obtain high-resolution mass measurements with fewer atoms?

Atomic Masses – MR-TOF

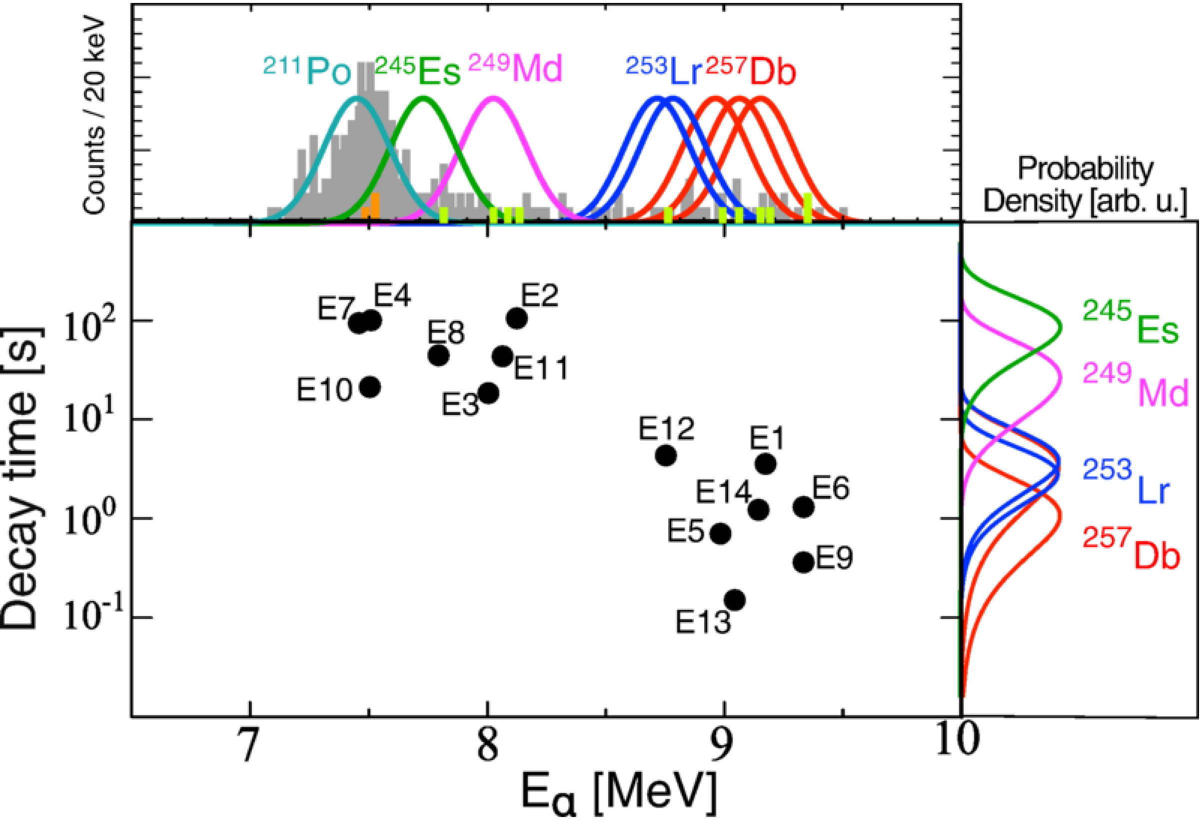
Multi-Reflection Time-of-Flight (MR-TOF)

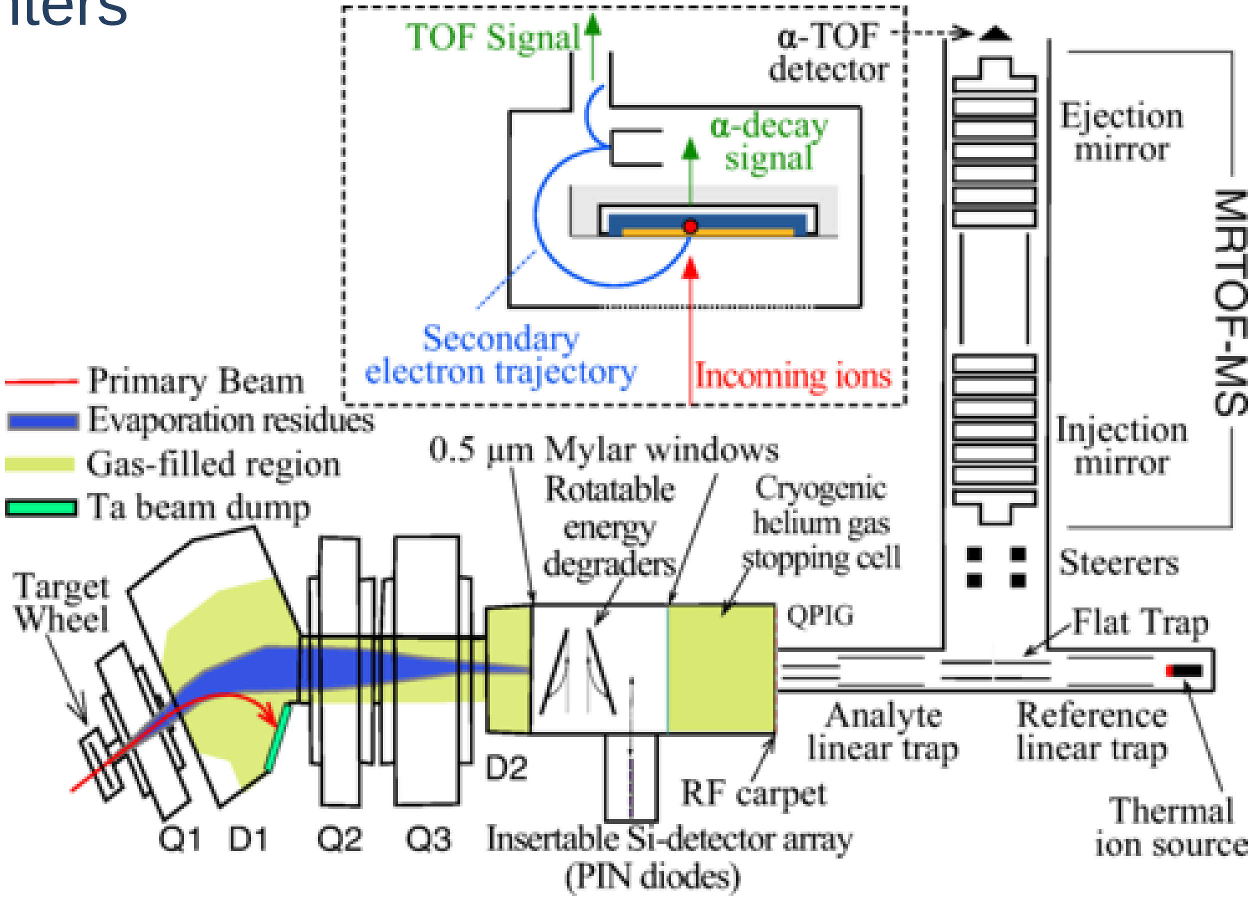
- Accelerate ions across a known voltage gap
- Trap ion between two electrostatic mirrors
- Ions separate during flight path according differing A/q



Atomic Masses – MR-TOF

Observed time-of-flight and alpha decay energy for 11 events attributed to ^{257}Db and its daughters





Schury, P. Phys. Rev. C **104** (2021) L021304: https://doi.org/10.1103/PhysRevC.104.L021304

In-Beam Spectroscopy

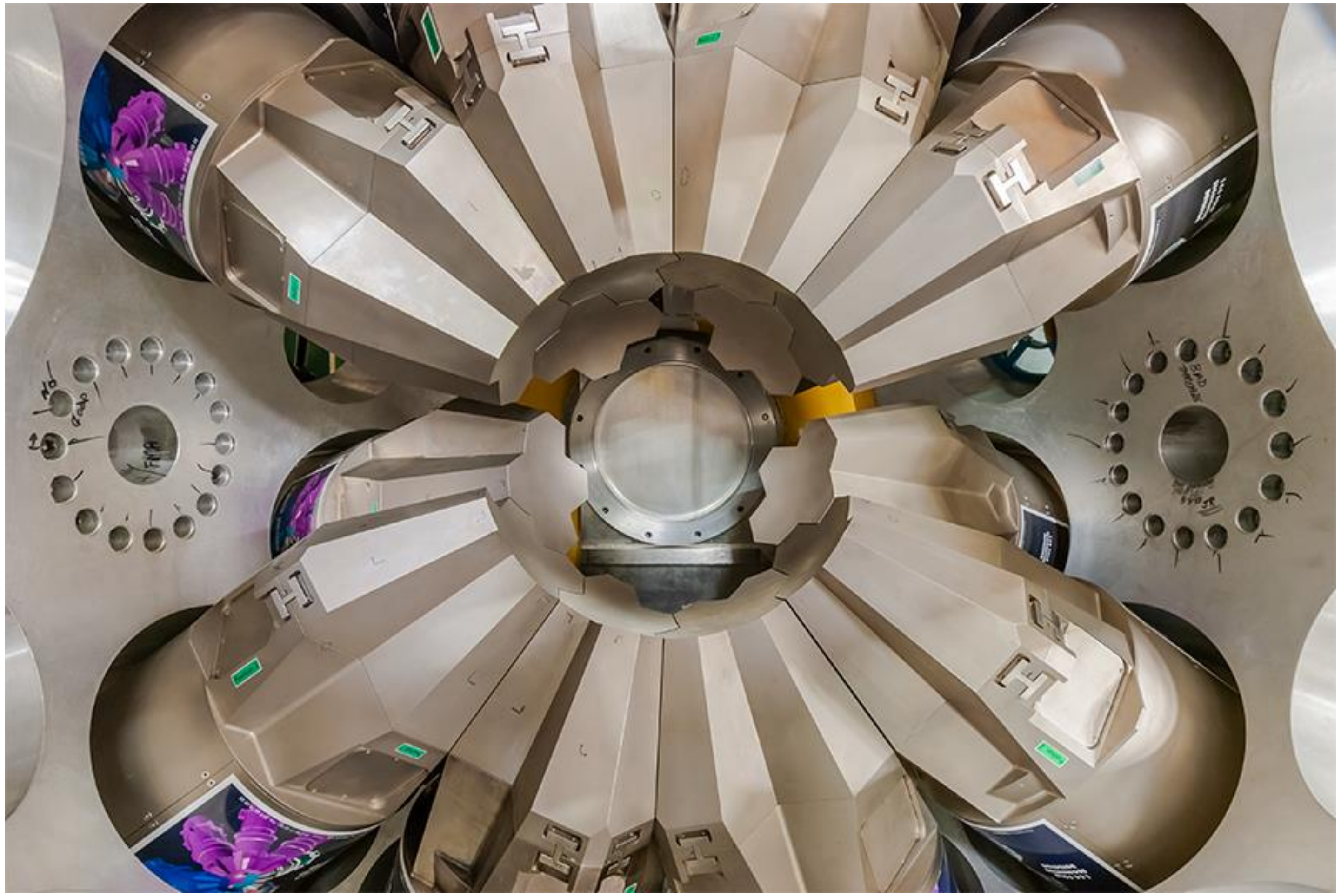
In-beam Spectroscopy

Probe highly excited nuclear levels populated during de-excitation of a nucleus

Step 1: Surround target with lots of germanium

Step 2: Make SHE in nuclear reaction

Step 3: Observe gamma rays emitted during deexcitation of SHE



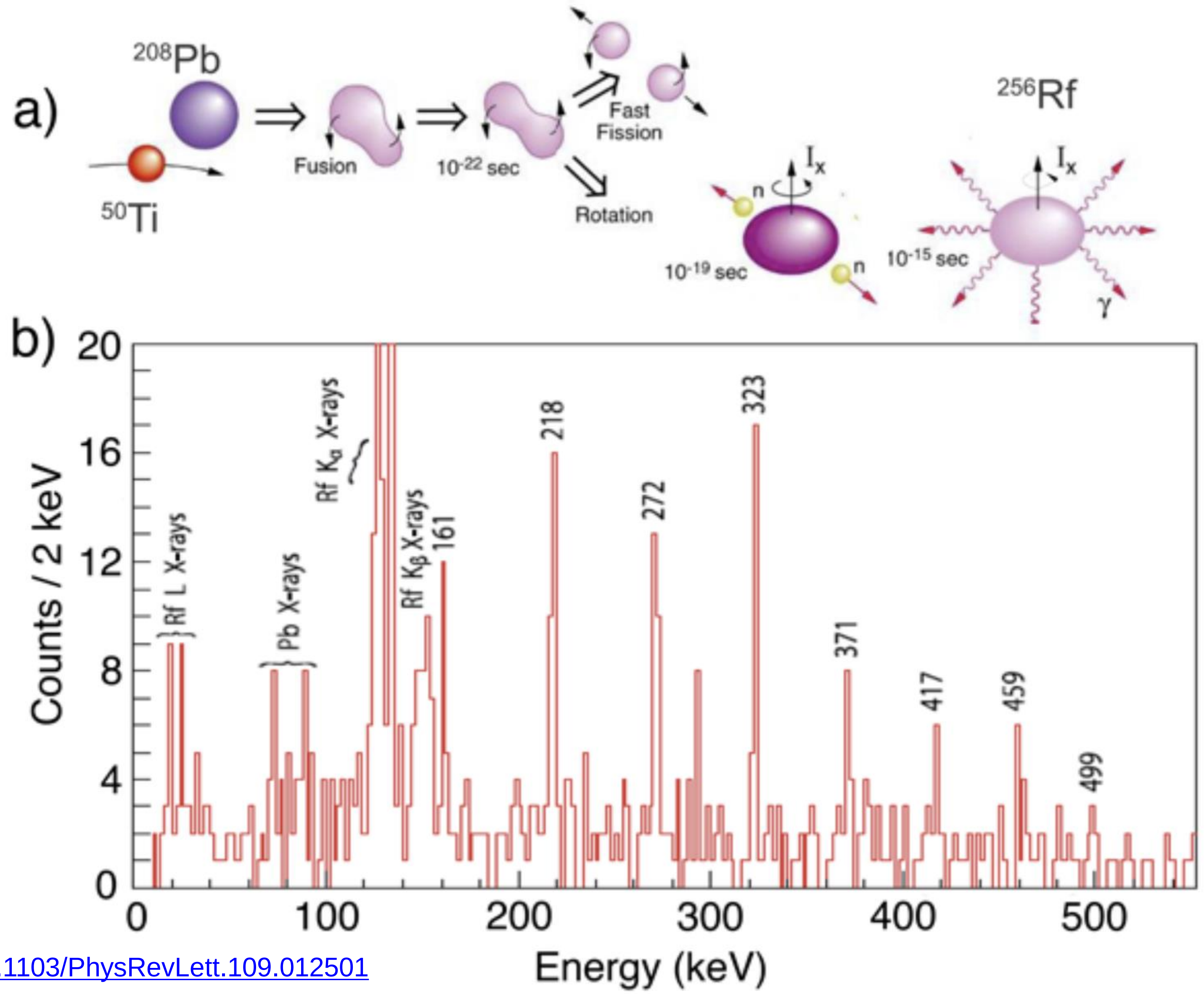
GRETINA

In-beam Spectroscopy

Observed gamma ray spectrum from the de-excitation of ^{256}Rf

Picket-fence pattern ➔ emission of photons from rotational states ➔ ^{256}Rf is quadrupole-deformed

Spacing on picket-fence pattern ➔ rotational moment of inertia ➔ orbital level density (bigger energy gap ➔ higher moment of inertia)

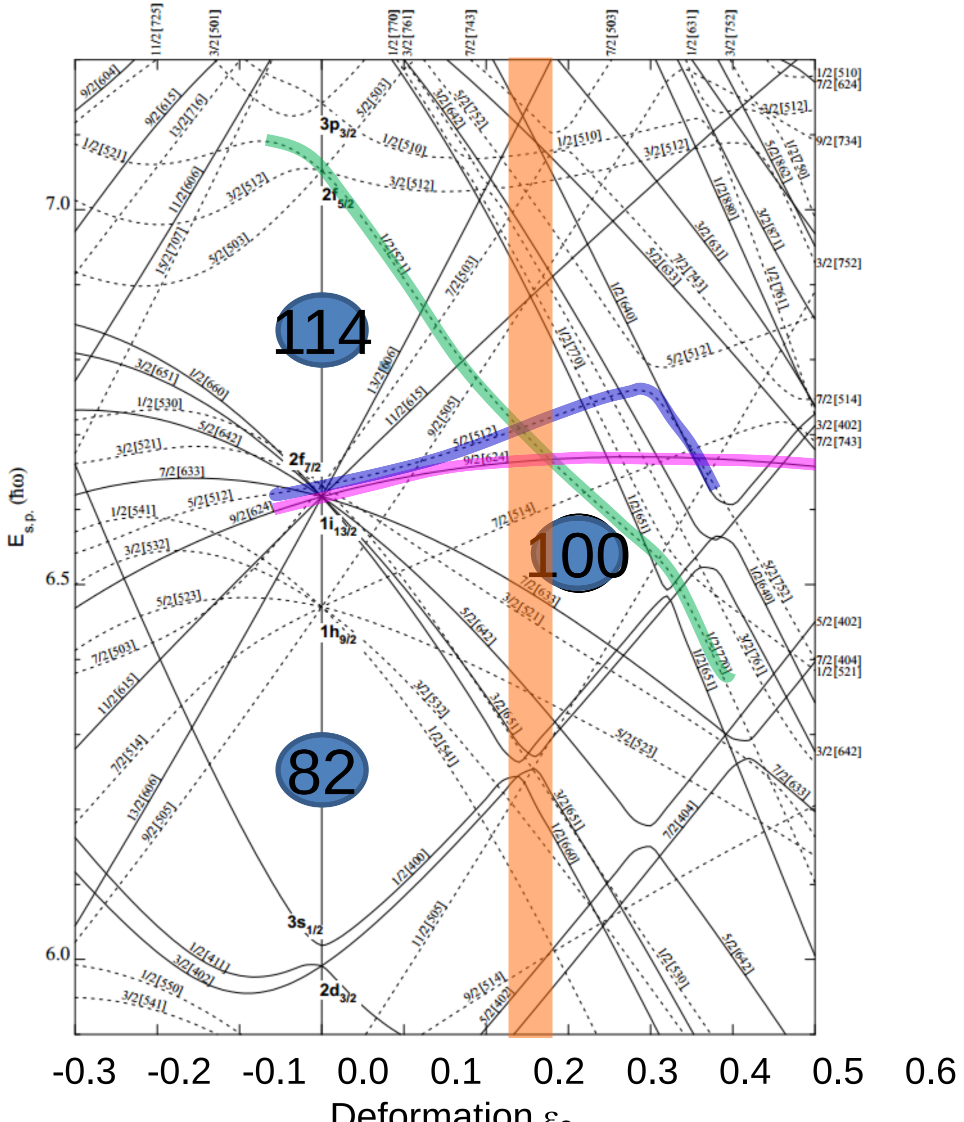


Greenlees, P.T. Phys. Rev. Lett., **109 (**2012) 012501: http://link.aps.org/doi/10.1103/PhysRevLett.109.012501

Spectroscopy:

K-Isomer: excited metastable states that are found amongst the rotational states of deformed atomic nuclei

Determining Location of the Next Shells



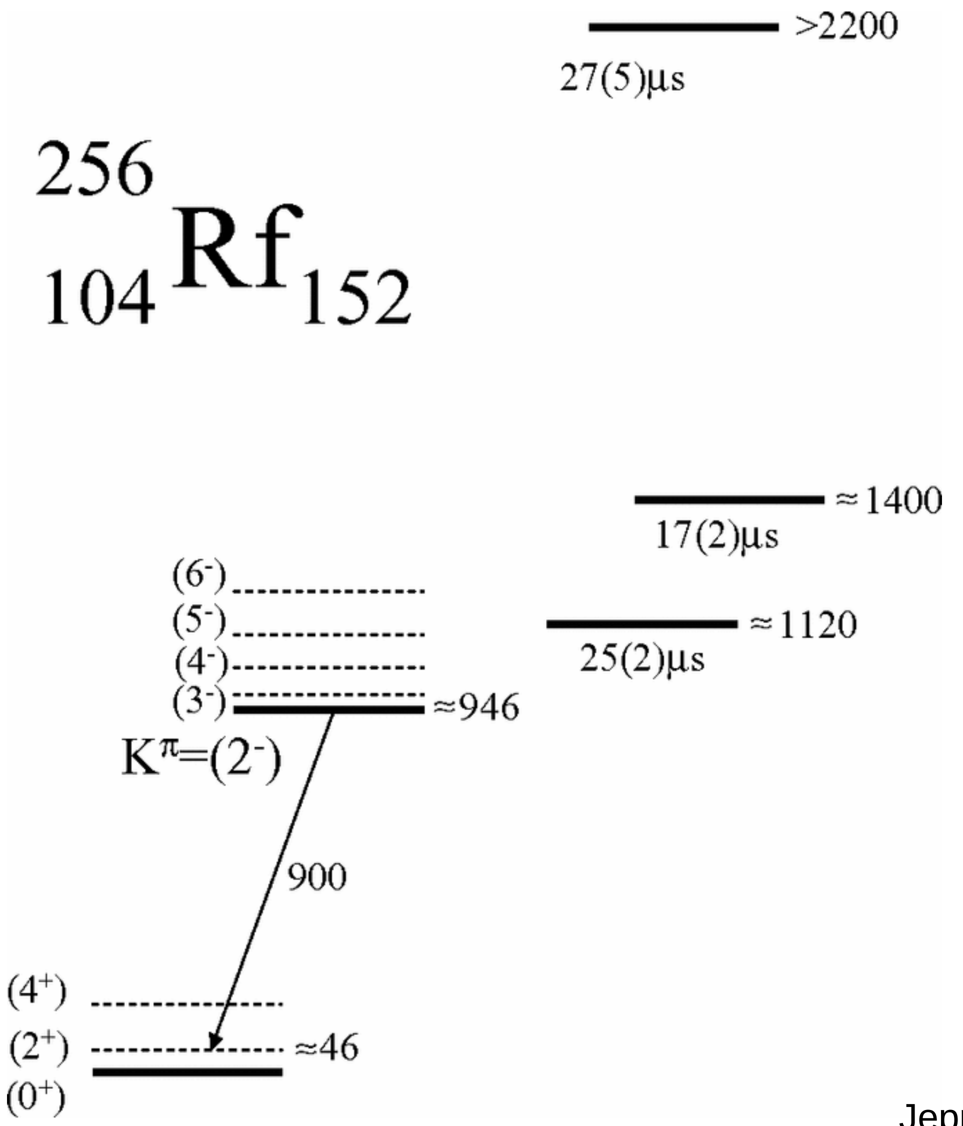
Nilsson diagram for protons with Z≥82

Single-particle states responsible for the stability of SHE can be probed via:

1) States which are near the ground state in deformed nuclei near *Z*=102 are also near the ground state for spherical SHE. We can study these states in *Z*=102-104 with production rates of up to atoms per second.

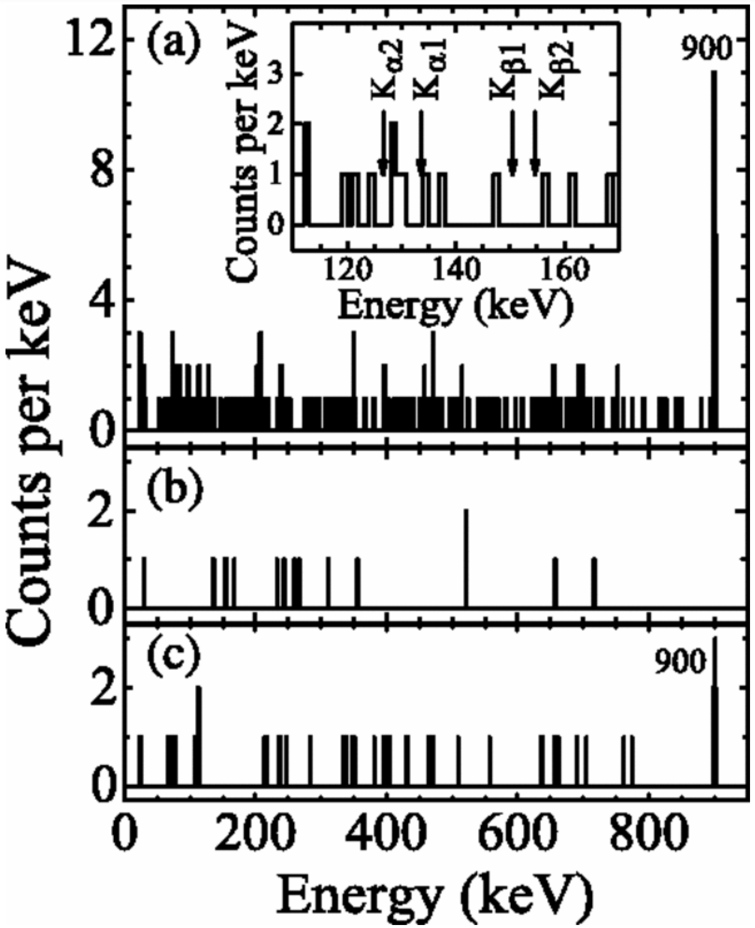
2) We can produce SHE at rates of nearly 1 atom per day. New capabilities allow us to perform spectroscopy directly with SHE.

K-isomers in ^{256}Rf

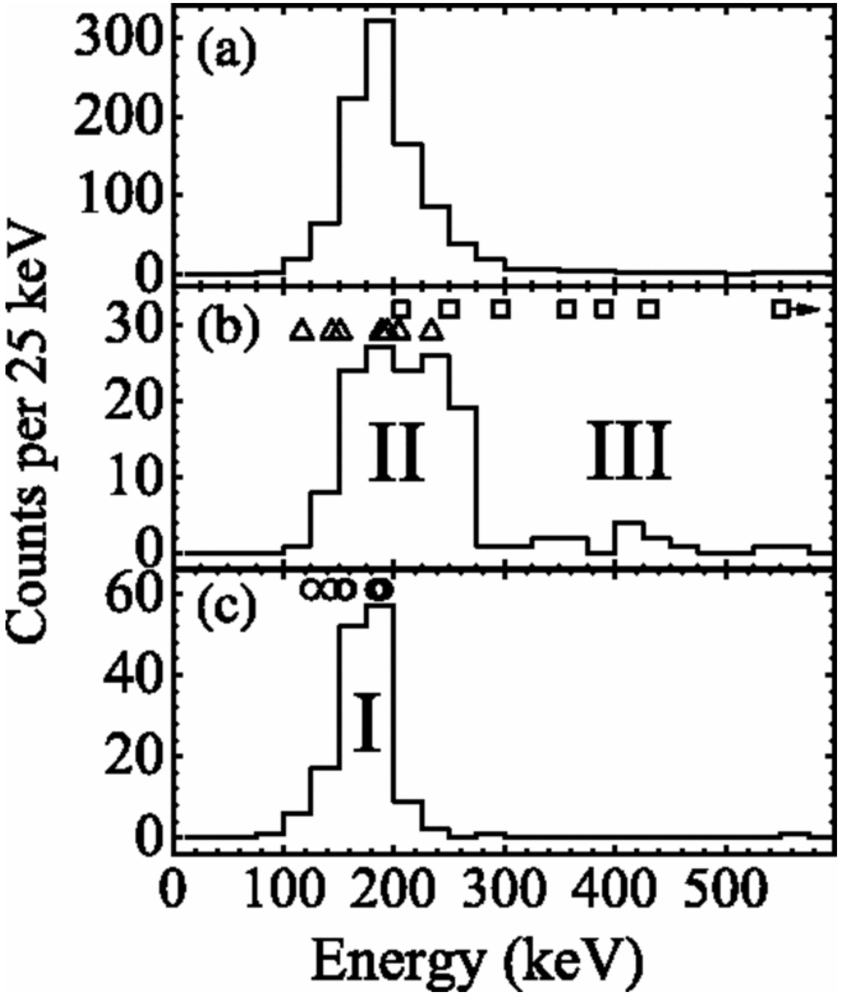


- Looking to observe low-energy (10-1000s of keV) signals just before the alpha/fission decay of a heavy element ➔ decay of isomeric state
- Measure energy of transitions and photons emitted during decay ➔ build level scheme to identify nuclear levels

Jeppeson: Phys. Rev. C **79** (2009) 031303 http://dx.doi.org/10.1103/PhysRevC.79.031303



Photons emitted with electrons



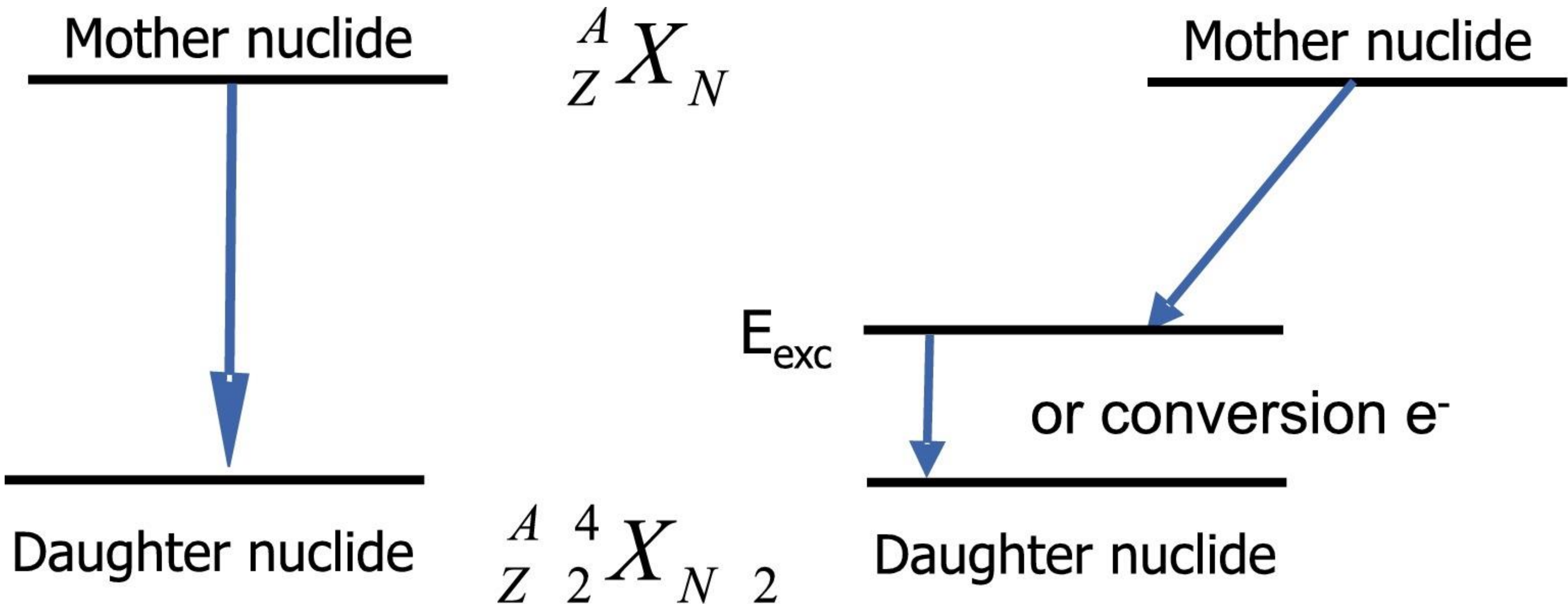
Electrons observed in silicon detector

Jeppeson: Phys. Rev. C **79** (2009) 031303 http://dx.doi.org/10.1103/PhysRevC.79.031303

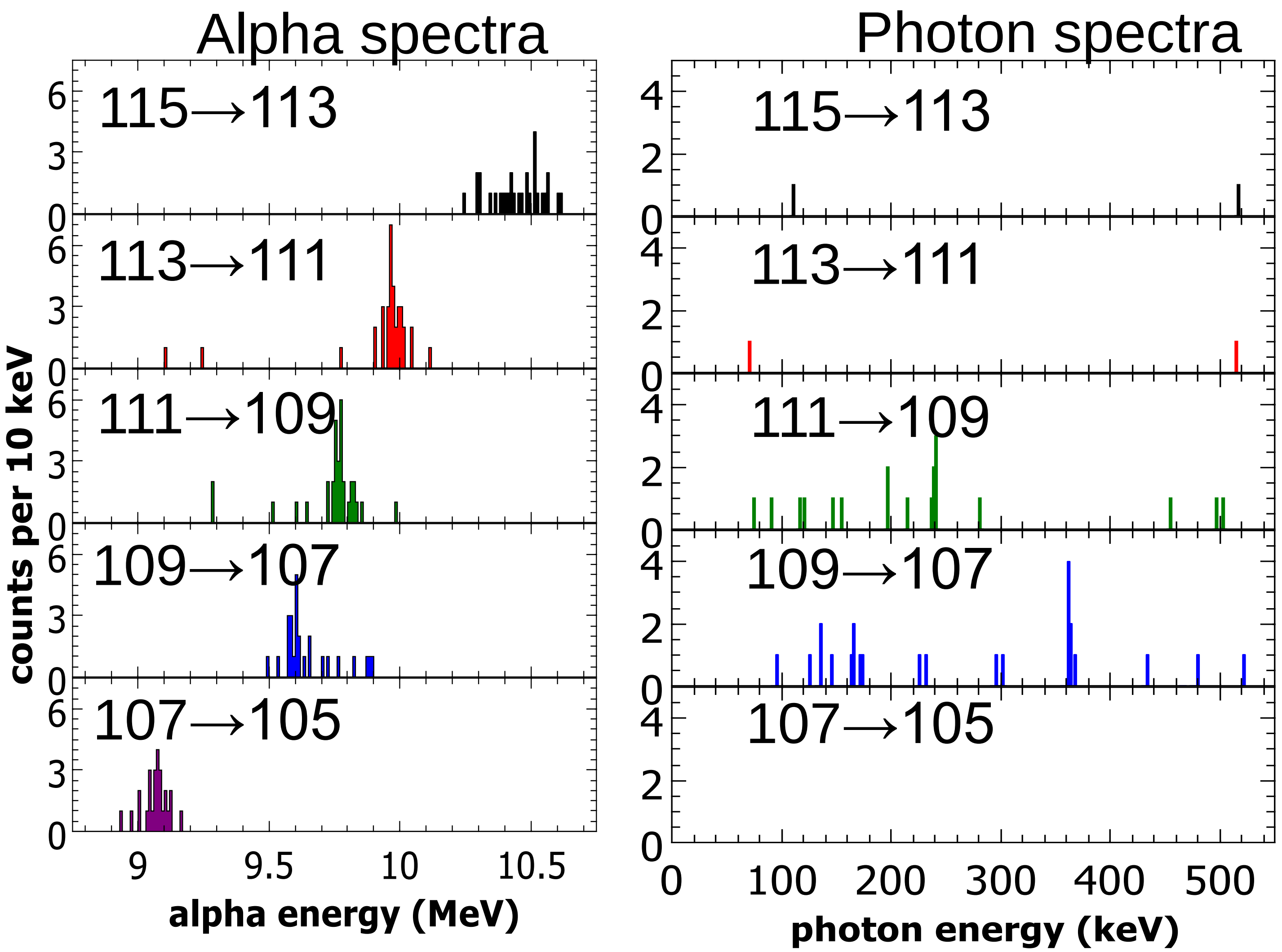
Spectroscopy:
Alpha-gamma

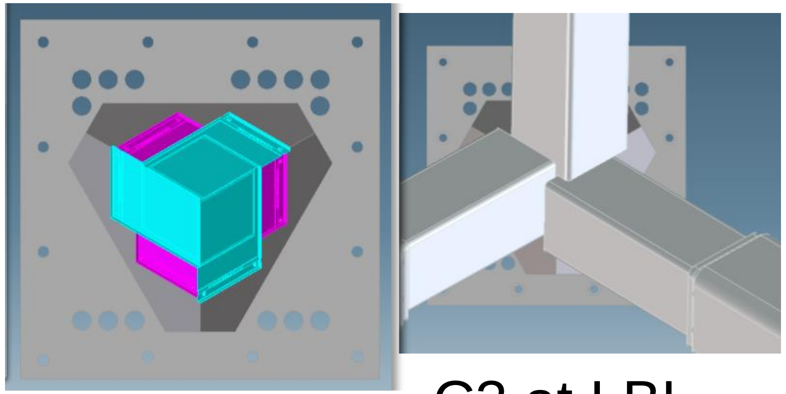
Alpha-gamma spectroscopy

Look for gamma or conversion electron decay in coincidence with alpha decay

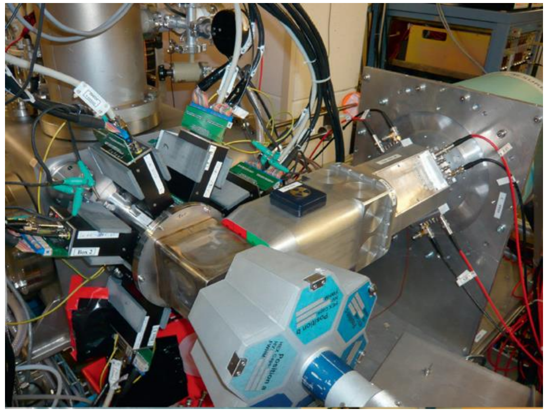


Decay Spectroscopy of E115

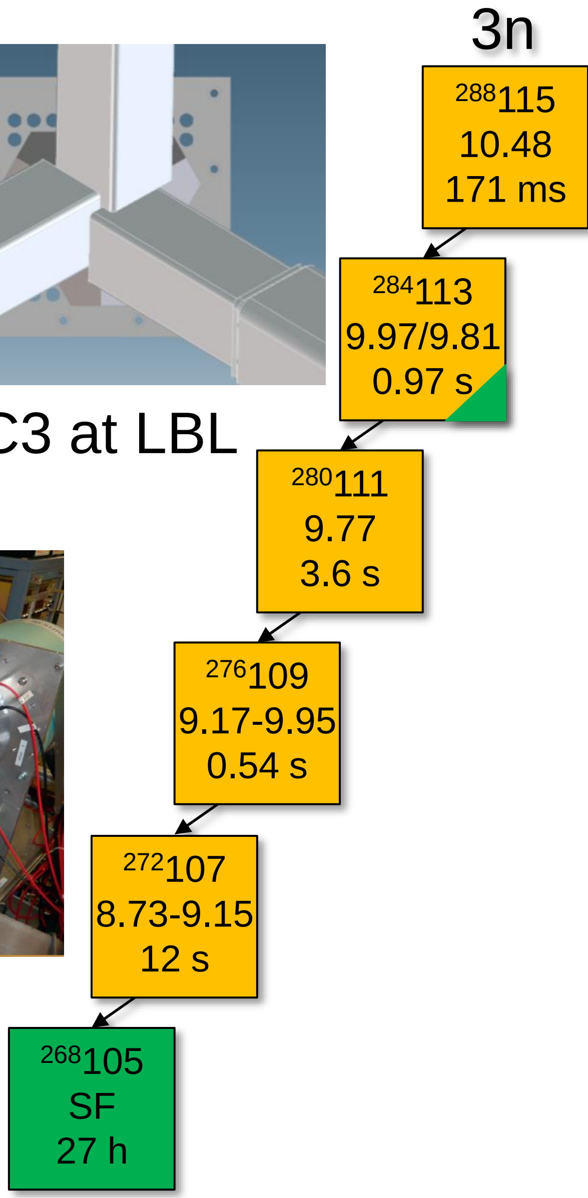




C3 at LBL



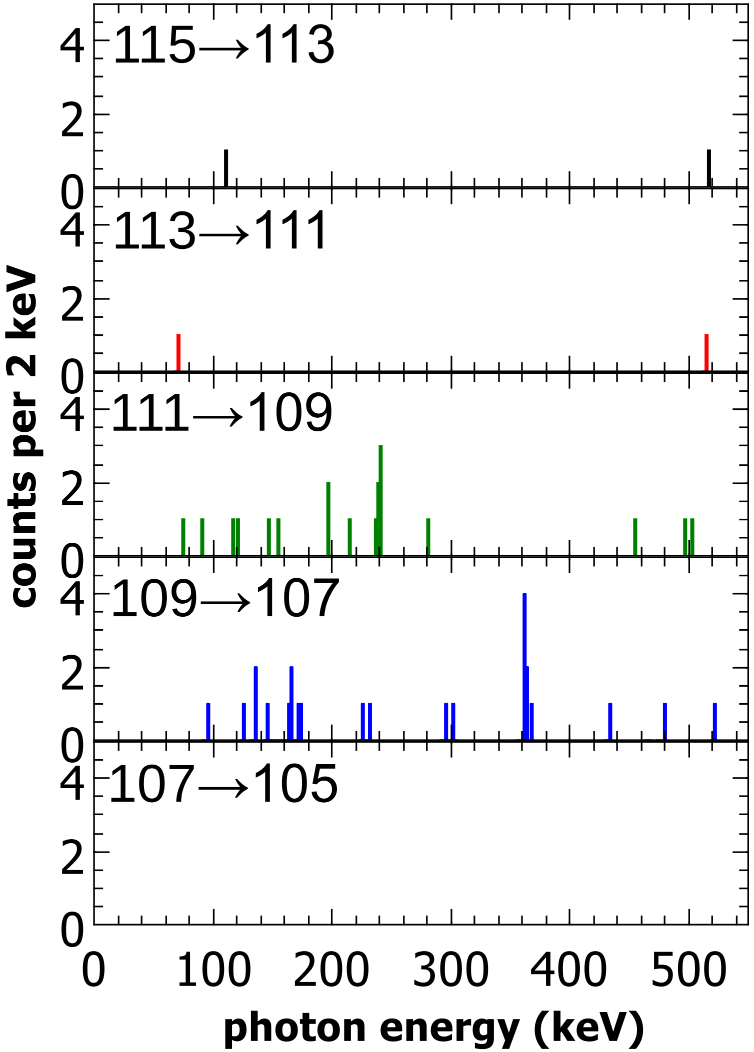
TASISpec

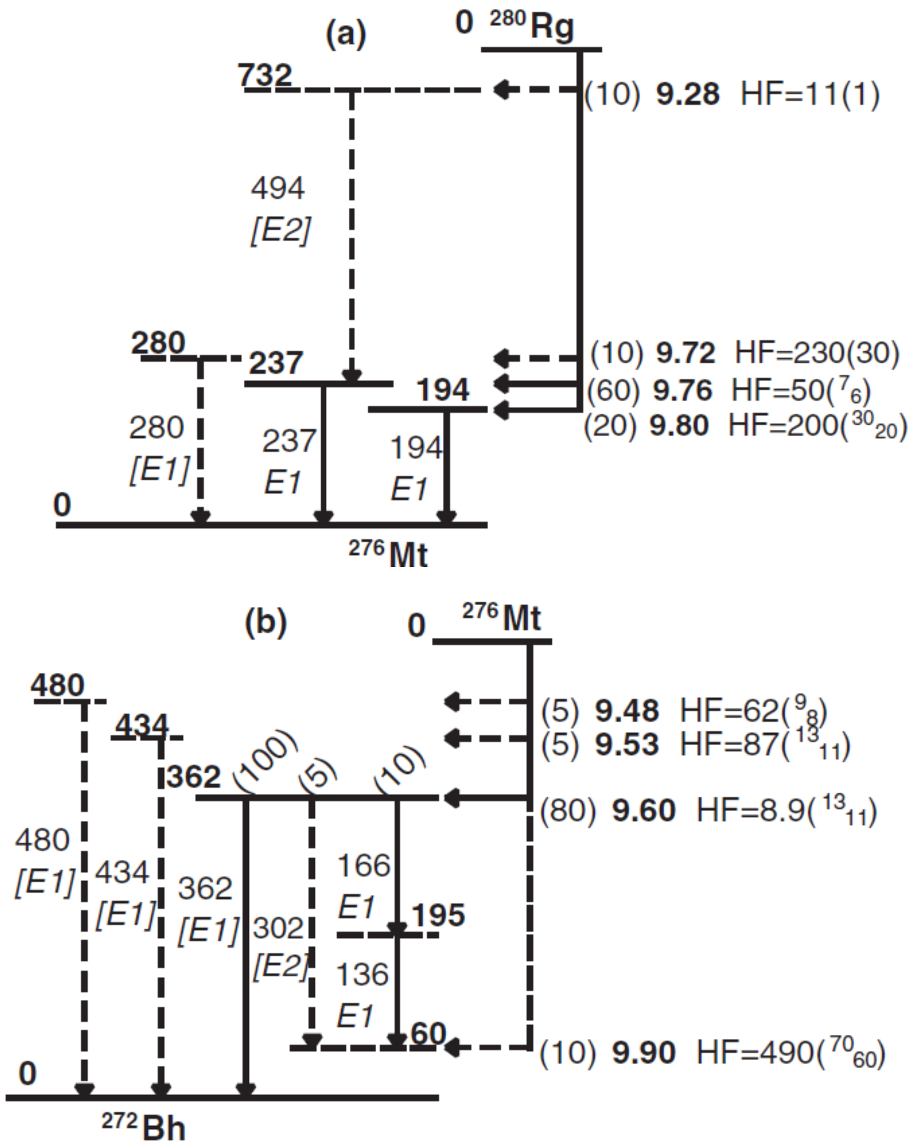


Decay Spectroscopy of Element 115

- **Observed photons in coincidence with alpha-decay**
- **Develop level scheme for low-lying states in ^{276}109 and ^{272}107**
- **Determine multipolarities for several transitions**
- **Close to identifying single-particle states**

Photon spectra





Chemistry

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]

Heavy Element Chemistry

Challenges with heavy element chemistry:

Only make one atom-at-a-time

Atoms formed with the momentum of the beam → 36000 m/s

Transactinides are short-lived with lifetimes of minutes or less

Common Techniques

- Gas chromatography
- Ion exchange
- Solvent extraction

Provide qualitative information only:

Does 112 behave more like Hg or Rn?

Does 105 form volatile chlorides?

Up & Coming Techniques:

- Laser spectroscopy
- Mass Analyzers

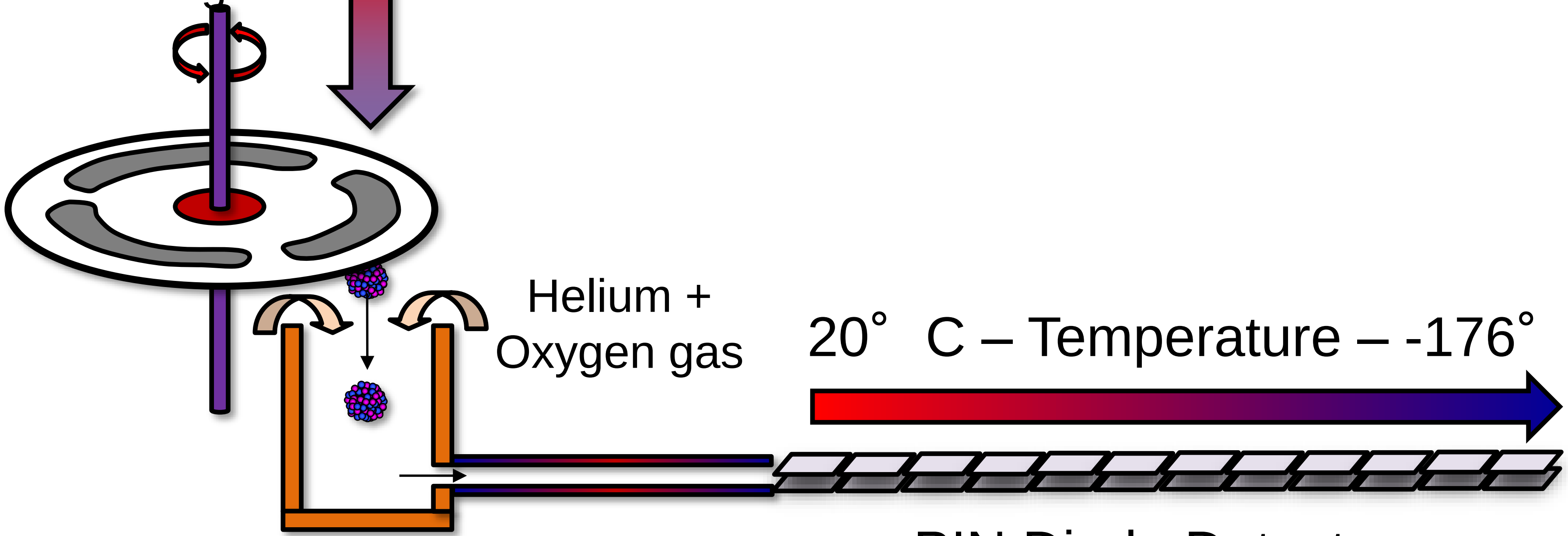
Provide quantitative information:

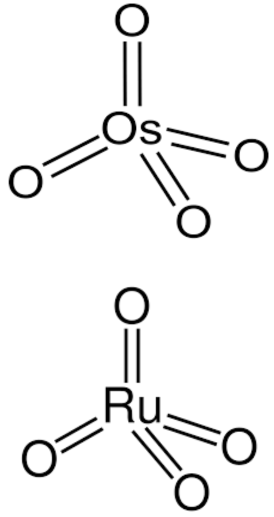
What is the first excited atomic state of Rf?

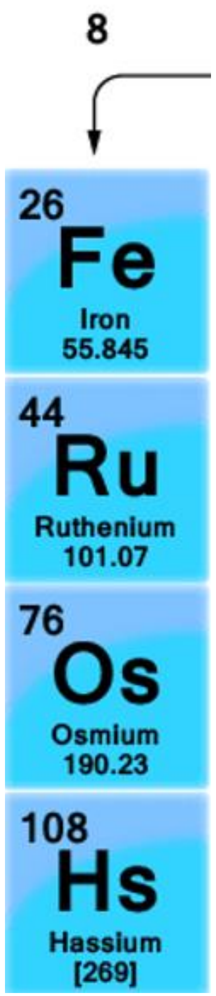
Is it $Sg(CO)_6$ or $Sg(CO)_5$?

First (and only) Chemistry on Hassium

- Os and Ru both known to form volitale tetroxides in the presence of oxygen and heat
- Does hassium also form volatile tetroxides?



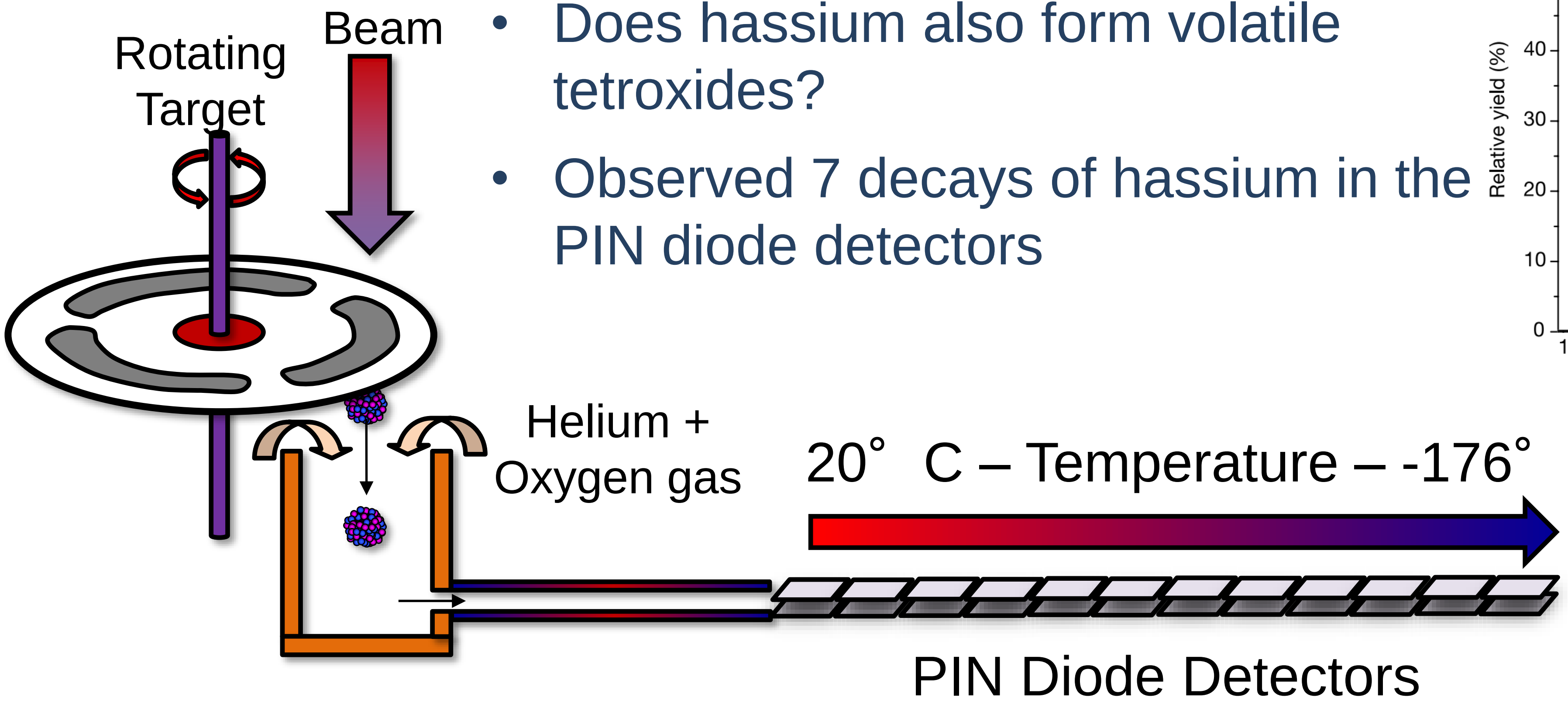


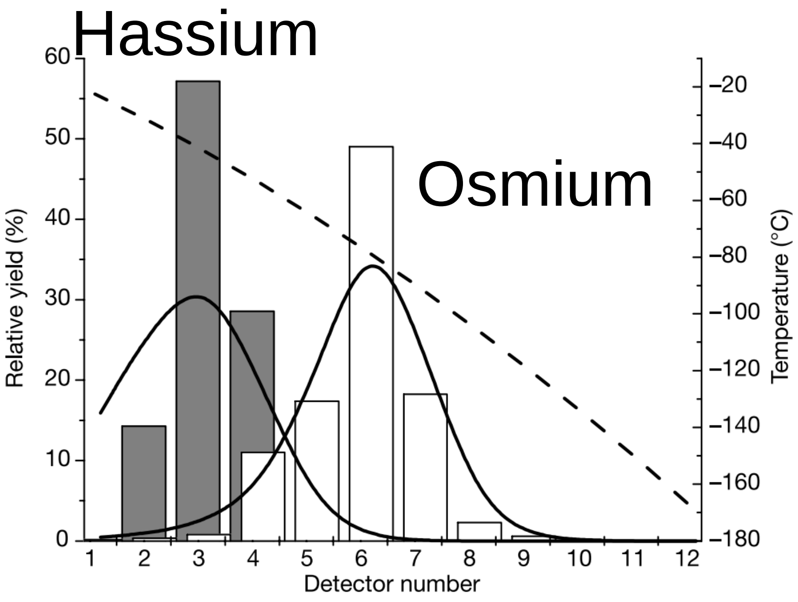


Duellmann, Ch.E. Nature **418** (2002) 859: https://doi.org/10.1038/nature00980

First (and only) Chemistry on Hassium

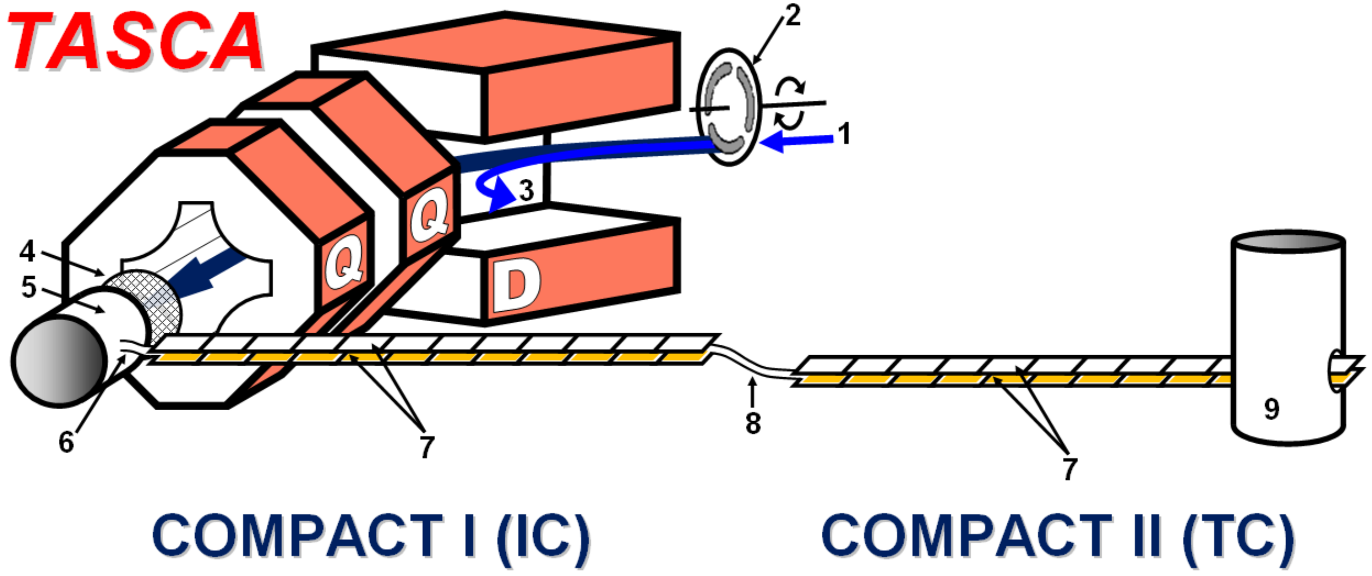
- Os and Ru both known to form volitale tetroxides in the presence of oxygen and heat
- Does hassium also form volatile tetroxides?
- Observed 7 decays of hassium in the PIN diode detectors

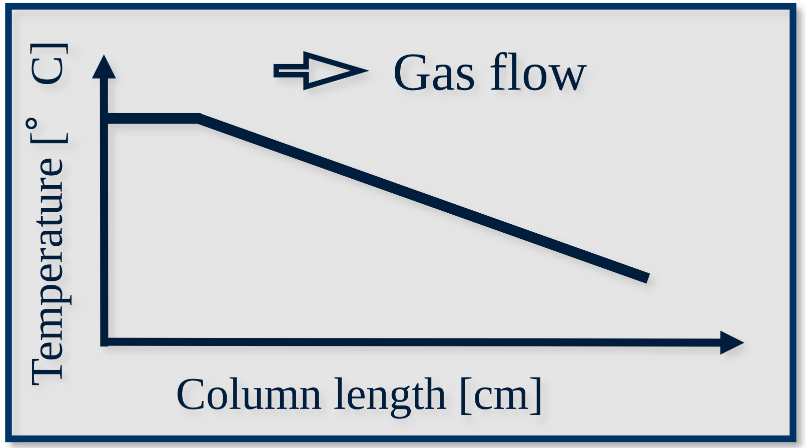


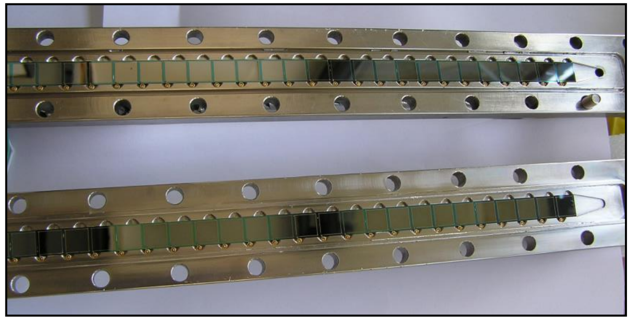


Duellmann, Ch.E. Nature **418** (2002) 859: https://doi.org/10.1038/nature00980

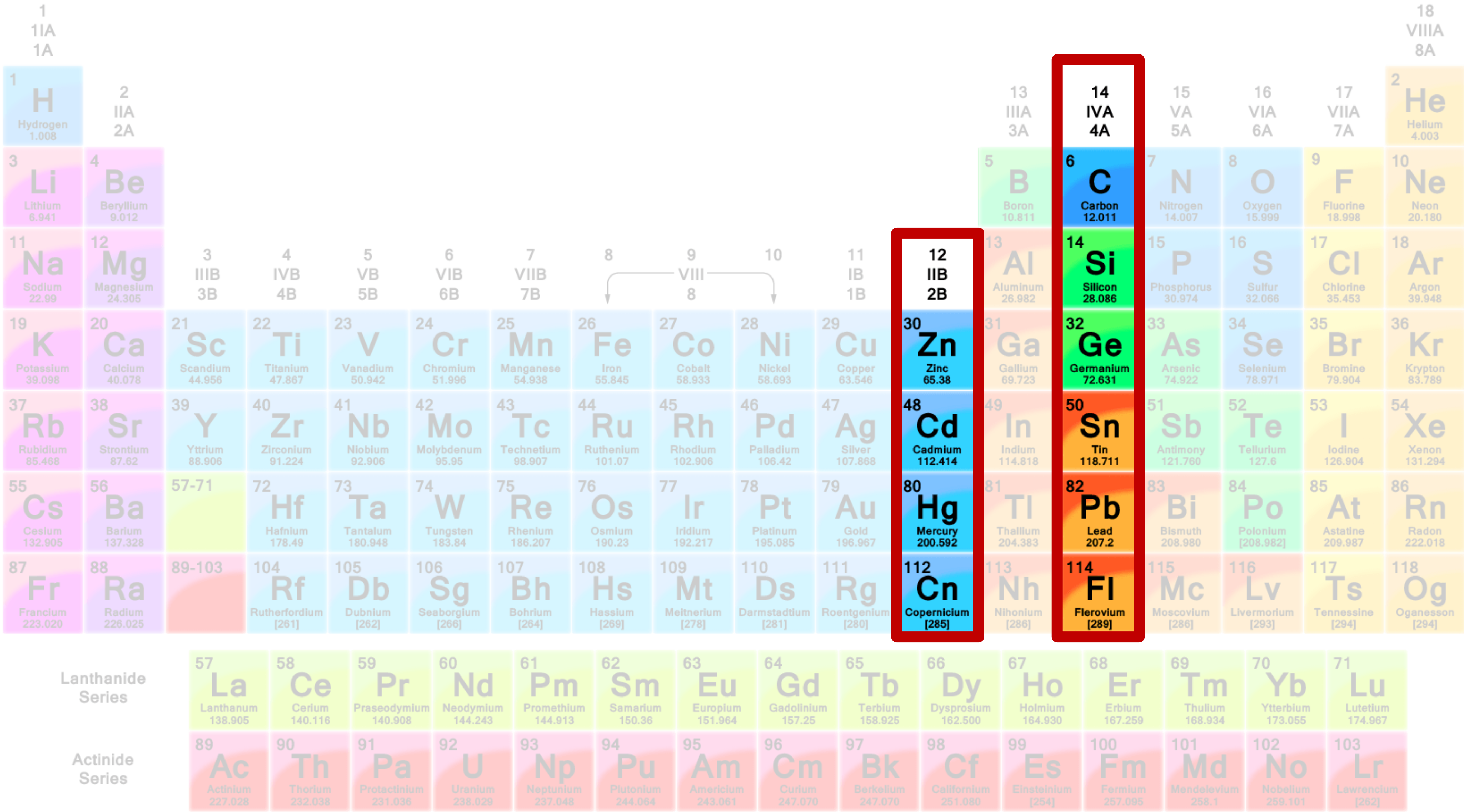
Thermal Chromatography of E114 and E112



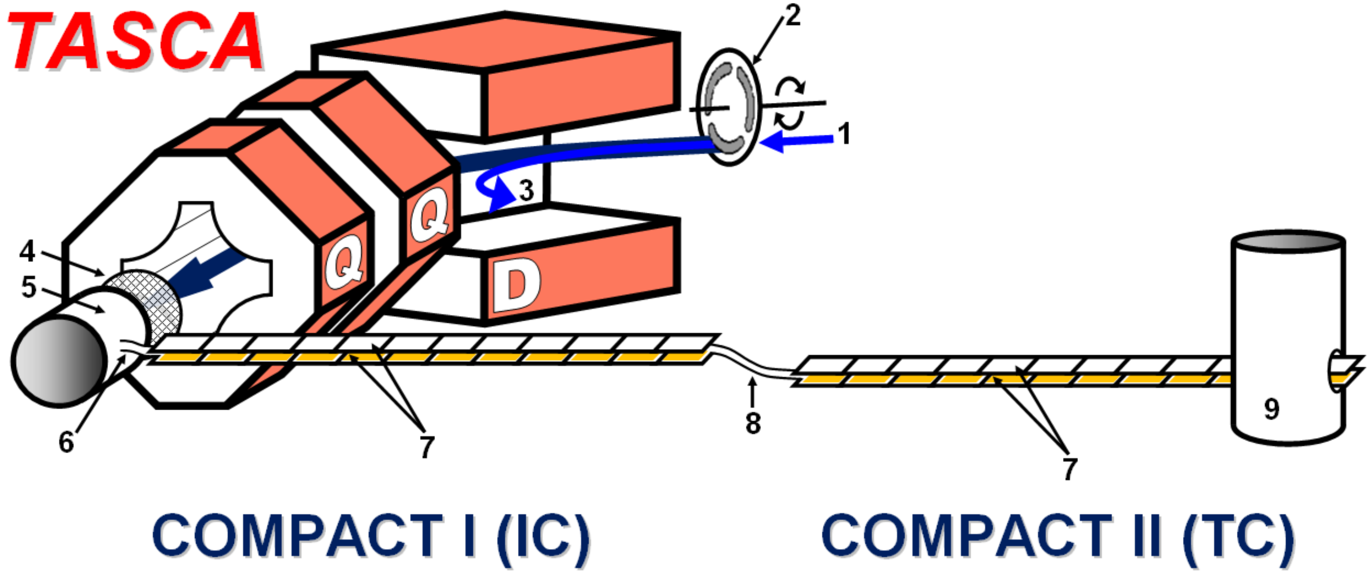


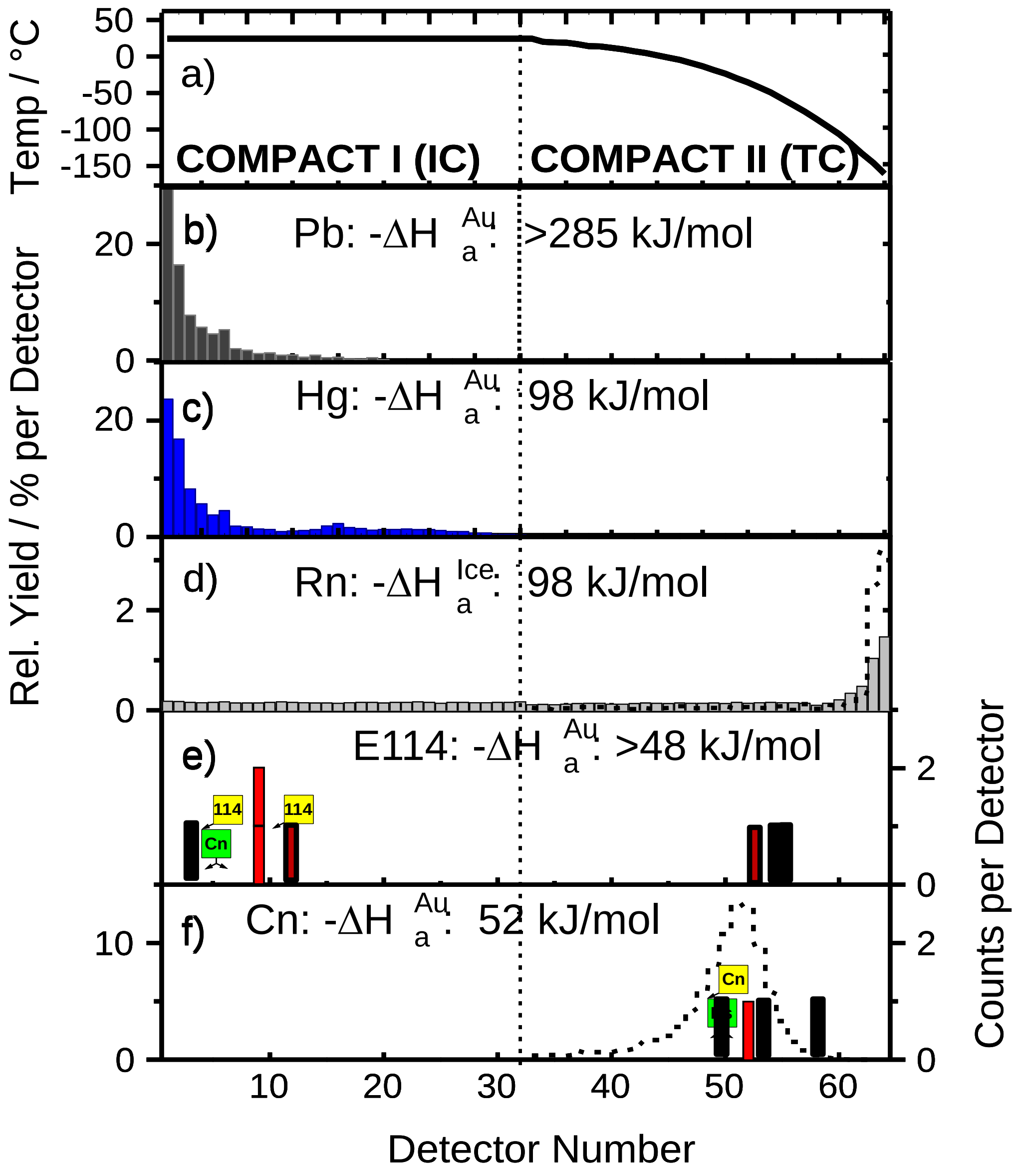


Periodic Table



Thermal Chromatography of E114 and E112

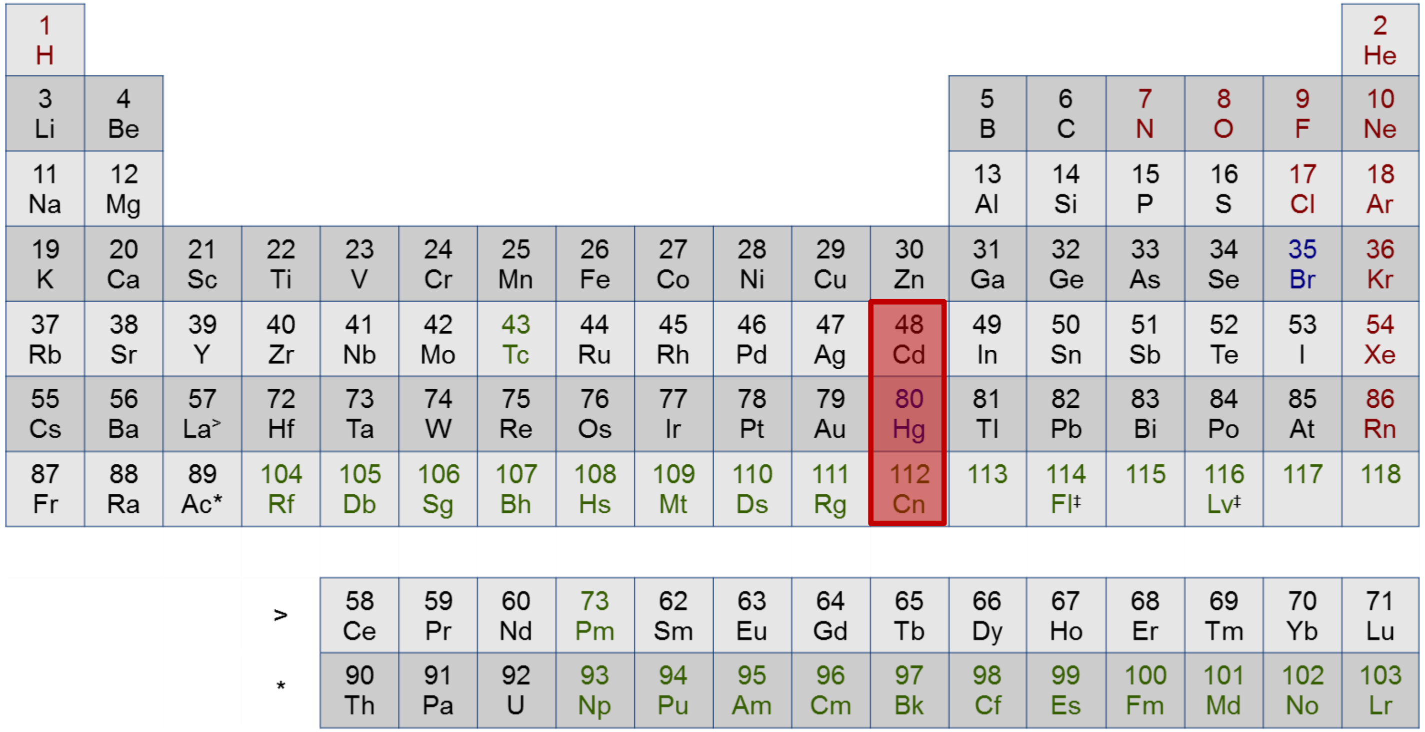


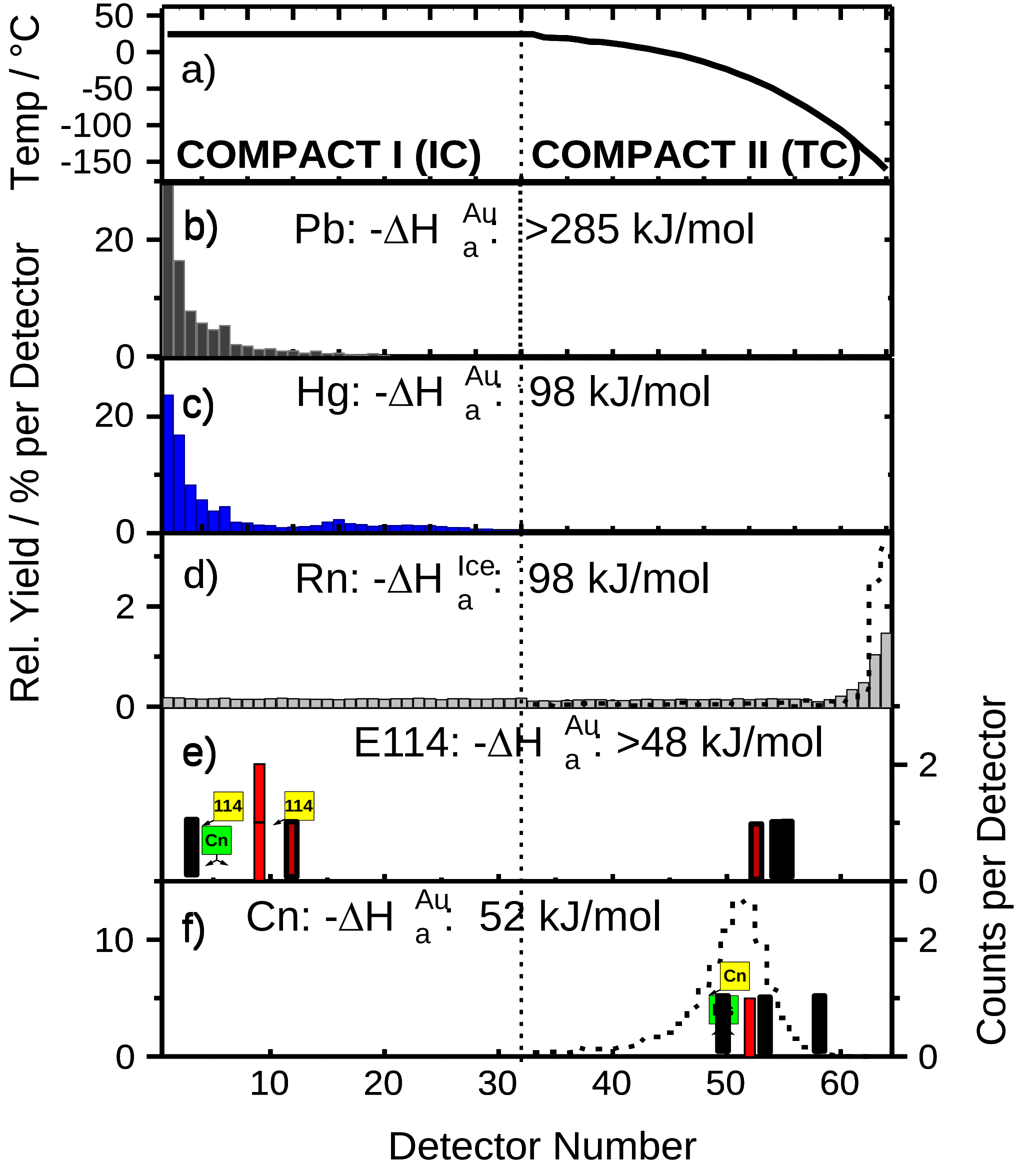


E114 observed to adsorb on Au at room temperature ***AND*** -80 C

Eichler: Radiochim. Acta **98** (2010) 133
Yakushev: Inorg. Chem. **53** (2014) 1624
Yakushev: Frontiers in Chem. **10** (2022) 1.

Thermal Chromatography of E114 and E112





E112 Exhibits noble gas-like behavior and does not form amalgams with Au

Eichler: Radiochim. Acta **98** (2010) 133
Yakushev: Inorg. Chem. **53** (2014) 1624

Seaborgium Carbonyl Chemistry

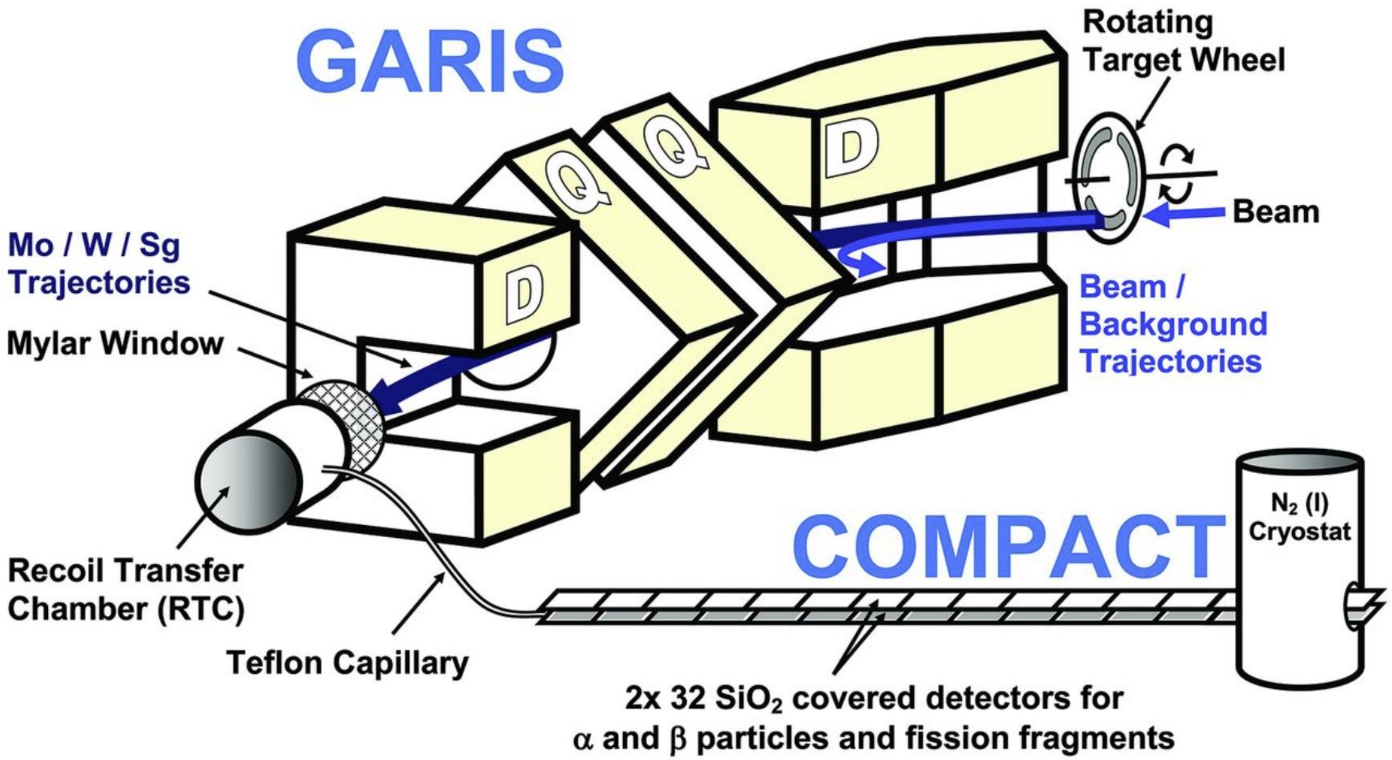
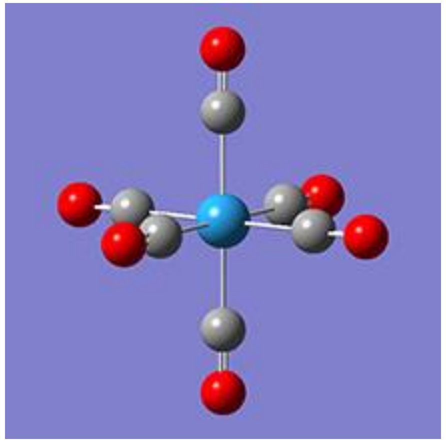
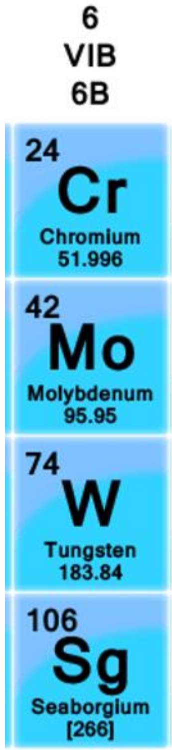


Fig. 1 Schematic drawing of the experimental setup.

Mo and W form volatile hexacarbonyls in the presence of carbon monoxide (CO)

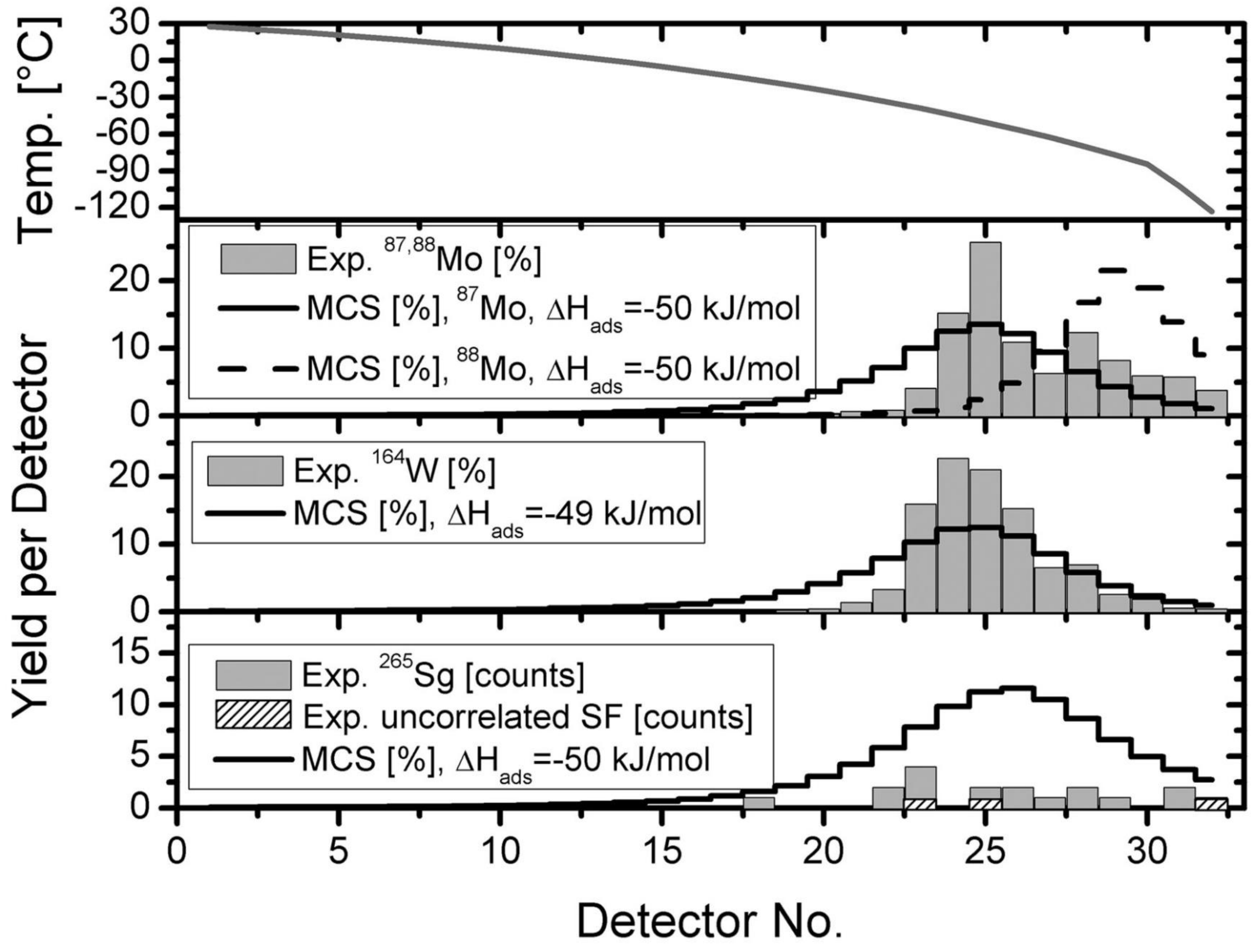
Does Sg form these same complexes?





Even, J., Science, **345** (2014) 1491: https://doi.org/10.1126/science.1255720

Seaborgium Carbonyl Chemistry



Even, J., Science, **345** (2014) 1491: https://doi.org/10.1126/science.1255720

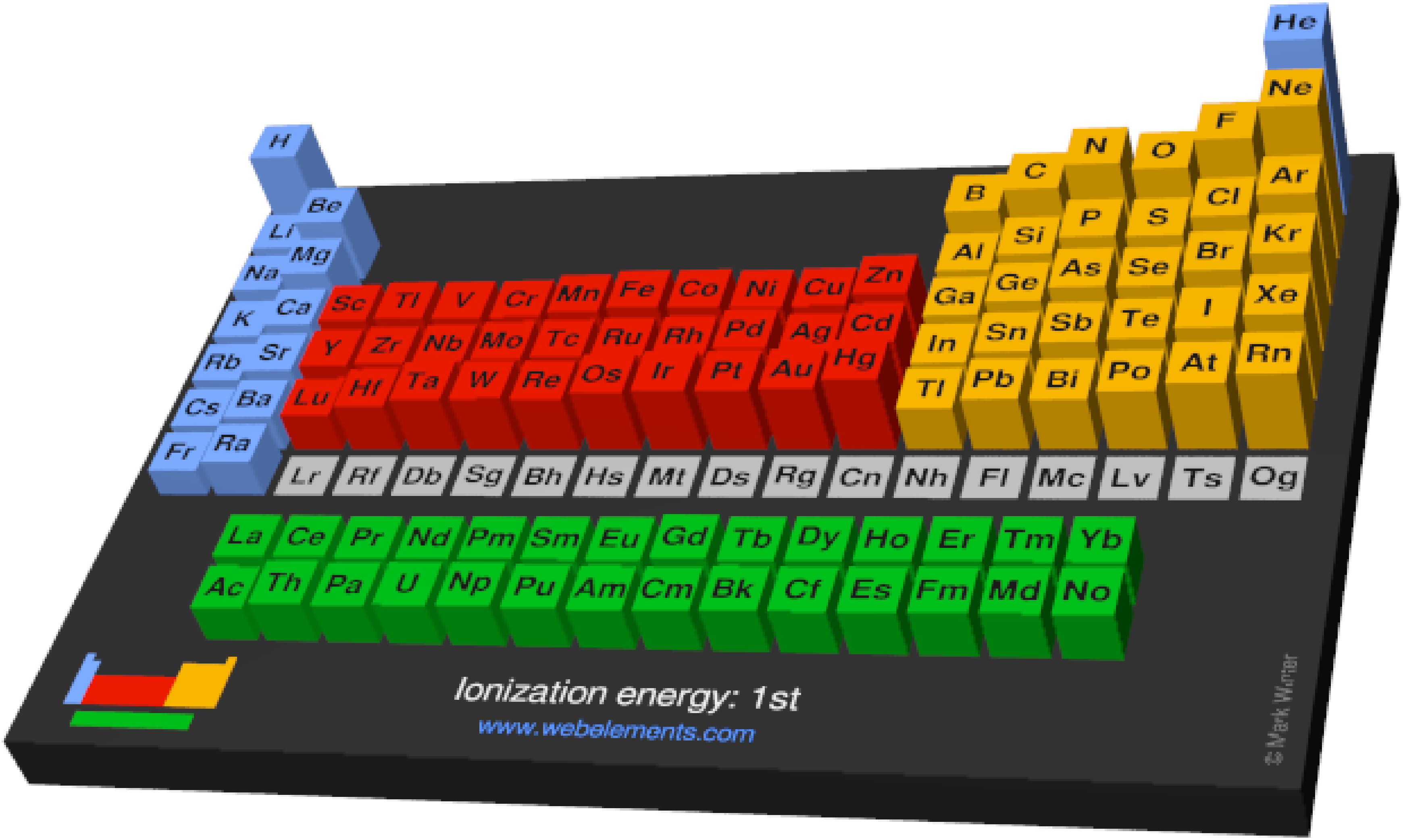
Sg reacted with CO at exit of GARIS

Sg has similar volatility to Mo and W

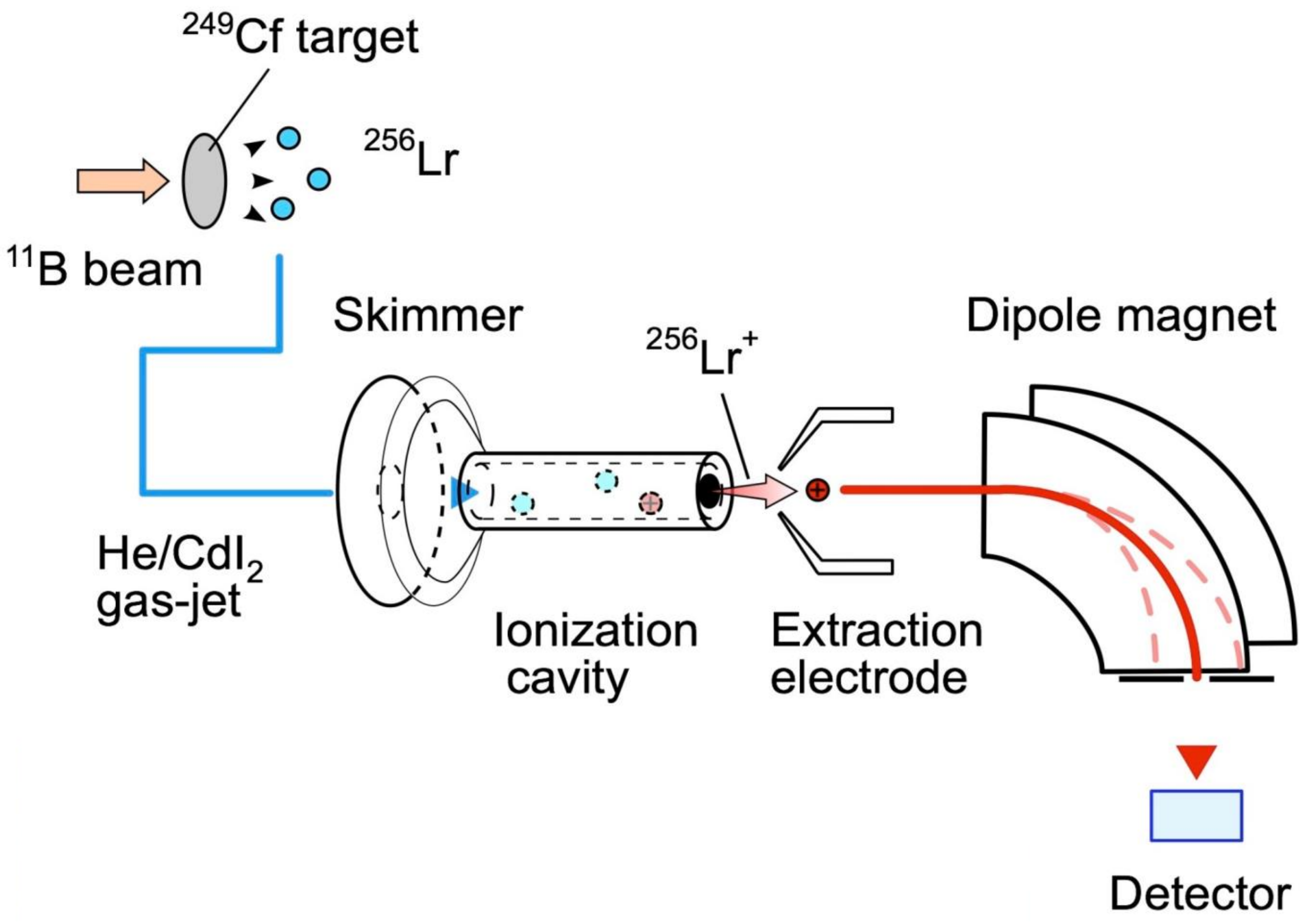
Question: what is missing from these chemistry experiments?

Ionization Potentials

Ionization potential ➔ How much energy is required to remove electron from an element



Ionization Potential of Lawrencium (Z=103)



1. Produced ^{256}Lr and neutralized it in a He/CdI_2 gas mixture
2. Transported ^{256}Lr atoms to ionization cavity
3. Ionized ^{256}Lr on tantalum surface
4. Counted number of ^{256}Lr ionized

Sato, T.K.: Nature **520,** 209 (2015): https://doi.org/10.1038/nature14342
Sato, T.K.: JACS **140** (2018) 14609: https://doi.org/10.1021/jacs.8b09068

Ionization Potential of Lawrencium (Z=103)

Well-known relationship between ionization efficiency and ionization potential

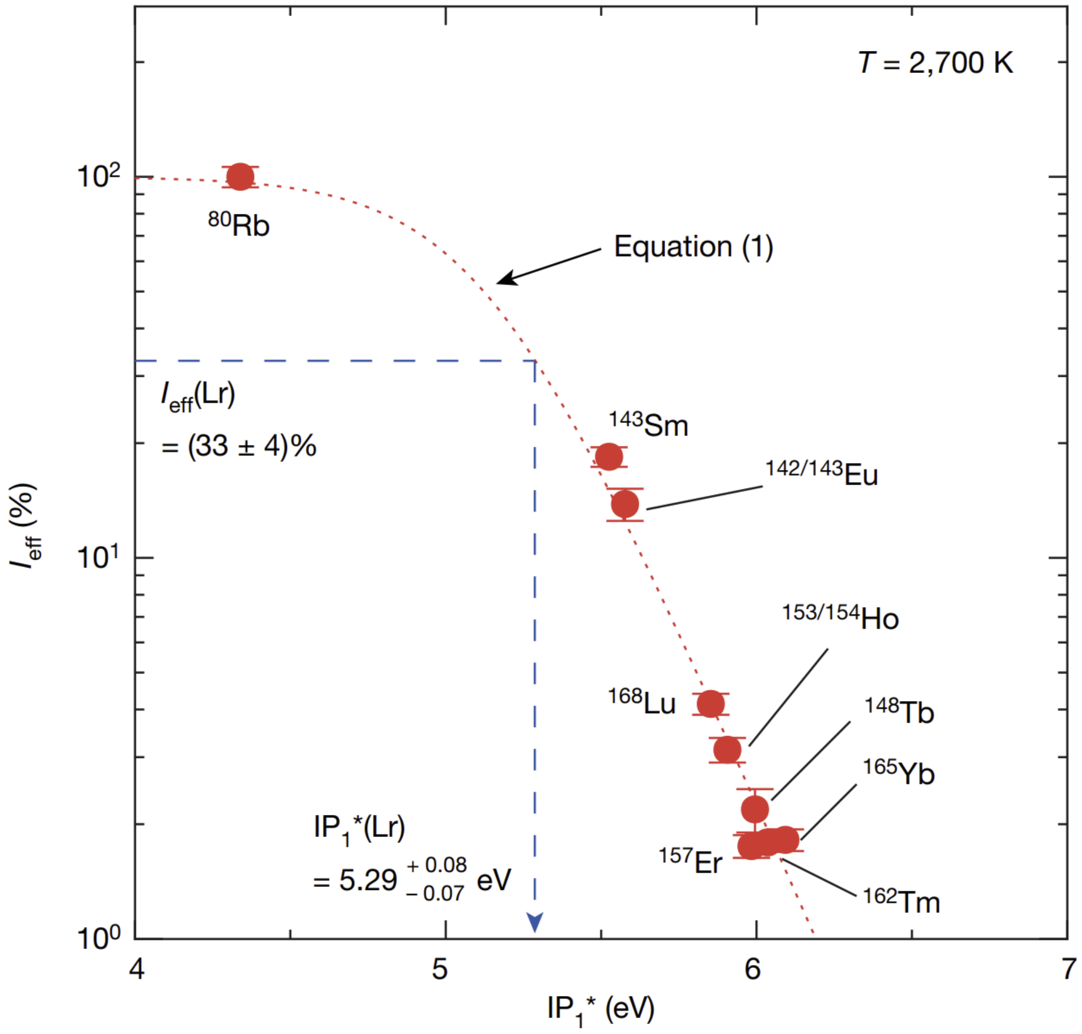
$$I_{\text{eff}} = \frac{N\exp\left(\frac{\phi - \text{IP}_1^*}{kT}\right)}{1 + N\exp\left(\frac{\phi - \text{IP}_1^*}{kT}\right)} \qquad (1)$$

ϕ = material dependent work function

K = Boltzmann constant

T = temperature of ionizing surface

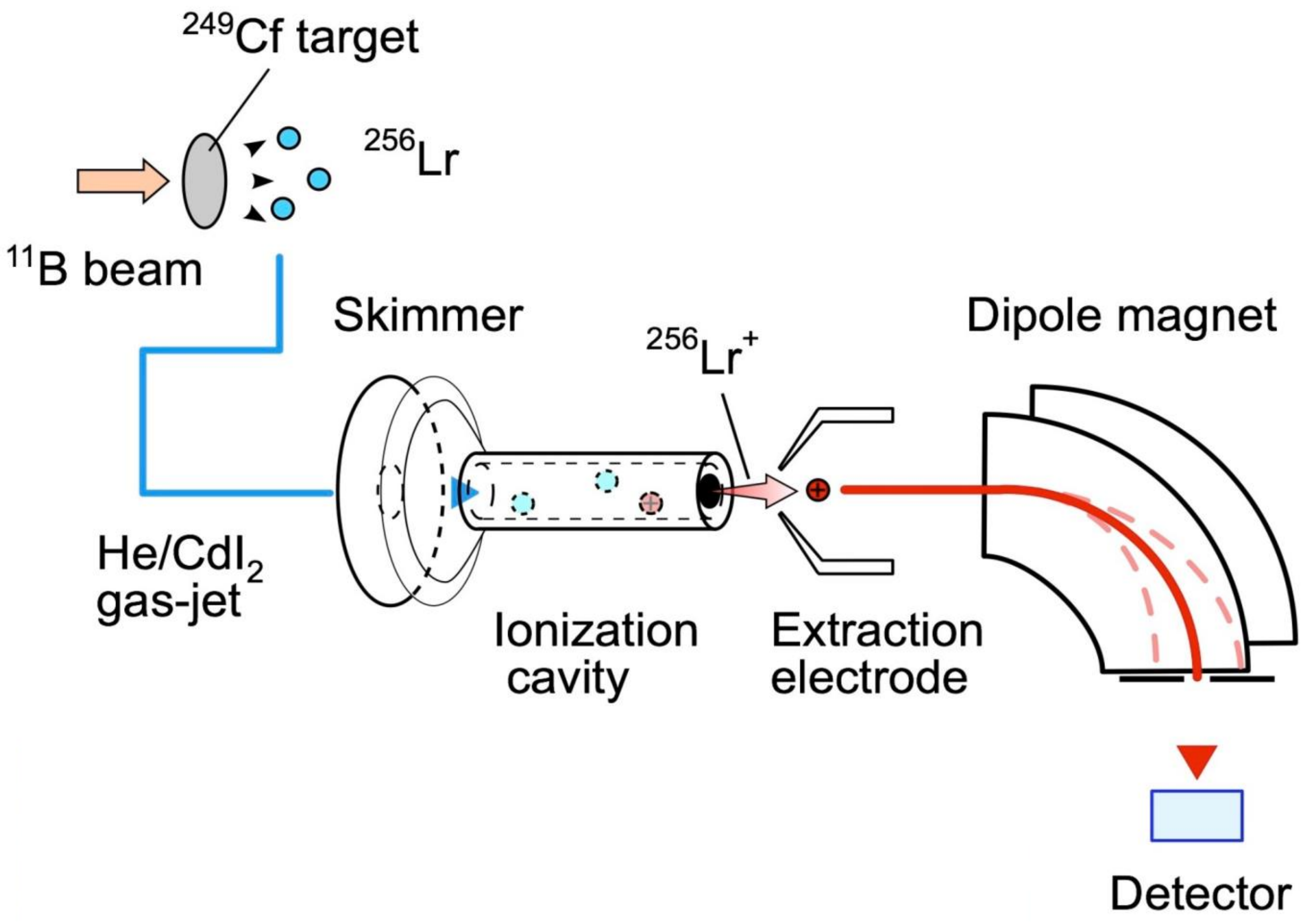
N = effective number of atom-surface interactions

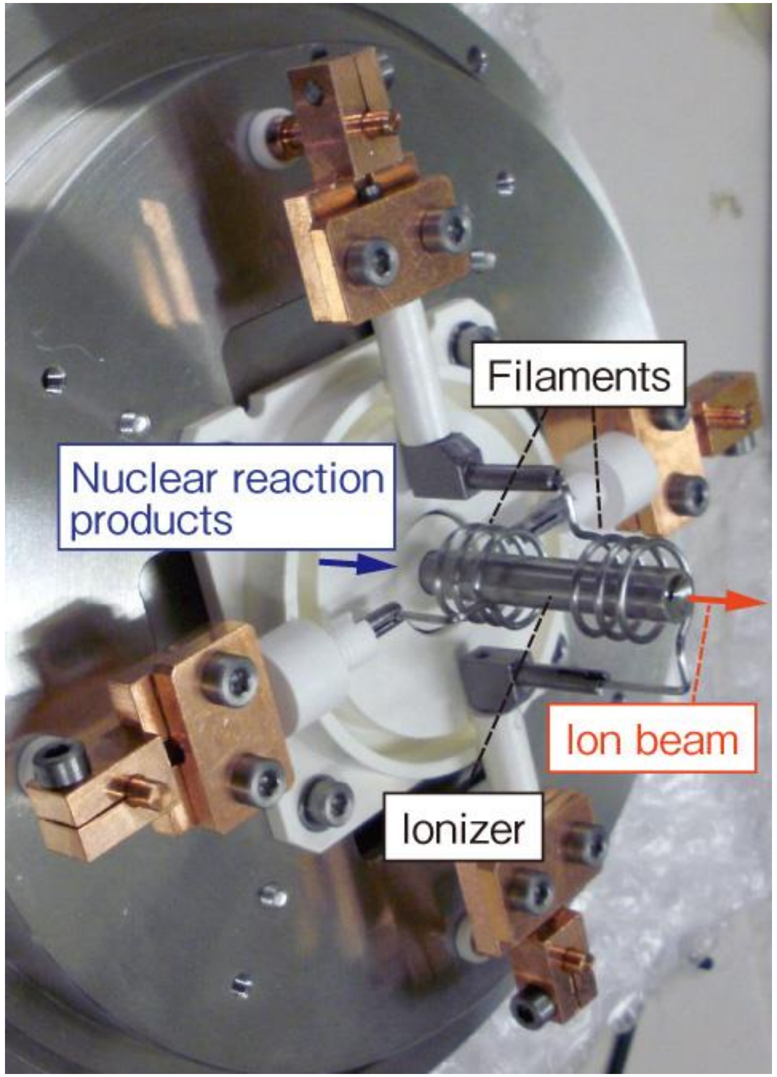


Sato, T.K.: Nature **520,** 209 (2015): https://doi.org/10.1038/nature14342

Sato, T.K.: JACS **140** (2018) 14609: https://doi.org/10.1021/jacs.8b09068

Ionization Potential of Lawrencium (*Z*=103)

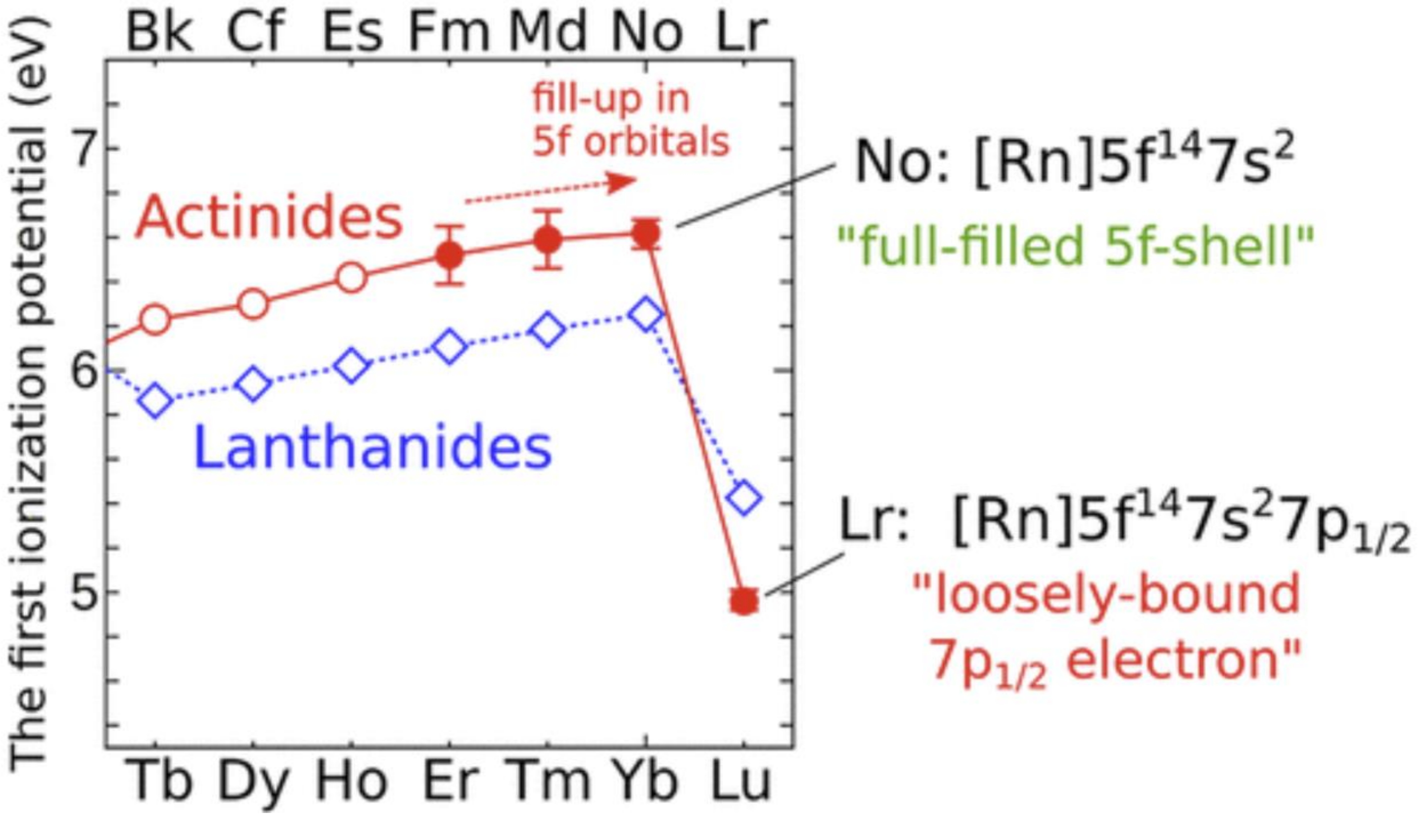




Sato, T.K.: Nature **520,** 209 (2015): https://doi.org/10.1038/nature14342
Sato, T.K.: JACS **140** (2018) 14609: https://doi.org/10.1021/jacs.8b09068

Ionization Potential of Lawrencium (*Z*=103)

- Measured No and Lr ionization potentials
- Lr has the most weakly-bound valence electron among all actinides
- Confirmed that No closes out the actinide series



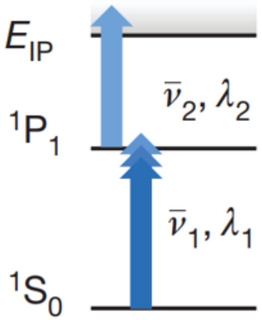
Sato, T.K.: Nature **520,** 209 (2015): https://doi.org/10.1038/nature14342
Sato, T.K.: JACS **140** (2018) 14609: https://doi.org/10.1021/jacs.8b09068

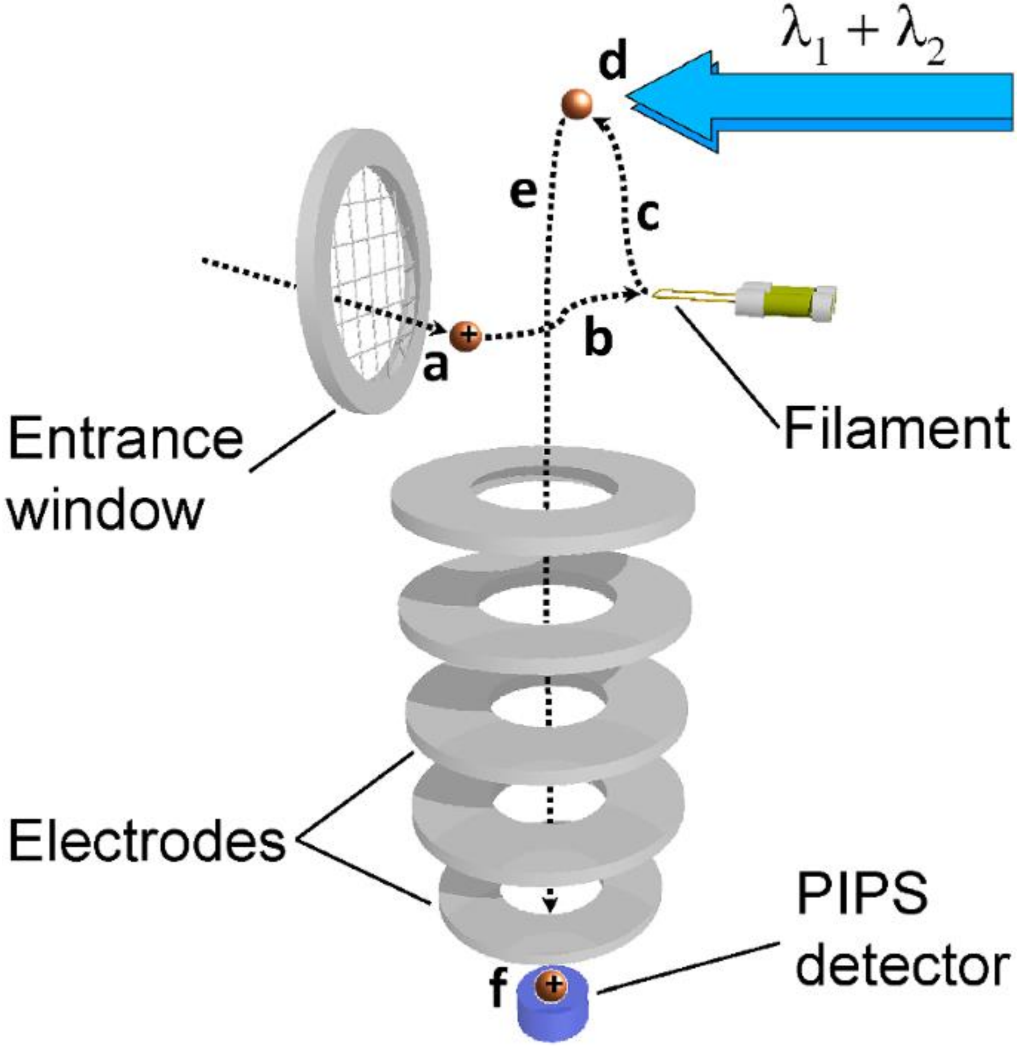
Laser Spectroscopy

Laser Spectroscopy

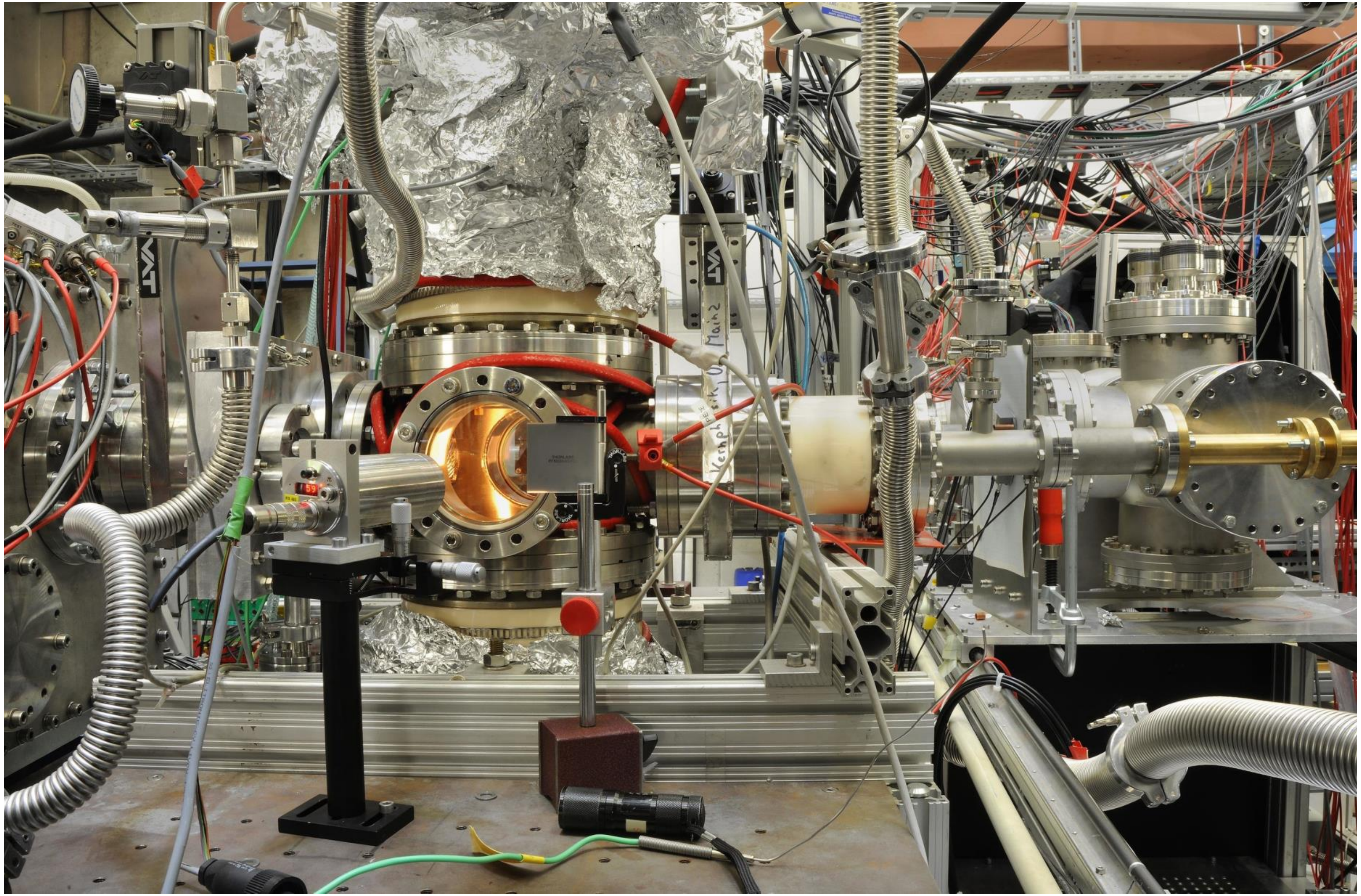
Energies of Nobelium atomic orbitals probed though RADIS (RAdiation Detected Resonant Ionization Spectroscopy)

1. Ion stopped (charged) in helium buffer gas
2. Accumulate and are neutralized on filament
3. Re-evaporated as neutral atoms
4. Excited by a two-step photoionization technique
5. Ions guided to silicon detector

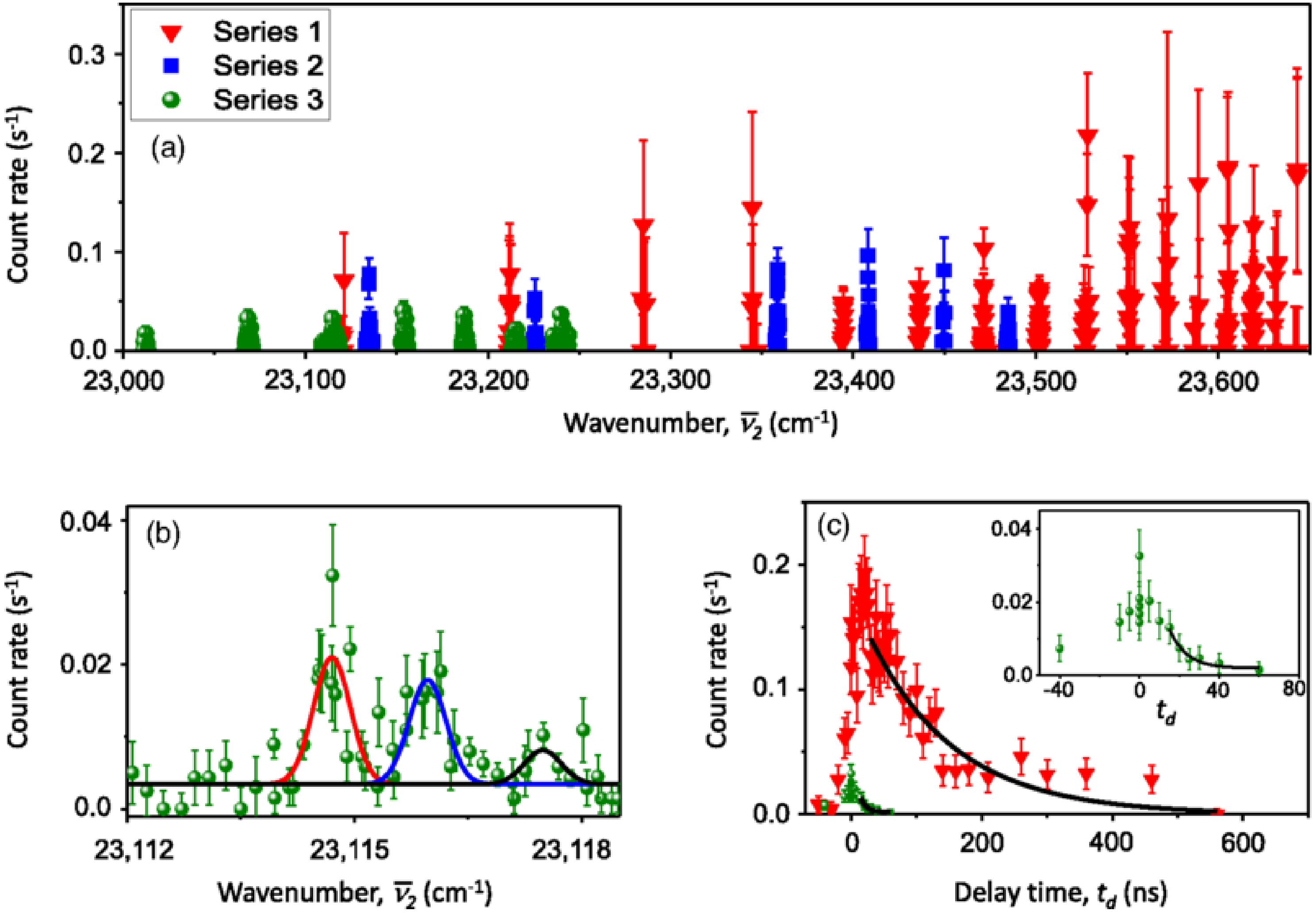




Block, M., Nucl. Phys. A, **944** (2015) 471: https://doi.org/10.1016/j.nuclphysa.2015.09.009
Block, M. La Rivista del Nuovo Cimento **45** (2022) 279: https://doi.org/10.1007/s40766-022-00030-5



Measured atomic levels of ^{254}No – Identified 30 Rydberg states – highly excited electronic states of an atom



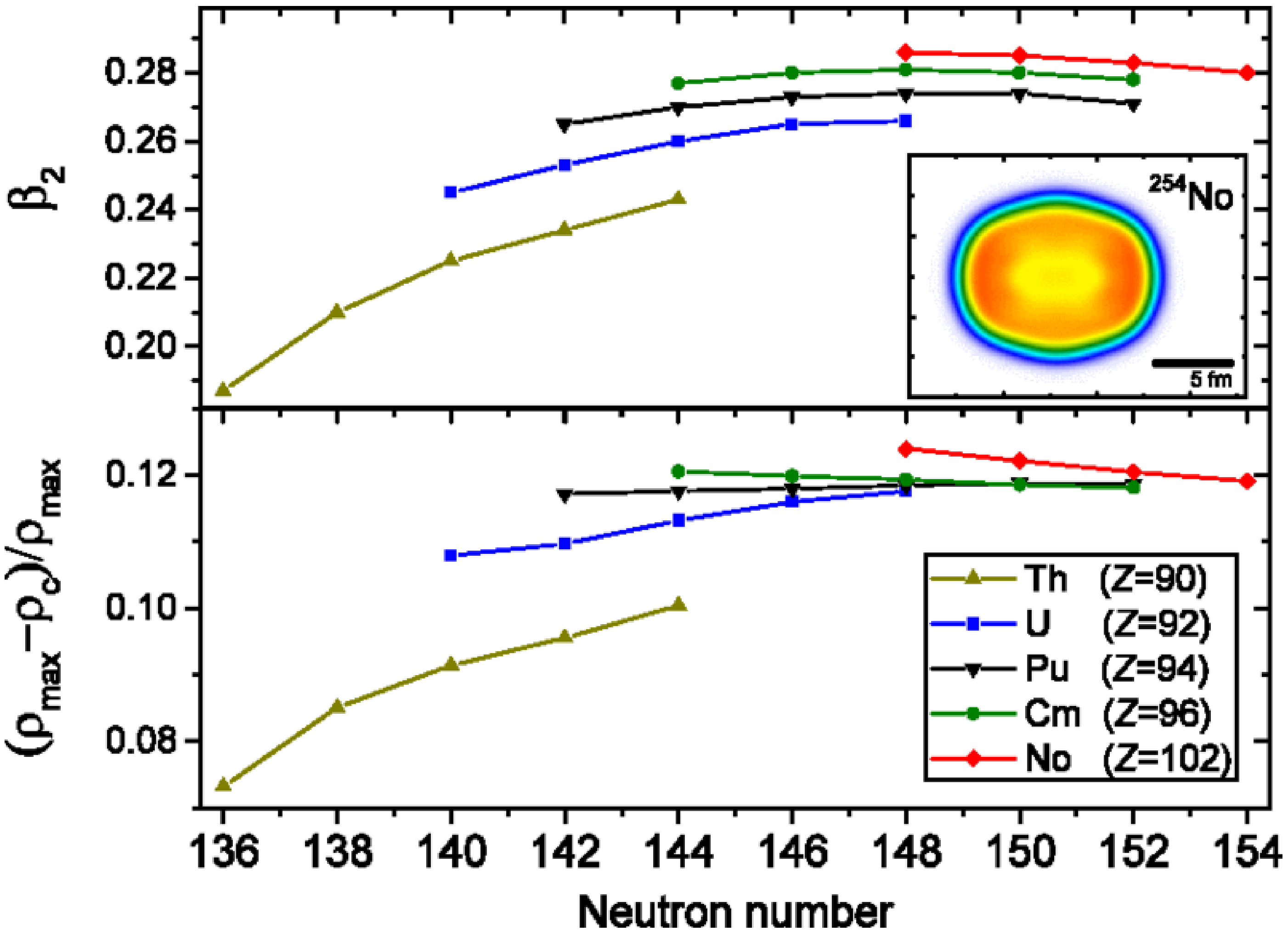
Chhetri, P. Phys. Rev. Lett. **120** (2018) 263003: https://doi.org/10.1103/PhysRevLett.120.263003

Laser Spectroscopy of Nobelium

Deformation parameter B2 for even-even isotopes

Relative depth of central depression:

$^{252,253,254}No$ = strong quadrupole deformation with central depression



Raeder, S. Phys. Rev. Lett. **120** (2018) 232503: https://doi.org/10.1103/PhysRevLett.120.232503

Chemistry with Mass Measurements

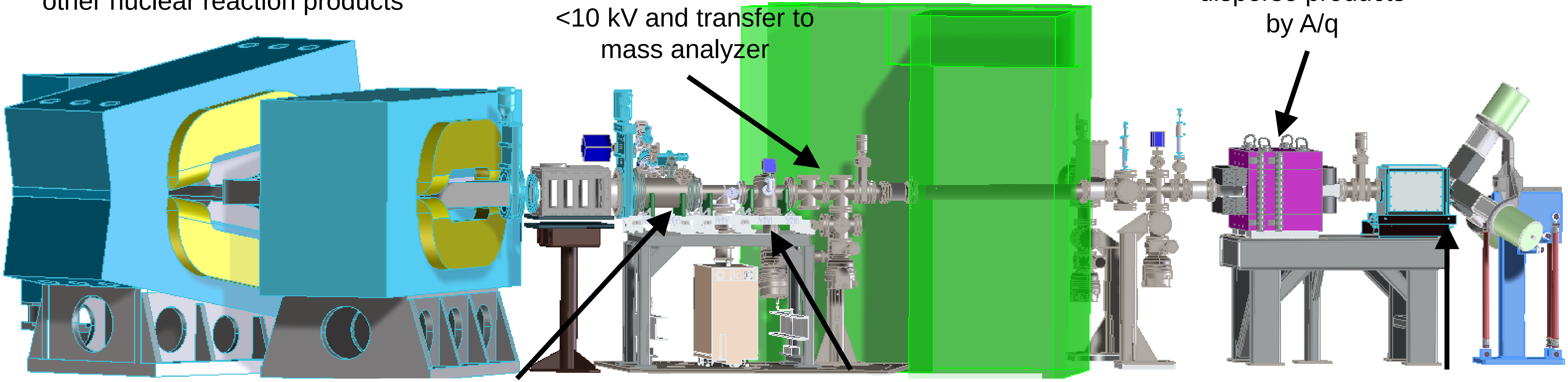
BGS + FIONA: The Concept

Berkeley Gas-filled Separator
Produce heavy element isotopes, separate from beam and other nuclear reaction products

Acceleration Region
re-accelerate ions to <10 kV and transfer to mass analyzer

Shielding Wall
allow detection in low-background environment

Trochoid Spectrometer
disperse products by A/q



RF Gas Catcher
stop ions He gas, RF and DC E-fields direct ions to an exit orifice

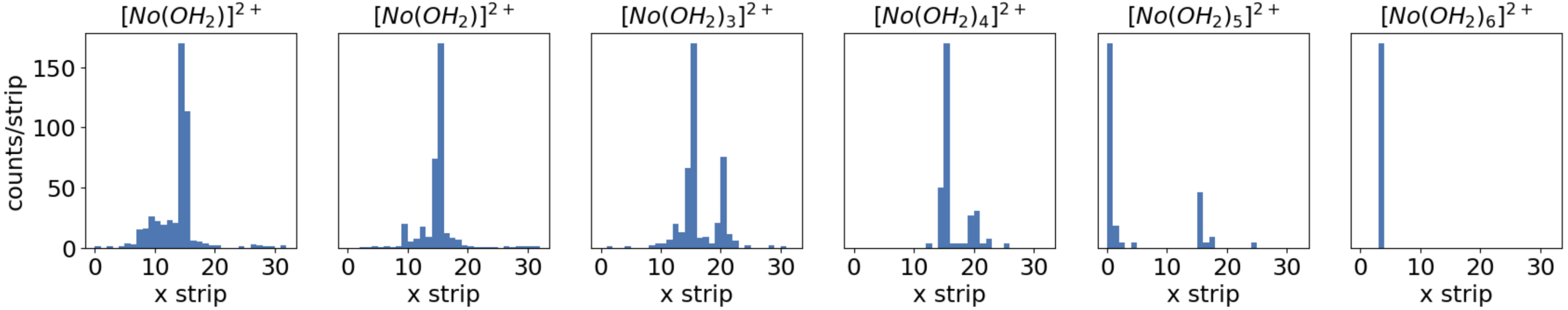
RF Quadrupole Trap
bunch and cool ions, Add in reactive gasses and perform chemistry

Detector Station
^{A}Z from α-decay
mass from x-position
lifetime from y-position

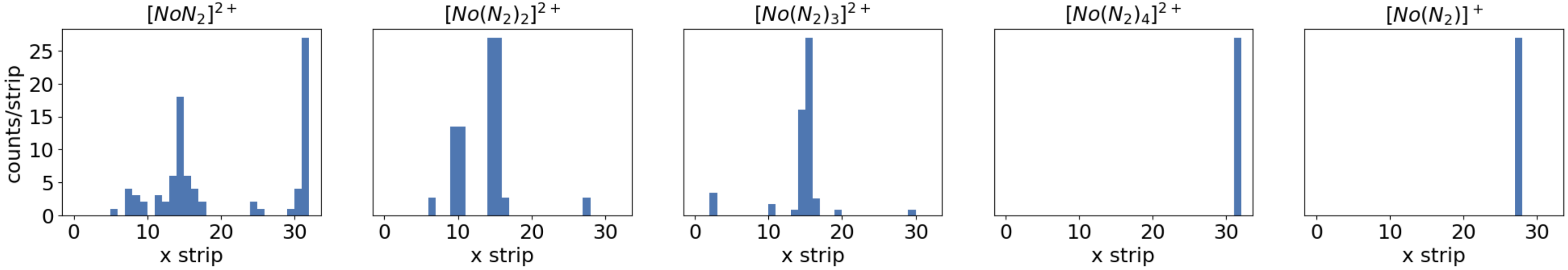
Other Fun Nobelium Complexes

Observed nobelium with 1-5 waters

Hints of small amounts of nobelium with mixtures of H_2O, OH and O



And Nobelium with 1-3 N_2 or CO

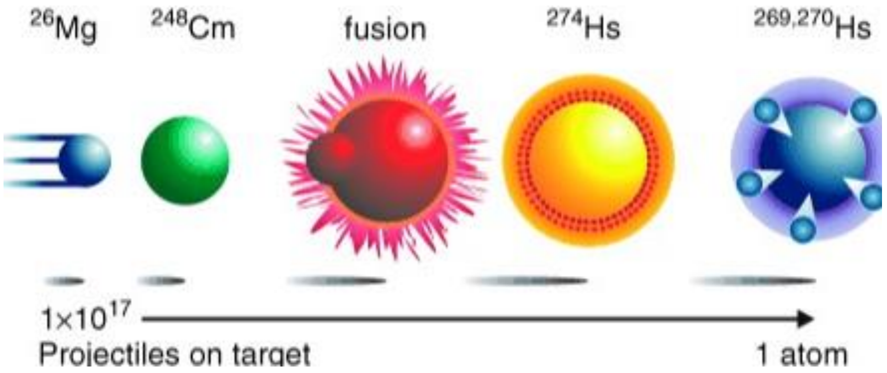


Where do we go from here?

Types of Fusion Reactions

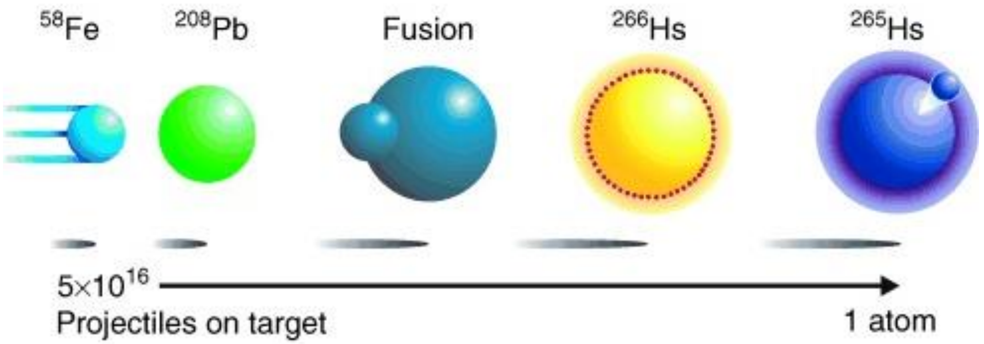
Hot Fusion

- 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



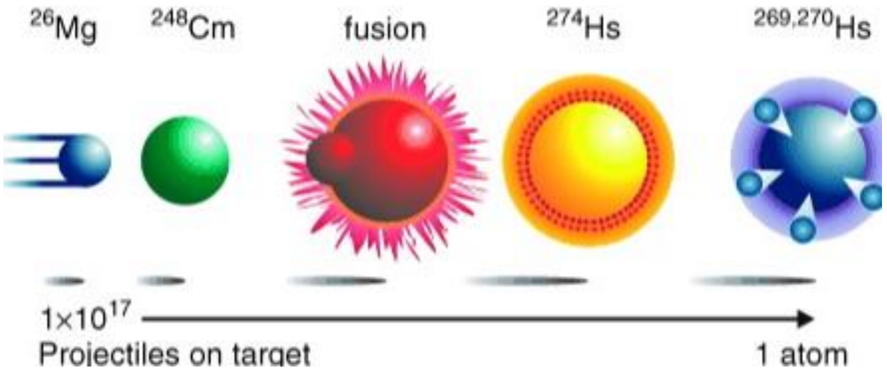
Excitation energy for a reaction:

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

Types of Fusion Reactions

Hot Fusion

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

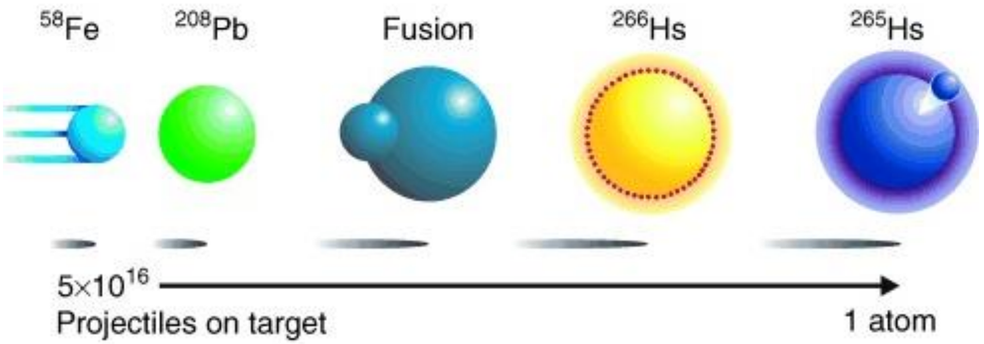


Bass barrier ≈ 125 MeV E_{cm}

$E^{*} \approx 40$ MeV

Cold Fusion

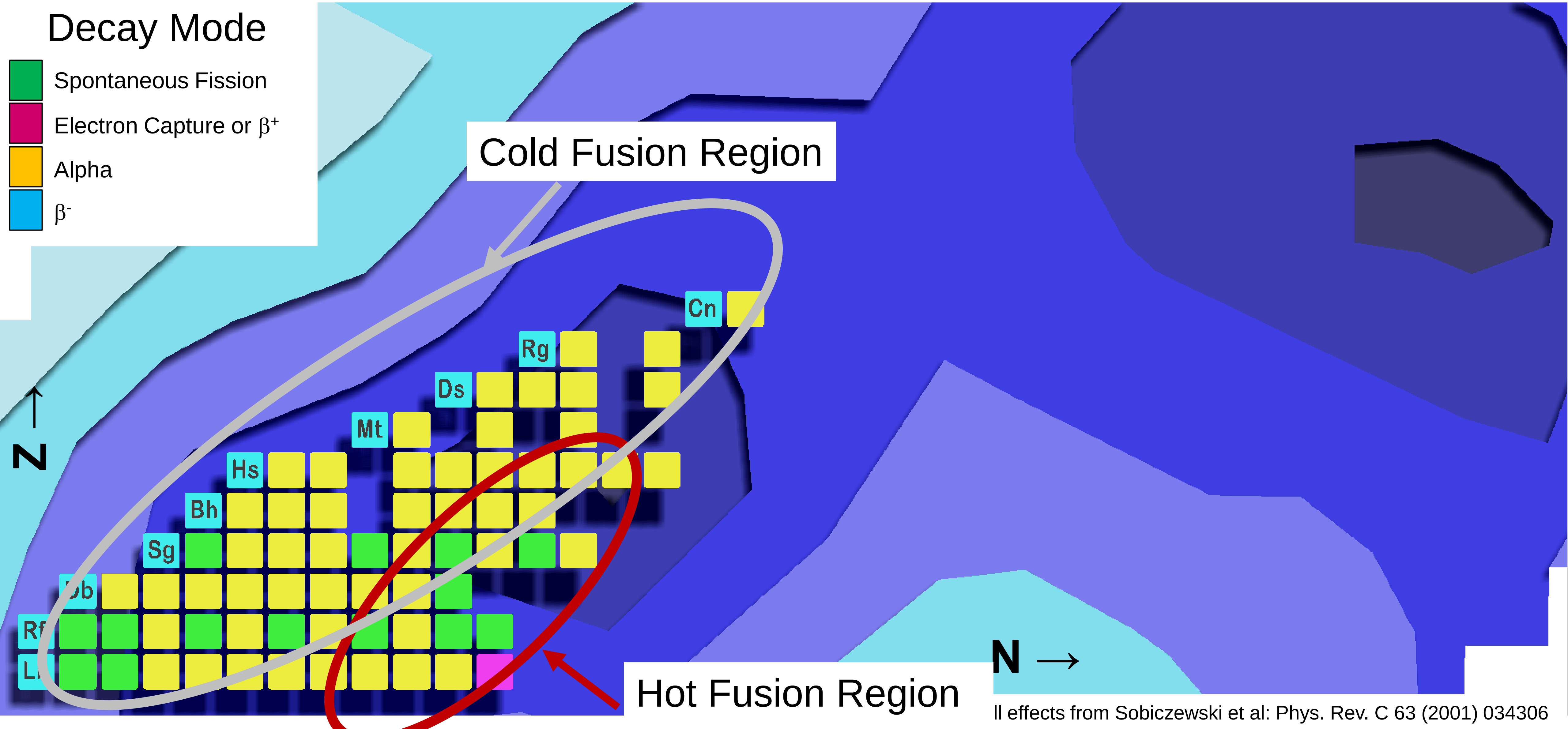
- Fusion of transition metals (^{48}Ca, ^{50}Ti, ^{54}Cr, etc) with Pb or Bi targets



Bass barrier ≈ 225 MeV E_{cm}

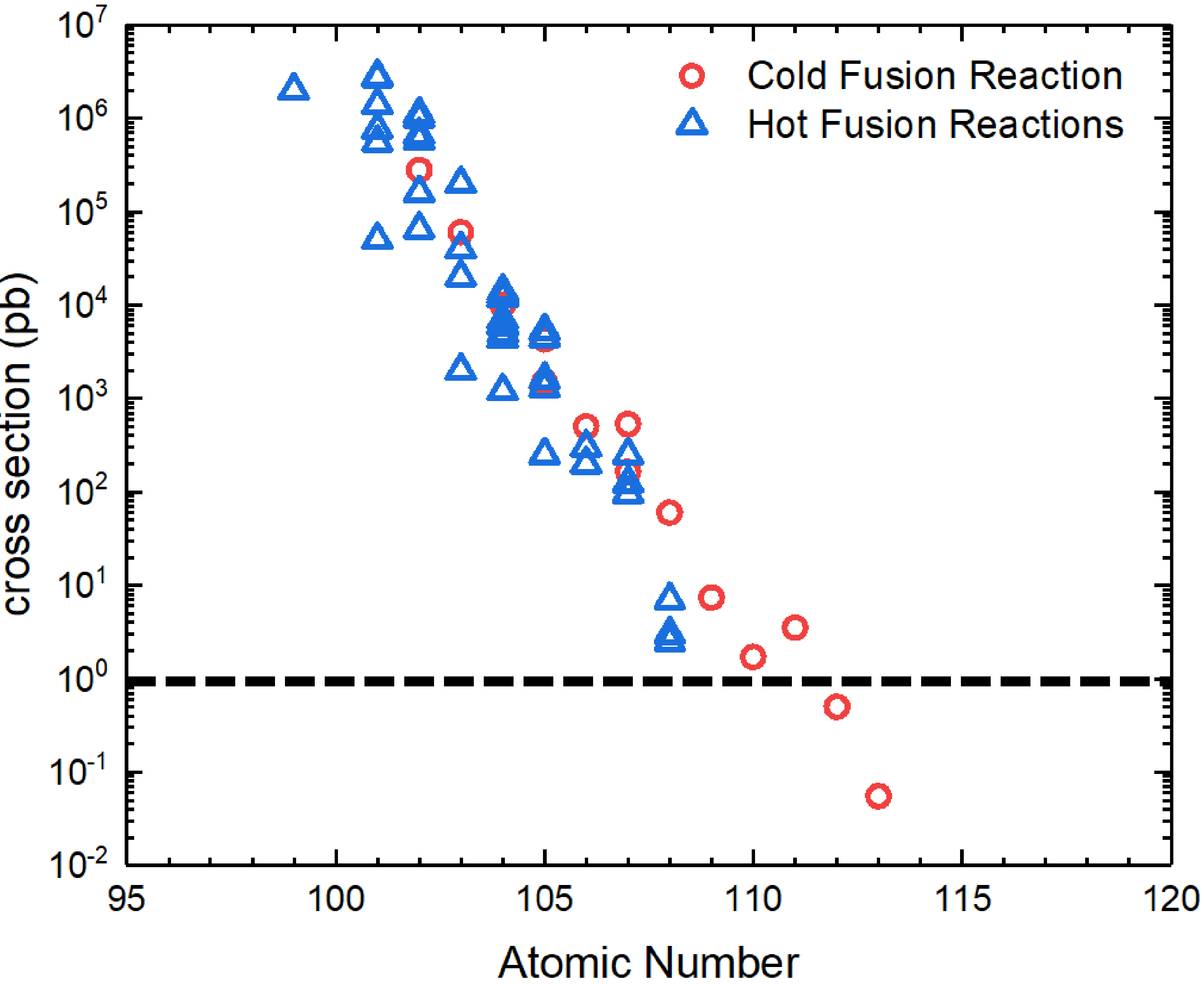
$E^{*} \approx 10$ MeV

Chart of the Nuclides: 2000



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

Discovery of Elements: Pre 2000

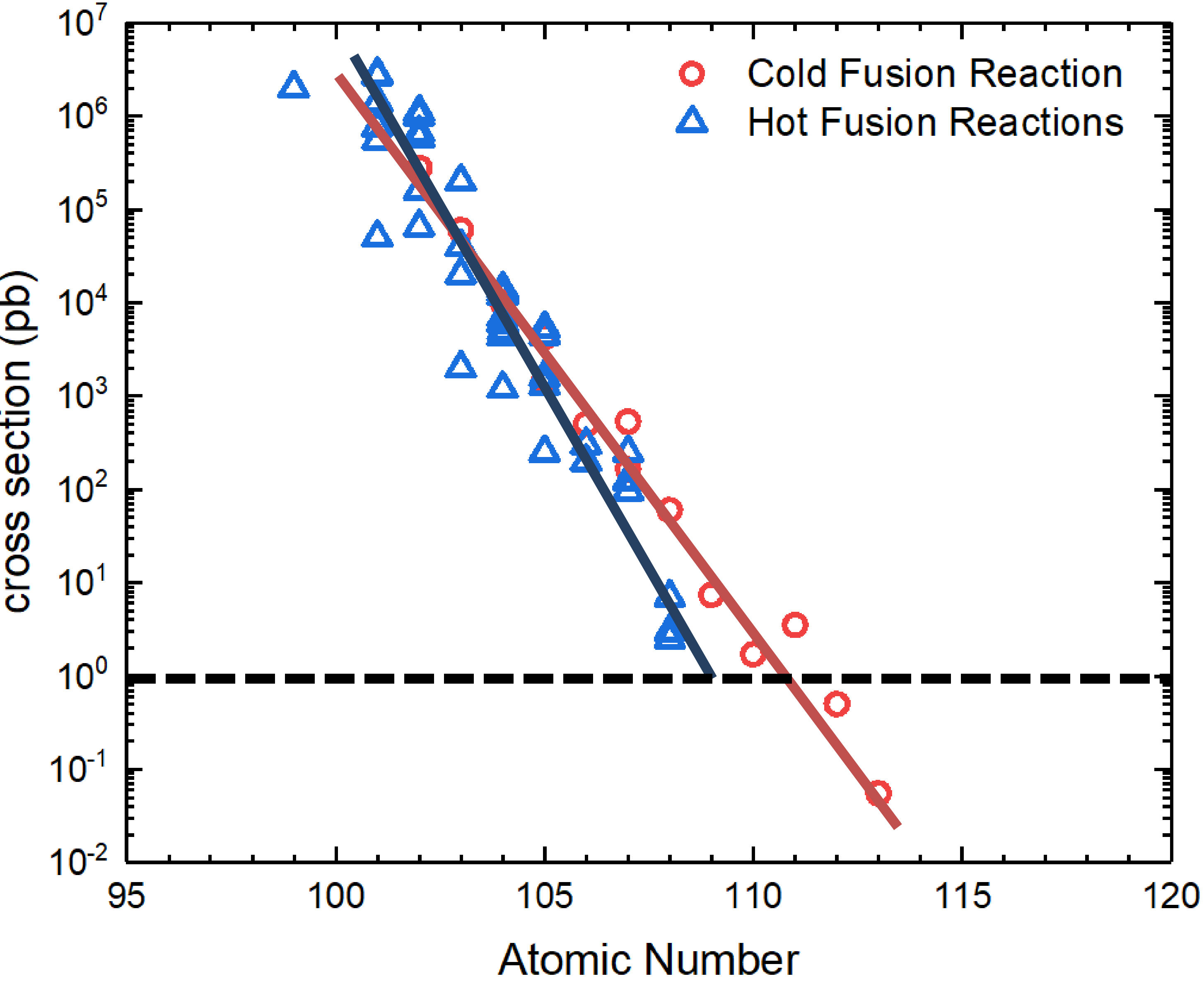


Two main types of reactions used for heavy element synthesis:

- 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

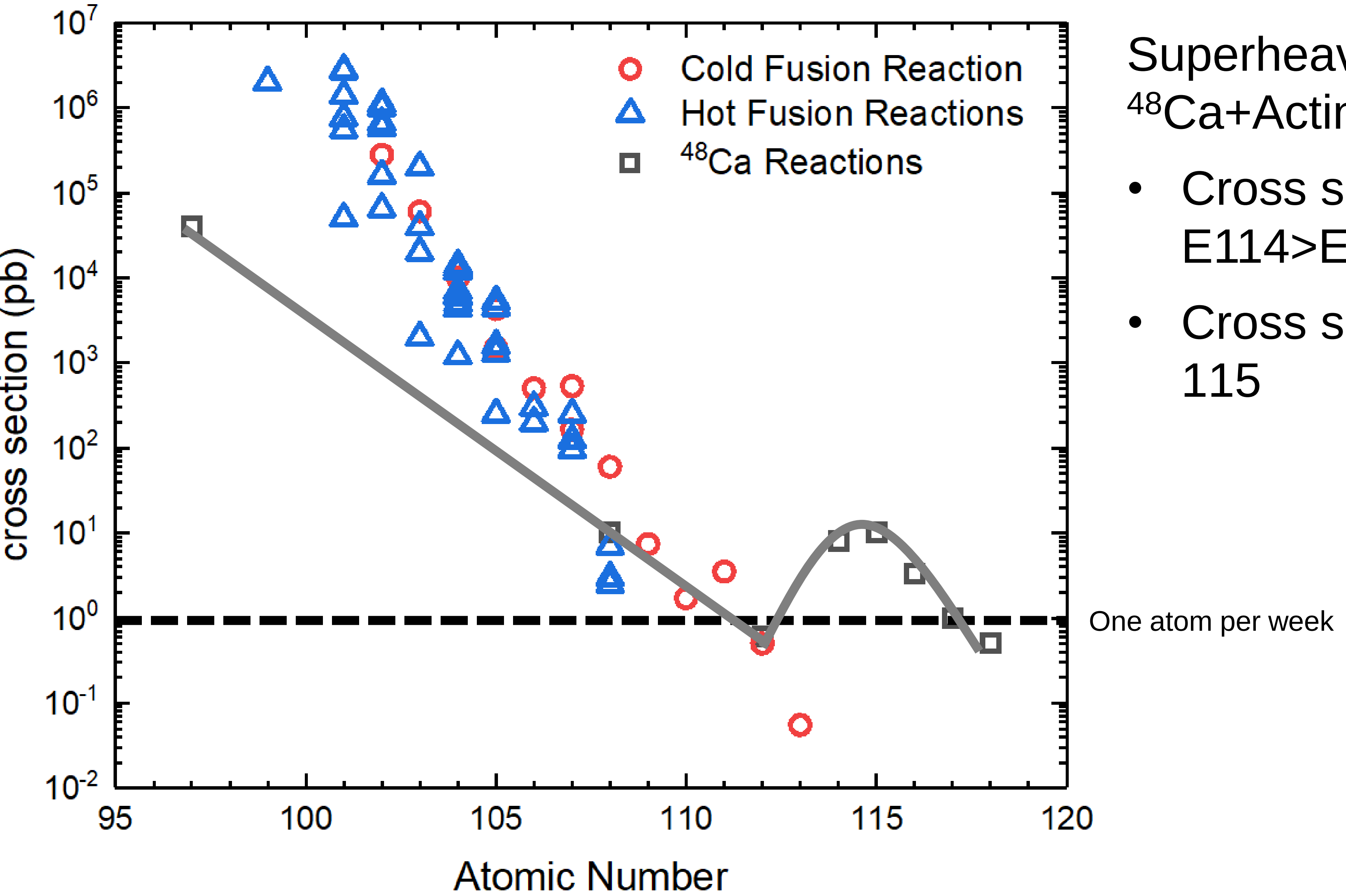


Two main types of reactions used for heavy element synthesis:

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

One atom per week

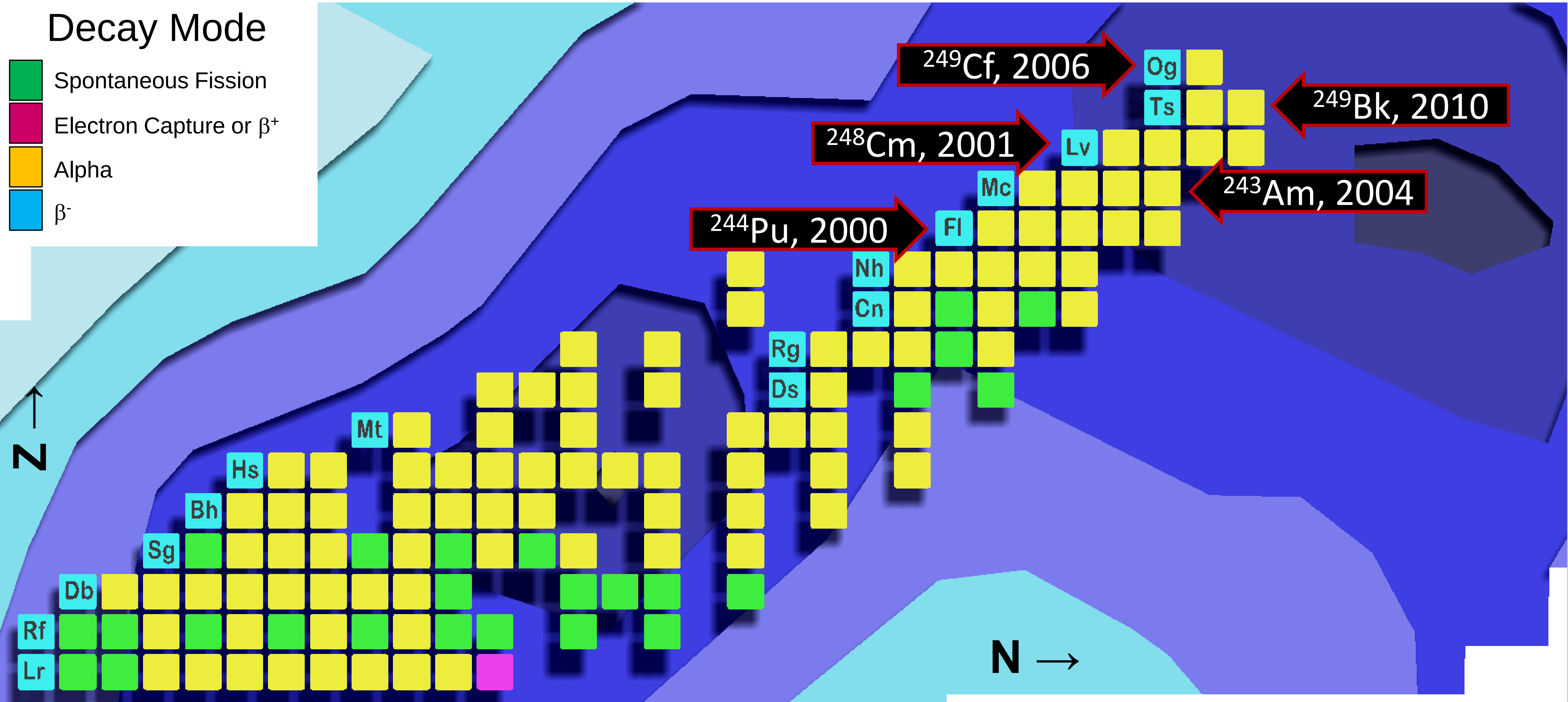
Discovery of Elements 2000-2010



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

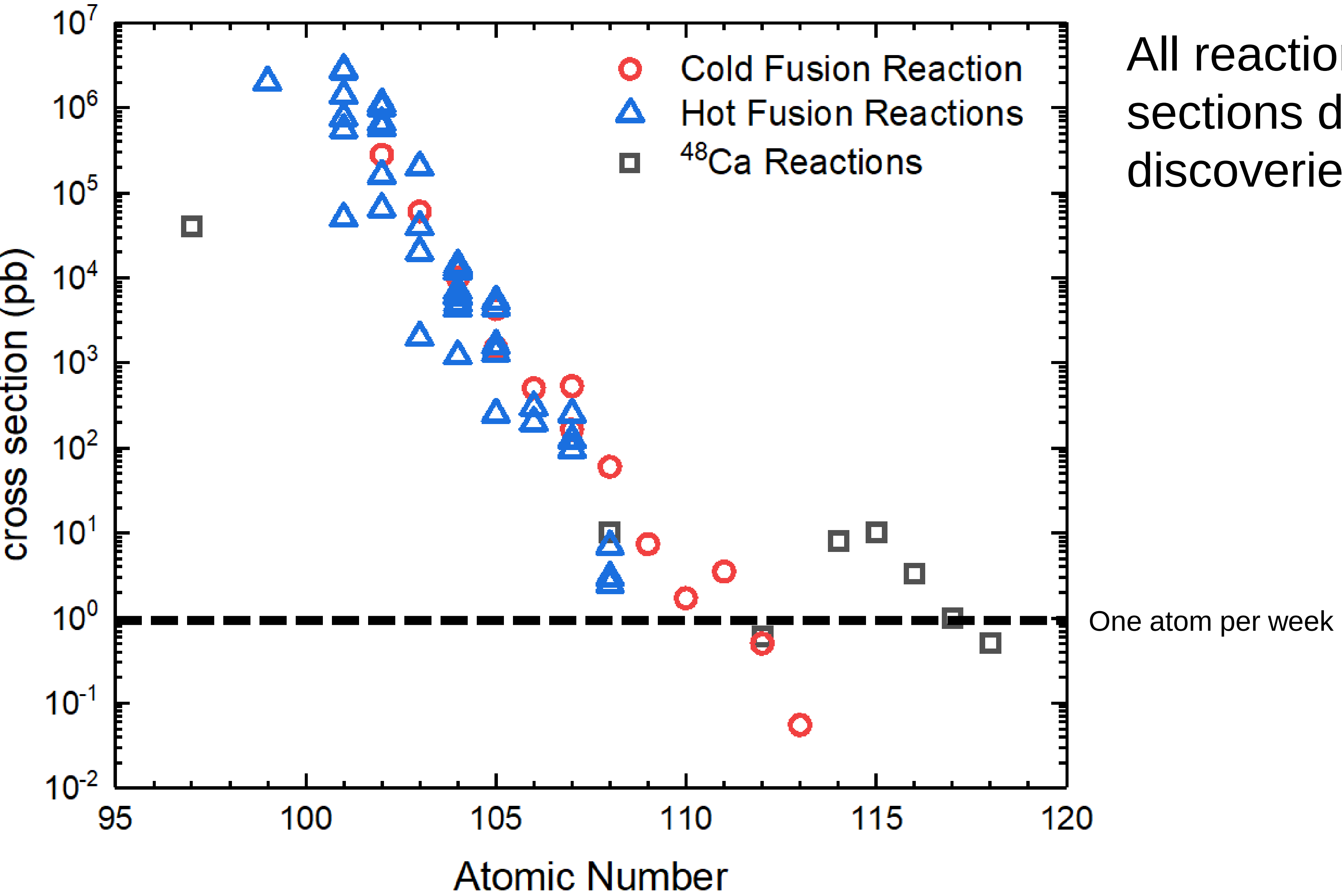
- Cross sections increase with E114>E112>E110
- Cross sections peaked Z~114-115

Chart of the Nuclides: 2019



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

Discovery of Elements: Post 2010



All reaction mechanisms ➔ cross sections dropping for new discoveries

Option 1: Change Beam

Heaviest available target material: Californium

^{249}Es 1.7 hr	^{250}Es 8.6 hr	^{251}Es 33 hr	^{252}Es 472 d	^{253}Es 20 d	^{254}Es 275 d	
^{248}Cf 333 d	^{249}Cf 350 yr	^{250}Cf 13 yr	^{251}Cf 898 yr	^{252}Cf 2.6 yr	^{253}Cf 17.8 d	^{254}Cf 60 d

^{48}Ca+Cf = Element 118

Question: How can we make elements heavier than E118?

E119 or E120 ➔ Switch to ^{50}Ti beam (or higher *Z*)

Question: What does that do to the cross section?

Experimental Attempts Z>118

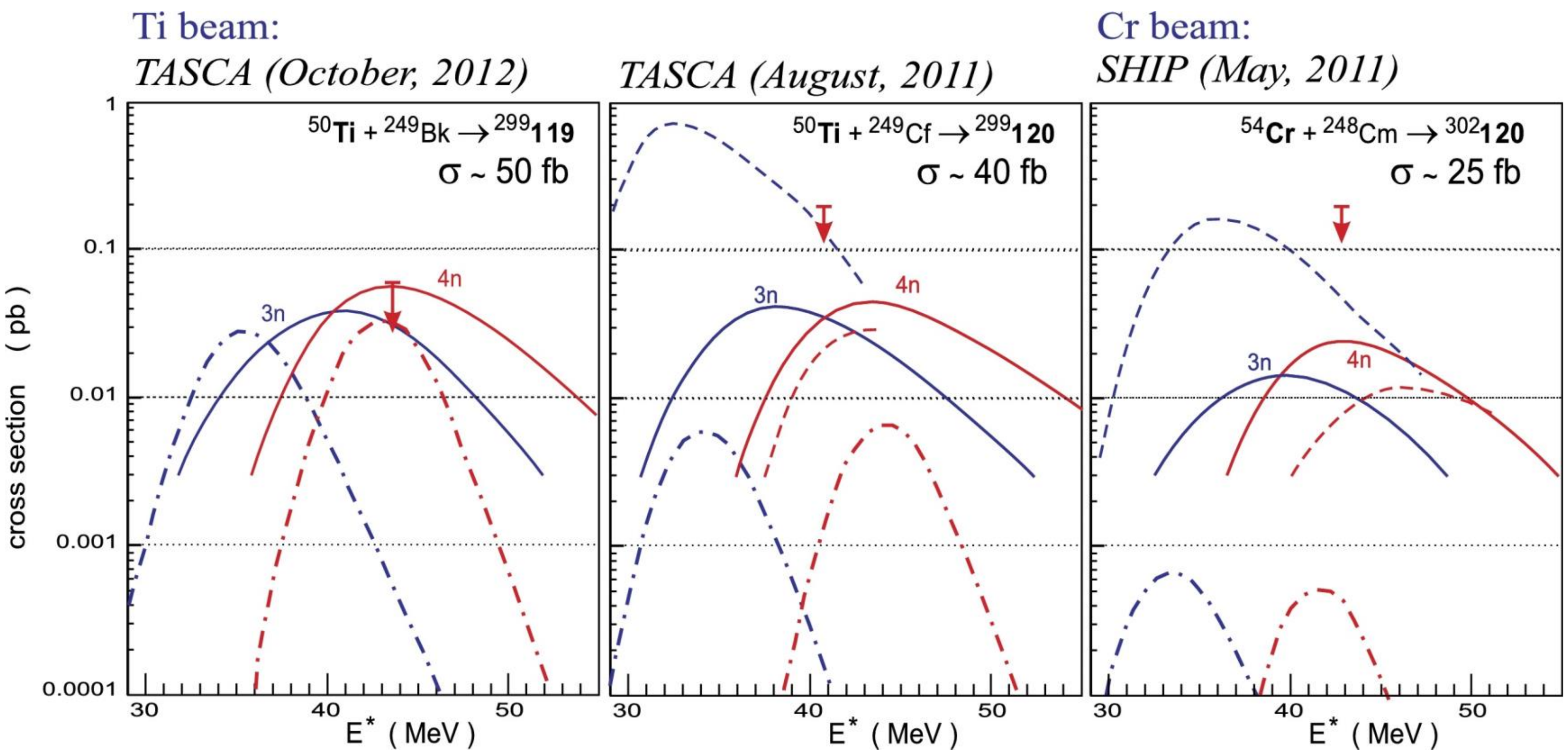
Multiple attempts have been made to push towards heavier elements

Most have not pushed much past cross sections observed with ^{48}Ca+Actinides

Beam	Target	CN	xn	Cross section	Separator	Ref.
^{136}Xe	^{136}Xe	^{272}Hs	0-3	<4 pb	Chem	Oganessian: PRC 79 (2009) 024608
^{244}Pu	^{58}Fe	^{302}120	2-5	<0.7 pb	DGFRS	Oganessian: PRC 79 (2009) 024603
^{238}U	^{64}Ni	^{302}120	1-2	<0.094 pb	SHIP	Hofmann: GSI Scientific Report (2008) NUSTAR-SHE-01
^{238}U	^{70}Zn	^{308}122	1-2	<7.2 pb	SHIP	Hofmann: EPJA 14 (2002) 147
^{249}Cf	^{50}Ti	^{299}120	3-4	<0.2 pb	TASCA	Khuyagbaatar: PRC 102 (2020) 064602.
^{249}Bk	^{50}Ti	^{299}119	3-4	<0.65 pb	TASCA	Khuyagbaatar: PRC 102 (2020) 064602.
^{248}Cm	^{54}Cr	^{302}120	3-4	<0.58 pb	SHIP	Hofmann: EPJA 52 (2016) 180
^{248}Cm	^{51}V	^{299}119			GARIS	Ongoing Experiment

^{50}Ti Beams

Theoretical predictions say ^{50}Ti beams ~10x lower cross section than ^{48}Ca beams

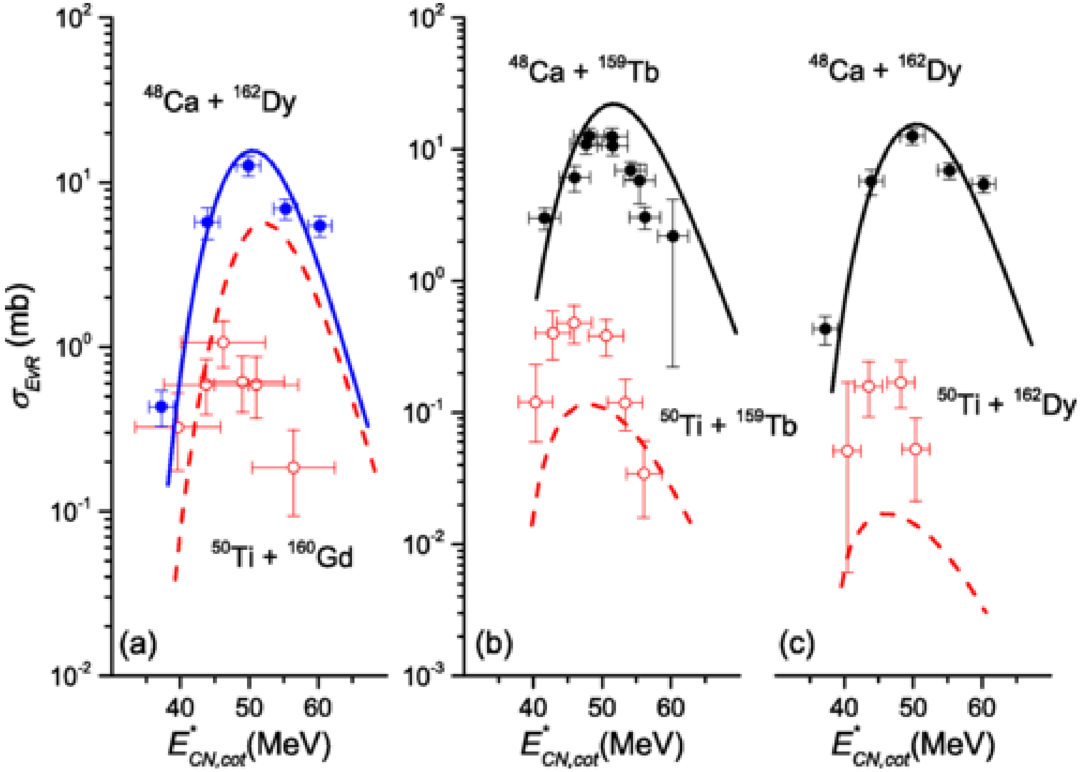


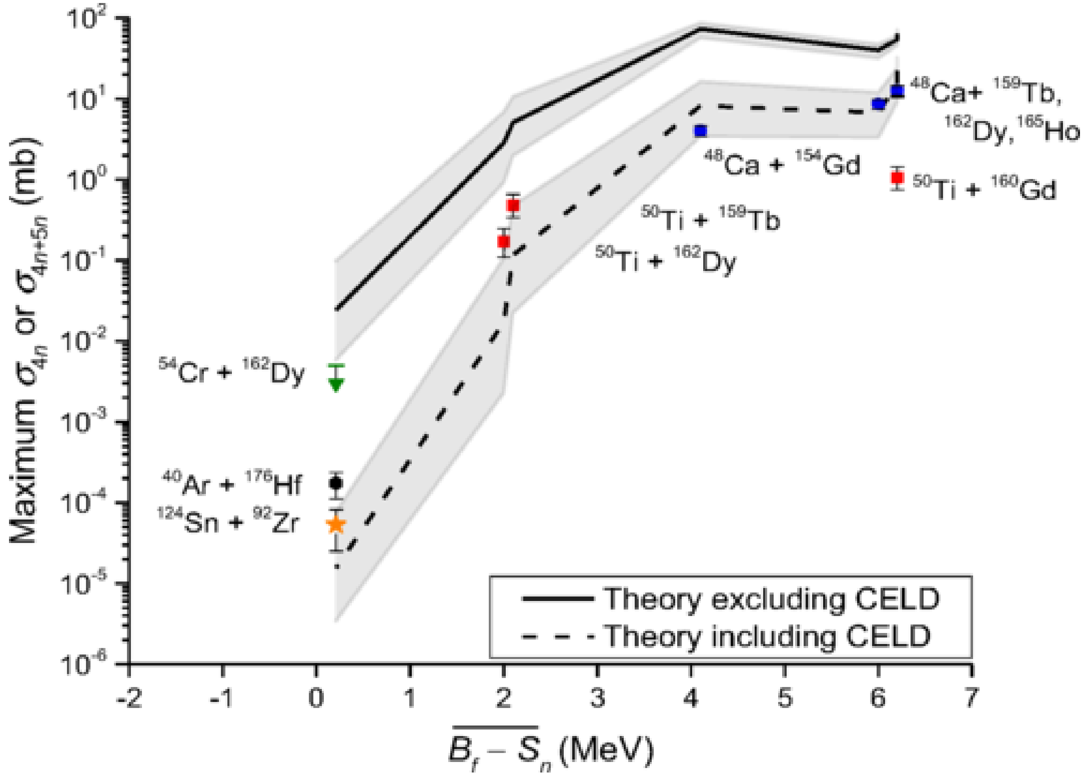
Cross section predictions for production of E119, E120 with ^{50}Ti and ^{54}Cr

Zagrebaev, V.I. Nucl. Phys. A **944** (2015) 275: https://doi.org/10.1016/j.nuclphysa.2015.02.010

What does experiment say?

- No one has measured ^{48}Ca vs ^{50}Ti superheavy element cross sections
- Test case: ^{48}Ca,^{50}Ti on lanthanide targets ➔ lose x10



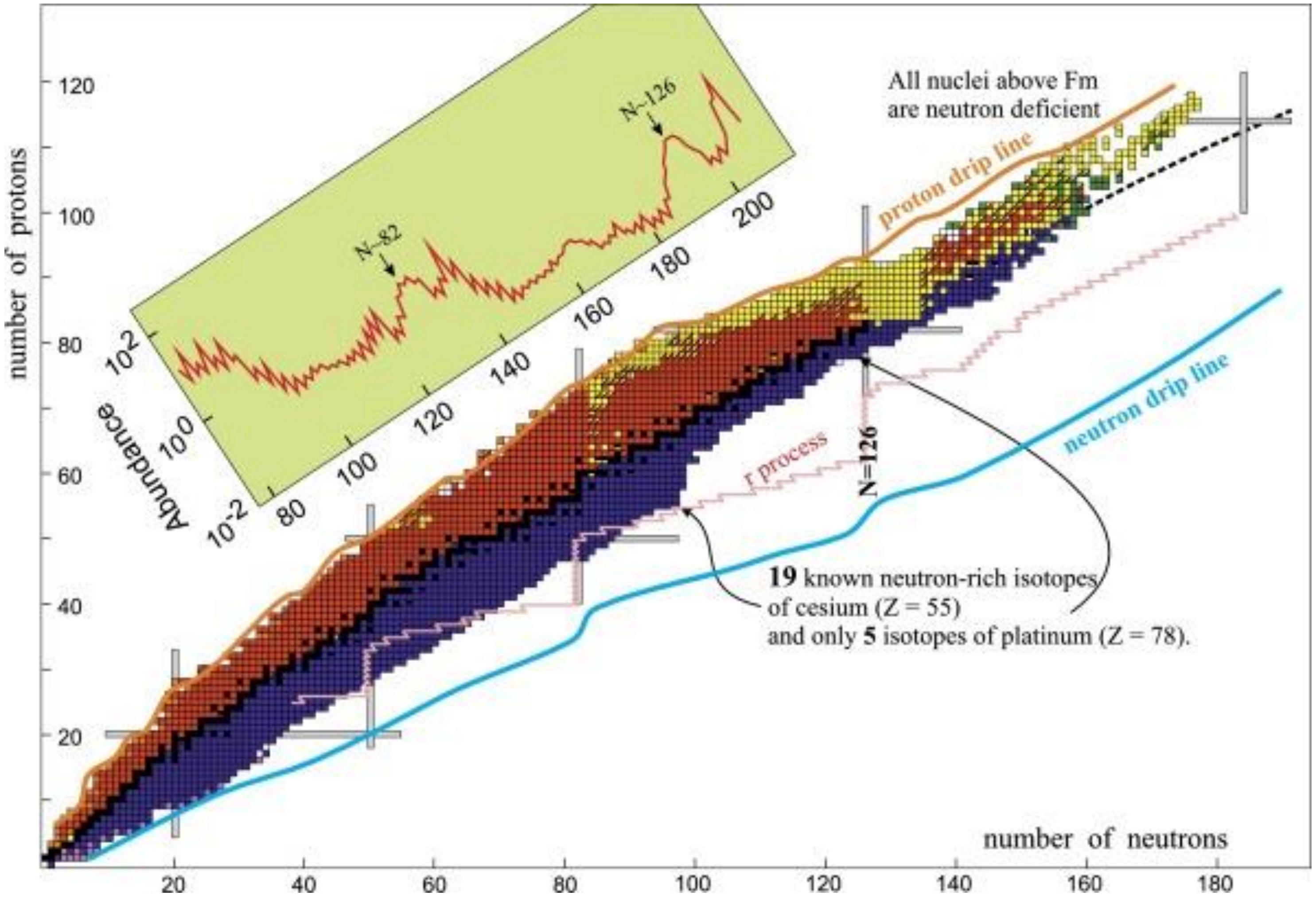


Mayorov, D.A. Phys. Rev. C **92** (2015) 054601: https://doi.org/10.1103/PhysRevC.92.054601

All known superheavy elements lie north of the line of beta stability and are approaching the proton-drip line

Compound nucleus reactions ➔ limited (no) opportunities to increase neutron number

Can multinucleon transfer reactions push towards more n-rich isotopes and heavier elements?



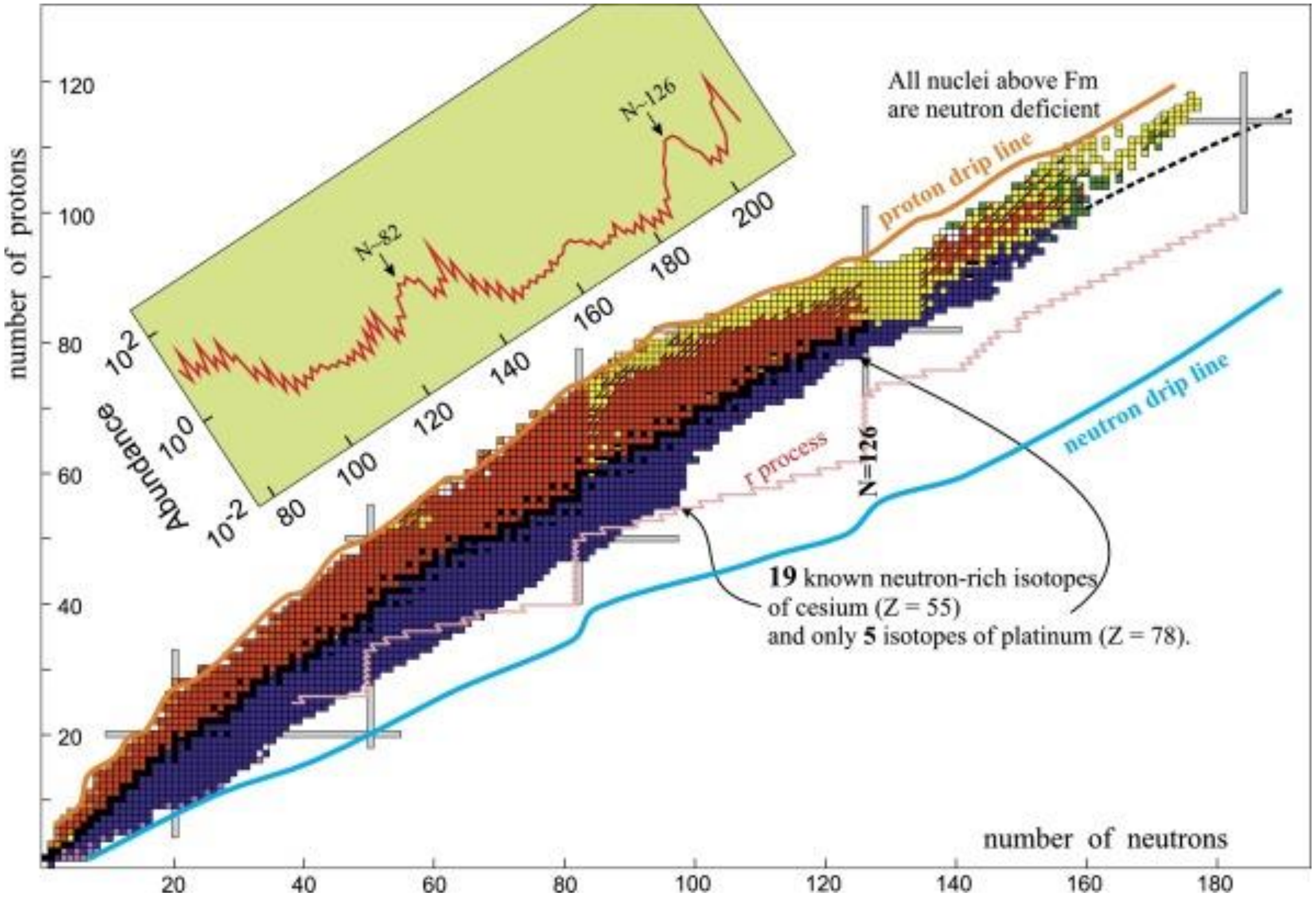
Zagrebaev, V.I. Nucl. Phys. A **944** (2015) 275: https://doi.org/10.1016/j.nuclphysa.2015.02.010

Question: Are there other ways of making SHE beyond compound-nucleus reactions?

All known superheavy elements lie north of the line of beta stability and are approaching the proton-drip line

Compound nucleus reactions ➔ limited (no) opportunities to increase neutron number

Can multinucleon transfer reactions push towards more n-rich isotopes and heavier elements?

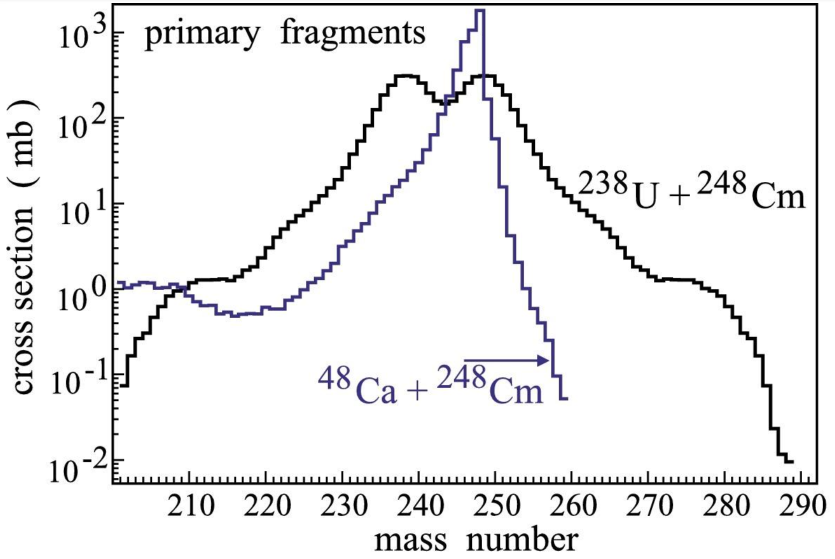


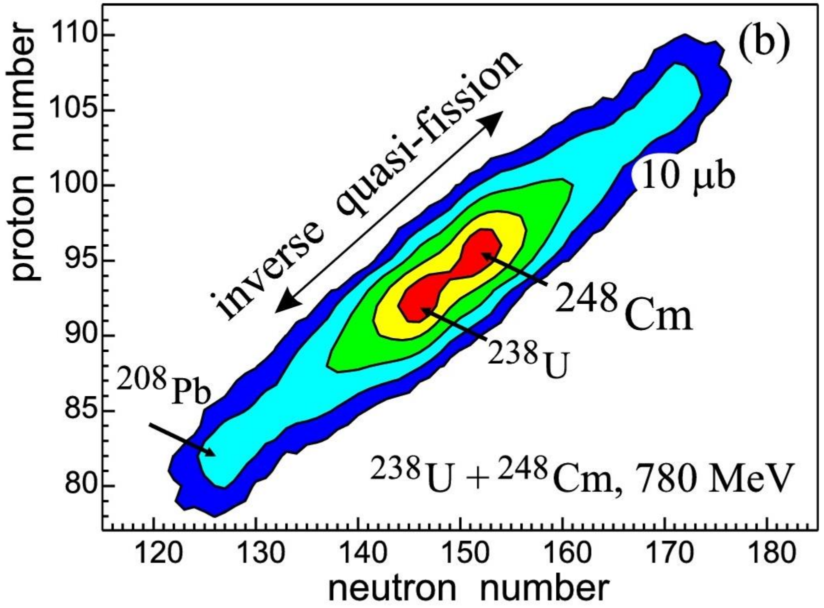
Zagrebaev, V.I. Nucl. Phys. A **944** (2015) 275: https://doi.org/10.1016/j.nuclphysa.2015.02.010

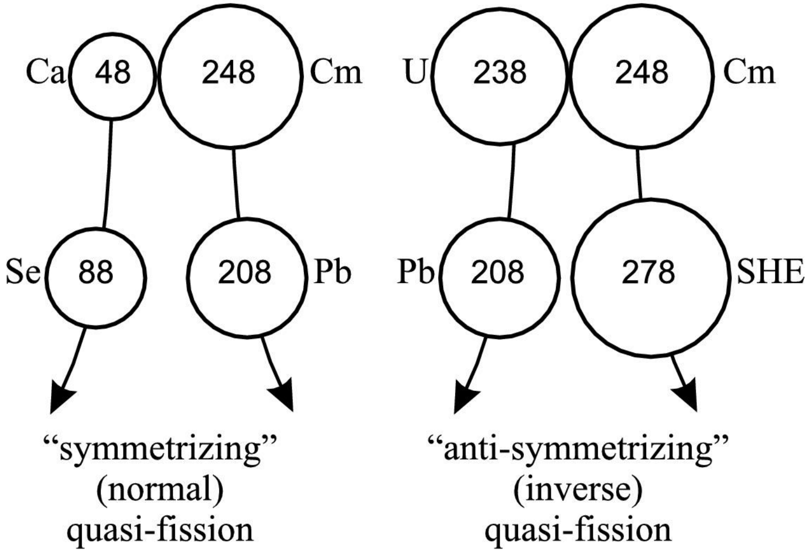
Multinucleon Transfer Reactions

Can multinucleon transfer reactions push towards more n-rich isotopes and heavier elements?

Theoretical predictions of MNT from two different systems





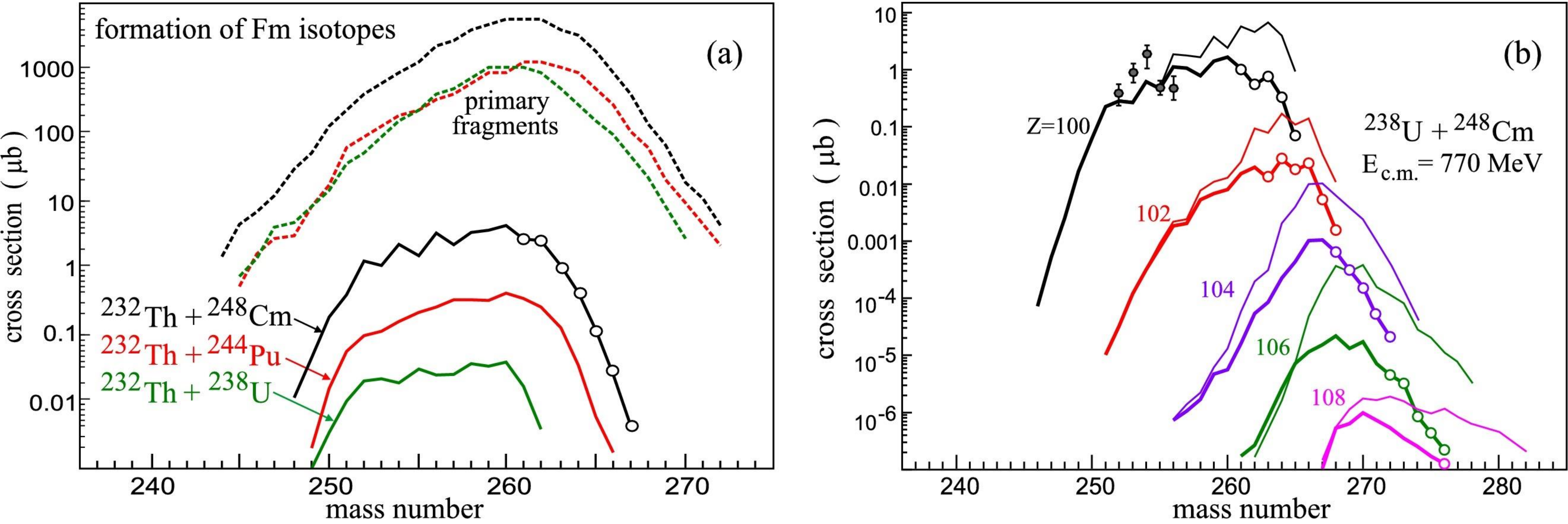


Zagrebaev, V.I. Nucl. Phys. A **944** (2015) 275: https://doi.org/10.1016/j.nuclphysa.2015.02.010

Multinucleon Transfer Reactions

Theoretical isotopic yields of fermium nuclei in collisions of ^{232}Th with ^{238}U, ^{244}Pu and ^{248}Cm

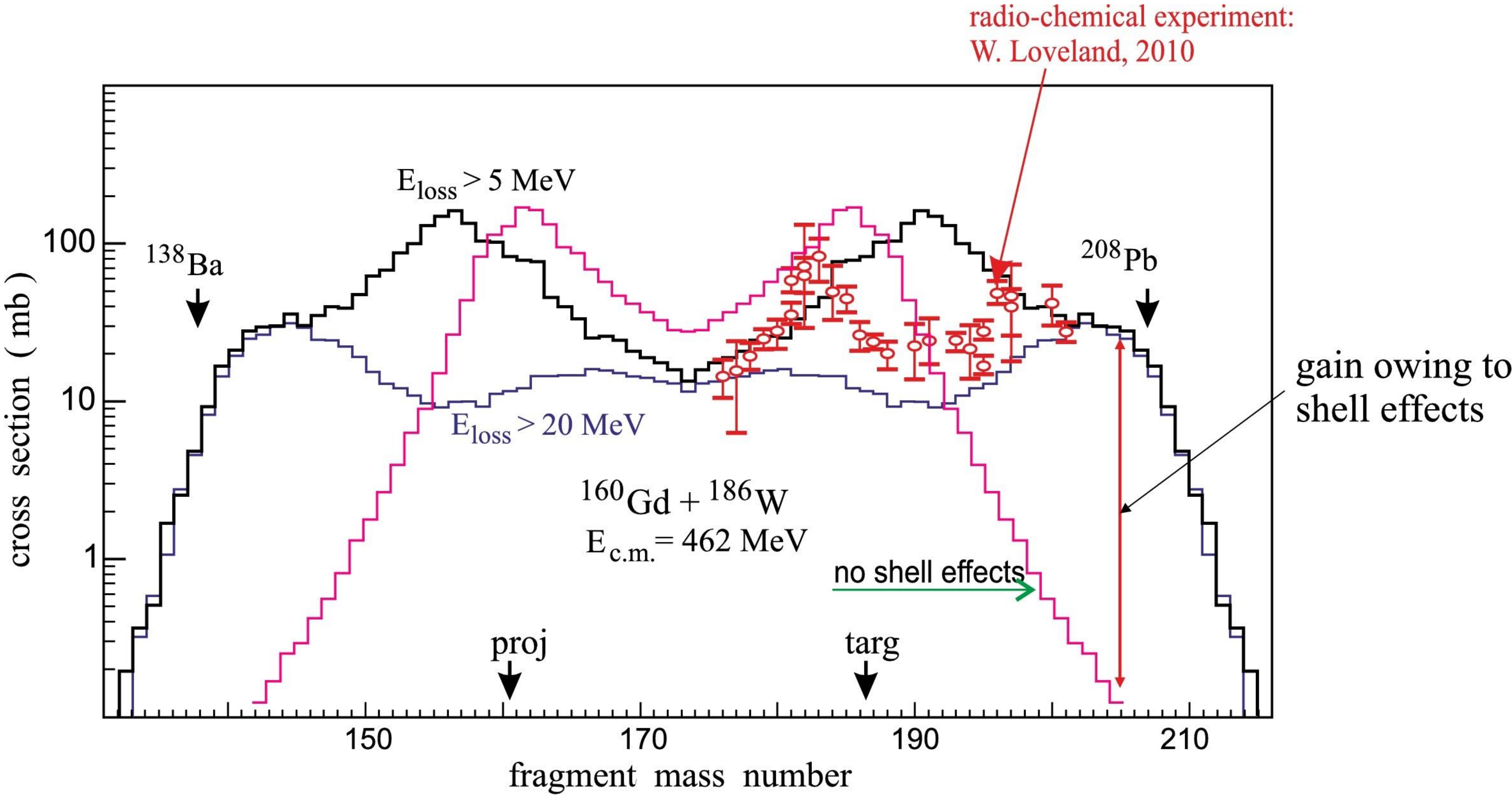
- Difficult experimentally: n-rich ➔ beta decay



Zagrebaev, V.I. Nucl. Phys. A **944** (2015) 275: https://doi.org/10.1016/j.nuclphysa.2015.02.010

Multinucleon Transfer Reactions

Comparisons between theory and experiment in rare-earth region

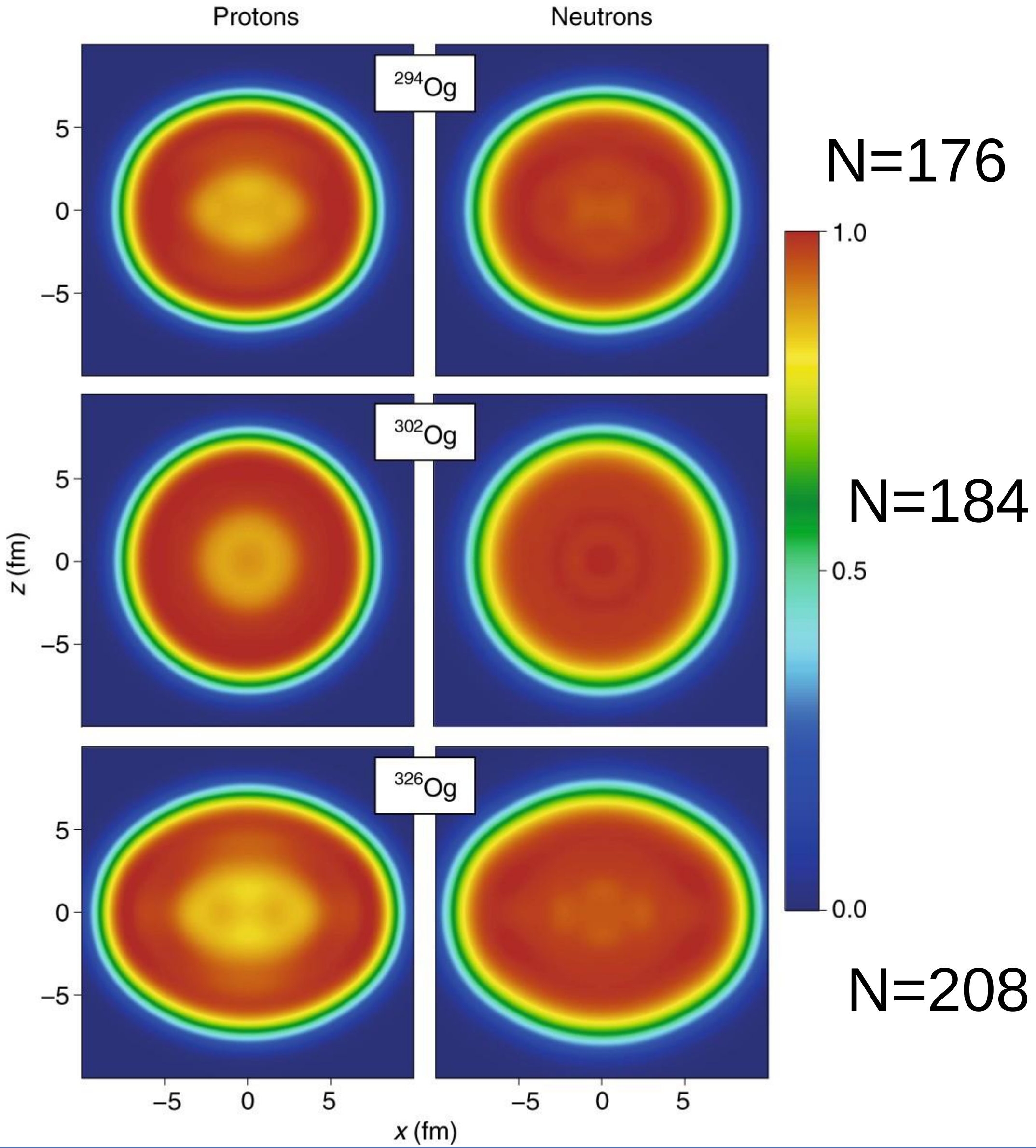


Zagrebaev, V.I. Nucl. Phys. A **944** (2015) 275: https://doi.org/10.1016/j.nuclphysa.2015.02.010

How heavy can we go?

How heavy can we go?

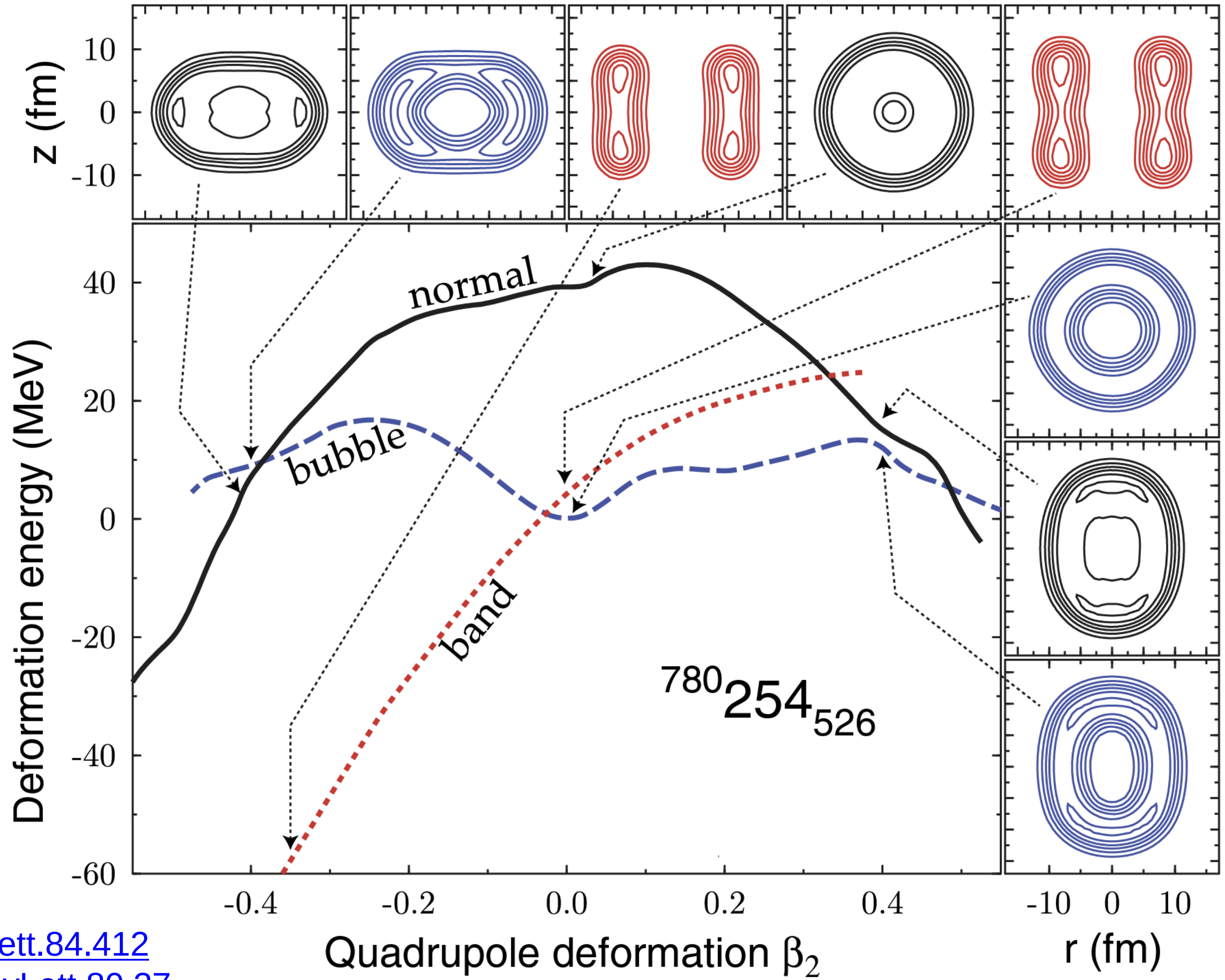
- Theoretical predictions of neutron and proton densities in Oganesson isotopes
- Predict region of lower proton density in center of most isotopes



Nazarewicz, Nature Phys. **14** (2018) 537: https://doi.org/10.1038/s41567-018-0163-3

How heavy can we go?

Theory suggests that nuclei with a sufficiently large number of nucleons (A≳450) may exist in the form of spherical bubbles



Yu, Y. Phys. Rev. Lett. **84** (2000) 412: https://doi.org/10.1103/PhysRevLett.84.412
Dietrich, K. Phys. Rev. Lett **80** 1998) 37: https://doi.org/10.1103/PhysRevLett.80.37
Nazarewicz, Nucl. Phys. A **701** (2002) 165: https://doi.org/10.1016/S0375-9474(01)01567-6
Dechargé, J. Phys. Lett. B **451** (1999) 274: https://doi.org/10.1016/S0370-2693(99)00225-7

Summary and Conclusions

Superheavy elements are fun

Lecture 1: Why superheavy elements exist, why study superheavy elements

Lecture 2: How superheavy elements are made

Lecture 3: Properties of superheavy elements and future of superheavy elements