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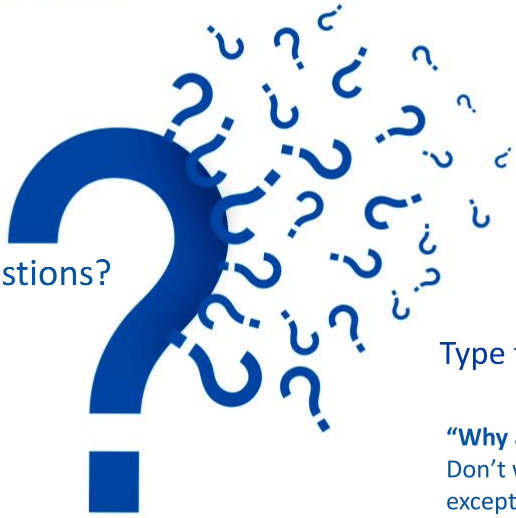

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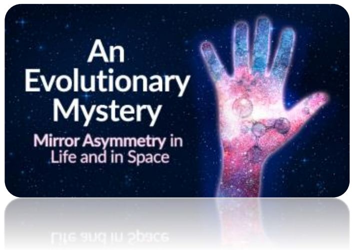

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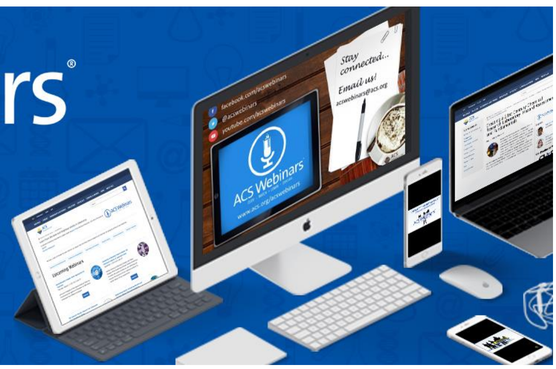

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c&en CHEMICAL & ENGINEERING NEWS

ACS Chemistry for Life®

Exploring the superheavy elements at the end of the periodic table

These scientists want to know how elements 104 through 118 look and behave

by *Laura Howes*

MAY 21, 2019 | APPEARED IN VOLUME 97, ISSUE 21

On a stage in the United Nations Educational, Scientific, and Cultural Organization headquarters in Paris, Yuri Oganessian holds a microphone in one hand and a small remote control in the other. Over the next 20 minutes, a hushed auditorium listens as he describes how the periodic table of elements has grown. To date, 118 elements currently populate it. The heaviest of those, oganesson, was named after Oganessian himself.

But during the talk, which took place in January at the launch of the International Year of the Periodic Table, Oganessian says, discovering the superheavy elements (SHEs) with proton numbers 104 and above has been like opening Pandora's box. Many unexpected problems have poured out, he says, some that are perhaps more difficult to solve than making SHEs in the first place. The discovery of these newer elements has prompted scientists to ask not just whether even heavier elements can be made but also what the chemical properties of the SHEs already discovered are and how to measure the properties of individual atoms of such short-lived species.

https://cen.acs.org/physical-chemistry/periodic-table/IYPT-Exploring-the-superheavy-elements-at-the-end-of-the-periodic-table/97/i21

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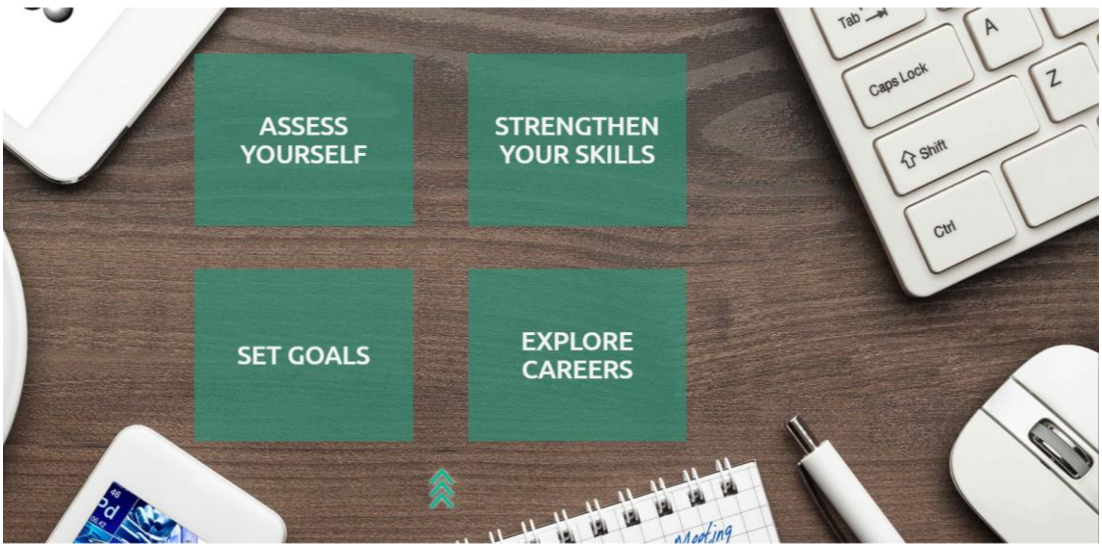
An individual development planning tool for you!



https://chemidp.acs.org

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Check out ACS NUCL!

ACS Technical Division
Nuclear Chemistry & Technology (NUCL)

"The Future of the Periodic Table"

Upcoming symposia from ACS NUCL at the ACS National Meeting & Expo

Philadelphia, PA
March 22-26, 2020

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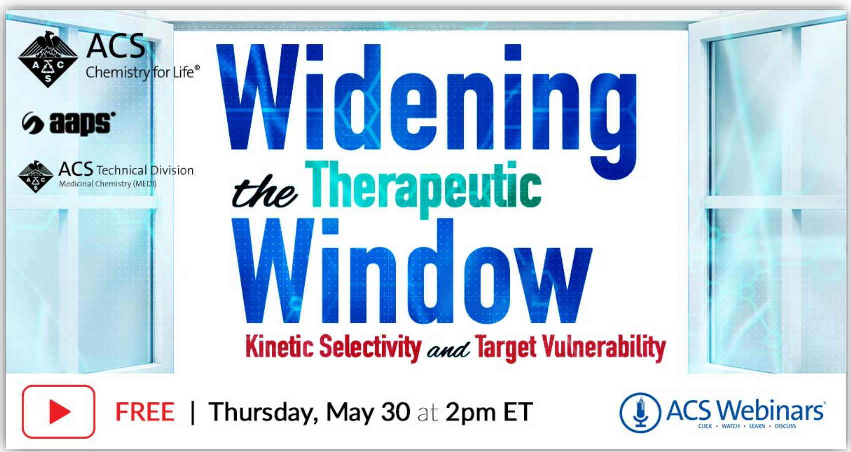

https://www.acs.org/content/acs/en/acs-webinars/popular-chemistry/heavy-elements.html

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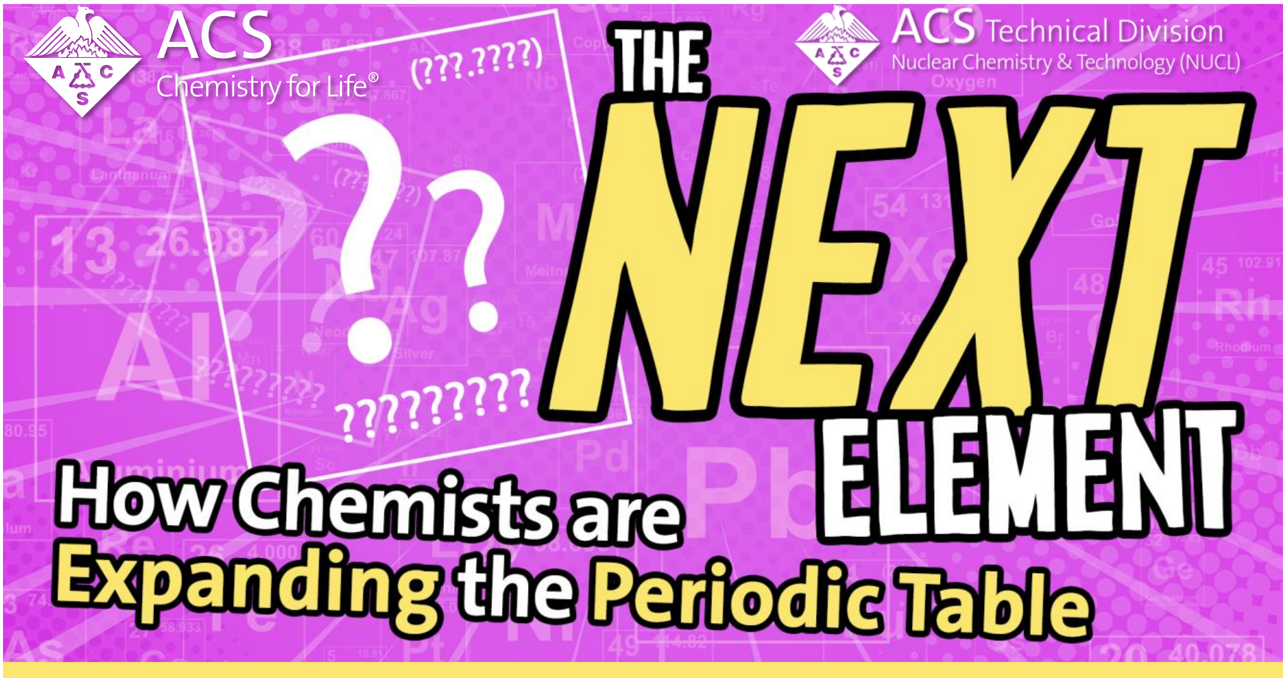

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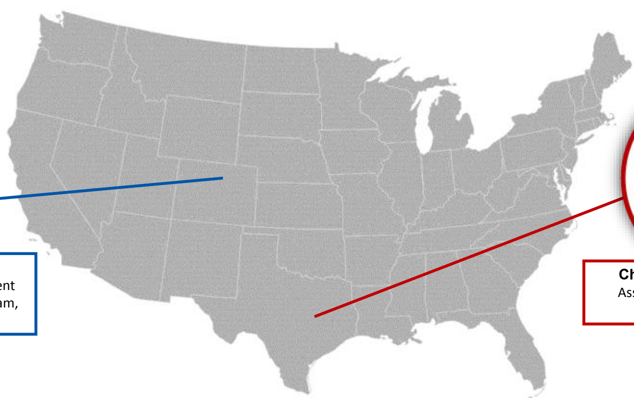
The Next Element: How Chemists are Expanding the Periodic Table



Jenifer Shafer
Associate Professor, Chemistry Department and Nuclear Science & Engineering Program, Colorado School of Mines

Charles "Cody" M. Folden III
Associate Professor of Chemistry, Texas A&M University

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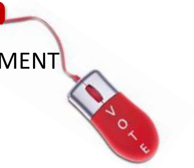
Outline

- The Elements as They Stand Today
- Nuclear Reactions Used to Make the Heaviest Elements
- How Are the Experiments Performed?
- The Future of New Elements
- How Do You Study Chemistry with Only a Few Atoms?

Prof. Cody Folden
Texas A&M University
ACS NUCL
Cyclotron.tamu.edu/folden

Audience Survey Question

ANSWER THE QUESTION ON BLUE SCREEN IN ONE MOMENT



How many naturally occurring elements are there?

- Less than 80
- 80-85
- 86-90
- 91-95
- More than 95

The Elements as They Stand Today

- There are **91 naturally occurring elements** (but it depends on how you count them).
  - The heaviest element that occurs in large quantity is uranium (atomic number 92). You can mine it like gold.
  - Technetium (atomic number 43) does not occur naturally.
  - Promethium (atomic number 61) does not occur naturally.
  - ^{244}Pu *has* been discovered in nature. This isotope has a half-life of "only" 80 million years.

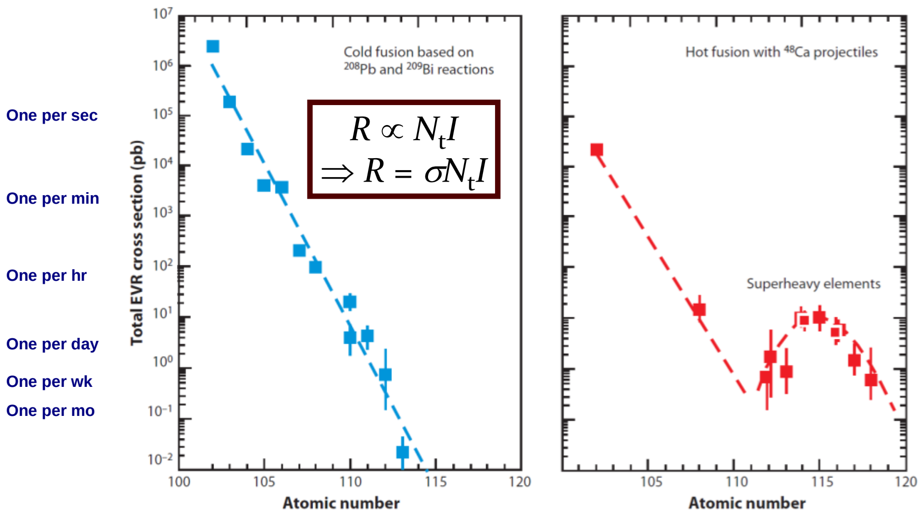
- The artificial elements bring the **total to 118**.

The Periodic Table Today

Group → / Period ↓	1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
				**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Offnfopt, Wikimedia Commons (retrieved 2019-05-19). (link)

New Element Discoveries ca. 1980-2010



J. H. Hamilton *et al.*, Ann. Rev. Nucl. Part. Sci. **63**, 383 (2013). (link)

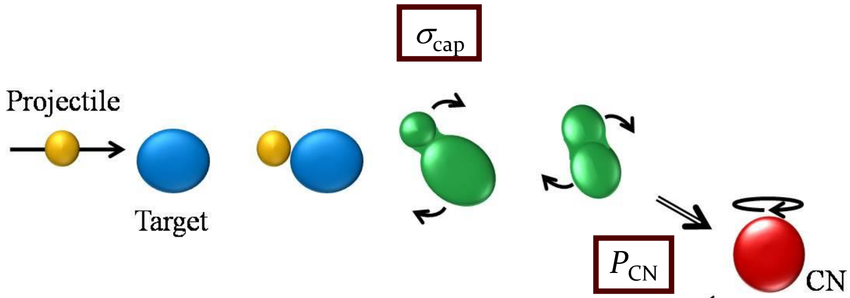
Current and Future History of Elements Above Oganesson (Z = 118)

- The problem: Targets above **Cf** are not available.
- A number of reactions have been studied using projectiles heavier than ^{48}Ca, but none have succeeded:
  - $^{58}Fe + {}^{244}Pu \rightarrow {}^{298}120 + 4n$
  - $^{54}Cr + {}^{248}Cm \rightarrow {}^{298}120 + 4n$
  - $^{50}Ti + {}^{249}Cf \rightarrow {}^{295}120 + 4n$
  - $^{50}Ti + {}^{249}Bk \rightarrow {}^{295}119 + 4n$
  - $^{64}Ni + {}^{238}U \rightarrow {}^{298}120 + 4n$

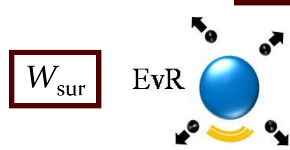
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

- The great question is, "What reaction is most likely to lead to the discovery of the next new element?"

How does the nuclear reaction proceed?



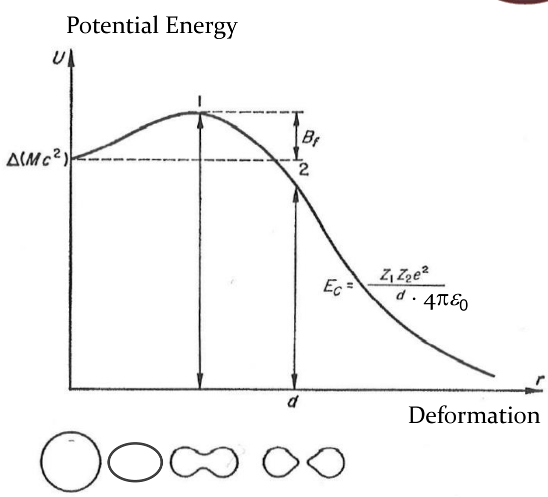
- Overall, a fusion reaction is described by:



$$\boxed{\sigma = \sigma_{cap} P_{CN} W_{sur}}$$

Fission Barrier

- The ***fission barrier*** is caused by a change in the surface and Coulomb energies at constant volume and density.
- The ***fission barrier*** is critical in determining the survival probability of a compound nucleus.



How do you make a heavy nucleus?

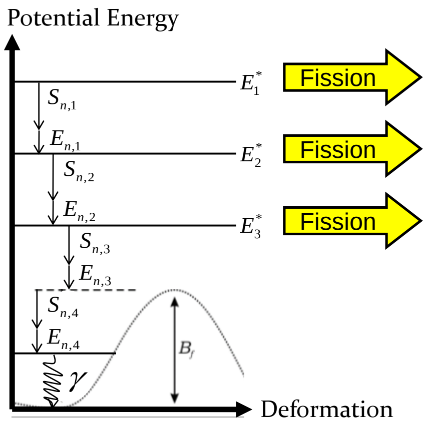
- The production of a heavy nucleus is a competition between neutron emission and fission.
- The evaporation residue cross section can be written as:

$$\sigma = \sigma_{\text{cap}} P_{\text{CN}} W_{\text{sur}}$$

$$= \sigma_{\text{cap}} P_{\text{CN}} P_{\text{xn}} \prod_{i=1}^{x} \left(\Gamma_{\text{n}} / \Gamma_{\text{tot}}\right)_i$$

$$\approx \sigma_{\text{cap}} P_{\text{CN}} P_{\text{xn}} \prod_{i=1}^{x} \left(\Gamma_{\text{n}} / \Gamma_{\text{f}}\right)_i$$

$$\boxed{\Gamma_{\text{n}} / \Gamma_{\text{f}} \propto \exp[-(S_{\text{n}} - B_{\text{f}}) / T]}$$



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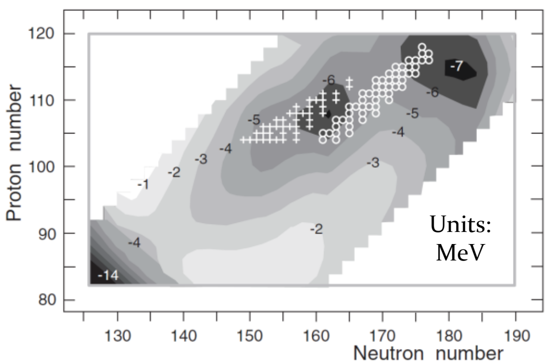
Importance of Shell Effects on the Fission Barrier

- The **known isotopes are shown as crosses and circles**. The background colors indicate the strength of *shell effects*, with more negative values being more stable.
- Our success in discovering elements may be due to proximity to strong shell effects, which increase fission barriers.

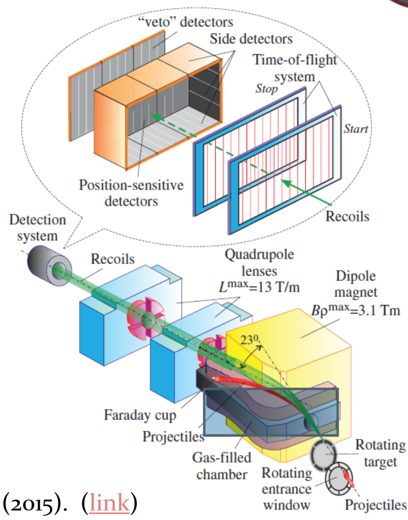


Yu. Ts. Oganessian and V. K. Utyonkov, Rep. Prog. Phys. **78**, 036301 (2015). (link)

24

How is the experiment conducted?

- We use very intense beams, rotating target wheels (to spread out the heat), and a *separator* to filter away the projectiles after the reaction. Beamtimes can last as long as one month or more.
- The separator removes the beam because exposing it to the ultra-sensitive detectors would damage them permanently.

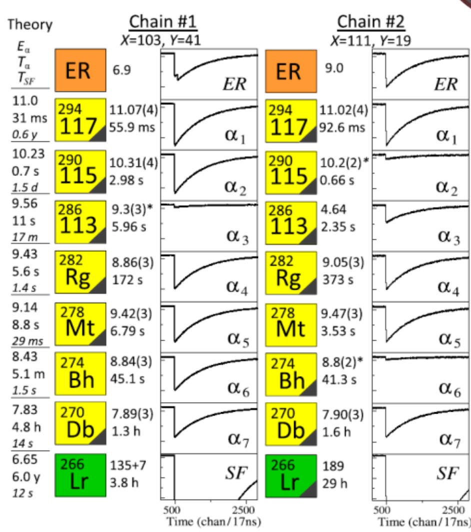


Yu. Ts. Oganessian and V. K. Utyonkov, Rep. Prog. Phys. **78**, 036301 (2015). (link)

25

How do we know when we have made one of these elements?

- We observe rare isotopes through their radioactive decay. We can observed several decays and recreate the *decay chain*, which identifies the parent nucleus definitively (sometimes).
- These decay chains confirmed the discovery of tennessine (Z = 117).



J. Khuyagbaatar *et al.*, Phys. Rev. Lett. **112**, 172501 (2014). (link)

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Criteria for a New Element

- Must exist for approximately 10^{-14} s. This is roughly the time needed for a nucleus to collect a cloud of electrons.
- The atomic number must be different from all known atomic numbers, beyond a reasonable doubt. It does *not* have to actually be determined, though.
- Physical or chemical methods can be used.
- Confirmatory experiments are preferred, although this may not be feasible.
- In reality, these criteria have not stopped arguments about who discovered what. They can last for years.

Primary Source: A. H. Wapstra, Pure Appl. Chem. **63**, 879 (1991). (link)
Modern Summary: P. J. Karol *et al*., Pure Appl. Chem. **88**, 139 (2016). (link)

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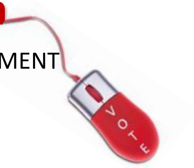
Audience Survey Question

ANSWER THE QUESTION ON BLUE SCREEN IN ONE MOMENT



The discovery of Nihonium was based on three atoms. How many days of beamtime were required to produce these three atoms?

- Less than 100
- 100-300
- 300-500
- More than 500

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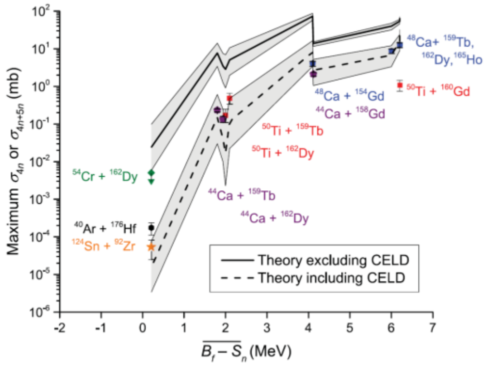
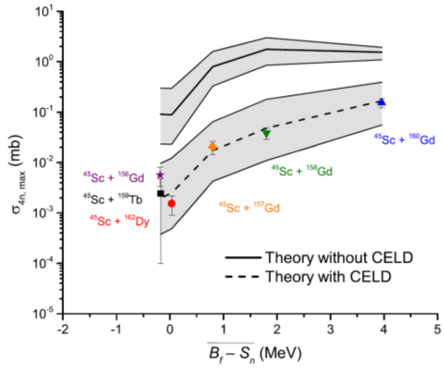
The Big Picture: ^{48}Ca versus Other Projectiles

- The left figure suggests that discovering new elements could be very difficult. The right figure suggests that ^{45}Sc is a very poor projectile for heavy element production.

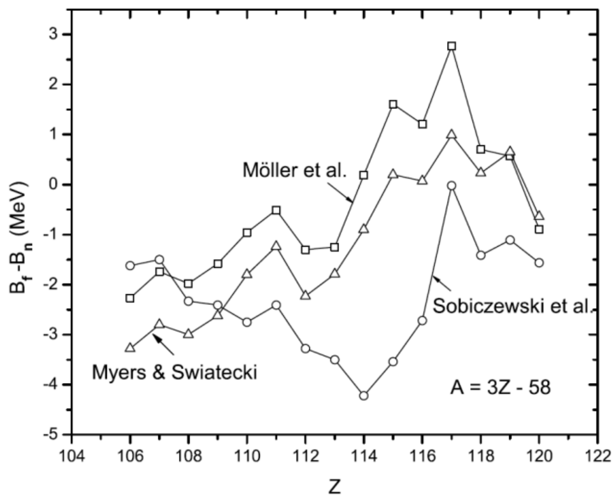




T. A. Werke *et al.*, PRC **92**, 034613 (2015); D. A. Mayorov *et al.*, PRC **90**, 024602 (2014).
D. A. Mayorov *et al.*, PRC **92**, 054601 (2015); T. A. Werke *et al.*, PRC **92**, 054617 (2015).

Dependence of $B_f - S_n$ on Model

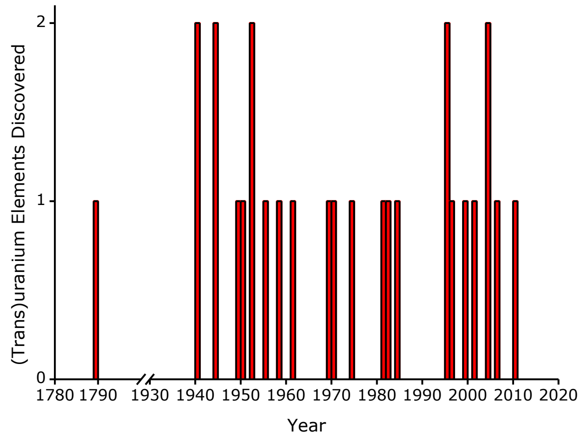
- The model in use has a dramatic impact on $B_f - S_n$.
- This has a dramatic impact on calculated cross sections.



K. Siwek-Wilczyńska *et al.*, Int. J. Mod. Phys. E **18**, 1079 (2009). (link)

Prospects for the Discovery of the Next New Element

- Element discovery has progressed in groups.
- We are likely in another period of few new elements.



Adapted from a figure by D. C. Hoffman.

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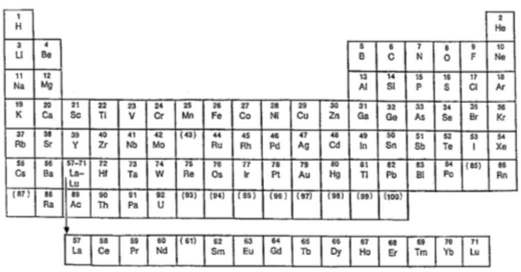
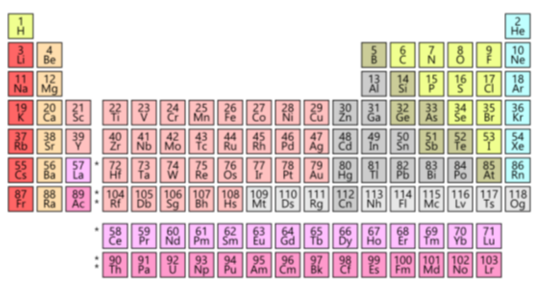
What has heavy element chemistry told us?

- The chemistry of the heavy elements has been critical to our understanding of the periodic table.
- Glenn Seaborg developed the *actinide concept*, which places certain elements in a separate *actinide series*.



Pre-World War II Periodic Table



Modern Periodic Table

Modern Table: Offnfopt, Wikimedia Commons (retrieved 2019-05-19). (link)

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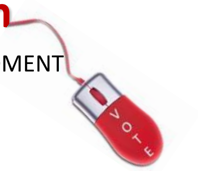

What is the most important technique for chemical investigation of the heaviest elements ($Z \geq 108$)**?**

- Laser Spectroscopy
- Standard Reduction Potentials
- X-Ray Crystallography
- Surface Adsorption Enthalpy

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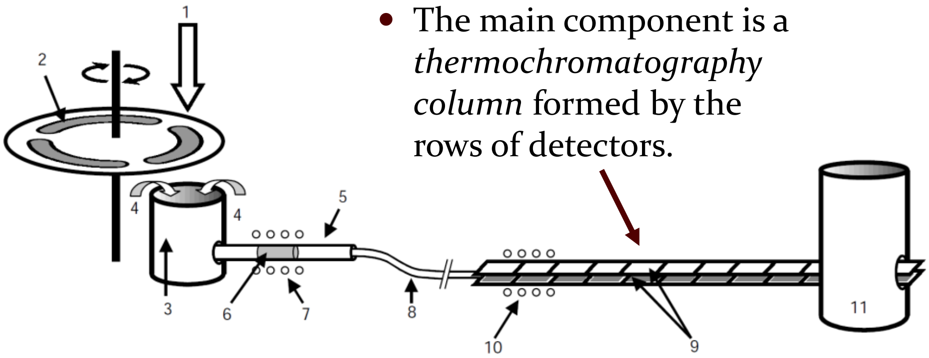
Hassium (Z = 108) Chemistry Experiment

- $^{26}Mg + ^{248}Cm \rightarrow ^{269}Hs + 5n$ (a *nuclear* reaction)
- $^{269}Hs + 2O_2 \rightarrow ^{269}HsO_4$ (a *chemical* reaction)



- The main component is a *thermochromatography column* formed by the rows of detectors.

Ch. E. Düllmann *et al.*, Nature (London) **418**, 859 (2002). (link)

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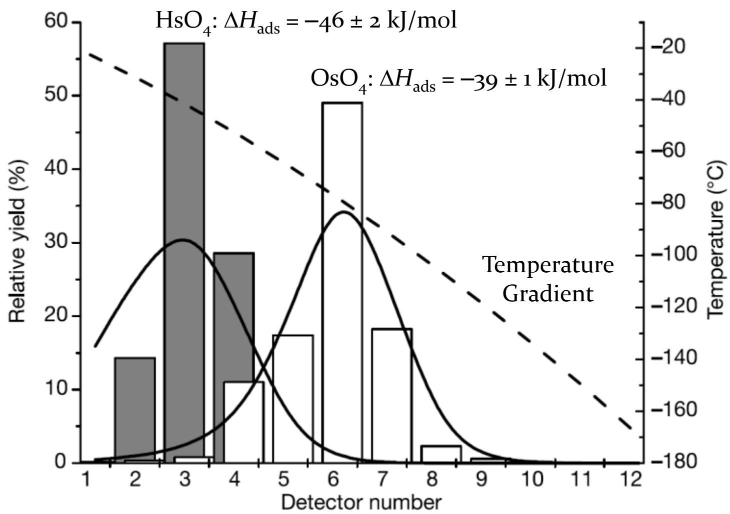
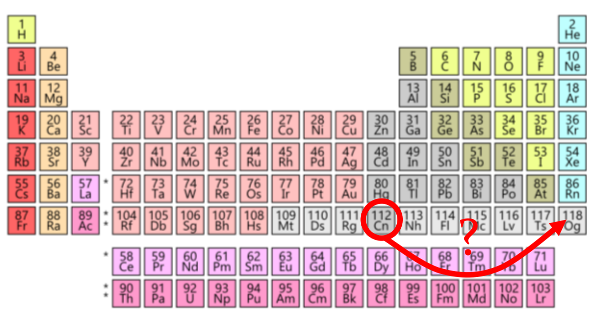
Comparison with Hassium's Lighter Homolog Osmium



Ch. E. Düllmann *et al.*, Nature (London) **418**, 859 (2002). (link)

Relativistic Effects and Copernicium (Z = 112) Chemistry

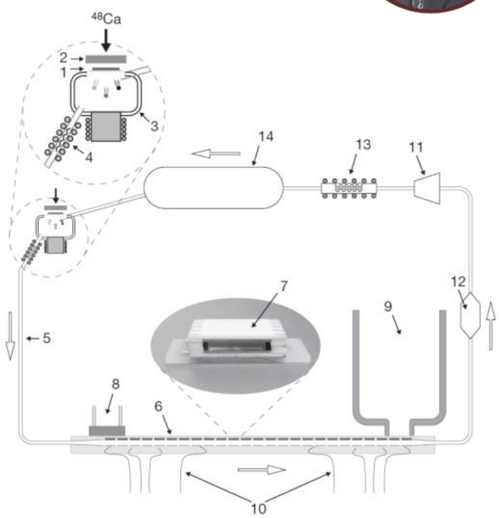
- The effect is that s and p orbitals are contracted and stabilized, while the d and f orbitals are expanded and destabilized due to *relativistic effects*.
- For Cn, this may mean that the filled $6d^{10}$ shell may behave like the filled $6s^2 6p^6$ orbitals of a noble gas.
- Does Cn behave chemically like the noble gas radon or like its periodic table homolog mercury?



K. S. Pitzer, J. Chem. Phys. **63**, 1032 (1975). (link)

Copernicium (Z = 112) Chemistry Setup

- The *nuclear* reaction is $^{48}Ca + ^{238}U \rightarrow ^{283}Cn + 3n$.
- The reaction products are stopped in a mixture of He and Ar.
- They go through a purification step into a closed-loop system with minimal oxygen and water.
- The main component is a *thermochromatography column*.



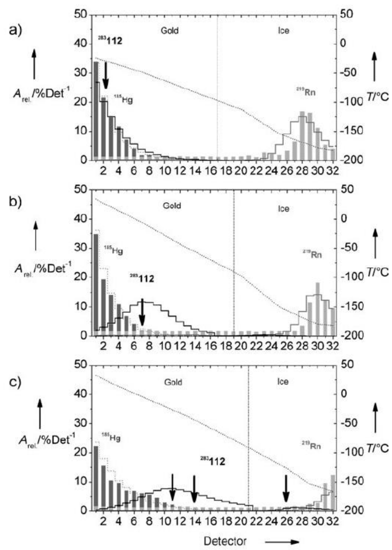
R. Eichler *et al.*, Nature (London) **447**, 72 (2007). (link)

37

Copernicium (Z = 112) Chemistry Results

- The experiment was designed to produce Cn, Hg, and Rn at the same time.
- Hg is not volatile and deposits even at high temperatures.
- Rn is volatile and only deposits at low temperatures.
- Cn was more like Hg.

R. Eichler *et al.*, Angew. Chem. Int. Ed. **47**, 3262 (2008). (link)



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Nihonium (Z = 113) Chemistry Experiment

- Dmitriev *et al*. reported a broad distribution of nihonium on room-temperature Au surfaces with $-\Delta H_{ads}$ > 60 kJ/mol.

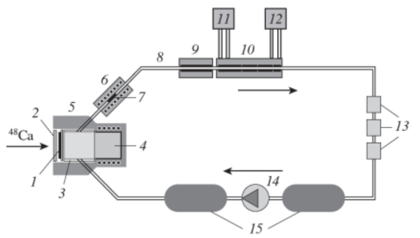

Figure 1 Schematic diagram of the experimental setup for studying the chemical properties of element 113: (*1*) ^{243}Am (1.5 mg cm^{-2}) + ^{nat}Nd (15 µg cm^{-2}) target on the backing of Ti (2 µm); (*2*) vacuum window (4 µm Ti foil); (*3*) cylindrical quartz insertion; (*4*) beam-stop with water cooling; (*5*) target chamber; (*6*) oven; (*7*) quartz filter; (*8*) transport capillary; (*9*) isothermal detector of 16 pairs of Au(Si) detectors at ambient temperature; (*10*) cryodetector of 32 pairs of Au(Si) detectors; warm end at +20 °C and cold end at −50 °C; (*11*) water thermostat; (*12*) cryothermostat; (*13*) gas purification system; (*14*) pump; and (*15*) buffer volumes.

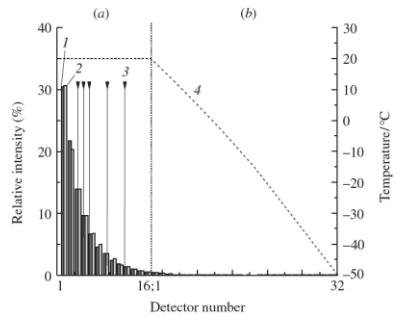

Figure 3 Distribution of (*1*) ^{185}Hg and (*2*) ^{211}At in the detector modules together with (*3*) the position of the observed decay chains attributed to ^{284}113; dashed line (*4*) represents the temperature gradient from +20 to −50 °C at (*a*) isothermal and (*b*) cryomodules of the detector.

S. N. Dmitriev *et al.*, Mendeleev Comm. **24**, 253 (2014). (link)

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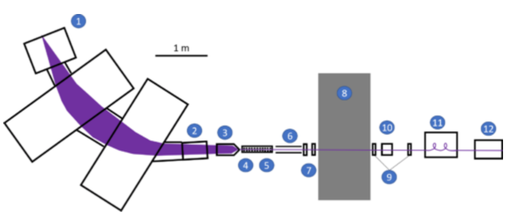
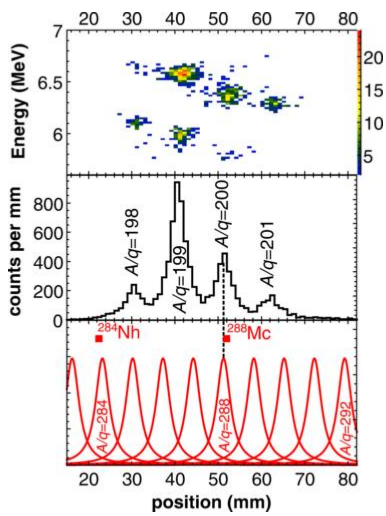
Mass Spectrometry of Moscovium (Z = 115)

- A recent experiment directly measured the mass numbers of the products of ^{48}Ca + ^{243}Am for the first time.
- The results suggested that one atom of ^{288}Mc and one atom of ^{284}Nh were detected.





J. M. Gates *et al.*, Phys. Rev. Lett. **121**, 222501 (2018). (link)

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Summary

- On the upside, many scientists believe that the compound nucleus mechanism is still viable for discovering new elements.
- On the downside, there are both theoretical and experimental challenges to discovering new elements.
- Gas-solid thermochromatography has become the primary technique for chemical characterization of the heaviest elements.
- There are still many open questions to answer!

Prof. Cody Folden
Texas A&M University
ACS NUCL
Cyclotron.tamu.edu/folden

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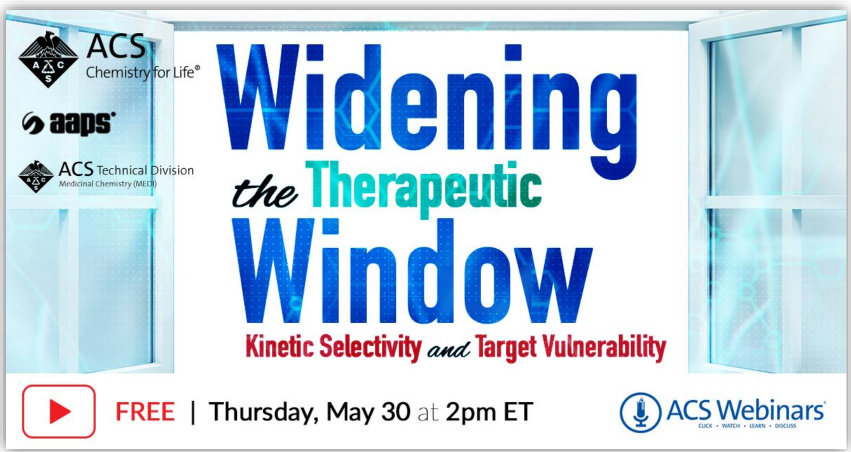

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CHEMICAL & ENGINEERING NEWS

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Exploring the superheavy elements at the end of the periodic table

These scientists want to know how elements 104 through 118 look and behave

by ***Laura Howes***

MAY 21, 2019 | APPEARED IN VOLUME 97, ISSUE 21

On a stage in the United Nations Educational, Scientific, and Cultural Organization headquarters in Paris, Yuri Oganessian holds a microphone in one hand and a small remote control in the other. Over the next 20 minutes, a hushed auditorium listens as he describes how the periodic table of elements has grown. To date, 118 elements currently populate it. The heaviest of those, oganesson, was named after Oganessian himself.

But during the talk, which took place in January at the launch of the International Year of the Periodic Table, Oganessian says, discovering the superheavy elements (SHEs) with proton numbers 104 and above has been like opening Pandora's box. Many unexpected problems have poured out, he says, some that are perhaps more difficult to solve than making SHEs in the first place. The discovery of these newer elements has prompted scientists to ask not just whether even heavier elements can be made but also what the chemical properties of the SHEs already discovered are and how to measure the properties of individual atoms of such short-lived species.

https://cen.acs.org/physical-chemistry/periodic-table/IYPT-Exploring-the-superheavy-elements-at-the-end-of-the-periodic-table/97/i21

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"The Future of the Periodic Table"

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Philadelphia, PA
March 22-26, 2020

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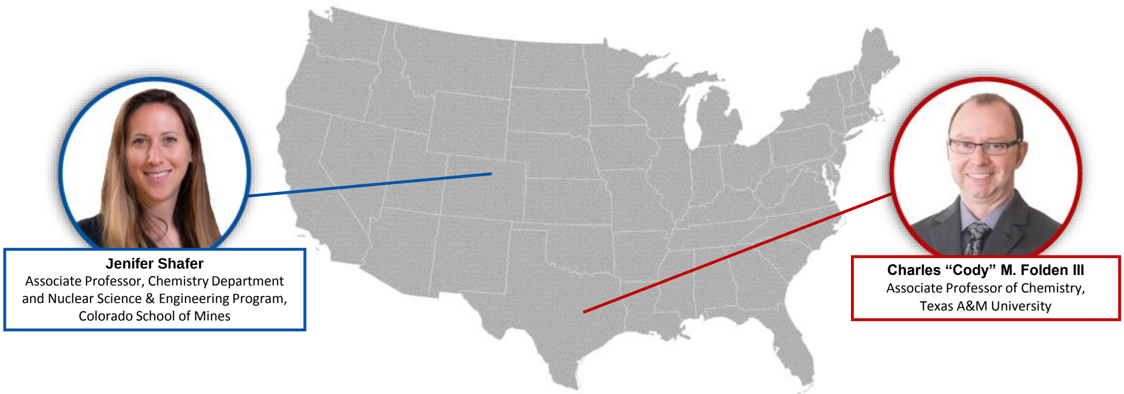

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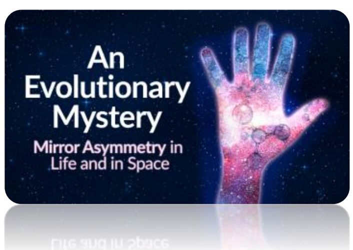
"As an undergraduate student, Brett McGuire's work has and continues to inspire and guide me along my own educational path. Thanks for taking the time to educate and motivate future scientists through events such as this!"

Fan of the Week

Megan Farrah
ACS member for 3 years strong!



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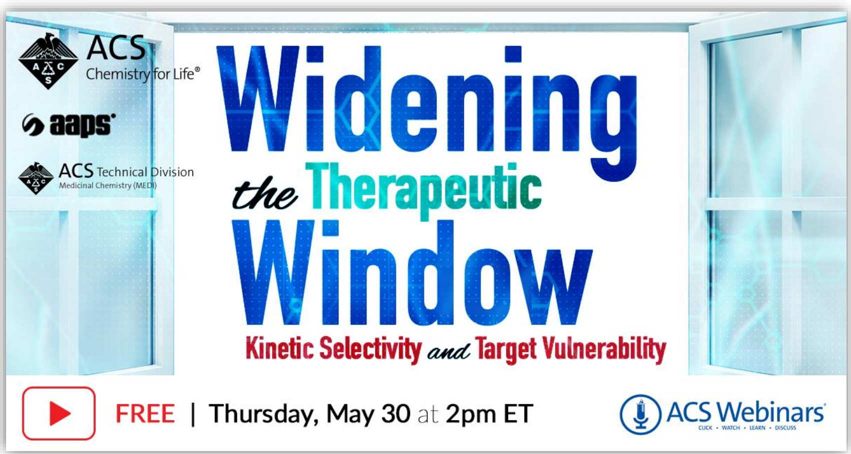

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