# **Superheavy Elements**

Jacklyn M. Gates





#### Outline

#### Lecture 1: Introduction to Superheavy Elements (SHE)

- Introduction to manmade elements
- History of element discovery
- Why study these elements

#### Lecture 2: How to Make and Detect SHE

- Theory of SHE production
- Experimental production of SHE
- **Lecture 3: Properties of SHE**
- How do we study SHE
- What can we learn about SHE





# Lecture 1: What are Superheavy Elements Why do they exist Why Study Superheavy Elements

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## Alchemy

#### al-che-my

#### noun

the medieval forerunner of chemistry, based on the supposed transformation of matter. It was concerned particularly with **attempts to convert base metals into gold** or to find a universal elixir.



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#### Mendeleev's Periodic Table from 1869

**Question**: Why is this the most famous early periodic table?

- Mendeleev wanted to organize all known elements by their chemical properties
- Noticed repeating chemical property trend as masses increased
- Orders of some elements are reversed
- Left holes and predicted properties of elements to fill those holes

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#### опытъ системы элементовъ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВЪСВ И ХИМИЧЕСКОМЪ СХОДСТВЪ.

Ti = 50 ? - 180. Zr == 90 V == 51 Ta = 182. W = 186. Cr = 52 Mo = 96Mn = 55 Rh-104,4 Pt= 197,1 Fe= 56 Rn-104.4 Ir=198. PI=106.6 0-=199. NI - Co = 59 H = 1 Cu=63,4 Ag=108 Hg=200. Cd = 112 $Be = 9_A Mg = 24 Zn = 65.2$ A1=27.1 ?=68 Ur=116 Au=197? C = 12Si - 28 ?= 70 Sn = 118N=14 Bl = 210?P-31 As-75 Sb=122 S=32 Se=79,4 Te=128? 0 = 16F=19 Cl == 35,6 Br == 80 1-127 Li = 7 Na = 23K = 39 Rb = 85 A Cs = 133TI-204. Ca=40 Sr=87. Ba=137 Pb=207. ?=45 Ce=92 ?Er=56 La=94 ?Y1=60 Di=95 ?In - 75,6 Th = 1 18?

#### Д. Мендальнаь



# Question: How many elements are known?







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#### Periodic Table: Naturally Occurring Elements



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#### Periodic Table: Manmade Elements



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# Question: Where does the periodic table end?





# Question: Where does the periodic table end?

#### What is the definition of an element?

When can we no longer make something that fits that definition





# Question: What is the definition of an element?





#### Criteria For Discovery

#### Joint IUPAC/IUPAP Report from 2018 detailing criteria used to verify claims for discovery of a new element

			1101p01// dollo16/1011j1j/
6	Crit	eria and guidelines for establishing discovery of a new element	1790
	6.1	Definition of what is a new element	1791
	6.2	Criterion of time for assigning priority of discovery	1793
	6.3	Criteria related to genetic relation	
		6.3.1 Technical criteria for establishing genetic relations	1795
		6.3.2 Physical criteria for establishing genetic relations	1796
		6.3.3 Genetic relations used for identification of elements 107 to 118	
		6.3.4 Expectations for discovery of elements 119 and 120 based on genetic relations	
	6.4	Criteria related to cross-reactions	
	6.5	Criteria related to excitation functions or yield curves	
	6.6	Criteria related to properties of heavy ion separators	
	6.7	Criteria related to precision mass measurement	
	6.8	Criteria related to characteristic X-rays and Auger electrons	
	6.9	Criteria related to systematics of experimental results and theoretical predictions	
	6.10	Criteria related to atomic physics	1813
	6.11	Criteria related to chemistry	1815
	6.12	Criteria related to statistical and experimental uncertainties	1815
		6.12.1 Errors related to cross-sections	1816
		6.12.2 Errors related to the measurement of energies, in particular $\alpha$ -energies	1816
		6.12.3 Errors related to the measurement of lifetimes	1817
		6.12.4 Probability of being true or false	1817





#### C Publicly Available Published by De Gruyter November 8, 2018

#### On the discovery of new elements (IUPAC/IUPAP Provisional Report)

Provisional Report of the 2017 Joint Working Group of IUPAC and IUPAP

Sigurd Hofmann 🖾, Sergey N. Dmitriev, Claes Fahlander, Jacklyn M. Gates, James B. Roberto and Hideyuki Sakai From the journal Pure and Applied Chemistry https://doi.org/10.1515/pac-2018-0918



#### Criteria For Discovery

'Discovery of a chemical element is the experimental demonstration, beyond reasonable doubt, of the existence of a nuclide with an atomic number *Z* not identified before, existing for at least 10<sup>-14</sup> s.'

- 10<sup>-14</sup> s ≈ time it takes for a nucleus to acquire its outer electrons and nucleus to deexcite to ground-state or isomeric state
- Discovery of an element can be based on chemical or physical methods or on both.
- The exact value of Z does not need be determined, only that it is different from all Zvalues observed before, beyond reasonable doubt.
- Neither is it required that the exact value of the mass number A be known.





# Question: What is the heaviest nuclide that meets the criteria?





Liquid Drop Model: treats the nucleus as a drop of incompressible fluid of very high density, held together by the nuclear force and gives a rough prediction of binding energy

$$m = Zm_H + Nm_n - \frac{B(N,Z)}{c^2}$$

- m =mass of an atomic nucleus with Z protons and N neutrons
- $m_{H}$  = rest mass of hydrogen
- $m_n$  = rest mass of a neutron

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- $c^2$  = speed of light in a vacuum
- B = binding energy of the nucleus

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Semi-Empirical Mass Model:  $m = Zm_H + Nm_n - \frac{B(N,Z)}{c^2}$ 

$$B(N,Z) = \mathbf{a}_{v}\mathbf{A} - a_{s}A^{\frac{2}{3}} - a_{c}\frac{Z^{2}}{A^{\frac{1}{3}}} - a_{I}\frac{(N-Z)^{2}}{A} - \delta(A)$$

 $a_v A$  = volume term: This term represents the attractive nuclear forces that act on all nucleons within the nucleus. It is proportional to the number of nucleons (A), representing the volume of the nucleus.







Semi-Empirical Mass Model:  $m = Zm_H + Nm_n - \frac{B(N,Z)}{c^2}$ 

$$B(N,Z) = a_{v}A - a_{s}A^{\frac{2}{3}} - a_{c}\frac{Z^{2}}{A^{\frac{1}{3}}} - a_{I}\frac{(N-Z)^{2}}{A} - \delta(A)$$

 $a_s A^{\frac{2}{3}}$  = surface term: This term accounts for the fact that nucleons at the surface of the nucleus experience different forces compared to those in the interior. It takes into consideration the reduction in the number of neighboring nucleons at the surface.







Semi-Empirical Mass Model:  $m = Zm_H + Nm_n - \frac{B(N,Z)}{c^2}$ 

$$B(N,Z) = a_{v}A - a_{s}A^{\frac{2}{3}} - a_{c}\frac{Z^{2}}{A^{\frac{1}{3}}} - a_{I}\frac{(N-Z)^{2}}{A} - \delta(A)$$

 $a_c \frac{Z^2}{A^{\frac{1}{3}}}$  = Coulomb term: This term represents the electrostatic

repulsion between protons in the nucleus. It is proportional to the square of the atomic number (Z) and inversely proportional to the cubic root of the number of nucleons (A).



Weizsäcker, C.F.v., Zur Theorie der Kernmassen. Z. Physik 96, 431–458 (1935). <u>https://doi.org/10.1007/BF01337700</u> H.A. Bethe and R.F. Bacher, Rev. Mod. Phys. 8, 82 (1936): <u>https://doi.org/10.1103/RevModPhys.8.82</u>.



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Semi-Empirical Mass Model:  $m = Zm_H + Nm_n - \frac{B(N,Z)}{c^2}$ 

$$B(N,Z) = a_{v}A - a_{s}A^{\frac{2}{3}} - a_{c}\frac{Z^{2}}{A^{\frac{1}{3}}} - a_{I}\frac{(N-Z)^{2}}{A} - \delta(A)$$

 $a_I \frac{(N-Z)^2}{A}$  = Asymmetry term: This term accounts for the difference in the number of protons (Z) and neutrons (N) in the nucleus. It represents the energy associated with the preference for equal numbers of protons and neutrons in stable nuclei.







Semi-Empirical Mass Model:  $m = Zm_H + Nm_n - \frac{B(N,Z)}{c^2}$ 

$$B(N,Z) = a_{v}A - a_{s}A^{\frac{2}{3}} - a_{c}\frac{Z^{2}}{A^{\frac{1}{3}}} - a_{I}\frac{(N-Z)^{2}}{A} - \boldsymbol{\delta}(A)$$

 $\delta(A)$  = Pairing term: This term accounts for the additional stabilization resulting from the pairing of nucleons with similar quantum numbers (spin and isospin).







$$B(N,Z) = a_{\nu}A - a_{s}A^{\frac{2}{3}} - a_{c}\frac{Z^{2}}{A^{\frac{1}{3}}} - a_{I}\frac{(N-Z)^{2}}{A} - \delta(A)$$

- Gives nuclear binding energies for heavy elements of ~1600 MeV (8 MeV/nucleon) → accurate to ~1%
- Highly useful for interpreting decay chains
- Issue arose when bombarding uranium with neutrons in 1939

## **Question:** what happens when <sup>235</sup>U is bombarded with neutrons?





#### <sup>235</sup>U bombarded with Neutrons

- Observed confusing decay properties not consistent with the semi-empirical mass model
- 1939: Hahn and Strassmann identify barium as one of the decay products
- 1939: Meitner and Frisch suggest fission → think of nucleus as deformable charged liquid drop that can split into two smaller nuclei





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# Question: How heavy can nuclei be before they begin to spontaneously fission?





#### Periodic Table: Naturally Occurring Elements



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#### Liquid Drop Model: When nuclei begin to fission

After discovery of fission, Bohr and Wheeler added deformation dependance to the semiempirical mass model

$$B(N,Z) = a_{v}A - a_{s}A^{\frac{2}{3}}\boldsymbol{B}_{s}(\boldsymbol{\alpha}) - a_{c}\frac{Z^{2}}{A^{\frac{1}{3}}}\boldsymbol{B}_{c}(\boldsymbol{\alpha}) - a_{I}\frac{(N-Z)^{2}}{A} - \delta(A)$$

Only Coulomb and surface energies depend on deformation!

Bohr and Wheeler showed that nucleus would instantaneously fission when  $\frac{E_c}{2E_s} > 1$ 

### **Question**: When does this begin to happen?

N. Bohr and J.A. Wheeler, Phys. Rev. 56, 426 (1939), https://doi.org/10.1103/PhysRev.56.426.





### Liquid Drop Model: When nuclei begin to fission

 $\frac{E_c}{2E_s} > 1 \rightarrow$  Instantaneously fission  $\rightarrow$  last element is ~Z=124

Z	50	82	100	102	114	124	130
А	124	208	252	254	288	306	335
$E_c/2E_s$	0.40	0.65	0.79	0.82	0.90	1.00	1.01

Remember our rules for what makes a new element?

- Must exist for >10<sup>-14</sup> s before decaying
- At  $\frac{E_c}{2E_s} > 0.8$  barrier in liquid-drop model becomes so low that nuclei fission before detection is possible  $\rightarrow$  last element around Z=100-104





- 1936: Bethe and Bacher noted that in an oscillator potential there are large gaps in the corresponding single-particle level spectrum
- Investigated to see if there were unusually large deviations between their theory and measured masses at Z=20 and N=20 (<sup>40</sup>Ca)
- Didn't see any unusually large deviations, but concluded that experimental measurements were accurate enough
- Later calculations by Wigner and Barkas supported magicity of Z=20 and N=20

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H.A. Bethe and R.F. Bacher, Rev. Mod. Phys. 8, 82 (1936): https://doi.org/10.1103/RevModPhys.8.82.





- 1948: Maria Goeppert Mayer makes the case for magic numbers beyond 20
- 1. Isotopic abundance

57 6.8 s	Lu 158 10.6 s	Lu 159 12.1 s	Lu 160 40 s 36.1 s	Lu 161 77 s	Lu 162 81 8 93 8	Lu 163 4.1 m	Lu 164 3,14 m	Lu 165 11.8 m	Lu 166 2.12 m 1.41 m 245 m	Lu 167 51.5 m	Lu 168	Lu 169	Lu 170 2.012 d	Lu 171	LU 172 3.7 m 6.70 d	LU 1/3 1:37 a	Lu 174 142 d 331 a T (58.) a	Lu 175 97.401	Lu 176 2.599 168h 3.8-1011 a	Lu 177
z 4.925 z → m	γ 358, 477 α 4.669 α → g	ε γ 151, 188, 369 α 4,419	т <u>т</u> <u>т 243.395</u> 577	к у 111, 100, 44 156, 256, 67	2 7 167, 825 726	e 9 163, 54, 396 372	6, 8° y 123, 740, 262 864, 6°	p* 7 121, 132, 174 204	1477 1477 1487 1497 1000 11 (14) = 123 1298 11 (14) = 122	30, 239, 279 13, 1267	2 7 106. 070 11 1.2. 806. 105. 104. 299 17 (2007 - 103.	17 (29) 1450 a" 0, m	8* 7 84, 1280, 2042 985	(71) 730 10 (67,78 (781 (7)	(T (42) 810 912 Vb 171	34 3 Vh 172	Vb 172	16.7 + 6.6 Inu < 6E-5	1.2 0.6. 1	
156	Yb 157 38.6 s	Yb 158 1.49 m	Yb 159 1.67 m	Yb 160 4.8 m	Yb 161 4.2 m	Yb 162 18,87 m	Yb 163 11.1 m	Yb 164 75.8 m	Yb 165 9.9 m	Yb 166 56.7 h	YD 167 17.5 m	0.126	46 s 32018 d	Yb 170 3.023	14.216	21.754	16.098	31.896	YD 175 4.185 d	Yb 176 11.4 s 12.887 6
12	γ 23, 242, 231 164, 339 α 4.51	ε. β* γ 74 α 4.065	r y 166, 177, 390 330	p* 0.9, 1.1. - 174, 216, 140. - 9	в р* у 78, 600, 631	р* 163, 119 9	μ* 2.4 γ 880, 64, 123	y (41, 675) e* g	ε β* 1.6 γ 80, 69, 1090	182.0	7 113, 106 176	o 3033 m <sub>n.e</sub> < 0.0001	(T (24) 110_ #" 110_ # 3800	6 10.2 dnu < 1.0E-5	or 58.8 onu < 1.5E-6	σ 1.3, σ <sub>θ.s</sub> < 1E-6	σ 15.5, σ <sub>%e</sub> < 1E-6 Trn 172	± 63, an.a < 2E-5	396, 283	106 #2.85 # 293, 389 #4.8 90, 82, 6* 415-6 *
155	Tm 156 83.8 s	Tm 157 3.63 m	Tm 158 -20 ms? 3.98 m	Tm 159 9.13 m	Tm 160 74.5 s 9.4 m	Tm 161 30.2 m	Tm 162 24.3 ± 21.70 m	Tm 163 1.810 h	Tm 164 51m 1.95m	30,06 h	7,70 h	9.25 d	93.1 d	100	128.6 d p-10	1.92 a	63.6 h p 1.8, 1.9, 7 79, 1094	8,24 h	2.29 s 5.4 m	15.2 m
1 227 53 88 . 0 1 4.452 1 - 9	<sup>2</sup> γ 345, 453 586 α 4.232, α → g	β* 7 455, 386, 348 110, 357	1 192, 335 1150 (17) 628.	6   1* 3.0 1 38, 85, 271 289, 220	1 42 4 1 1 4 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	ε β* 1.8 γ 46, 1648, 84	y 67,4- 0,00 102,000 12,000	0* v 104, 69, 241 1434, 1397	1000 1155 115 769 8	243, 47, 297 807	779,2052 184,1274	v 67, 532 er m	Er 167	a 107	a 92 Er 169	r (67), e <sup>-</sup> e -160 Er 170	1387, 1530 1466, 1609 Er 171	Er 172	T 152, er 1386, 940 100, er 273, 177	515,941 3 364 9 Fr 174
154 9 m	Er 155 5.3 m	Er 156 19.5 m	Er 157 18.65 m	Er 158 2.29 h	Er 159 36 m	Er 160 28.58 h	Er 161 3,21 h	Er 162 0.139	75.0 m	1.601	10.36 h	33.503	2,200 6 22,669	26.978	9.392 d 8- 0.4	14.910	7.516 h 8-1.1, 1.5_ 7 308, 296, 112	49.3 h	1.4 m	3.2 m
	y 110, 242 234, e* u 4.012	e 7 35, 30, e* m	β* 2.3 y 53, 391, 121 150, 67, e*	e", 72, 387, 249. e", mi	p* 1.1 + 624, 649 g, m	е у 7	₽* 9 827 9. m	ซ 19 ซ <sub>กม</sub> < 0.011	y (1114) g	σ 13 σ <sub>n.a</sub> < 0.0012	no y Ho 164	a 15.0 + 1.9 an.: < 7E-5 Ho 165	17 208 <b>7649</b> 17 208 <b>7649</b> 11 100 166	a 2.74, anu 9E-5	Y (8, 110) Ho 168	<b>48.15</b> Ho 169	124e # 280 Ho 170	рг 0.3, 0.9. у 610, 407. Но 171	Ho 172	Ho 173
153 201 m	Ho 154	Ho 155 48 m	Ho 156	Ho 157 12.6 m	Ho 158	HO 159 8.30 s 33.05 m	HO 160 3.2 ± 5.02 ± 256 m (T T (P0)	HO 101 6.76 s 2.48 h	67.5 m 17 (10) # 138, 55	1.09 s 4570 a	36.6 m 28.8 m	100	1132.6 a 26.824 h pr 0.07 C3. pr 1.8	3.1 h	132 s 2.99 m	4.6 m β= 1.2, 2.0	43 s 2.76 m p <sup>+</sup> 4.0_ 8 <sup>+</sup> 1.7 + 812 3.3_ 1894, 79 + 258	53 s β	25 s	6.9 s
290,63 589 x 3.910 x - m	7 0' 0' 0 3.72 0 3.937 1 335, 412 1 335, 412 477 873	ε β* 2.1 γ 240, 136	7566 766  17 (52) 7 9 138	β* 1.2, 1.5 γ 280, 341, 193 87, 61, e*	25 F. 10 50 255 F. 15 50 255 F. 15 50 1451 F. 15 50 1451 F. 15 50	17 206. P. 121, 13 100, 250	51, 51, 51, 51, 51, 51, 51, 51, 51, 51,	IT 211, e 78	Dy 161	Dy 162	Dv 163	σ 3.5 + 60.9 σ <sub>n.a</sub> < 2E-5 Dv 164	Dy 165	y 347, 321 g. m Dv 166	17 (59) or 818 Dy 167	y 788, 853, 761 778 Dy 168	1973. 932 182 890_ Dy 169	7 903, 199, 279 532, 907 Dy 170	y 134, 178, 757 291 Dy 171	Bn? Dy 172
152 3 h	Dy 153 6.4 h	Dy 154 3.0·10 <sup>6</sup> a	Dy 155 9.9 h	Dy 156 0.056	B.14 h	0.095	144.4 d	2.329	18.889	25.475	24.896	28.260	1.257 m 2.334 h IT 108, er pr 1.3 pr 0.9 y 95 1.0	81.5 h 51.5 h	6.2 m p- 1.8, 2.0	8.7 m γ 193, 487, 443	78.0 s	55 s	4.1 s	3.94 s
	1 81, 214, 100 254	a 2.87	ε β=0.9, 1.1 γ 227	σ 33 σ <sub>n.s</sub> < 0.009	ς, β* 7 326	ი 43 ი <sub>ია</sub> < 0.006	y 58, e-	a 55	σ 600, σ <sub>n,u</sub> < 3E-5	σ 194 Tb 161	σ 134, σ <sub>h,s</sub> < 2E-3	5 σ 1610 + 1040 Tib 163	7 515 2000 = 3600 Th 164	g Th 165	y 570, 259, 310 259 Tb 166	g Tb 167	βn? Tb 168	⊮ Tb 169	p- Tb 170	Bn? Tb 171
151 17.609 h	Tb 152 42m 17.5h	Tb 153 2.34 d	Tb 154 227 h 8994 # 21.5	Tb 155 5.32 d	TD 156 \$3h 244h 535t (T 88	10 157 71 a	10.70 s 180 a	100	72.3 d β- 0.6, 1.7	6.89 d	7.76 m	19.5 m 8- 0.8, 1.3	3.0 m 8- 1.7, 3.7	2,11 m β=2,1 γ 1179, 539	25.1 s	19.4 s	8.2 s	5.13 s	960 ms 7790, 1169	1.24 s
2.41 252.28 108	285 10 10 1344, 27 144 554 411?	τ, β* 7,212, 110, 102 170, 83	1991	v 87, 105, 180 262	с нт 199 112 у 50 1222	ι γ (54), e <sup>-</sup>	(T (110) 00 e-	o 23.8	966 o 570	γ 26, 49, 75 e <sup>-</sup>	7 260, 808 888	y 351, 390 494 Gd 162	9 169, 755, 215 688, 611	1292, 1665 m. g Gd 164	7 173, 1040 857, 781 Gd 165	β <sup>-</sup> y 70, 57 Gd 166	97 7 173, 227, 75 Gd 167	Gd 168	Gd 169	Gd 170
150 10 <sup>6</sup> a	Gd 151 120 d	Gd 152 0.20 1.08/10 <sup>14</sup> a	Gd 153 240.4 d	Gd 154 2.18	Gd 155 14.80	Gd 156 20.47	Gd 157 15.65	24.84	18.479 h	21.86	3.66 m β <sup>-</sup> 1.6, 1.7	8.2 m	68 s	45 s	10.3 s	4.8 s 8-	4.26 s	3.03 s	750 ms	410 ms
	u 2.60 y 154, 243 175	a 2.147, a 755 ans 0.007	y 97, 103, 70 o 22460 ana 0.033	σ 85	σ 60330 σ <sub>nu</sub> 8E-5	σ 1.8	σ 254000 σ <sub>п.α</sub> 0.00055	σ 2.22	β <sup>-</sup> 1.0 γ 364, 58	σ 1.4	102 σ 19000	β-1.0 γ 442, 403 Ευ 161	y 288, 214 1562, 1685 Fu 162	Fg 163	β- 7 50 Fu 164	y 1016, 976 536 Eu 165	β- βn? Eu 166	Bn? Eu 167	Eu 168	pr pn? Eu 169
149 1 d	Eu 150	Eu 151 47.81	Eu 152 96 m 9.312 h 13.517	Eu 153 52.19	Eu 154 46.0 m E.601 a # 0.5, 1.5	Eu 155 4.753 a	Eu 156 15.19 d	Eu 157 15.18 h	EU 158 45.9 m	18.1 m	30.8 s 42.6 s β-2.4 3.4	26 s	10.6 s	7.7 s	4.15 s	2.3 s	1.7 s	1.33 s	200 ms	>247 ns
77	17 7 334 7 334 439 407 584	σ 4.0 + 3310 + 5920	17 40 6 642 42 7 92 92 44 1364 6 1364 1364	σ 312, σn.s 1E-	17 (9), e <sup>-</sup> 723, 127           γ 58         6', 6           1010         1445	β <sup>-</sup> 0.15, 025 γ 87, 105 σ 3950	β <sup>-</sup> 0.5, 2.4 γ 812, 89 1231	p 1.3, 1.4 y 64, 411, 371 55, 619, e	р 2.4, 3.4 у 944, 977, 898 80, 1108 е	γ 68, 79, 96 146, 665	β- 2464 516, 41 1302 822	3 β- γ72-314	β <sup>-</sup> 771, 165 Sm 161	sm 162	β <sup>-</sup> γ 169, 73 Sm 163	β- Sm 164	y 161, 70 jln? Sm 165	Bn? Sm 166	Bn? Sm 167	107 3.40E-7
148 25	Sm 149 13.82	Sm 150 7.37	Sm 151 94.7 a	Sm 152 26.74	Sm 153 46.284 h	Sm 154 22.74	Sm 155 22.18 m	9.4 h	Sm 157 8.03 m	5.30 m	11.37 s	9.6 s	4.8 s	2.4 s	1.23 s	1.43 s	980 ms	800 ms	>247 ns	4.18E-5
	σ 40140 σ <sub>0.0</sub> 0.0307	σ 100	β <sup>-</sup> 0.1 γ (22), e <sup>-</sup> α 15140	σ 206	β <sup>-</sup> 0.7, 0.8 γ 103, 70, e <sup>-</sup> σ 420	σ 8.5	β 1.5, 1.6 γ 104, 246 141	β <sup>+</sup> 0.7 γ 88, 204, 166. e <sup>-</sup>	β 2.6, 2.8 γ 198, 196, 394 121, 1463	y 189, 364, 325 324, 321	5 γ 190, 862, 254 797, 179	4 β- γ 110	β- 7 264	β <sup>+</sup> 736,741,737 Pm 161	β- βn? Pm 162	β <sup>*</sup> βn? Pm 163	β- βn? Pm 164	β <sup>-</sup> βn? Pm 165	002 002	106
147	Pm 148	Pm 149	Pm 150	Pm 151	Pm 152	Pm 153	Pm 154	Pm 155	Pm 156	Pm 157	Pm 158	Pm 159	725 ms	.05 ms	630 ms	430 ms	>247 ns	>247 ns	1 98E	9.31E-5

Mayer, Phys. Rev. **74** (1948) 235: <u>https://doi.org/10.1103/PhysRev.74.235</u>

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- 1948: Maria Goeppert Mayer makes the case for magic numbers beyond 20
- 1. Isotopic abundance: Isotopes with *Z*>32 and abundance >60%



Lightest isotopes of an elements with Z>32 and isotopic abundance >2%



Mayer, Phys. Rev. 74 (1948) 235: https://doi.org/10.1103/PhysRev.74.235





- 1948: Maria Goeppert Mayer makes the case for magic numbers beyond 20
- 1. Isotopic abundance
- 2. Number of isotones
- *N*=82 neutrons has 7 stable isotones
- *N*=50 has 6 stable isotones
- Almost all other values of N have <4 isotones</li>

Eu 151 47.81

Sm 150



31

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Mayer, Phys. Rev. 74 (1948) 235: https://doi.org/10.1103/PhysRev.74.235

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- 1948: Maria Goeppert Mayer makes the case for magic numbers beyond 20
- 1. Isotopic abundance
- 2. Number of isotones
- 3. Number of stable odd-Z isotopes
  - Most neutron numbers have one odd Z isotone
  - Exception are *N*=20, *N*=50 and *N*=82



32

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Mayer, Phys. Rev. 74 (1948) 235: https://doi.org/10.1103/PhysRev.74.235





- 1948: Maria Goeppert Mayer makes the case for magic numbers beyond 20
- 1. Isotopic abundance
- 2. Number of isotones
- 3. Number of stable odd-*Z* isotopes
  - Most neutron numbers have one odd Z isotone
  - Exception are N=20, N=50 and N=82

Arguments for N=50, 82 being magic numbers

- Similar arguments used to justify magic numbers of:
- Z=20, Z=50, Z=82, and N=126
- Number of stable isotopes, energy of radioactive decay, abundances, neutron absorption cross sections, location of delayed neutron emitters

Mayer, Phys. Rev. 74 (1948) 235: https://doi.org/10.1103/PhysRev.74.235



#### Development of the Single Particle Model

- 1950: modern single-particle model was developed
- Showed large gaps at nucleon numbers where there were large deviations between semi-empirical mass model and measured masses (aka: magic numbers)
- Agreed with some observed ground-state spins
- Did not explain spin for large portions of the nuclear chart, specifically nuclei with large quadrupole moments → nuclei can be deformed??

Mayer, Phys. Rev. **75** (1949) 1969: <u>https://doi.org/10.1103/PhysRev.75.1969</u> Mayer, Phys. Rev. **78** (1950) 16: <u>https://doi.org/10.1103/PhysRev.78.16</u> Mayer, Phys. Rev. **78** (1950) 22: <u>https://doi.org/10.1103/PhysRev.78.22</u> Rainwater, Phys. Rev. **79** (1950) 432: <u>https://doi.org/10.1103/PhysRev.79.432</u>







Who first predicted the existence of superheavy elements?





Gertrud Scharff-Goldhaber mentions the possibility of a stable region centered at Z=126 [Nucleonics **15** (1957) 122]

- Later theoretical papers say next proton magic number could be:
- Z=126: Myers and Swiatecki, Nucl. Phys. A 18 (1966) 1, <u>https://doi.org/10.1016/0029-</u> <u>5582(66)90639-0</u>



#### Shell correction to macroscopic masses as function of the neutron number N

39

July 9, 2023

 Z=114: Sobiczewski: Phys. Lett. 22 (1966) 500, <u>https://doi.org/10.1016/0031-</u> <u>9163(66)91243-1</u>

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- Z=126: Myers and Swiatecki, Nucl. Phys. A 18 (1966) 1, <u>https://doi.org/10.1016/0029-</u> <u>5582(66)90639-0</u>
- Z=114: Sobiczewski: Phys. Lett. 22 (1966) 500, <u>https://doi.org/10.1016/0031-</u> <u>9163(66)91243-1</u>

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#### 7.8. SUPER-HEAVY NUCLEI

In our mass formula we have included, for purposes of illustration, magic numbers at Z = 126 and N = 184, 258 – see fig. 19. (The latter numbers are obtained by following the sequence of major shells in a harmonic oscillator potential with spinorbit coupling). We do not wish to imply that there are grounds for believing that any of these magic numbers would show up in practice, and we use them only to illustrate what some of the consequences would be if a magic number turned out to be present in the general neighbourhood of super-heavy nuclei somewhat beyond the end of the periodic table. The actual values of the magic numbers might be different; for example, we have recently learned <sup>23</sup>) that Z = 114, N = 184 is a possible candidate for a doubly magic nucleus (see also p. 269, ref. <sup>24</sup>)). What we wish to point out is that if a (doubly) magic number exists then an important consideration affecting the possible stability of the corresponding nucleus is the considerable increase in the barrier against fission and, consequently, in the spontaneous fission half-life. This is illustrated in fig. 2 where we have plotted the deformation energy predicted by our mass formula for the case Z = 126, N = 184. This nucleus has a fissility parameter x = 1.05; as a result, in the absence of shell effects, it would have a vanishing barrier against fission and a spontaneous fission half-life of the order of nuclear collective oscillations or  $10^{-22}$  sec. Because of the assumed doubly magic

July 9, 2023 40

#### Seaborg's Map of the Isotopes



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View until ~1967:

- Actinide peninsula ends around Z=102-104
- Next magic number Z=114 or Z=126 and N=182
- No observable elements
  would exist after Rf →
  needed to "jump" or sail
  across a sea of instability
  to reach Z=114



#### Introduction of Deformed Shells

# 1967: Strutinsky introduces method that combines macroscopic liquid-drop model and single particle model

1.D.2

Nuclear Physics A122 (1968) 1-33; C North-Holland Publishing Co., Amsterdam

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#### **"SHELLS" IN DEFORMED NUCLEI**

#### V. M. STRUTINSKY

I.V. Kurchatov Institute of Atomic Energy, Moscow, USSR and The Niels Bohr Institute, University of Copenhagen, Denmark

> Received 17 July 1967 Revised 17 May 1968

Abstract: New calculation results based on the shell correction method are described. The results are presented in such a way as to illustrate more clearly many effects of nucleon shells in deformed and spherical nuclei. Some complementary theoretical arguments related to the shell correction method and details of the calculation are given.

P. Möller, A.J. Sierk, T. Ichikawa, H. Sagawa, At. Data Nucl. Data Tables 109–110,1 (2016). V.M. Strutinsky, Nucl. Phys. A 95, 420 (1967). <u>https://doi.org/10.1016/0375-9474(67)90510-6</u> V.M. Strutinsky, Nucl. Phys. A 122, 1 (1968). <u>https://doi.org/10.1016/0375-9474(68)90699-4</u>

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#### Introduction of Deformed Shells

- 1967: Strutinsky introduces method that combines macroscopic liquid-drop model and single particle model
- Is able to reproduce known spherical shells and "low-density" regions of single particle states in deformed nuclei → deformed shells

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Fig. 1. Qualitative picture of the distribution of the single-particle states in the deformed nucleus. The low-density regions (shells) are shown by circles. Arrows on the energy axis show where transitions between sphericity and non-sphericity occur.

P. Möller, A.J. Sierk, T. Ichikawa, H. Sagawa, At. Data Nucl. Data Tables 109–110,1 (2016). V.M. Strutinsky, Nucl. Phys. A 95, 420 (1967). <u>https://doi.org/10.1016/0375-9474(67)90510-6</u> V.M. Strutinsky, Nucl. Phys. A 122, 1 (1968). <u>https://doi.org/10.1016/0375-9474(68)90699-4</u>





#### Introduction of Deformed Shells

- 1967: Strutinsky introduces method that combines macroscopic liquid-drop model and single particle model
- Is able to reproduce known spherical shells and "low-density" regions of single particle states in deformed nuclei → deformed shells
- Modern-day single-particle levels vs nuclear shape show plethora of deformed shells

P. Möller, A.J. Sierk, T. Ichikawa, H. Sagawa, At. Data Nucl. Data Tables 109–110,1 (2016).
V.M. Strutinsky, Nucl. Phys. A 95, 420 (1967). <u>https://doi.org/10.1016/0375-9474(67)90510-6</u>
V.M. Strutinsky, Nucl. Phys. A 122, 1 (1968). <u>https://doi.org/10.1016/0375-9474(68)90699-4</u>





44

July 9, 2023

#### Seaborg's Map of the Isotopes



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1968: Deformed shells allow for nuclides that 'bridge the gap' between actinide peninsula and the magic island

July 9, 2023 [45]



#### Modern Macroscopic-Microscopic Mass models

Top: difference between experimental mases and calculated masses from macroscopic liquid-drop model

Middle: microscopic corrections calculated using Strutinsky's methods

**Bottom: difference** 



July 9, 2023

46

P. Möller, A.J. Sierk, T. Ichikawa, H. Sagawa, At. Data Nucl. Data Tables 109–110,1 (2016).

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When was the first manmade element discovered?





#### **Towards Man-made Elements**

- First linac built in 1928 by Rolf Wideroe as part of his Ph.D. thesis
- First cyclotron invented in 1930 by E.O. Lawrence and M.S. Livingston at UC Berkeley







#### First Discovery of a Man-made Element!

SEPTEMBER, 1937

JOURNAL OF CHEMICAL PHYSICS

VOLUME 5

July 9, 2023

49

#### Some Chemical Properties of Element 43

C. PERRIER AND E. SEGRÈ, Royal University, Palermo, Italy (Received June 30, 1937)

#### 1. INTRODUCTION

**P**ROFESSOR E. O. LAWRENCE gave us a piece of molybdenum plate which had been bombarded for some months by a strong deuteron beam in the Berkeley cyclotron. The molybdenum has been also irradiated with secondary neutrons which are always generated by the cyclotron. The molybdenum plate shows a strong activity, chiefly due to very slow electrons. The

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radioactivity is due to more than one substance of a half-value period of some months and to the radioactive phosphorus isotope P<sup>32,1</sup> The substance was sent from Berkeley on December 17, 1936 and we started our chemical investigation on January 30, 1937; all short period substances have decayed in these 6 weeks and we could



<sup>&</sup>lt;sup>1</sup> We will give more details on the radioactive side of this investigation in a later paper to appear in the *Physical Review*.

#### First Transuranic Discovery

1937: Meitner, Hahn & Strassmann irradiated <sup>nat</sup>U foils with neutrons and identified the following non-recoiling activities, but were unable to make elemental identifications

1. 
$$U + n \longrightarrow \frac{10''}{92}U \longrightarrow \frac{\beta}{93}^{2,2'}Eka \operatorname{Re} \longrightarrow \frac{\beta}{94}^{59'}Eka \operatorname{Os} \longrightarrow \frac{\beta}{94}^{66 h}Eka \operatorname{Ir} \longrightarrow \frac{\beta}{96}^{2,5 h}Eka \operatorname{Pt} \longrightarrow \frac{\beta}{97}^{7}Eka \operatorname{Au} ?$$
  
2.  $U + n \longrightarrow \frac{40''}{92}U \longrightarrow \frac{\beta}{93}^{16'}Eka \operatorname{Re} \longrightarrow \frac{\beta}{94}^{5,7 h}Eka \operatorname{Os} \longrightarrow \frac{\beta}{95}^{5}Eka \operatorname{Ir} ?$   
3.  $U + n \longrightarrow \frac{23'}{92}U \longrightarrow \frac{\beta}{93}^{8}Eka \operatorname{Re} ?$ 

Meitner, Zeits. F. Physik **106** (1937) 249: <u>https://doi.org/10.1007/BF01340321</u> McMillan, E. Phys. Rev. **55** (1939) 510: <u>https://doi.org/10.1103/PhysRev.55.510</u> McMillan, E. Phys. Rev. **57** (1940) 1185: <u>https://doi.org/10.1103/PhysRev.57.1185.2</u>



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#### First Transuranic Discovery

1939: McMillan irradiated <sup>nat</sup>U foils with neutrons and caught recoiling nuclei on stacks of cigarette paper – isolated 23-min <sup>239</sup>U and watched growth of 2.3-day <sup>239</sup>93



FIG. 1. Growth of 2.3-day  $93^{239}$  from 23-minute  $U^{239}$ . The points indicate the activities of successive fluoride extractions, plotted at the times of extraction. Decay measurements were made a day later on the first six fractions, and the resulting slopes are shown on the plot.

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Meitner, Zeits. F. Physik **106** (1937) 249: <u>https://doi.org/10.1007/BF01340321</u> McMillan, E. Phys. Rev. **55** (1939) 510: <u>https://doi.org/10.1103/PhysRev.55.510</u> McMillan, E. Phys. Rev. **57** (1940) 1185: <u>https://doi.org/10.1103/PhysRev.57.1185.2</u>



#### History of Element Discovery

First transuranic element identified 1940

- Kicked off 8+ decades of new element discoveries
- 26 transuranic elements discovered to date







#### Latest Elements Discovered



For Release 8 June 2016

#### INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

## 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.

87	88	89-103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
Fr	Ra		Rf	Db	Sq	Bh	Hs	Mt	Ds	Rg	Cn	Nh	FI	Мс	Lv	Ts	Oq
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]

6 new elements discovered in the last 2 decades









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1

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#### Chart of the Nuclides: 2019





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# Question: Why Study Superheavy Elements?





#### Why Study New Elements: Understanding Origins

Do these elements exist somewhere in the universe, even for just fractions of a second?

Are there long-lived isotopes formed in neutron star mergers?

What are the limits of nuclear stability?







#### Periodic Table Origins



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#### Why study new elements: Relativistic Effects

Where does the periodic table break down?

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#### Why study new elements: Relativistic Effects

- caused by the mass increase in electrons with large average speed.
- Increase approximately by Z<sup>2</sup>
- can lead to strong deviations between observed chemical properties and values derived from "classical extrapolations" along the periodic table



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Velocity of 1s electron:  $v_e \sim Zc/137$ 

Relativistic mass of electron:

$$m_{rel} = \frac{m_e}{\sqrt{1 - (v_e/c)^2}}$$

Relativist bohr radius:

$$\frac{a_{rel}}{a_0} = \sqrt{1 - (v_e/c)^2}$$
For Og (Z=118)  $\rightarrow v \approx 0.86c$ 
 $m_{rel} \approx 1.97m_e$ ,  $a_{rel} \approx 0.51a_0$ 

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#### Why study new elements: Relativistic Effects

Electron Orbital Energy (eV)



Desclaux: At. Data Nucl. Data Tables, 12 (1973) 311

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Change in orbital

energy  $\rightarrow$  change

in chemistry

# **Question**: What applications exist for manmade elements?







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	Actinide Series	90 Th Thorium 232.038	91 Paa Protectinium 231.036 92 U U Uranium 238.029	93 Np Neptuniur 237.048	94 Pu Plutoniun 244.064	95 Americiu 243.061	96 <b>Crr</b> Curium 247.070	97 <b>Bk</b> Berkeliur 247.070	98 Cf Californiu 251.080	99 Es Einsteiniu [254]	100 <b>F n</b> 57.09	101 Mendelev 258.1	102 Nobeliu 259.10	103 Lewrenci [262]	ium
	Smoke	e Det	ector	SPromethiu 144.913	62 Sm Samarium 150.36	63 Europiur 151.964	64 Gadolinit 157.25	65 Tb Terbium 158.925	66 Dy Dysprosiu 162.500	67 HO Holmiun 164.930	68 Erbiun 167.25	69 <b>T m</b> 59 Thuliun 168.93	70 Yb Ytterbiu 173.055	71 Lu m 5 174.96	m 7
		SPA .			108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 DS Darmstadtium [281]	111 Rg Roentgenium [280]	112 Copernicium [285]	113 Nh Nihonium [286]	114 Flerovium [289]	115 Mc Moscovium [286]	116 Lv Livermorium [293]	117 TS Tennessine [294]	118 Og Oganesso [294]
				H.	76 <b>OS</b> Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 TI Theilium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Polonium [208.982]	85 At Astatine 209.987	86 <b>Rn</b> Radon 222.018
		K. AVER	Ch	1	44 Ru Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 Pd Palladium 106.42	47 <b>Ag</b> Silver 107.868	48 <b>Cd</b> Cadmium 112.414	49 In Indium 114.818	50 <b>Sn</b> 118.711	51 <b>Sb</b> Antimony 121.760	52 Te Tellurium 127.6	53 Iodine 126.904	54 Xe Xenon 131.294
		-			26 Fe Iron 55.845	27 <b>Co</b> Cobalt 58.933	28 Ni Nickel 58.693	29 Cu <sub>Copper</sub> 63.546	30 <b>Zn</b> Zinc 65.38	31 Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 <b>Se</b> Selenium 78.971	35 Br Bromine 79.904	36 Krypton 83.789
					8	9 	10	11 IB 1B	12 IIB 2B	13 Aluminum 26.982	14 <b>Sili</b> 28.086	15 P Phosphorus 30.974	16 <b>S</b> Sulfur 32.066	17 Cl Chlorine 35.453	18 Argon 39.948
	6									5 B Boron 10.811	6 Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 Fluorine 18.998	10 Ne Neon 20.180
										13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 He Hellum 4.003
1 11/ 17	A A														18 VIIIA 8A

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#### Summary and Conclusions

- **New Element**: demonstrated existence of a nuclide with an atomic number Z not identified before, existing for at least 10<sup>-14</sup> s
- **Superheavy**: element with  $Z \ge 104$ , existence is due to shell effects
- Tomorrow: How are elements made









#### Summary



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26 New elements discovered in last 80 years using a variety of techniques

- Dissolve the Target Chemistry
- Catcher Foil Chemistry
- Tape system

3

- Gas-jet/Wheel system
- First Generation Separators and Accelerators
- Current Generation Separators and **Accelerators**
- Next Generation Separators and Accelerators

Once again we are at the limits of current technology

Next element discovery requires higher beam intensities and/or new production methods