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

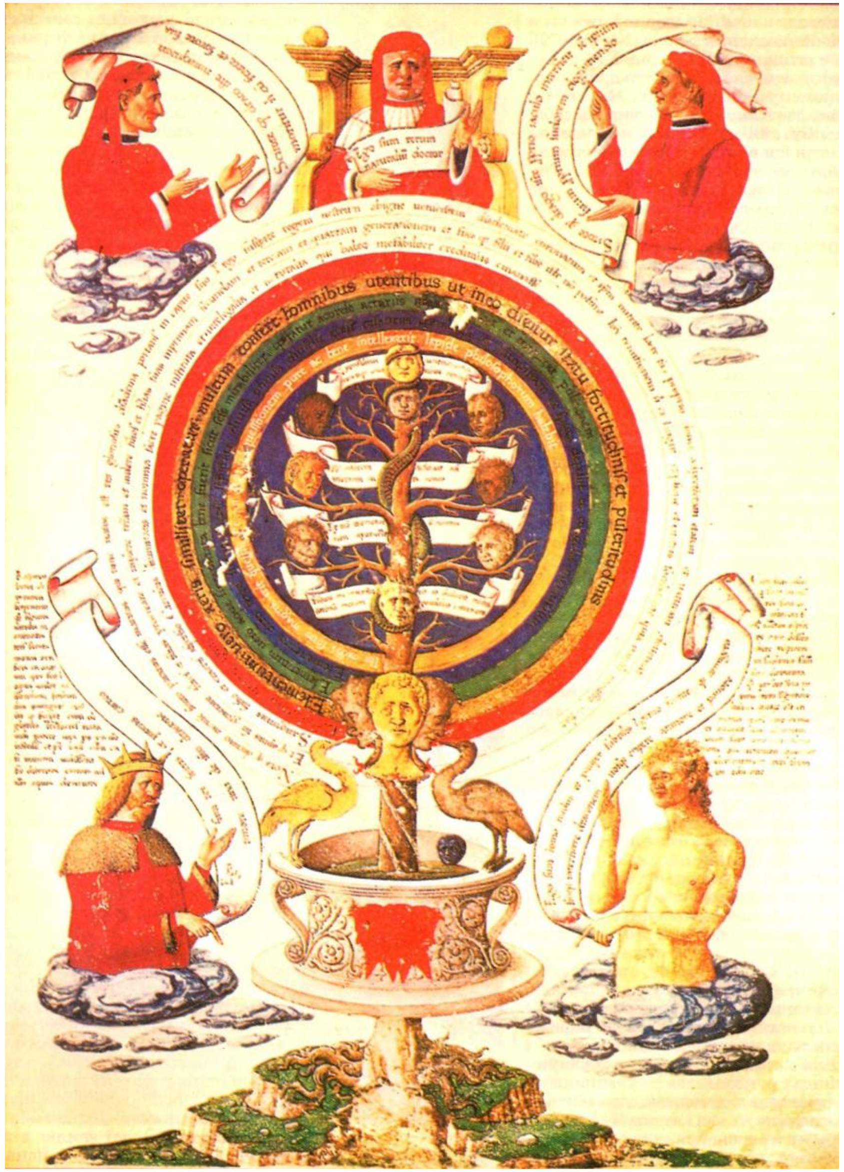
Why Study Superheavy Elements

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.

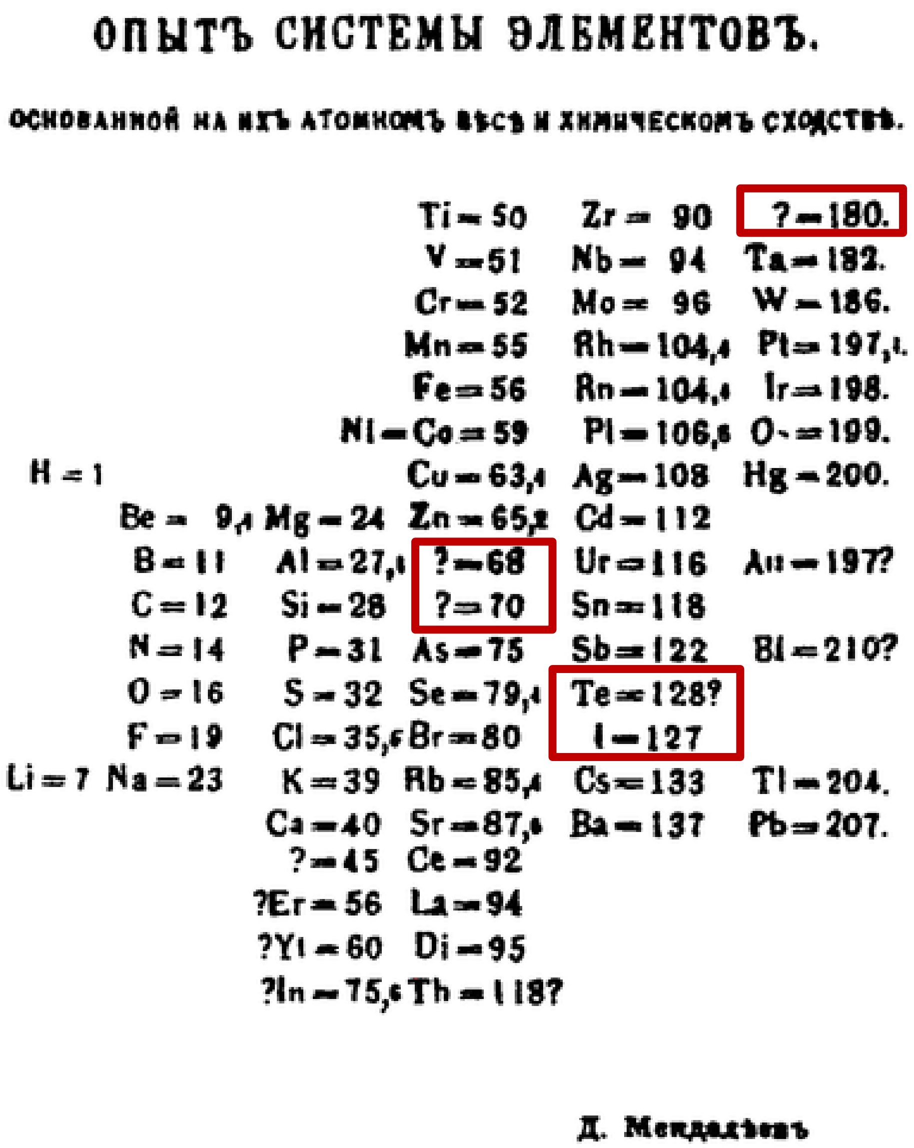


Mendeleev's Periodic Table from 1869

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



ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

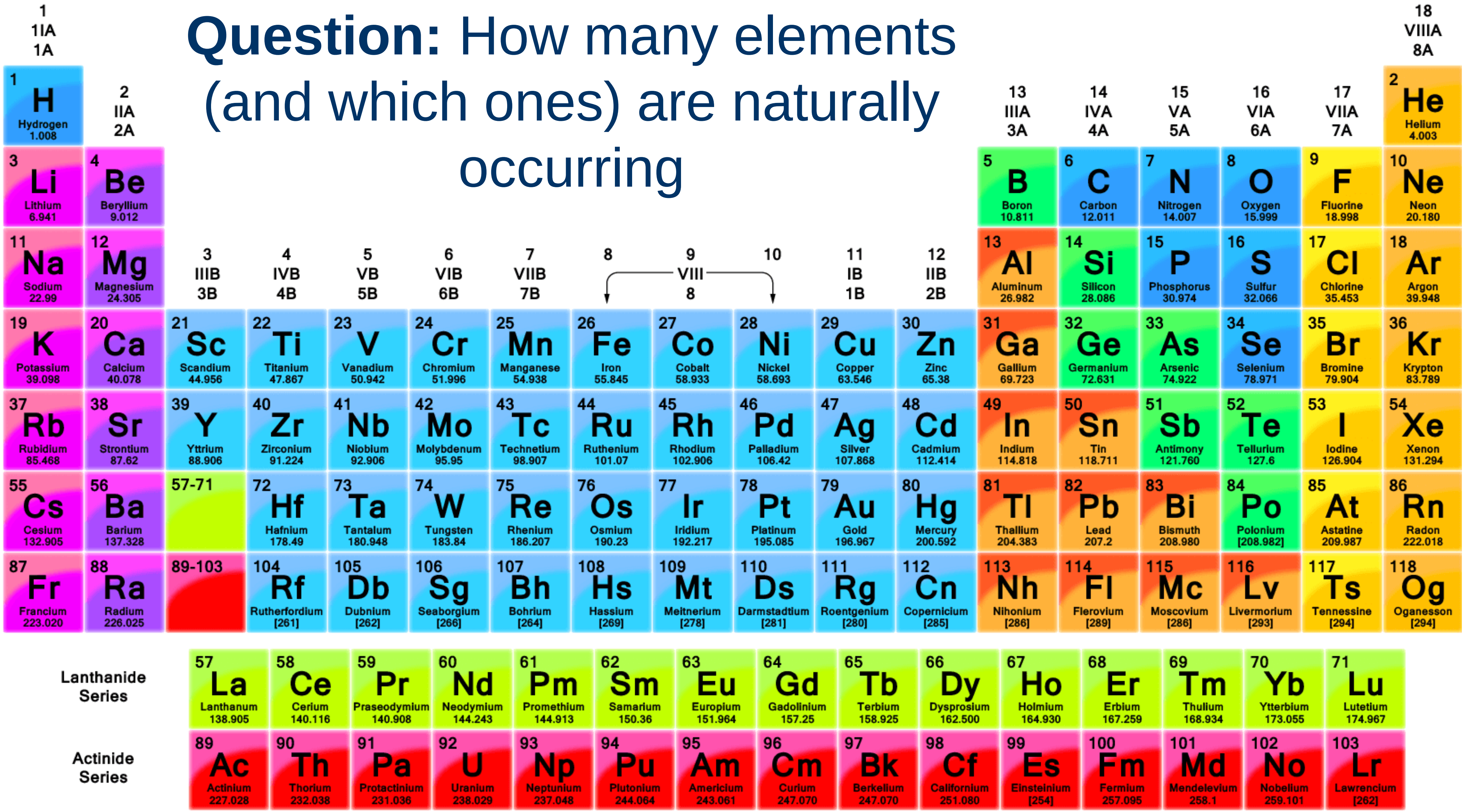
ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,4.
			Fe=56	Rn=104,4	Ir=198.
			Ni=Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

Д. Менделѣевъ

Question: How many elements are known?

Question: How many elements (and which ones) are naturally occurring

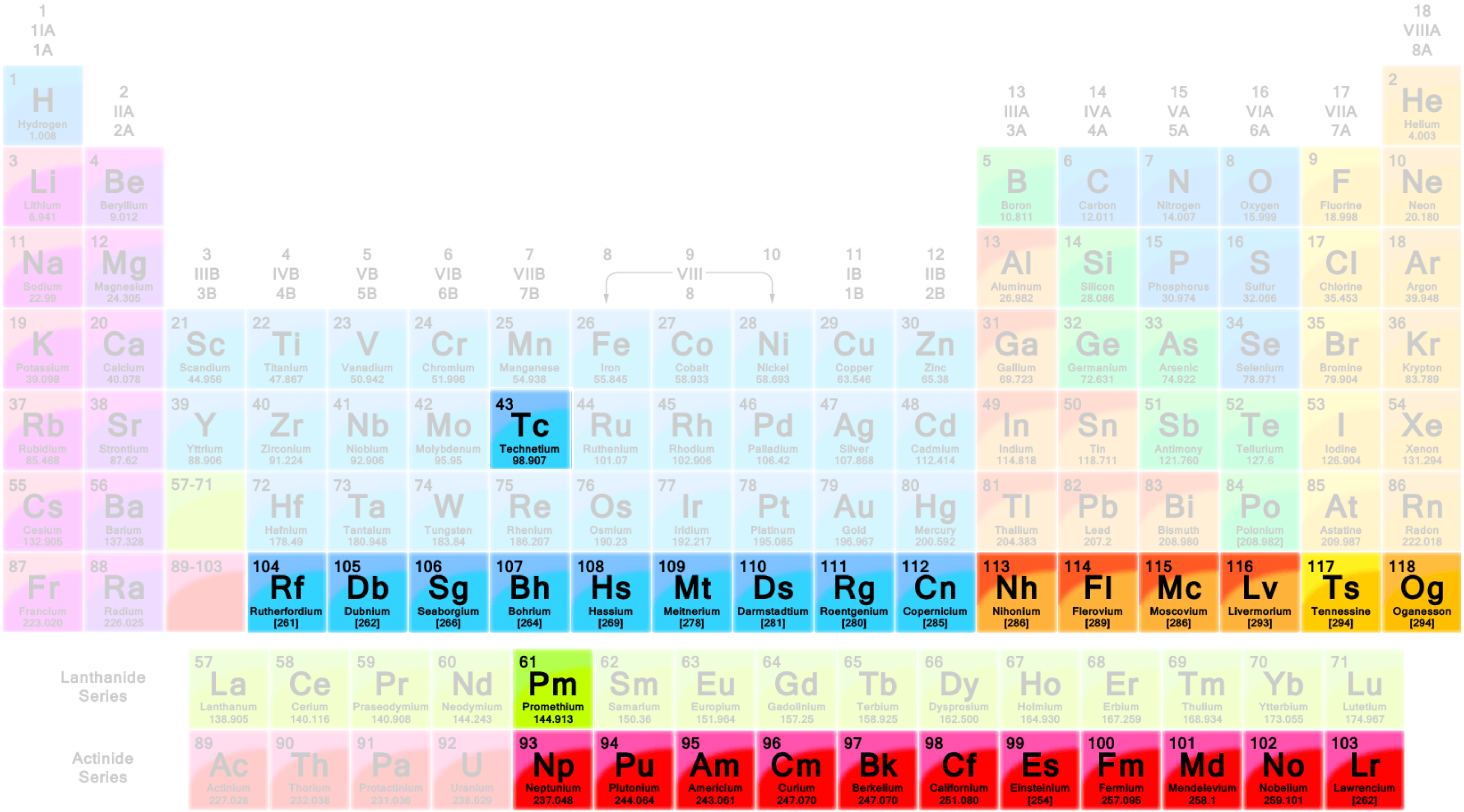


Periodic Table: Naturally Occurring Elements

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		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															

Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243		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											

Periodic Table: Manmade Elements



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

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^{-14} s.'

- 10^{-14} s ≈ time it takes for a nucleus to acquire its outer electrons and nucleus to de-excite 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 Z-values 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?

Overview of the Semi-Empirical Mass Model

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

c^2= speed of light in a vacuum

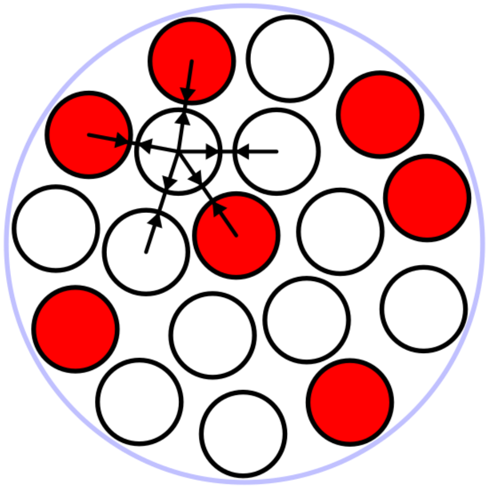
B = binding energy of the nucleus

Overview of the Semi-Empirical Mass Model

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

$$B(N,Z) = \boldsymbol{a_v A} - a_s A^{\frac{2}{3}} - a_c \frac{Z^2}{A^{\frac{1}{3}}} - a_I \frac{(N-Z)^2}{A} - \delta(A)$$

$\boldsymbol{a_v A}$ = 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.


Volume

Weizsäcker, C.F.v., Zur Theorie der Kernmassen. Z. Physik 96, 431–458 (1935). https://doi.org/10.1007/BF01337700
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Overview of the Semi-Empirical Mass Model

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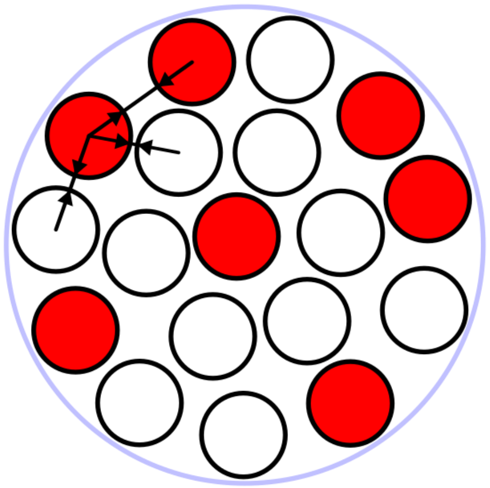
$$B(N,Z) = a_v A - \boldsymbol{a_s A^{\frac{2}{3}}} - a_c \frac{Z^2}{A^{\frac{1}{3}}} - a_I \frac{(N-Z)^2}{A} - \delta(A)$$

$\boldsymbol{a_s A^{\frac{2}{3}}}$ = 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.



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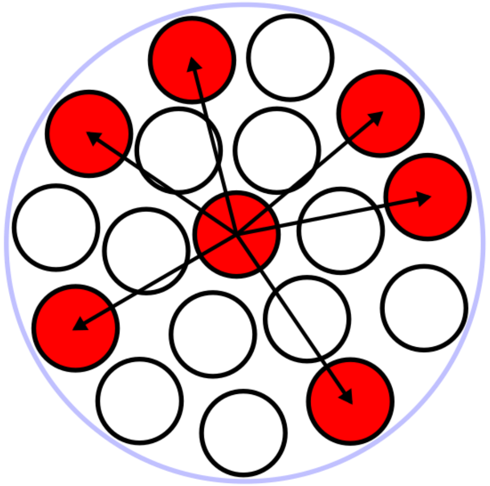
Semi-Empirical Mass Model: $m = Zm_H + Nm_n - \frac{B(N,Z)}{c^2}$

$$B(N,Z) = a_v A - a_s A^{\frac{2}{3}} - \boldsymbol{a_c \frac{Z^2}{A^{\frac{1}{3}}}} - a_I \frac{(N-Z)^2}{A} - \delta(A)$$

$\boldsymbol{a_c \frac{Z^2}{A^{\frac{1}{3}}}}$ = 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).



Coulomb

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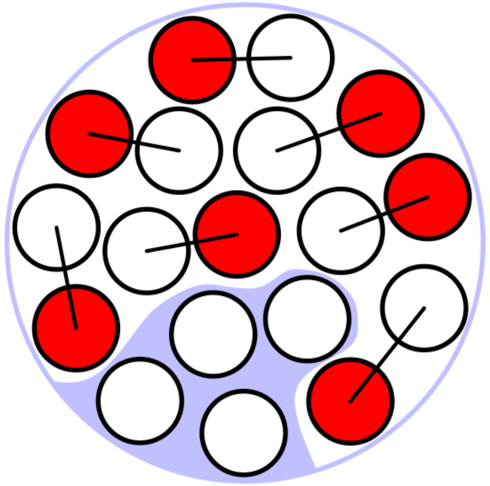
Overview of the Semi-Empirical Mass Model

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

$$B(N,Z) = a_v A - a_s A^{\frac{2}{3}} - a_c \frac{Z^2}{A^{\frac{1}{3}}} - \boldsymbol{a_I} \frac{\boldsymbol{(N-Z)^2}}{\boldsymbol{A}} - \delta(A)$$

$\boldsymbol{a_I} \frac{\boldsymbol{(N-Z)^2}}{\boldsymbol{A}}$ = 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.



Asymmetry

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Overview of the Semi-Empirical Mass Model

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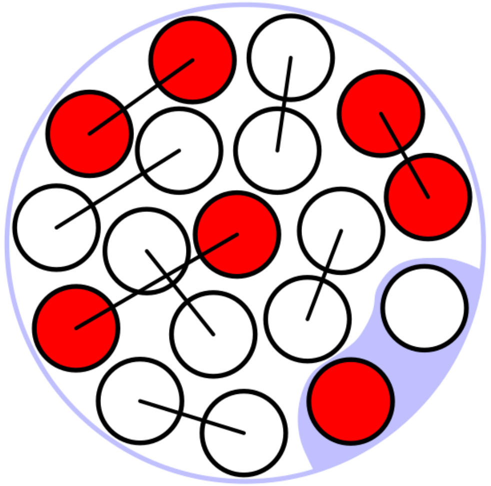
$\boldsymbol{\delta(A)}$ = Pairing term: This term accounts for the additional stabilization resulting from the pairing of nucleons with similar quantum numbers (spin and isospin).



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- 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 ^{235}U is bombarded with neutrons?

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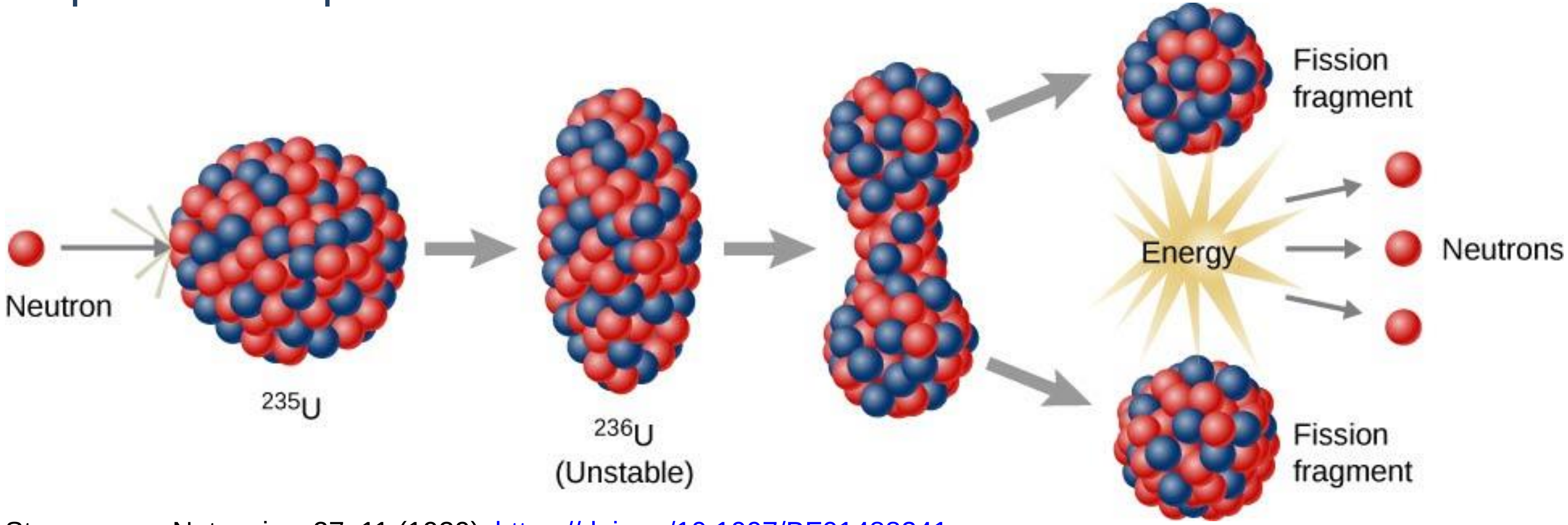
^{235}U bombarded with Neutrons

- 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



O. Hahn and F. Strassmann, Naturwiss. 27, 11 (1939): https://doi.org/10.1007/BF01488241.
L. Meitner and O.R. Frisch, Nature 143, 239 (1939): https://doi.org/10.1038/143471a.

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

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Liquid Drop Model: When nuclei begin to fission

After discovery of fission, Bohr and Wheeler added deformation dependance to the semi-empirical mass model

$$B(N,Z) = a_v A - a_s A^{\frac{2}{3}} \boldsymbol{B_s(\alpha)} - a_c \frac{Z^2}{A^{\frac{1}{3}}} \boldsymbol{B_c(\alpha)} - a_I \frac{(N-Z)^2}{A} - \delta(A)$$

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

$\frac{E_C}{2E_S} > 1$ ➔ Instantaneously fission ➔ last element is ~Z=124

Z	50	82	100	102	114	124	130
A	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?

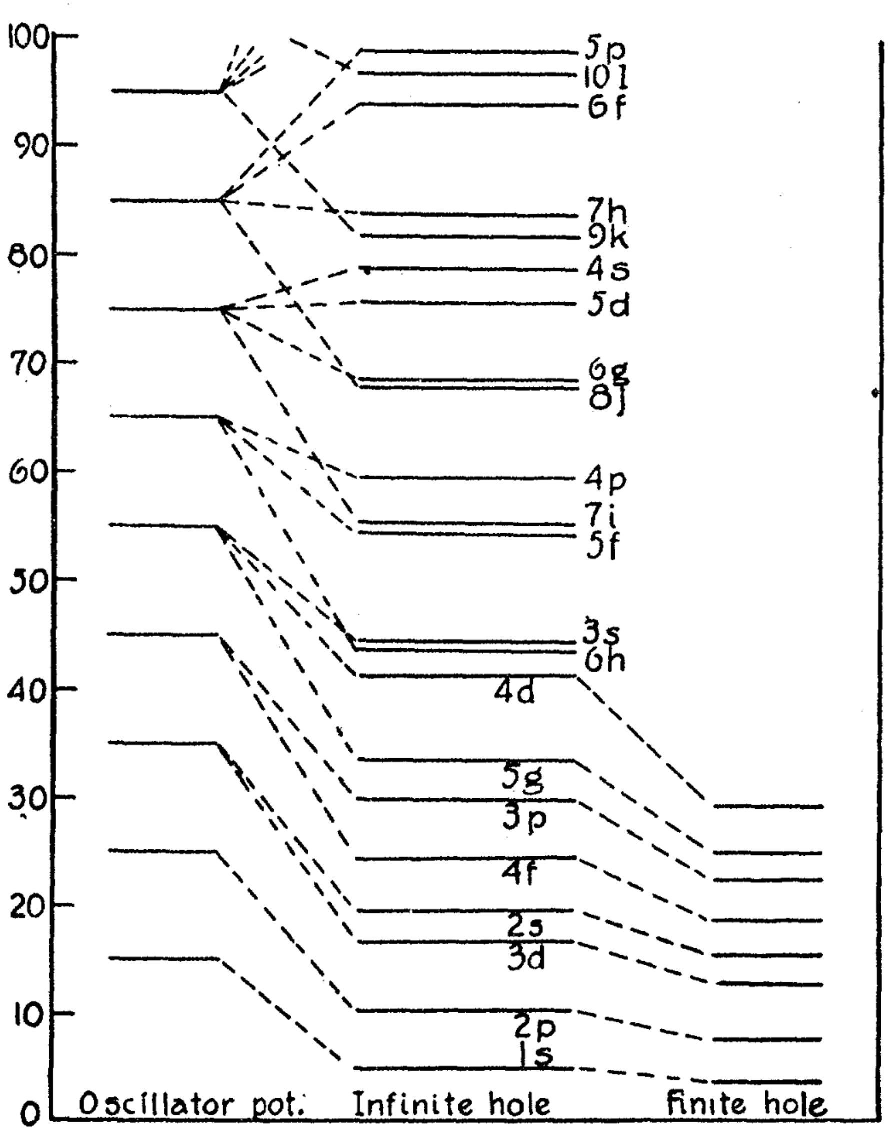
- Must exist for >10^{-14} s before decaying
- At $\frac{E_C}{2E_S} > 0.8$ barrier in liquid-drop model becomes so low that nuclei fission before detection is possible ➔ last element around Z=100-104

- 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 (^{40}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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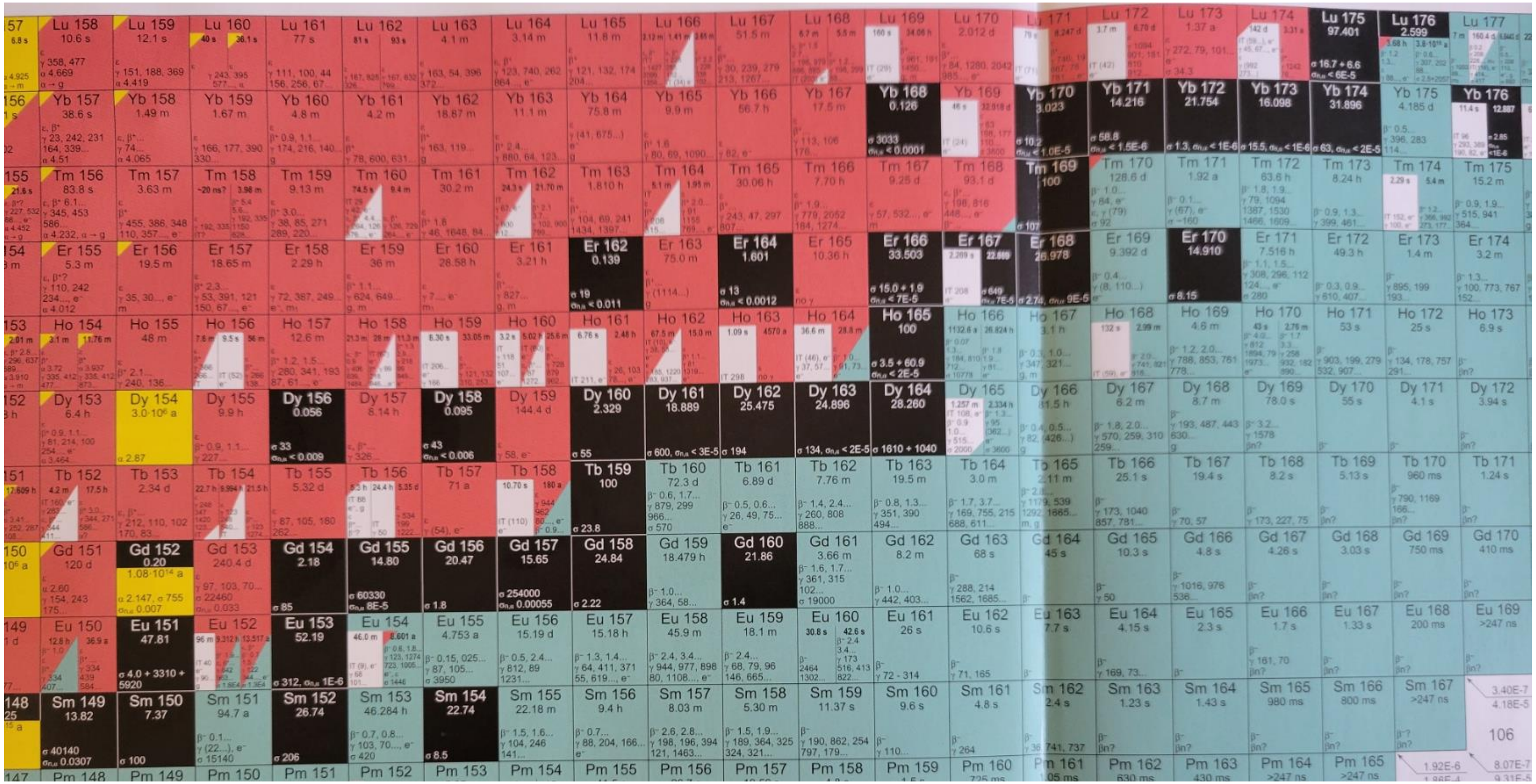
The Case for Closed Shells

1948: Maria Goeppert Mayer makes the case for magic numbers beyond 20

1. Isotopic abundance



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

The Case for Closed Shells

1948: Maria Goeppert Mayer makes the case for magic numbers beyond 20

1. Isotopic abundance: Isotopes with *Z*>32 and abundance >60%

^{88}Sr	^{138}Ba	^{140}Ce
N=50	N=82	N=82
82.6%	71.2%	88.4%

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

^{90}Zr	^{92}Mo	^{96}Ru	^{142}Nd	^{144}Sm
N=50	N=50	N=52	N=82	N=82
51.5%	14.6%	5.5%	27.2%	3.08%

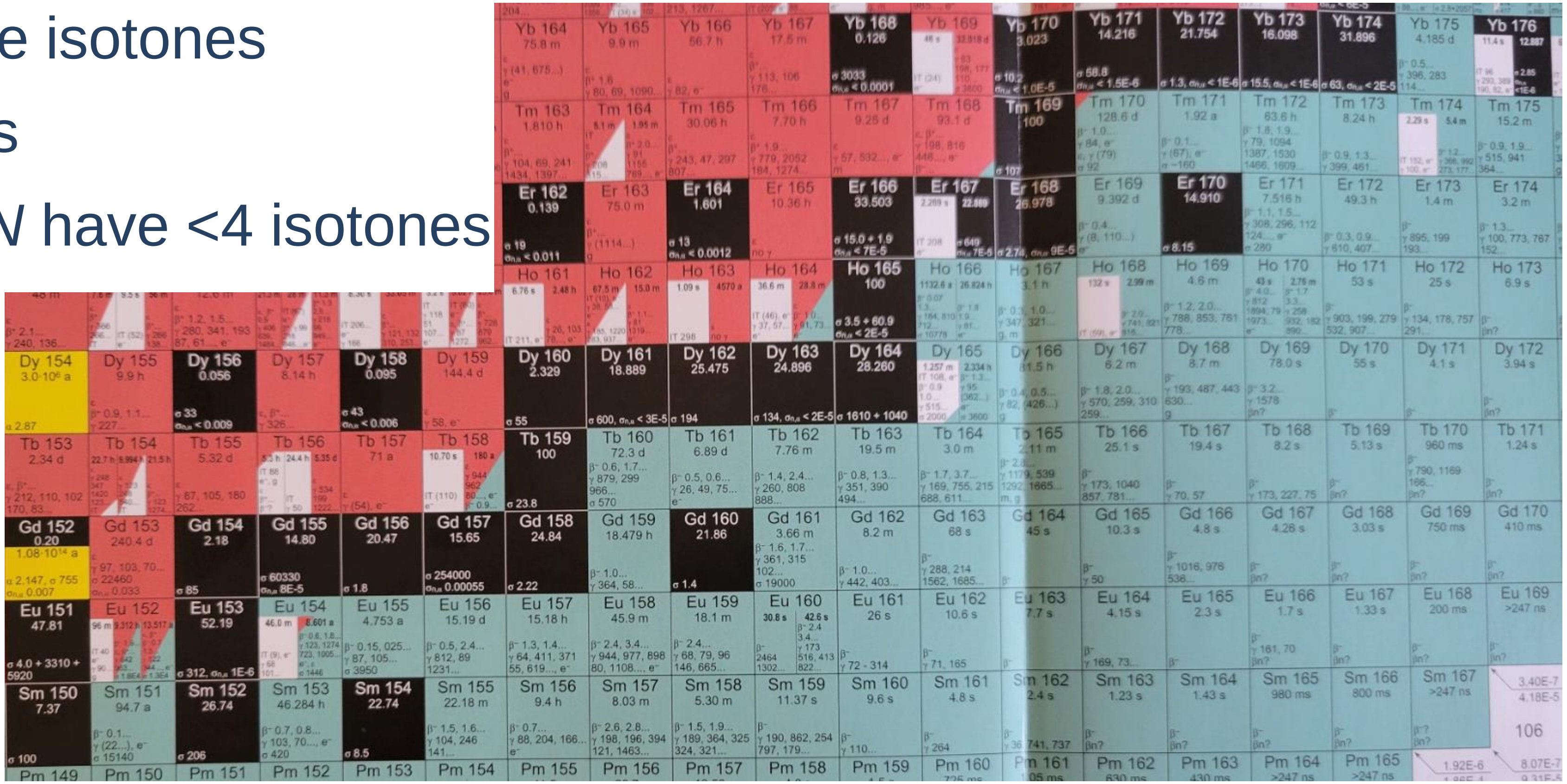
Mayer, Phys. Rev. **74** (1948) 235: https://doi.org/10.1103/PhysRev.74.235

The Case for Closed Shells

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



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The Case for Closed Shells

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

^{92}Mo 14.6%	^{142}Nd 27.1%
^{91}Nb	^{141}Pr 100%
^{90}Zr 51.5%	^{140}Ce 88.5%
^{89}Y 100%	^{139}La 99.9%
^{88}Sr 82.6%	^{138}Ba 71.7%
^{87}Rb 27.8%	^{137}Cs
^{86}Kr 17.3%	^{136}Xe 8.9%

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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??

Osc. no.	Square well	Spin term	No. of states	Shells	Total no.
0	1s	$1s_{1/2}$	2	2	2
1	1p	$1p_{3/2}$	4		
		$1p_{1/2}$	2	6	8
2	1d	$1d_{5/2}$	6		
		$1d_{3/2}$	4	12	
	2s	$2s_{1/2}$	2		20
3	1f	$1f_{7/2}$	8	8	28
		$1f_{5/2}$	6		
	2p	$2p_{3/2}$	4	22	
		$2p_{1/2}$	2		
		$1g_{9/2}$	10		50
4	1g	$1g_{7/2}$	8		
	2d	$2d_{5/2}$	6		
		$2d_{3/2}$	4	32	
	3s	$3s_{1/2}$	2		
		$1h_{11/2}$	12		82
5	1h	$1h_{9/2}$	10		
	2f	$2f_{7/2}$	8		
		$2f_{5/2}$	6	44	
	3p	$3p_{3/2}$	4		
		$3p_{1/2}$	2		126
		$1i_{13/2}$	14		
6	1i, 2g, 3d, 4s	$1i_{11/2}$			

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

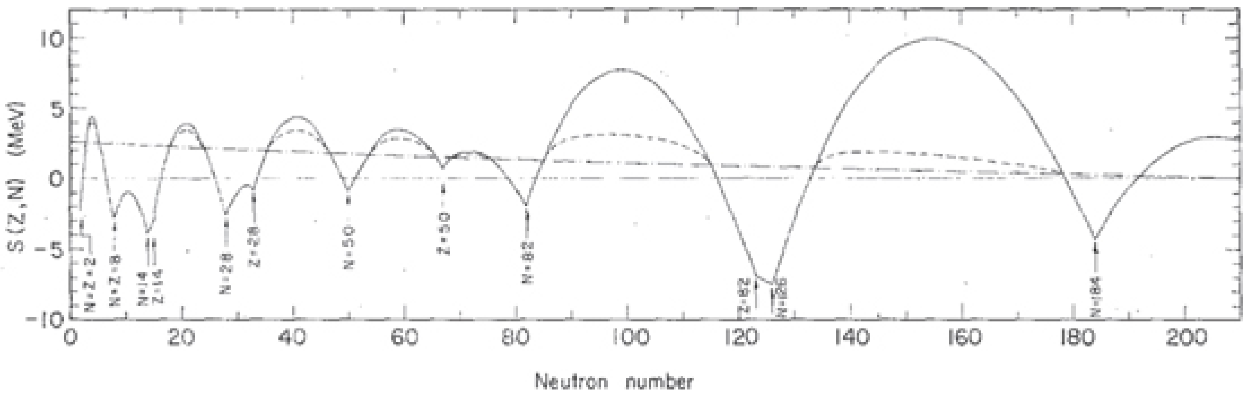
Who first predicted the existence of superheavy elements?

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, https://doi.org/10.1016/0029-5582(66)90639-0

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



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

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:

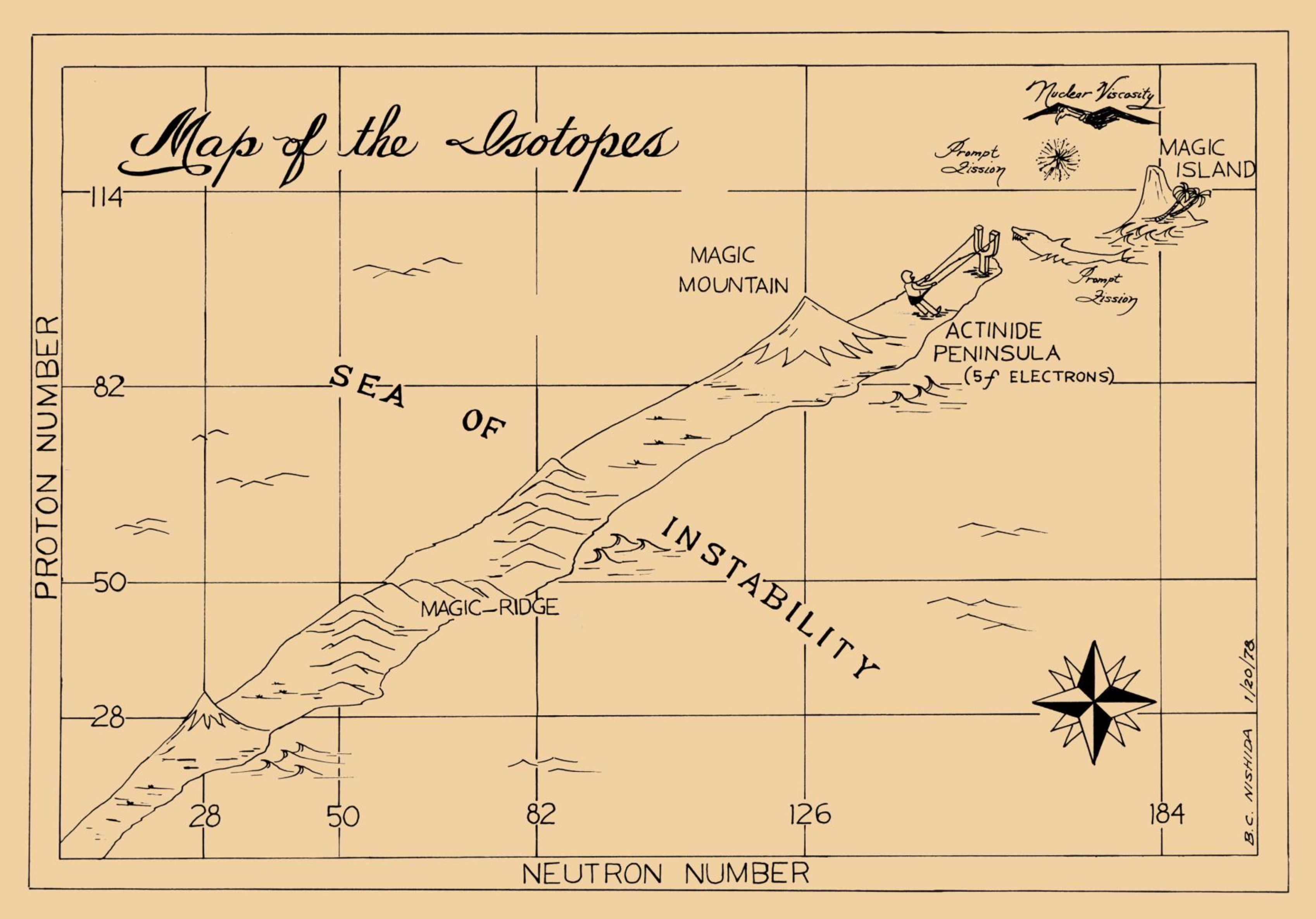
- Z=126: Myers and Swiatecki, Nucl. Phys. A **18** (1966) 1, https://doi.org/10.1016/0029-5582(66)90639-0

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

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 spin-orbit 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 [23]) that $Z = 114$, $N = 184$ is a possible candidate for a doubly magic nucleus (see also p. 269, ref. [24])). 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

Seaborg’s Map of the Isotopes



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; © *North-Holland Publishing Co., Amsterdam*

"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). https://doi.org/10.1016/0375-9474(67)90510-6
V.M. Strutinsky, Nucl. Phys. A 122, 1 (1968). https://doi.org/10.1016/0375-9474(68)90699-4

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

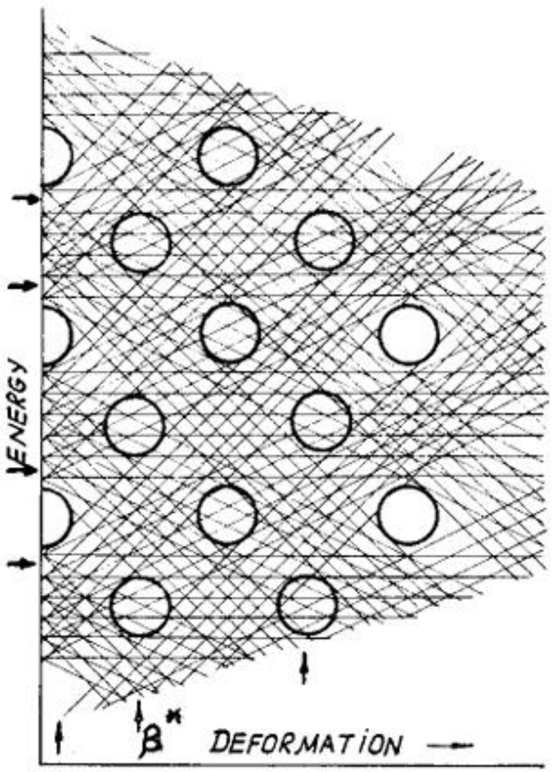


Fig. 1. Qualitative picture of the distribution of the single-particle states in the deformed nucleus. The low-density regions (shells) are shown by circles. Arrows on the energy axis show where transitions between sphericity and non-sphericity occur.

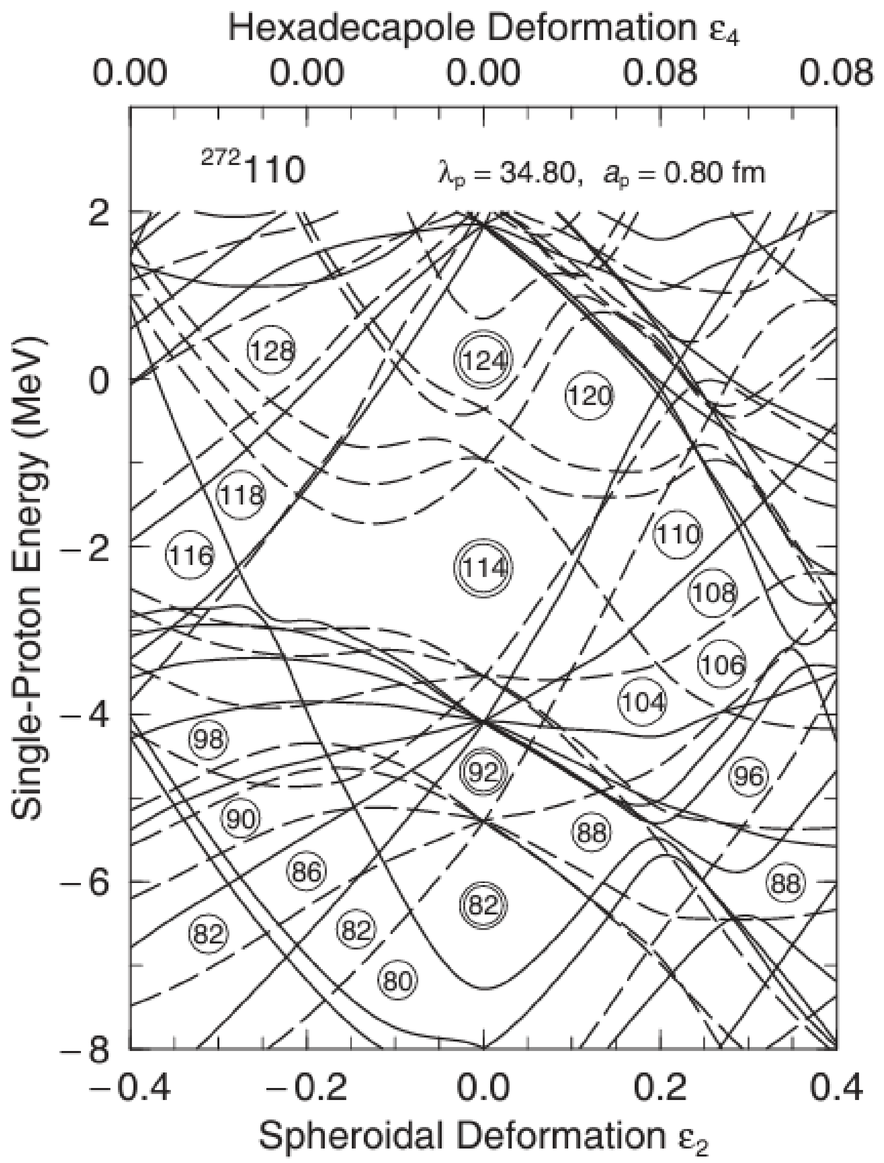
P. Möller, A.J. Sierk, T. Ichikawa, H. Sagawa, At. Data Nucl. Data Tables 109–110,1 (2016).
V.M. Strutinsky, Nucl. Phys. A 95, 420 (1967). https://doi.org/10.1016/0375-9474(67)90510-6
V.M. Strutinsky, Nucl. Phys. A 122, 1 (1968). https://doi.org/10.1016/0375-9474(68)90699-4

Introduction of Deformed Shells

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

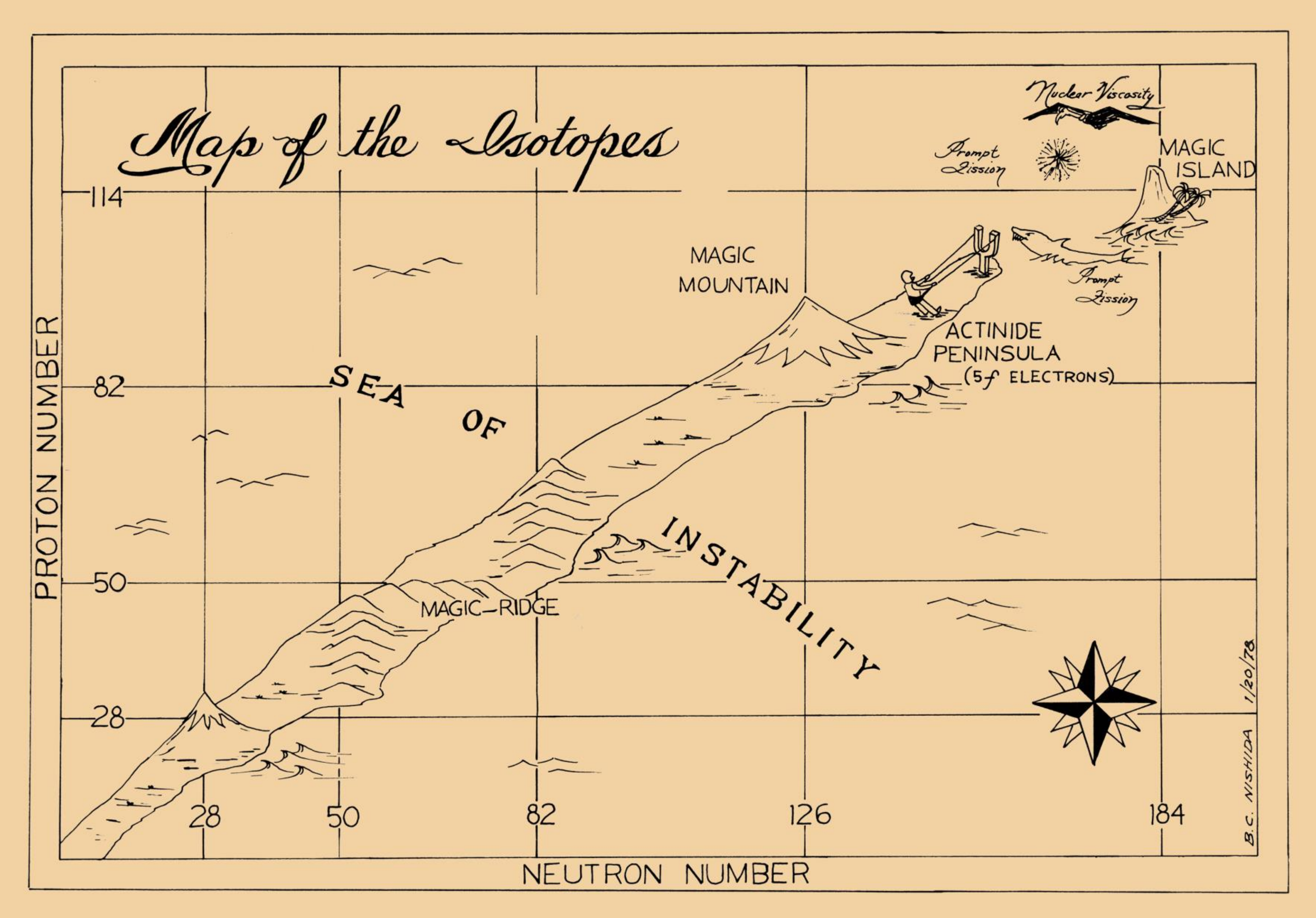
Is able to reproduce known spherical shells and "low-density" regions of single particle states in deformed nuclei ➔ deformed shells

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). https://doi.org/10.1016/0375-9474(67)90510-6
V.M. Strutinsky, Nucl. Phys. A 122, 1 (1968). https://doi.org/10.1016/0375-9474(68)90699-4

Seaborg's Map of the Isotopes



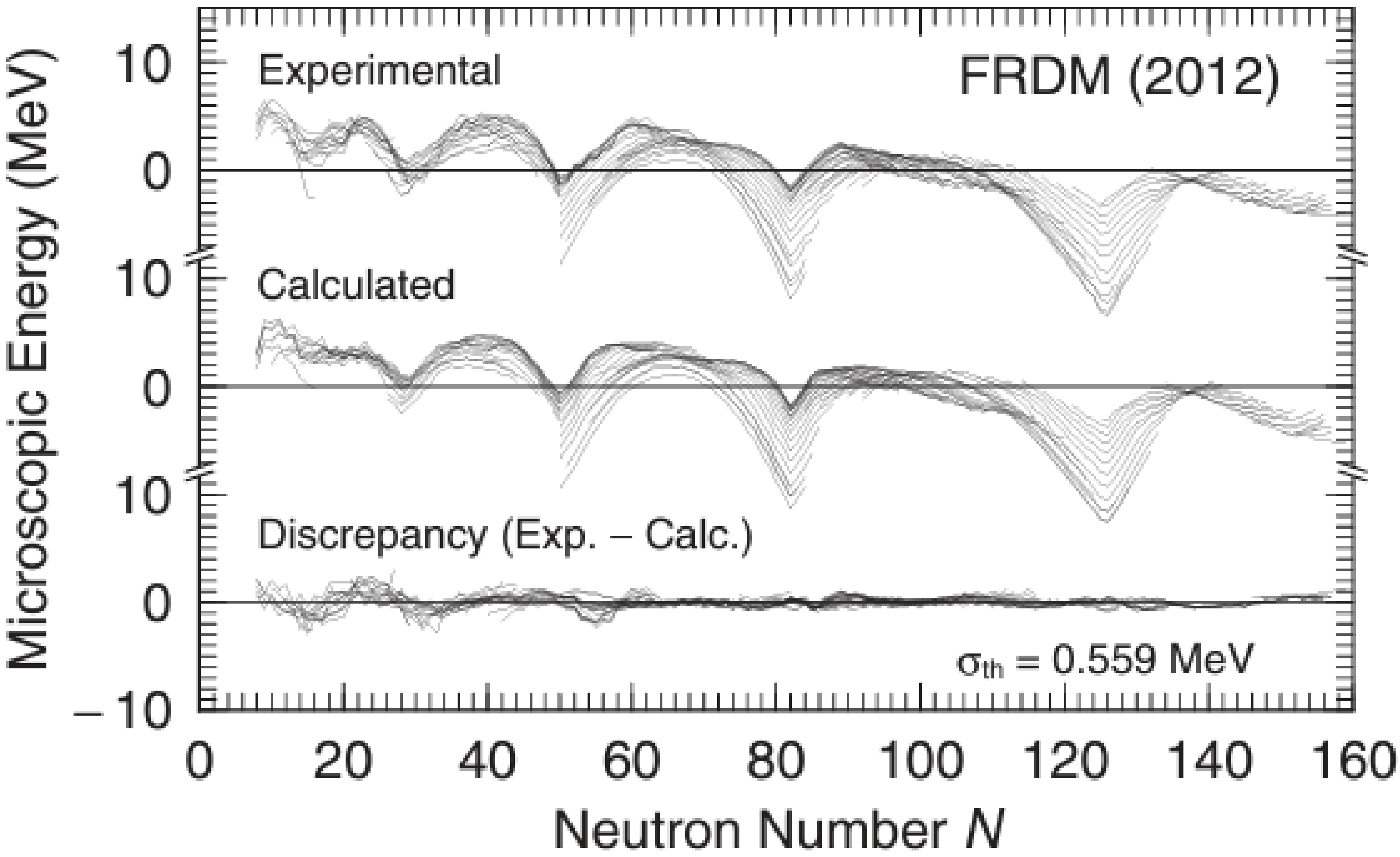
1968: Deformed shells allow for nuclides that 'bridge the gap' between actinide peninsula and the magic island

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



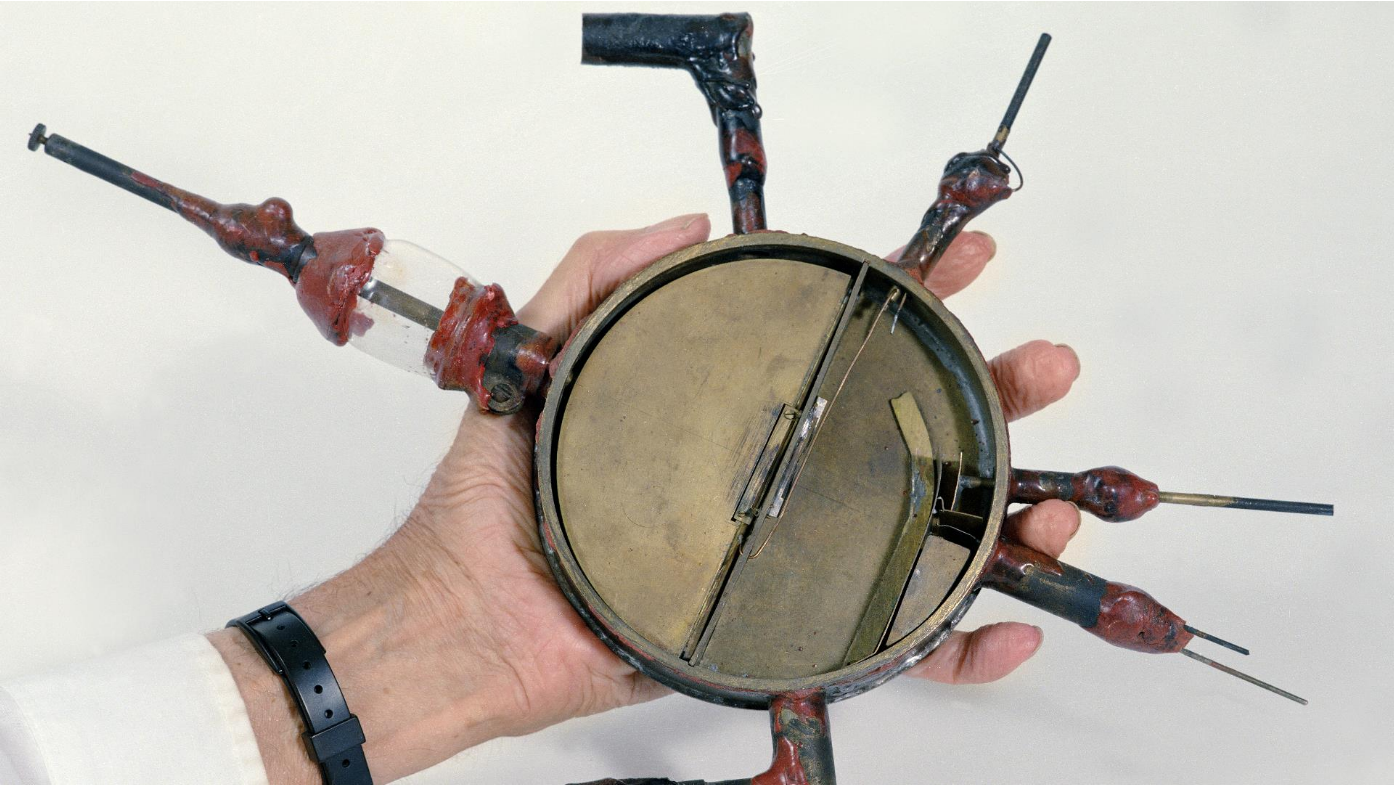
P. Möller, A.J. Sierk, T. Ichikawa, H. Sagawa, At. Data Nucl. Data Tables 109–110,1 (2016).

When was the first man-made 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

Some Chemical Properties of Element 43

C. PERRIER AND E. SEGRÈ,
Royal University, Palermo, Italy

(Received June 30, 1937)

1. INTRODUCTION

PROFESSOR 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 radioactivity is due to more than one substance of a half-value period of some months and to the radioactive phosphorus isotope P^{32}.[1] 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

[1] 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 ^{nat}U foils with neutrons and identified the following non-recoiling activities, but were unable to make elemental identifications

1. $$U + n \longrightarrow {}^{10''}_{92}U \xrightarrow{\beta} {}^{2,2'}_{93}\text{Eka Re} \xrightarrow{\beta} {}^{59'}_{94}\text{Eka Os} \xrightarrow{\beta} {}^{66\,h}_{95}\text{Eka Ir} \xrightarrow{\beta} {}^{2,5\,h}_{96}\text{Eka Pt} \xrightarrow{\beta} {}_{97}\text{Eka Au}\,?$$

2. $$U + n \longrightarrow {}^{40''}_{92}U \xrightarrow{\beta} {}^{16'}_{93}\text{Eka Re} \xrightarrow{\beta} {}^{5,7\,h}_{94}\text{Eka Os} \xrightarrow{\beta} {}_{95}\text{Eka Ir}\,?$$

3. $$U + n \longrightarrow {}^{23'}_{92}U \xrightarrow{\beta} {}_{93}\text{Eka Re}\,?$$

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

First Transuranic Discovery

1939: McMillan irradiated ^{nat}U foils with neutrons and caught recoiling nuclei on stacks of cigarette paper – isolated 23-min ^{239}U and watched growth of 2.3-day $^{239}93$

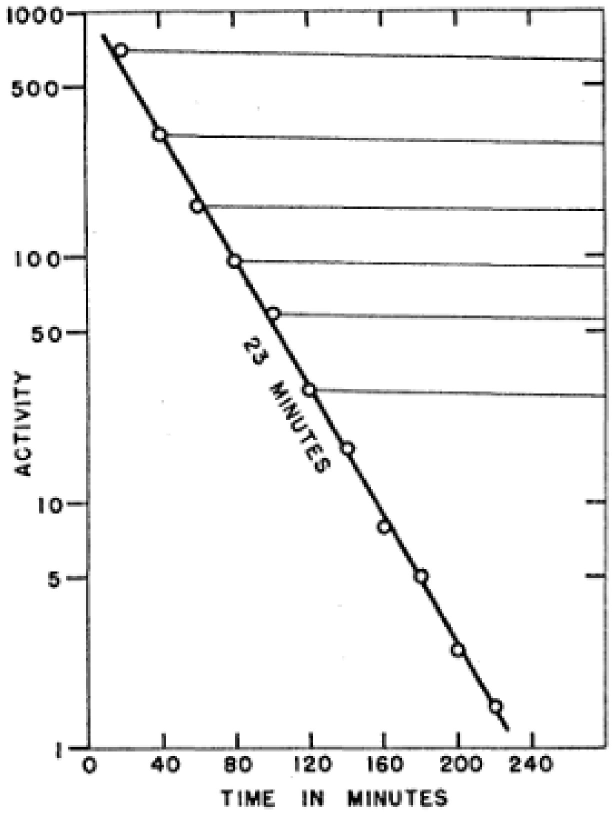
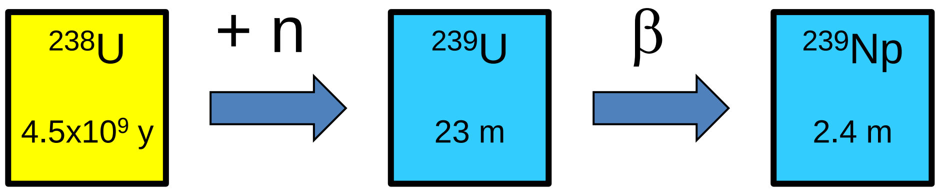


Fig. 1. Growth of 2.3-day 93^{239} from 23-minute U^{239}. The points indicate the activities of successive fluoride extractions, plotted at the times of extraction. Decay measurements were made a day later on the first six fractions, and the resulting slopes are shown on the plot.

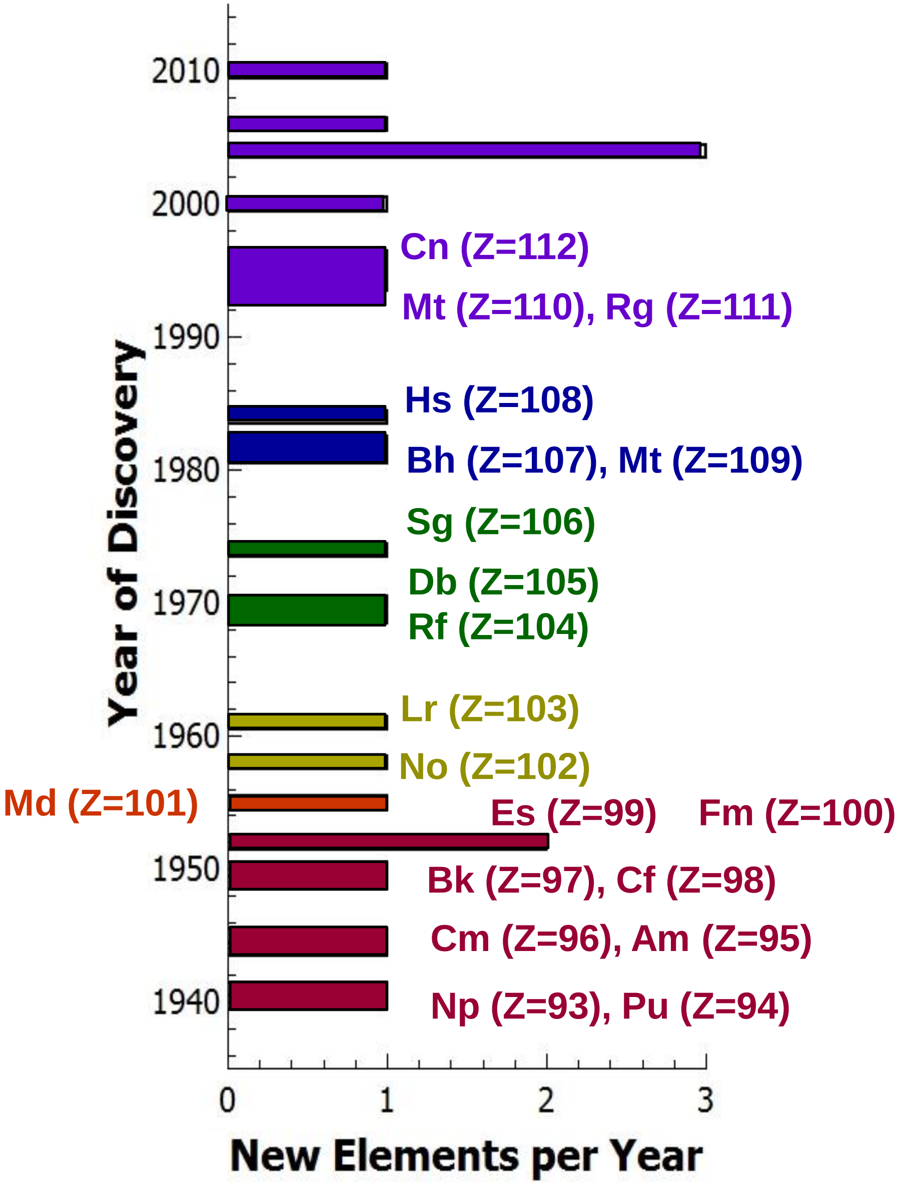


Meitner, Zeits. F. Physik **106** (1937) 249: https://doi.org/10.1007/BF01340321
McMillan, E. Phys. Rev. **55** (1939) 510: https://doi.org/10.1103/PhysRev.55.510
McMillan, E. Phys. Rev. **57** (1940) 1185: https://doi.org/10.1103/PhysRev.57.1185.2

History of Element Discovery

First transcuranic element identified 1940

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



Latest Elements Discovered

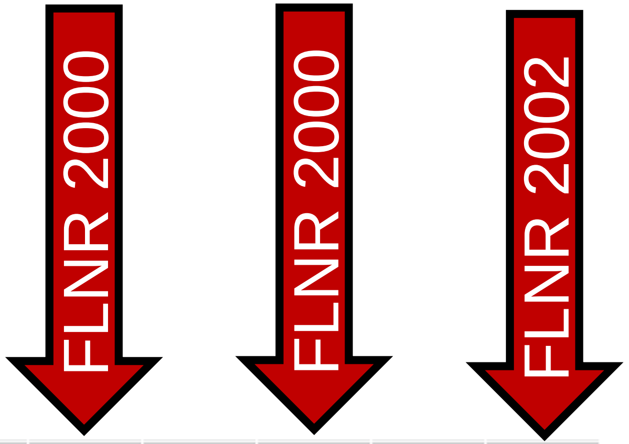
INTERNATIONAL UNION OF
PURE AND APPLIED CHEMISTRY

For Release 8 June 2016

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

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

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



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

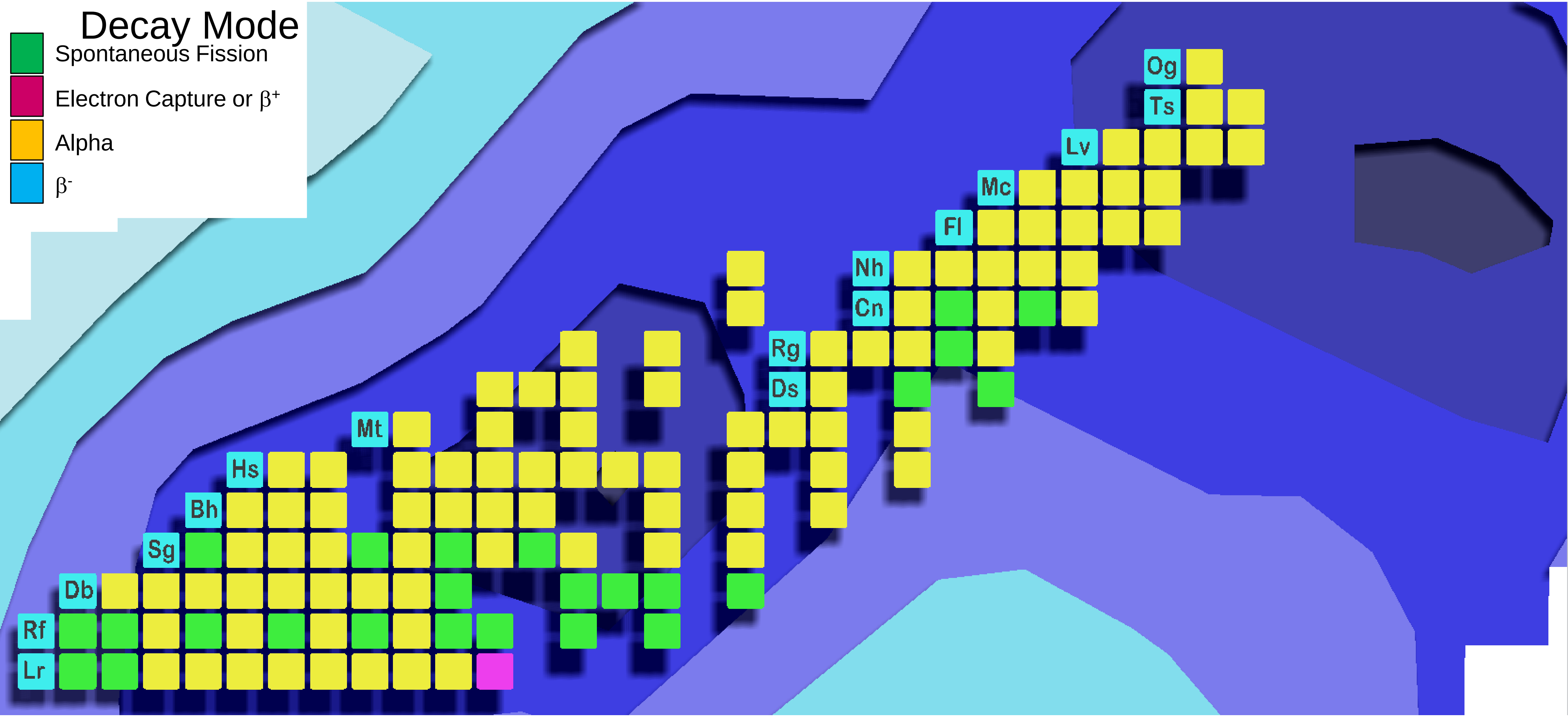
6 new elements discovered in the last 2 decades

Periodic Table

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

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

Chart of the Nuclides: 2019



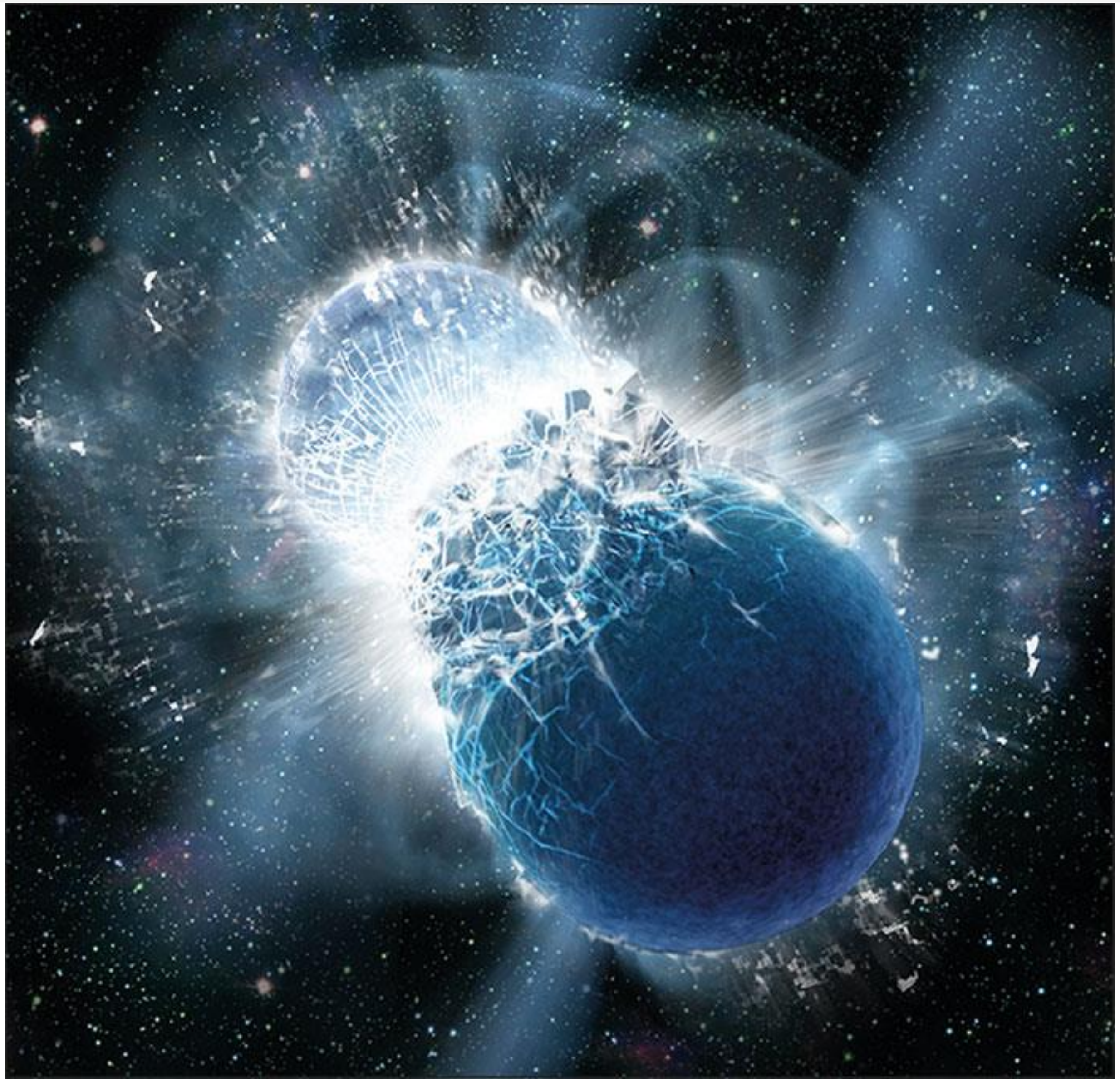
Question: Why Study Superheavy Elements?

Why Study New Elements: Understanding Origins

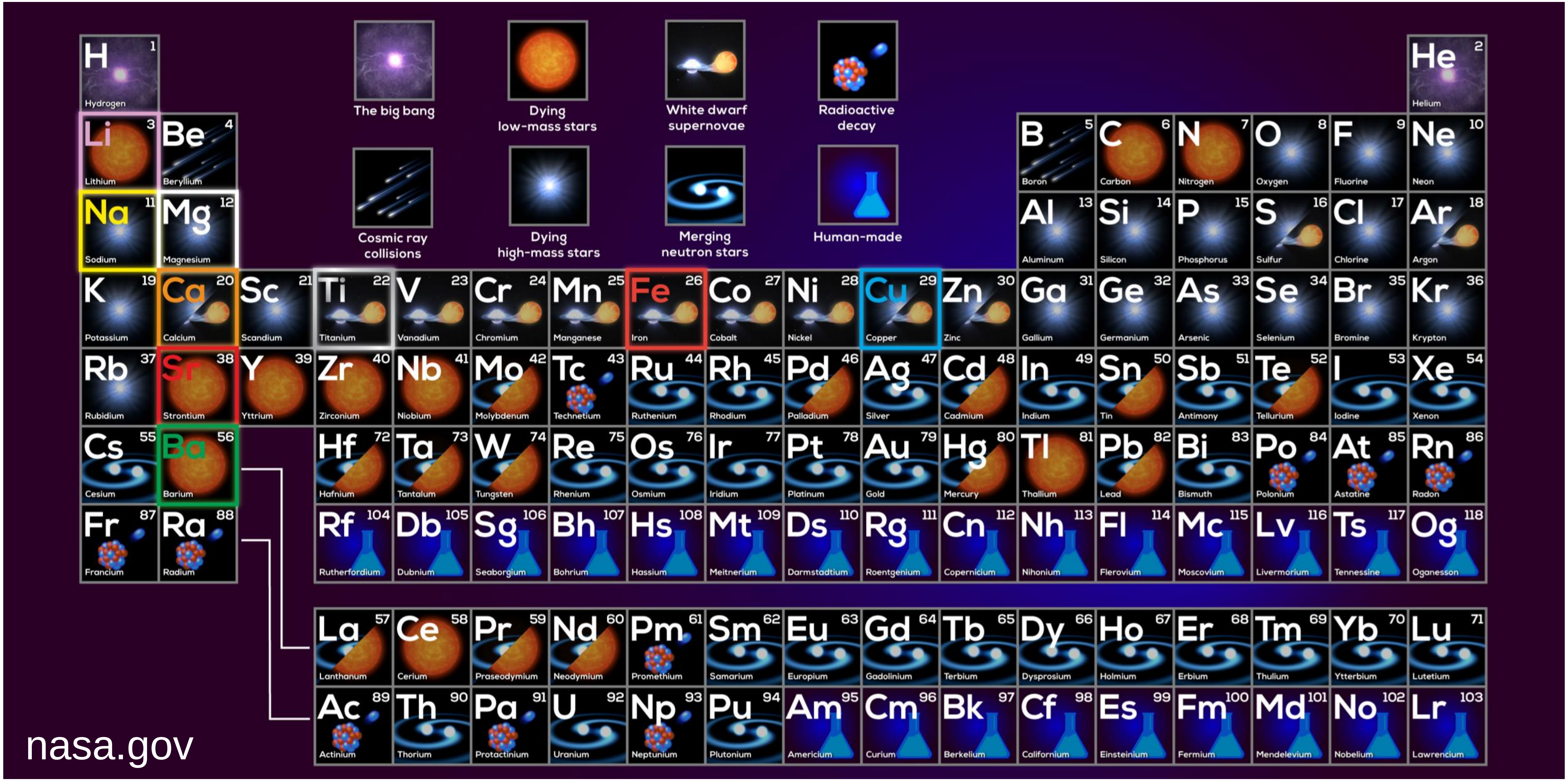
Do these elements exist somewhere in the universe, even for just fractions of a second?

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

What are the limits of nuclear stability?



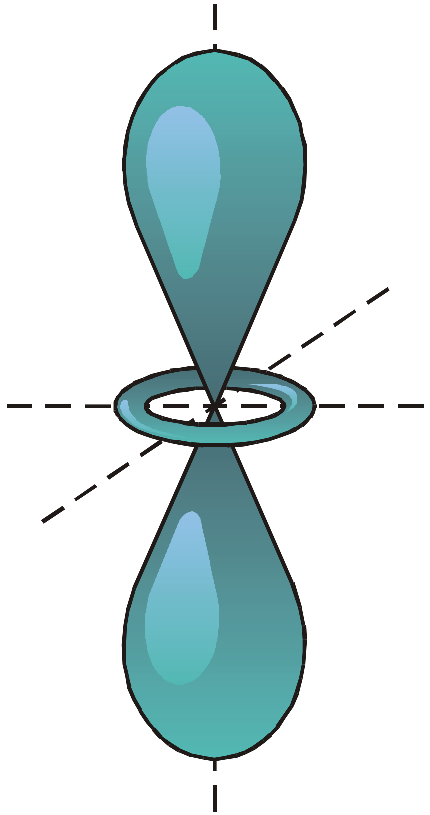
Periodic Table Origins



nasa.gov

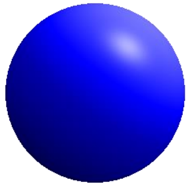
Why study new elements: Relativistic Effects

Where does the periodic table break down?



Why study new elements: Relativistic Effects

- **caused by the mass increase in electrons with large average speed.**
- **Increase approximately by Z²**
- **can lead to strong deviations between observed chemical properties and values derived from "classical extrapolations" along the periodic table**

1s electron 

Velocity of 1s electron:

$$v_e \sim Zc/137$$

Relativistic mass of electron:

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

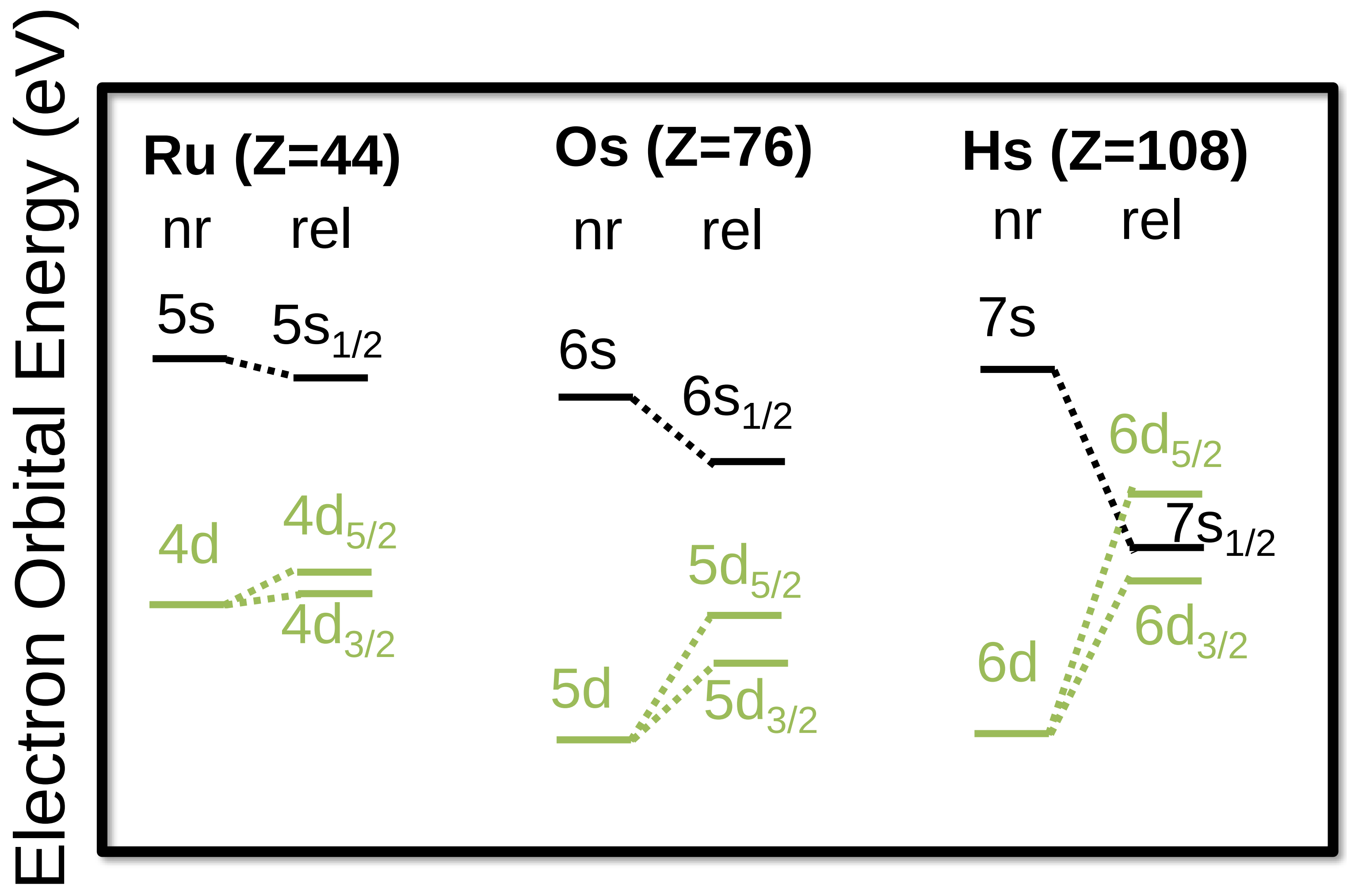
Relativist bohr radius:

$$\frac{a_{rel}}{a_0} = \sqrt{1-(v_e/c)^2}$$

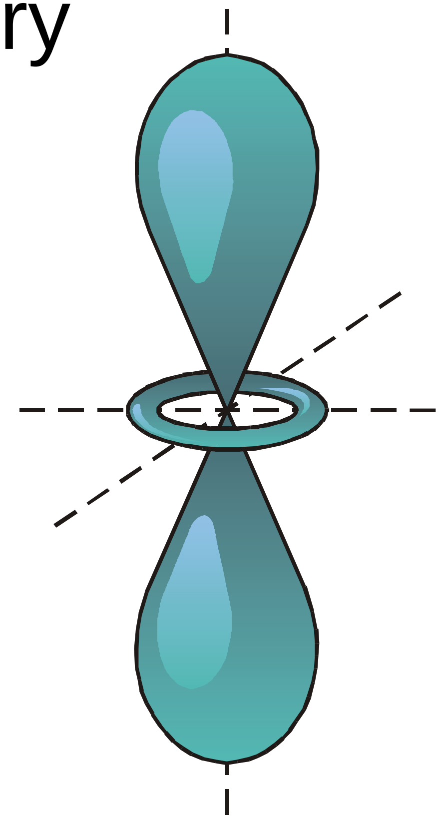
For Og (Z=118) ➔ $v \approx 0.86c$

$$\boldsymbol{m_{rel} \approx 1.97 m_e\ ,\ a_{rel} \approx 0.51 a_0}$$

Why study new elements: Relativistic Effects



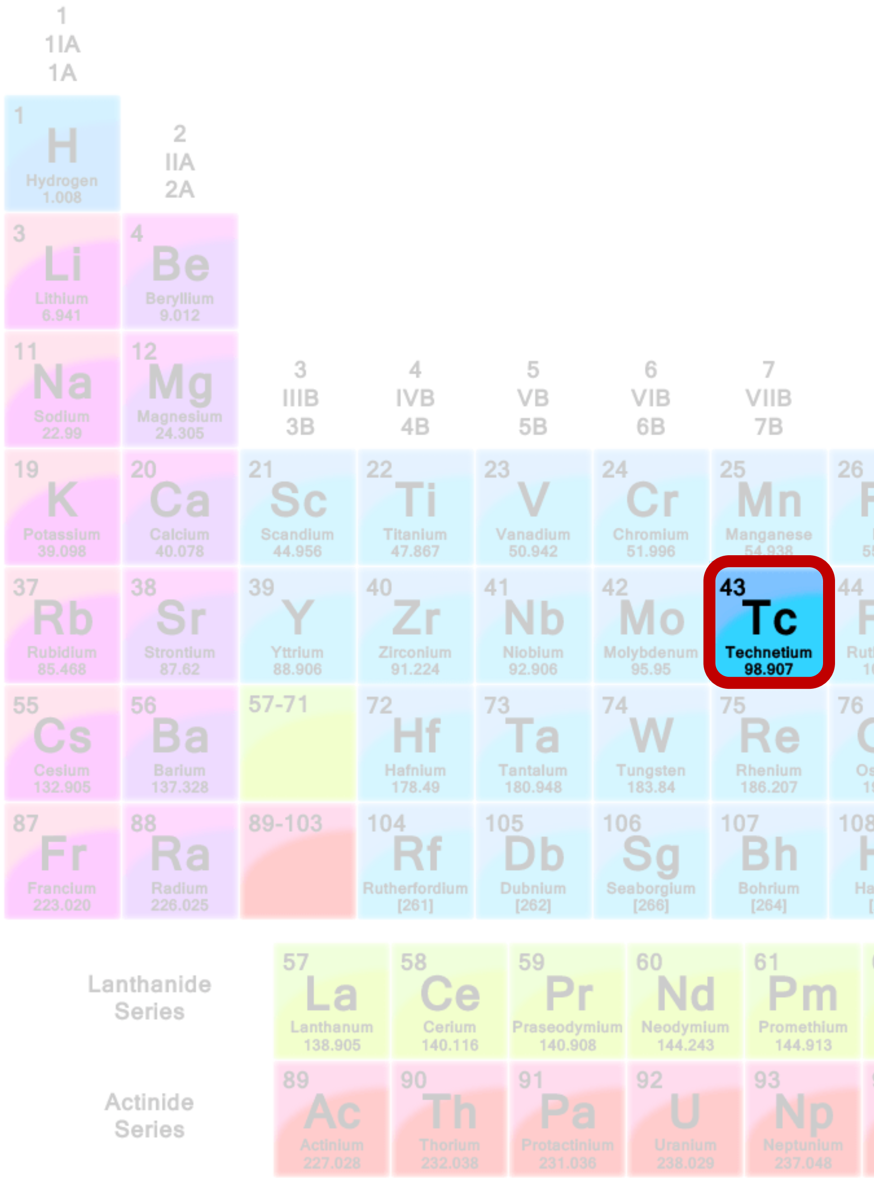
Change in orbital energy ➔ change in chemistry



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

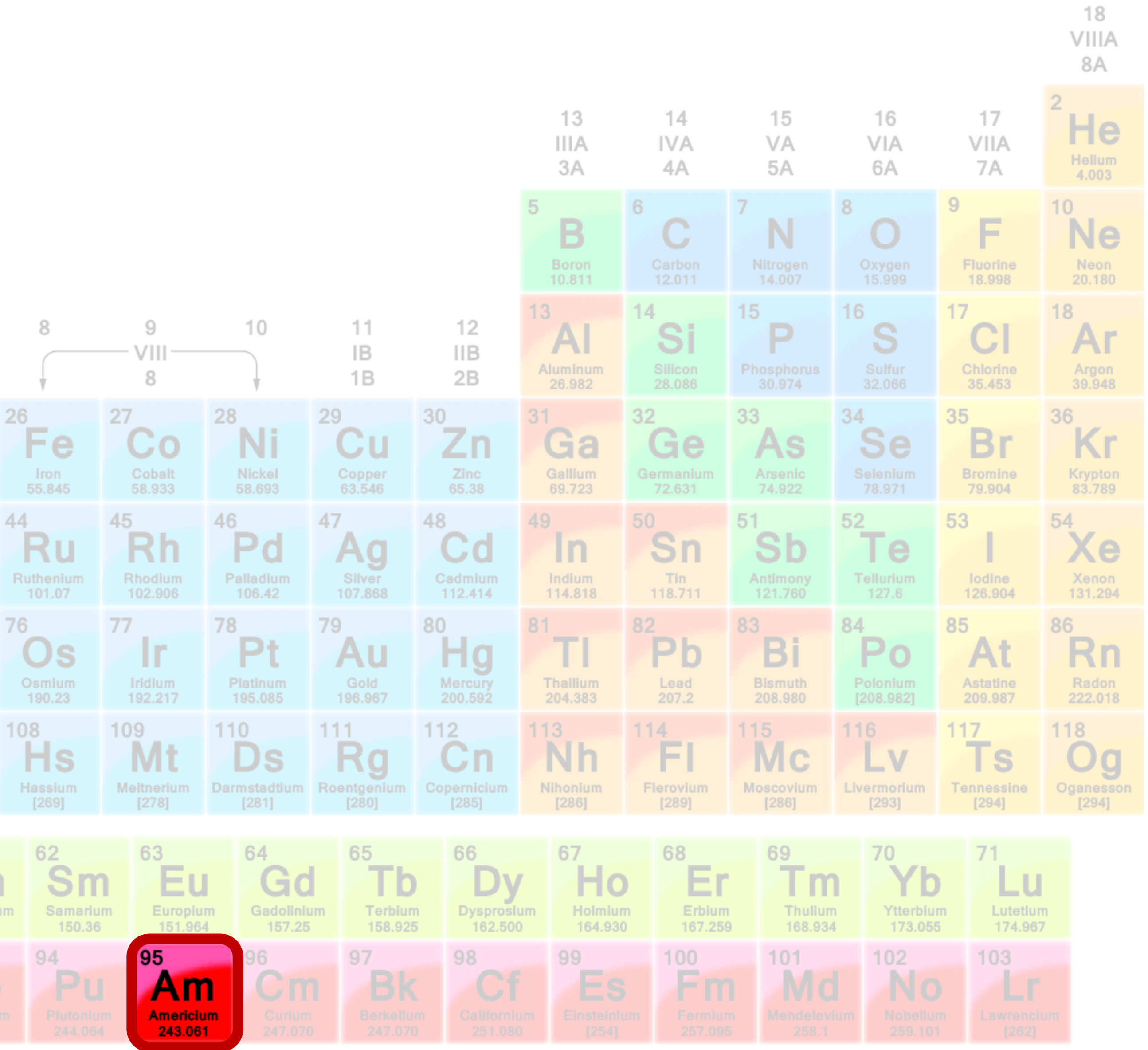
Question: What applications exist for manmade elements?

Why Study Manmade Elements?



Medical Imaging/Treatment

Why Study Manmade Elements?



Smoke Detectors

Why Study Manmade Elements?

Neutron Imaging

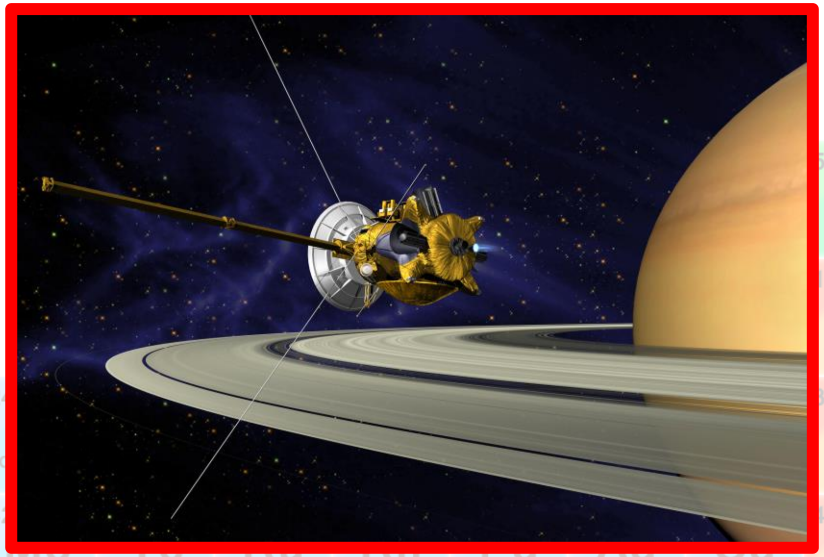
Neutron Probes

95 **Am** Americium 243.061

98 **Cf** Californium 251.080

Why Study Manmade Elements?

Curiosity



Cassini

Rosetta and Philae

94 **Pu** Plutonium 244.064

96 **Cm** Curium 247.070

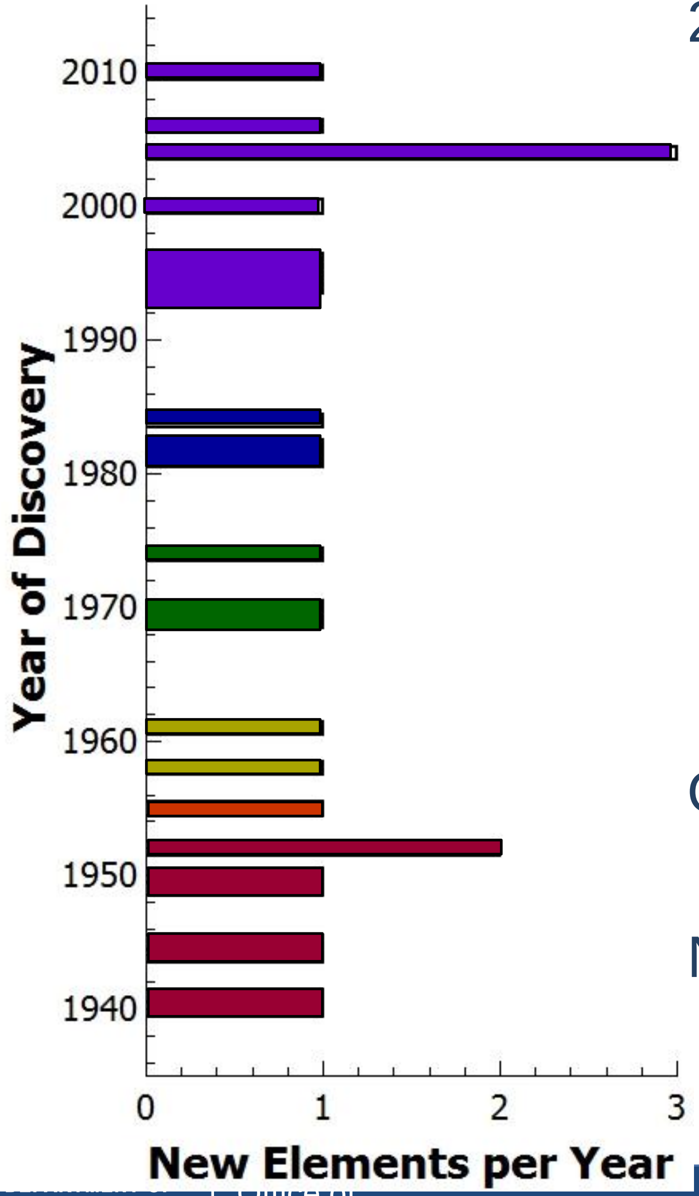
Summary and Conclusions

New Element: demonstrated existence of a nuclide with an atomic number Z not identified before, existing for at least 10^{-14} s

Superheavy: element with $Z \geq 104$, existence is due to shell effects

Tomorrow: How are elements made

Summary



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

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