



# The Quest for Gold Exploring Nuclear Transmutation

January 2025

Presented by Candace Davison, M. Engr.

# Alchemy

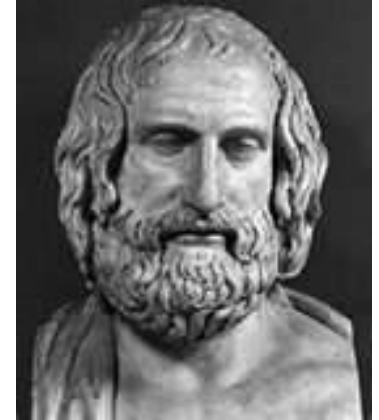


# A brief history of atoms and alchemy

## Anaxagoras

- Greek, born 500 B.C.
- Infinite divisibility of matter

*“Of what is small, there is no smallest part, but always a smaller.”*



## Empedocles

- Greek, born 490 B.C.
- Four basic elements: earth, air, fire, water
- Conservation of mass

*“Nothing new comes or can come into being; the only change that can occur is a change in the arrangement of the elements.”*



# A brief history of atoms and alchemy

## Democritus

- Greek, Born 460 B.C.
- Everything is composed of atoms
  - Indestructible, indivisible
  - Empty space between them
  - Always in motion
- Origin of the universe
  - Atoms came together to form larger substances
- More than four elements

*“Nothing exists but atoms and space, all else is opinion.”*

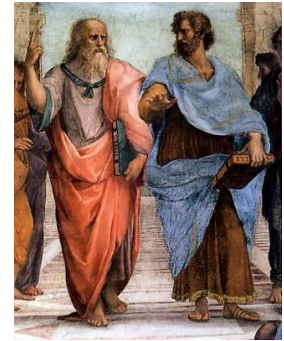
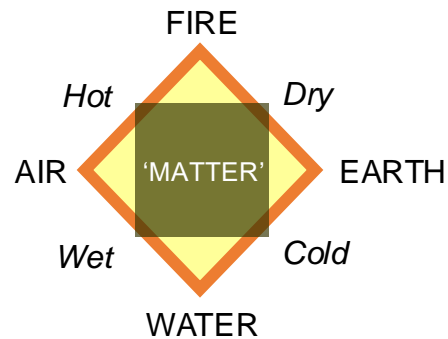


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# A brief history of atoms and alchemy

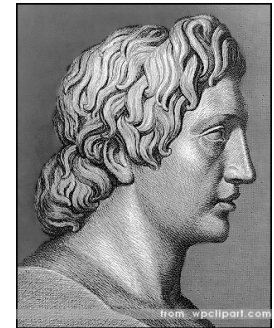
## Aristotle and Plato

- Believed there were only four elements
- Elements can transform to other elements

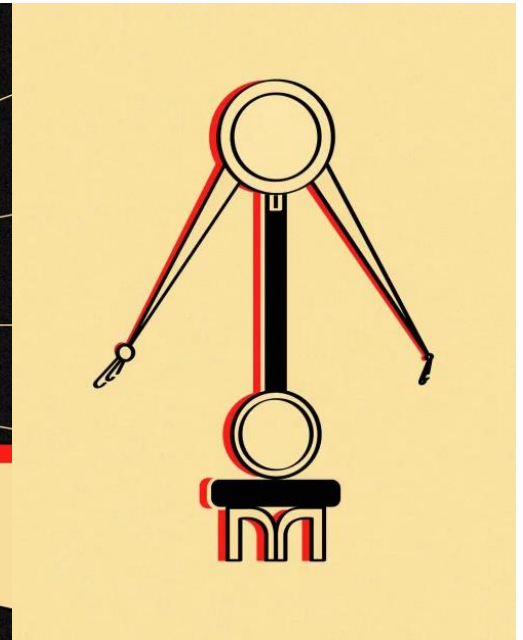
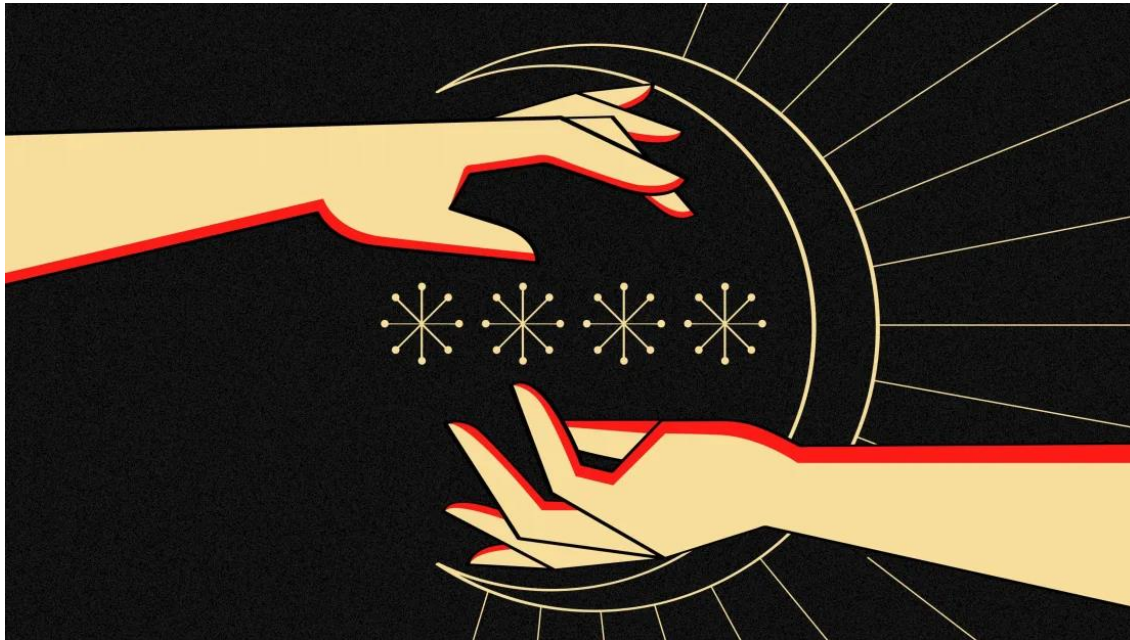


## Alexander the Great

- King of Macedon
- Tutored by Aristotle
- Alchemy was deemed only science worth pursuing



# Cleopatra Chrysopoeia



# Periodic Table of the Elements

IUPAC Periodic Table of the Elements

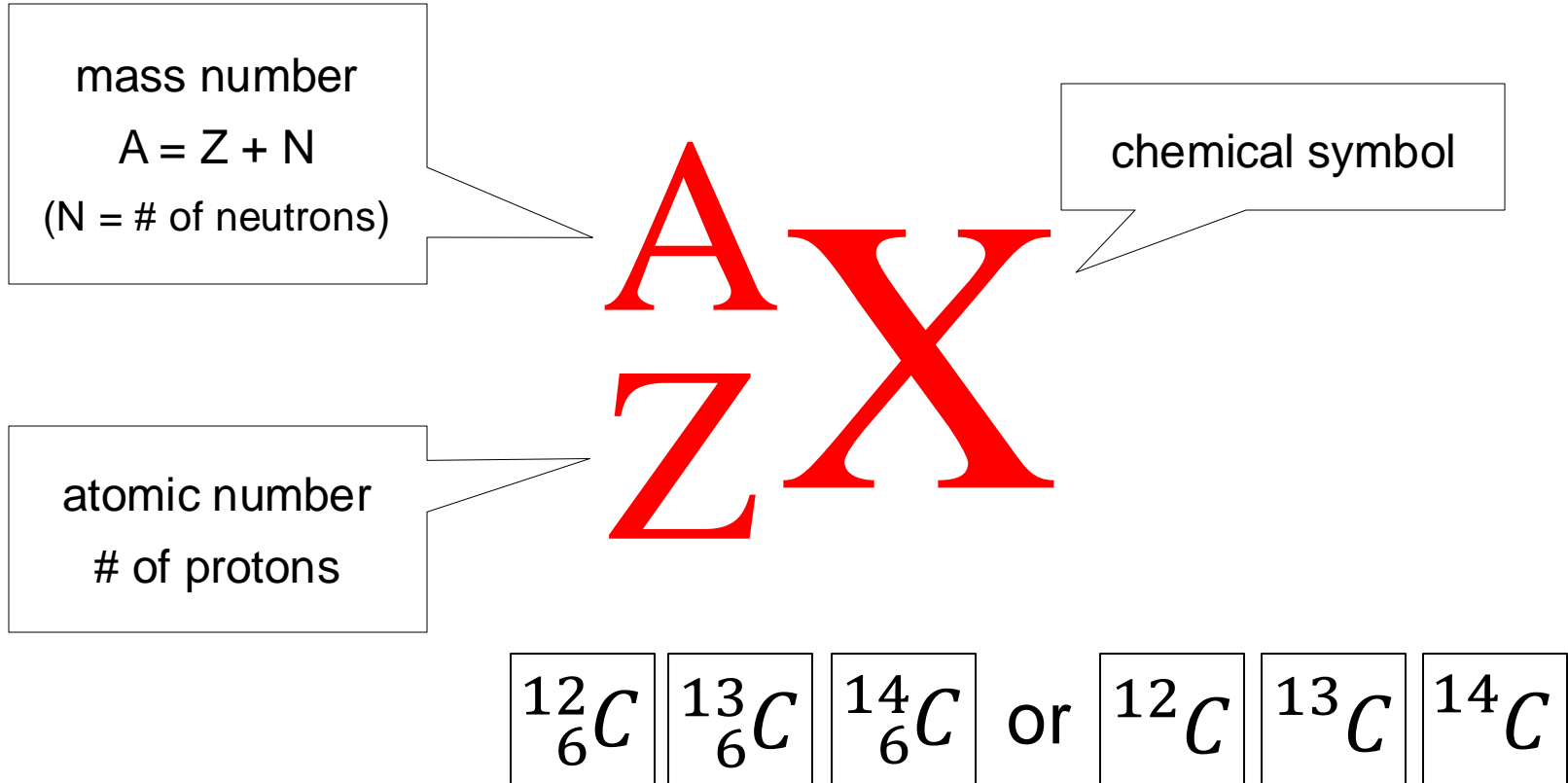
1 <b>H</b> hydrogen 1.008 [1.0078, 1.0082]																	2 <b>He</b> helium 4.0026
3 <b>Li</b> lithium 6.94 [6.938, 6.997]	4 <b>Be</b> beryllium 9.0122	Key: atomic number <b>Symbol</b> name conventional atomic weight standard atomic weight										13 <b>B</b> boron 10.81 [10.806, 10.821]	14 <b>C</b> carbon 12.011 [12.009, 12.012]	15 <b>N</b> nitrogen 14.007 [14.006, 14.008]	16 <b>O</b> oxygen 15.999 [15.999, 16.000]	17 <b>F</b> fluorine 18.998	18 <b>Ne</b> neon 20.180
11 <b>Na</b> sodium 22.990	12 <b>Mg</b> magnesium 24.305 [24.304, 24.307]											13 <b>Al</b> aluminium 26.982	14 <b>Si</b> silicon 28.085 [28.084, 28.086]	15 <b>P</b> phosphorus 30.974	16 <b>S</b> sulfur 32.06 [32.059, 32.076]	17 <b>Cl</b> chlorine 35.45 [35.446, 35.457]	18 <b>Ar</b> argon 39.948
19 <b>K</b> potassium 39.098	20 <b>Ca</b> calcium 40.078(4)	21 <b>Sc</b> scandium 44.956	22 <b>Ti</b> titanium 47.867	23 <b>V</b> vanadium 50.942	24 <b>Cr</b> chromium 51.996	25 <b>Mn</b> manganese 54.938	26 <b>Fe</b> iron 55.845(2)	27 <b>Co</b> cobalt 58.933	28 <b>Ni</b> nickel 58.693	29 <b>Cu</b> copper 63.546(3)	30 <b>Zn</b> zinc 65.38(2)	31 <b>Ga</b> gallium 69.723	32 <b>Ge</b> germanium 72.630(8)	33 <b>As</b> arsenic 74.922	34 <b>Se</b> selenium 78.971(8)	35 <b>Br</b> bromine 79.904 [79.901, 79.907]	36 <b>Kr</b> krypton 83.798(2)
37 <b>Rb</b> rubidium 85.468	38 <b>Sr</b> strontium 87.62	39 <b>Y</b> yttrium 88.906	40 <b>Zr</b> zirconium 91.224(2)	41 <b>Nb</b> niobium 92.906	42 <b>Mo</b> molybdenum 95.95	43 <b>Tc</b> technetium	44 <b>Ru</b> ruthenium 101.07(2)	45 <b>Rh</b> rhodium 102.91	46 <b>Pd</b> palladium 106.42	47 <b>Ag</b> silver 107.87	48 <b>Cd</b> cadmium 112.41	49 <b>In</b> indium 114.82	50 <b>Sn</b> tin 118.71	51 <b>Sb</b> antimony 121.76	52 <b>Te</b> tellurium 127.60(3)	53 <b>I</b> iodine 126.90	54 <b>Xe</b> xenon 131.29
55 <b>Cs</b> caesium 132.91	56 <b>Ba</b> barium 137.33	57-71 lanthanoids	72 <b>Hf</b> hafnium 178.49(2)	73 <b>Ta</b> tantalum 180.95	74 <b>W</b> tungsten 183.84	75 <b>Re</b> rhenium 186.21	76 <b>Os</b> osmium 190.23(3)	77 <b>Ir</b> iridium 192.22	78 <b>Pt</b> platinum 195.08	79 <b>Au</b> gold 196.97	80 <b>Hg</b> mercury 200.59	81 <b>Tl</b> thallium 204.38 [204.38, 204.39]	82 <b>Pb</b> lead 207.2	83 <b>Bi</b> bismuth 208.98	84 <b>Po</b> polonium	85 <b>At</b> astatine	86 <b>Rn</b> radon
87 <b>Fr</b> francium	88 <b>Ra</b> radium	89-103 actinoids	104 <b>Rf</b> rutherfordium	105 <b>Db</b> dubnium	106 <b>Sg</b> seaborgium	107 <b>Bh</b> bohrium	108 <b>Hs</b> hassium	109 <b>Mt</b> meitnerium	110 <b>Ds</b> darmstadtium	111 <b>Rg</b> roentgenium	112 <b>Cn</b> copernicium	113 <b>Nh</b> nihonium	114 <b>Fl</b> flerovium	115 <b>Mc</b> moscovium	116 <b>Lv</b> livermorium	117 <b>Ts</b> tennessine	118 <b>Og</b> oganesson



57 <b>La</b> lanthanum 138.91	58 <b>Ce</b> cerium 140.12	59 <b>Pr</b> praseodymium 140.91	60 <b>Nd</b> neodymium 144.24	61 <b>Pm</b> promethium 150.36(2)	62 <b>Sm</b> samarium 151.96	63 <b>Eu</b> europium 157.25(3)	64 <b>Gd</b> gadolinium 158.93	65 <b>Tb</b> terbium 162.50	66 <b>Dy</b> dysprosium 164.93	67 <b>Ho</b> holmium 167.26	68 <b>Er</b> erbium 168.93	69 <b>Tm</b> thulium 173.05	70 <b>Yb</b> ytterbium 174.97	71 <b>Lu</b> lutetium
89 <b>Ac</b> actinium 227.03	90 <b>Th</b> thorium 232.04	91 <b>Pa</b> protactinium 231.04	92 <b>U</b> uranium 238.03	93 <b>Np</b> neptunium	94 <b>Pu</b> plutonium	95 <b>Am</b> americium	96 <b>Cm</b> curium	97 <b>Bk</b> berkelium	98 <b>Cf</b> californium	99 <b>Es</b> einsteinium	100 <b>Fm</b> fermium	101 <b>Md</b> mendelevium	102 <b>No</b> nobelium	103 <b>Lr</b> lawrencium

For notes and updates to this table, see [www.iupac.org](http://www.iupac.org). This version is dated 28 November 2016.  
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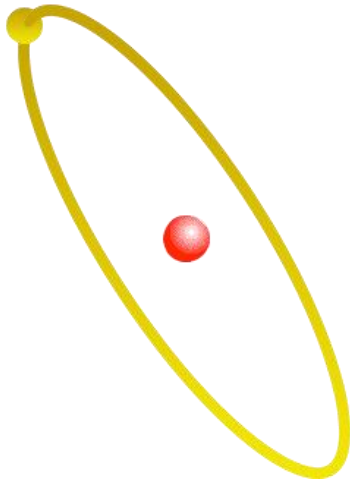
# Standard nuclear notation



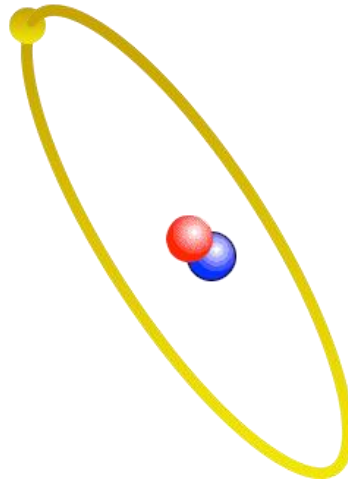


# Isotopes

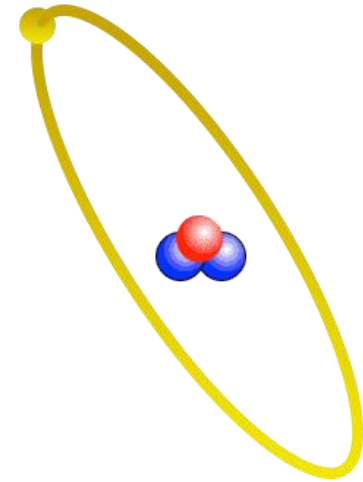
Three isotopes of hydrogen



Hydrogen  
H-1



Deuterium  
H-2



Tritium  
H-3

# Why are atoms radioactive?

	1																18	
1	H 1																He 2	
2	Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
3	Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
4	K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
5	Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
6	Cs 55	Ba 56	*	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
7	Fr 87	Ra 88	**	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Cn 112	Nh 113	Fl 114	Mc 115	Lv 116	Ts 117	Og 118

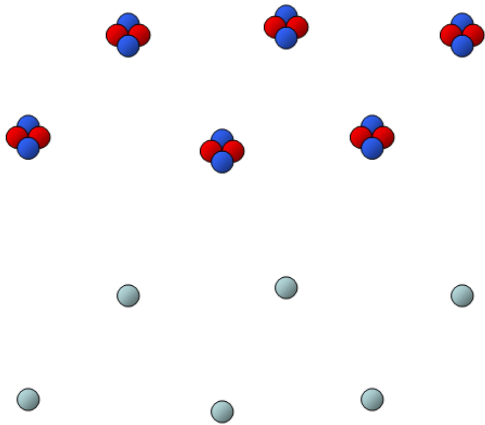
* lanthanoids	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
** actinoids	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

# Nuclear stability

- An unstable nucleus becomes more stable by rearranging its nuclear structure and emitting *radiation*.
- If unstable after radioactive decay, further decay is possible.

# What is radiation?

Transmission of energy via:



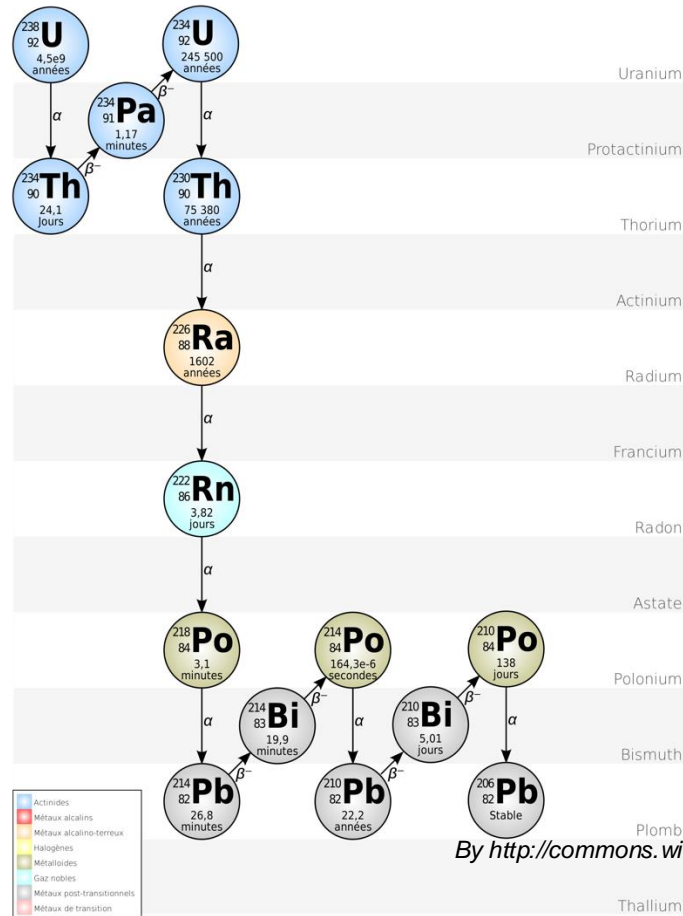
Particles

or



Waves

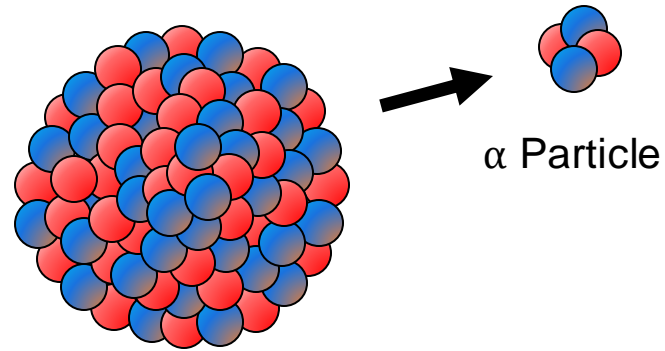
# Radioactive decay - transmutation



By <http://commons.wikimedia.org/wiki/User:BatesIsBack>

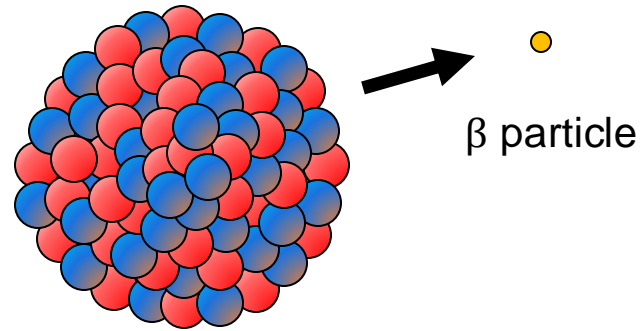
# Alpha particle $\alpha$

Helium nucleus that is emitted from a radioactive atom's nucleus



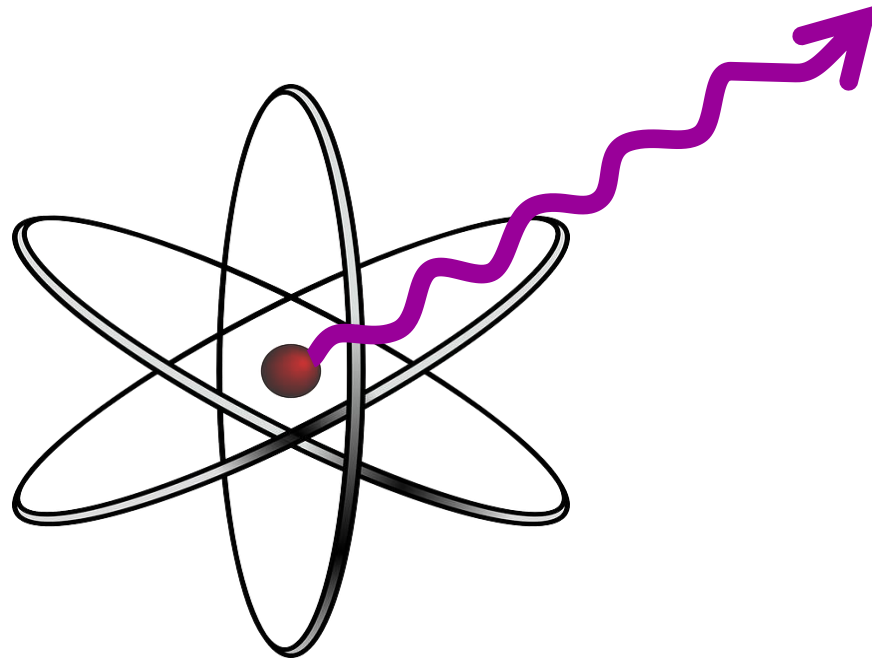
# Beta particle $\beta^-$

Electron emitted from  
an atom's nucleus  
when a neutron  
converts to a proton



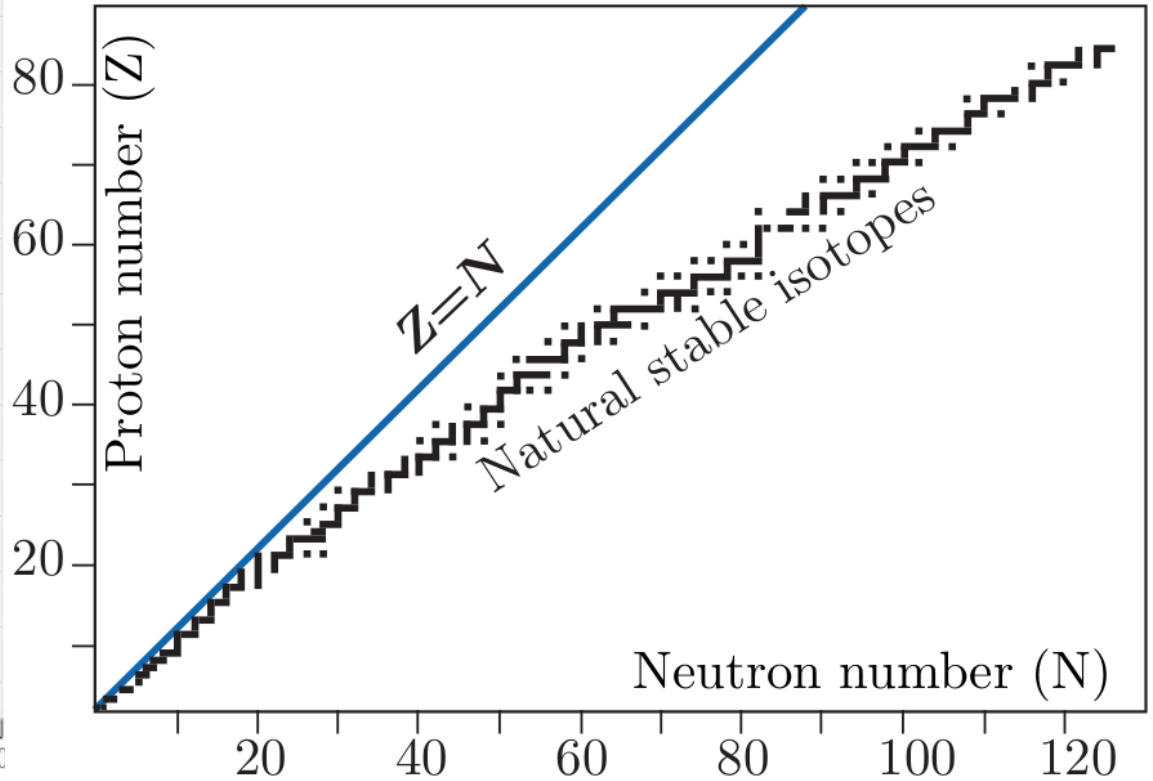
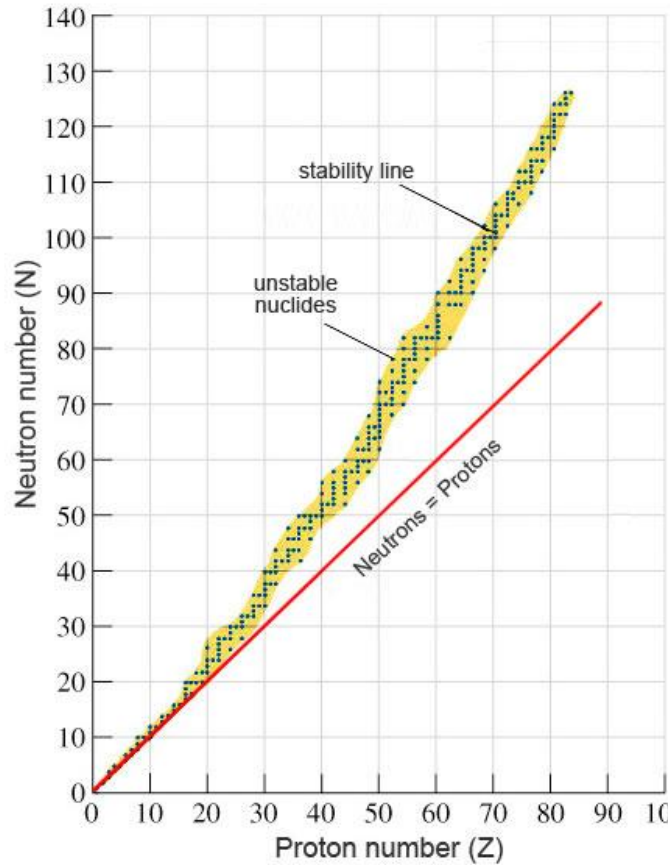
# Gamma ray $\gamma$

High-energy photon emitted from an atom's nucleus





# What make a nucleus unstable?



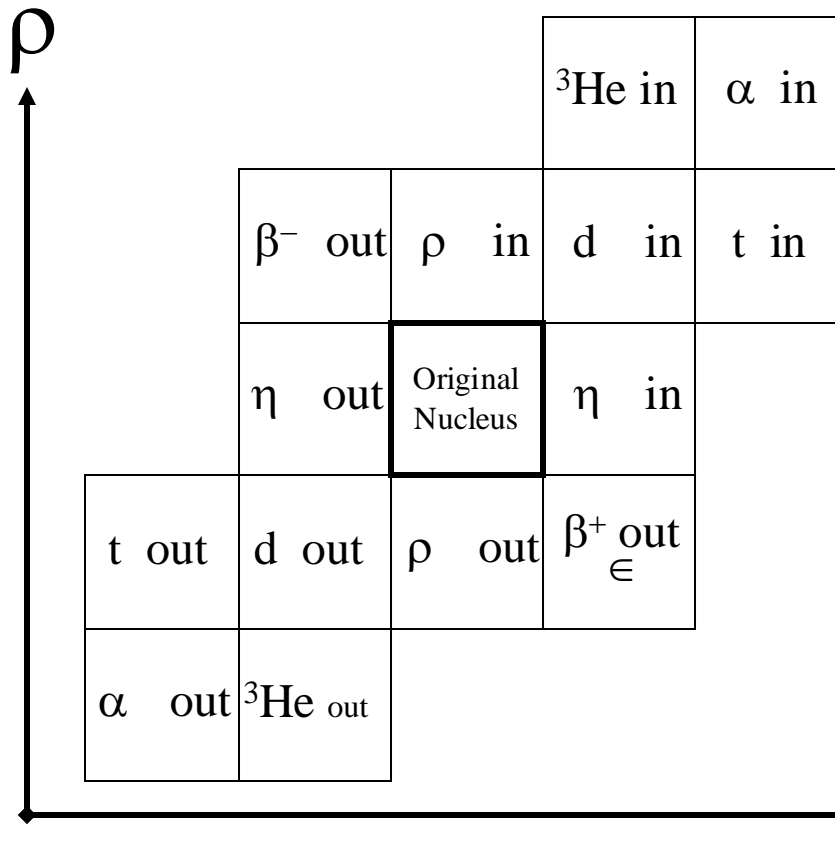
# Nuclear stability

- Only certain combinations of neutrons and protons lead to a stable atom.
- In a stable atom, the attractive and repulsive forces in the nucleus balance.

# Nuclear stability

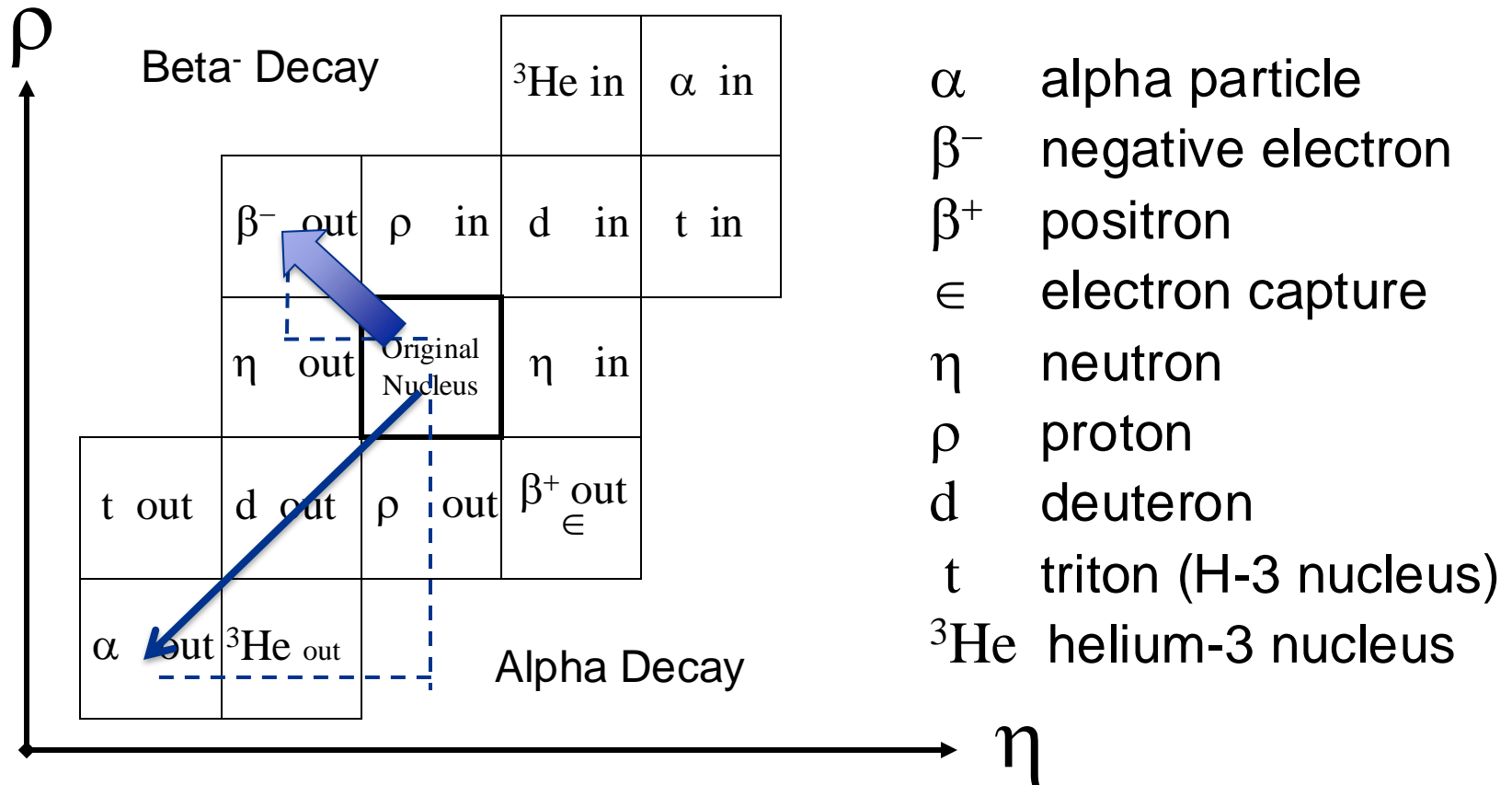
- Atoms with unstable nuclei are radioactive.
- If unstable after radioactive decay, further decay is possible.
- Nuclei decay toward the line of stability.

# Relative locations of products of various nuclear processes

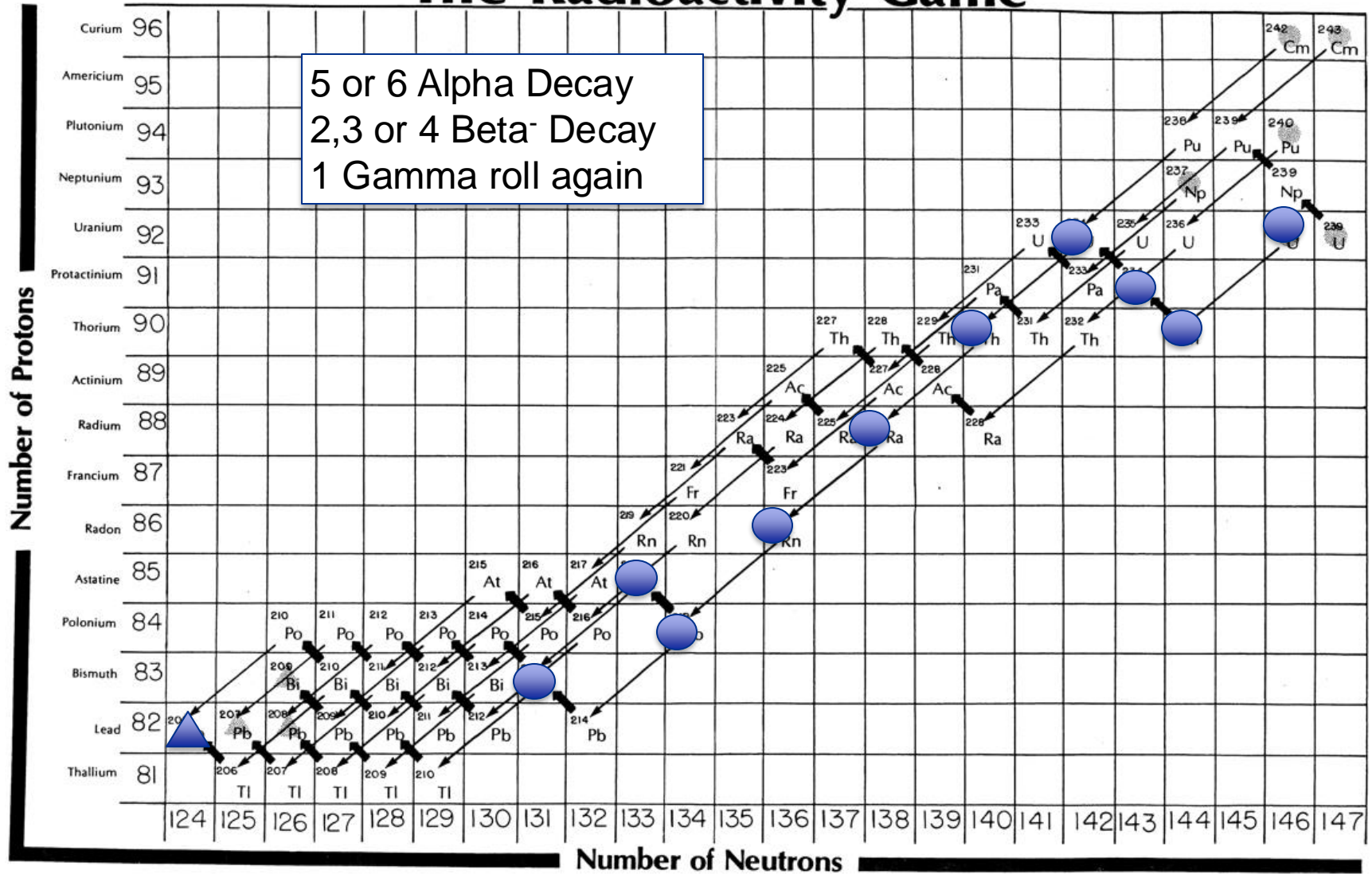


- $\alpha$  alpha particle
- $\beta^-$  negative electron
- $\beta^+$  positron
- $\epsilon$  electron capture
- $\eta$  neutron
- $\rho$  proton
- d deuteron
- t triton (H-3 nucleus)
- ${}^3\text{He}$  helium-3 nucleus

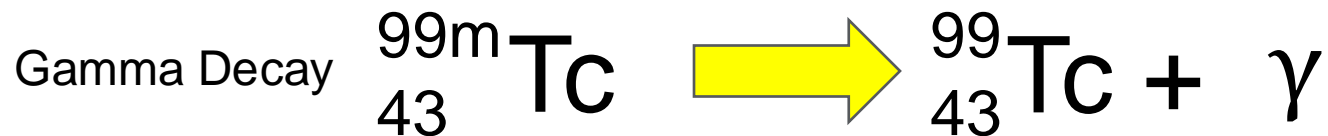
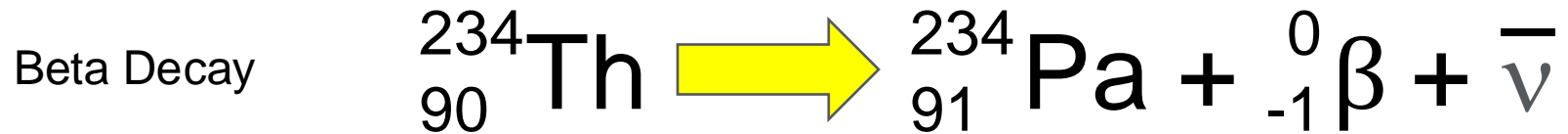
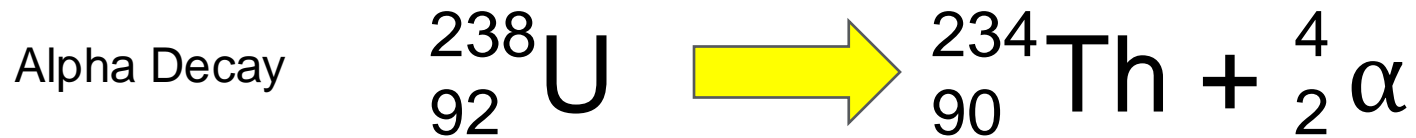
# Relative locations of products of various nuclear processes



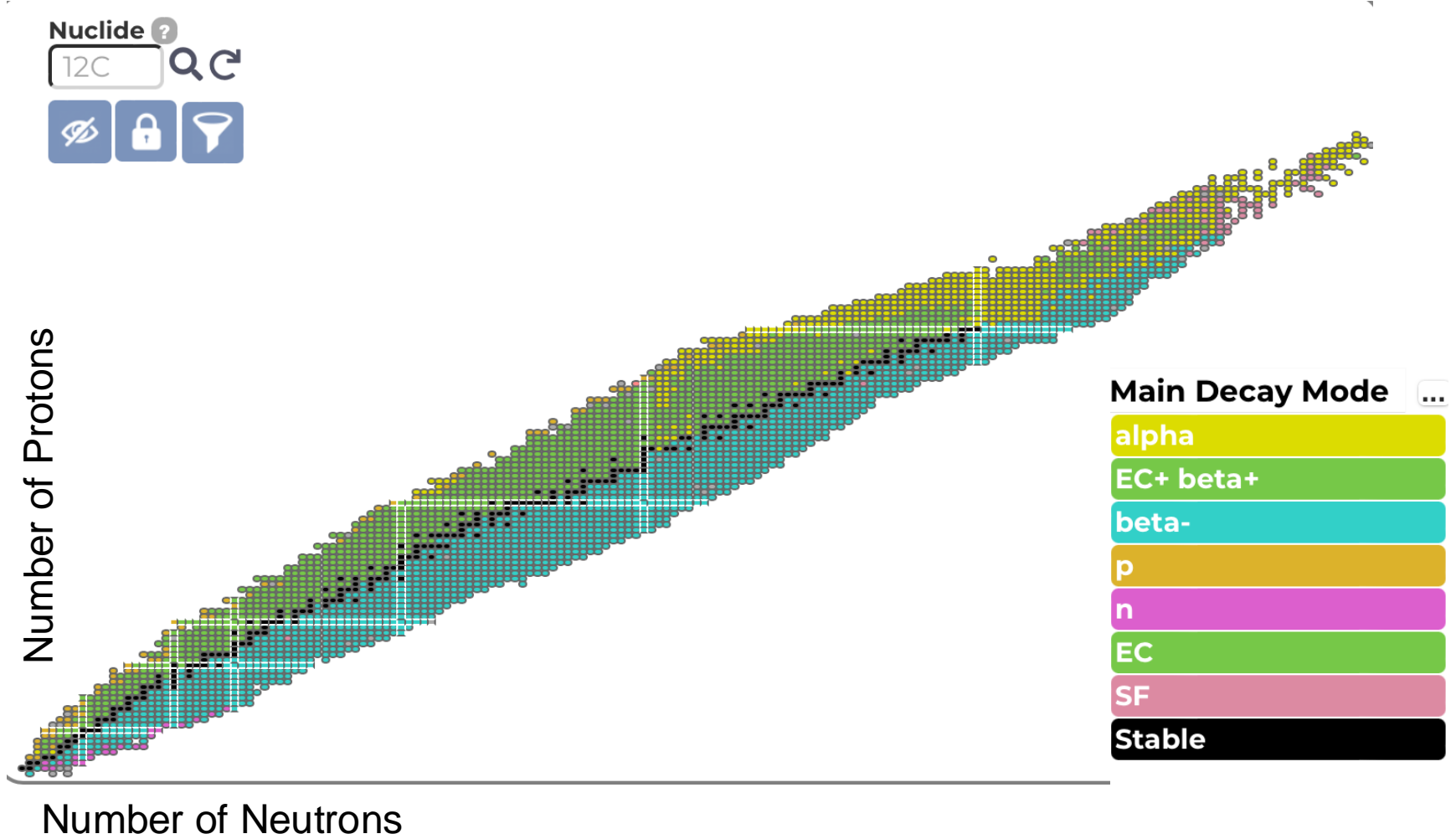
# The Radioactivity Game



# Radioactive decay equations



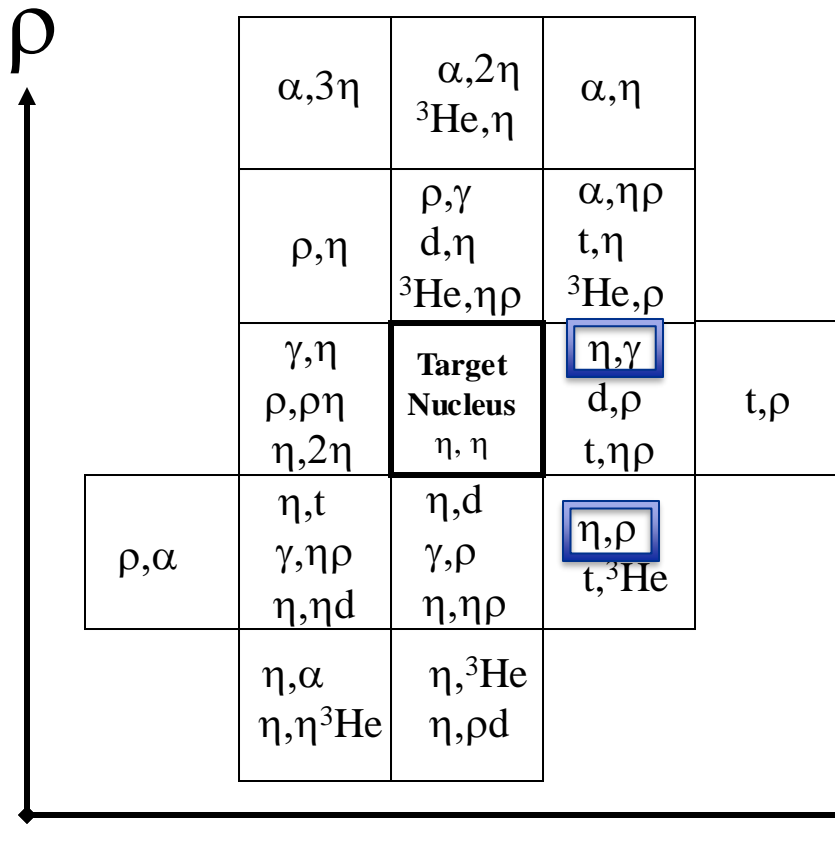
# IAEA Chart of Nuclides



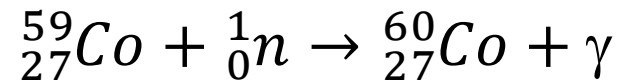
<https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html>



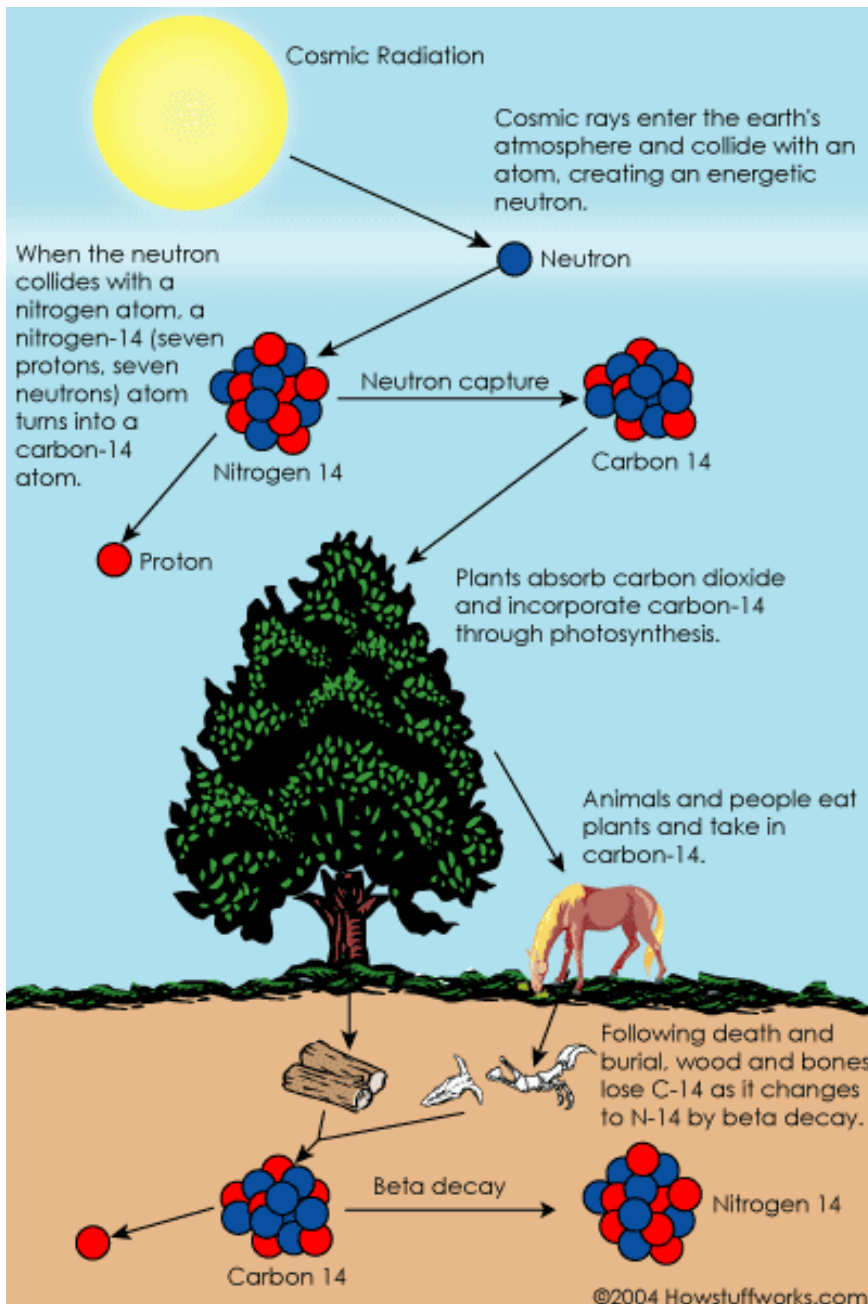
# Nuclear Reactions



- $\alpha$  alpha particle
- $\gamma$  gamma
- $\eta$  neutron
- $\rho$  proton
- $d$  deuteron ( ${}^2\text{H}$  nucleus)
- $t$  triton ( ${}^3\text{H}$  nucleus)
- ${}^3\text{He}$  helium-3 nucleus

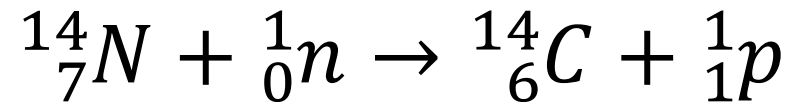


# Carbon-14

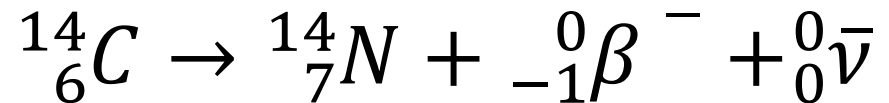


Production

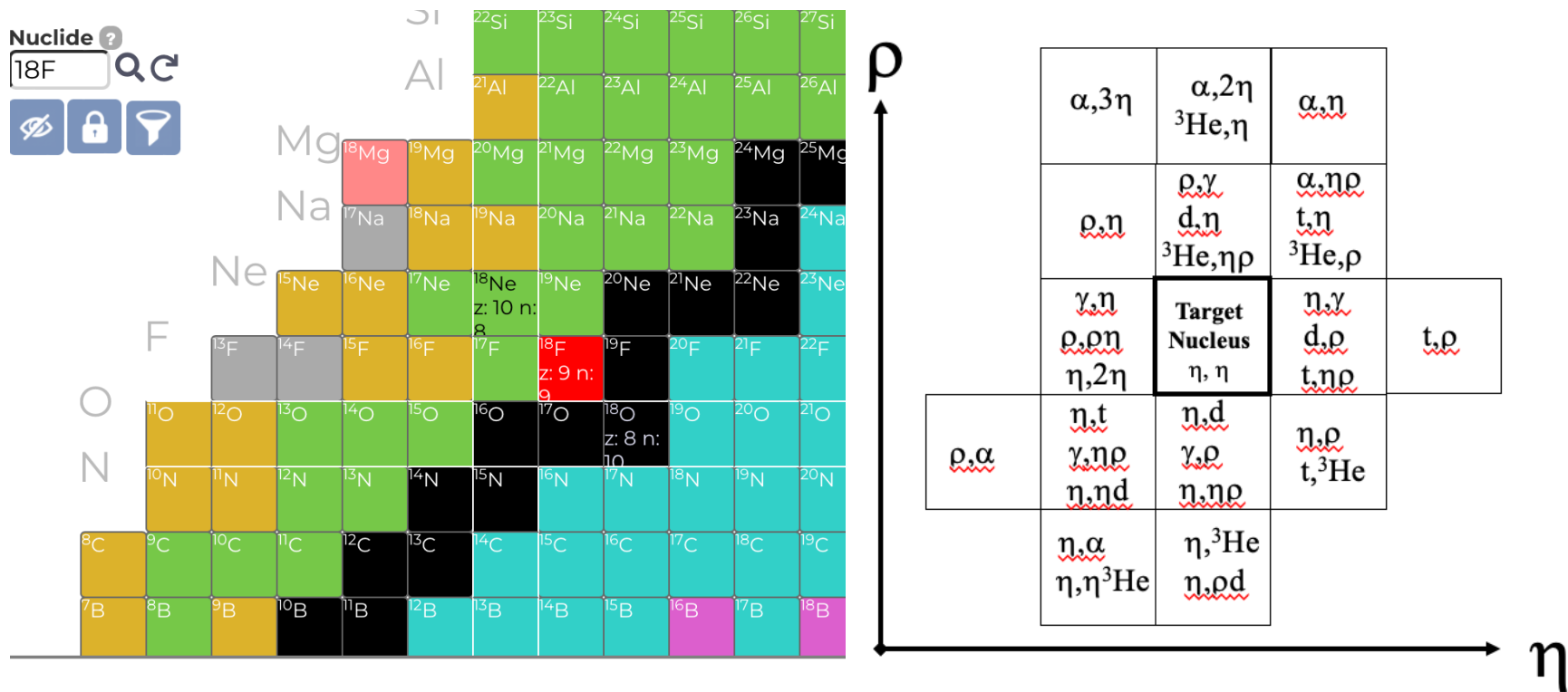
N-14 Target (n,p)



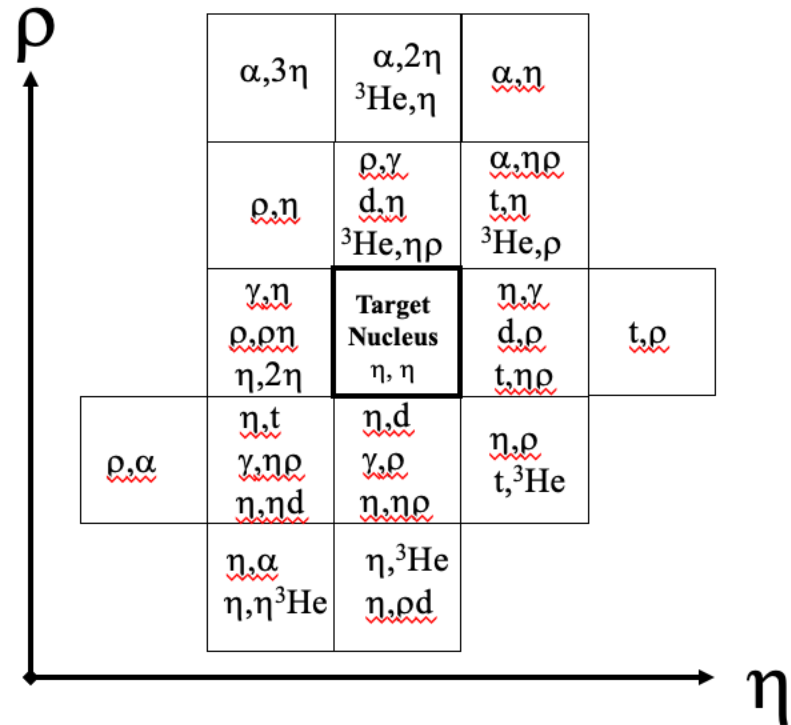
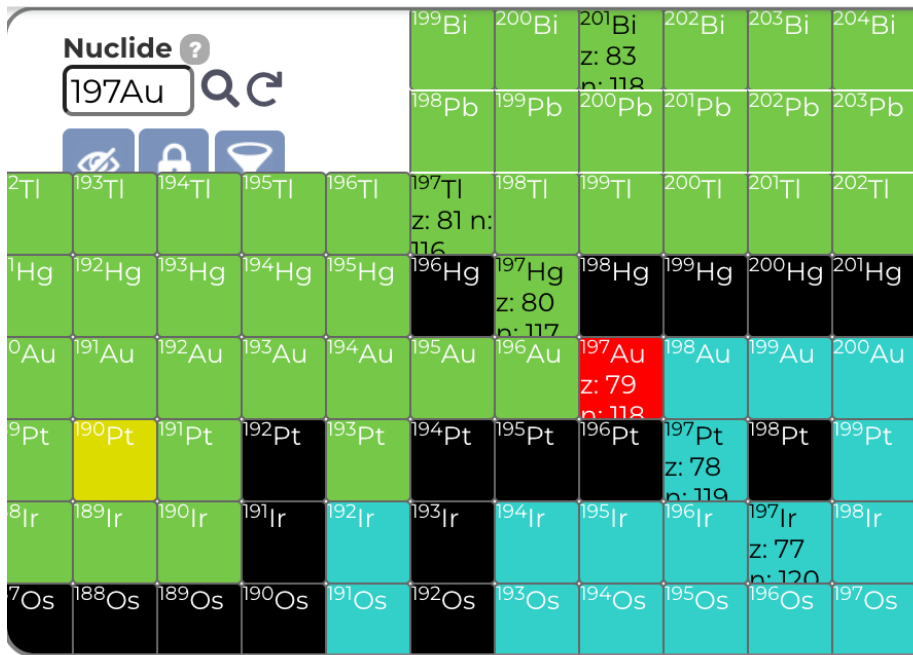
Radioactive Decay



# How can we make Fluorine-18?



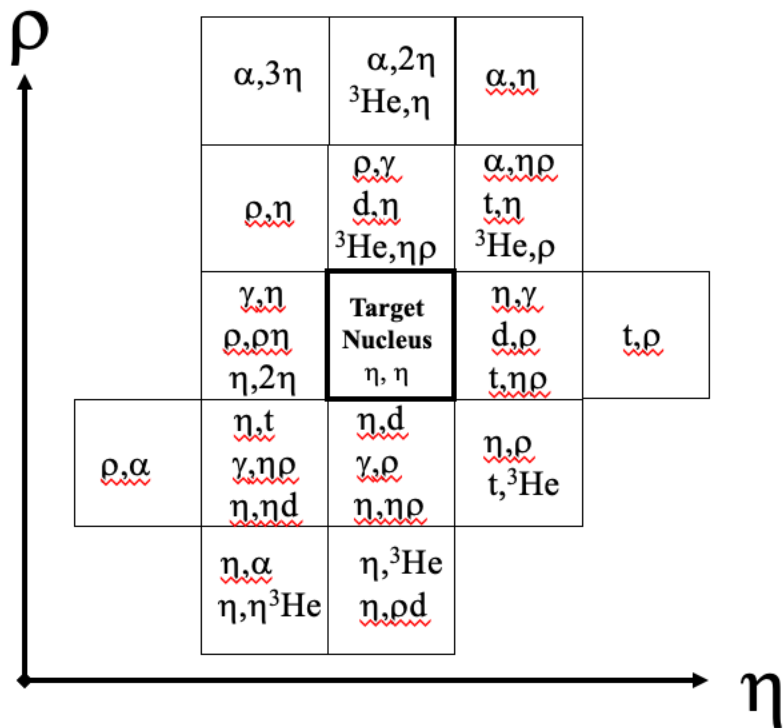
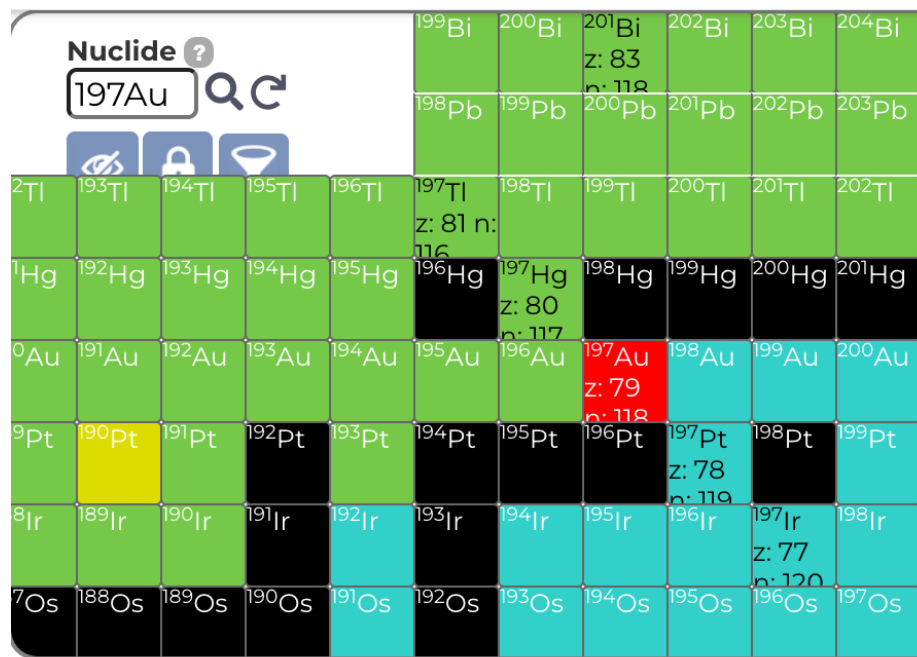
# What reactions can we use to make gold?



Screenshot from:

<https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html#lastnuc=197Au>

# Possible Reactions to Produce Gold

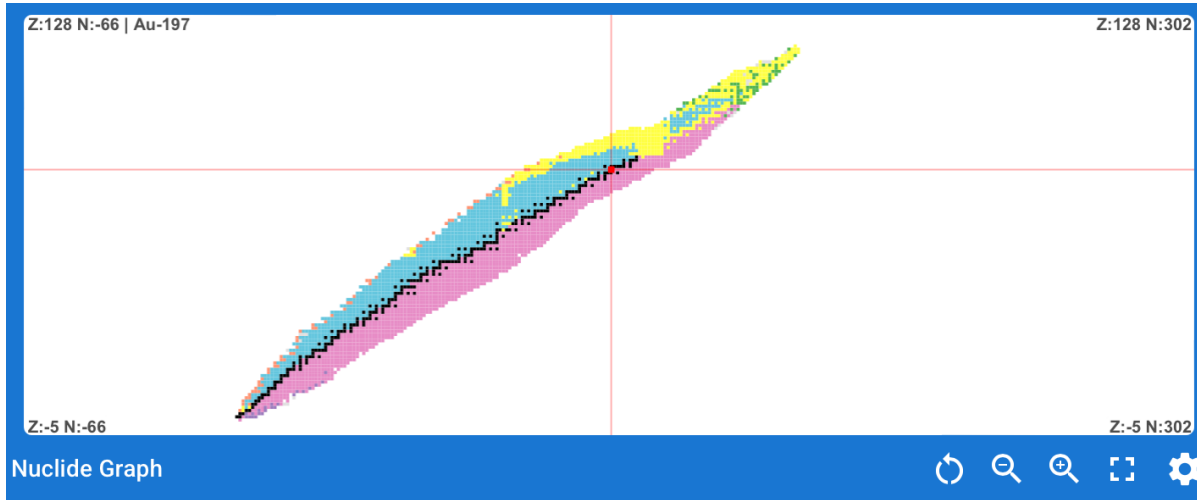


Survey Answers

- $^{196}\text{Pt}(p, \gamma)$
- $^{198}\text{Hg}(\gamma, p)$
- $^{199}\text{Hg}(n, t)$

# ANS Isotope Discovery App

Demo



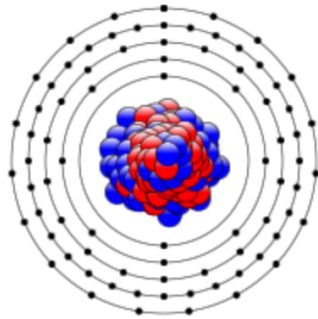
Proton

79

+



Gold-197



This form of Gold is **Stable**

Neutron

118

+



# ANS Resources

ANS Educational Resources  
[ans.org/nuclear](https://ans.org/nuclear)

Navigating Nuclear (nuclear science curriculum for grades 3-12)  
[ans.org/nuclear/navigatingnuclear](https://ans.org/nuclear/navigatingnuclear)

ANS Isotope Discovery App  
(link in chat)

Educator Training Webinars  
[ans.org/nuclear/k12programs/educator/](https://ans.org/nuclear/k12programs/educator/)

Build a Nucleus: K-12 Classroom Investigations  
[ans.org/webinars/view-edbn2024/](https://ans.org/webinars/view-edbn2024/)

Decoding Radioactive Decay: Alpha, Beta, Gamma, and More

[ans.org/webinars/view-etdd23/](https://ans.org/webinars/view-etdd23/)

Radioisotopes:  
Nuclear Applications Beyond Energy  
[ans.org/webinars/view-ediso2023/](https://ans.org/webinars/view-ediso2023/)

# Resources

Office of Nuclear Energy/  
Department of Energy  
<https://www.energy.gov/ne/office-nuclear-energy>

International Atomic Energy Agency  
IAEA. <https://www.iaea.org>  
Nuclear Explained  
<https://www.iaea.org/newscenter/nuclear-explained>

PhET Simulations  
[https://phet.colorado.edu/sims/html/build-an-atom/latest/build-an-atom\\_en.html](https://phet.colorado.edu/sims/html/build-an-atom/latest/build-an-atom_en.html)

Contemporary Physics Education  
Project CPEP  
<https://www.cpepphysics.org>

International Atomic Energy Agency  
IAEA. <https://www.iaea.org>  
Nuclear Explained  
<https://www.iaea.org/newscenter/nuclear-explained>

Hyperphysics – Georgia State  
University. <http://hyperphysics.phy-astr.gsu.edu/hbase/nuccon.html#c1>



# References

<https://www.discovermagazine.com/the-sciences/turning-lead-into-gold>

<https://www.scientificamerican.com/article/fact-or-fiction-lead-can-be-turned-into-gold/>

<https://www.mgsrefining.com/blog/alchemy-and-chrysopoeia/>

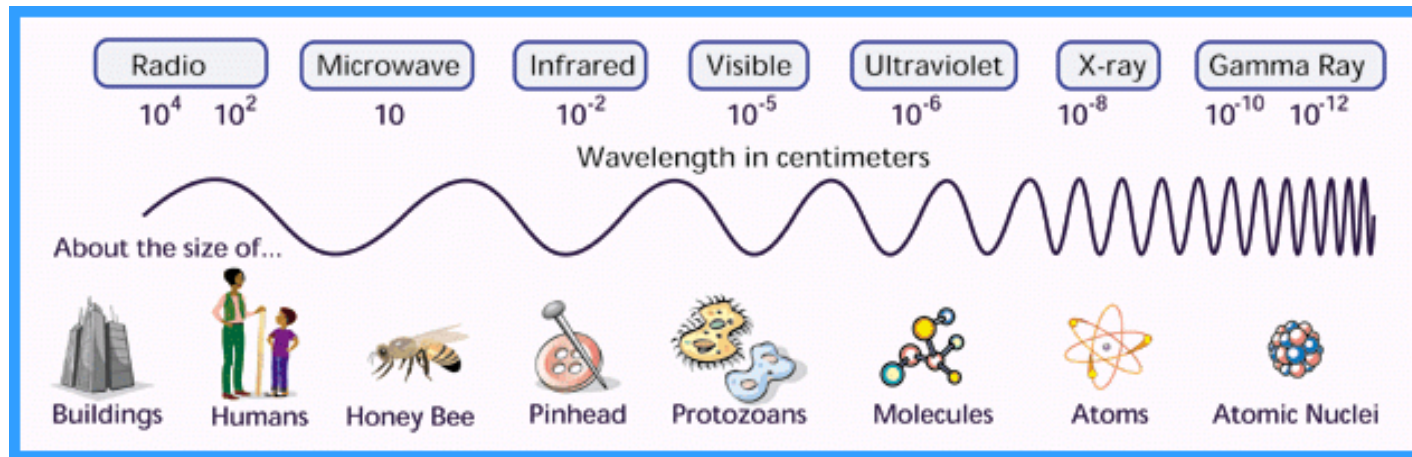
<https://www.cnn.com/style/article/cleopatra-chemist-louboutin/index.html>

<https://pmc.ncbi.nlm.nih.gov/articles/PMC4306521/>

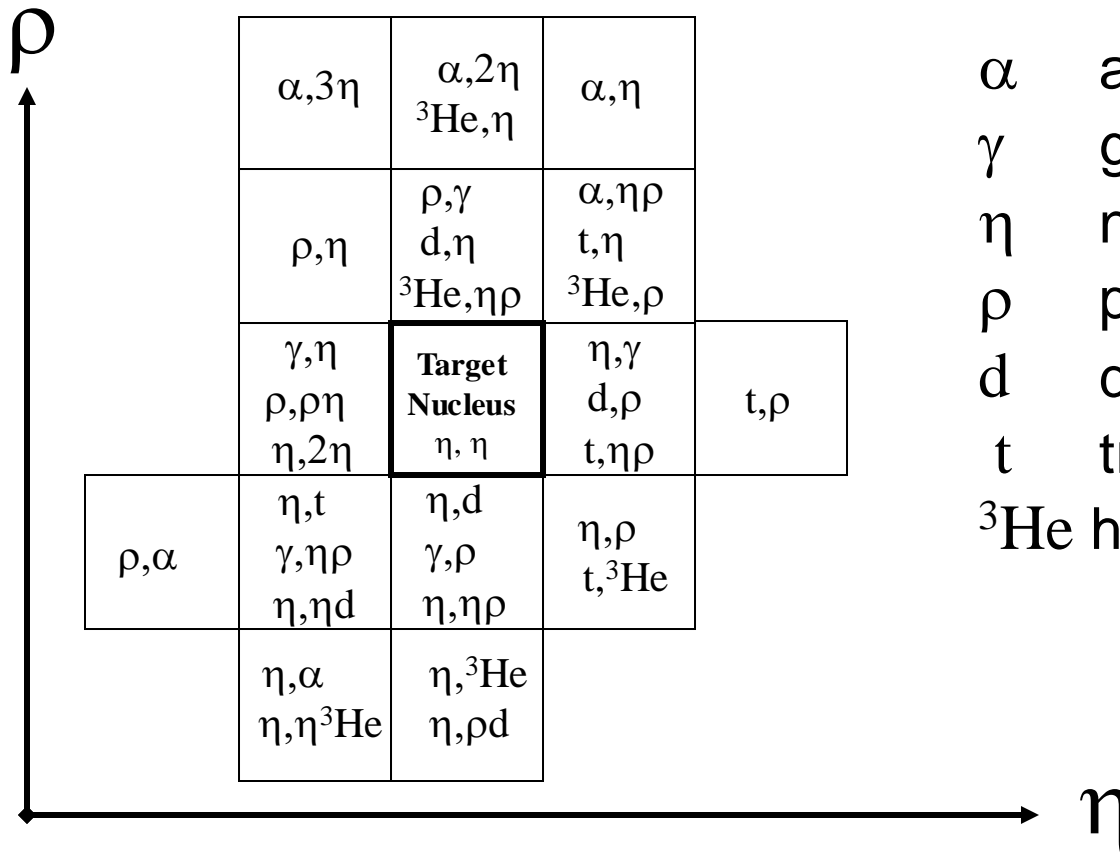
Cole EL, Stewart MN, Littich R, Hoareau R, Scott PJ. Radiosyntheses using fluorine-18: the art and science of late stage fluorination. *Curr Top Med Chem.* 2014;14(7):875-900. doi: 10.2174/1568026614666140202205035. PMID: 24484425; PMCID: PMC4140448.

**Questions?**

# Electromagnetic spectrum

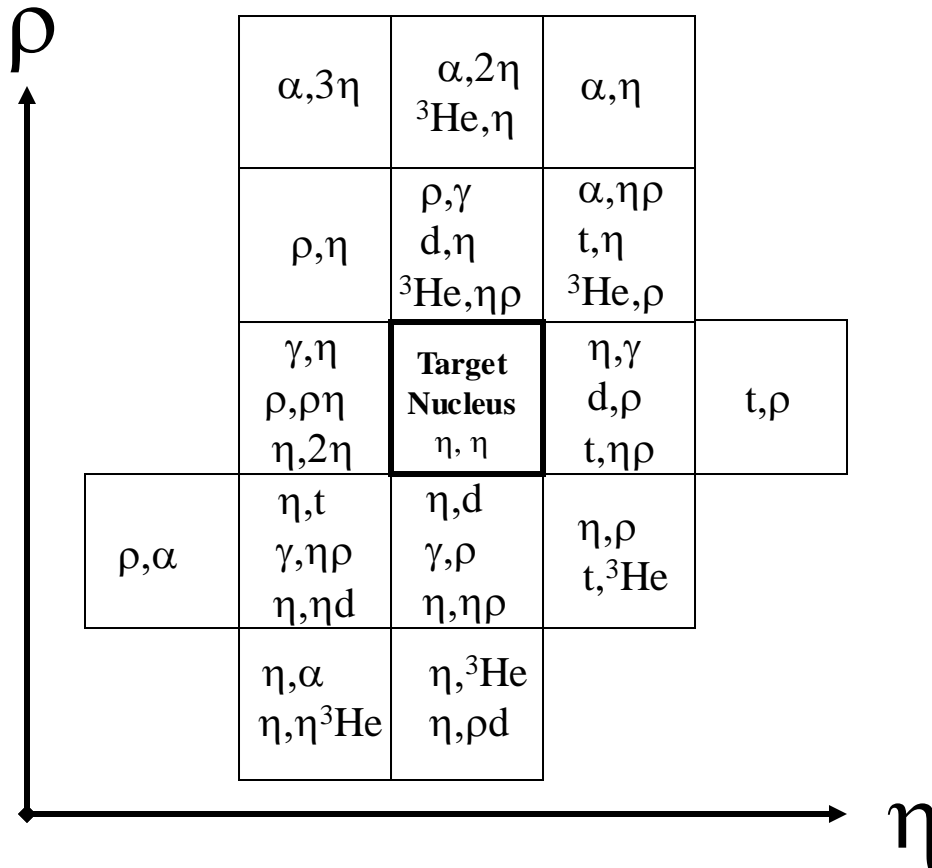


# Nuclear Reactions



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- ${}^3\text{He}$  helium-3 nucleus

# Nuclear Reactions

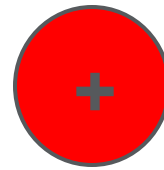


# More on this helium *isotope* . . .

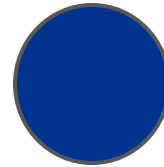
total number of  
**protons** and **neutrons**  
MASS NUMBER

**4**  
**He** ELEMENT  
SYMBOL

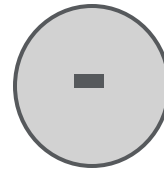
**2**  
ATOMIC NUMBER  
number of **protons**



Protons have a large mass and a positive charge. The number of protons identifies an element.



Neutrons have a large mass approximately equal to a proton's mass. Neutrons have no charge.



Electrons have a very small mass and a negative charge. Electrons travel outside the nucleus.