ATOMIC PHYSICS

IB PHYSICS | COMPLETED NOTES

Radioactive Decay

IB PHYSICS | ATOMIC PHYSICS

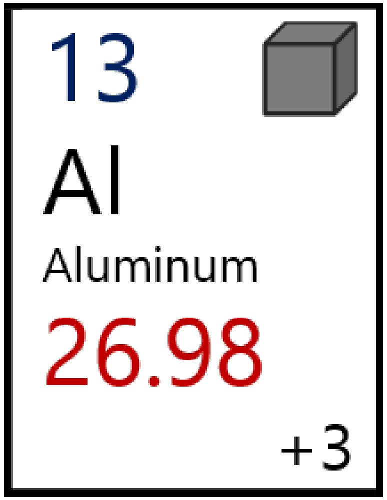
Standard Notation

What do you notice about the notation written below?
Can you determine what each color represents?

Mass Number

$$^{27}_{13}\mathrm{Al}$$

Atomic Number



$$^{A}_{Z}X$$

Try This

$^{23}_{11}Na$

$^{25}_{12}Mg$

Mass Number	23
Atomic Number	11
# of Protons	11
# of Neutrons	12

Mass Number	25
Atomic Number	12
# of Protons	12
# of Neutrons	13

Sample IB Question

A nucleus of Californium (Cf) contains 98 protons and 154 neutrons. Which of the following correctly identifies this nucleus of Californium?

$^{98}_{254}Cf$

$^{252}_{98}Cf$

$^{154}_{98}Cf$

$^{350}_{154}Cf$

Isotopes & Nuclides

$^{12}_{6}C$ $^{14}_{6}C$

Isotopes of Carbon

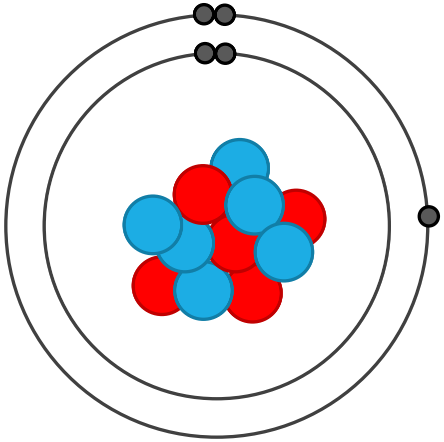
Same # of protons

Different # of neutrons

Nuclide

Single atom configuration

Fundamental Forces



$$ {}^{11}_{5}\mathrm{B} $$

Remember Coulomb's Law?

$$F = k\frac{q_1 q_2}{r^2}$$

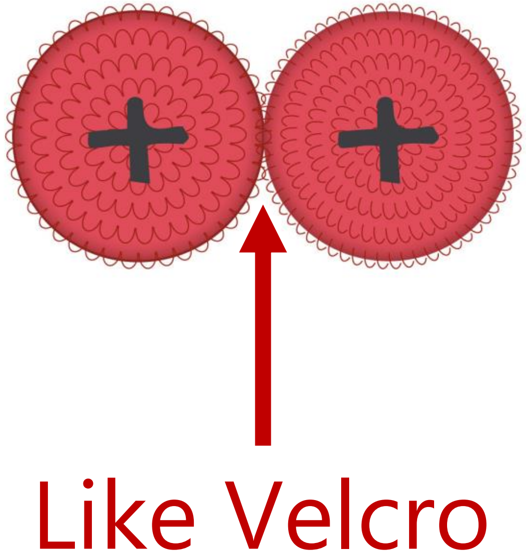
Opposite charges attract

Like charges repel

Fundamental Forces

Strong Nuclear Force

- Very short range
- Very <u>strong</u>

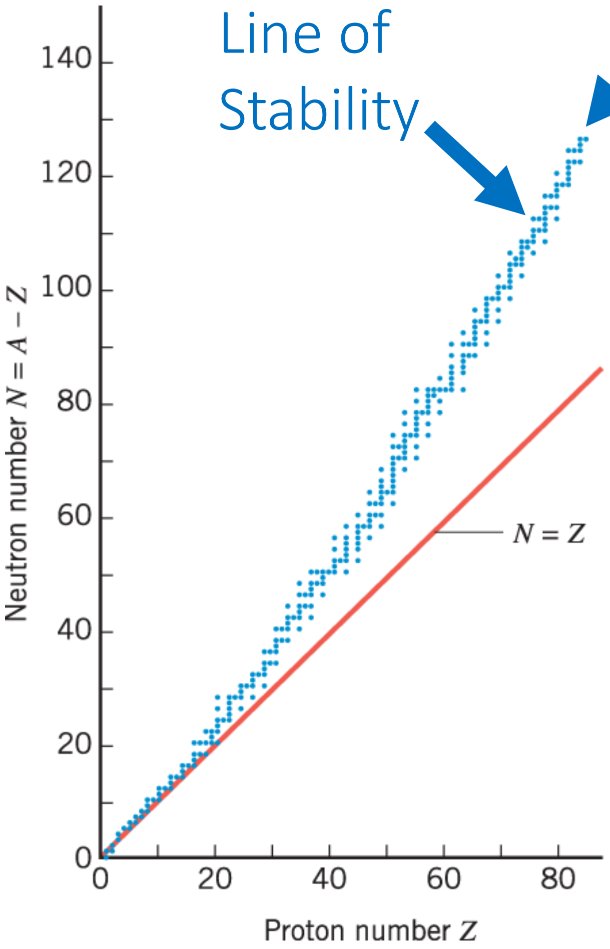


Electromagnetic Force

Gravitational Force

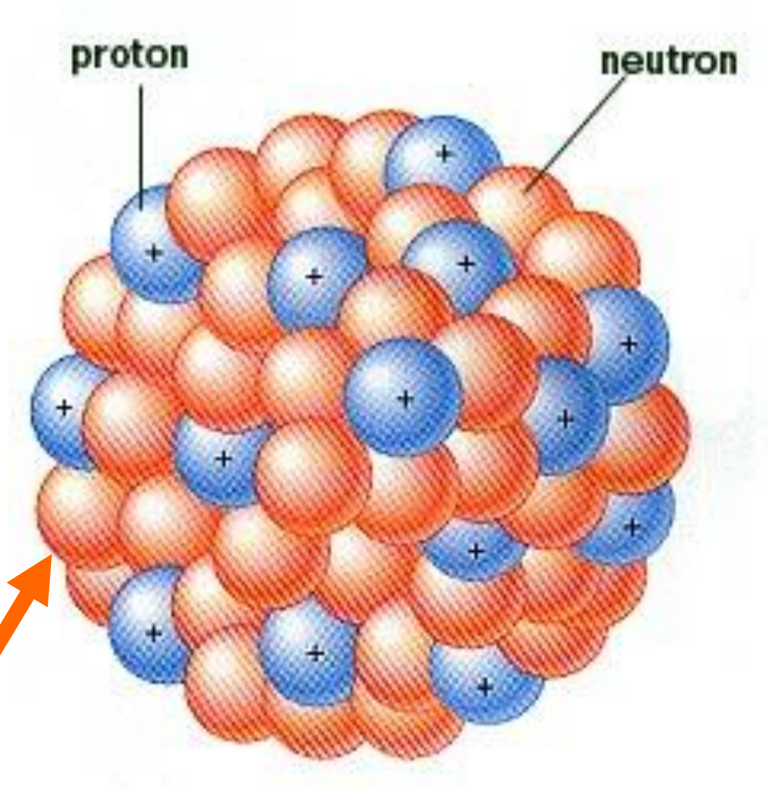
Weak Nuclear Force

Unstable Nuclei



Line of Stability

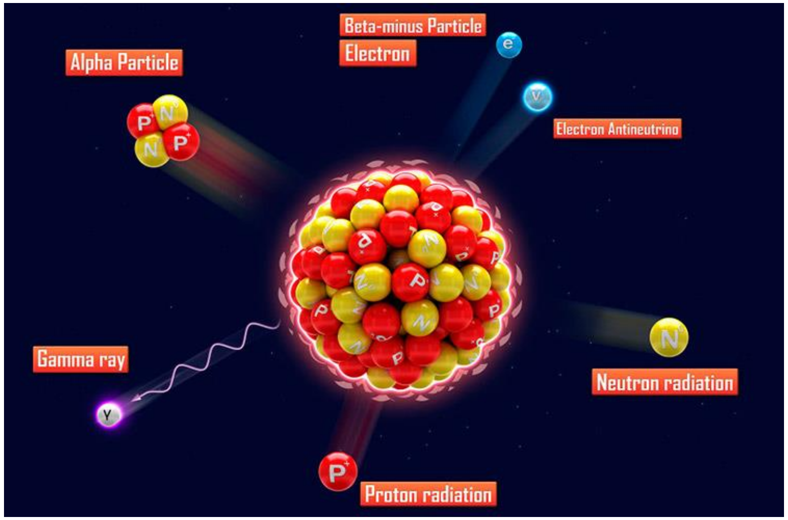
More neutrons than protons



Neutrons serve as a buffer between repelling protons

Radioactivity

Radioactivity is a process where unstable elements decay into new elements and release energy as particles and/or waves



Alpha Decay

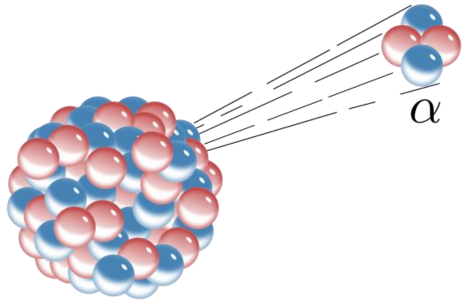
An unstable nucleus sheds alpha particle (helium nucleus) made from **2 protons** and **2 neutrons**

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}X + {}^{4}_{2}He$$

Parent Nuclide

Daughter Nuclide

Alpha Particle



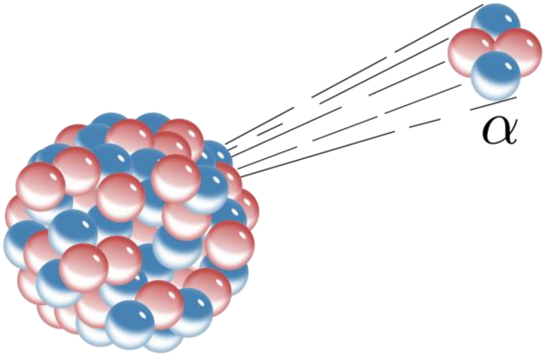
Complete the missing notation:

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

Alpha Decay - Predict

$$^{222}_{88}\mathrm{Ra} \rightarrow {}^{218}_{86}\mathrm{Rn} + \underline{\;^{4}_{2}\mathrm{He}\;}$$

$$^{208}_{84}\mathrm{Po} \rightarrow {}^{204}_{82}\mathrm{Pb} + {}^{4}_{2}\alpha$$

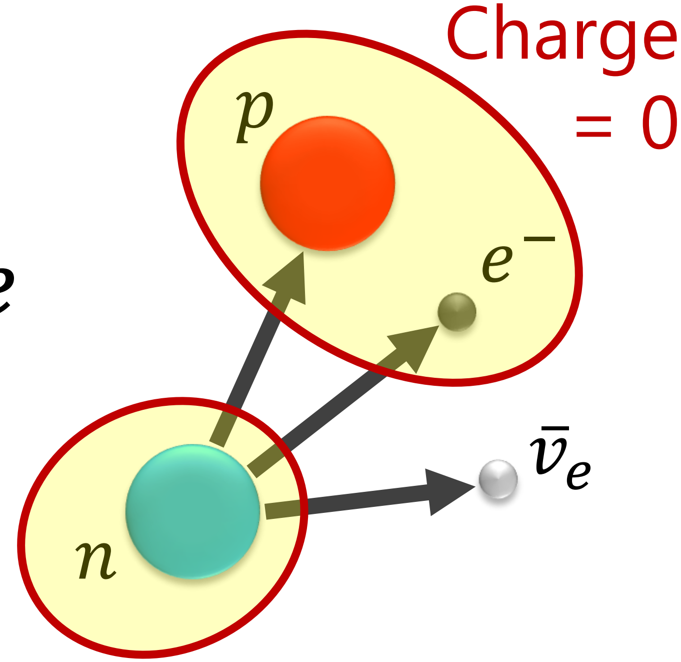


Beta-Negative Decay

In an unstable nucleus, sometimes a neutral neutron is converted into a positive proton and negative electron. When this happens, another particle called an antineutrino ($\bar{v}_e$) is also formed

"anti-"

$$ {}^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\text{e} + \bar{v}_e $$



Beta-Negative Decay

BETA-DECAY SET WITH MINI PARTICLES

$48.99

Qty

1

ADD TO CART

← Previous Product

SHARE:

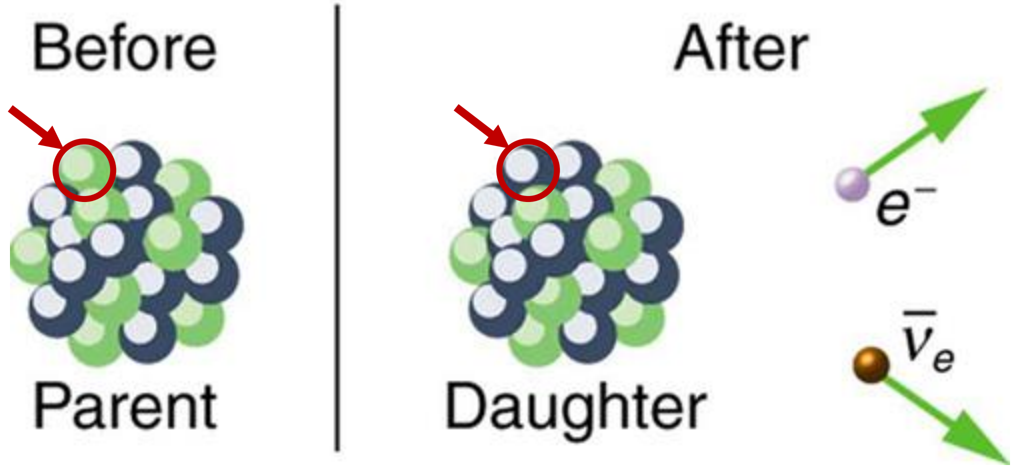
Share Tweet Pin it G+ +1

Beta-Negative Decay

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + {}^{0}_{-1}e + \bar{\nu}_e$$

Parent Nuclide — Daughter Nuclide — Electron — Antineutrino

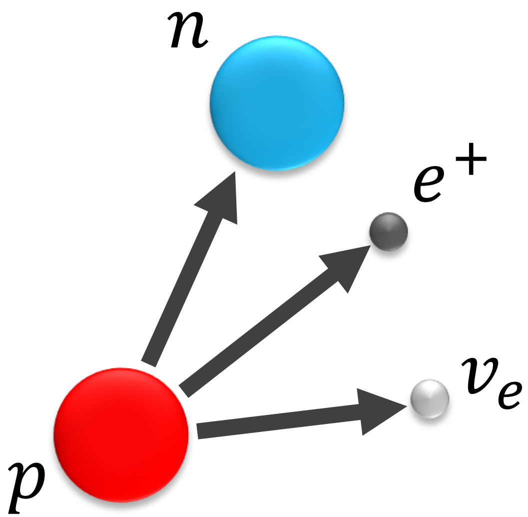
**The proton stays and the electron and antineutrino flies away as "radiation"



Beta-Positive Decay

In an opposite process, a positive proton can be converted into a neutral neutron and positively charged electron (known as a **positron**). When this happens, another particle called a neutrino (v_e) is also formed

$$^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{+1}\mathrm{e} + v_e$$



Beta-Positive Decay

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z-1}\mathrm{X} + {}^{0}_{+1}\mathrm{e} + v_e$$

Parent Nuclide

Daughter Nuclide

Positron

Neutrino

Beta Decay - Predict

$$^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_e$$

$$^{131}_{53}\mathrm{I} \rightarrow {}^{131}_{54}\mathrm{Xe} + \underline{{}^{0}_{-1}\mathrm{e}\quad} + \bar{\nu}_e$$

$$^{14}_{6}\mathrm{C} \rightarrow \underline{\;{}^{14}_{7}\;}\mathrm{N} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_e$$

$$^{23}_{12}\mathrm{Mg} \rightarrow \underline{\;{}^{23}_{11}\;}\mathrm{Na} + {}^{0}_{+1}\mathrm{e} + \nu_e$$

Gamma Decay

After an unstable nucleus has emitted an alpha or beta particle, it can contain excess energy that is released as gamma radiation

$$^{234}_{90}\mathrm{Th}^{*} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{0}_{0}\gamma$$

The Math Always Adds Up

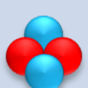
$$^{238}_{92}\mathrm{U} \rightarrow \, ^{234}_{90}\mathrm{Th} + \, ^{4}_{2}\mathrm{He}$$

$$^{234}_{90}\mathrm{Th} \rightarrow \, ^{234}_{91}\mathrm{Pa} + \, ^{0}_{-1}\mathrm{e} + \bar{v}_e$$

$$^{23}_{12}\mathrm{Mg} \rightarrow \, ^{23}_{11}\mathrm{Na} + \, ^{0}_{+1}\mathrm{e} + v_e$$

$$^{234}_{90}\mathrm{Th}^{*} \rightarrow \, ^{234}_{90}\mathrm{Th} + \, ^{0}_{0}\gamma$$

Particle Review

	Particle	Name
	${}^{1}_{1}\mathrm{p}$	Proton
	${}^{1}_{0}\mathrm{n}$	Neutron
	${}^{0}_{-1}\mathrm{e}$	Electron
	${}^{0}_{+1}\mathrm{e}$	Positron
	$\bar{v}_e$	Antineutrino
	v_e	Neutrino
	${}^{4}_{2}\mathrm{He}$	Alpha Particle

Sample IB Question

24. Which of the following correctly identifies the three particles emitted in the decay of the nucleus $^{45}_{20}Ca$ into a nucleus of $^{45}_{21}Sc$?

A. α, β^-, γ

B. $\beta^-, \gamma, \bar{\nu}$

C. $\alpha, \gamma, \bar{\nu}$

D. $\alpha, \beta^-, \bar{\nu}$

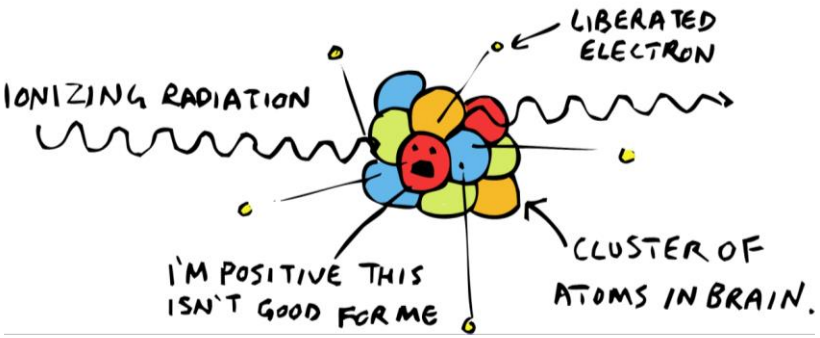
Ionizing Radiation

α

β

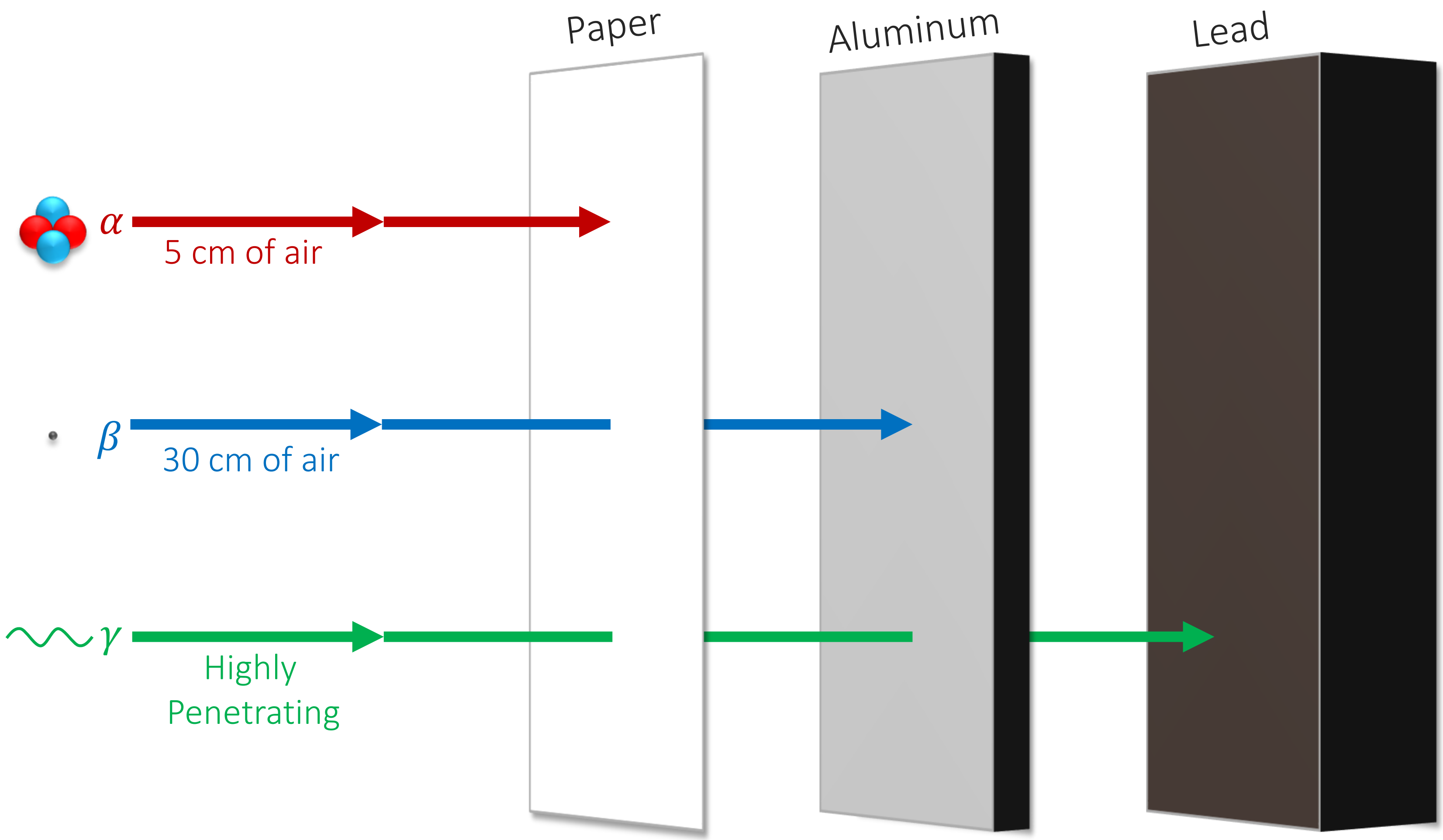
γ

Most mass
Most ionizing

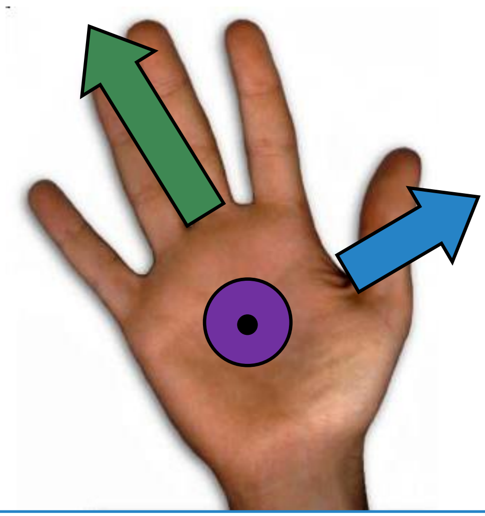


More mass allows particles to more efficiently transfer energy and ionize an atom

Radiation Penetration



Remember the Right Hand Rule?



Thumb points in direction of the current

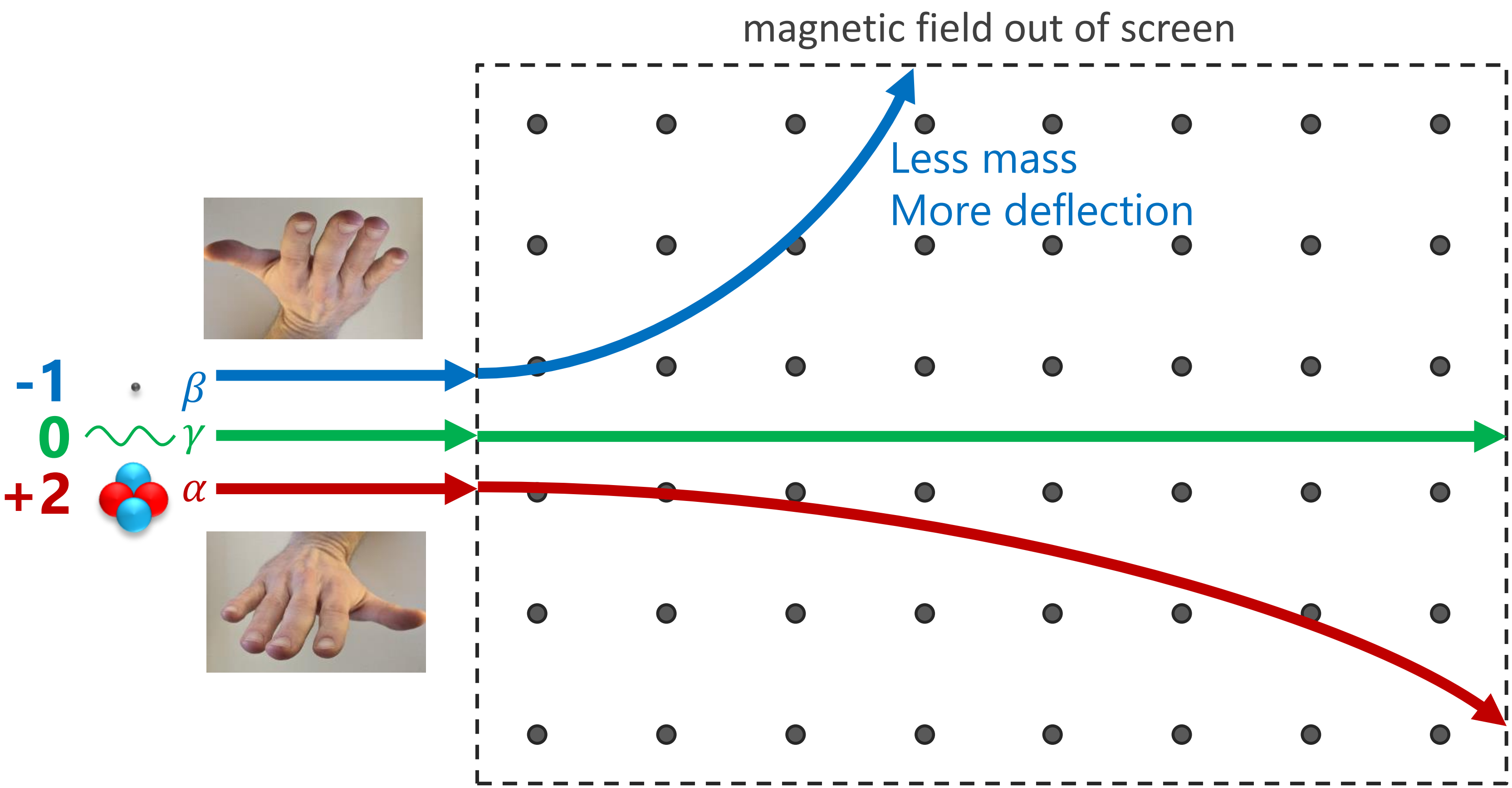
Fingers point in direction of the field lines

Palm points in direction of the force

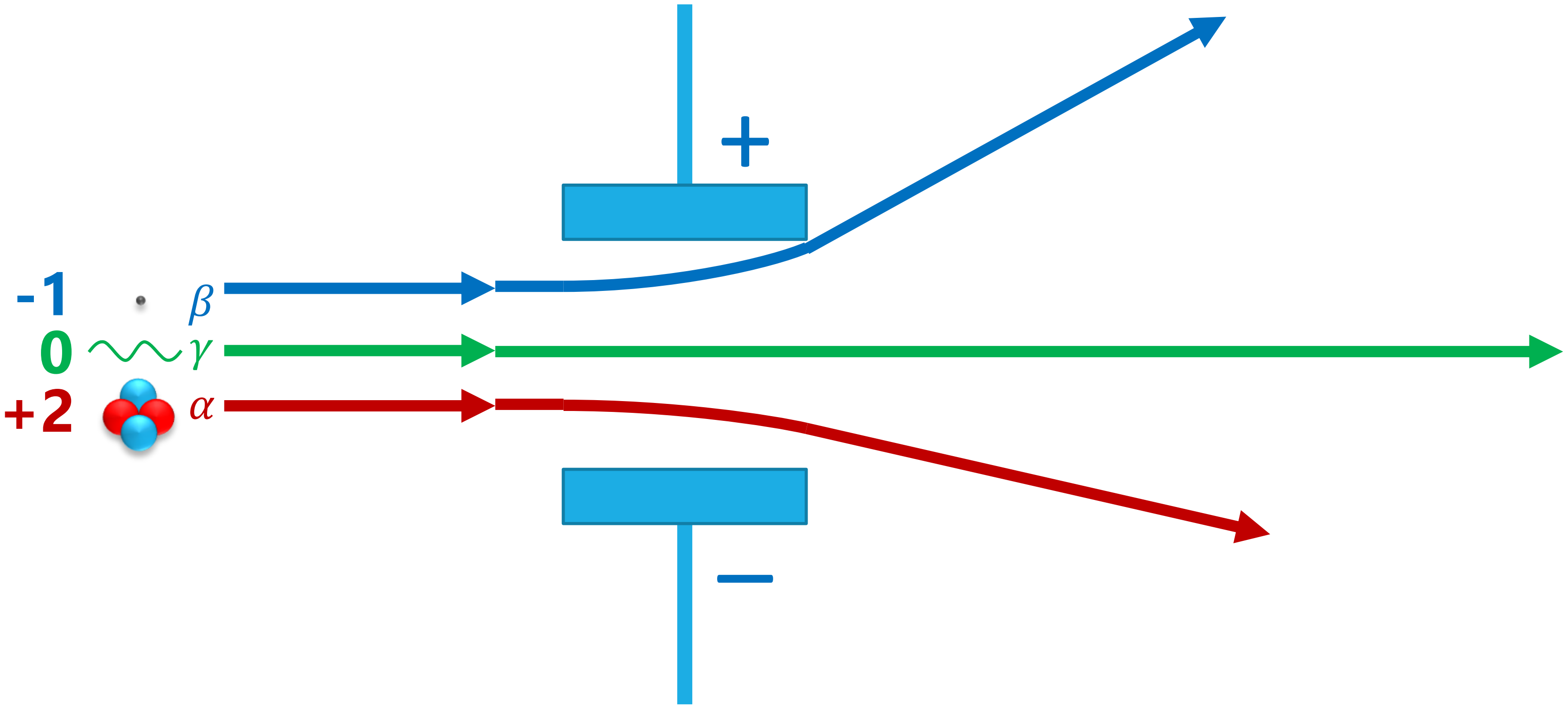
How do you represent a direction that's perpendicular to the paper?

Into the paper	✖
Out of the paper	●

Radiation Deflection



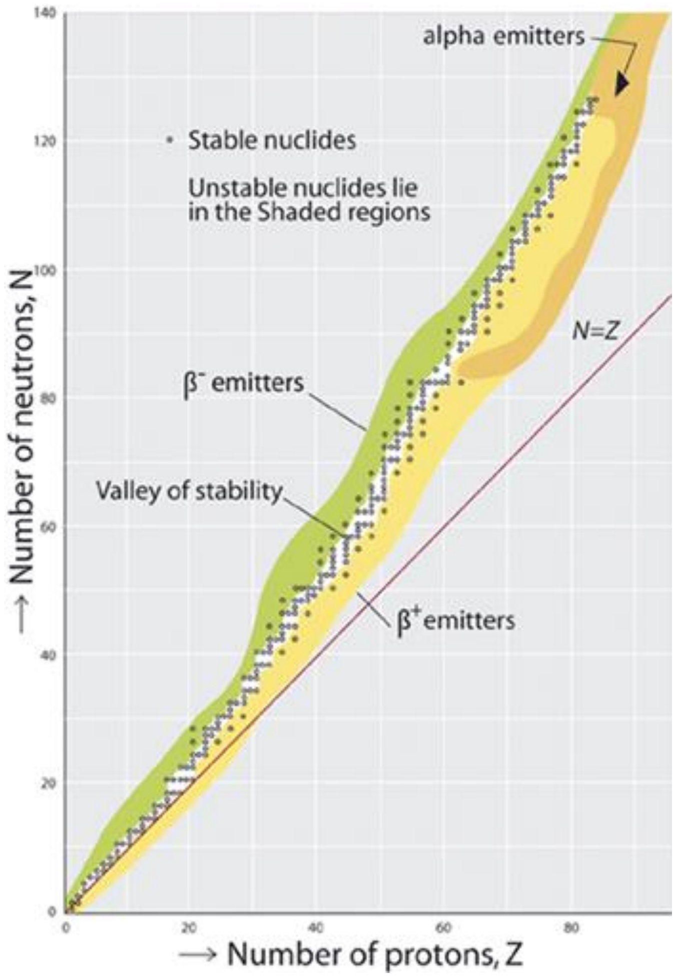
Radiation Deflection



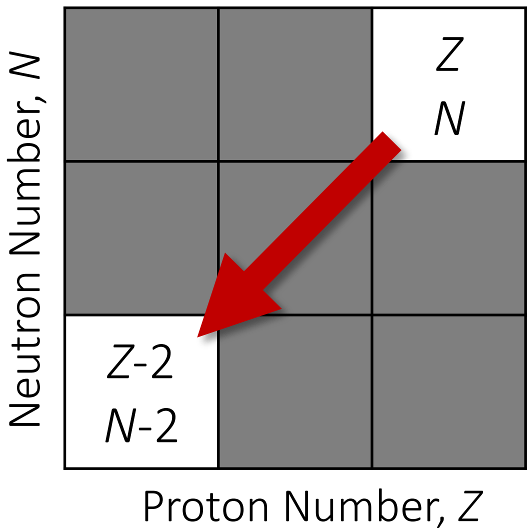
Summary of α, β, and γ

Property	Alpha (α)	Beta (β^+ or β^-)	Gamma (γ)
Relative Charge	+2	+1 or -1	0
Relative Mass	4	0.0005	0
Typical Penetration	5 cm of air	30 cm of air	Highly penetrating
Nature	Helium nucleus	Positron or Electron	Electromagnetic wave
Typical Speed	10^7 m s^{-1}	2.5×10^8 m s^{-1}	3.00×10^8 m s^{-1}
Notation	${}^{4}_{2}\mathrm{He}$ or ${}^{4}_{2}\alpha$	${}^{0}_{-1}\mathrm{e}$ or ${}^{0}_{-1}\beta$	γ or ${}^{0}_{0}\gamma$
Ionizing Effect	Strong	Weak	Very Weak
Abosorbed by	Paper or skin	3 mm of Aluminum	Intensity halved by 2 cm of Lead

Valley of Stability



Graphing Decay

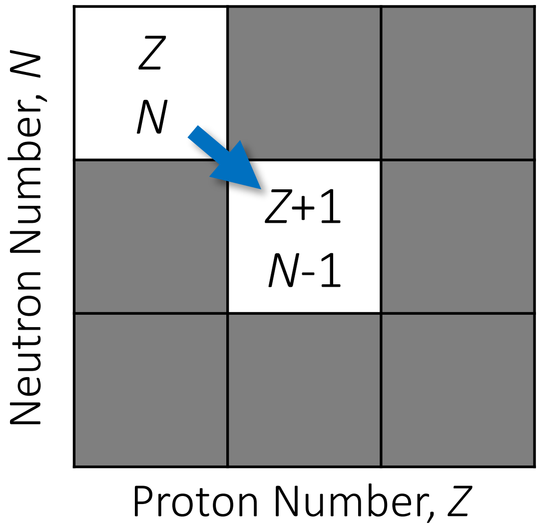


α Decay

Mass #

-4

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$



β⁻ Decay

Mass #

same

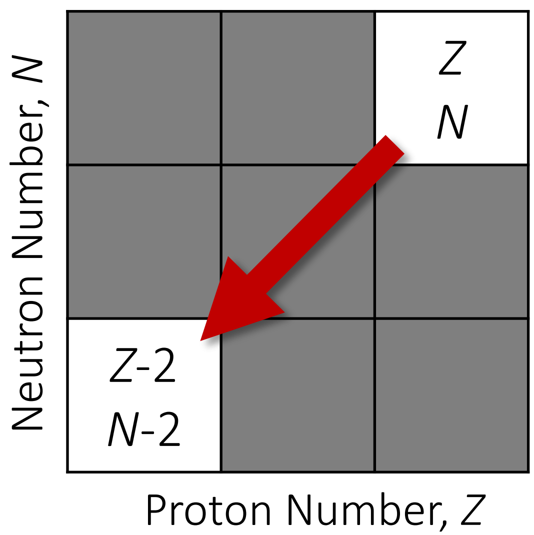
$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\text{e} + \bar{\nu}_e$$

Alpha Decay

82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98
Pb	Bi	Po	At	Rn	Fr	Ra	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf
Lead	Bismuth	Polonium	Astatine	Radon	Francium	Radium	Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium

α Decay of Radium-226

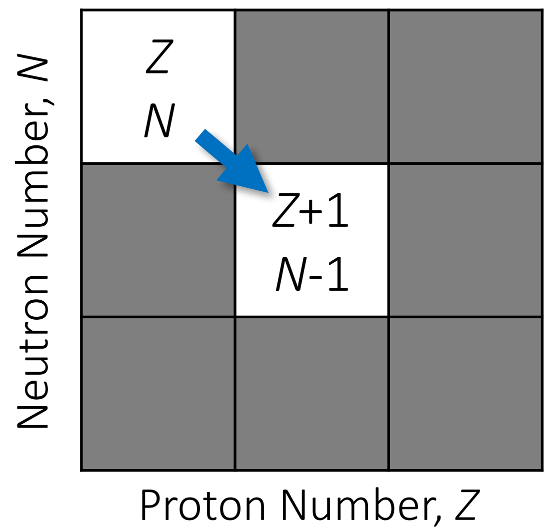
$$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$$



α Decay

Mass #

- 4



β^- Decay

Mass #

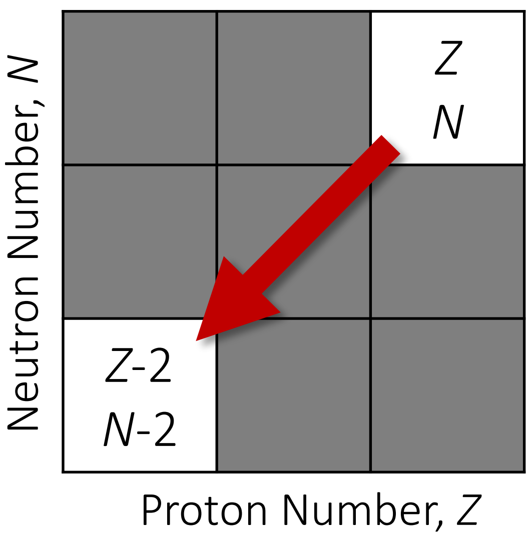
Same

Beta Decay

82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98
Pb	Bi	Po	At	Rn	Fr	Ra	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf
Lead	Bismuth	Polonium	Astatine	Radon	Francium	Radium	Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium

β^- Decay of Protactinium-234

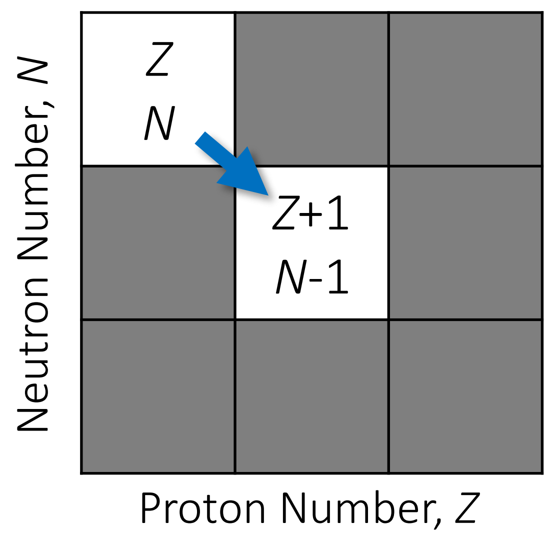
$$^{234}_{91}\mathrm{Pa} \rightarrow {}^{234}_{92}\mathrm{U} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_e$$



α Decay

Mass #

- 4



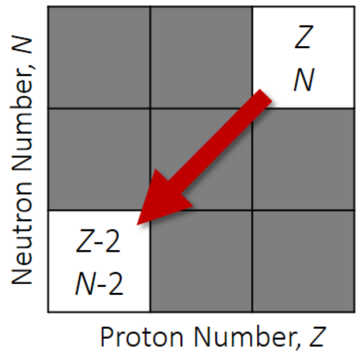
β^- Decay

Mass #

Same

Keeps right on going…

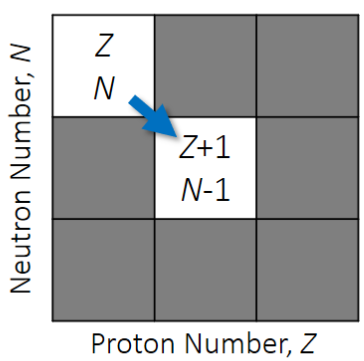
82	83	84	85	86	87	88	89	90	91	92
Pb	Bi	Po	At	Rn	Fr	Ra	Ac	Th	Pa	U
Lead	Bismuth	Polonium	Astatine	Radon	Francium	Radium	Actinium	Thorium	Protactinium	Uranium



α Decay

Mass #

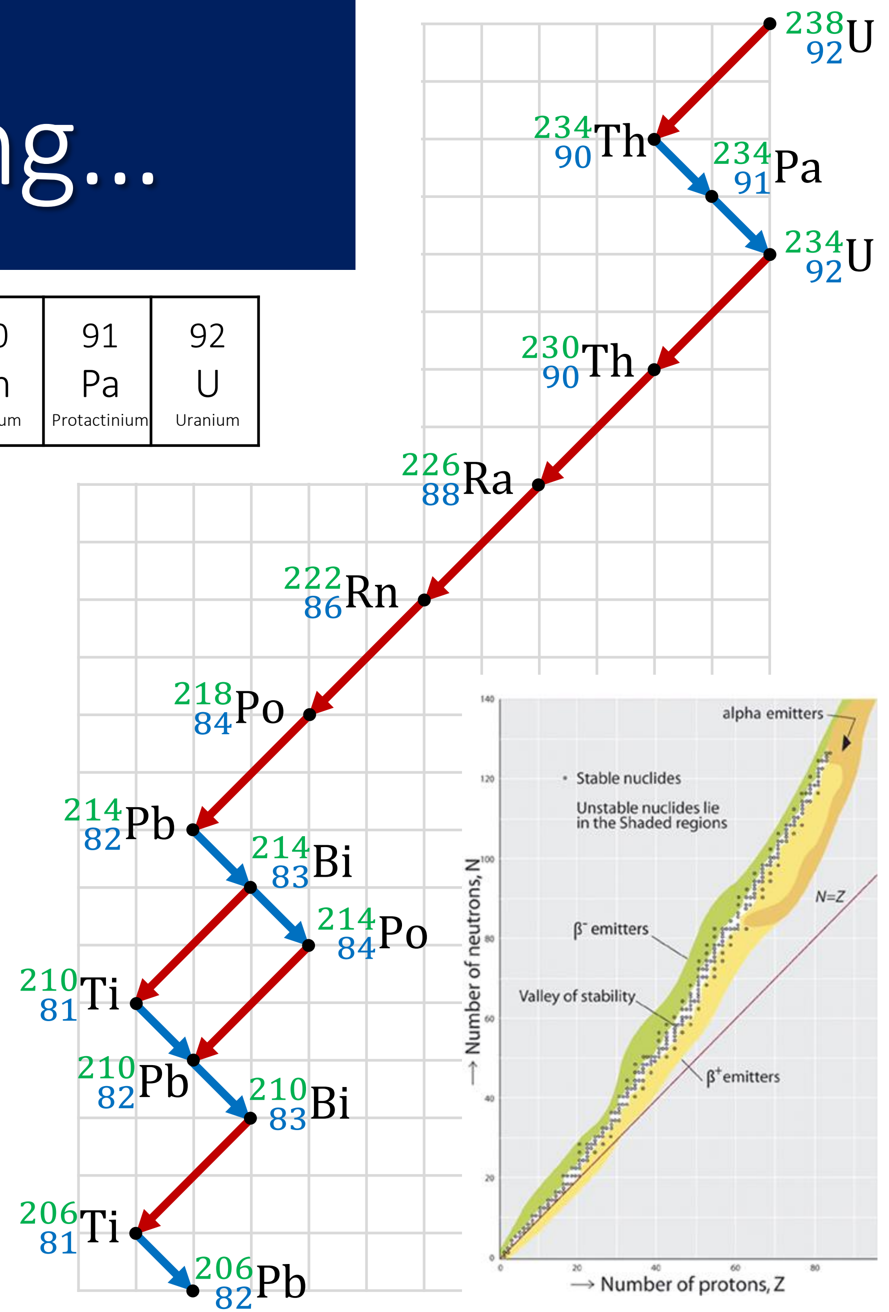
\- 4



β^- Decay

Mass #

Same

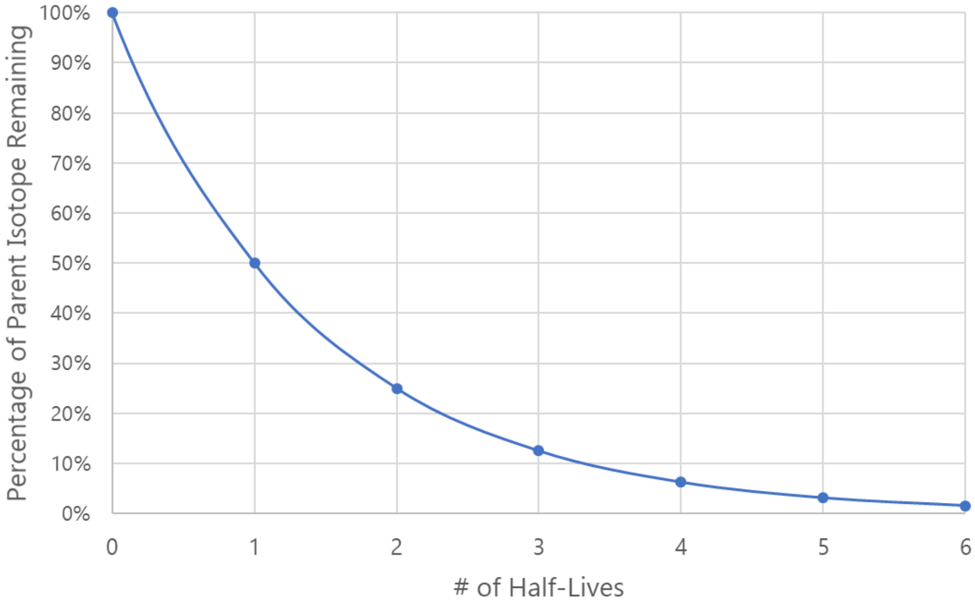


Half-Life

The amount of time it takes for one half of the original sample to **decay**

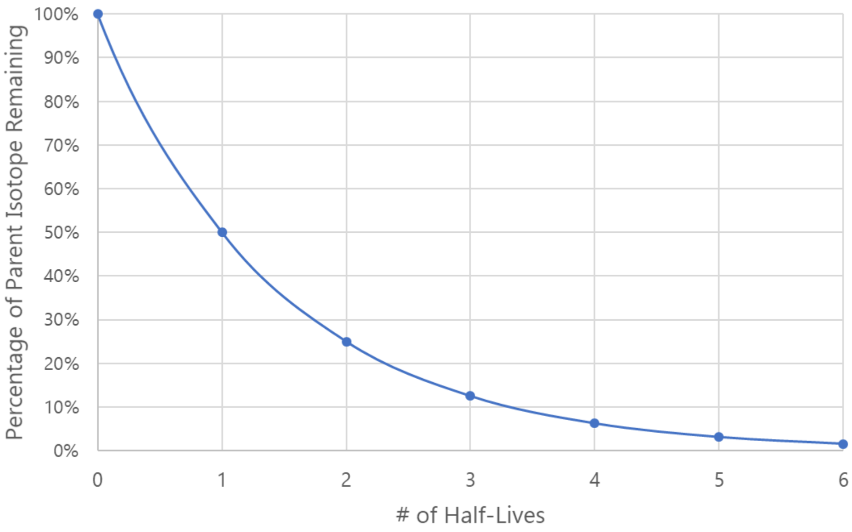
Radioactive Nuclide	Half-life
Uranium-238	4.5×10^9 years
Radium-226	1,600 years
Radon-222	3.8 days
Francium-221	4.8 minutes
Astatine-217	0.03 seconds

This can be in the scale of seconds, minutes, days or even years!



Half-Life Example

How many half-lives does it take for there to only be __% of the original sample remaining?



100% / 2 = 50% remains after 1 half-life

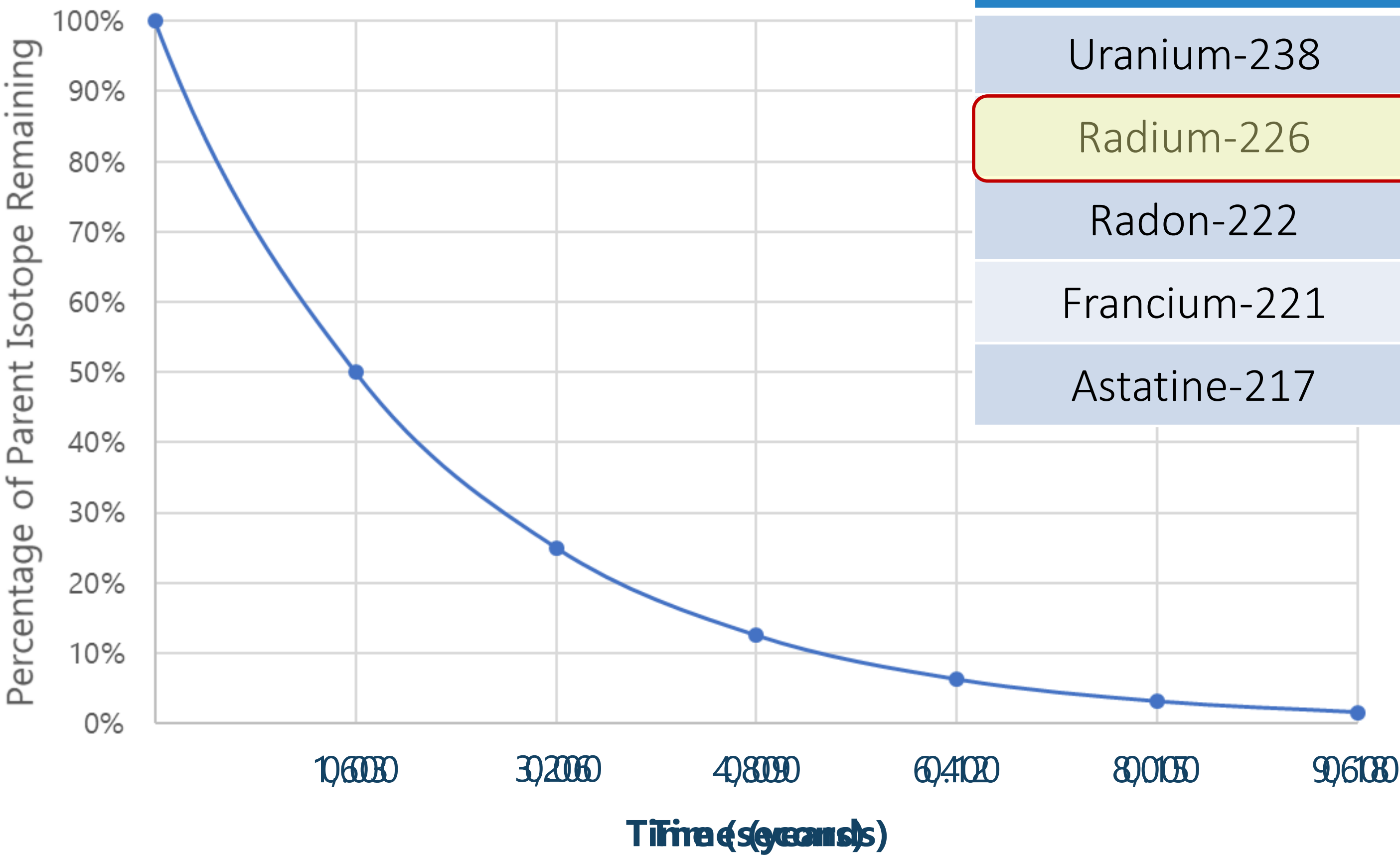
50% /2 = 25% remains after 2 half-lives

25% /2 = 12.5% remains after 3 half-lives

12.5% /2 = 6.25% remains after 4 half-lives

6.25% /2 = 3.125% remains after 5 half-lives

The length of a half life depends...



Radioactive Nuclide	Half-life
Uranium-238	4.5×10^9 years
Radium-226	1,600 years
Radon-222	3.8 days
Francium-221	4.8 minutes
Astatine-217	0.03 seconds

Half Life Problem:

How many half-lives does it take for 100 g of a radioactive sample to decay to 12.5 g?

$$100\text{ g} \xrightarrow{1} 50\text{ g} \xrightarrow{2} 25\text{ g} \xrightarrow{3} 12.5\text{ g}$$

3 Half-Lives

If the half-life of the sample is 7 years, how long will this take?

$$(3\text{ half-lives}) \times (7\text{ years}) = \boxed{21\text{ years}}$$

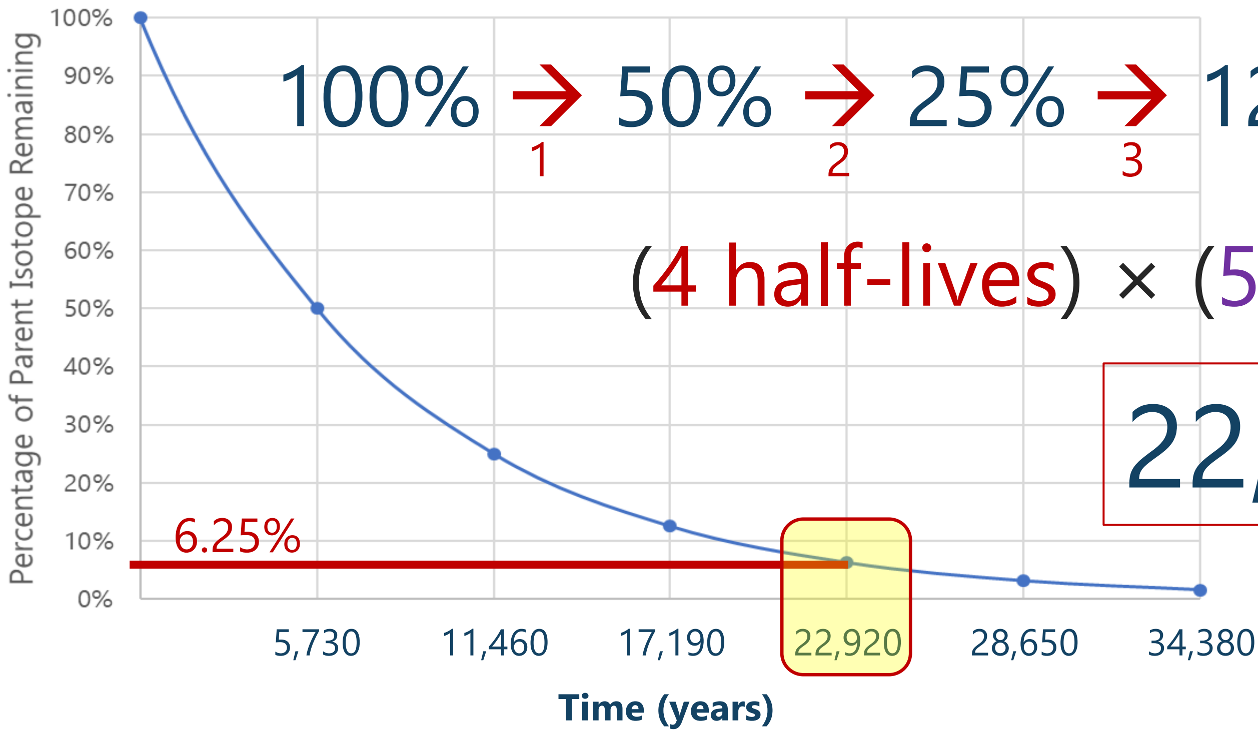
The half-life of radium-226 is 1600 years. What percentage remains undecayed after 3200 years?

$$(3200\text{ years}) \div (1600\text{ years}) = 2\text{ Half-Lives}$$

$$100\% \xrightarrow[1]{} 50\% \xrightarrow[2]{} \mathbf{25\%}$$

Radiocarbon Dating

How old is a sample of rock that has 6.25% of its original C-14. The half-life of C-14 is 5,730 years.



100% → 50% → 25% → 12.5% → **6.25%**

1 2 3 4

(4 half-lives) × (5730 years) =

22,920 years

1 + 1 > 2

Energy and Mass Defects

IB PHYSICS | ATOMIC PHYSICS

Unified Atomic Mass Unit

When measuring and reporting the mass of individual atoms and subatomic particles, kilograms are inconveniently large…

The **unified atomic mass unit** is defined as one-twelfth of the mass of an isolated carbon-12 atom

1 mole of Carbon Atoms = 0.012 kg

$$\frac{0.012\ \text{kg}}{6.02\times 10^{23}} = 1.99\times 10^{-26}\ \text{kg}$$

↓

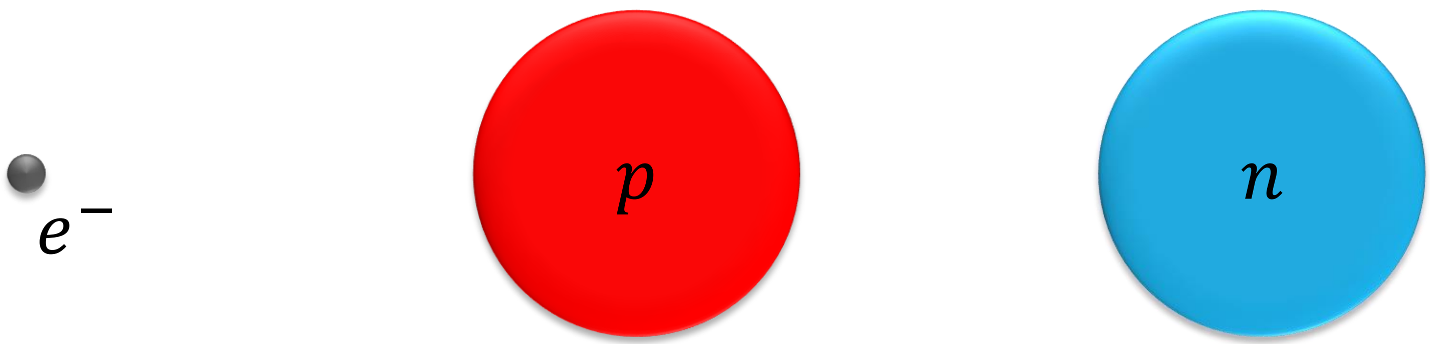
$$\frac{1.99\times 10^{-26}\ \text{kg}}{12} = 1.661\times 10^{-27}\ \text{kg} = 1\ \text{u}$$

Unified Atomic Mass Unit

Electron (m_e)	9.110×10^{-31} kg	0.000549 u
Proton (m_p)	1.673×10^{-27} kg	1.007276 u
Neutron (m_n)	1.675×10^{-27} kg	1.008665 u

Unified atomic mass unit	1.661×10^{-27} kg

This is the only time that we will ever use 7 sig figs. In this case, rounding to 1.01 u just wouldn't cut it…

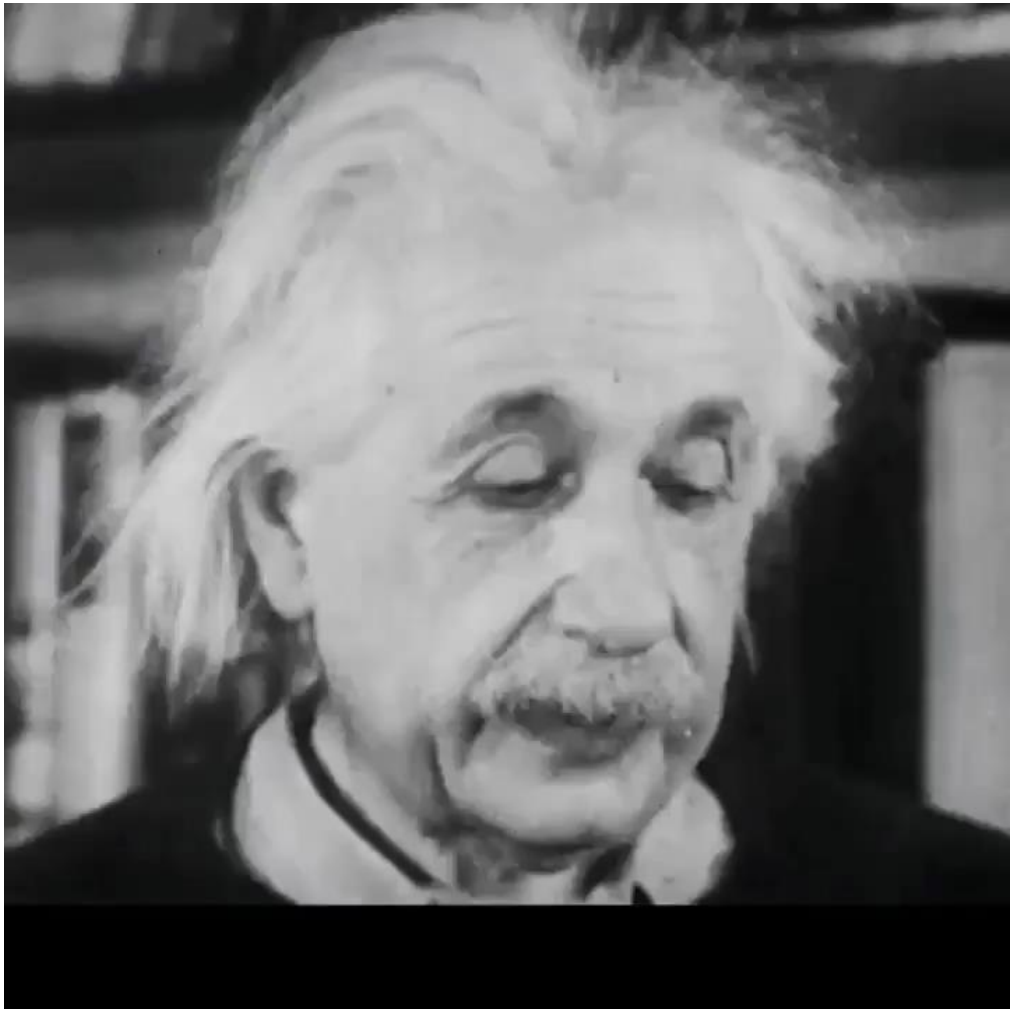


IB Physics Data Booklet

Fundamental constants

Quantity	Symbol	Approximate value
Speed of light in vacuum	c	$3.00 \times 10^{8}\ \mathrm{m\,s^{-1}}$
Planck's constant	h	$6.63 \times 10^{-34}\ \mathrm{J\,s}$
Elementary charge	e	$1.60 \times 10^{-19}\ \mathrm{C}$
Electron rest mass	m_e	$9.110 \times 10^{-31}\ \mathrm{kg} = 0.000549\ \mathrm{u} = 0.511\ \mathrm{MeV\,c^{-2}}$
Proton rest mass	m_p	$1.673 \times 10^{-27}\ \mathrm{kg} = 1.007276\ \mathrm{u} = 938\ \mathrm{MeV\,c^{-2}}$
Neutron rest mass	m_n	$1.675 \times 10^{-27}\ \mathrm{kg} = 1.008665\ \mathrm{u} = 940\ \mathrm{MeV\,c^{-2}}$
Unified atomic mass unit	u	$1.661 \times 10^{-27}\ \mathrm{kg} = 931.5\ \mathrm{MeV\,c^{-2}}$
Solar constant	S	$1.36 \times 10^{3}\ \mathrm{W\,m^{-2}}$
Fermi radius	R_0	$1.20 \times 10^{-15}\ \mathrm{m}$

Einstein's Famous Equation



According to Albert Einstein, *"mass and energy are different manifestations of the same things"*

$$E = mc^2$$

Einstein's Famous Equation

$$E = mc^2$$

Energy [J]

Mass [kg]

Speed of Light $3.00 \times 10^8\ m\ s^{-1}$

What is the energy equivalence of 1 g of matter?

$$E = (0.001\ kg)(3.00 \times 10^8\ m\ s^{-1})^2 = 9 \times 10^{13}\ J$$

IB Physics Data Booklet

Sub-topic 7.1 – Discrete energy and radioactivity	Sub-topic 7.2 – Nuclear reactions
$E = hf$ $\lambda = \frac{hc}{E}$	$\Delta E = \Delta m\, c^2$

Sub-topic 7.3 – The structure of matter

Charge	Quarks			Baryon number
$\frac{2}{3}e$	u	c	t	$\frac{1}{3}$
$-\frac{1}{3}e$	d	s	b	$\frac{1}{3}$

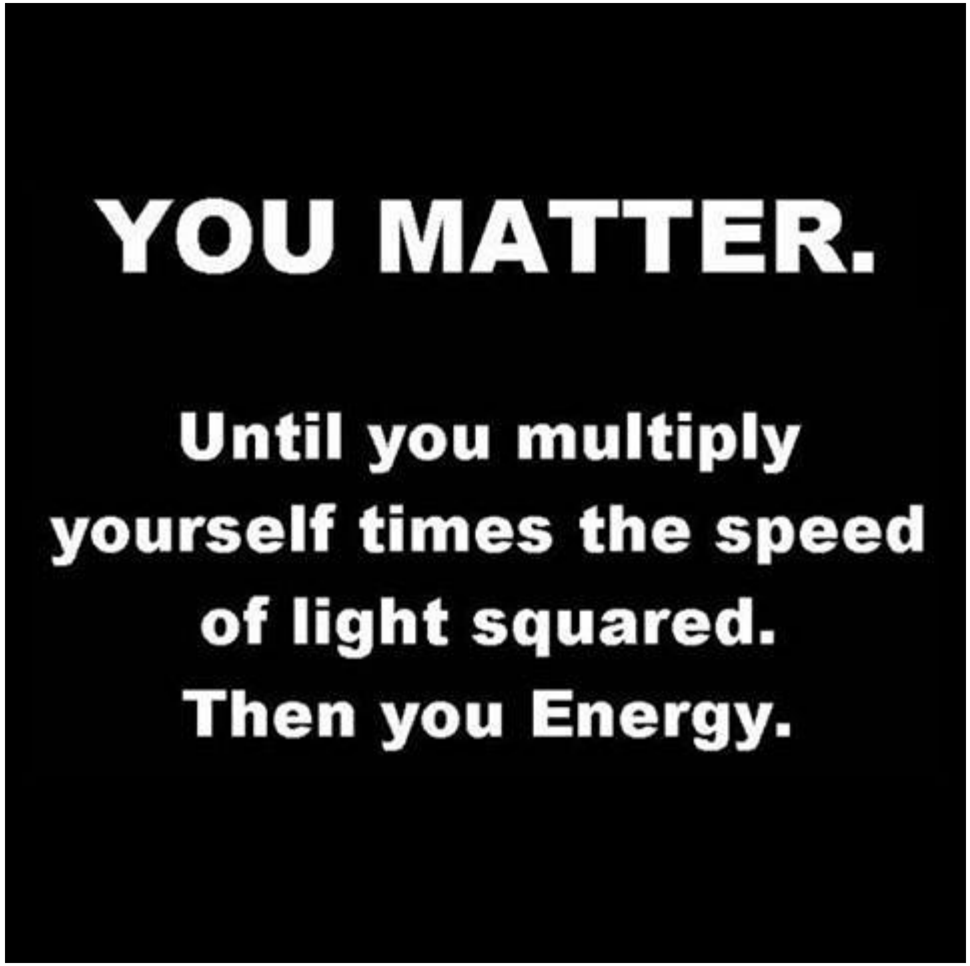
All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of −1

Charge	Leptons		
−1	e	μ	τ
0	υ_e	υ_μ	υ_τ

All leptons have a lepton number of 1 and antileptons have a lepton number of −1

	Gravitational	Weak	Electromagnetic	Strong
Particles experiencing	All	Quarks, leptons	Charged	Quarks, gluons
Particles mediating	Graviton	W^+, W^-, Z^0	γ	Gluons

$E = mc^2$


YOU MATTER.
Until you multiply yourself times the speed of light squared.
Then you Energy.

New Unit for Energy!

Electron-Volt	eV
1 MeV = 10^6 eV	

$$\{Energy\ in\ eV\} = \frac{\{Energy\ in\ J\}}{1.60 \times 10^{-19}}$$

What is the energy equivalence of 1 proton (1.673×10^{-27} kg)?

$$E = (1.673 \times 10^{-27})(3 \times 10^{8})^2 = 1.5057 \times 10^{-10}\ \text{J}$$

$$\frac{1.5057 \times 10^{-10}\ \text{J}}{1.60 \times 10^{-19}} = 941{,}062{,}500\ eV \approx \mathbf{941\ MeV}$$

New Unit for Mass

$$E = mc^2$$

$$m = \frac{E}{c^2} = \frac{MeV}{c^2}$$

$$\boldsymbol{MeV\ c^{-2}}$$

Unified Atomic Mass Unit

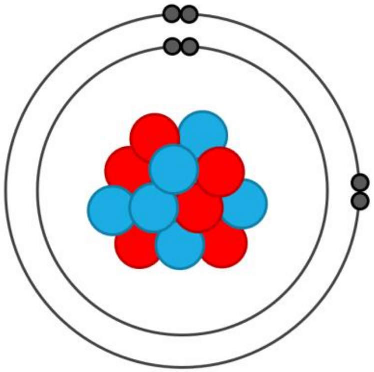
Electron rest mass (m_e)	9.110×10^{-31} kg	0.000549 u	0.511 MeV c^{-2}
Proton rest mass (m_p)	1.673×10^{-27} kg	1.007276 u	938 MeV c^{-2}
Neutron rest mass (m_n)	1.675×10^{-27} kg	1.008665 u	940 MeV c^{-2}

Unified atomic mass unit	1.661×10^{-27} kg	1.000000 u	931.5 MeV c^{-2}

Mass of the Nucleus

A neutral Carbon-12 atom contains:

6 protons
6 neutrons
6 electrons



Electron rest mass (m_e)	0.000549 u
Proton rest mass (m_p)	1.007276 u
Neutron rest mass (m_n)	1.008665 u

Unified atomic mass unit	1.000000 u

If the mass of Carbon-12 is defined as exactly 12.00000*u*, then the nucleus mass is:

$$12.00000\text{u} - (6 \times 0.000549\text{u}) = \mathbf{11.996706u}$$

Component Mass

A nucleus of Carbon-12 contains:

6 protons
6 neutrons

What is the total mass in terms of u?

Electron rest mass (m_e)	0.000549 u
Proton rest mass (m_p)	1.007276 u
Neutron rest mass (m_n)	1.008665 u
Unified atomic mass unit	1.000000 u

$$\left.\begin{array}{l} 6 \times 1.007276\text{ u} \\ 6 \times 1.008665\text{ u} \end{array}\right\} 12.095646\text{ u}$$

Mass Defect | 1+1 > 2

Mass sum of the Carbon-12 subatomic particles:

$$(6 \times 1.007276\text{u}) + (6 \times 1.008665\text{u}) = 12.095646\text{u}$$

Mass of Carbon-12 nucleus: 11.996706u

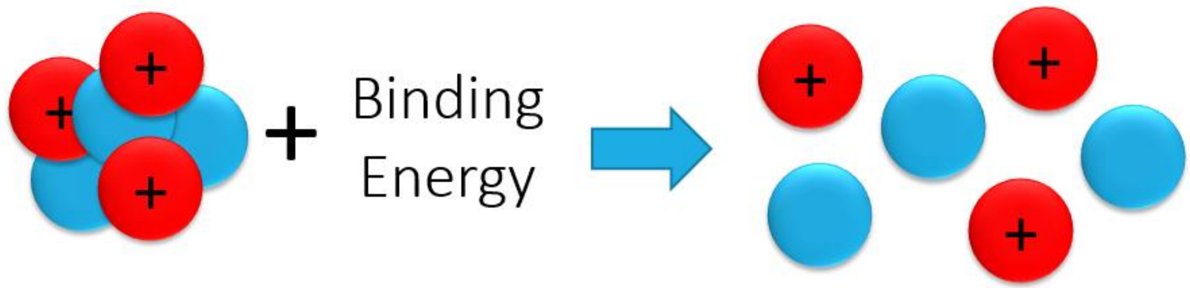
Mass Defect → $12.095646\text{u} - 11.99670\text{u} = \mathbf{0.098946u}$

Where did the mass go?

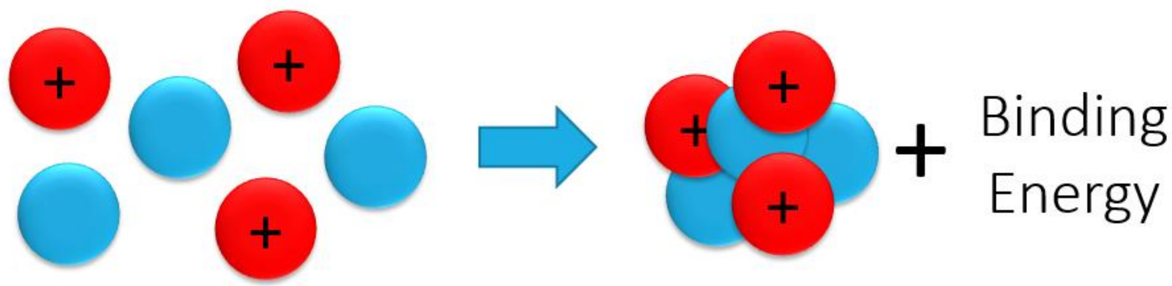
Energy

Binding Energy

Binding Energy is the energy required to separate all of the nucleons



…or the energy released when a nucleus is formed from its nucleons



Mass Defect → Binding Energy

Unified atomic mass unit	1.661×10^{-27} kg	1.000000 u	931.5 MeV c^{-2}

$$\mathbf{0.098946u} \times \frac{931.5\ MeV\ c^{-2}}{1\ \text{u}} =$$

$$92.1682\ MeV\ c^{-2}$$

$$E = mc^2$$

$$= (92.1682\ MeV\ \cancel{c^{-2}})(\cancel{c^{2}})$$

$$= \mathbf{92.17\ MeV}$$

Binding Energy per Nucleon

Binding Energy for Carbon-12 = 92.2 MeV

Number of Nucleons for Carbon-12 = **12**

6 protons
6 neutrons

Binding Energy per Nucleon = $\dfrac{92.16\ MeV}{12}$

$7.68\ MeV\ per\ Nucleon$

Calculate Binding Energy per Nucleon

Nuclide	# of p	# of n	Nucleus Mass
Iodine-**127**	**53**	**74**	**126.87544u**

m_e	0.000549u
m_p	1.007276u
m_n	1.008665u
1u	931.5 MeV c^{-2}

53 × 1.007276 u
74 × 1.008665 u

128.026838u – 126.87544u = 1.15140u

Mass Defect

$$1.15140\ u \times \frac{931.5\ MeV\ c^{-2}}{1\ u} = 1072.53\ MeV\ c^{-2}$$

Convert mass to MeV c^{-2}

$$E = mc^2 = (1072.53\ MeV\ \cancel{c^{-2}})\cancel{c^2} = 1072.53\ MeV$$

$$1072.53\ MeV / 127 = \mathbf{8.45\ MeV\ per\ Nucleon}$$

Calculate Binding Energy per Nucleon

*For your assigned nuclide, calculate the binding energy per Nucleon and record data in shared spreadsheet

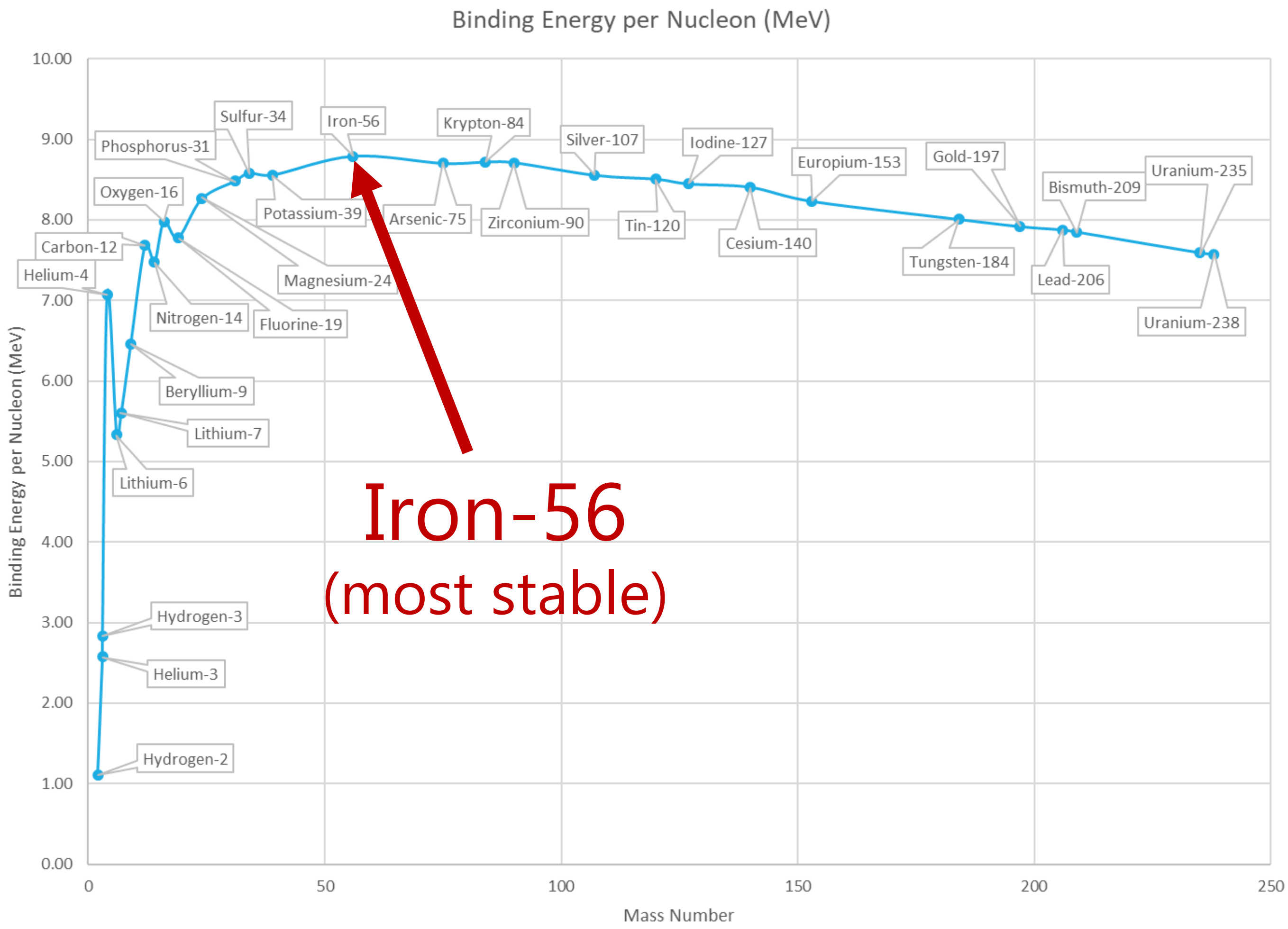
Use a periodic table to determine atomic # for your element

m_e	0.000549u
m_p	1.007276u
m_n	1.008665u
1u	931.5 MeV c^{-2}

	Element	Nucleus Mass (u)
1	Hydrogen-2	2.013553
2	Helium-3	3.014931
3	Hydrogen-3	3.015500
4	Helium-4	4.001505
5	Lithium-6	6.013476
6	Lithium-7	7.014356
7	Beryllium-9	9.009987
8	Carbon-12	11.996706
9	Nitrogen-14	13.999231
10	Oxygen-16	15.990523
11	Fluorine-19	18.993462
12	Magnesium-24	23.978454
13	Phosphorus-31	30.965527
14	Sulfur-34	33.959083
15	Potassium-39	38.953275

	Element	Nucleus Mass (u)
16	Iron-56	55.920662
17	Arsenic-75	74.903478
18	Krypton-84	83.891734
19	Zirconium-90	89.882739
20	Silver-107	106.879287
21	Tin-120	119.874752
22	Iodine-127	126.875373
23	Cesium-140	139.873608
24	Europium-153	152.886650
25	Tungsten-184	183.910307
26	Gold-197	196.923199
27	Lead-206	205.929447
28	Bismuth-209	208.934833
29	Uranium-235	234.993420
30	Uranium-238	238.000282

Binding Energy per Nucleon



Atomic Spectra

IB PHYSICS | ATOMIC PHYSICS

What is Light?

Energy

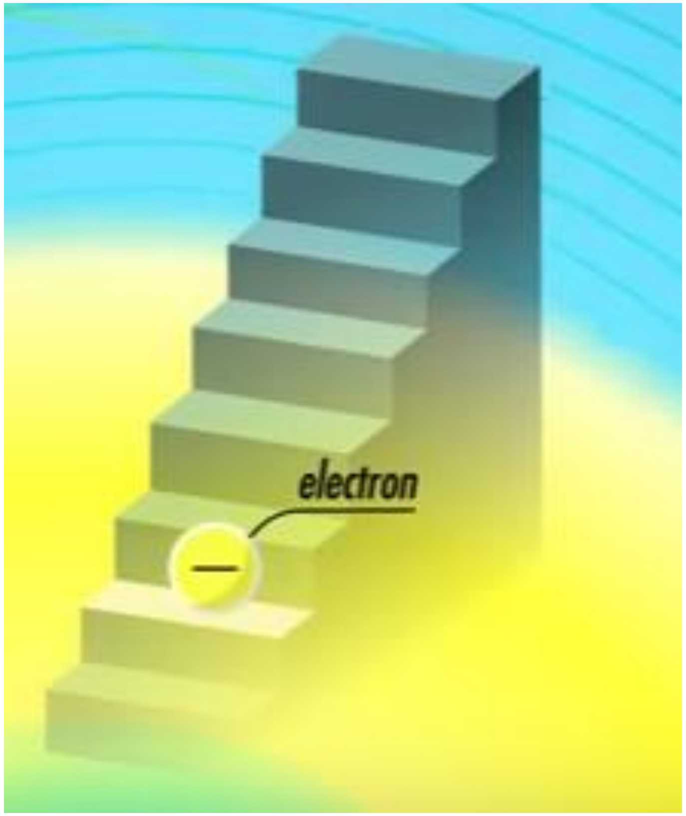
- Wave
- Particle (photon)

Light is Quantized

Photons of light can only have certain

discrete
____

values of energy



Energy of a Photon

$$E = hf$$

Energy

[J]

Frequency

[Hz]

Planck's Constant	h	6.63×10^{-34} J s

Energy of a Photon

$$E = hf \qquad c = f\lambda$$

$$E = h\left(\frac{c}{\lambda}\right) \longleftarrow f = \frac{c}{\lambda}$$

$$\lambda = \frac{hc}{E}$$

$$c = 3.00 \times 10^{8}\ m\ s^{-1}$$

Quick Recap of eV

$$eV \rightarrow electron - volts$$

Unit of Energy

$$\{Energy\ in\ eV\} = \frac{\{Energy\ in\ J\}}{1.60 \times 10^{-19}}$$

IB Physics Data Booklet

Sub-topic 7.1 – Discrete energy and radioactivity	Sub-topic 7.2 – Nuclear reactions
$E = hf$ $\lambda = \frac{hc}{E}$	$\Delta E = \Delta m\, c^2$

Stefan–Boltzmann constant	σ	$5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$
Coulomb constant	k	$8.99 \times 10^{9}\ \mathrm{N\,m^{2}\,C^{-2}}$
Permittivity of free space	ε_0	$8.85 \times 10^{-12}\ \mathrm{C^{2}\,N^{-1}\,m^{-2}}$
Permeability of free space	μ_0	$4\pi \times 10^{-7}\ \mathrm{T\,m\,A^{-1}}$
Speed of light in vacuum	c	$3.00 \times 10^{8}\ \mathrm{m\,s^{-1}}$
Planck's constant	h	$6.63 \times 10^{-34}\ \mathrm{J\,s}$
Elementary charge	e	$1.60 \times 10^{-19}\ \mathrm{C}$

Try This...

Calculate the energy carried by one photon of microwaves of wavelength 9 cm (as might be used in wifi signals) in J and eV

↓

0.09 m

$$E = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34})(3 \times 10^{8})}{(0.09)} = \boxed{2.21 \times 10^{-24}\ \mathrm{J}}$$

$$\frac{1.99 \times 10^{-24}}{1.60 \times 10^{-19}} = \boxed{1.38 \times 10^{-5}\ \mathrm{eV}}$$

Shortcut time ☺

Unit conversions

1 radian (rad) $\equiv \frac{180°}{\pi}$

Temperature (K) = temperature (°C) + 273

1 light year (ly) = 9.46×10^{15} m

1 parsec (pc) = 3.26 ly

1 astronomical unit (AU) = 1.50×10^{11} m

1 kilowatt-hour (kWh) = 3.60×10^{6} J

$hc = 1.99 \times 10^{-25}$ J m = 1.24×10^{-6} eV m

Since *h* and *c* are both constants, *hc* acts as a constant as well

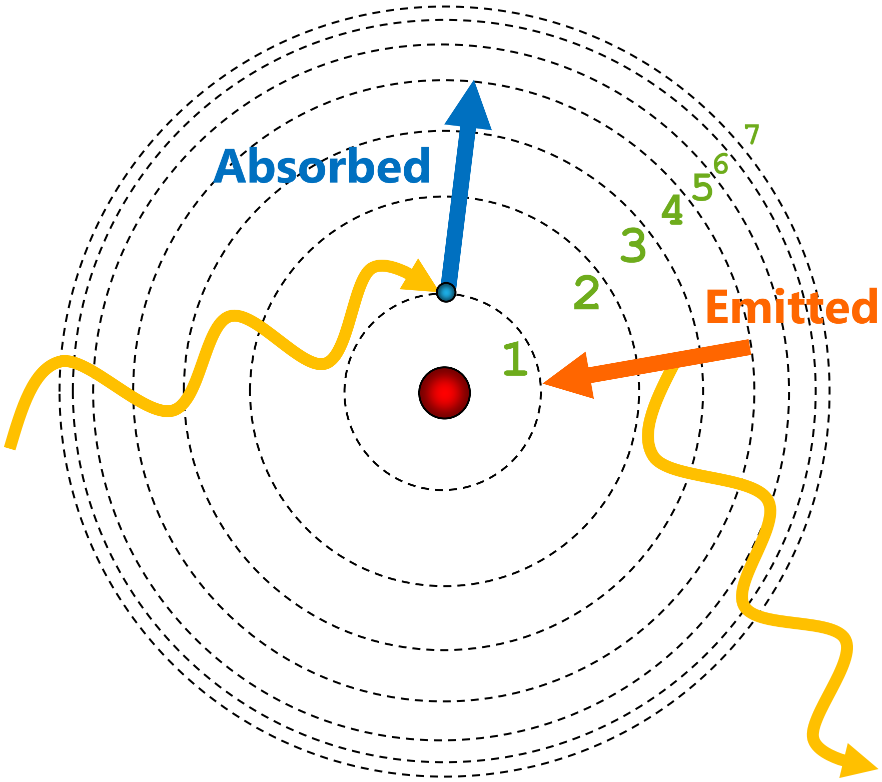
$$E = \frac{hc}{\lambda}$$

$$\frac{1.99 \times 10^{-25}\ \text{J}\ \cancel{\text{m}}}{0.09\ \cancel{\text{m}}} = \boxed{2.21 \times 10^{-24}\ \text{J}}$$

$$\frac{1.24 \times 10^{-6}\ \text{eV}\ \cancel{\text{m}}}{0.09\ \cancel{\text{m}}} = \boxed{1.38 \times 10^{-5}\ \text{eV}}$$

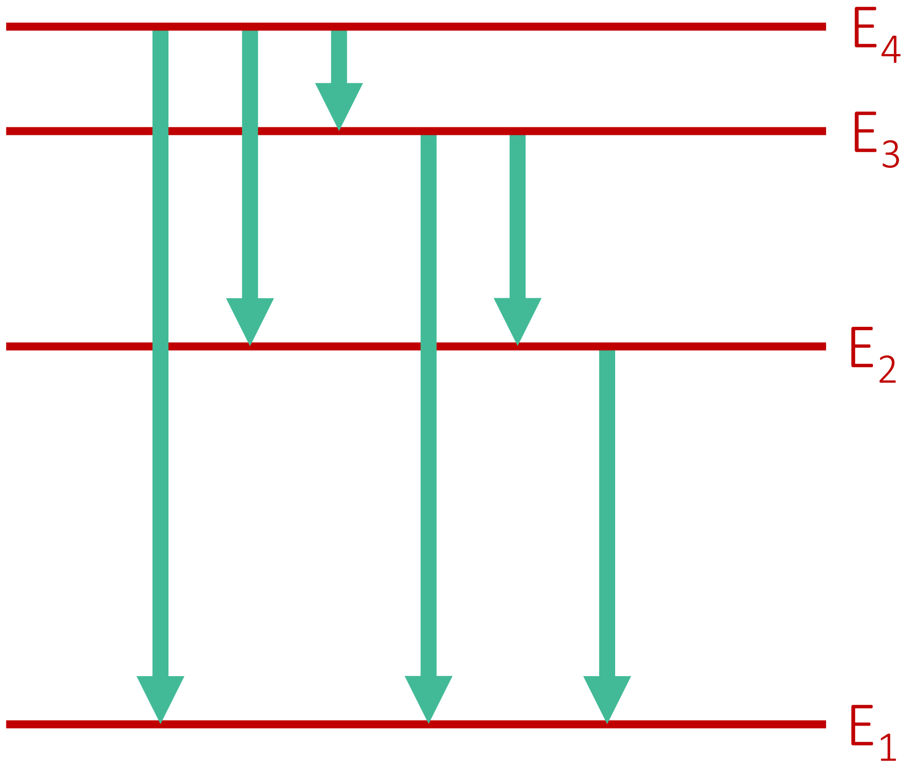
Energy Levels

Electrons in an atom exist at discrete energy levels



Energy Levels

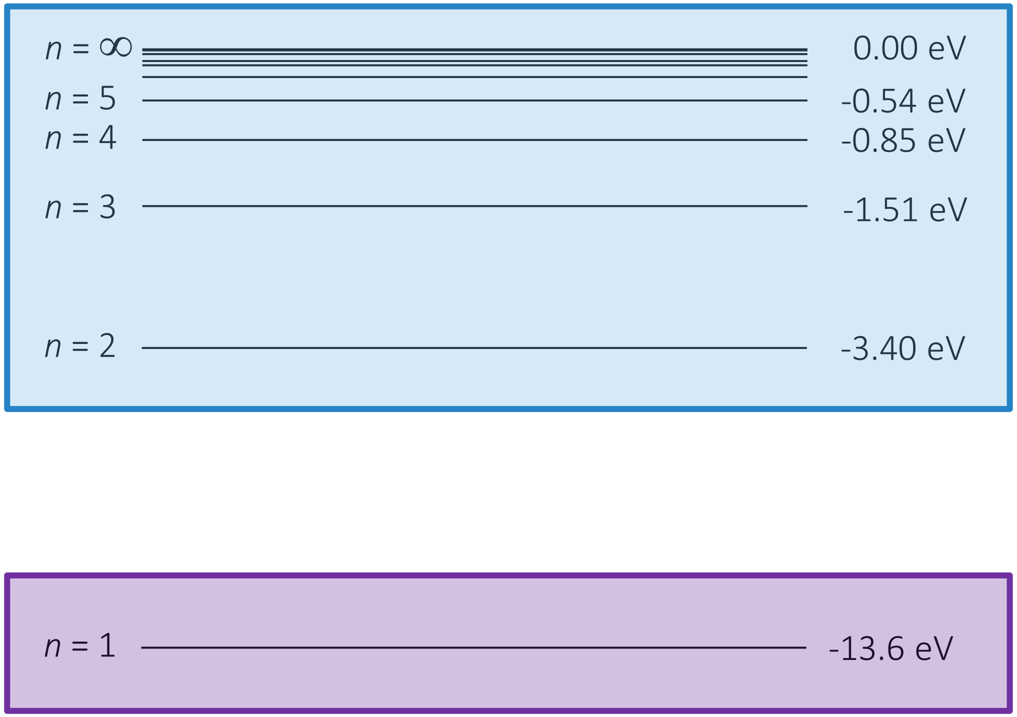
A photon is emitted whenever an electron transitions from one energy level down to a lower energy level



How many different transitions are possible between these four energy levels?

6

Energy Levels

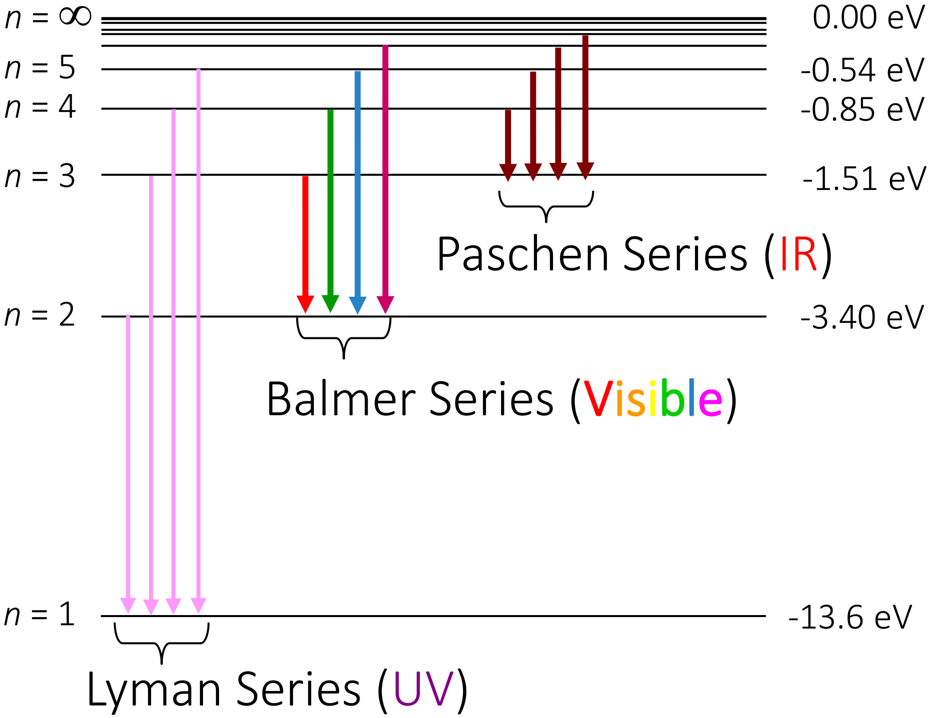


Excited States

Ground State

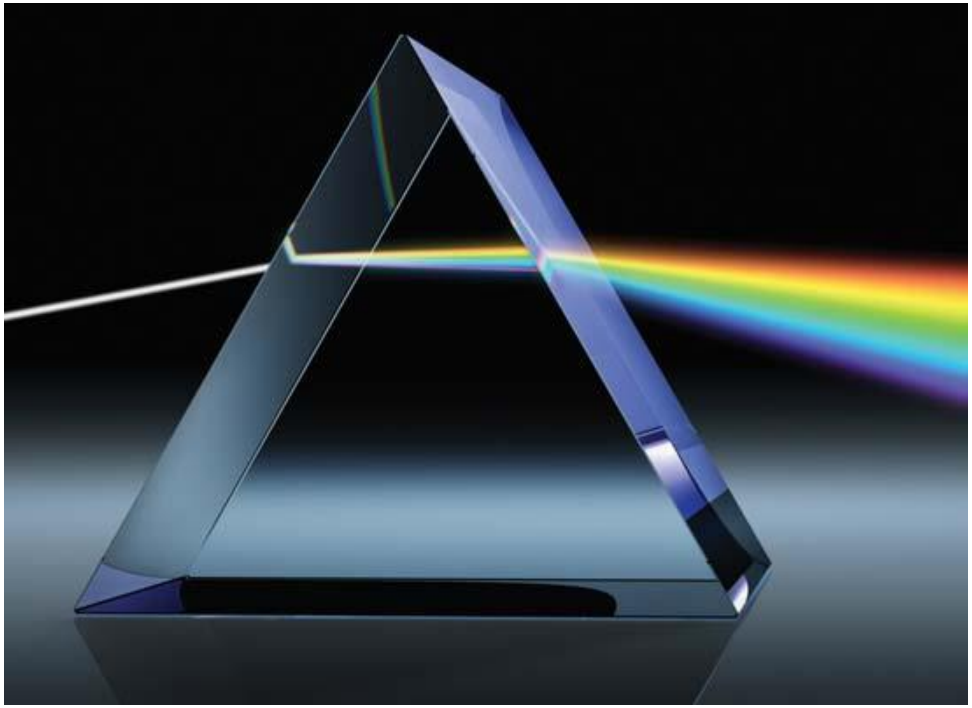
Energy Transitions

Different Energy transitions result in different energies (wavelengths) of light that are absorbed or emitted



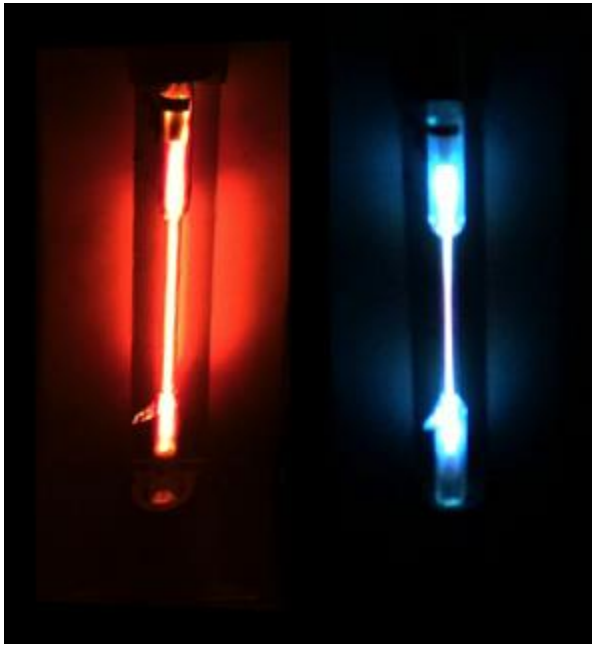
Continuous Spectrum

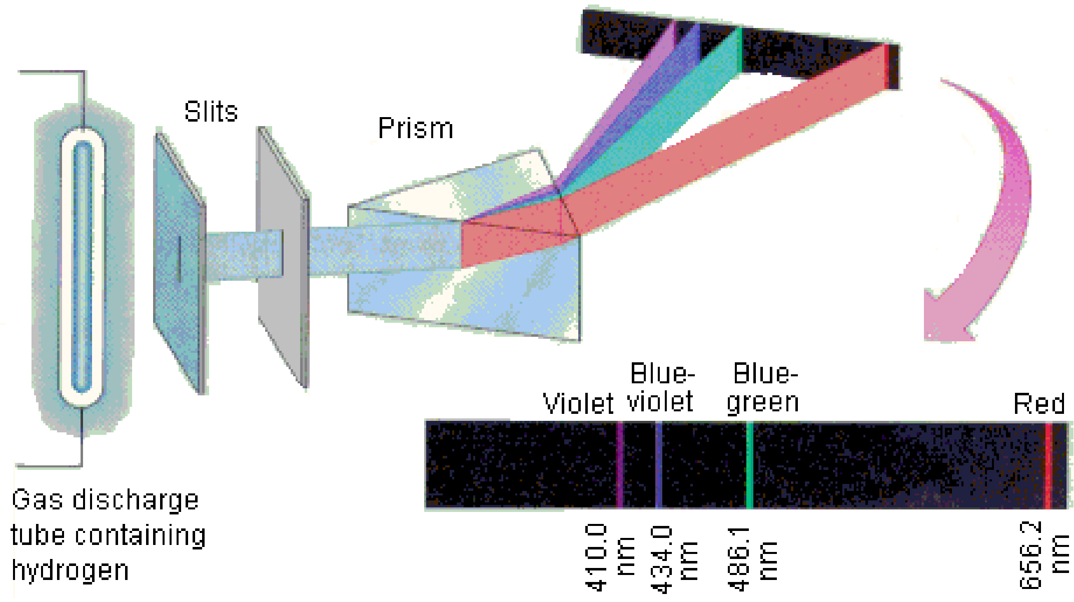
When white light from the sun passes through a prism, the light is dispersed into its component colors in a continuous spectrum



Emission Spectrum

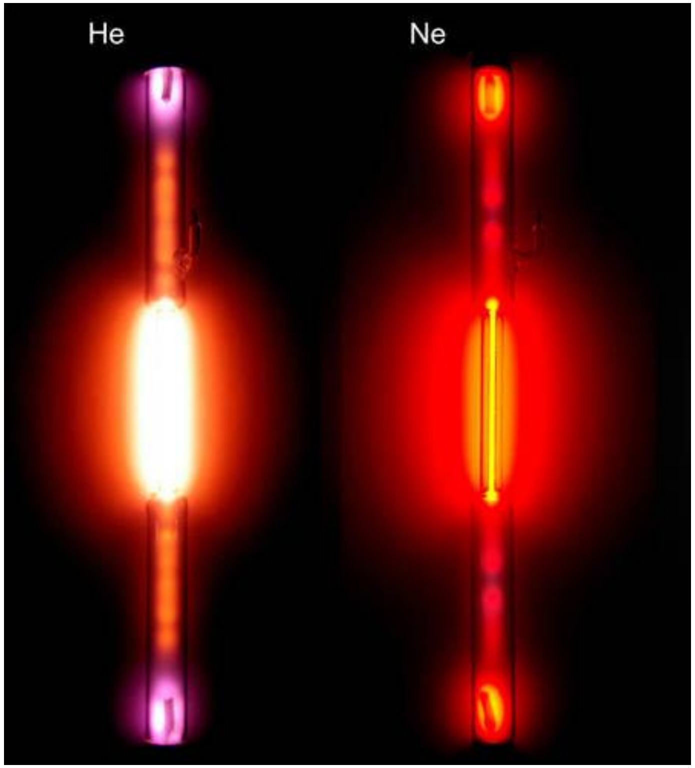
If an electric current is passed through an element in the form of a low-pressure gas, it will produce its own unique emission spectrum



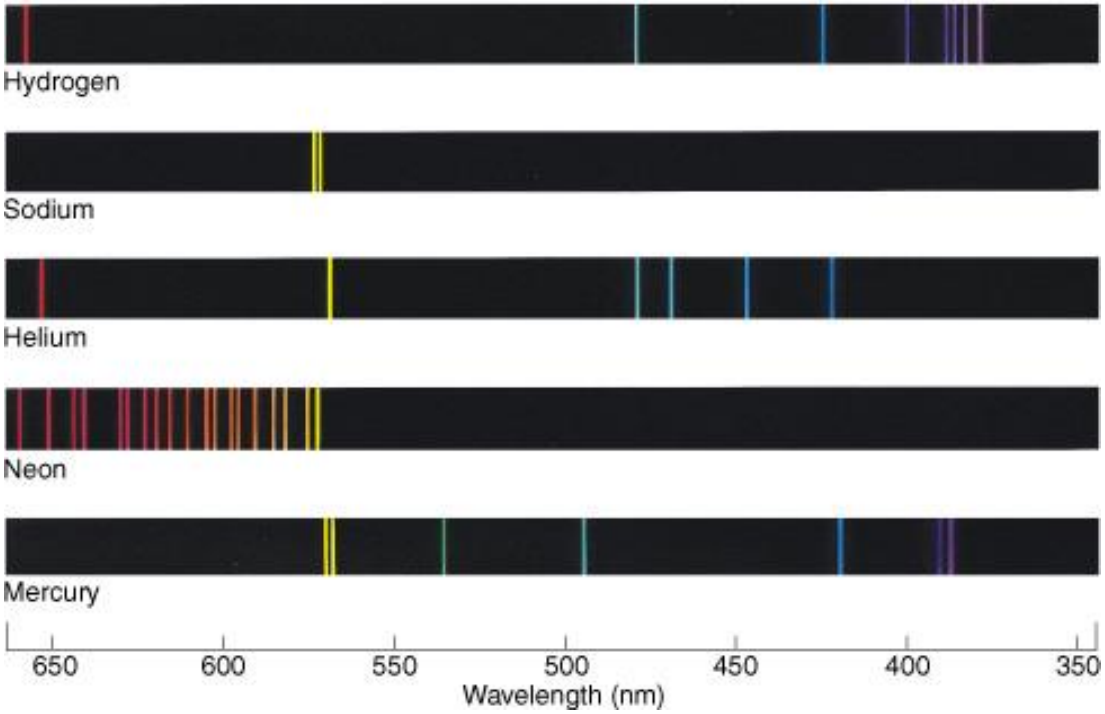


Emission Spectrum

These spectra can be used to identify elements like a fingerprint

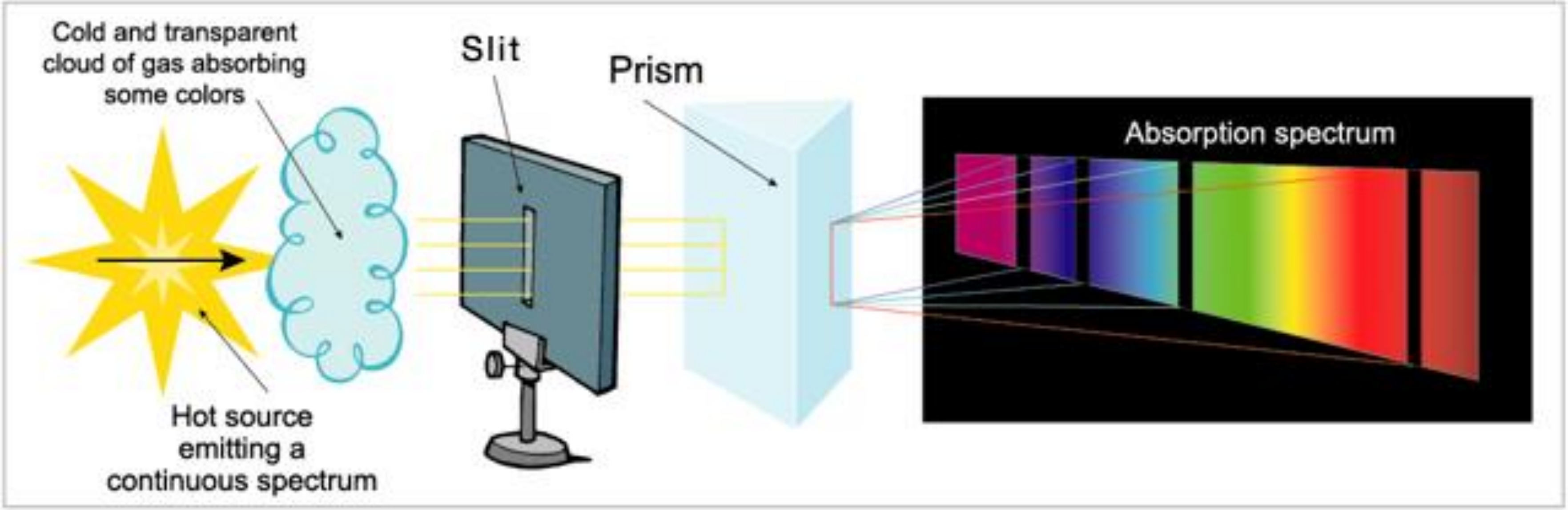


These are known as Line Spectra

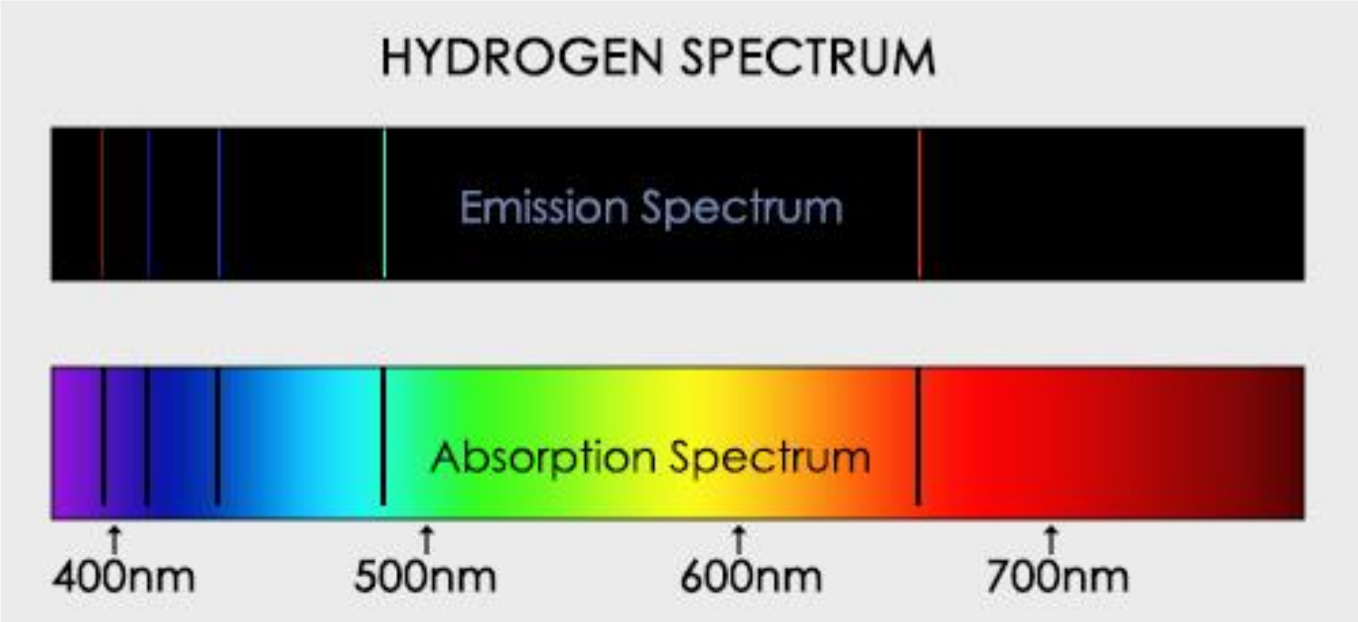


Absorption Spectrum

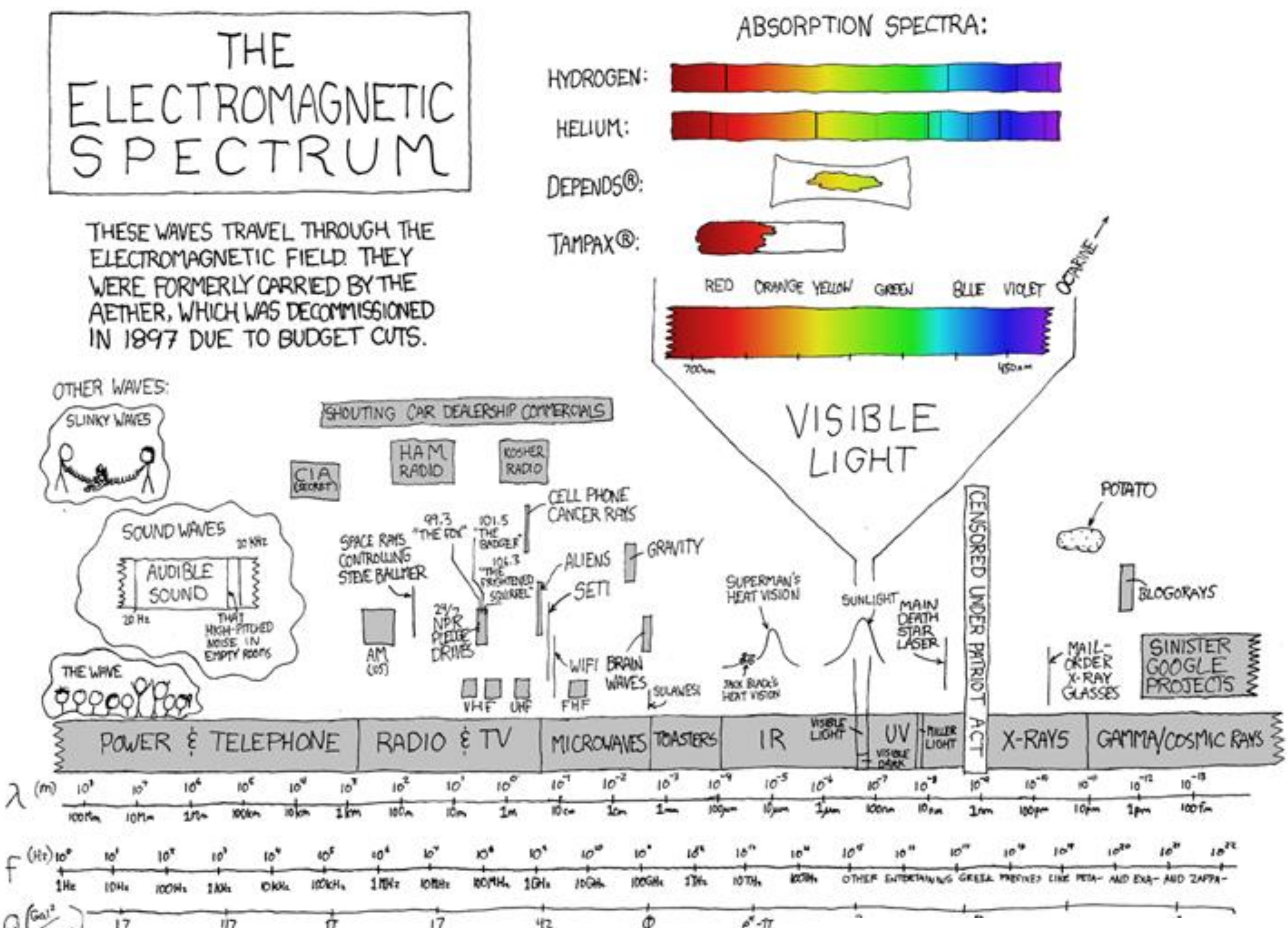
If white light is passed through a sample of gaseous atoms or molecules, it is found that the light of certain wavelengths is missing



Absorption Spectrum

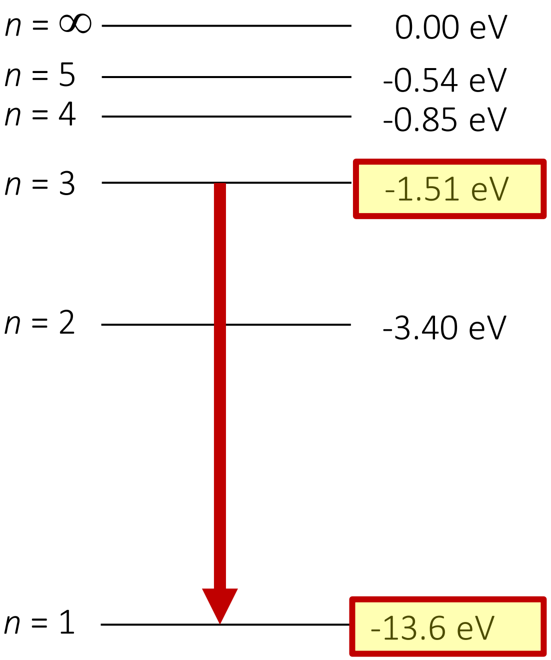


The emission and absorption spectra are negative images of each other



From Randall Monroe | xkcd.com

Calculating Wavelength Emitted



What is the wavelength emitted?

$$E = 13.6 - 1.51 = 12.09\ \text{eV}$$

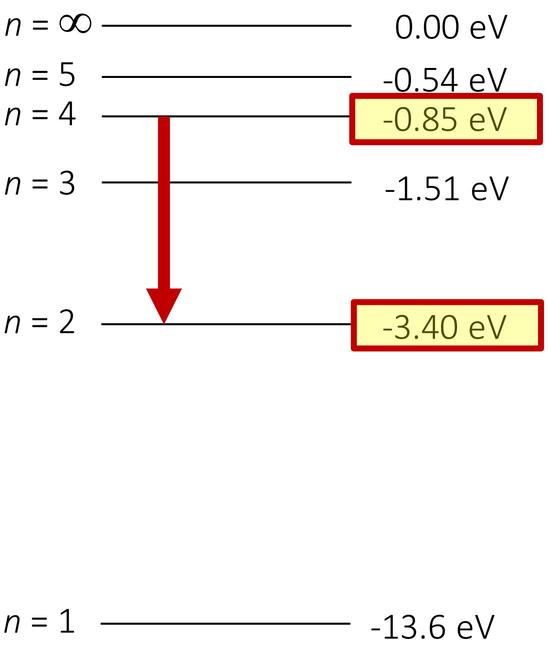
$$\lambda = \frac{1.24 \times 10^{-6}\ \cancel{\text{eV}}\ \text{m}}{12.09\ \cancel{\text{eV}}} = 1.03 \times 10^{-7}\ \text{m}$$

103 nm

$$\lambda = \frac{hc}{E}$$

hc	1.99×10^{-25} J m	1.24×10^{-6} eV m

Try This...



What is the wavelength emitted?

$$E = 3.40 - 0.85 = 2.55 \text{ eV}$$

$$\lambda = \frac{1.24 \times 10^{-6} \text{ eV m}}{2.55 \text{ eV}} = 4.86 \times 10^{-7} \text{ m}$$

486 nm

$$\lambda = \frac{hc}{E}$$

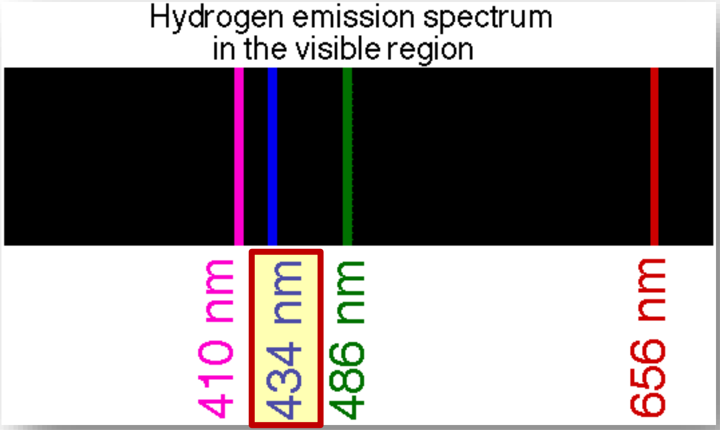
hc	1.99×10^{-25} J m	1.24×10^{-6} eV m

Working Backwards...

What is the energy in eV for a 434 nm blue emission line?

↓

434×10^{-9} m

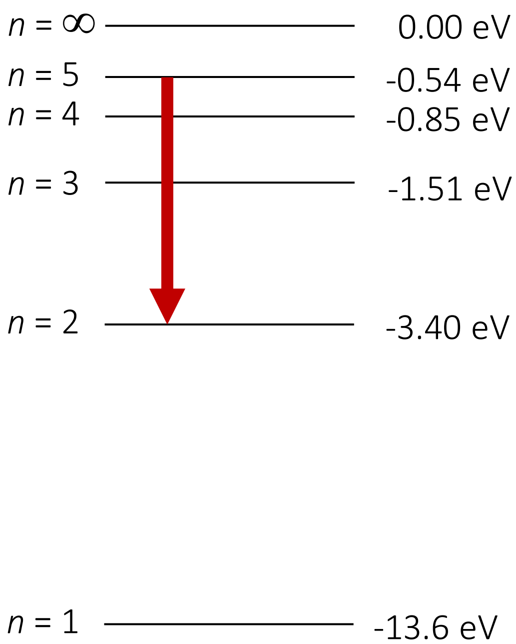


$$E = \frac{hc}{\lambda} = \frac{1.24 \times 10^{-6}\ \text{eV}\ \cancel{\text{m}}}{434 \times 10^{-9}\ \cancel{\text{m}}} = \boxed{2.86\ \text{eV}}$$

$$\lambda = \frac{hc}{E}$$

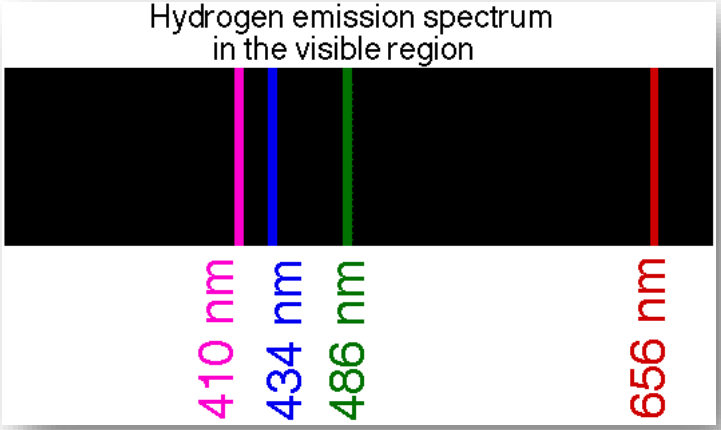
hc	1.99×10^{-25} J m	1.24×10^{-6} eV m

Working Backwards…



Draw in the Energy Transition for a 434 nm blue emission line?

What transition has an energy difference of 2.86 eV?



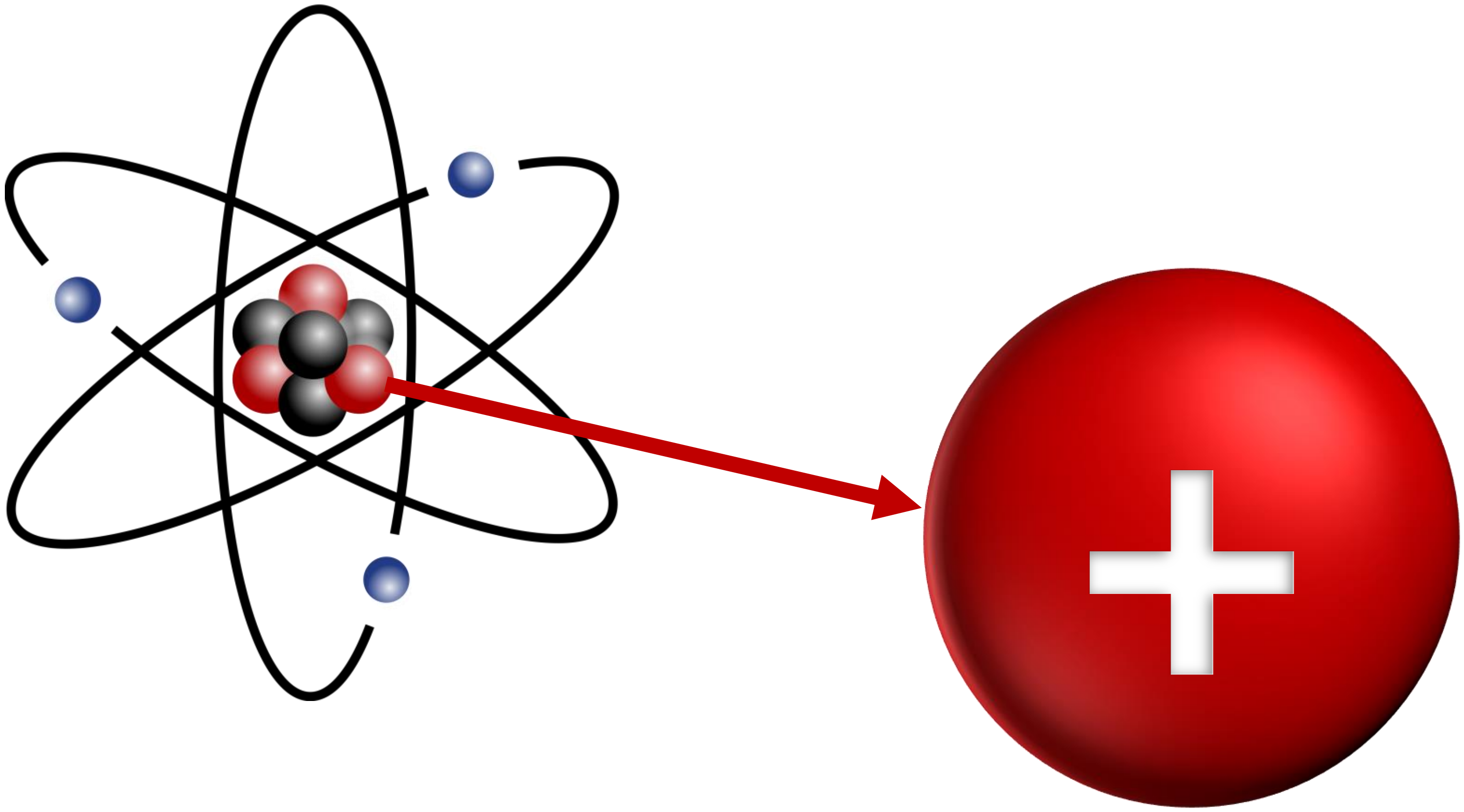
$$E = 3.40 - 0.54 = 2.86 \text{ eV}$$

4

Particles and the Standard Model

IB PHYSICS | ATOMIC PHYSICS

What is the "Fundamental Particle"?



Fundamental Particles

Charge	Quarks			Baryon Number
$\frac{2}{3}$	u	c	t	$\frac{1}{3}$
$-\frac{1}{3}$	d	s	b	$\frac{1}{3}$
All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of –1				

Charge	Leptons		
-1	e	μ	τ
0	v_e	v_μ	v_τ
All leptons have a lepton number of 1 and antileptons have a lepton number of –1			

Symbol	Name
u	Up
d	Down
c	Charm
s	Strange
t	Top
b	Bottom

Symbol	Name
e	Electron
μ	Muon
τ	Tau
v_e	Electron Neutrino
v_μ	Muon Neutrino
v_τ	Tau Neutrino

Antiparticles have the opposite charge as their corresponding particle and have a bar over their symbol

Symbol	Name	Charge
s	Strange	$-\frac{1}{3}$
$\bar{s}$	Antistrange	$+\frac{1}{3}$

IB Physics Data Booklet

Sub-topic 7.1 – Discrete energy and radioactivity	Sub-topic 7.2 – Nuclear reactions
$E = hf$ $\lambda = \frac{hc}{E}$	$\Delta E = \Delta m\, c^2$

Sub-topic 7.3 – The structure of matter

Charge	Quarks			Baryon number
$\frac{2}{3}e$	u	c	t	$\frac{1}{3}$
$-\frac{1}{3}e$	d	s	b	$\frac{1}{3}$

All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of −1

Charge	Leptons		
−1	e	μ	τ
0	υ_e	υ_μ	υ_τ

All leptons have a lepton number of 1 and antileptons have a lepton number of −1

	Gravitational	Weak	Electromagnetic	Strong
Particles experiencing	All	Quarks, leptons	Charged	Quarks, gluons
Particles mediating	Graviton	W^+, W^-, Z^0	γ	Gluons

Fundamental Particles

Symbol	Name	Charge	Baryon #
u	Up	$+\frac{2}{3}$	$\frac{1}{3}$
d	Down	$-\frac{1}{3}$	$\frac{1}{3}$
c	Charm	$+\frac{2}{3}$	$\frac{1}{3}$
s	Strange	$-\frac{1}{3}$	$\frac{1}{3}$
t	Top	$+\frac{2}{3}$	$\frac{1}{3}$
b	Bottom	$-\frac{1}{3}$	$\frac{1}{3}$

Symbol	Name	Charge	Lepton #
e	Electron	-1	1
μ	Muon	-1	1
τ	Tau	-1	1
ν_e	Electron Neutrino	0	1
ν_μ	Muon Neutrino	0	1
ν_τ	Tau Neutrino	0	1

Symbol	Name	Charge	Baryon #
$\bar{\mathrm{u}}$	Antiup	$-\frac{2}{3}$	$-\frac{1}{3}$
$\bar{\mathrm{d}}$	Antidown	$+\frac{1}{3}$	$-\frac{1}{3}$
$\bar{\mathrm{c}}$	Anticharm	$-\frac{2}{3}$	$-\frac{1}{3}$
$\bar{\mathrm{s}}$	Antistrange	$+\frac{1}{3}$	$-\frac{1}{3}$
$\bar{\mathrm{t}}$	Antitop	$-\frac{2}{3}$	$-\frac{1}{3}$
$\bar{\mathrm{b}}$	Antibottom	$+\frac{1}{3}$	$-\frac{1}{3}$

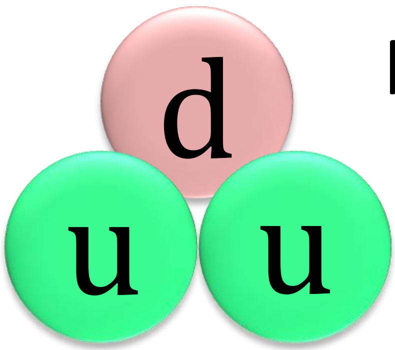
Symbol	Name	Charge	Lepton #
$\bar{\mathrm{e}}$	Antielectron (positron)	$+1$	-1
$\bar{\mu}$	Antimuon	$+1$	-1
$\bar{\tau}$	Antitau	$+1$	-1
$\bar{\nu}_e$	Electron Antineutrino	0	-1
$\bar{\nu}_\mu$	Muon Antineutrino	0	-1
$\bar{\nu}_\tau$	Tau Antineutrino	0	-1

Classifying Particles

- Leptons
  - Electrons
  - Muons
  - Tau
  - Neutrinos
- Hadrons
  - Mesons
    - Pion (π)
    - Kaon (K)
    - Others
  - Baryons
    - Proton
    - Neutron
    - Others

Baryons

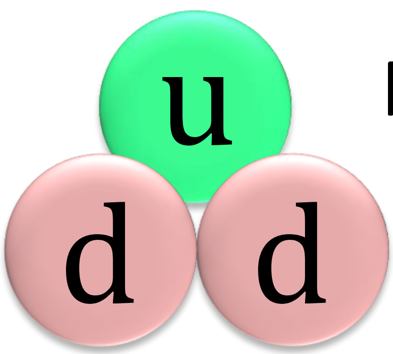
All Baryons are formed from a combination of 3 quarks or antiquarks



Proton

+1

(uud)



Neutron

0

(udd)

Rule:	Charge must be an integer value (-1, 0, or +1)

Up Quark

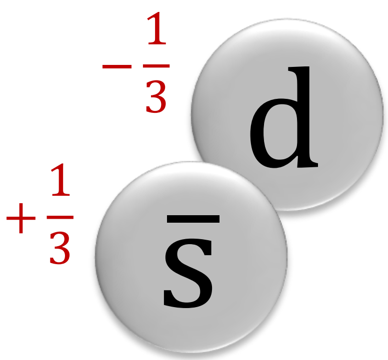
Charge = 2/3

Down Quark

Charge = -1/3

Mesons

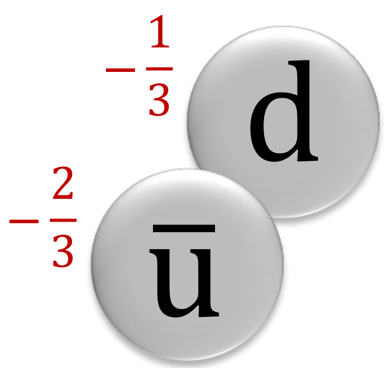
All Mesons are formed from a combination of a quark and antiquark



Kaon

0

Rule:	Charge must be an integer value (-1, 0, or +1)



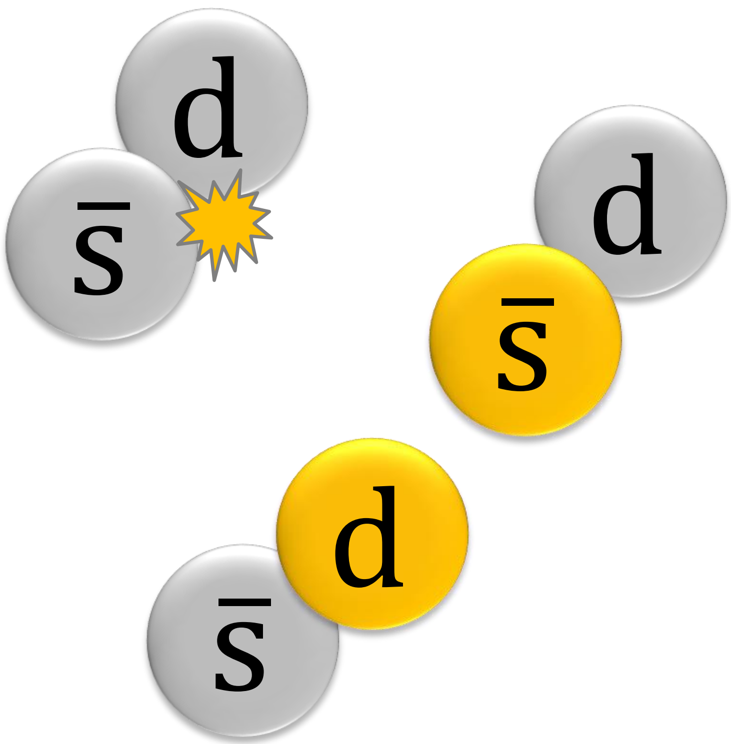
D-Meson

-1

Charge	Quarks			Baryon Number
$\frac{2}{3}$	u	c	t	$\frac{1}{3}$
$-\frac{1}{3}$	d	s	b	$\frac{1}{3}$
All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of –1				

Quark Confinement

Quarks have never been observed on their own



The amount of energy required to overcome the strong nuclear force holding the quarks together gets converted into mass and forms a new quark pair

Conservation

For an interaction to be possible, the following must stay conserved:

Baryon #	Lepton #	Charge	Strangeness

$$n \rightarrow p + e^{-} + \bar{v}_e$$

Baryon #	1	1	0	0
Lepton #	0	0	1	-1
Charge	0	1	-1	0

This interaction is valid because all properties are conserved

Conservation

$$p + e^- \rightarrow n + v_e$$

	p	e^-	n	v_e
Baryon #	1	0	1	0
Lepton #	0	1	0	1
Charge	+1	-1	0	0

Yes
Valid

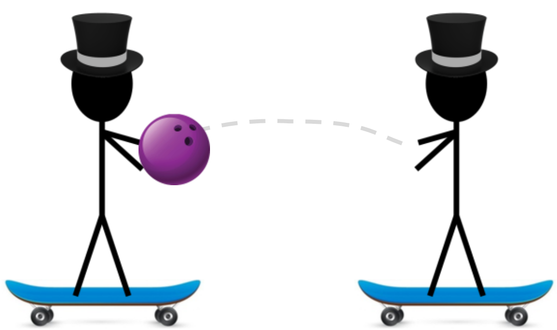
$$n + p \rightarrow e^+ + \bar{v}_e$$

	n	p	e^+	$\bar{v}_e$
Baryon #	1	1	0	0
Lepton #	0	0	-1	-1
Charge	0	+1	+1	0

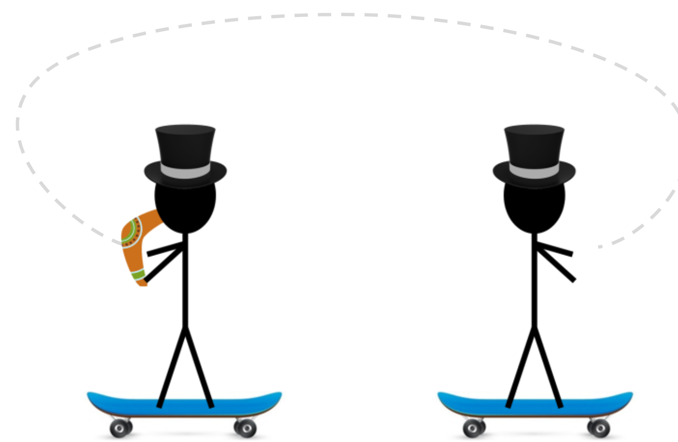
No
Invalid

Exchange Particles

At the fundamental level of particle physics, forces are explained in terms of the transfer of **exchange particles** (**gauge bosons**) between the two particles experiencing the force



Repulsion



Attraction

These interactions are not observable, so we call them ***virtual particles***

Types of Forces

	Gravitational	Weak	Electromagnetic	Strong
Particles experiencing	All	Quarks, leptons	Charged	Quarks, gluons
Particles mediating	Graviton	W^+, W^-, Z^0	γ photon	Gluons

Weakest → Strongest

Sample IB Question

26. Which of the following lists three fundamental forces in increasing order of strength?

A. electromagnetic, gravity, strong nuclear

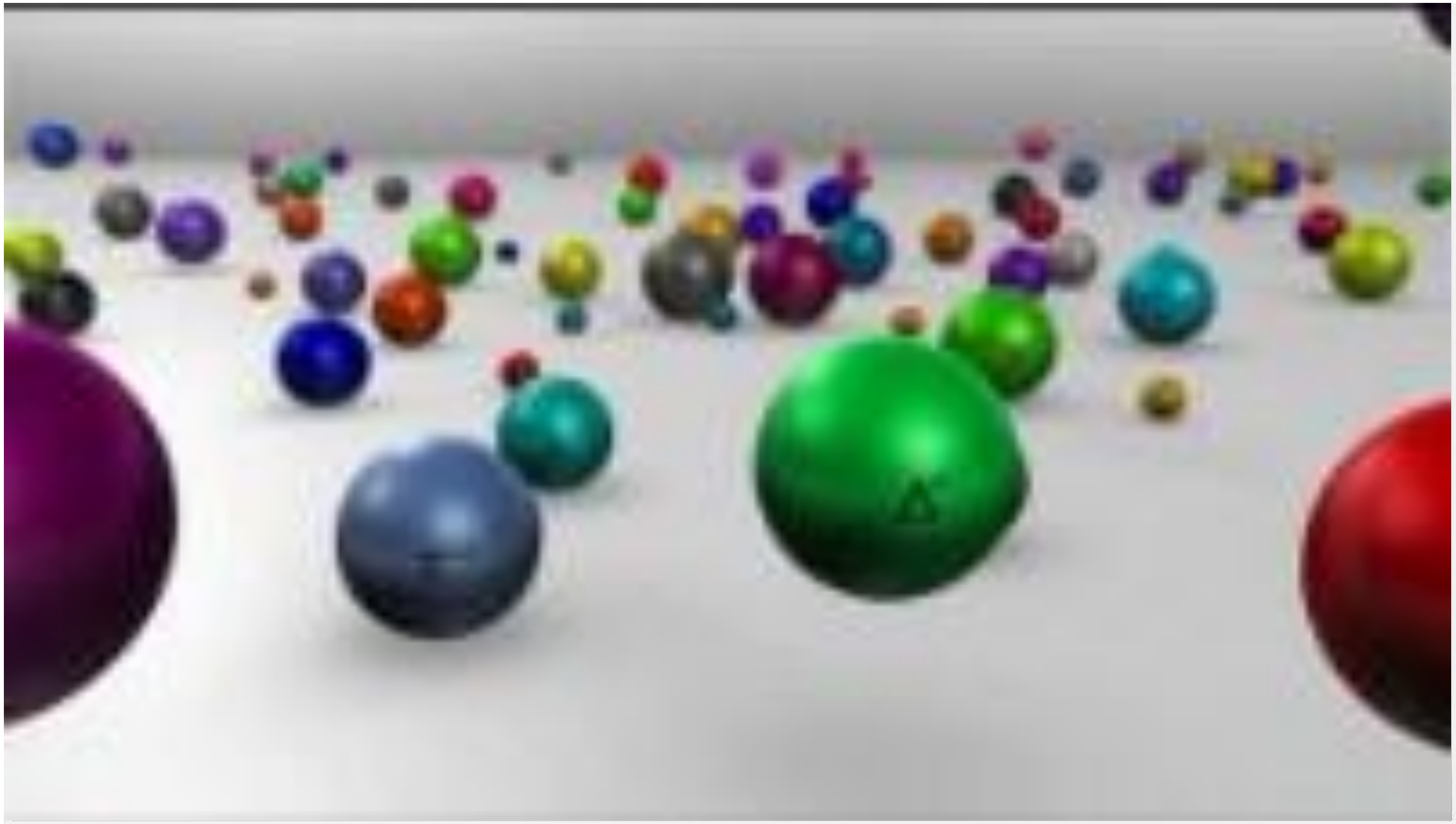
B. weak nuclear, gravity, strong nuclear

C. gravity, weak nuclear, electromagnetic

D. electromagnetic, strong nuclear, gravity

	Gravitational	Weak	Electromagnetic	Strong
Particles experiencing	All	Quarks, leptons	Charged	Quarks, gluons
Particles mediating	Graviton	W^+, W^-, Z^0	γ	Gluons

The Standard Model



CERN: The Standard Model Of Particle Physics

Sample IB Question

27. For which reason were quarks first introduced?

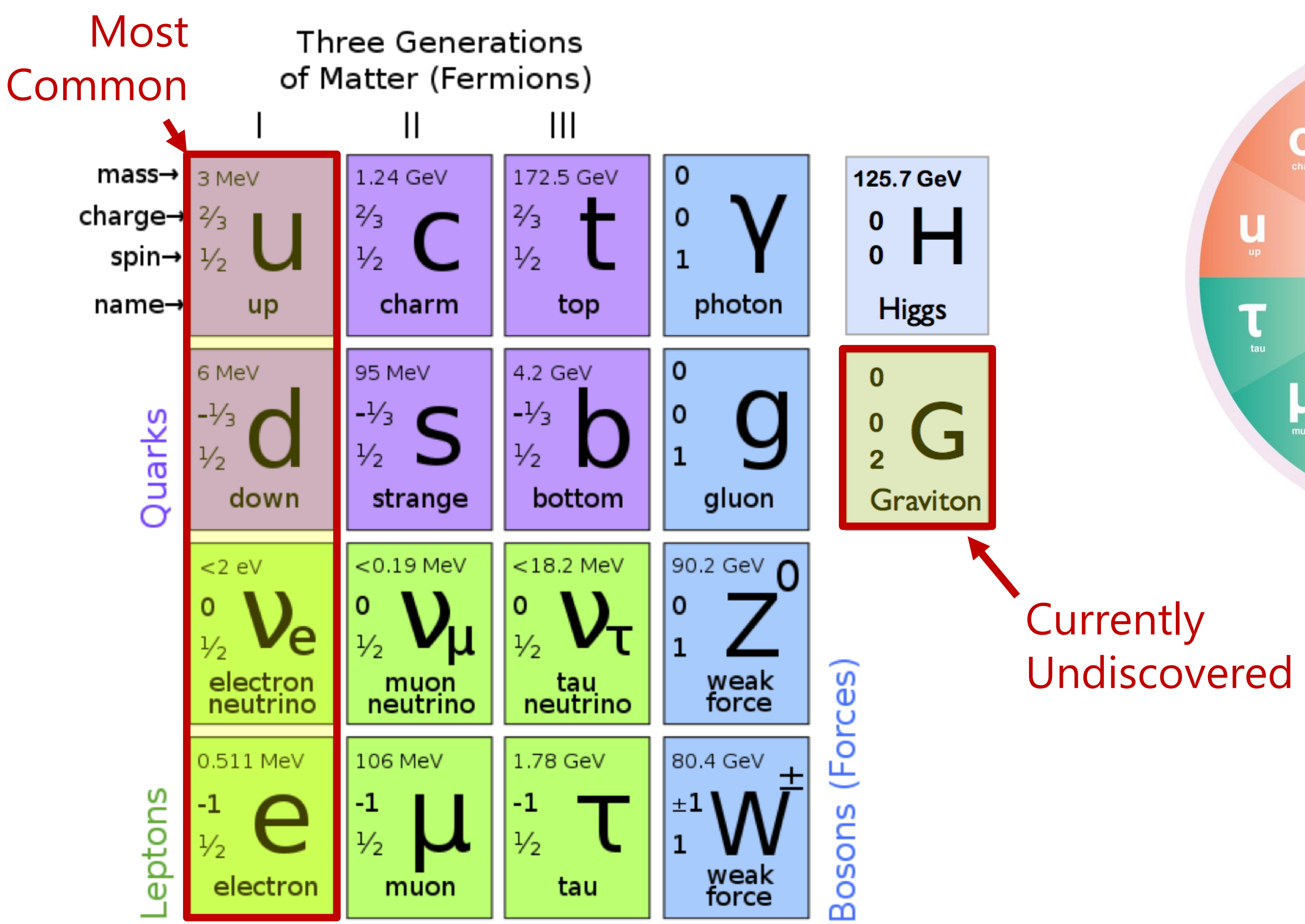
A. To explain the existence of isotopes

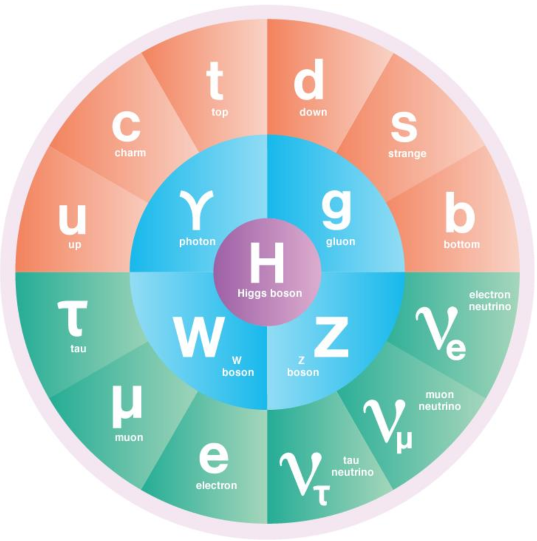
B. To describe nuclear emission and absorption spectra

C. To account for patterns in properties of elementary particles

D. To account for the missing energy and momentum in beta decay

The Standard Model





Feynman Diagrams & the Higgs Boson

IB PHYSICS | ATOMIC PHYSICS

IB Physics Data Booklet

Sub-topic 7.1 – Discrete energy and radioactivity	Sub-topic 7.2 – Nuclear reactions
$E = hf$ $\lambda = \frac{hc}{E}$	$\Delta E = \Delta m\, c^2$

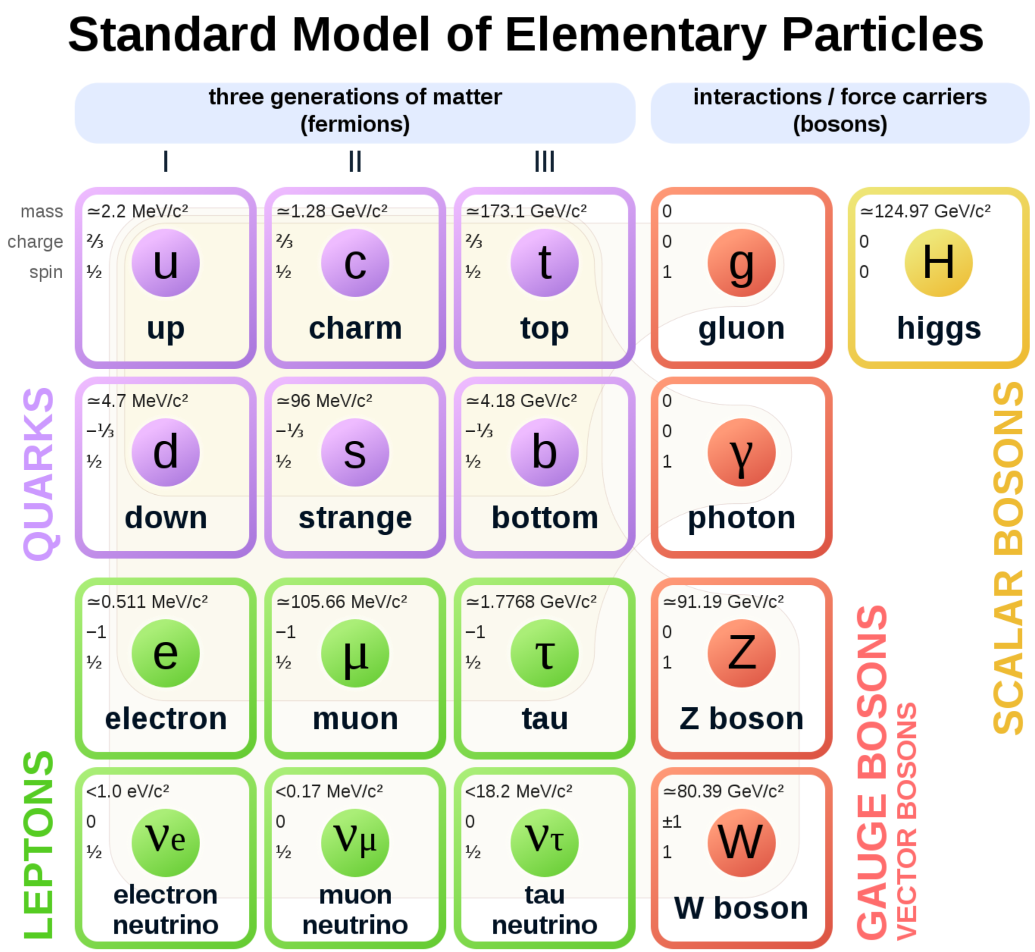
Sub-topic 7.3 – The structure of matter

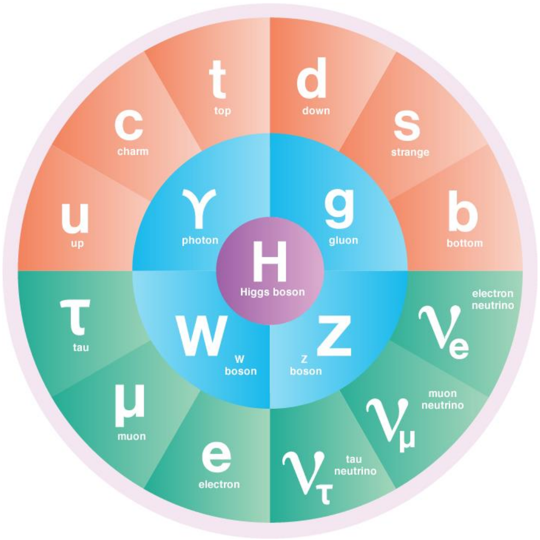
Charge	Quarks			Baryon number
$\frac{2}{3}e$	u	c	t	$\frac{1}{3}$
$-\frac{1}{3}e$	d	s	b	$\frac{1}{3}$
All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of −1				

Charge	Leptons		
−1	e	μ	τ
0	υ_e	υ_μ	υ_τ
All leptons have a lepton number of 1 and antileptons have a lepton number of −1			

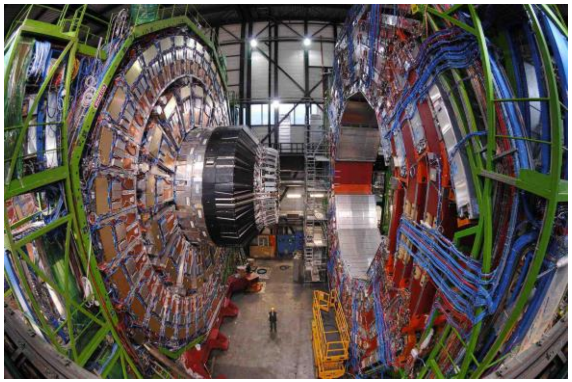
	Gravitational	Weak	Electromagnetic	Strong
Particles experiencing	All	Quarks, leptons	Charged	Quarks, gluons
Particles mediating	Graviton	W^+, W^-, Z^0	γ	Gluons

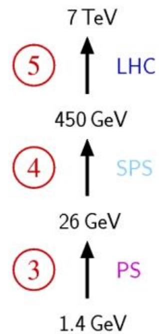
The Standard Model

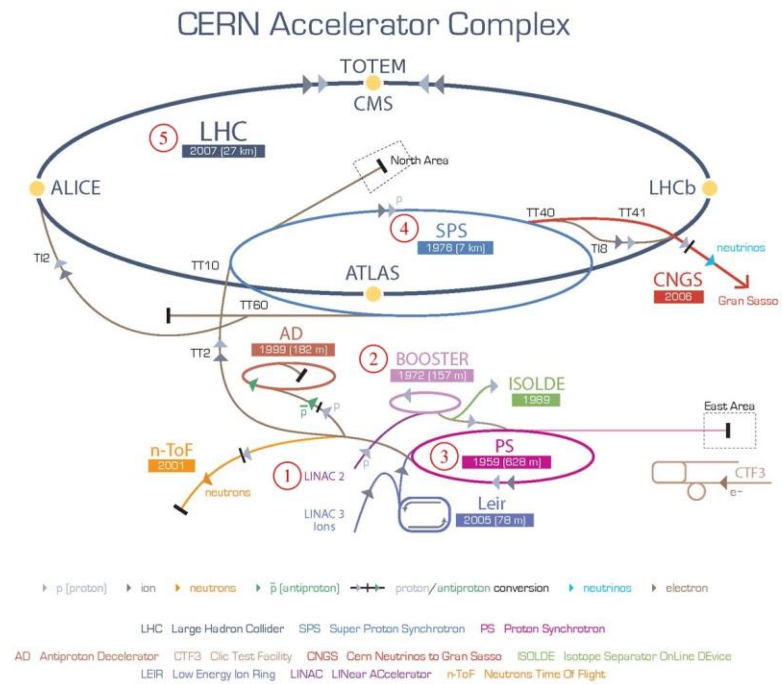




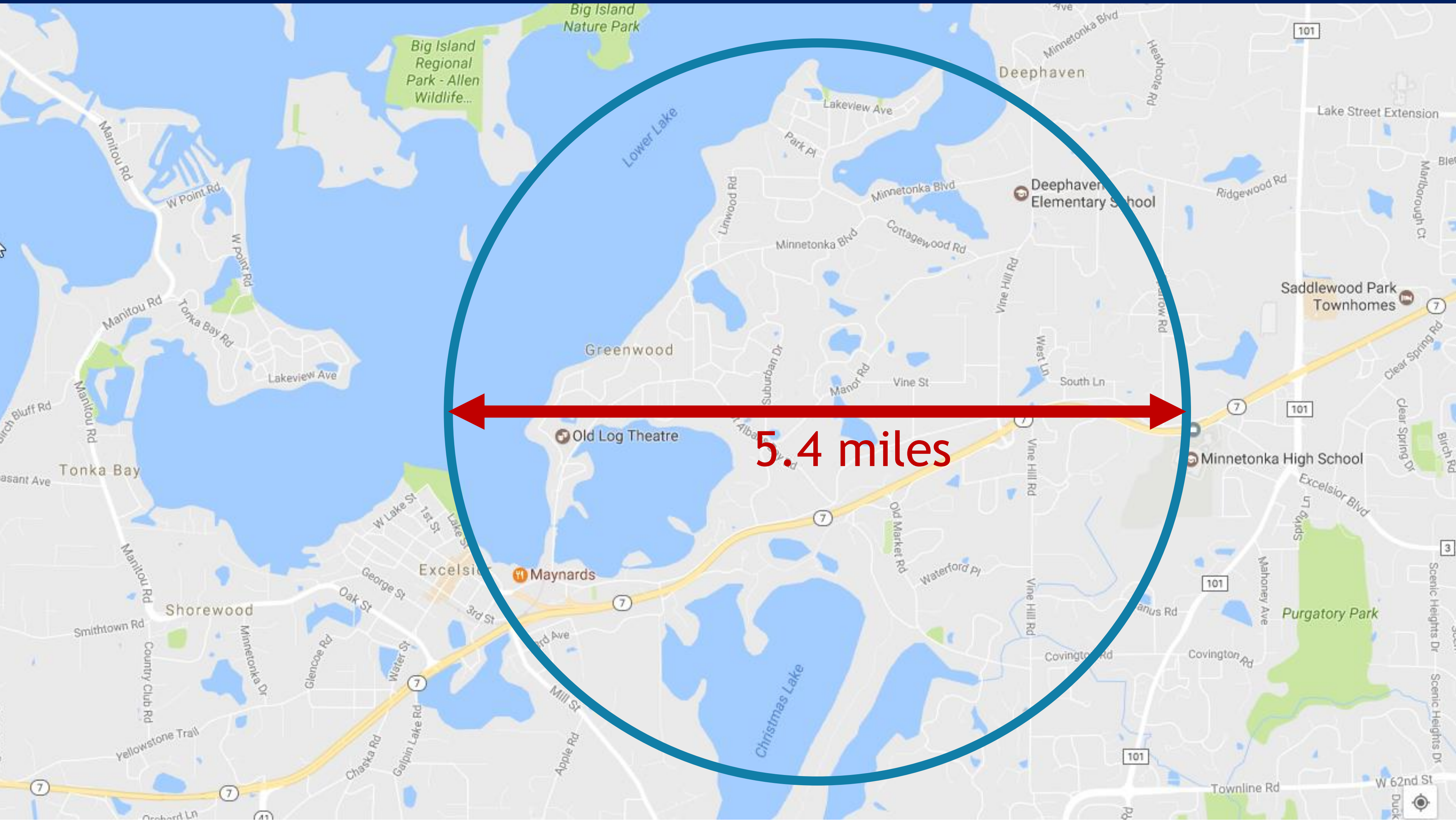
The Large Hadron Collider



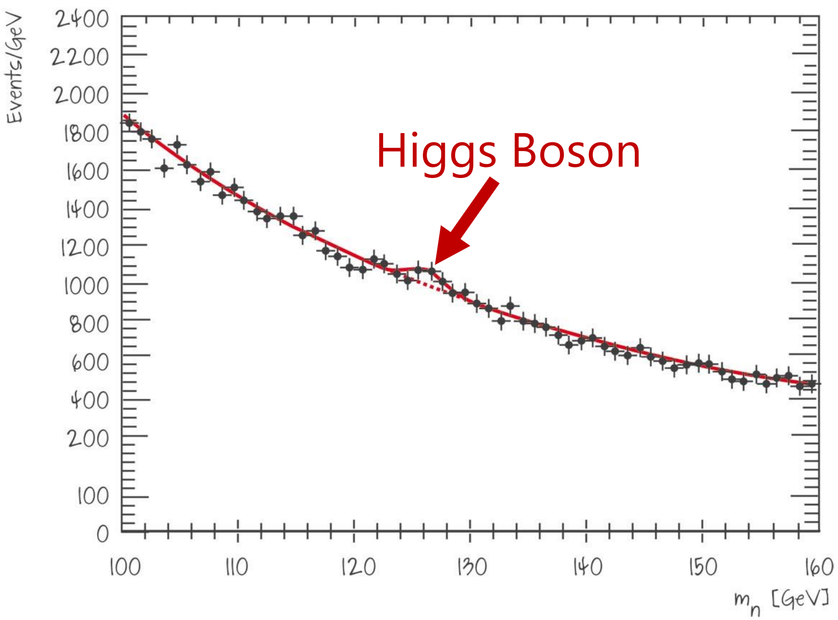


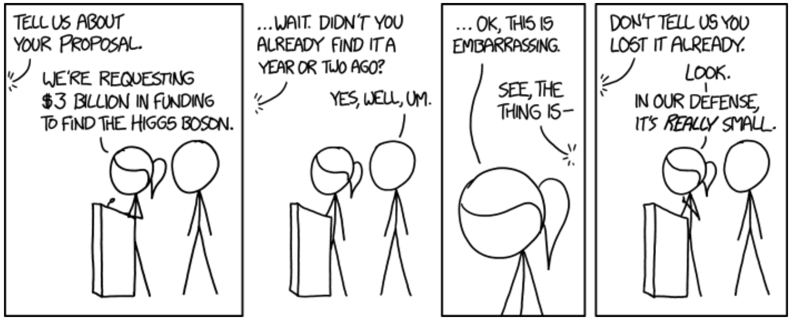


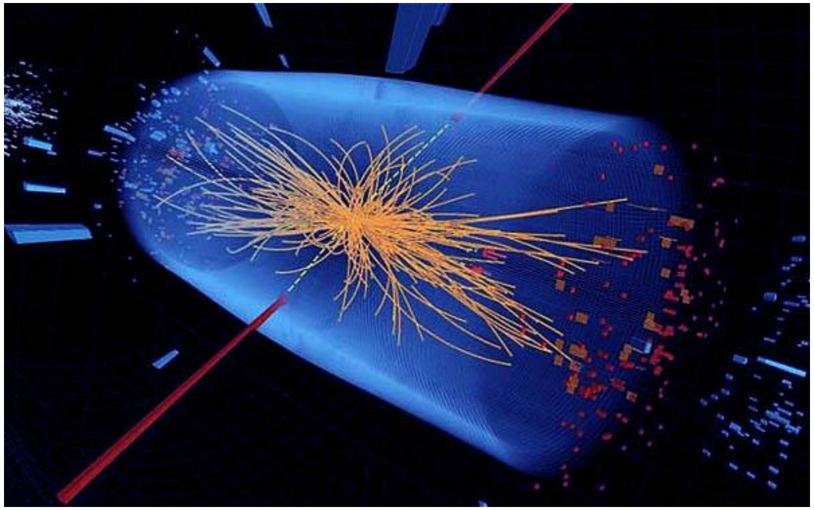
The Large Hadron Collider



The Higgs Boson

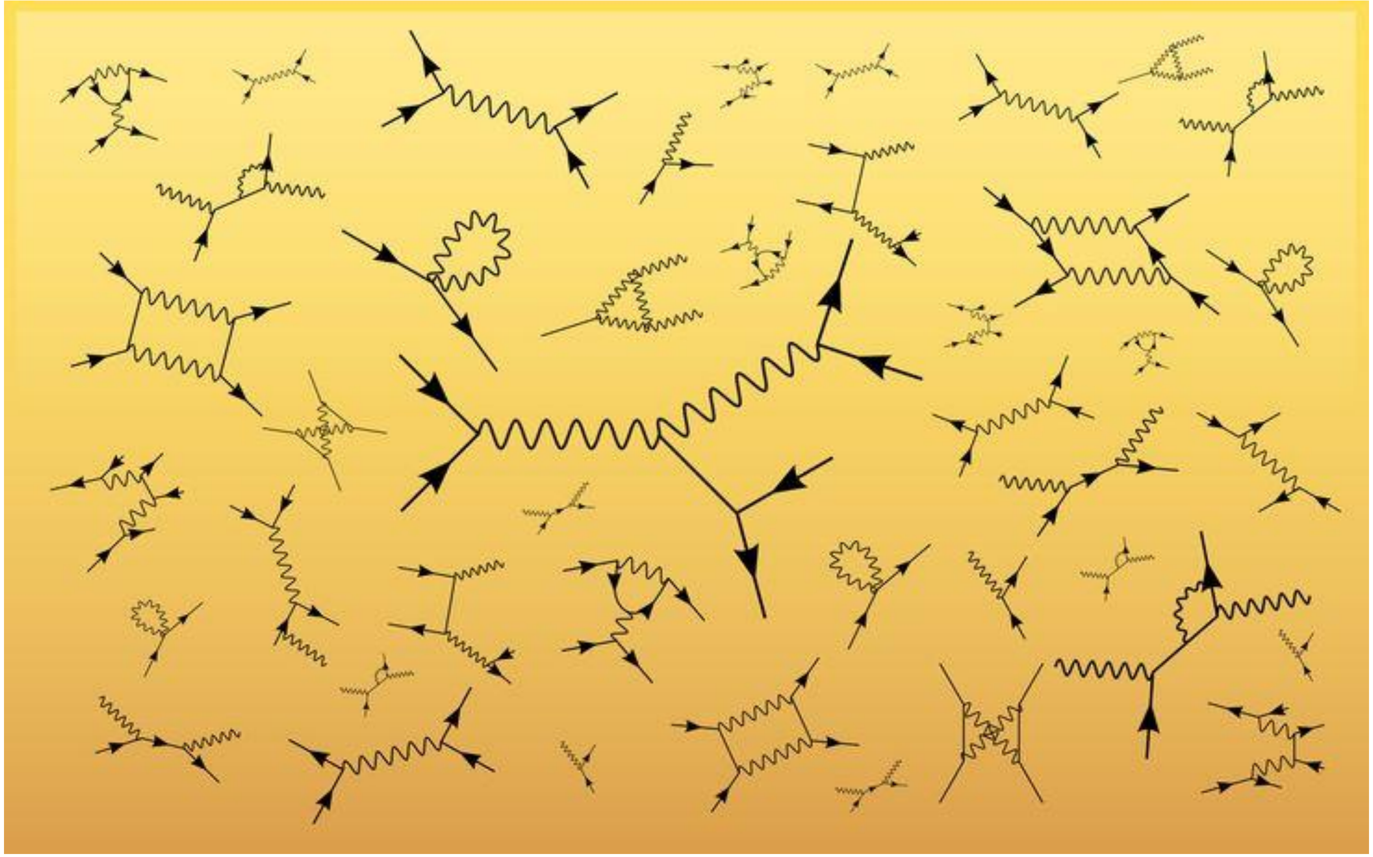




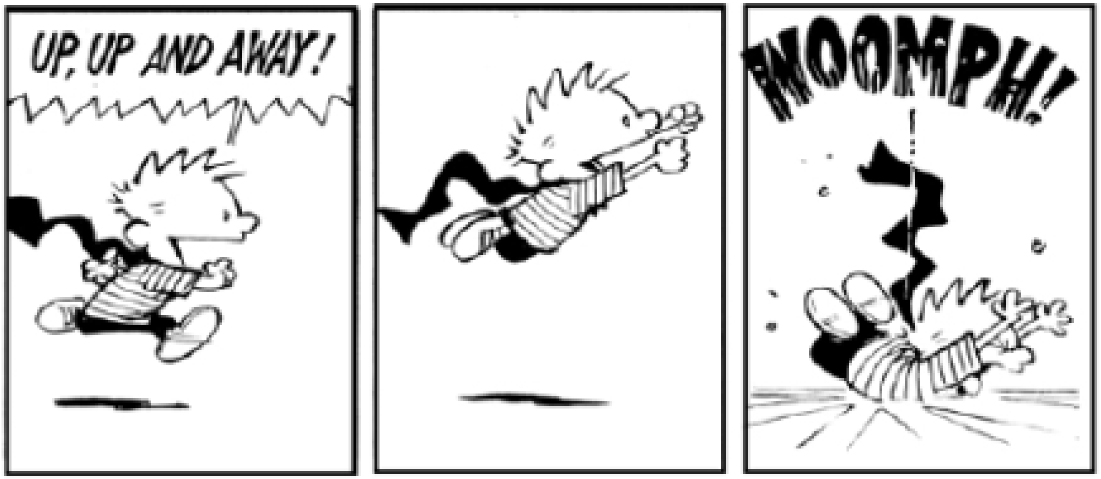


Feynman Diagrams

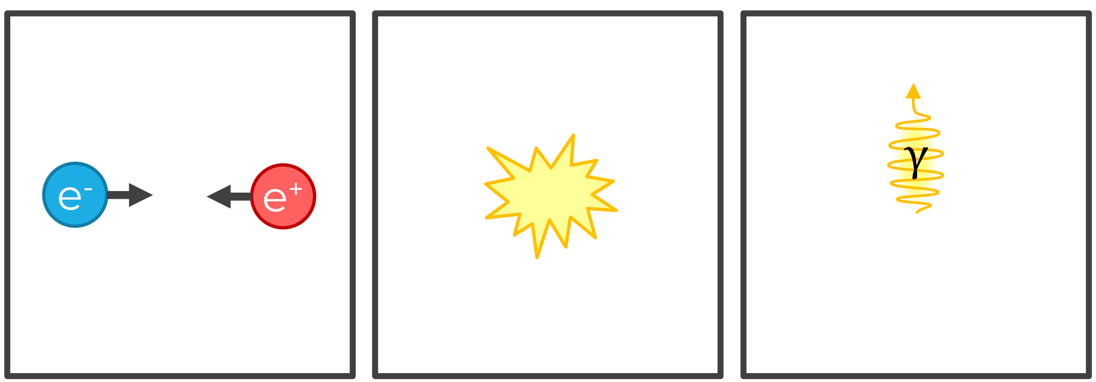
Useful to represent, analyze, and predict particle interactions



Feynman Diagrams are like Comics



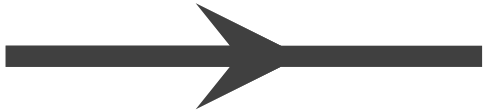
Set Up **Event** **Result**



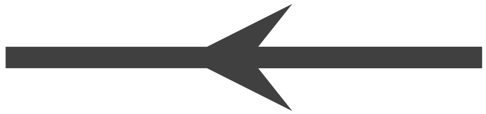
An electron and positron (antielectron) annihilate into a photon

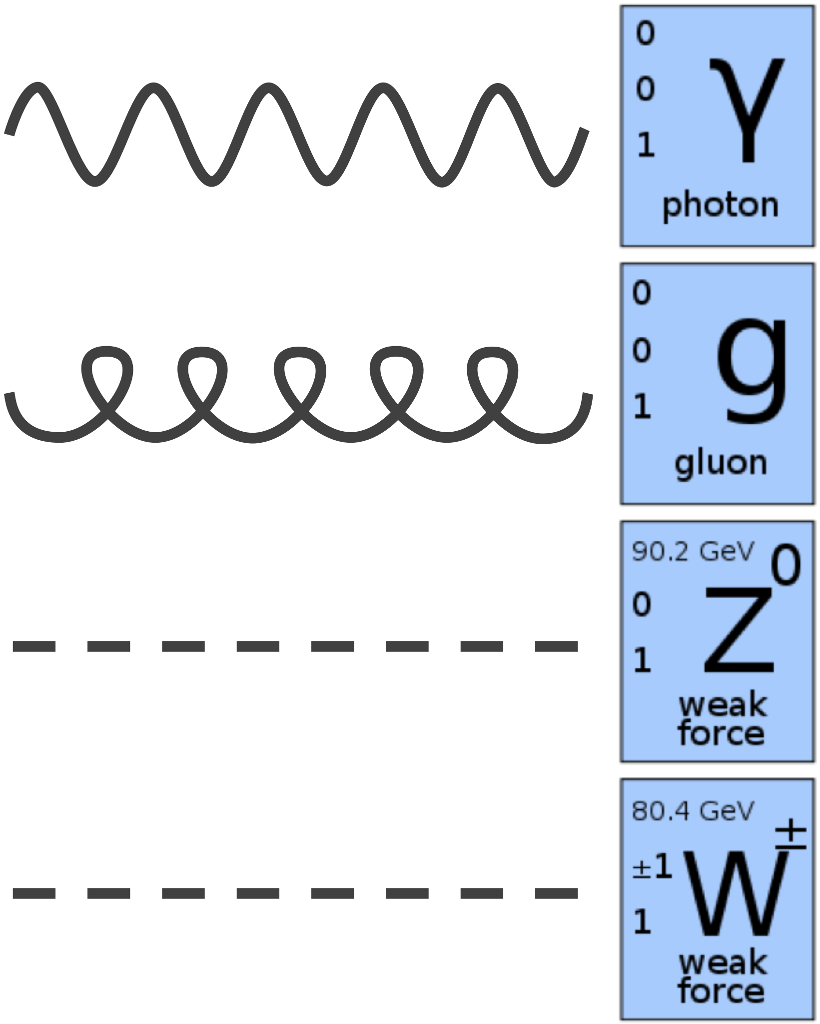
“The Characters”

Matter Particle



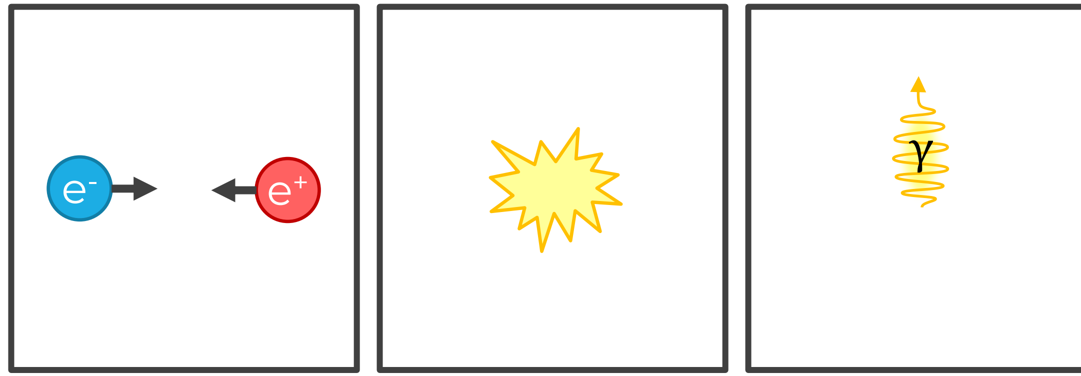
Antimatter Particle

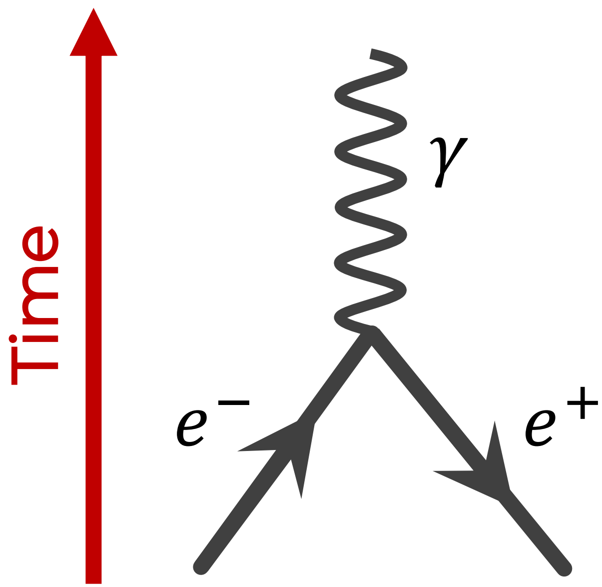


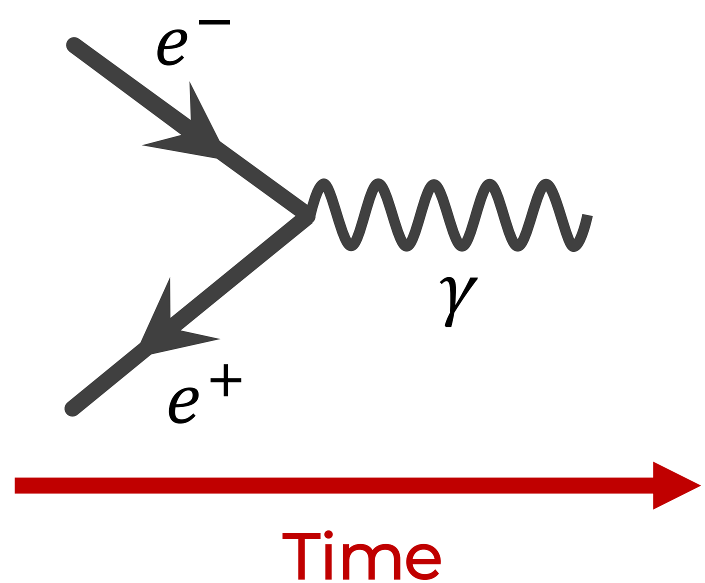


Representing Time

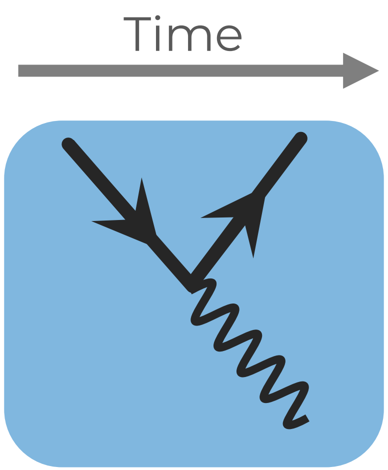
An electron and positron (antielectron) annihilate into a photon

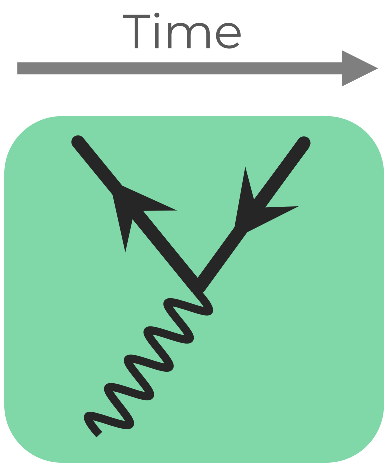


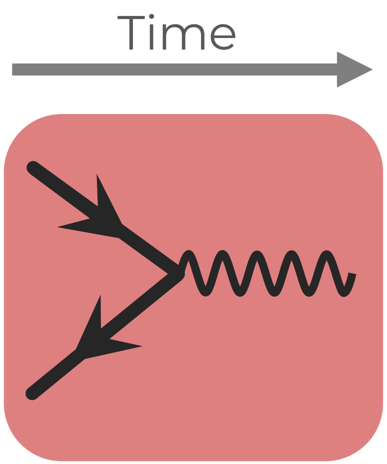


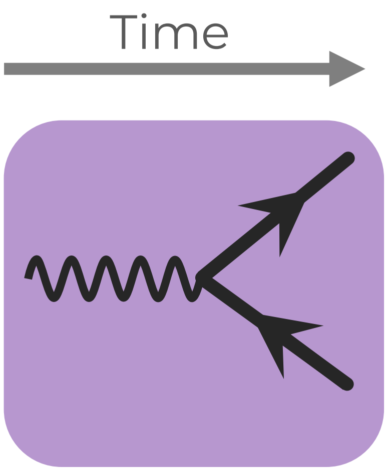


Match these!





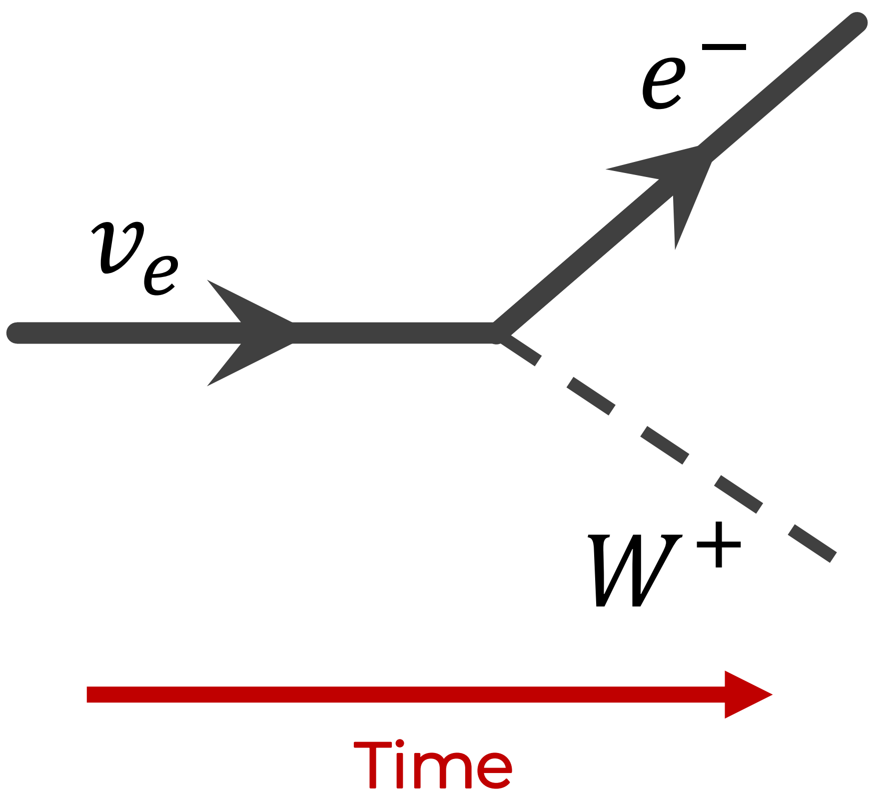




a photon spontaneously "pair produces" an electron and positron	a positron absorbs a photon and keeps going	an electron emits a photon and keeps going	an electron and positron annihilate into a photon

Junction Conservation

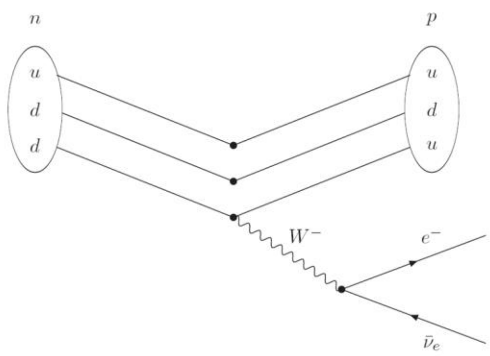
Every junction will have two lines with arrows (one pointing in, one pointing out) meeting a single exchange particle and all properties are conserved before/after

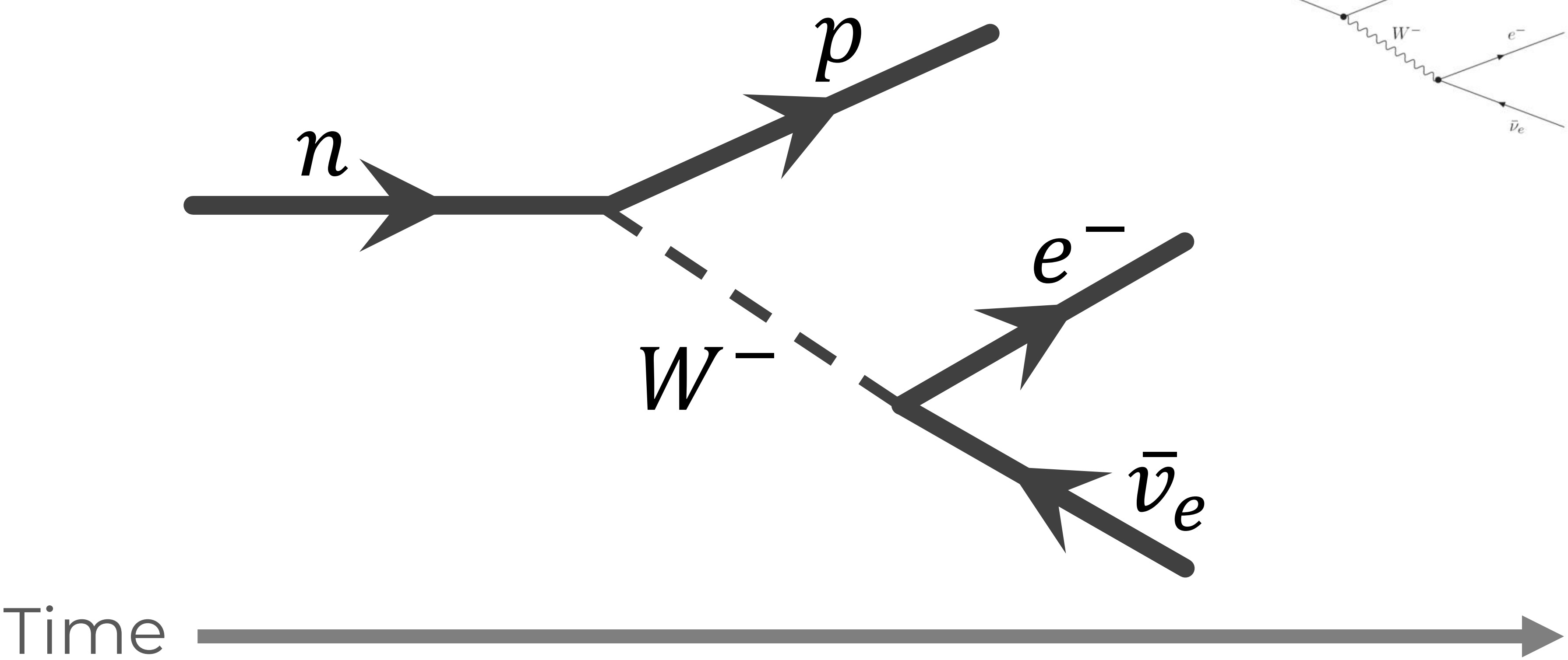


	ν_e	e^-	W^+
Baryon #	0	0	0
Lepton #	1	1	0
Charge	0	-1	+1

Beta-Negative Decay

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$





Beta-Positive Decay

$$p \rightarrow n + e^{+} + v_{e}$$