Quantum physics

A-level overview

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Quantum calculation overview

Wave model	Conversion	Particle model
Intensity	Conservation of energy	Number of particles or Probability of a particle or Particles flowing per second
Frequency *f*	$E_k = hf$	Kinetic energy of individual particle E_k
Wavelength λ	$\lambda = \frac{h}{mv}$	Momentum of individual particle *p=mv*

h = Planck constant 6.63×10^{-34} Js, *c* = 3.00×10^{8} m/s, 1eV = 1.60×10^{-19} J

Photons (no rest mass): $E = hf$, $c = f\lambda$, so $E = \frac{hc}{\lambda}$. For massive particle $p^2 = 2mE_k$

Energy equivalence		
Energy *E* (J)	$E = mc^2$	Mass *m* (kg)
Energy E_{MeV} (MeV)	$E_{MeV} = m_u \times 931$	Mass m_u (u)

Calculation examples

1. Calculate the wavelength of an electron accelerated by a 1.5MV accelerator.

2. Calculate the energy of a 500nm photon in eV

3. Calculate the equivalent energy of an electron with mass $5.49 x 10^{-4}$u

Calculation practice

1. Calculate the wavelength of a 2.50eV photon.

2. Calculate the energy (in eV) of an electron with a wavelength of 25nm.

3. What is the energy equivalent to the mass of a proton (1.67×10^{-27}kg)?

Photoelectric effect

Metal surfaces can emit electrons when illuminated

- no electrons unless frequency $f > f_{th}$ threshold
- increased frequency gives faster electrons
- brighter light gives more electrons each second
- light intensity does not affect speed of electrons
- no delay between turning on light and electron emission

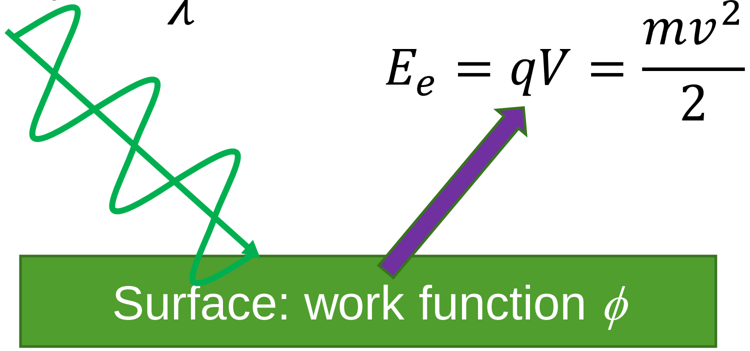
Photoelectric effect

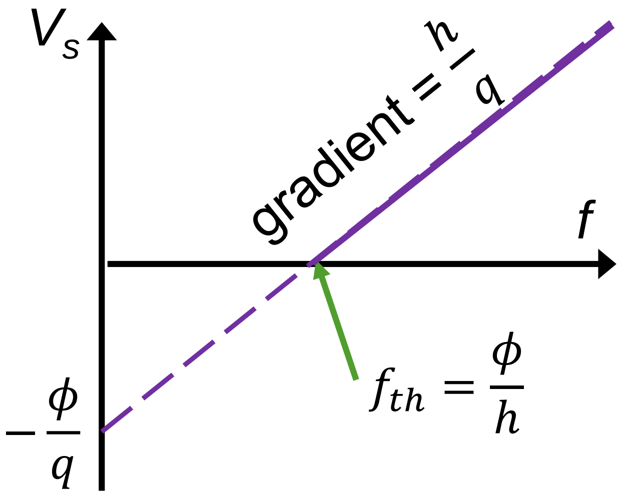
Photon:

$$E_p = hf = \frac{hc}{\lambda}$$

Electron:

$$E_e = qV = \frac{mv^2}{2}$$





Work function ϕ is minimum energy needed to remove one electron from the surface (in J or eV)

Maximum electron kinetic energy

$$K_{max} = hf - \phi$$

Stopping potential

$$V_s = \frac{K_{max}}{q} = \frac{hf}{q} - \frac{\phi}{q}$$

Photoelectric example

The work function of iron is 4.5eV. What is the wavelength of light needed to obtain photoelectrons with a stopping potential of 1.5V?

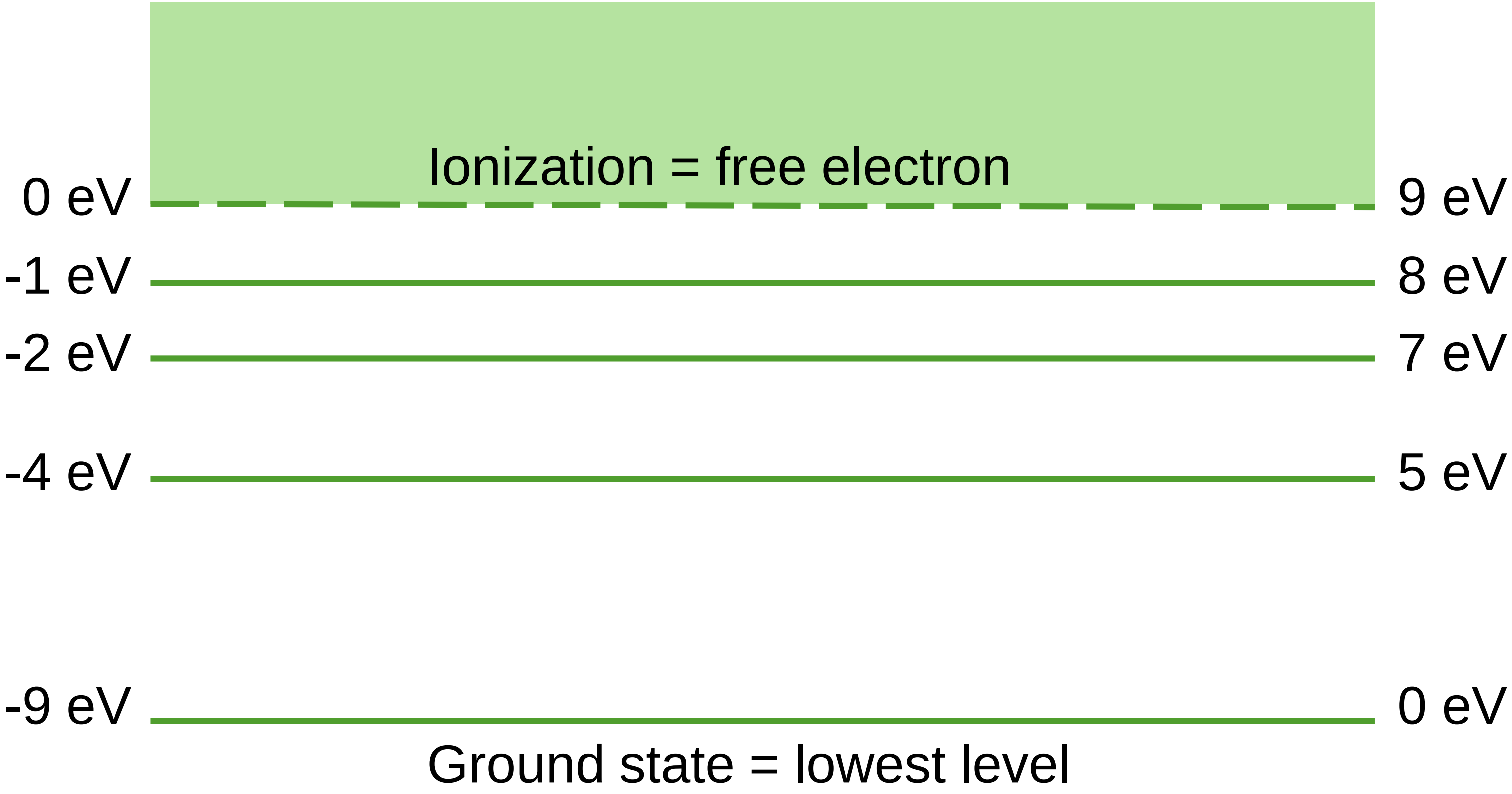
Photoelectric practice

1. Calculate the threshold frequency for aluminium, which has a work function of 4.08eV

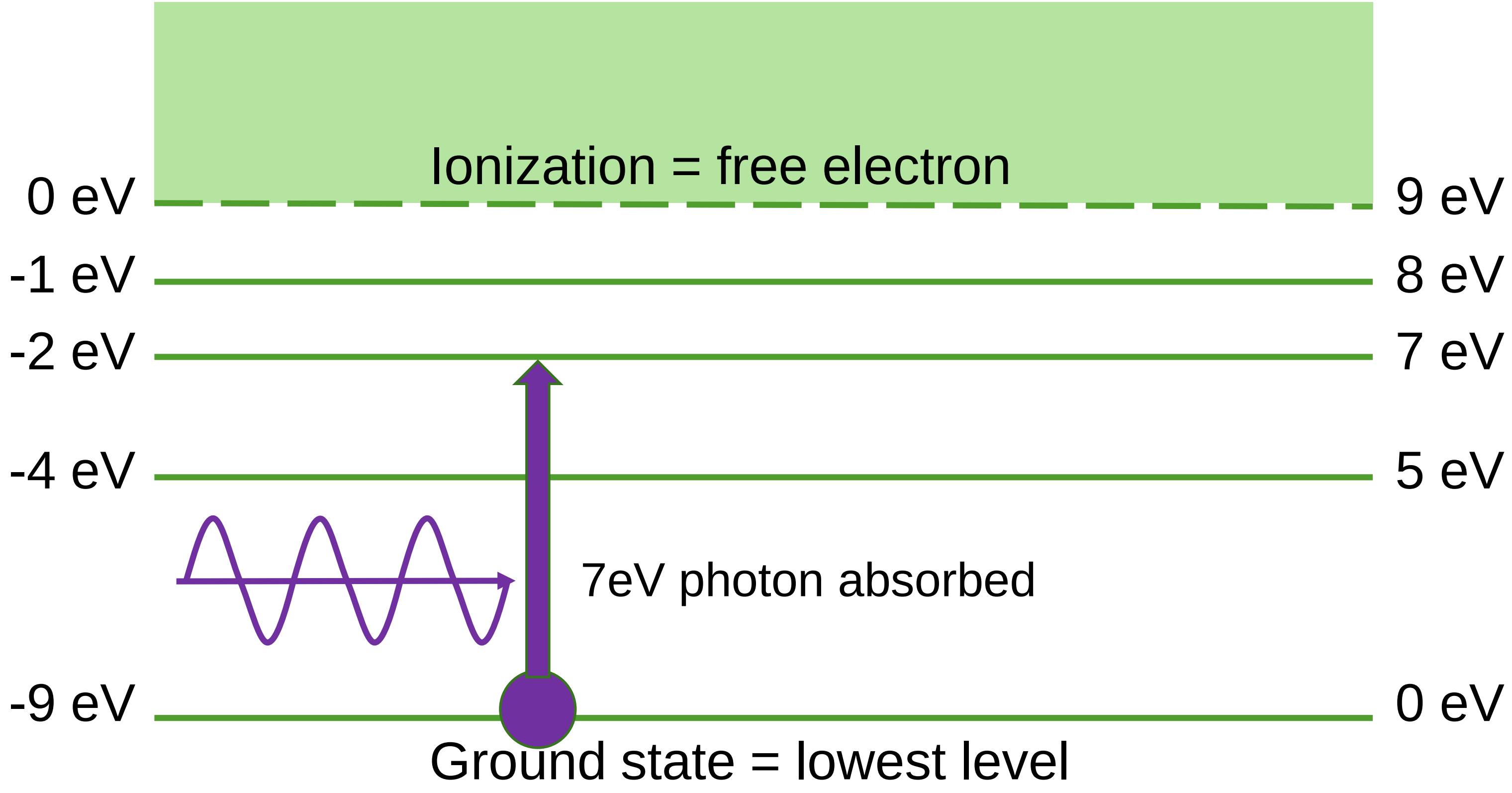
2. Calculate the work function of a material if the stopping potential is 0.65V when illuminated with 400nm light.

3. Why can the photoelectric effect not be explained if light is simply a wave?

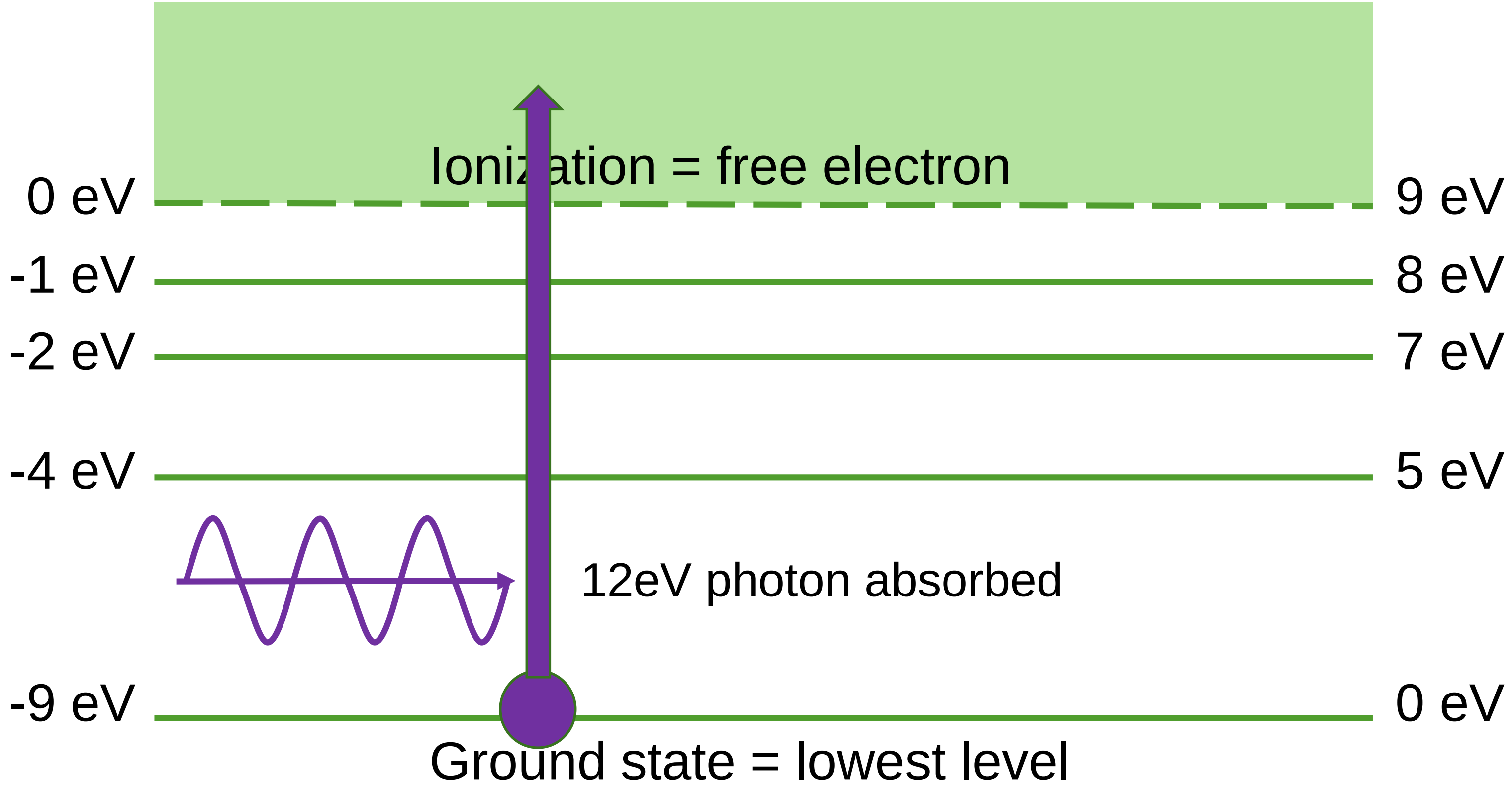
Energy levels



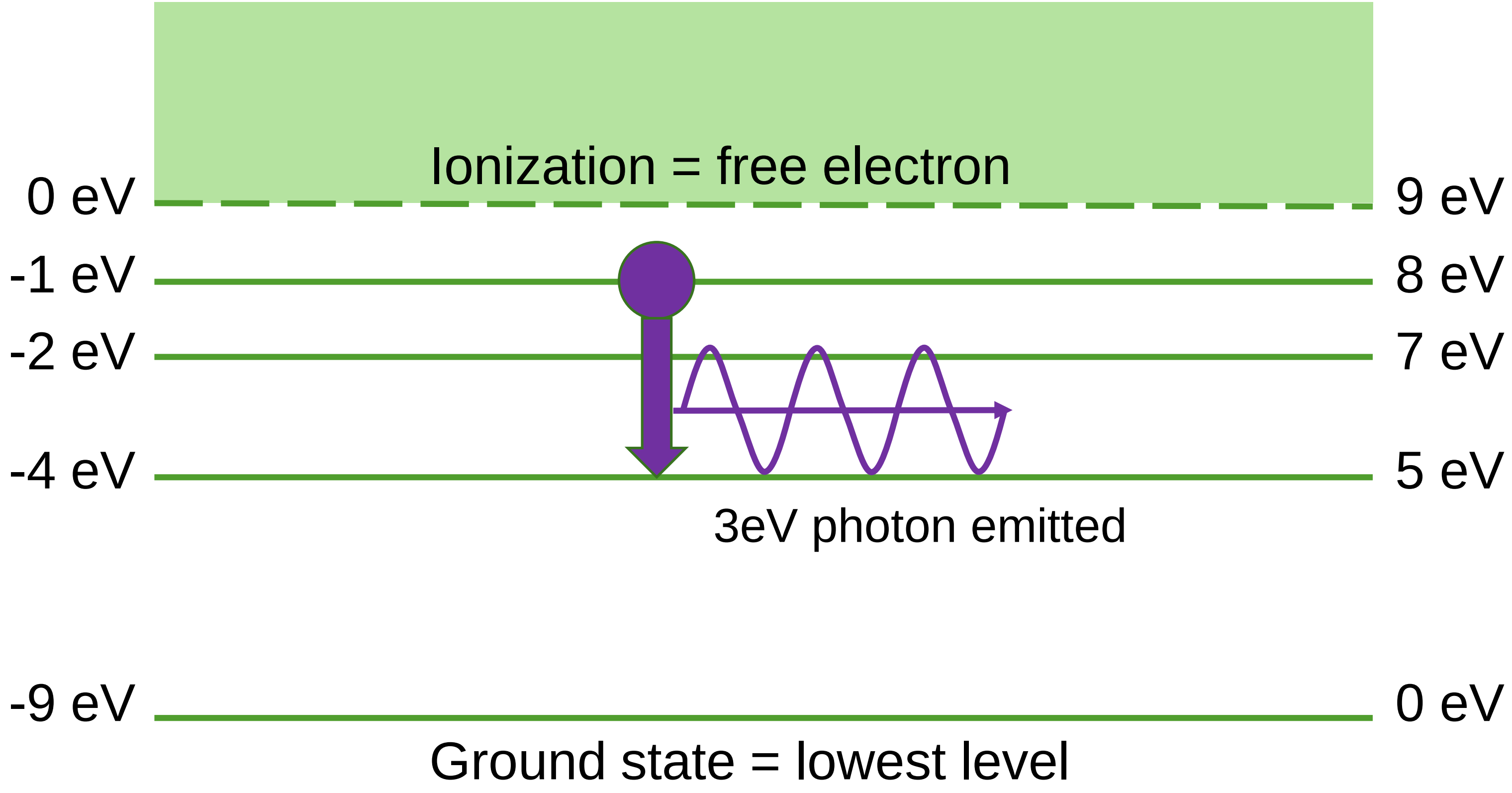
Excitation


Ionization = free electron
0 eV
9 eV
-1 eV
8 eV
-2 eV
7 eV
-4 eV
5 eV
7eV photon absorbed
-9 eV
0 eV
Ground state = lowest level

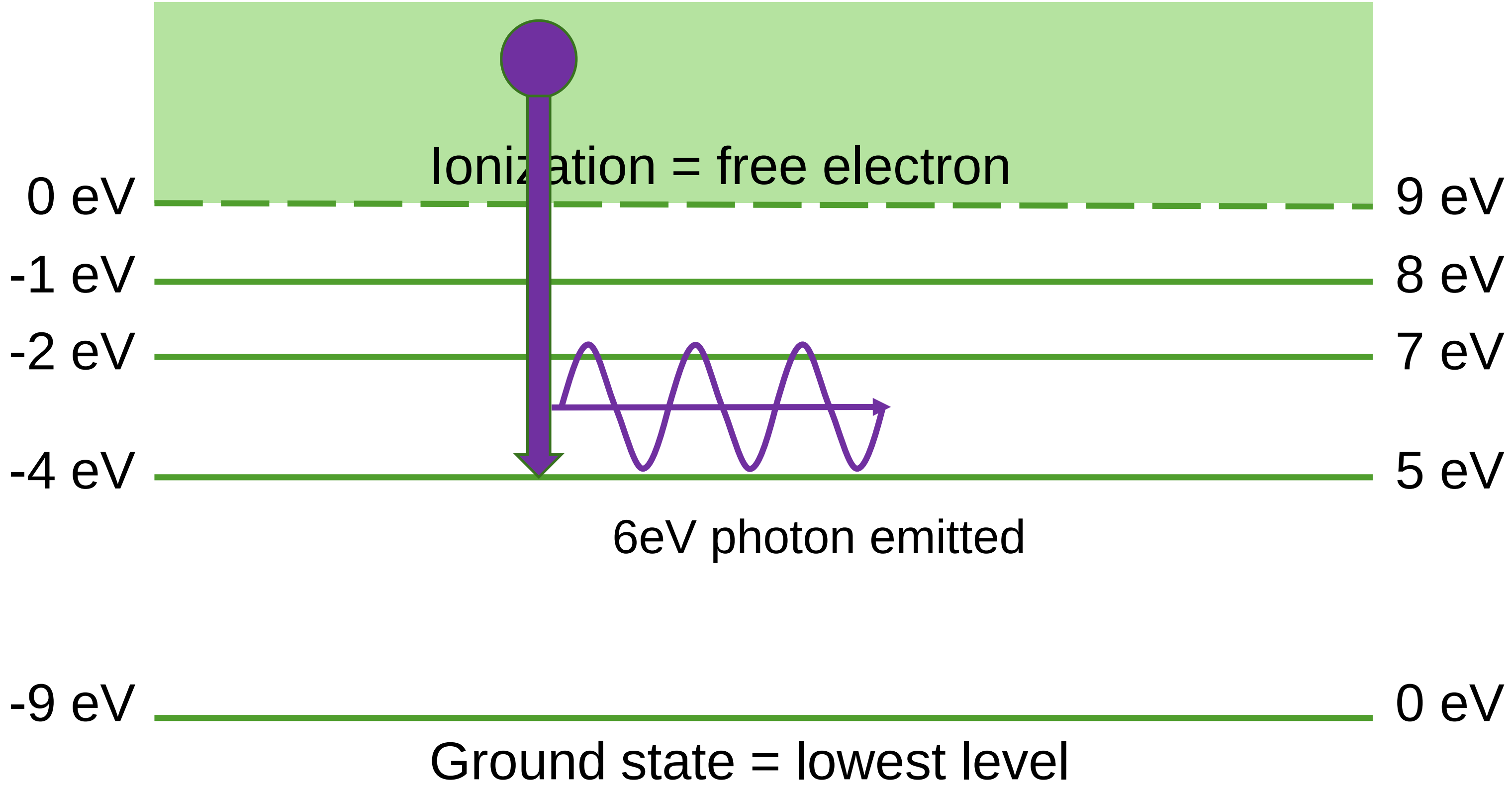
Ionisation


Ionization = free electron
0 eV
-1 eV
-2 eV
-4 eV
-9 eV
9 eV
8 eV
7 eV
5 eV
0 eV
12eV photon absorbed
Ground state = lowest level

De-excitation or relaxation



Recombination



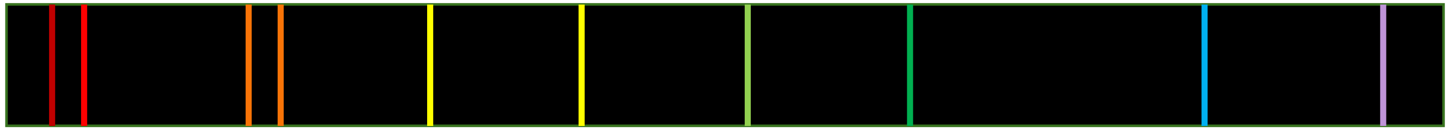
Spectra

Absorption spectra

dark ‘lines’ for transitions involving ground state

Emission spectra

bright lines for transitions involving all allowed transitions



Scattering

Photons

- must either be absorbed in full or not at all
- if photon energy must either match a transition exactly, or be sufficient to ionize

Electrons

- the electron is not absorbed, and can lose any amount of its kinetic energy

Example

- Atomic energy levels: 0, -1, -3, -7eV, assume in ground state
- 5eV photon can not be absorbed (there is no -2eV level)
- 5eV electron can collide, excite atom to the -3eV level, and depart with 1eV of energy

Discharge tubes

Regions of high electric field ionize atoms

Freed electrons and ions carry current

Freed electrons and ions accelerate in the electric field

Electrons collide with other atoms, ionizing & exciting them

Recombination and de-excitation gives off light

Gas pressure needs to be low enough that electrons accelerate to speeds sufficient to ionize atoms before they collide

Fluorescent lights – UV emitted, absorbed by phosphor coating which then de-excites giving out visible photons

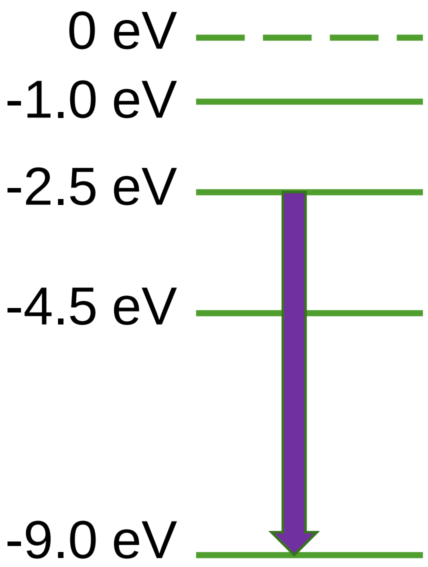
Energy level practice

1. What is the ionization energy of the atom?

2. What is the wavelength of light emitted by the transition shown?

3. What will happen if the atom in the ground state is struck by a 3eV electron?

4. What will happen if the atom in the ground state is struck by a 4.5eV photon?

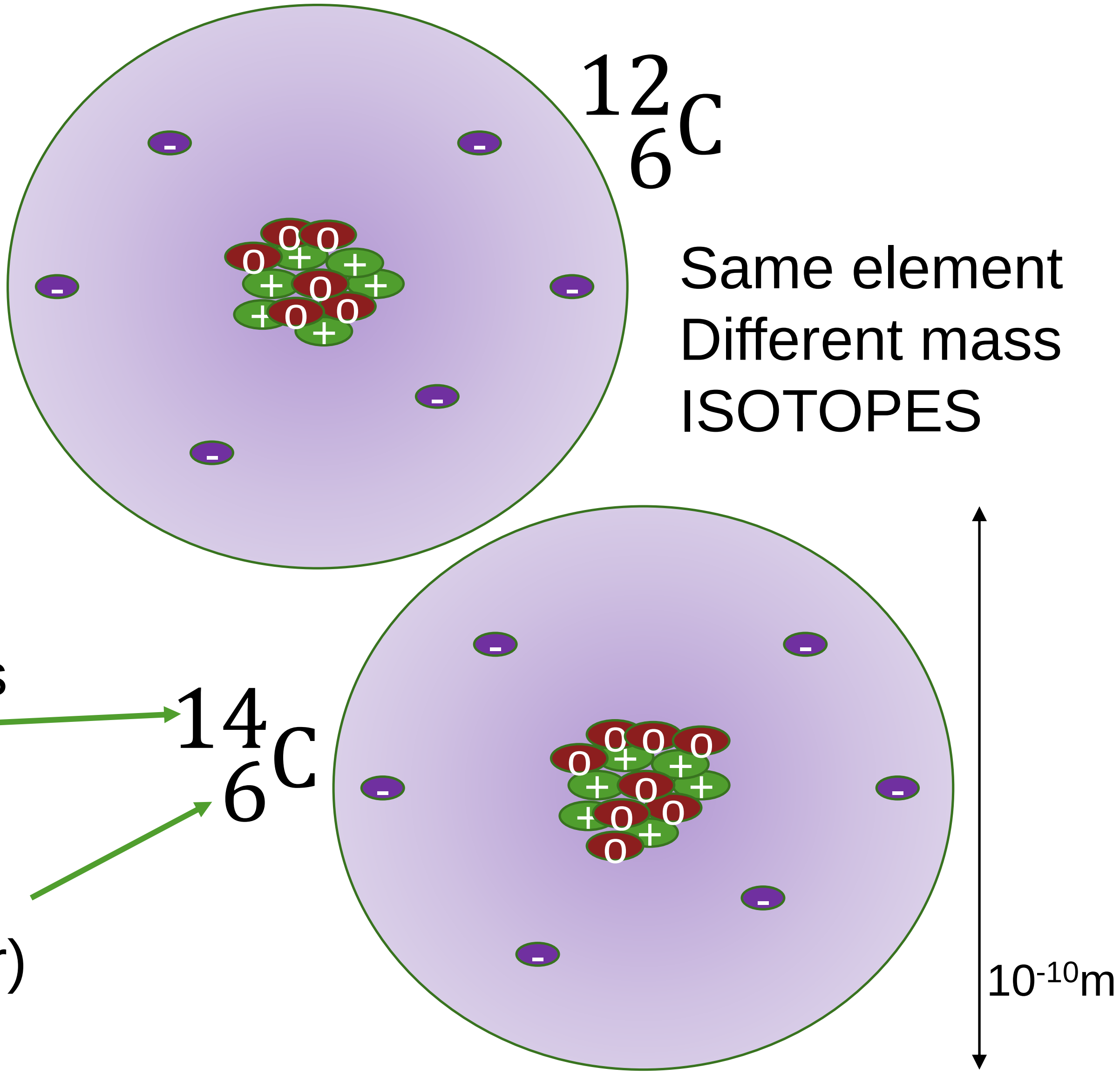


Meet the atom

Particle	Charge (C)	Mass (kg)
Proton	$+1.6\times10^{-19}$	1.67×10^{-27}
Neutron	0	1.67×10^{-27}
Electron	-1.6×10^{-19}	9.11×10^{-31}
Positron	*$+1.6\times10^{-19}$*	*9.11×10^{-31}*
Specific charge Ckg^{-1}= charge / mass		

Mass of nucleus (or atom) approx. proportional to number of neutrons and protons (mass number)

Charge of nucleus proportional to number of protons (atomic number)



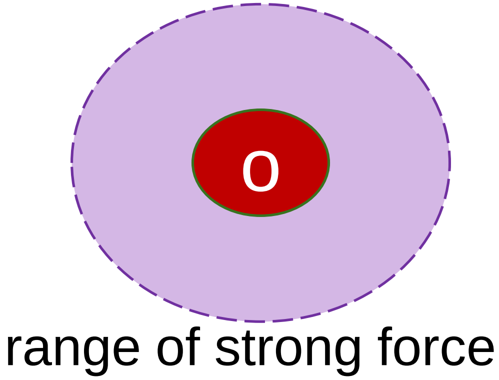
Same element
Different mass
ISOTOPES

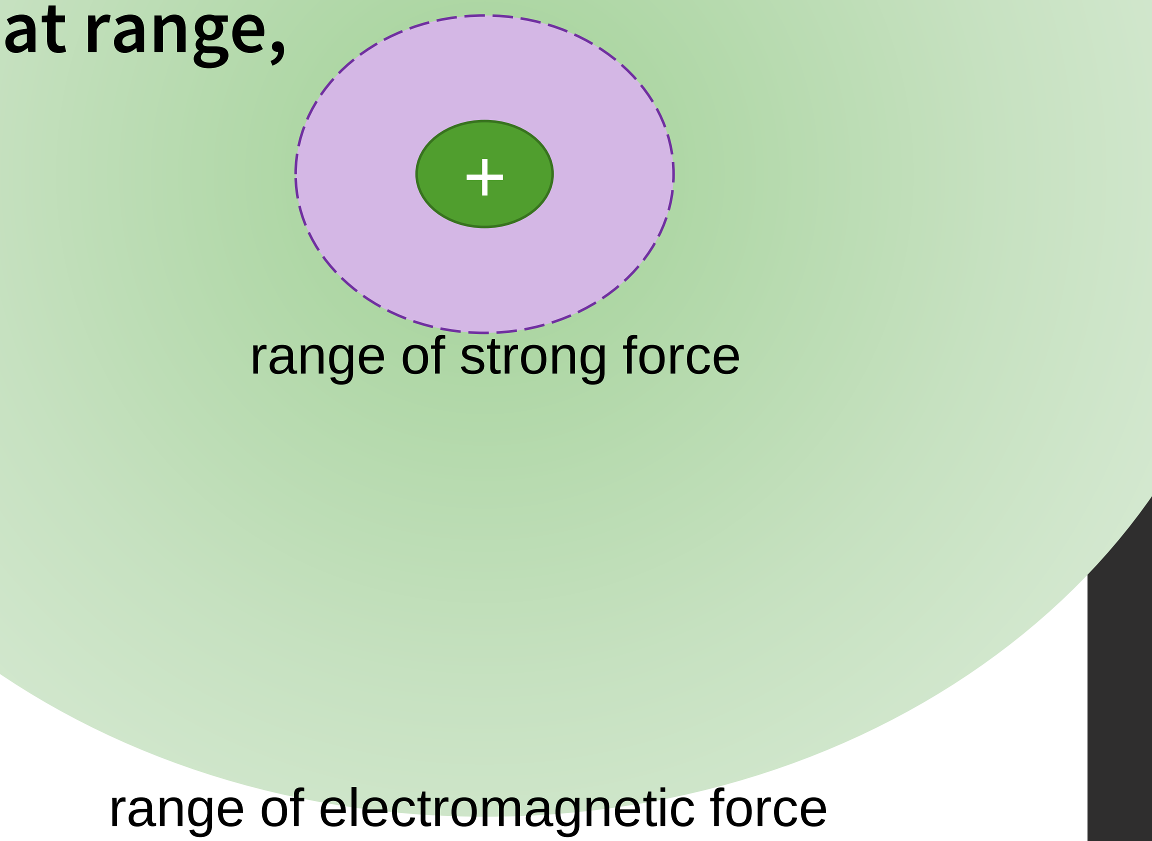
Strong nuclear force

Holds nucleons (protons & neutrons) together in the nucleus

Short range (<4fm), but within that range, stronger than electromagnetism

Becomes repulsive if <0.5fm





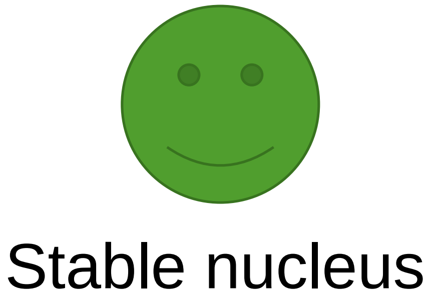
Nuclide practice

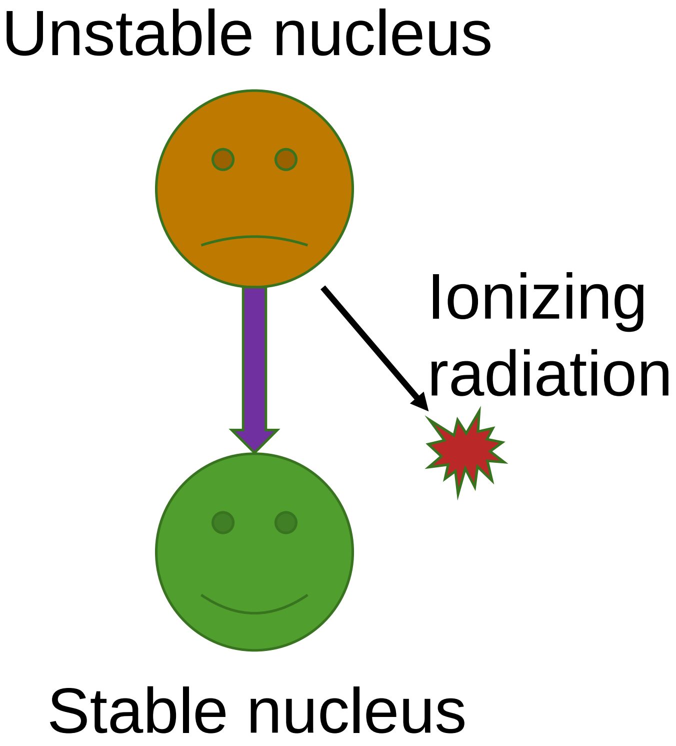
1. How many protons, neutrons and electrons are there in these nuclides? ${}^{2}_{1}H,\ {}^{3}_{1}H,\ {}^{15}_{8}O,\ {}^{56}_{26}Fe,\ {}^{238}_{92}U$

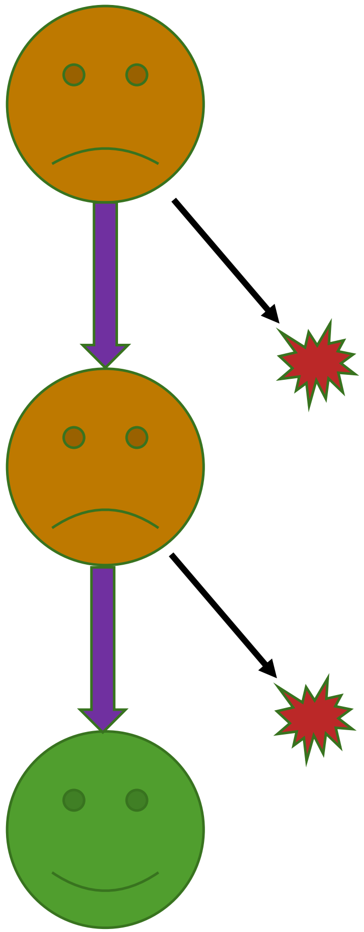
2. Write the symbol for the isotope of...
   a) carbon (6) with 7 neutrons
   b) hydrogen (1) with no neutrons
   c) neon (10) with mass number of 21

3. Calculate the specific charge of a ${}^{56}_{26}Fe$ nucleus

Ionizing radiation







When ionizing radiation passes another atom, it will take out electrons. The atom's chemistry will be altered.

This makes ionizing radiation harmful to life

Types of radiation

$$^{241}_{95}\mathrm{Am} \rightarrow \mathrm{Np} + {}^{4}_{2}\alpha$$

$$^{14}_{6}\mathrm{C} \rightarrow \mathrm{N} + {}^{0}_{-1}\beta + \overline{\nu}_e$$

$$^{11}_{6}\mathrm{C} \rightarrow \mathrm{B} + {}^{0}_{+1}\beta + \nu_e$$

$$^{99}_{43}\mathrm{Tc} \rightarrow \mathrm{Tc} + {}^{0}_{0}\gamma$$

	What it is	Range in air	Stopped by	Ionizing?
Alpha	helium nucleus (2p+2n)	5cm	paper skin	very
Beta -	high energy electron	1m	1cm Al	moderately
Beta +	high energy positron		anything	N/A annihilates
Gamma	high freq. electromag. wave	far	few cm Pb	weakly

Nuclear equation practice

Write the equations for the following decays

1. **Beta- decay of** $^{3}_{1}\mathrm{H}$ **to helium (He)**

2. **Alpha decay of** $^{238}_{92}\mathrm{U}$ **to thorium (Th)**

3. **Gamma decay of** $^{60}_{27}\mathrm{Co}$

Particles

Leptons **fundamental**	**Hadrons** **contain quarks** **'feel' strong force**	**Gauge bosons** **carry interactions**
electron (e^-) positron (e^+)	baryon (qqq) (e.g. proton, neutron)	graviton (gravity)
muon (μ^-) anti-muon (μ^+)	meson $(q\bar{q})$ (e.g. pion, kaon)	photon (electromagnetism)
taon (τ^-) anti-tauon (τ^+)	anti-baryon $(\bar{q}\bar{q}\bar{q})$ (e.g. antiproton)	gluon (strong nuclear force)
neutrino $(\nu_e, \nu_\mu, \nu_\tau)$ anti-neutrino $(\text{eg } \overline{\nu_e})$		W^+, W^-, Z boson (weak nuclear force)

Electron and proton are the only stable particles
Neutron is stable within a nucleus

Fundamental particles of matter

Leptons $L = +1$		Anti-leptons $L = -1$		Generation	Quarks $B = +\frac{1}{3}$		Anti-quarks $B = -\frac{1}{3}$	
$q = -1$	$q = 0$	$q = +1$	$q = 0$		$q = -\frac{1}{3}$	$q = +\frac{2}{3}$	$q = +\frac{1}{3}$	$q = -\frac{2}{3}$
e^-	ν_e	e^+	$\overline{\nu_e}$	1	d	u	$\overline{d}$	$\overline{u}$
μ^-	ν_μ	μ^+	$\overline{\nu_\mu}$	2	s	c	$\overline{s}$	$\overline{c}$
τ^-	ν_τ	τ^+	$\overline{\nu_\tau}$	3	b	t	$\overline{b}$	$\overline{t}$

L is lepton number, B is baryon number

s quarks have strangeness $S = -1$
$\bar{s}$ quarks have strangeness $S = +1$

Baryons	Mesons	Strange mesons
$p = uud$ proton	$\pi^+ = u\,\overline{d}$	$\mathrm{K}^+ = u\,\overline{s}$
$n = udd$ neutron	$\pi^0 = d\,\overline{d}$ or $u\,\overline{u}$	$\mathrm{K}^0 = d\,\overline{s}$
$\overline{p} = \overline{uud}$ anti-proton	$\pi^- = d\,\overline{u}$	$\overline{K_0} = s\,\overline{d}$
$\overline{n} = \overline{udd}$ anti-neutron		$\mathrm{K}^+ = s\,\overline{d}$

Conservation laws

All interactions conserve *B, L, q*, energy, momentum

Only the weak interaction does not conserve quark flavour

- $s \rightarrow d$ can only happen as part of a weak interaction
- even the weak interaction prefers to conserve generation if it can
- all other interactions conserve strangeness *S*

Electromagnetic interactions only affect charged particles

Strong interactions only affect hadrons/quarks

Where a particle can only decay by weak interaction e.g. π^-

- it will take longer to decay (e.g. ns or μs)

Weak reactions

β^- **decay**

$$n \to p + e^- + \overline{\nu_e}$$

β^+ **decay**

$$p \to n + e^+ + \nu_e$$

followed by $e^+ + e^- \to 2\gamma$

Electron capture

$$p + e^- \to n + \nu_e$$

followed by X ray emission

Annihilation and pair production

Annihilation

$$e^+ + e^- \rightarrow 2\gamma$$

rest energy of electron is 511keV, so minimum γ energy is 511keV

Pair production

$$\gamma \rightarrow e^+ + e^-$$

minimum γ energy at least 1022keV

Example decays/reactions

Decay of muon

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu_e}$$

Strong interaction – formation of $\Lambda = uds$

$$\mathrm{K}^- + n \rightarrow \boxed{} + \Lambda^0$$

Particle practice

1. Is this reaction possible, and if so, which interaction is responsible?

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

2. Which other particle is produced in this weak interaction?

$$K^0 + p \rightarrow \pi^+ + \boxed{}$$

3. Which interaction is responsible for

$$e^+ + e^- \rightarrow \gamma \rightarrow \bar{d} + d$$

Links

A Level Topic Revision

https://isaacphysics.org/pages/a_level_topic_index#a_level_revision

Consolidation Programme

https://isaacphysics.org/pages/summer_programmes_2021