AQA-AS/A-Level Physics

AQA-AS-Unit-1-Particles-Quantum Phenomena-and-Electricity

1 Particles and Radiation

1-1 Nucleus structure of atoms Atomic nucleus

1.1 The nucleus structure model of atom

In 1909-1911, the British physicist Rutherford (1871-1937) and his assistants did experiments using α particle scattering. **Fig. 1-1** shows the experimental setup. Using α particle to shine on gold foil, some α particle change direction after passing through the gold foil. This is because the tiny charged particles inside the gold atom have Coulomb interactions with the α particles. This phenomenon is called **the scattering of α particle**.

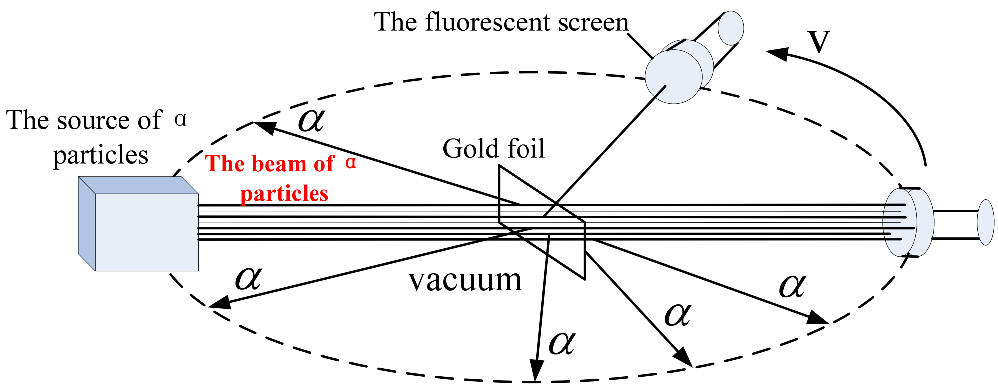


Fig. 1-1 the sketch map of an α particle scattering experiment. The fluorescent screen can be rotated along the dashed lines in the figure and is used to count the number of particles scattered to different directions. The whole setup is placed in vacuum.

The result of the experiment was that most α particles passed through the gold foil and almost all moved in their previous direction. But there were a tiny number of α particles which showed a large deflection.

Rutherford made precise records of the number of α particles scattered in various directions. Based on this, he put forward the nucleus structure model of the atom. There is a tiny nucleus at the center of the atom called the atomic nucleus. All the positive charge and nearly all the mass of the atom are concentrated in the atomic nucleus. The electrons carrying a negative charge move in space outside the nucleus.

According to this model, since the atomic nucleus is tiny when it passes through the gold foil, most of the α particles are far from the nuclei and feel a very small repulsive force. Their movement is hardly influenced. Only a very small number of α particles pass close to the atomic nucleus, and are affected considerably by the nucleus Coulomb repulsive force and so make a large angle deflection (**Fig. 1-2**)

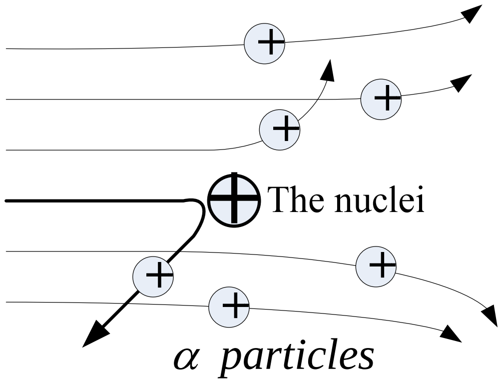


Fig. 1-2 most of the α particles are far from the nuclei when they pass through a gold foil. Only a very small number of α particles fly close to the atomic nucleus and are affected considerably by the nucleus repulsive force and so make a large angle deflection

1.2 Constituents of the atom

Inside an atom: ① a positively charged nucleus composed of proton and neutrons, ② Electrons that surround the nucleus.

Note: inside the atom, the number of proton = the number of electron, and if the atom do not loss or gain electrons, it is neutral (that is no charge)

Nucleon: a proton or a neutron in the nucleus.

Inside an atom:

	Charge (/C)	Mass (/Kg)
a proton	$+1.60\times10^{19}$	1.67×10^{-27}
a neutron	0	1.67×10^{-27}
an electron	-1.60×10^{19}	9.11×10^{-31}

Isotopes: atoms of the same element that has the same numbers of proton but different numbers of neutrons.

Represent an atom: $^{A}_{Z}X$

X: chemical symbol

A: total number of protons and neutrons, sometimes called nucleon number or mass number.

Z: number of protons, sometimes called atomic numbers.

So, the number of neutrons in the nucleus = A－Z

Specific charge:

For charged particles, specific charge is defined as its charge divided by its mass, that is

$$specific\ charge = \frac{charge}{mass}$$

Unit: C/kg

1-2 Natural radiation phenomenon Decay half-life

2.1 Natural radiation phenomenon

The property of a substance emitting rays is called **radioactivity**. Elements with radioactivity are called **radioactive elements**.

The phenomenon of elements' spontaneous radiation of rays is called **natural radioactivity phenomenon**.

2.2 Three types of radiation

(i) Alpha radiation

Alpha particle is the atom ${}_2^4He$; symbol is ${}_2^4\alpha$, sometimes in symbol α.

An unstable nucleus of an element X emits an alpha particle; the product nucleus is a different element Y.

Equation below:

$${}_Z^AX \rightarrow {}_{Z-2}^{A-4}Y + {}_2^4\alpha$$

Note: conservation of mass number and atomic number.

(ii) Beta decay

Beta is electron, in symbol ${}_{-1}^{0}\beta$ or β^-,

Equation below:

$${}_Z^AX \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}\beta + \bar{\nu}$$

$\bar{\nu}$: is called antineutrino, which has no charge and no mass.

(iii) Gamma radiation

In symbol γ, it is emitted by a nucleus with too much energy, following an alpha or beta emission.

1-3 Particles, antiparticles and photons

3.1 Electromagnetic waves

Table 3.1 the main parts of the electromagnetic spectrum

type	radio	microwave	infrared	visible	ultraviolet	X-rays	Gamma rays
Wavelength range	>0.1m	0.1m to 1mm	1mm to 700nm	700nm to 400nm	400nm to 1nm	<1nm	<1nm

Note:

(i) In a vacuum, all electromagnetic waves travel at the speed of light, $c = 3.0 \times 10^8 m/s$

(ii) And, in a vacuum, $\lambda = \frac{c}{f}$

Where λ is wavelength of the electromagnetic waves, f is frequency, $c = 3.0 \times 10^8 m/s$

(iii) Electromagnetic waves are emitted as short 'bursts' of waves, each burst leaving the source in a different direction. Each burst is a packet of electromagnetic waves and is referred to as a photon.

(iv) And Einstein assumed that the energy E of a photon depends on its frequency f in accordance with the equation:

Photon energy: $E = hf$

Where $h = 6.63 \times 10^{-34} Js$ is referred to as the Planck constant.

(v) $1nm = 10^{-9} m$

3.2 Particles and antiparticles

Table 3.2 particles

particles	symbol	charge	mass	Rest energy $E_0 = mc^2$
Proton	p	$+1.60 \times 10^{19} C$	$1.67 \times 10^{-27} kg$	$1.5 \times 10^{-10} J = 937.5 MeV$
Neutron	n	0 C	$1.67 \times 10^{-27} kg$	$1.5 \times 10^{-10} J = 937.5 MeV$
Electron	$e^-, \beta^-, {}^{0}_{-1}\beta$	$-1.60 \times 10^{19} C$	$9.11 \times 10^{-31} kg$	$8.2 \times 10^{-14} J = 0.511 MeV$
neutrino	ν	0 C	0 kg	0 J

Table 3.3 corresponding antiparticles

corresponding antiparticles	symbol	charge	mass	Rest energy $E_0 = mc^2$

Antiproton	$\overline{p}$	$-1.60\times10^{19}C$	$1.67\times10^{-27}kg$	$1.5\times10^{-10}J=937.5MeV$
Antineutron	$\overline{n}$	0 C	$1.67\times10^{-27}kg$	$1.5\times10^{-10}J=937.5MeV$
Positron	β^{+}, ${}^{0}_{+1}\beta$	$+1.60\times10^{19}C$	$9.11\times10^{-31}kg$	$8.2\times10^{-14}J=0.511MeV$
antineutrino	$\overline{\nu}$	0 C	0 kg	0 J

Dirac's theory of antiparticles predicted that,

(i) When particles and corresponding antiparticles meet, annihilation happens, that converting the total mass of particles and corresponding antiparticles into photons.

(ii) Particles and corresponding antiparticles have the same rest mass, the same rest energy, but exactly opposite charge if the particle has a charge.

Notion:

(i) Annihilation:

The process that when a particle and a corresponding antiparticle meet and their mass is converted into radiation energy, emitting two photons.

Diagram:

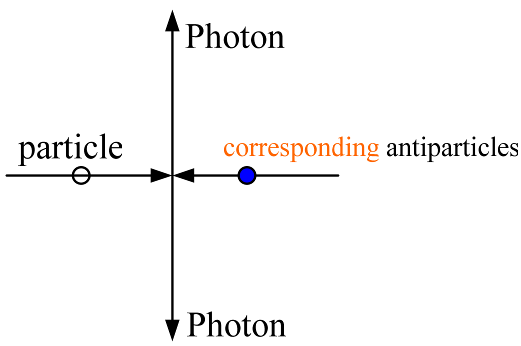


Fig. 1-3 Annihilation

(ii) Pair production

The process that a photon with sufficient energy could suddenly change into a particle-antiparticle pair

Diagram:

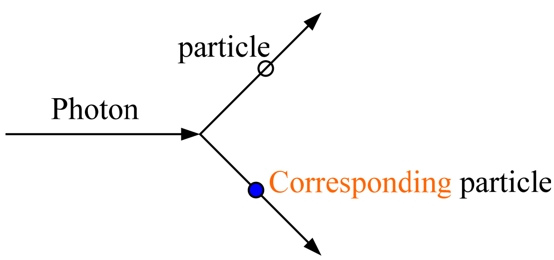


Fig. 1-4 Pair production

(iii) Unit of energy converting:

$1eV = 1.60 \times 10^{-19} J$, $1MeV = 1.60 \times 10^{-13} J$

1-4 Particle interactions

4.1 Electromagnetic force and Feynman diagram

The electromagnetic force between charged particles is due to the exchange of virtual photons.

For example:

The Feynman diagram for the electromagnetic force between two protons:

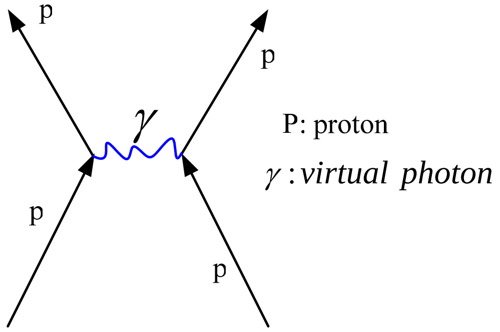


Fig. 1-5 Feynman diagram of electromagnetic force between two protons

4.2 The weak nuclear force and Feynman diagram

The weak nuclear force is due to the exchange of particle which is called W bosons.

W bosons: have a non-zero rest mass, and are positively charged (W^+) or negatively charged (W^-).

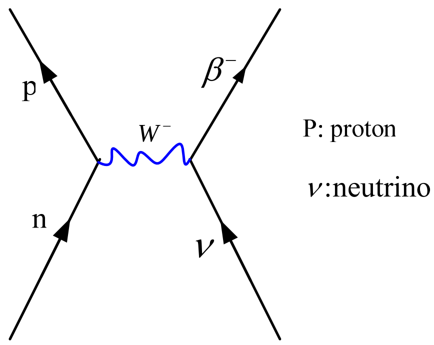
Note:

The interaction below is duo to the weak nuclear force:

(i) Equation: W^- as the exchange particle.

$$n + \nu \xrightarrow{W^-} p + \beta^-$$

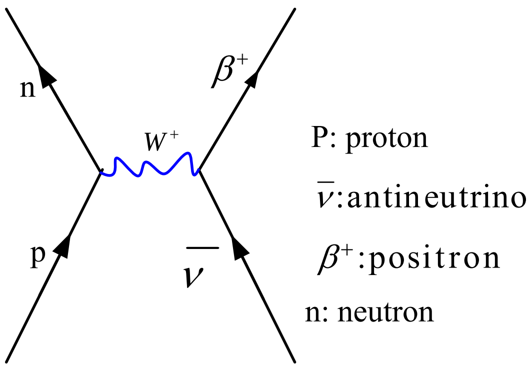
Feynman diagram:



(ii) Equation: W^+ as the exchange particle.

$$p+\bar{\nu} \xrightarrow{W^+} n+\beta^+$$

Feynman diagram:



(iii) β^- *decay*

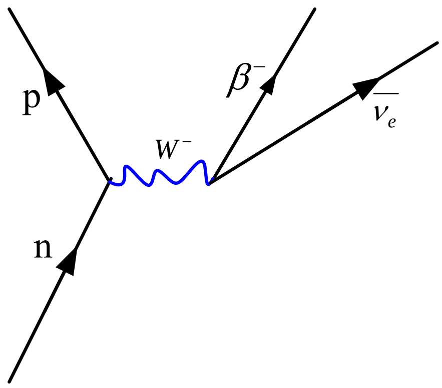
Equation: W^- as the exchange particle.

$${}^A_ZX \xrightarrow{W^-} {}_{Z+1}^{A}Y + {}^{0}_{-1}\beta+\bar{\nu}$$

Where X, Y is chemical symbol, and essentially, is the neutron inside X decay into proton (neutron numbers decrease inside X), to become a stable atom Y. emitting β^- and $\bar{\nu}$. That is

$$n \xrightarrow{W^-} p+\beta^- +\bar{\nu}$$

Feynman diagram:



Note: $n \xrightarrow{W^-} p+\beta^- +\bar{\nu}$ is $n \to p+W^-$

Then $W^- \to \beta^- +\bar{\nu}$

(iv) β^+ *decay*

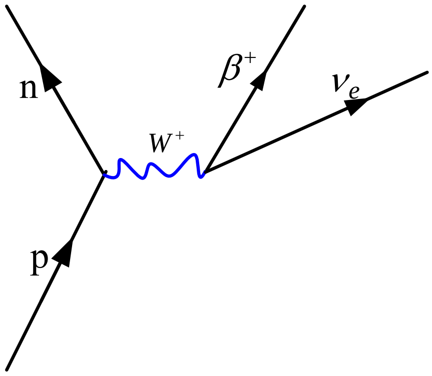
Equation: W^+ as the exchange particle.

$${}^A_ZX \xrightarrow{W^+} {}_{Z-1}^{A}Y + {}^{0}_{+1}\beta+\nu$$

Where X, Y is chemical symbol, and essentially, is the proton inside X decay into neutron (proton numbers decrease inside X), to become a stable atom Y. emitting β^+ and ν. That is

$$p \xrightarrow{W^+} n + \beta^+ + \nu$$

Feynman diagram:



Note: $p \xrightarrow{W^+} n + \beta^+ + \nu$ is $p \to n + W^+$

Then $W^+ \to \beta^+ + \nu$

(v) Electron capture

Equation: W^+ as the exchange particle.

$$p + e^- \xrightarrow{W^+} n + \nu$$

Feynman diagram:

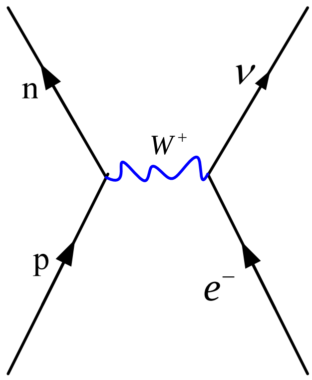


Fig. 1-6 Feynman diagram of Electron capture

1-5 Properties of particles and antiparticles

Hadrons: are particles and antiparticles that interact through the strong interaction.

Leptons: are particles and antiparticles that interact through the weak interaction.

Muon: is sometimes called 'heavy electron', in symbol μ or μ^-, is negatively charged. $charge = -1.60 \times 10^{-19} C$

With a rest mass over 200 times the rest mass of the electron.

Antimuon: is positively charged, in symbol μ^{+}, the same rest mass of muon.
Muons and antimuons decay into electrons and antineutrinos, or positrons and neutrinos.
Pion or 'π meson': positively charged (π^{+}), negatively charged (π^{-}), neutral (π^{0}), rest mass: greater than muon but less than a proton. And charged π meson decays into muons and antineutrino, or antimuons and neutrinos. The π^{0} meson decays into high energy photons.
Kaon or 'K meson': positively charged (k^{+}), negatively charged (k^{-}), neutral (k^{0}), rest mass: greater than pion but less than a proton. And K mesons can decay into π mesons, muons and antineutrinos, and antimuons and neutrino.
Fig. 1-7 shows the Classification of particles

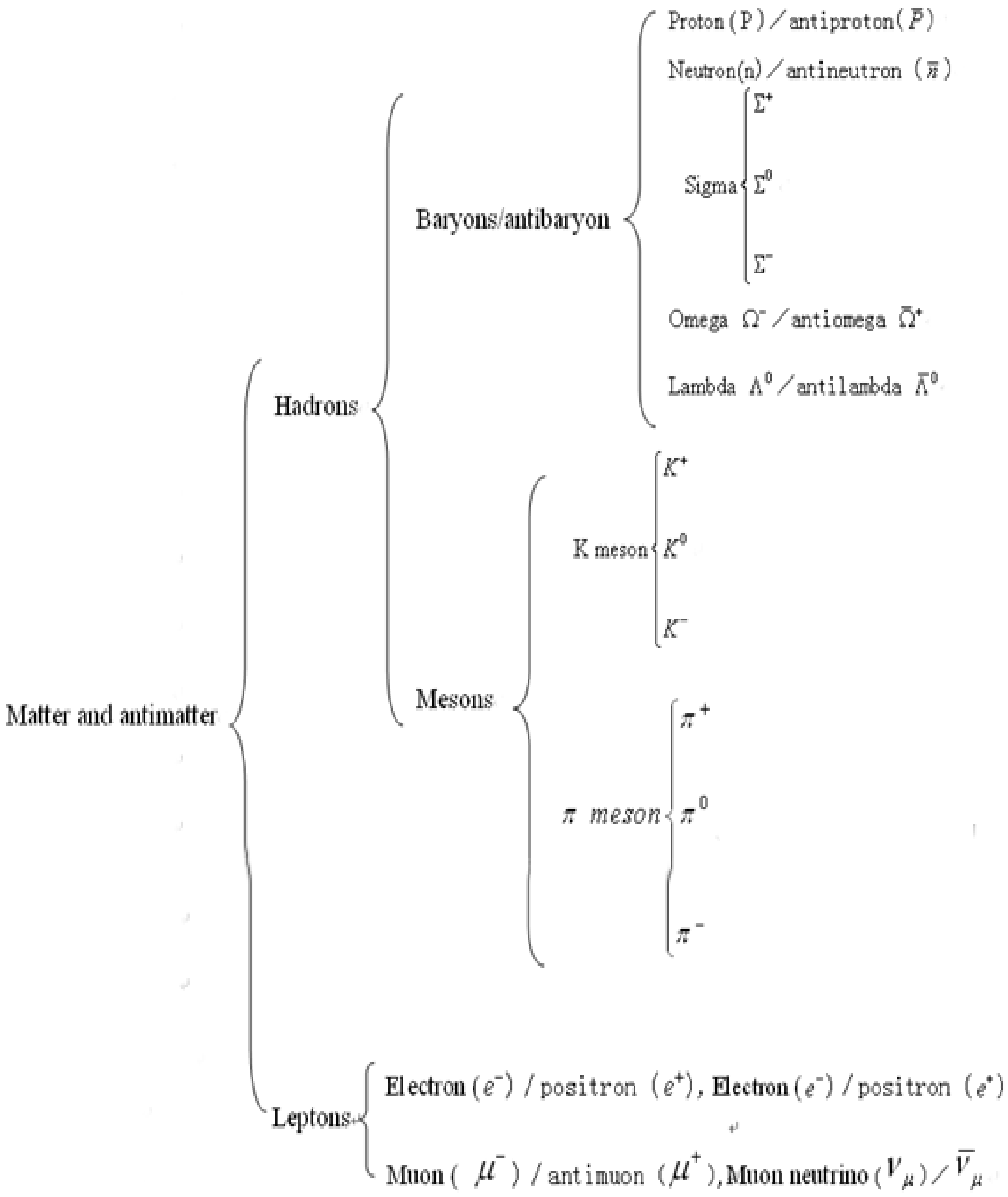


Fig. 1-7 Classification of particles

Note: the decays always obey the conservation rules for energy (and momentum) and for charge.

Conservation rules apply to particles and antiparticles interaction and decays:

(i) Conservation of energy and conservation of charge (in symbol Q).

(ii) Conservation of baryon number. +1 to any baryon and -1 to any antibaryon, 0 to other particles and antiparticles. In symbol B

(iii) Conservation of lepton number. +1 to any lepton and -1 to any antilepton, 0 to other particles and antiparticles. In symbol L

(ⅳ) Conservation of strangeness, only for any strong interaction. In symbol

S

So, an interaction between particles and antiparticles happens or not, sometimes just according to the conservation of charge, baryon number, and lepton number.

Table 5.1 Properties of particles and antiparticles

Particles / antiparticle	Charge	Lepton number	Baryon number	Strangeness number
Proton (P)	Q=+1	L=0	B=+1	S=0
antiproton($\bar{P}$)	Q=−1	L=0	B=−1	S=0
Neutron(n)	Q=0	L=0	B=+1	S=0
antineutron ($\bar{n}$)	Q=0	L=0	B=−1	S=0
Sigma Σ^+	Q=+1	L=0	B=+1	S=−1
Sigma Σ^0	Q=0	L=0	B=+1	S=−1
Sigma Σ^-	Q=−1	L=0	B=+1	S=−1
Omega Ω^-	Q=−1	L=0	B=+1	S=−3
antiomega $\bar{\Omega}^+$	Q=+1	L=0	B=−1	
Lambda Λ^0	Q=0	L=0	B=+1	S=−1
antilambda $\bar{\Lambda}^0$	Q=0	L=0	B=−1	
K meson K^+	Q=+1	L=0	B=0	S=+1
K meson K^0	Q=0	L=0	B=0	S=+1
K meson K^-	Q=−1	L=0	B=0	S=−1
π meson π^+	Q=+1	L=0	B=0	S=0
π meson π^0	Q=0	L=0	B=0	S=0
π meson π^-	Q=−1	L=0	B=0	S=0

Electron (e^-)	Q=−1	L=+1	B=0	S=0
positron (e^+)	Q=+1	L=−1	B=0	S=0
Electron neutrino (ν_e)	Q=0	L=+1	B=0	S=0
Electron antineutrino $\bar{\nu}_e$	Q=0	L=−1	B=0	S=0
Muon (μ^-)	Q=−1	L=+1	B=0	S=0
antimuon (μ^+)	Q=+1	L=−1	B=0	S=0
Muon neutrino (ν_μ)	Q=0	L=+1	B=0	S=0
Muon antineutrino $\bar{\nu}_\mu$	Q=0	L=−1	B=0	S=0

Q = +1 / Q = -1 means per unit charge.

For example:

Equation below:

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

Before interaction:

Charge = 0 + 0 = 0

Baryon number B = 0 + 1 = 1

Lepton number L = 1 + 0 = 1

After interaction:

Charge = 1 + (-1) = 0

Baryon number B = 1 + 0 = 1

Lepton number L = 0 + 1 = 1

So charge, baryon number, lepton number are all conserved, the interaction is permitted.

1-6 Quarks and Antiquarks

6.1 Quarks and antiquarks properties

Table 6.1 Quarks and antiquarks properties

	quarks			antiquarks		
Types	up	down	strange	up	down	strange
Symbol	u	d	s	$\bar{u}$	$\bar{d}$	$\bar{s}$
Charge	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$	$+\frac{1}{3}$	$+\frac{1}{3}$
Strangeness	0	0	-1	0	0	+1
Baryon number	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$

6.2 Quark combinations

Note: only hadrons have quark combinations, lepton is fundamental particles that mean no quark combinations.

Combination rules:

Mesons: consist of a quark and an antiquark.

Baryons: consist of three quarks.

Antibaryons: consist of three antiquarks.

Note: all combinations obey charge conservation. Also strangeness is conserved.

4.3 Quarks and beta decays

(i) *β^- decay*

Equation:

$${}^{A}_{Z}X \xrightarrow{W^-} {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \overline{\upsilon_e}$$

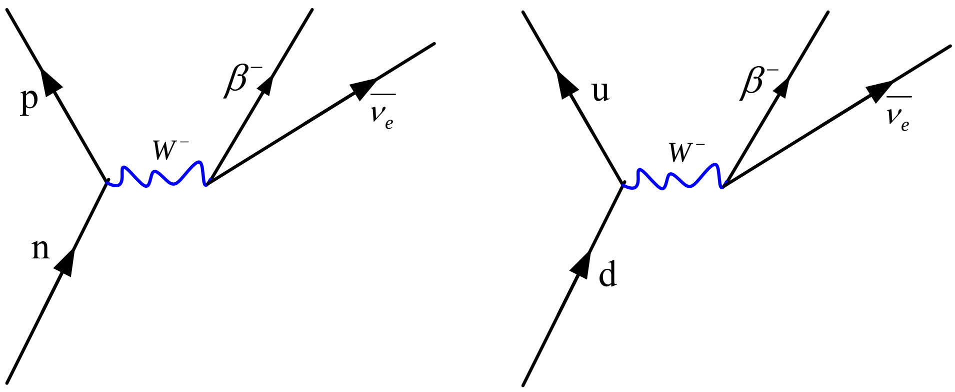
Or

$$n \xrightarrow{W^-} p + \beta^- + \overline{\upsilon_e}$$

Or in quark model

$$d \xrightarrow{W^-} u + \beta^- + \overline{\upsilon_e}$$

Feynman diagram: (n = neutron, p = proton)



Note: $n \xrightarrow{W^-} p + \beta^- + \overline{\upsilon_e}$ is $n \to p + W^-$

Then $W^- \to \beta^- + \overline{\upsilon_e}$

And $d \xrightarrow{W^-} u + \beta^- + \overline{\upsilon_e}$ is $d \to u + W^-$

Then $W^- \to \beta^- + \overline{\upsilon_e}$

(ii) β^{+} *decay*

Equation:

$${}_{Z}^{A}X \xrightarrow{W^{+}} {}_{Z-1}^{A}Y + {}_{+1}^{0}\beta + \nu_e$$

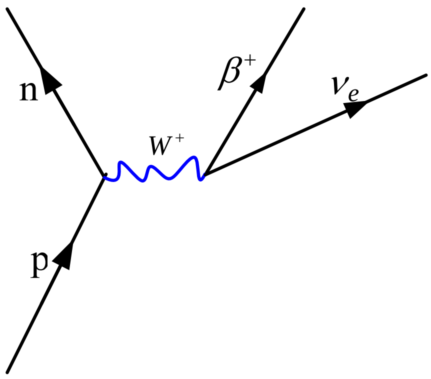
Or

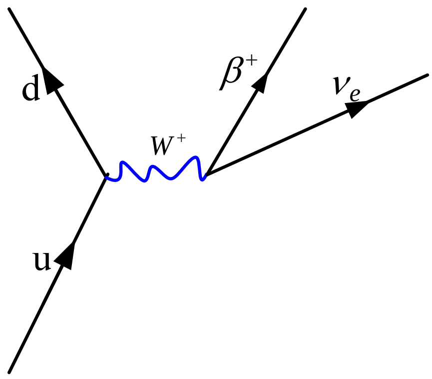
$$p \xrightarrow{W^{+}} n + \beta^{+} + \nu_e$$

Or in quark model

$$u \xrightarrow{W^{+}} d + \beta^{+} + \nu_e$$

Feynman diagram:





Note: $p \xrightarrow{W^{+}} n + \beta^{+} + \nu$ is $p \to n + W^{+}$

Then $W^{+} \to \beta^{+} + \nu_e$

And $u \xrightarrow{W^{+}} d + \beta^{+} + \nu_e$ is $u \to d + W^{+}$

Then $W^{+} \to \beta^{+} + \nu_e$

1-7 45 Worked examples

1. State the nucleon numbers, the atomic numbers, the number of neutrons, and the number of electrons of the atom ${}_{29}^{63}Cu$ and the ion ${}_{29}^{63}Cu^{2+}$ (loss two electrons).

Detail answers:

For ${}_{29}^{63}Cu$, A = 63, Z = 29, so the nucleon numbers = 63, the atomic numbers = 29, the number of electrons = 29

the number of neutrons = A − Z = 63 − 29 = 34.

For ${}_{29}^{63}Cu^{2+}$, A = 63, Z = 29, so the nucleon numbers = 63, the atomic numbers = 29, the number of electrons = 27, the number of neutrons = A − Z = 63 − 29 = 34.

2. Calculation:

i : for one electron

$charge = -1.60\times10^{-19}C, mass = 9.11\times10^{-31}kg$

$$specific\ charge = \frac{charge}{mass} = \frac{-1.60\times10^{-19}C}{9.11\times10^{-31}kg} = 1.75\times10^{11}C/kg$$

ii : for the nucleus $^{4}_{2}He$

As the nucleus $^{4}_{2}He$, just contains 2 protons and 2 neutrons (no charge), so

charge of $^{4}_{2}He, Q = 2\times1.60\times10^{-19}C = 3.2\times10^{-19}C$

$mass = 4\times1.67\times10^{-27}kg = 6.68\times10^{-27}kg$

So $specific\ charge = \frac{charge}{mass} = \frac{3.2\times10^{-19}C}{6.68\times10^{-27}kg} = 4.8\times10^{7}C/kg$

iii: for the ion $^{63}_{29}Cu^{2+}$

As ion $^{63}_{29}Cu^{2+}$ loss 2 electrons, so

Charge of $^{63}_{29}Cu^{2+}, Q = 2\times1.60\times10^{-19}C = 3.2\times10^{-19}C$

$mass = 63\times1.67\times10^{-27}kg = 1.05\times10^{-25}kg$

$$specific\ charge = \frac{charge}{mass} = \frac{3.2\times10^{-19}C}{1.05\times10^{-25}kg} = 3\times10^{6}C/kg$$

iv: for the atom $^{63}_{29}Cu$

As the atom is neutral, charge of $^{63}_{29}Cu = 0C$

$mass = 63\times1.67\times10^{-27}kg = 1.05\times10^{-25}kg$

$$specific\ charge = \frac{charge}{mass} = \frac{0C}{1.05\times10^{-25}kg} = 0C/kg$$

3. Complete the following decay equations:

$$^{229}_{90}Th \rightarrow {}^{229-4}_{90-2}Ra + \alpha \rightarrow {}^{225}_{88}Ra + \alpha$$

$$^{65}_{28}Ni \rightarrow {}^{65}_{28+1}Cu + {}^{0}_{-1}\beta + \bar{\nu} \rightarrow {}^{65}_{29}Cu + {}^{0}_{-1}\beta + \bar{\nu}$$

4. The bismuth $^{213}_{83}Bi$ emits an alpha particle and two beta particles, to become a stable nucleus Y, finish the equation, and show that Y is bismuth isotope.

Equation:

$$^{213}_{83}Bi \rightarrow {}^{A}_{Z}Y + \alpha + 2\beta \rightarrow {}^{A}_{Z}Y + {}^{4}_{2}\alpha + {}^{0}_{-1}\beta + {}^{0}_{-1}\beta$$

As A + 4 + 0 + 0 = 213, then A = 209

Z + 2 – 1–1 = 83, then Z = 83

Then

$$^{213}_{83}Bi \rightarrow {}^{209}_{83}Y + {}^{4}_{2}\alpha + {}^{0}_{-1}\beta + {}^{0}_{-1}\beta$$

We get that $^{213}_{83}Bi$ and $^{209}_{83}Y$ have the same number of protons (= 83), but different number of neutrons, by the notion of isotope, the product $^{209}_{83}Y$ is isotope of $^{213}_{83}Bi$, that is $^{209}_{83}Bi$.

5. A certain light has a wavelength of 430 nm, calculate:

i : the frequency of light of this wavelength,

Solution:

$$\lambda = \frac{c}{f}, \text{ then } f = \frac{c}{\lambda} = \frac{3\times10^{8}ms^{-1}}{430nm} = \frac{3\times10^{8}ms^{-1}}{430\times10^{-9}m} = 7.0\times10^{14}s^{-1}$$

Note: $1s^{-1} = 1Hz$

ii : the energy of a photon of this wavelength.

$$E = hf = 6.63\times10^{-34}Js\times7.0\times10^{14}s^{-1} = 4.6\times10^{-19}J$$

6. A laser emits light of wavelength 430nm in a beam of power 1.5mW. Calculate the number of photons emitted by the laser per 10 second.

Solution:

Number of photons = N

$$f = \frac{c}{\lambda} = \frac{3\times10^{8}ms^{-1}}{430nm} = \frac{3\times10^{8}ms^{-1}}{430\times10^{-9}m} = 7.0\times10^{14}s^{-1}$$

Photon energy $E = hf = 6.63\times10^{-34}Js\times7.0\times10^{14}s^{-1} = 4.6\times10^{-19}J$

$$power = \frac{total\ energy}{time\ taken} = \frac{N\cdot E}{10s} = 1.5mW$$

$$\Rightarrow N\times4.6\times10^{-19}J = 1.5\times10^{-6}W\times10s$$

$$\Rightarrow N = \frac{1.5\times10^{-6}W\times10s}{4.6\times10^{-19}J} = 3.3\times10^{13}$$

Thus, number of photons = 3.3×10^{13}

7. i : what is the minimum photon energy needed to produce proton-antiproton pair?

Solution:

For the proton-antiproton pair, total rest energy is

937.5Mev + 937.5Mev = 1875 Mev.

By conservation of energy,

The minimum photon energy needed = 1875 Mev.

ii : what is the minimum photon energy needed to produce proton-antiproton pair with Kinetic energy 125Mev?

Solution:

For the proton-antiproton pair, total rest energy is 937.5Mev + 937.5Mev = 1875 Mev.

Total energy before pair production= rest energy + Kinetic energy

= 1875 + 125 =2000Mev.

So the minimum photon energy needed = 2000Mev.

8. A proton with 5Mev collides with an antiproton at rest, creating two photons of equal energies as a result of annihilation.

i : calculate the total energy of the proton and antiproton.

Solution:

Total rest energy of proton and antiproton is 937.5Mev + 937.5Mev = 1875 Mev.

Total energy = total rest energy + total kinetic energy

= 1875 Mev + 5Mev =1880 Mev.

ii : show that the minimum energy of each photon is 940 Mev.

Solution:

After annihilation, total two photons energy = total energy before = 1880 Mev.

So each photon energy = 940 Mev

9. Please state the interaction below is permitted or not?

(i) $p+\bar{\nu}_e \rightarrow n+\beta^+$

Before interaction:	After interaction:
Charge =	Charge =
Baryon number B =	Baryon number B =
Lepton number L =	Lepton number L =

Permitted or not? Your answer:

(ii) $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

Before interaction:
Charge =
Baryon number B =
Lepton number L =

After interaction:
Charge =
Baryon number B =
Lepton number L =

Permitted or not? Your answer:

(iii) $\mu^- \rightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu$

Before interaction:
Charge =
Baryon number B =
Lepton number L =

After interaction:
Charge =
Baryon number B =
Lepton number L =

Permitted or not? Your answer:

(iv) $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Before interaction:
Charge =
Baryon number B =
Lepton number L =

After interaction:
Charge =
Baryon number B =
Lepton number L =

Permitted or not? Your answer:

(v) $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$

Before interaction:
Charge =
Baryon number B =
Lepton number L =

After interaction:
Charge =
Baryon number B =
Lepton number L =

Permitted or not? Your answer:

(vi) $\nu_e + p \rightarrow n + e^-$

Before interaction:
Charge =
Baryon number B =
Lepton number L =

After interaction:
Charge =
Baryon number B =
Lepton number L =

Permitted or not? Your answer:

(vii) $\nu_e + p \rightarrow n + e^+$

Before interaction:
Charge =

Baryon number B = | Charge =
Lepton number L = | Baryon number B =
After interaction: | Lepton number L =

Permitted or not? Your answer:

(viii) $\bar{\nu}_e + p \to n + \mu^+$

Before interaction:
Charge =
Baryon number B =
Lepton number L =

After interaction:
Charge =
Baryon number B =
Lepton number L =

Permitted or not? Your answer:

Answers for above equations:

(i) $p+\overline{\nu_e}\rightarrow n+\beta^+$ is permitted.

(ii) $\mu^-\rightarrow e^-+\overline{\nu_e}+\nu_\mu$ is permitted.

(iii) $\mu^-\rightarrow e^-+\overline{\nu_e}+\overline{\nu_\mu}$ is not permitted. Because lepton number is not conserved, and μ^- can only produce ν_μ

(iv) $\mu^+\rightarrow e^++\nu_e+\overline{\nu_\mu}$ is permitted.

(v) $\mu^+\rightarrow e^++\overline{\nu_e}+\nu_\mu$ is not permitted. Because μ^+ can only produce $\overline{\nu_\mu}$. And positron can only be created with an electron neutrino. (Though charge baryon number lepton number is all conserved.

(vi) $\nu_e+p\rightarrow n+e^-$ is not permitted, because charge is not conserved.

(vii) $\nu_e+p\rightarrow n+e^+$ is not permitted, because lepton number is not conserved

(viii) $\overline{\nu_e}+p\rightarrow n+\mu^+$ is not permitted, because $\overline{\nu_e}$ can not produce μ^+. (Though charge baryon number lepton number is all conserved.)

10. Finish the quark combination of particles below:

(i) π^+ meson: charge = +1, strangeness = 0, and mesons consist of a quark and an antiquark.

So π^+ quark combination is $u\overline{d}$

(ii) Proton: charge = +1, strangeness = 0, and proton (is baryon) consist of three quarks.

Then proton quark combination is uud

Because total charge of uud is $+\frac{2}{3}+\frac{2}{3}+(-\frac{1}{3})=+1$

(iii) Antineutron:

Charge = 0, strangeness = 0, and antineutron (is antibaryon) consist of three antiquarks

Then the antineutron $\overline{n}$ quark combination is $\overline{u}\overline{d}\overline{d}$.

Note: the necessary data will be given in the data sheet.

11. i : determine the quark composition of each of the following hadrons, given its strangeness.

a: Omega minus Ω^- (S= -3)
b: antiproton ($\bar{P}$) (S = 0)
c: k^+ meson (S = +1)
d: k^- meson (S = -1)
e: neutron (n) (S = 0)
f: sigma minus Σ^- (S= -1)
g: sigma plus Σ^+ (S= -1)

Answers:

a: Omega Ω^- (S= -3): sss
b: antiproton ($\bar{P}$) (S=0): $\bar{u}\bar{u}\bar{d}$
c: k^+ meson (S= +1): $u\bar{s}$
d: k^- meson (S = -1): $\bar{u}s$
e: neutron (n) (S=0): udd
f: sigma minus Σ^- (S= -1): sdd
g: sigma plus Σ^+ (S= -1): suu

ii : A K^- meson is found to decay into three charged π mesons.

a. What type of interaction takes place in this decay?
b. Is strangeness conserved in this decay?
c. writes down the equation for this decay.

Answers:

a. weak interaction (any decays are due to weak interaction)

b. No, because decay is due to weak interaction, and strangeness is only conserved in strong interaction.

c. $K^- \to \pi^+ + \pi^- + \pi^-$ (charge is conserved)

iii: A K^+ meson was found to decay into a charged π meson and a π^0 meson.

a. Write down the equation for this decay.
b. Explain this change in terms of quarks.

Answers:

a. $K^+ \to \pi^+ + \pi^0$

b. $K^+ \to \pi^+ + \pi^0$

In quark model:

$u\bar{s} \rightarrow u\bar{d} + u\bar{u}$

iv: An Omega minus Ω^- decays into a π^- meson and a baryon X composed of two strange quarks and an up quark.

a. Determine the charge and the strangeness of X from its quark composition.

b. What type of interaction occurs in this change.

Answers:

a. by information told, X= ssu by the data sheet,

$$charge = -\frac{1}{3} + \left(-\frac{1}{3}\right) + \frac{2}{3} = 0$$

Strangeness = -1 + (-1) + 0 = -2

b. Weak interaction. (Any decays are due to weak interaction)

12. (a) Give the number of nucleons and the number of electrons in an atom of ${}^{22}_{11}Na$.

Nucleons: 22

Electrons: 11

(b) The isotope ${}^{22}_{11}Na$ is a positron emitter. In positron emission an up quark undergoes the following change,

$$u \rightarrow d + \beta^+ + \nu_e$$

Show that charge, lepton number and baryon number are conserved in this decay.

Charge: before emission, charge of u is $+\frac{2}{3}$, after emission, total charge =

$-\frac{1}{3} + 1 + 0 = +\frac{2}{3}$, so charge is conserved.

Lepton number: $0 \rightarrow 0 + (-1) + 1$ is conserved.

Baryon number: $\frac{1}{3} \rightarrow \frac{1}{3} + 0 + 0$ is conserved.

(c) Describe what happens when a positron collides with an electron.

Annihilate with each other; convert their total mass to energy, emitting two photons.

13. (a) Quarks may be combined together in a number of ways to form sub-groups of hadrons.

Name two of these sub-groups and for each, state its quark composition.

sub-group 1: baryon consist of three quarks

sub-group 2: meson consist of a quark and an antiquark

(b) A free neutron is an unstable particle.

(i) Complete the following to give an equation that represents the decay of a neutron.

$$n \xrightarrow{W^-} p + \beta^- + \overline{\nu}_e$$

(ii) Describe the change that occurs to the quark structure when a neutron decays.

$$d \xrightarrow{W^-} u + \beta^- + \overline{\nu}_e$$

A down quark change to up quark

14. (a) (i) determine the charge, in C, of a $^{239}_{92}U$ nucleus.

(ii) A positive ion with a $^{239}_{92}U$ nucleus has a charge of $4.80\times10^{-19}\,\mathrm{C}$.

Determine how many electrons are in this ion.

Solutions:

(a) (i) $charge, Q = 92\times1.60\times10^{-19}C = 1.5\times10^{-17}C$

(ii) the neutral $^{239}_{92}U$ nucleus has 92 electrons,

And now the ion has positive charge $4.80\times10^{-19}\,\mathrm{C}$, charge of one electron is $-1.60\times10^{-19}C$, that means it losing 3 electrons, so the number of electrons in this ion is 92 - 3=89.

(b) A $^{239}_{92}U$ nucleus may decay by emitting two β^- particles to form a plutonium nucleus $^{X}_{Y}\mathrm{Pu}$.

State what X and Y represent and give the numerical value of each.

X=

Y=

$$^{239}_{92}U \rightarrow {}^{0}_{-1}\beta + {}^{0}_{-1}\beta + {}^{X}_{Y}\mathrm{Pu}$$

X= 239

Y= 94

15. In a radioactive decay of a nucleus, a β^+ particle is emitted followed by a γ photon of wavelength $8.30 \times 10^{-13}\,\text{m}$.

(a) (i) State the rest mass, in kg, of the β^+ particle.

(ii) Calculate the energy of the γ photon.

(iii) Determine the energy of the γ photon in MeV.

Solutions:

(a) (i) β^+ particle is positron, which has the same mass of the electron,

$$\text{rest mass} = 9.11 \times 10^{-31} kg$$

(ii) $photon\ energy,\ E = hf = h\dfrac{c}{\lambda} = \dfrac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{8.30 \times 10^{-13}} = 2.4 \times 10^{-13} J$

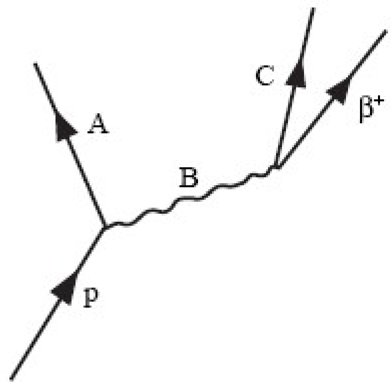
(iii) $2.4 \times 10^{-13} J = \dfrac{2.4 \times 10^{-13}}{1.6 \times 10^{-13}} MeV = 1.5 MeV$

Memo: $1 MeV = 1.60 \times 10^{-13} J$

(b) Name the fundamental interaction or force responsible for β^+ decay.

Solution: Weak interaction.

(c) β^+ decay may be represented by the Feynman diagram.



Name the particles represented by A, B and C.

A : n

B: W^+

C: ν_e

16. Some subatomic particles are classified as hadrons.

(a) What distinguishes a hadron from other subatomic particles?

Solution:

Hadrons have quark structure, and interact with strong nuclear force.

(b) Hadrons fall into two subgroups.

Name each subgroup and describe the general structure of each.
Subgroup 1: baryons consist of three quarks
Subgroup 2 : mesons consist of a quark and an antiquark
(c) The following equation represents an event in which a positive muon collides with a neutron to produce a proton and an antineutrino.

$$n+\mu^{+} \rightarrow p+\overline{\nu}_{\mu}$$

Show that this equation obeys the conservation laws of charge, lepton number and baryon number.
Solution:
Charge: $0+1 \rightarrow 1+0$
Lepton number: $0+(-1) \rightarrow 0+(-1)$
Baryon number: $1+0 \rightarrow 1+0$

17. (a) Name the constituent of an atom which
(i) Has zero charge?
Answers: neutron
(ii) Has the largest charge to mass ratio?
Answers: electron
(iii) When removed leaves a different isotope of the element?
Answers: neutron.
(b) An α particle is the same as a nucleus of helium, ${}^{4}_{2}He$
The equation ${}^{229}_{90}Th \rightarrow {}^{x}_{y}Ra + \alpha$ represents the decay of thorium by the emission of an α particle.
Determine
(i) The values of X and Y, shown in the equation,
X = 225
Y = 88
(ii) The ratio $\dfrac{mass\ of\ {}^{X}_{Y}Ra\,nucleus}{mass\ of\ \alpha\ particle}$
Solution:
$mass\ of\ {}^{X}_{Y}Ra\,nucleus$:
For ${}^{X}_{Y}Ra\ \ nucleus$, Y=88 means has 88 protons, and number of neutrons is 225－88=137

So $mass\ of\ {}^{X}_{Y}Ra\,nucleus = mass\ of\ protons + mass\ of\ neutrons$

And mass of one proton $= 1.67\times10^{-27}\,kg$ mass of one neutron $= 1.67\times10^{-27}\,kg$

Then

$mass\ of\ {}^{X}_{Y}Ra\,nucleus = mass\ of\ protons + mass\ of\ neutrons$

$= 88\times1.67\times10^{-27} + 137\times1.67\times10^{-27} = 225\times1.67\times10^{-27}\,kg$

The same way, we can get

$mass\ of\ \alpha\ particle = 4\times1.67\times10^{-27}\,kg$

So

$$\frac{mass\ of\ {}^{X}_{Y}Ra\,nucleus}{mass\ of\ \alpha\ particle} = \frac{225\times1.67\times10^{-27}\,kg}{4\times1.67\times10^{-27}\,kg} = 56.3$$

18. (a) (i) Name a force which acts between an up quark, u, and an electron. Explain, with reference to an exchange particle, how this force operates.

You may be awarded marks for the quality of written communication in your answer.

Solution:

Electromagnetic force, the exchange particle is virtual photons. Its role is transferring energy and momentum. When up quark interacts with the electrons, new particles create.

(ii) With what particle must a proton collide to be annihilated?

Solution:

Antiproton

(b) A sigma plus particle, Σ^+, is a baryon.

(i) How many quarks does the Σ^+ contain?

Three quarks

(ii) If one of these quarks is an s quark, by what interaction will it decay?

Weak interaction

(iii) Which baryon will the Σ^+ eventually decay into?

Proton

19. The equation

$$p \rightarrow n + \beta^+ + \nu_e$$

represents the emission of a positron from a proton.

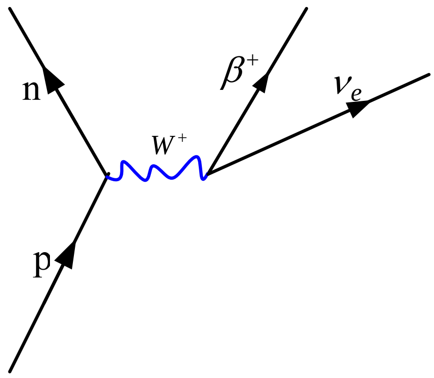
(a) Energy and momentum are conserved in this emission.

What other quantities are conserved in this emission?

Solution:

Charge and baryon number and lepton number

(b) Draw the Feynman diagram that corresponds to the positron emission represented in the equation.



Notes: p changing to n, exchange particle is W^+.

(c) Complete the following table using ticks √ and crosses ×.

particle	Fundamental particle	meson	baryon	lepton
p	×	×	√	×
n	×	×	√	×
β^+	√	×	×	√
ν_e	√	×	×	√

Notes: leptons are fundamental particles.

20. (a) What are isotopes?

Isotopes: atoms of the same element that has the same numbers of proton but different numbers of neutrons.

(b) One of the isotopes of nitrogen may be represented by $^{15}_{7}\mathrm{N}$.

(i) State the number of each type of particle in its nucleus.

Number of protons: 7

Number of neutrons: 15 – 7 = 8

(ii) Determine the ratio $\frac{charge}{mass}$, in C kg^{-1}, of its nucleus.

$\text{Charge} = 7 \times 1.60 \times 10^{-19} C = 1.12 \times 10^{-18} C$

$\text{Mass} = 15 \times 1.67 \times 10^{-27} kg = 2.5 \times 10^{-26} kg$

$$\frac{charge}{mass} = \frac{1.12\times10^{-18}C}{2.5\times10^{-26}kg} = 4.48\times10^{7}Ckg^{-1}$$

(c) (i) What is the charge, in C, of an atom of $^{15}_{7}N$ from which a single electron has been removed?

Solution:

$charge, Q = +1.60\times10^{-19}C$

(ii) What name is used to describe an atom from which an electron has been removed?

Answers: ion

21. The equation represents the collision of a neutral kaon with a proton, resulting in the production of a neutron and a positive pion.

$$K^{0} + p \longrightarrow n + \pi^{+}$$

(a) Show that this collision obeys three conservation laws in addition to energy and momentum.

Answers:

Charge: $0+1 \rightarrow 0+1$

Baryon number: $0+1 \rightarrow 1+0$

Lepton number: $0+0 \rightarrow 0+0$

Charge, Baryon number, Lepton number are all conserved.

(b) The neutral kaon has a strangeness of +1.

Write down the quark structure of the following particles.

K^{0}: $d\bar{s}$

π^{+}: $u\bar{d}$

p: uud

22. (a) (i) complete the equation that represents the collision between a proton and an antineutrino.

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

(ii) What fundamental force is responsible for the interaction shown in part (i)?

Solution:

Weak interaction

(iii) Name an exchange particle that could be involved in this interaction.

Solution:

$$W^{+} \text{ or } W^{-}$$

(b) Describe what happens in pair production and give one example of this process.

You may be awarded marks for the quality of written communication in your answer.

Answers:

Photons with high energy converted to a particle and corresponding antiparticle.

Examples: $p+\overline{p}$ $\quad or \quad$ $e^{-}+e^{+}$

23. A radioactive isotope of carbon is represented by $^{14}_{6}C$.

(a) Using the same notation, give the isotope of carbon that has two fewer neutrons.

Solution:

$^{12}_{6}C$

Isotopes: atoms of the same element that has the same numbers of proton but different numbers of neutrons.

(b) Calculate the charge on the ion formed when **two** electrons are removed from an atom of $^{14}_{6}C$.

Two electrons are removed, the ion formed is positively charged,

$the\ charge = +2\times1.60\times10^{-19}C = +3.2\times10^{-19}C$

(c) Calculate the value of $\frac{charge}{mass}$ for the nucleus of an atom of $^{14}_{6}C$.

Solution:

Nucleus of $^{14}_{6}C$ has 6 protons,

Its charge $Q = 6\times1.60\times10^{-19}C = 9.6\times10^{-19}C$

its mass $= 14\times1.67\times10^{-27}kg$

Then $\frac{charge}{mass} = \frac{9.6\times10^{-19}C}{14\times1.67\times10^{-27}kg} = 4.1\times10^{7}C/kg$

24. (a) (i) Give an example of an exchange particle other than a W^{+} or

W^- particle, and state the fundamental force involved when it is produced.
Exchange particle: virtual photon
Fundamental force: electromagnetic force
(ii) State what roles exchange particles can play in an interaction.
Answers:
To transfer energy and momentum
(b) From the following list of particles,
$p \quad \bar{n} \quad \nu_e \quad e^+ \quad \mu^- \quad \pi^0$
Identify all the examples of
(i) Hadrons: $p \quad \bar{n} \quad \pi^0$
(ii) Leptons: $\nu_e \quad e^+ \quad \mu^-$
(iii) Antiparticles: $\bar{n} \quad e^+$
(iv) Charged particles: $p \quad e^+ \quad \mu^-$

25. (a) An ion of plutonium $^{239}_{94}\mathrm{Pu}$ has an overall charge of $+1.6 \times 10^{-19}$ C.
For this ion state the number of
(i) Protons: 94
(ii) neutrons: 239—94=145
(iii) Electrons: 93
Note: the ion has charge $+1.6 \times 10^{-19}$ C means losing one electron.
(b) Plutonium has several isotopes. Explain the meaning of the word isotopes.
Isotopes: atoms of the same element that has the same numbers of proton but different numbers of neutrons.

26. Under certain conditions a γ photon may be converted into an electron and a positron.
(a) What is this process called?
Answers: Pair-production
(b) (i) Explain why there is a minimum energy of the γ photon for this conversion to take place and what happens when a γ photon has slightly more energy than this value.
Answers:

The γ photon must have a minimum energy to convert to the rest mass of the particle-antiparticle pair.
Because the particle-antiparticle pair has kinetic energy when produced
(ii) Using values from the data sheet calculate this minimum energy in MeV.
0.511 + 0.511 = 1.022MeV
(c) Under suitable conditions, a γ photon may be converted into two other particles rather than an electron and positron.
Give an example of the two other particles it could create.
Solution:
$p \text{ and } \overline{p}$

27. (a) Complete the following equations
$p + e^- \rightarrow$
$n + \nu_\mu \rightarrow p +$
$p + p \rightarrow p + p + K^- +$
Answers:
$p + e^- \rightarrow n + \nu_e$
$n + \nu_\mu \rightarrow p + \mu^-$
$p + p \rightarrow p + p + K^- + K^+$
(b) Give an equation that represents β^- decay, using quarks in the equation rather than nucleons.
$d \rightarrow u + \beta^- + \overline{\nu}_e$
(c) (i) Which fundamental force is responsible for electron capture?
Answers: Weak interaction
(ii) What type of particle is an electron?
Answers: lepton
(iii) State the other fundamental forces that electrons may experience.
Answers: Electromagnetic force and gravitational force.

28. The equation shows a carbon-carbon fusion reaction.
$${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{a}_{b}X + {}^{3}_{2}He$$
(a) Determine the number of protons and the number of neutrons in the nuclide X.

Solution:

Strategy: the total mass number and total atomic number is conserved before and after reaction.

Thus

12 + 12 = a + 3, then a = 21

6 + 6 = b + 2, then b = 10

Therefore

Numbers of protons: 10

Numbers of neutrons: 21 — 10 = 11

(b) Two ${}^{12}_{6}C$ nuclei may also undergo a fusion reaction that produces other isotopes of X and He.

State what is meant by the term isotopes.

Solution:

Isotopes: atoms of the same element that has the same numbers of proton but different numbers of neutrons.

(c) Calculate the ratio $\frac{charge}{mass}$ for the helium nucleus ${}^{3}_{2}He$.

Solution:

Strategy:

For the nucleus ${}^{3}_{2}He$

Its charge is $Q = 2 \times 1.60 \times 10^{-19} C = 3.2 \times 10^{-19} C$

Its mass is $M = 3 \times 1.67 \times 10^{-27} kg = 5.01 \times 10^{-27} kg$

Thus

$$\frac{charge}{mass} = \frac{3.2 \times 10^{-19} C}{5.01 \times 10^{-27} kg} = 6.39 \times 10^{7} C/kg$$

29. (a) The decay shown in the equation

$$p \rightarrow \overline{n} + e^{+} + \overline{\nu_e}$$

cannot occur because it violates two conservation laws.

(i) State the two conservation laws that are violated.

Solution:

Baryon number and lepton number are not conserved.

(ii) Give the correct equation for positron emission.

Solution:

β^+ decay

Equation:

$$ {}_{Z}^{A}X \xrightarrow{W^+} {}_{Z-1}^{A}Y + {}_{+1}^{0}\beta + \nu_e $$

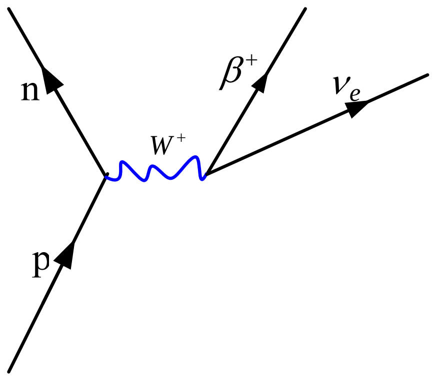
Or

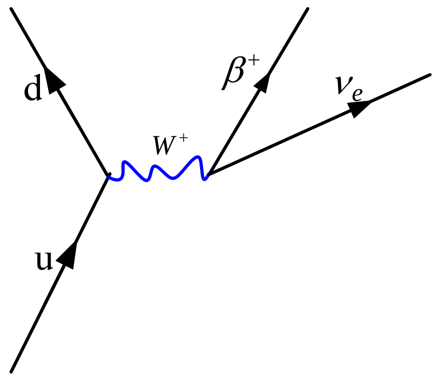
$$ p \xrightarrow{W^+} n + \beta^+ + \nu_e $$

Or in quark model

$$ u \xrightarrow{W^+} d + \beta^+ + \nu_e $$

Feynman diagram:





Note: $p \xrightarrow{W^+} n + \beta^+ + \nu$ is $p \to n + W^+$

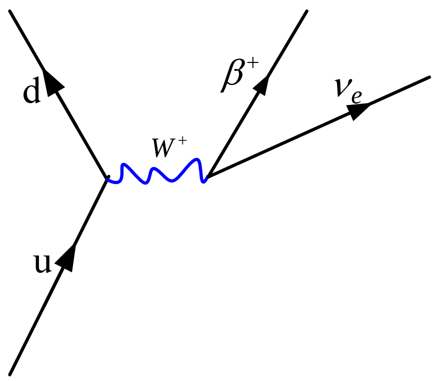
Then $W^+ \to \beta^+ + \nu_e$

And $u \xrightarrow{W^+} d + \beta^+ + \nu_e$ is $u \to d + W^+$

Then $W^+ \to \beta^+ + \nu_e$

(b) Draw a Feynman diagram in terms of quarks, to represent positron emission.

Solution:



30. (a) Give the number of protons, neutrons and electrons in an atom of the isotope ${}_{26}^{55}Fe$.

Solution:

Represent an atom: ${}^{A}_{Z}X$

X: chemical symbol

A: total number of protons and neutrons, sometimes called nucleon number or mass number.

Z: number of protons, sometimes called atomic numbers.

So, the number of neutrons in the nucleus= A−Z

Thus

Protons: 26

Neutrons: 29

Electrons: 26

(b) Calculate the ratio $\frac{charge}{mass}$ for the nucleus of a ${}^{55}_{26}Fe$ atom.

Solution:

Strategy:

For the nucleus ${}^{55}_{26}Fe$

Its charge is $Q = 26\times1.60\times10^{-19}C = 4.16\times10^{-18}C$

Its mass is $M = 55\times1.67\times10^{-27}kg = 91.85\times10^{-27}kg$

Thus

$$\frac{charge}{mass} = \frac{4.16\times10^{-18}C}{91.85\times10^{-27}kg} = 4.53\times10^{7}C/kg$$

(c) Determine the values of a and b in the decay represented by the equation:

$${}^{a}_{b}x \rightarrow {}^{55}_{26}Fe + e^{+} + \nu_e$$

Strategy: the total mass number and total atomic number is conserved before and after decay.

Thus

a = 55 + 0 + 0, then a = 55

b = 26 + (+1) + 0, then b = 27

31. The Ω^- particle is a baryon with strangeness -3. It rapidly decays in stages to a baryon and several pions.

(a) State the general quark structure of a baryon.

Solution:

Combination rules:

Mesons: consist of a quark and an antiquark.

Baryons: consist of three quarks.

Antibaryons: consist of three antiquarks.

Note: all combinations obey charge conservation. Also strangeness is conserved.

(b) State what class of particle a pion is. Give its general quark structure.

Solution:

Pion is meson, its quark structure may be represented by $q\bar{q}$.

(c) State what pion is identical to its antiparticle.

Solution:

π^+: Its antiparticle is π^-.

π^0: Its antiparticle is π^0.

Thus π^0 is identical to its antiparticle.

(d) State what baryon the Ω^- particle finally decays into.

Solution:

Protons

(e) State why the weak interaction must be involved at some stage in the decay of the Ω^- particle.

Solution:

The strangeness is not conserved.

32. The fluorine isotope ${}^{18}_{9}F$ can be produced in the process represented by

$$X + {}^{1}_{1}p \rightarrow {}^{18}_{9}F + {}^{1}_{0}n$$

In which nucleus X combines with a fast moving proton to form the nucleus ${}^{18}_{9}F$ with the ejection of a neutron.

(a) (i) Determine the number of protons and neutrons in nucleus X.

(ii) Only one isotope of X produces this reaction.

Explain what is meant by isotope.

Solution:

(i) Represent an atom: ${}^{A}_{Z}X$

X: chemical symbol

A: total number of protons and neutrons, sometimes called nucleon number or mass number.

Z: number of protons, sometimes called atomic numbers.

So, the number of neutrons in the nucleus= A − Z

We can get A and Z by the conservation of mass number and atomic number:

A + 1 = 18 + 1

Z + 1 = 9 + 0

Thus A = 18, Z = 8.

So, the number of neutrons in the nucleus= A − Z = 18 − 8 = 10.

(ii) Isotopes: atoms of the same element that has the same numbers of proton but different numbers of neutrons.

(b) (i) Determine the $\frac{charge}{mass}$ ratio for the ${}^{18}_{9}F$ nucleus, in Ckg^{-1}.

(ii) Show that the $\frac{charge}{mass}$ ratio for the ${}^{18}_{9}F$ nucleus is larger than that of nucleus X.

Solution:

(i) Strategy:

For the nucleus ${}^{18}_{9}F$

Its charge is $Q = 9 \times 1.60 \times 10^{-19} C = 1.44 \times 10^{-18} C$

Its mass is $M = 18 \times 1.67 \times 10^{-27} kg = 30.06 \times 10^{-27} kg$

Thus

$$\frac{charge}{mass} = \frac{1.44 \times 10^{-18} C}{30.06 \times 10^{-27} kg} = 4.79 \times 10^{7} C/kg$$

(ii) For the nucleus X, mass number: A = 18, atomic number: Z = 8. it has the same mass as that of ${}^{18}_{9}F$; but less charge than that of ${}^{18}_{9}F$. Thus the $\frac{charge}{mass}$ ratio for the ${}^{18}_{9}F$ nucleus is larger than that of nucleus X.

33. (a) A muon can decay via the weak interaction

$$\mu^{-} \rightarrow e^{-} + X + \nu_{\mu}$$

(i) Name a mediating particle of the weak interaction.

(ii) Identify particle X.

Solution:

(i) The weak nuclear force is due to the exchange of particle which is called W bosons.

W bosons: have a non-zero rest mass, and are positively charged (W^{+})

or negatively charged (W^-).

(ii) μ^- can only produce ν_μ; and at the same time, for the product e^- is corresponding to the anti-electro-neutrino $\overline{\nu_e}$:

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

μ^+ can only produce $\overline{\nu_\mu}$; and at the same time, for the product e^+ is corresponding to the anti-electron-neutrino ν_e:

$$\mu^+ \to e^+ + \nu_e + \overline{\nu_\mu}$$

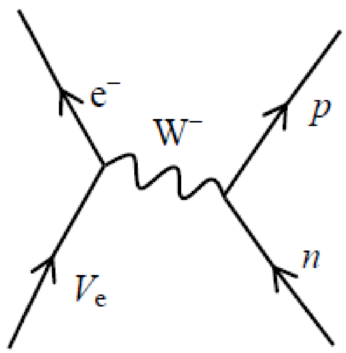
Thus X = $\overline{\nu_e}$

(b) An electron-neutrino may interact with a neutron as represented in the following equation.

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

Draw a Feynman diagram to represent this interaction.

Solution:



(c) In a head-on collision between a proton and an antiproton the following reaction was observed.

$$p + \overline{p} \to 4\pi^+ + 4\pi^-$$

(i) What name is given to the type of process in which a particle and its antiparticle interact?

(ii) Immediately following the process named in part (c)(i), what was formed before the $4\pi^+$ and $4\pi^-$ were created?

Solution:

(i) Annihilation:

The process that when a particle and a corresponding antiparticle meet and their mass is converted into radiation energy, emitting two photons.

(ii) Two photons with high energy!

(d) Determine the quark structure of an antiproton, $\overline{p}$.

Solution:

Combination rules:

Mesons: consist of a quark and an antiquark.

Baryons: consist of three quarks.

Antibaryons: consist of three antiquarks.

Thus

$\overline{p} = \overline{u}\overline{u}\overline{d}$

34. The equation represents an event in which, following a neutron impact, a $^{233}_{92}U$ nucleus is split into two nuclei and two neutrons.

$$^{233}_{92}U + ^{1}_{0}n \rightarrow X + ^{95}_{37}Rb + ^{1}_{0}n + ^{1}_{0}n$$

(a) How many protons, neutrons and electrons are there in an atom of $^{95}_{37}Rb$?

Strategy:

Represent an atom: $^{A}_{Z}X$

X: chemical symbol

A: total number of protons and neutrons, sometimes called nucleon number or mass number.

Z: number of protons, sometimes called atomic numbers. And for an atom, the number of protons is equal to the number of electrons.

So, the number of neutrons in the nucleus= A－Z

Thus, for the atom $^{95}_{37}Rb$

Protons: 37

Neutrons: 95-37 = 58

Electrons: 37

(b) Determine for a nucleus of X

(b) (i) the mass number, A,

(b) (ii) the atomic number, Z.

Strategy: the total mass number and total atomic number is conserved before and after impact.

Thus

233 + 1 = A + 95 + 1 + 1, then A = 137

92 + 0 = Z + 37 + 0 + 0, then Z = 55

(c) Calculate the $\frac{charge}{mass}$ ratio of a $^{95}_{37}Rb$ nucleus, in Ckg^{-1}.

Strategy:

For the nucleus $^{95}_{37}Rb$

Its charge is $Q = 37 \times 1.60 \times 10^{-19} C = 5.92 \times 10^{-18} C$

Its mass is $M = 95 \times 1.67 \times 10^{-27} kg = 158.65 \times 10^{-27} kg$

Thus

$$\frac{charge}{mass} = \frac{5.92 \times 10^{-18} C}{158.65 \times 10^{-27} kg} = 3.7 \times 10^{7} C/kg$$

35. A $\overline{K^0}$ meson decays into two π mesons in the following event.

$$\overline{K^0} \to \pi^- + \pi^+$$

The $\overline{K^0}$ has strangeness -1.

(a) Determine the quark structure of these three mesons.

$\overline{K^0}$:

π^-:

π^+:

Strategy:

Mesons: consist of a quark and an antiquark. All combinations obey charge conservation. Also strangeness is conserved. And

	quarks			antiquarks		
Types	up	down	strange	up	down	strange
Symbol	u	d	s	$\overline{u}$	$\overline{d}$	$\overline{s}$
Charge	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$	$+\frac{1}{3}$	$+\frac{1}{3}$
Strangeness	0	0	-1	0	0	$+1$
Baryon number	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$

Thus

$$\overline{K^0} = s\overline{d}$$

$$\pi^- = d\overline{u}$$

$$\pi^+ = u\overline{d}$$

(b) Complete the following table with ticks and crosses.

	Baryon	Lepton	Hadron	Charged
$\overline{K^0}$	×	×	√	×
π^-	×	×	√	√

(c) (i) by which fundamental interaction does the $\overline{K^0}$ decay?

(c) (ii) Give a reason for your answer.

Solution:

(i) Any decay is weak interaction.

(ii) Because the quark structure is changed before and after interaction.

36. (a) **Fig. 36.1** shows the Feynman diagram for a particular interaction.

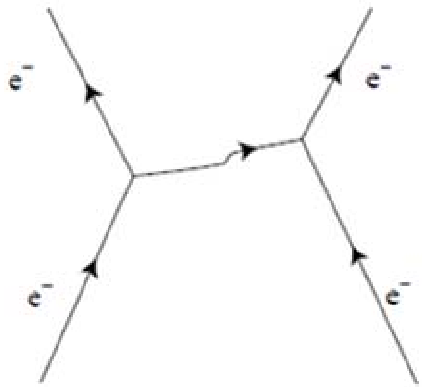


Fig. 36.1

(a) (i) State the type of interaction involved and name the exchange particle.

Solution:

The electromagnetic force between charged particles is due to the exchange of virtual photons.

(a) (ii) State two quantities other than energy and momentum, that are conserved in this interaction.

Solution:

Mass, charge, lepton number, baryon number

(b) **Fig. 36.2** shows the Feynman diagram for another type of interaction.

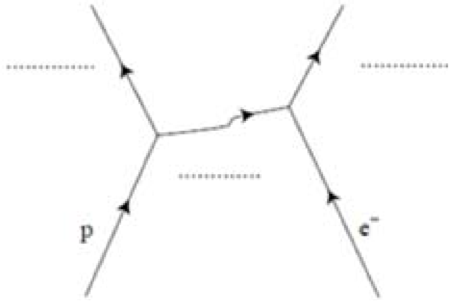


Fig. 36.2

(b) (i) Complete the diagram to show the two particles formed in the interaction and the exchange particle.

(b) (ii) Name the type of interaction responsible for this exchange particle.

Solution:

(i)Electron capture:

Equation: W^+ as the exchange particle.

$$p+e^- \xrightarrow{W^+} n+\nu$$

Feynman diagram:

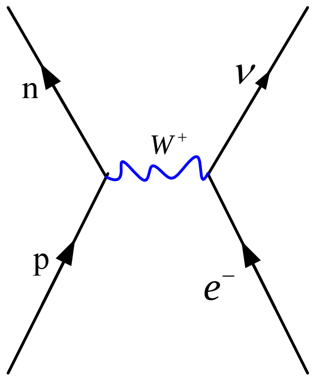


Fig. 36.3 Feynman diagram of Electron capture

(ii) Weak interaction

(b) (iii) Energy and momentum are conserved in this interaction.

State two other quantities that must be conserved and show that they are conserved in this interaction.

Solution:

Charge and baryon number are conserved.

Before interaction:

Charge=1+(-1)=0

Baryon number B=1+0=1

After interaction:

Charge=0+ 0 =0

Baryon number B=1+0=1

(b) (iv) The exchange particle in this interaction was discovered by experiment with a rest mass that had been predicted. Why is it important to test by experiment the prediction of a scientific theory?

Solution:

If a reliable experiment does not support a hypothesis, the hypothesis must be changed.

37. (a) Explain what is meant by an isotope.

Solution:

Isotopes: atoms of the same element that has the same numbers of proton but different numbers of neutrons.

(b) The incomplete table shows information for two isotopes of uranium.

	Number of protons	Number of neutrons	Specific charge of nucleus/ Ckg^{-1}
First isotope	92	143	
Second isotope			3.7×10^{7}

(b) (i) Write the unit for the specific charge in the heading of the last column of the table.

(b) (ii) In the above table write down the number of protons in the second isotope in the table.

(b) (iii) Calculate the specific charge of the first isotope and write this in the table.

(b) (iv) Calculate the number of neutrons in the second isotope and put this number in the table

Solution:

Review:

(i) Represent an atom: $^{A}_{Z}X$

X: chemical symbol

A: total number of protons and neutrons, sometimes called nucleon number or mass number.

Z: number of protons, sometimes called atomic numbers.

So, the number of neutrons in the nucleus= A－Z

(ii) Specific charge:

For charged particles, specific charge is defined as its charge divided by its mass:

$$specific\ charge = \frac{charge}{mass}$$

Unit: C/kg

Thus

For the first isotope,

Its charge is $Q = 92 \times 1.60 \times 10^{-19} C = 1.47 \times 10^{-17} C$

Its mass is $M = (92 + 143) \times 1.67 \times 10^{-27} kg = 3.92 \times 10^{-25} kg$

Thus

$$\frac{charge}{mass} = \frac{1.47 \times 10^{-17} C}{3.92 \times 10^{-25} kg} = 3.75 \times 10^{7} C/kg$$

For the second isotope, it has the same number of protons as that of the first isotope. Thus,

Its charge is $Q = 92 \times 1.60 \times 10^{-19} C = 1.47 \times 10^{-17} C$

And

$$\frac{charge}{mass} = \frac{1.47 \times 10^{-17} C}{M} = 3.7 \times 10^{7} C/kg$$

Therefore, its mass is given by

$$M = \frac{1.47 \times 10^{-17} C}{3.7 \times 10^{7} C/kg}$$

And let the mass number of the second isotope A, thus

$$(1.67 \times 10^{-27} kg) \times A = M = \frac{1.47 \times 10^{-17} C}{3.7 \times 10^{7} C/kg}$$, gives

$$A = \frac{1.47 \times 10^{-17} C}{(3.7 \times 10^{7} C/kg)(1.67 \times 10^{-27} kg)} = 238$$

Hence, the number of neutrons of the second isotope = 238 - 92 = 146.

	Number of protons	Number of neutrons	Specific charge of nucleus/ $C \cdot kg^{-1}$
First isotope	92	143	3.75×10^{7}
Second isotope	92	146	3.7×10^{7}

38. (a) The Σ^{+} particle is a baryon with strangeness -1.

(a) (i) How many quarks does the Σ^{+} particle contain?

Solution:

Review:

Quark combination rules:

Mesons: consist of a quark and an antiquark.

Baryons: consist of three quarks.

Antibaryons: consist of three antiquarks.

Note: all combinations obey charge conservation. Also strangeness is conserved.

Thus, Σ^+ has three quarks.

(a) (ii) How many of the quarks are strange?

Solution:

Because its strangeness is -1, only one quark is strange.

(b) The Σ^+ decays in the following reaction:

$$\Sigma^+ \rightarrow \pi^+ + n$$

(b) (i) State two quantities that are conserved in this reaction.

Solution:

Review:

Conservation rules apply to particles and antiparticles interaction and decays:

(i) Conservation of energy and conservation of charge (in symbol Q).

(ii) Conservation of baryon number. +1 to any baryon and −1 to any antibaryon, 0 to other particles and antiparticles. In symbol B

(iii) Conservation of lepton number. +1 to any lepton and −1 to any antilepton, 0 to other particles and antiparticles. In symbol L

(iv) Conservation of strangeness, only for any strong interaction. In symbol S

So, an interaction between particles and antiparticles happens or not, sometimes just according to the conservation of charge, baryon number, and lepton number.

(b) (ii) State a quantity that is not conserved in this reaction.

Solution:

Strangeness

(b) (iii) What interaction is responsible for this reaction?

Solution:

Weak interaction

(b) (iv) Into what particle will the neutron formed in this reaction eventually decay?

Solution:

Proton

39. (a) Hadrons are a group of particles composed of quarks. Hadrons can either be baryons or mesons.

(a) (i) What property defines a hadron?

Solution:

Hadrons: are particles and antiparticles that interact through the strong interaction.

Note:

Leptons: are particles and antiparticles that interact through the weak interaction.

(a) (ii) What is the quark structure of a baryon?

Solution:

Baryons: consist of three quarks.

(a) (iii) What is the quark structure of a meson?

Solution:

Mesons: consist of a quark and an antiquark.

(b) State one similarity and one difference between a particle and its antiparticle.

Solution:

Similarity: both have the same rest mass.

Difference: opposite in charge.

(c) Complete the table below which lists properties of the antiproton.

	Charge/C	Baryon number	Quark structure
antiproton			

Solution:

	Charge/C	Baryon number	Quark structure
antiproton	$-1.60\times10^{-19}C$	-1	$\overline{u}\overline{u}\overline{d}$

(d) The K^- is an example of a meson with strangeness –1. The K^- decays in the following way:

$$K^- \to \mu^- + \overline{\nu_\mu}$$

(d) (i) State, with a reason, what interaction is responsible for this decay.

Solution:

Weak interaction as the strangeness is not conserved. (Any decay is due to the weak interaction).

(d) (ii) State two properties, other than energy and momentum, that are conserved in this decay.

Solution:

Charge and baryon number are conserved.

Note:

An interaction between particles and antiparticles happens or not, sometimes just according to the conservation of charge, baryon number, and lepton number.

40. (a) An unstable nucleus, ${}_{Z}^{A}X$, can decay by emitting a β^- particle.

(a) (i) What part of the atom is the same as a β^- particle?

Solution:

Beta decay

Beta is electron, in symbol ${}_{-1}^{0}\beta$ or β^- ,

Equation below:

$${}_{Z}^{A}X \to {}_{Z+1}^{A}Y + {}_{-1}^{0}\beta + \overline{\nu_e}$$

$\overline{\nu}$: is called antineutrino, which has no charge and no mass.

(a) (ii) State the changes, if any, in A and Z when X decays.

Solution:

Change in A: A = 0.

Change in Z: Z= +1.

(b) In the process of β^- decay an anti-neutrino is also released.

(b) (i) Give an equation for this decay.

Solution:

${}_{Z}^{A}X \to {}_{Z+1}^{A}Y + {}_{-1}^{0}\beta + \overline{\nu_e}$

(b) (ii) State and explain which conservation law may be used to show that it is an anti-neutrino rather than a neutrino that is released.

Solution:

The lepton number must be conserved. And the lepton number before decay equals zero, hence after decay lepton number of electrons cancels with lepton.

(b) (iii) What must be done to validate the predictions of an unconfirmed scientific theory?

Solution:

The hypothesis needs to be tested by experiment which can be repeatable.

41. A $^{22}_{11}Na$ nucleus decays, forming a new nucleus, by releasing a β^+ particle and one other particle which is difficult to detect.

(a) Name the particle which is difficult to detect.

Solution:

Electron neutrino

(b) Write down the proton number and the nucleon number of the new nucleus.

Solution:

From the equation: $^{A}_{Z}X \xrightarrow{W^+} {}^{A}_{Z-1}Y + {}^{0}_{+1}\beta + \nu_e$, gives

$$^{22}_{11}Na \xrightarrow{W^+} {}^{22}_{10}Y + {}^{0}_{+1}\beta + \nu_e$$

Thus, for the new nucleus:

Proton numbers: 10

Neutron numbers: 22－10 = 12

(c) Name the baryon and each of the leptons formed as a result of this decay.

Solution:

From the decay equation: $p \xrightarrow{W^+} n + \beta^+ + \nu_e$

Baryon: neutron

Lepton: positron

Lepton: electron neutrino

(d) Give the quark structure for a neutron and a proton.

Solution:

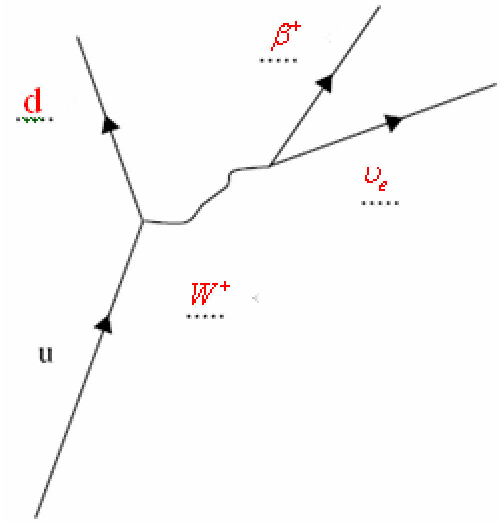
Neutron: ddu

Proton: uud

Note:

Quark combination rules:

Mesons: consist of a quark and an antiquark.
Baryons: consist of three quarks.
Antibaryons: consist of three antiquarks.
Note: all combinations obey charge conservation. Also strangeness is conserved.
(e) Complete the following Feynman diagram so that it represents β^+ decay.



42. (a) Describe how the strong nuclear force between two nucleons varies with the separation of the nucleons quoting suitable values for separation.
Solution:
(i) Its range is no more than about 3-4 femtometres (fm), where $1\,fm = 10^{-15}\,m$
(ii) It is an attractive force from 3-4 fm down to about 0.5 fm. At separations smaller than this, it is a repulsive force that acts to prevent the nucleons being pushed into each other.

(b) An unstable nucleus can decay by the emission of an alpha particle.
(b) (i) State the nature of an alpha particle.
Solution:
Review:
Alpha radiation
Alpha particle is the atom ${}_2^4He$; symbol is ${}_2^4\alpha$, sometimes in symbol α
An unstable nucleus of an element X emits an alpha particle; the product nucleus is a different element Y.
Equation below:

$$ {}_Z^AX \rightarrow {}_{Z-2}^{A-4}Y + {}_2^4\alpha $$

Conservation of mass number and atomic number

(b) (ii) Complete the equation below to represent the emission of an α particle by a $^{238}_{92}U$ nucleus.

$$^{238}_{92}U \rightarrow ^{......}_{......}Th + ^{......}_{......}\alpha$$

Solution:

From the equation $^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}\alpha$, gives

$$^{238}_{92}U \rightarrow ^{238-4}_{92-2}Th + ^{4}_{2}\alpha$$

Thus,

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

(c) $^{238}_{92}U$ decays in stages by emitting α particles and β^- particles, eventually forming $^{206}_{82}Pb$, a stable isotope of lead.

(c) (i) State what is meant by isotopes.

Solution:

Isotopes: atoms of the same element that has the same numbers of proton but different numbers of neutrons.

(c) (ii) If there are eight alpha decays involved in the sequence of decays from $^{238}_{92}U$ to $^{206}_{82}Pb$ deduce how many β^- decays are involved.

Solution:

We can write the equation as follows:

$^{238}_{92}U \rightarrow ^{206}_{82}Th + 8(^{4}_{2}\alpha) + N(^{0}_{-1}\beta)$

Where N is number of β^- particle

Mass number and atomic number are conserved before and after decay, thus

238 = 206 + 8×4 + N×0

92 = 82 + 8×2 + N×(-1)

Therefore, N = 82 + 16 – 92 = 6

43. In a β^+ decay, a positron is emitted along with a neutrino, and a $\gamma - ray$ photon.

Although the energy spectrum for $\gamma - ray$ involved is discrete, the energy spectrum for the positrons is continuous.

(i) State the difference between a discrete energy spectrum and a continuous energy spectrum.

Solution:

A discrete energy spectrum means the energy is restricted to certain values; a continuous energy spectrum means the energy can take on any value.

(ii) Explain how the existence of the neutrino accounts for the continuous nature of the positron energy spectrum.

Solution:

The total energy is constant before and after decay. The energy is shared between positron and neutrino.

44. Sub-atomic particles can either be hadrons or leptons.

(a) (i) State one difference between these two groups of particles.

(a) (ii) Give an example of a non-strange hadron and an example of a lepton.

Hadron:

Lepton:

(a) (iii) Hadrons can be further divided into two groups. Name these two groups and state a difference between them.

(b) The Feynman Diagram in Figure 44.1 represents an interaction known as electron capture.

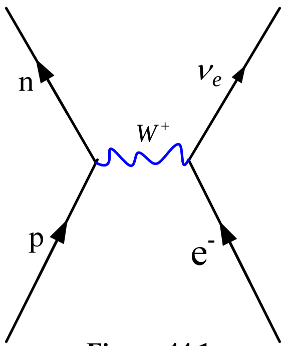


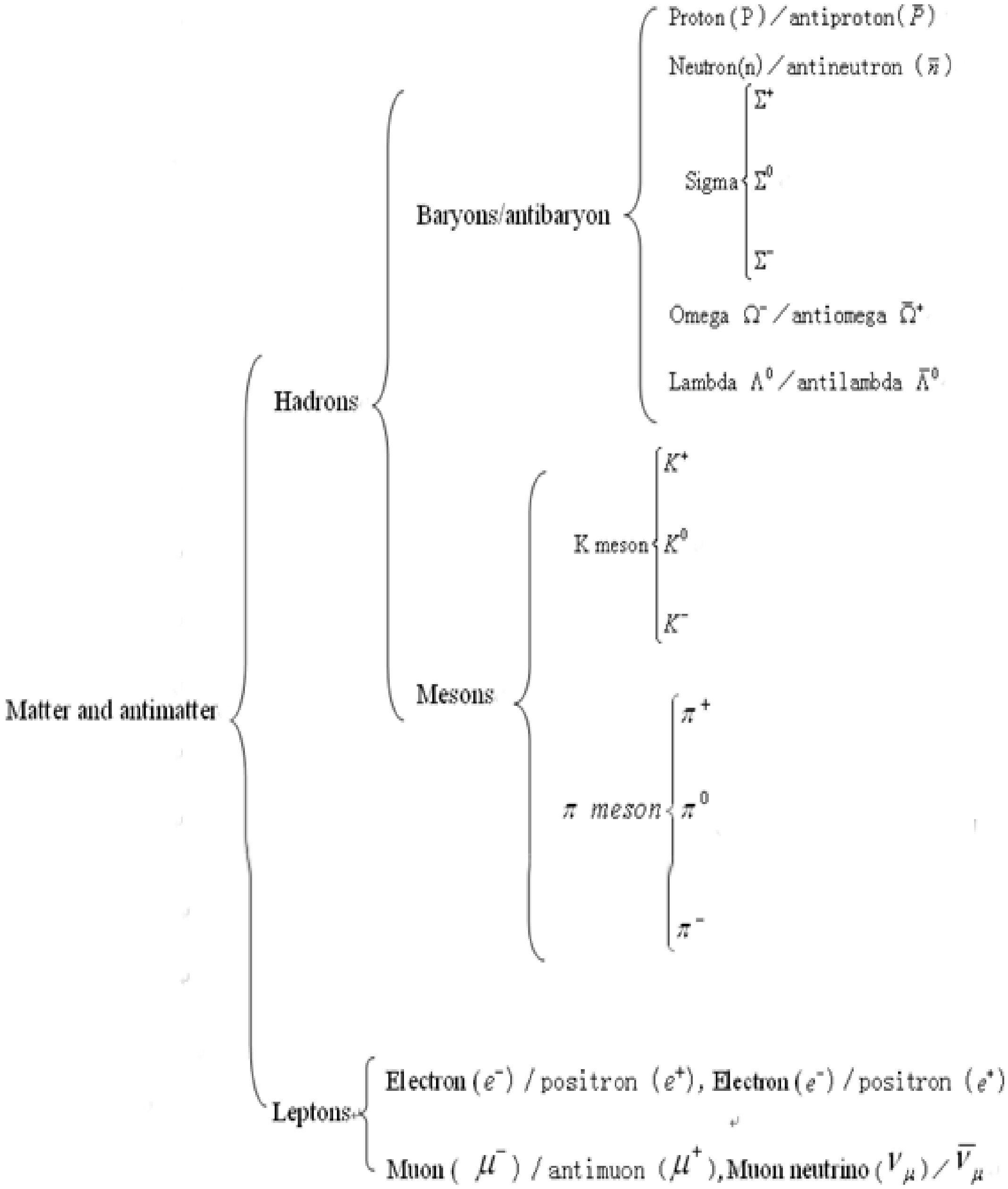
Figure 44.1

(b) State a conservation laws obeyed in this interaction. Show how the property mentioned in the law is conserved.

Review & Solution:

Hadrons: are particles and antiparticles that interact through the strong interaction. For example, proton, neutron…

Leptons: are particles and antiparticles that interact through the weak interaction. Lepton is fundamental particles. For example, electron, neutrino…



Mesons: consist of a quark and an antiquark.
Baryons: consist of three quarks.
Antibaryons: consist of three antiquarks.

Conservation rules apply to particles and antiparticles interaction and decays:

(i) Conservation of energy and conservation of charge (in symbol Q).

(ii) Conservation of baryon number. +1 to any baryon and -1 to any antibaryon, 0 to other particles and antiparticles. In symbol B

(iii) Conservation of lepton number. +1 to any lepton and -1 to any antilepton, 0 to other particles and antiparticles. In symbol L

(iv) Conservation of strangeness, only for any strong interaction. In symbol

S
So, an interaction between particles and antiparticles happens or not, sometimes just according to the conservation of charge, baryon number, and lepton number.

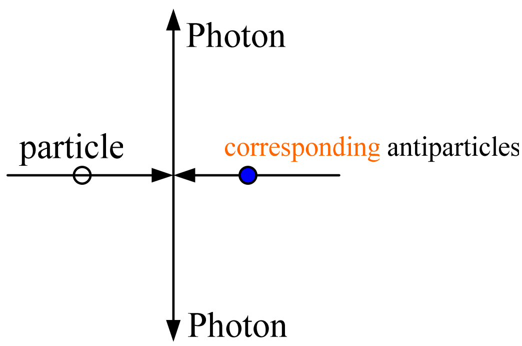
45. Under certain circumstances, a photon moving through a material can interact with the nucleus of an atom of the material to produce an electron and a positron.
(i) What is the name of this process?
(ii) Give one reason why the photon could not produce a single electron instead of an electron and a positron.
(iii) Make use of the Data and Formulae booklet to show that the minimum energy of the photon required for this process is 1.02MeV.
(iv) Photons whose wavelength exceeds a certain value will not cause this process.
Calculate the maximum wavelength for the process to occur stating your answer to an appropriate number of significant figures.
(v) Explain what will happen to the positron produced by the interaction.

Review:

(i) Annihilation:

The process that when a particle and a corresponding antiparticle meet and their mass is converted into radiation energy, emitting two photons.

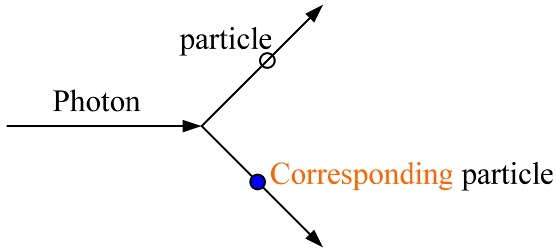
Diagram:



(ii) Pair production

The process that a photon with sufficient energy could suddenly change into a particle-antiparticle pair

Diagram:



(iii) Unit of energy converting:

$1eV = 1.60 \times 10^{-19} J$, $1MeV = 1.60 \times 10^{-13} J$

Solution:

(i) Pair production

(ii) The momentum or the lepton number must be conserved. Before interaction lepton number of photon equals 0, after interaction, sum of lepton number of electron (+1) and positron (-1) equals 0.

(iii) From the Data and Formulae booklet, rest energy of electron = 0.510 MeV, the minimum energy of the photon required for this process is $2 \times 0.510 = 1.02\text{MeV}$.

(iv) The wavelength exceeds a certain value, the photon energy decreases, thus the photon has not enough energy to produce electron-positron pair. Therefore, the maximum wavelength $\lambda_{\max}$ is given by

$$h\frac{c}{\lambda_{\max}} = 1.02MeV = 1.02 \times 1.60 \times 10^{-13} J$$

$$\lambda_{\max} = \frac{hc}{1.02 \times 1.60 \times 10^{-13}} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{1.02 \times 1.60 \times 10^{-13}} = 1.22 \times 10^{-12} m$$

(v) The positron will encounter an electron and the two particles will annihilate to form photons.

2 Electromagnetic Radiation and Quantum Phenomena

2-1 The photoelectric effect

Photo electrons are emitted without delay whenever metal is illuminated by light of a certain minimum frequency, which is called threshold frequency irrespective of the intensity of the light. And different metals have different threshold frequency.

This effect is called photoelectric effect.

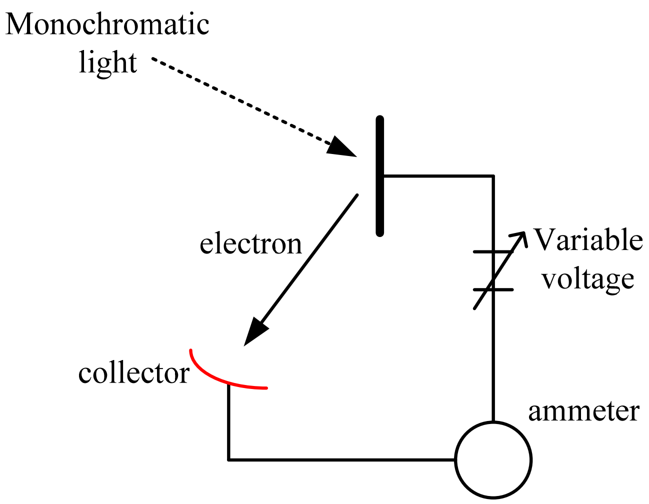


Fig. 2.1 The photoelectric effect

Puzzling problems:

The wave theory of light can not explain the threshold frequency, if light is a classical wave the conduction electrons should absorb energy continuously, and lower intensity, it will take longer time for an the conduction electrons have sufficient energy to escape, and stronger intensity take less time. So there should be no threshold frequency.

1.1 Einstein's explanation of photoelectricity

Einstein assumed that:

i : light is composed of wave packets or photons, each photon of energy is equal to hf, where f is frequency, $h = 6.63 \times 10^{-34}\ Js$ is Planck constant. So the intensity of light depends on the number of photons; and the energy of each photon depends only on the frequency.

$$energy\ of\ a\ photon = hf = h\frac{c}{\lambda}$$

Where c is speed of light, λ is wavelength of light.

Note: photon energy is proportional to frequency, inversely proportional to wavelength.

ii : An electron can leave the metal surface if the energy gained from a single photon exceeds the work function, ϕ of the metal, which is the minimum energy needed by the conduction electrons to escape from the metal surface.

Hence the maximum kinetic energy of the emitted electrons

$$E_{k\max} = hf - \phi$$

So $hf = E_{k\max} + \phi$, where f is the frequency of directed light.

$E_{k\max} = 0$, work function $\phi = hf$,

Thus the threshold frequency of the metal:

$$f_0 = \frac{\phi}{h}$$

Conditions for photoelectricity emission:

$E_{k\max} > 0$ or $hf > \phi = hf_0$

Where f is the frequency of directed light, f_0 is the threshold frequency.

2-2 Collisions of electrons with atoms

2.2.1 The Bohr model and Energy levels

Bohr considered that the orbit radius of an electron moving around a nucleus can only have certain values. This phenomenon is called **orbit quantization**.

Different orbits correspond to different states. Though electrons in these states still make speed-varying motion, they do not emit energy and so these states are stable. Atoms in different states have different energies and so atomic energy is also quantized.

In Bohr's model, the possible states of atom are not continuous and so the corresponding energies are not continuous. These energy values are called **energy levels**. Draw in **Fig. 2.2** is the energy levels of a hydrogen atom.

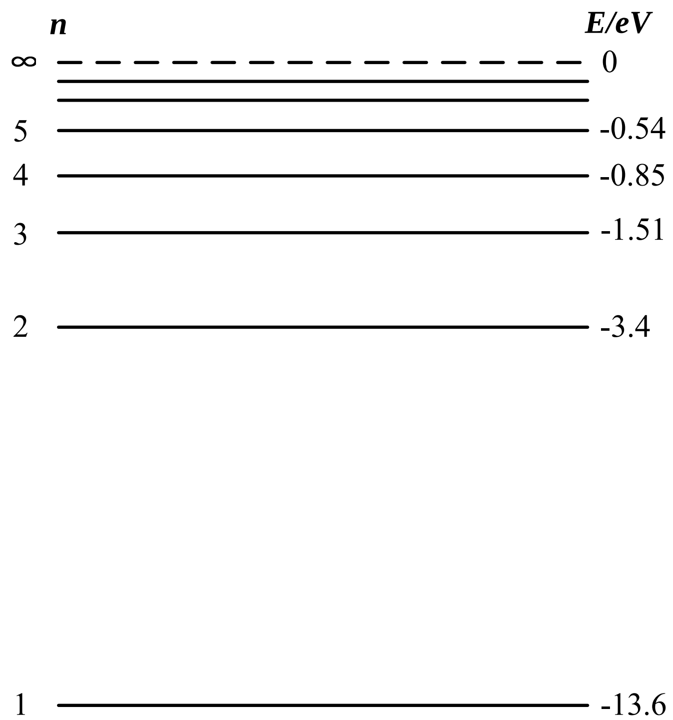


Fig. 2.2 The energy levels of a hydrogen atom

If we label the energy of the atom after ionization as 0, then the energy of other states are all negative. The state labeling 1, 2, 3… is called a quantum number, and it is usually denoted by n. the lowest energy state is called **the ground state**, and the rest of the states are called **excited states**. The energies of the ground and excited states are denoted by E_1, E_2, E_3 …and so on.

2.2.2 The emission and absorption of photons

An atom is most stable when it is in the ground state, and when it is in an excited state it will transit to energy levels with lower energy and arrives at the ground state after one or more transitions. During the transition the energy is released in the form of photons. The frequency f of the photon emitted during a transition from initial energy level E_m to final energy level E_n ($m > n$) is determined by the equation

$$h f = E_m - E_n$$

An atom will transit from a lower energy level to a higher energy level after it absorbs photons.

2.2.3 Atomic spectrum

A dilute gas will glow if electrified. Using a spectroscope, you can get the spectrum of the light emitted. But the spectrum is not continuous. It has only a few discrete bright lines. In other words, a dilute gas can only emit light at certain frequencies after electrified. The positions of the bright lines are different for different gases, and this shows that the frequency of light emitted by different gases is different.

Bohr's theory explained the spectrum of a hydrogen atom very well. When the atom transits from a higher energy level to a lower one, the energy of the emitted photon is equal to the energy difference of energy levels before and after transition. Because the energy levels are discontinuous, the energy of the emitted photons are discontinuous too. From the spectrum, the frequency of the light wave from an atom can only take certain discrete values. If you use Bohr's theory to calculate the position of hydrogen spectral lines, it agrees with real observations well, and it also predicts some spectral lines not ye seen.

Because structures of different atoms are different, their energy levels are different too. The wavelengths of photons they emit will be different. The spectral distribution of one element is different from that of all other elements. Thus, we can tell which element is emitting photons by analyzing its spectrum. Because of this, a spectrum shaped with discrete lines is also called an **atomic spectrum.**

Summary:

Ionization: any process of creating ions is called ionization.

Ionization energy: the energy needed for ionization.

Excitation: Any process that e**lectro**ns moved from lower energy level (inner shell) to higher energy level (outer shell) in the atom.

Excitation energy: the energy absorbed by the atom for excitation.

Excitation by: (1) electron collision. (2) Photon absorption.

(1) Electron collision: kinetic energy of the electrons must be greater than or equal to the excitation energy.

(2) Photon absorption: kinetic energy of the photons must be just equal to the excitation energy.

De-excite (de-excitation): electrons in the atom moved from the higher energy level to lower energy level, emitting photons.

Ground state: the lowest energy state of an atom is called its ground state.

Excited state: other energy state except ground state.

2.2.4 Fluorescent tube explanation

The fluorescent tube is a glass tube with a fluorescent coating on its inner surface. The tube contains mercury vapour at low pressure. When the tube is on, it emits visible light because:

ⅰ: ionization and excitation of the mercury atoms occurs as they collide with each other and with electrons in the tube.

ⅱ: the mercury atoms emit ultraviolet photons, as well as visible photons and photons of much less energy when they de-excite.

ⅲ: the ultraviolet photons are absorbed by the atoms of the fluorescent coating, causing excitation of the atoms.

ⅳ: the coating atoms de-excite and emit visible photons.

2-3 Wave-particle duality

3.1 The dual nature of particles of matter

Evidence of particle-like nature of matter: electrons can be deflected in the magnetic field.

Wave-like nature of matter was considered by de Broglie in 1923. de Broglie put forward the hypothesis that:

(i) Matter particles have a dual wave-particle nature.

(ii) The wave-like behaviour of a matter particle is characterized by a wavelength, its **de Broglie wavelength**, λ, which is related to the momentum, p, of the particle by means of the equation

$$de\ Broglie\ wavelength\ \lambda = \frac{h}{p} = \frac{h}{mv}$$

Where m is mass of particle, v is velocity of the particle.

2-4 44 Worked examples

1. A zinc plate has a threshold wavelength of 310nm,calculate:

ⅰ: the threshold frequency.

ⅱ: the work function in eV.

ⅲ: an ultraviolet radiation of wavelength 240 nm is directed at the zinc plate; determine the maximum kinetic energy of the photoelectricity in eV. $\left(1eV = 1.60\times10^{-19} J\right)$

Solution:

i :

Data: threshold wavelength of zinc $\lambda = 310nm = 3.1\times10^{-7}m$

And threshold frequency $f_0 = \frac{c}{\lambda} = \frac{3\times10^{8}ms^{-1}}{3.1\times10^{-7}m} = 9.7\times10^{14}Hz$

ii :

Work function $\phi = hf_0$

$$\phi = 6.63\times10^{-34}Js\times9.7\times10^{14}Hz = 6.4\times10^{-19}J = \frac{6.4\times10^{-19}J}{1.60\times10^{-19}J}ev = 4.0eV$$

iii: Wavelength of directed light,

$$\lambda = 240nm = 240\times10^{-9}m = 2.4\times10^{-7}m$$

Frequency of directed light,

$$f = \frac{c}{\lambda} = \frac{3\times10^{8}ms^{-1}}{2.4\times10^{-7}m} = 12.5\times10^{14}Hz$$

Maximum kinetic energy:

$$E_{k\max} = hf - \phi = 6.63\times10^{-34}Js\times12.5\times10^{14}s^{-1} - 6.4\times10^{-19}J$$

$$= 1.9\times10^{-19}J = \frac{1.9\times10^{-19}J}{1.6\times10^{-19}J}ev = 1.2eV$$

2. Work function of a certain metal is $1.96eV$, calculate

i : the threshold wavelength of the metal.

ii : an ultraviolet radiation of wavelength 425 nm is directed at the metal plate; determine the maximum kinetic energy of the photoelectricity in eV. $\left(1eV = 1.60\times10^{-19}J\right)$

iii: explain why photoelectric emission happens with light of wavelength 425nm but not with light of wavelength 650nm.

Solution:

i :

Data: work function

$$\phi = 1.96eV = 1.96\times1.60\times10^{-19}J = 3.1\times10^{-19}J$$

And $\phi = hf_0 \Rightarrow threshold\ \ frequency\ f_0 = \frac{\phi}{h}$

$$f_0 = \frac{\phi}{h} = \frac{3.1\times10^{-19}J}{6.63\times10^{-34}Js} = 4.7\times10^{14}Hz$$

Threshold wavelength $\lambda = \frac{c}{f_0} = \frac{3\times10^{8}ms^{-1}}{4.7\times10^{14}Hz} = 6.4\times10^{-7}m$

ii : Wavelength of directed light,

$$\lambda = 425nm = 425\times10^{-9}m = 4.25\times10^{-7}m$$

Frequency of directed light,

$$f = \frac{c}{\lambda} = \frac{3\times10^{8}ms^{-1}}{4.25\times10^{-7}m} = 7.1\times10^{14}Hz$$

Maximum kinetic energy:

$$E_{k\max} = hf - \phi = 6.63\times10^{-34}Js\times7.1\times10^{14}s^{-1} - 3.1\times10^{-19}J$$

$$= 1.6\times10^{-19}J = \frac{1.6\times10^{-19}J}{1.6\times10^{-19}J}ev = 1.0ev$$

iii:

Photon energy of directed light of wavelength 425nm

$$E_1 = hf = h\frac{c}{\lambda} = 6.63\times10^{-34}J\times\frac{3\times10^{8}ms^{-1}}{425\times10^{-9}m} = 4.7\times10^{-19}J$$

Photon energy of directed light of wavelength 650nm

$$E_1 = hf = h\frac{c}{\lambda} = (6.63\times10^{-34}Js)\times\frac{3\times10^{8}ms^{-1}}{650\times10^{-9}m} = 3.06\times10^{-19}J$$

And $E_1 > \phi$, $E_2 < \phi$

So there is no photoelectric emission with directed light of wavelength 650nm.

3. Fig. 3.1 shows an energy level:

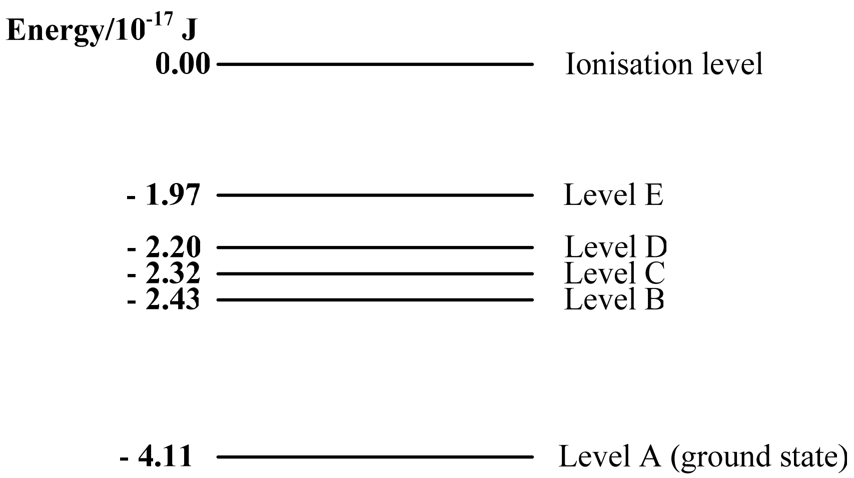


Fig. 3.1

i : an electron in the atom excite from level B to D, this process is called excitation.

$$\begin{aligned}&\textit{excitation energy needed}\\&= E_D - E_B = -2.20\times10^{-17}J - (-2.43\times10^{-17}J) = 0.23\times10^{-17}J\end{aligned}$$

ii : an electron in the atom de-excite from level D to B, this process is called de-excitation.

$$\begin{aligned}&\textit{the emitting photon energy}\\&= E_D - E_B = -2.20\times10^{-17}J - (-2.43\times10^{-17}J) = 0.23\times10^{-17}J\end{aligned}$$

And photon energy $= hf = 0.23\times10^{-17}J$

So frequency of emitting photon, $f = \dfrac{0.23\times10^{-17}J}{6.63\times10^{-34}Js} = 3.5\times10^{15}Hz$

iii: from the graph, ionization energy is greater or equal to 4.11×10^{-17} J

4. An atom absorbs a photon of energy 3.8eV and subsequently emits photons of energy 0.6eV and 3.2eV.

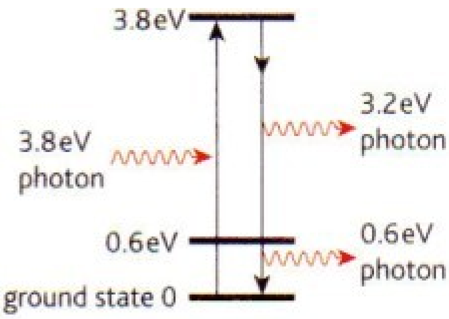
i : Sketch an energy level diagram representing these changes.

ii : Describe how the above changes take place.

Solution:

i : The atom absorbs photon energy 3.8eV, and then emits energy 0.6eV and 3.2eV, that is from energy level 3.8eV to energy level 0.6eV, and then from energy level 0.6eV to ground state. (Or from energy level 3.8eV to energy level 3.2eV then from energy level 3.2eV to ground state. Please sketch the diagram by yourself.)

So energy level diagram:



ii : an electron in the atom absorbs the 3.8eV photon and moves to an outer shell. It moves to an inner shell and emits a 3.2eV photon. An electron moves from this shell to the ground state, emitting a 0.6eV photon.

5. A mercury atom de-excites from 5.7eV to 4.9eV. For the photon emitted, calculate i : its energy in J

ii : its wavelength.

Solution:

i : emitted photon energy=5.7eV—4.9 eV=0.8 eV

ii : emitted photon energy = hf

$$hf = 0.8eV = 0.8 \times 1.6 \times 10^{-19} J = 1.28 \times 10^{-19} J$$

$$\Rightarrow f = \frac{1.28 \times 10^{-19} J}{h} = \frac{1.28 \times 10^{-19} J}{6.63 \times 10^{-34} Js} = 1.9 \times 10^{14} Hz$$

$$f = \frac{c}{\lambda} \Rightarrow \lambda = \frac{c}{f} = \frac{3 \times 10^{8} ms^{-1}}{1.9 \times 10^{14} Hz} = 1.6 \times 10^{-6} m$$

6. An electron moving at the speed of $5.1 \times 10^{6} ms^{-1}$, calculate:

i : momentum of the electron?

ii : de Broglie wavelength of the electron?

(Mass of electron, $m = 9.11 \times 10^{-31} kg$)

Solution:

Given: $v = 5.1 \times 10^{6} ms^{-1}$

Strategy: momentum, $p = mv$,

$$de\ Broglie\ wavelength\ \lambda = \frac{h}{p} = \frac{h}{mv}$$

Answers:

i :

$$p = mv = 9.11 \times 10^{-31} kg \times 5.1 \times 10^{6} ms^{-1}$$
$$= 4.6 \times 10^{-24} kgms^{-1}$$

ii :

$$de\ Broglie\ wavelength\ \lambda = \frac{h}{p} = \frac{h}{mv}$$
$$= \frac{6.63 \times 10^{-34} Js}{4.6 \times 10^{-24} kgms^{-1}}$$
$$= 1.4 \times 10^{-10} m = 0.14 nm$$

7. A football of mass 0.5kg moving at speed of 15 ms^{-1}, calculate

i : de Broglie wavelength of the football?

ii : do we observe the wave nature of the ball? Why?

Solution:

i :

Given: $m = 0.5kg \quad v = 15ms^{-1}$

Determine: de Broglie wavelength

Strategy: $\lambda = \frac{h}{p} = \frac{h}{mv}$

Answers: $\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6.63 \times 10^{-34} Js}{0.5kg \times 15ms^{-1}} = 8.84 \times 10^{-35} m$

ii : can not be observed, because of the very short of wavelength.

8. An electron has kinetic energy of 13.65eV, calculate:

i : speed of the electron

ii : de Broglie wavelength of the electron?

Solution:

Given:

$$E_k = 13.65eV = 13.65eV \times 1.60 \times 10^{-19} J$$
$$= 2.2 \times 10^{-18} J$$

Strategy: $E_k = \frac{mv^2}{2} \Rightarrow v = \sqrt{\frac{2E_k}{m}}$

de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{mv}$

Answers:

i :

$$E_k = \frac{mv^2}{2} \Rightarrow v = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 2.2 \times 10^{-18} J}{9.11 \times 10^{-31} kg}} = 2.2 \times 10^6 ms^{-1}$$

ii :

de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{mv}$

$$= \frac{6.63 \times 10^{-34} Js}{9.11 \times 10^{-31} kg \times 2.2 \times 10^6 ms^{-1}}$$
$$= 3.3 \times 10^{-10} m = 0.33nm$$

9. De Broglie wavelength of a proton is $0.4nm$, calculate

i : speed of the proton?

ii : kinetic energy of the proton?

Solution:

Given: de Broglie wavelength λ

Strategy: de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{mv} \Rightarrow v = \frac{h}{m\lambda}$

$$E_k = \frac{mv^2}{2}$$

Answers:

i :

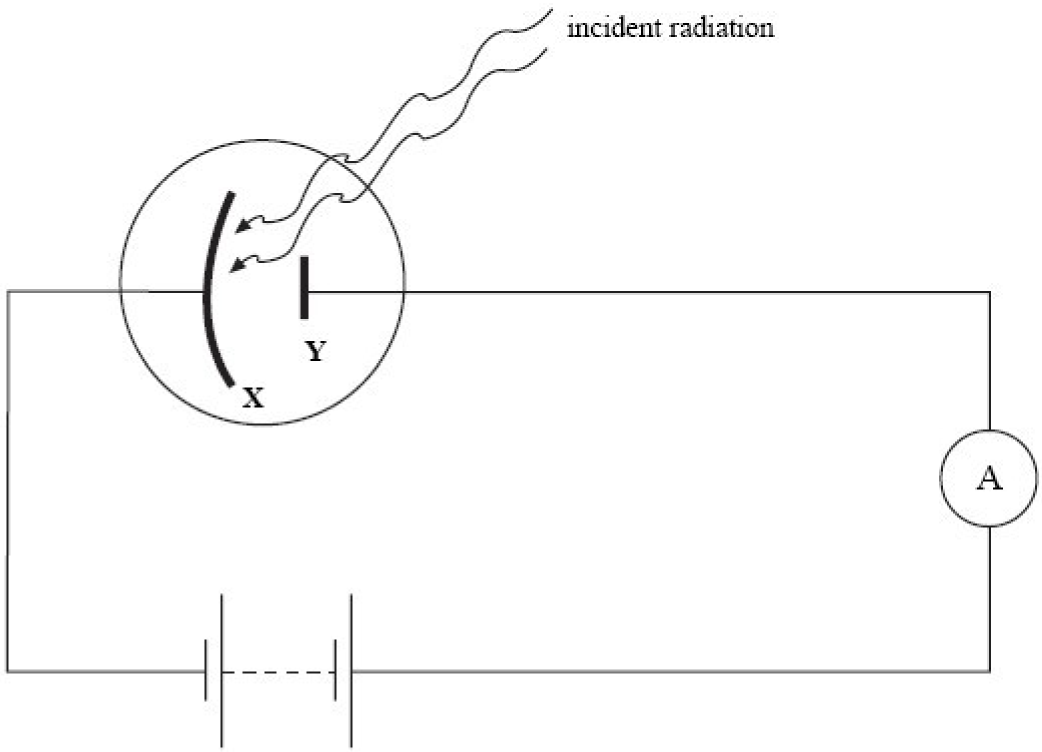
$$v = \frac{h}{m\lambda} = \frac{6.63\times10^{-34}\,Js}{1.67\times10^{-27}\,kg\times0.4\times10^{-9}\,m} = 10^3\,ms^{-1}$$

ii :

$$E_k = \frac{mv^2}{2} = \frac{1.67\times10^{-27}\,kg\times(10^3\,ms^{-1})^2}{2} = 8.35\times10^{-22}\,J$$

10. In the apparatus shown, monochromatic ultraviolet radiation is incident on the surface of metal **X**.

Photoelectrons are emitted from **X** and are collected at electrode **Y**.



(a) Calculate the work function of X, given that each photon in the incident radiation has $3.2\times10^{-19}\,J$ of energy.

The maximum kinetic energy possessed by a single photoelectron is $2.1\times10^{-19}\,J$.

Solution:

$E_{k\max} = hf - \phi \quad \Rightarrow \quad \phi = hf - E_{k\max}$

$\phi = hf - E_{k\max} = 3.2\times10^{-19} - 2.1\times10^{-19} = 1.1\times10^{-19}\,J$

Where hf is the photon energy of directed light.

(b) The source of the incident radiation is replaced with a new source. The wavelength of the radiation from the new source is half the wavelength of the original radiation.

Calculate the maximum kinetic energy of the emitted photoelectrons.

Solution:

For the original radiation,

Photon energy $hf_0 = h\dfrac{c}{\lambda_0} = 3.2\times10^{-19}\,J$

For the new source, $\lambda_{new} = \dfrac{1}{2}\lambda_0$

Photon energy $hf_{new} = h\dfrac{c}{\lambda_{new}} = h\dfrac{c}{(\frac{1}{2}\lambda_0)} = 2h\dfrac{c}{\lambda_0}$

$= 2\times3.2\times10^{-19}\,J = 6.4\times10^{-19}\,J$

New incident energy of each photon is doubled

$E_{k\max} = hf - \phi = 6.4\times10^{-19}\,J - 1.1\times10^{-19}\,J = 5.3\times10^{-19}\,J$

11. Fig. 11.1 shows some energy levels, in eV, of an atom.

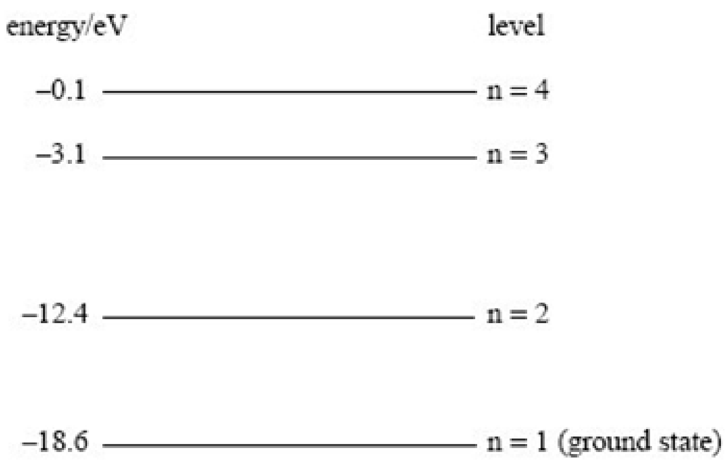


Fig. 11.1

Photons of specific wavelengths are emitted from these atoms when they are excited by collisions with electrons.
You may be awarded marks for the quality of written communication in your answer.
(a) Explain
(i) What is meant by the process of excitation?
Excitation: Any process that electrons moved from lower energy level (inner shell) to higher energy level (outer shell) in the atom.
(ii) Why the emitted photons have specific wavelengths.
Because the photons emits when the electrons in the fixed higher energy level de-excite to the fixed lower energy level. Then giving the photons of specific energy (specific wavelength).
(b) One of the emitted photons has an energy of 9.92×10^{-19} J.
(i) Calculate the wavelength of this photon.

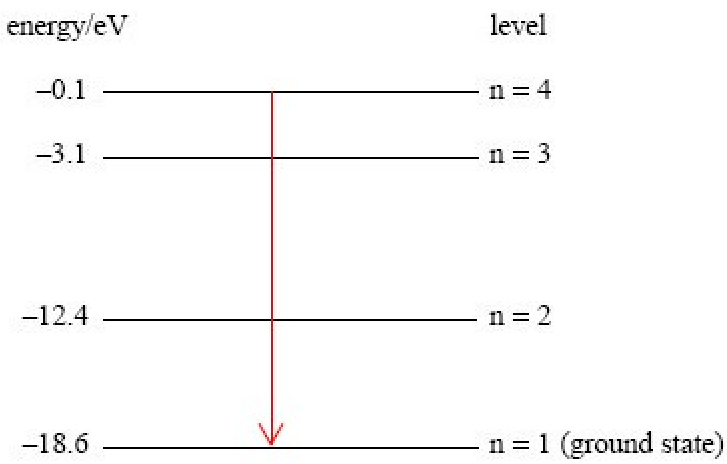
$$photon \quad energy = hf = h\frac{c}{\lambda} = 9.92\times10^{-19}J$$

$$\lambda = \frac{hc}{9.92\times10^{-19}} = \frac{6.63\times10^{-34}\times3\times10^{8}}{9.92\times10^{-19}} = 2.0\times10^{-7}m$$

(ii) Determine which transition is responsible for this emitted photon.

$$9.92\times10^{-19}\ \text{J} = \frac{9.92\times10^{-19}}{1.6\times10^{-19}}eV = 6.2eV$$

From the diagram, the transition is from level 2 to level 1.
(iii) Draw an arrow on the energy level diagram to show the transition responsible for the emission of a photon with the shortest wavelength.
Note: the shortest wavelength means the highest energy of the emission photon.



12. Electromagnetic waves and electrons have properties of both particles and waves.

Explain what evidence there is to support this statement.

Experimental details are not required.

You may be awarded marks for the quality of written communication in your answer.

Diffraction of electrons shows wave property.

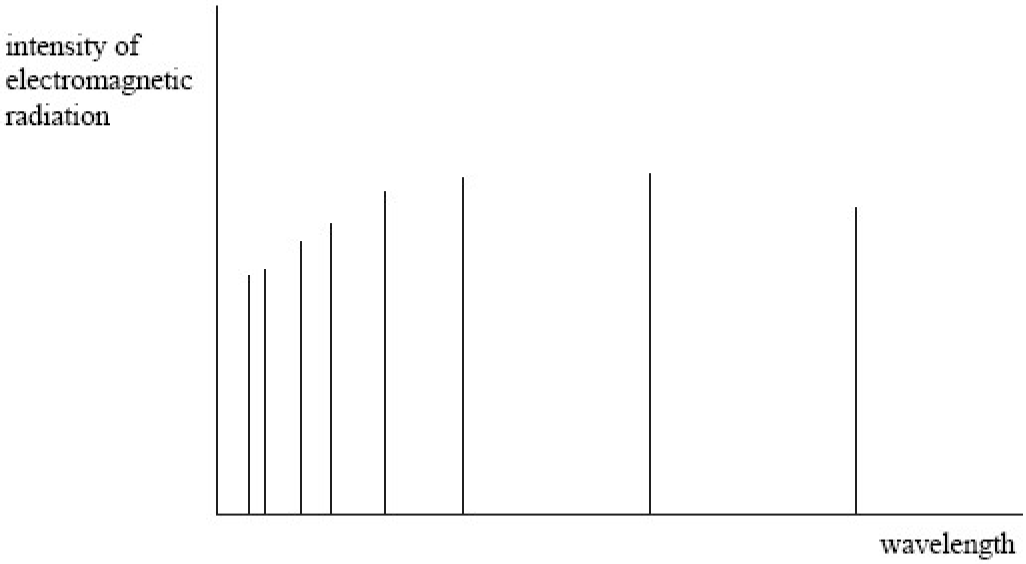
Electrons can be deflected in the magnetic field shows the particle property.

Interference of electromagnetic waves shows the wave property.

Photoelectric effect shows the wave property of the electromagnetic waves

13. (a) Explain what happens to electrons in hydrogen atoms when a spectrum, such as that represented below, is produced.

You may be awarded marks for the quality of written communication in your answer.



Solutions:

Electrons in the lower energy level excite to the higher energy level, then electrons fall down to fill the vacancy, emitting photons, and the photon energy is discrete, that is, the wavelength is discrete.

(b) A fluorescent tube is normally coated on the inside with a powder. The tube is then filled with mercury vapour at low pressure. When the tube is

switched on, the mercury vapour emits ultraviolet electromagnetic radiation. Explain how this ultraviolet radiation causes the powder to emit electromagnetic radiation as well. State the difference between the radiations emitted by the mercury vapour and the powder.
You may be awarded marks for the quality of written communication in your answer.

Solutions:

The ultraviolet electromagnetic radiation from the mercury vapour was absorbed by the atom of the powder, then excitation and de-excitation happens, and then producing radiation. and the radiation is visible light.

14. A proton and an electron have the same velocity. The de Broglie wavelength of the electron is $3.2\times10^{-8}\text{m}$.

(a) Calculate,

(i) The velocity of the electron,

Solution:

Strategy:

de Boglie wavelength $\lambda = \dfrac{h}{mv}$, $v = \dfrac{h}{m\lambda}$

$$v = \frac{h}{m\lambda} = \frac{6.63\times10^{-34}}{9.11\times10^{-31}\times3.2\times10^{-8}} = 2.27\times10^{4}\,ms^{-1}$$

(ii) The de Broglie wavelength of the proton.

Data: speed of the proton $v = 2.27\times10^{4}\,ms^{-1}$

Solution:

$$\text{de Boglie wavelength } \lambda = \frac{h}{mv}$$

$$= \frac{6.63\times10^{-34}}{1.67\times10^{-27}\times2.27\times10^{4}} = 1.75\times10^{-11}\,m$$

(b) (i) State what kind of experiment would confirm that electrons have a wave-like nature. Experimental details are not required.

Diffraction of electrons shows that electrons have a wave-like nature

(ii) State why it is easier to demonstrate the wave properties of electrons than to demonstrate wave properties of protons.

Answers:

The electrons are easier to accelerate, and easier to detect the wavelength of the electrons.

15. Fig. 15.1 shows some of the electron energy levels of an atom.

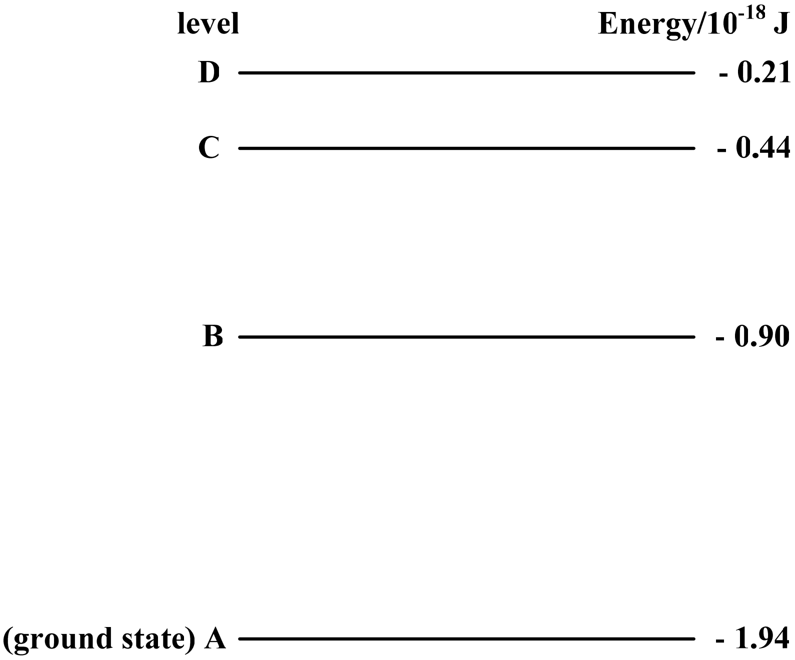


Fig. 15.1

An incident electron of kinetic energy $4.1\times10^{-18}J$ and speed $3.0\times10^{6}ms^{-1}$. Collides with the atom represented in the diagram and excites an electron in the atom from level B to level D.

(a) For the incident electron, calculate

(i) The kinetic energy in eV,

Solution:

$1eV = 1.60\times10^{-19}J$

$$so\ \ 4.1\times10^{-18}J = \frac{4.1\times10^{-18}J}{1.60\times10^{-19}J}eV = 25.6eV$$

(ii) The de Broglie wavelength.

For the incident electron, de Broglie wavelength $\lambda = \dfrac{h}{mv}$,

$h\ and\ m\ is\ known, but\ v\ is\ unknown$, how to get v?

$$\text{kinetic energy} = \frac{mv^2}{2} = 4.1\times10^{-18}J$$

$$\Rightarrow v = \sqrt{\frac{2\times4.1\times10^{-18}}{m}} = \sqrt{\frac{2\times4.1\times10^{-18}}{9.11\times10^{-31}}} = 3\times10^{6}ms^{-1}$$

de Broglie wavelength $\lambda = \frac{h}{mv} = \frac{6.63\times10^{-34}}{9.11\times10^{-31}\times3\times10^{6}} = 0.24\times10^{-9}m = 0.24nm$

(b) When the excited electron returns directly from level D to level B it emits a photon.

Calculate the wavelength of this photon?

Solution:

The excited electron returns directly from level D to level B it emits a photon, the process is called de-excitation.

Emitting photon energy, $E = E_D - E_B = -0.21\times10^{-18} - (-0.9\times10^{-18})$

$= 0.69\times10^{-18}J$

And

$E = 0.69\times10^{-18}J = hf = h\frac{c}{\lambda}$

$\Rightarrow \lambda = \frac{hc}{0.69\times10^{-18}} = \frac{6.63\times10^{-34}\times3\times10^{8}}{0.69\times10^{-18}} = 2.9\times10^{-7}m$

16. (a) The photoelectric effect is represented by the equation

$$hf = \Phi + E_k$$

What does E_k represent?

Solution:

E_k: Maximum Kinetic energy of the photoelectrons

(b) A metal plate is illuminated with electromagnetic radiation of wavelength 190 nm. The metal has a work function of $7.9\times10^{-19}J$.

(i) Calculate the frequency of the incident electromagnetic radiation.

Given: $\lambda = 190nm = 1.9\times10^{-7}m$

Strategy: $f = \frac{c}{\lambda}$

$so\quad f = \frac{c}{\lambda} = \frac{3\times10^{8}}{1.9\times10^{-7}} = 1.58\times10^{15}Hz$

(ii) Show that the metal plate will emit photoelectrons when illuminated with radiation of this wavelength.

The incident energy

$E = hf = 6.63\times10^{-34}\times1.58\times10^{15} = 1.0\times10^{-18}J$

Work function is $7.9\times10^{-19}J$

So incident energy is greater than work function. The plate will emit photoelectrons.

(iii) The radiation incident on the metal plate remains at a constant wavelength of 190 nm but its intensity is now doubled.

State and explain the effect this has on the emitted photoelectrons.

You may be awarded marks for the quality of written communication in your answer.

Solution:

Number of radiation photons is doubled.

Maximum Kinetic energy of emitting photons keeps the same.

But the emitting photons are doubled.

17. Some energy levels of an atom of a gas are shown in **Fig. 17.1**.

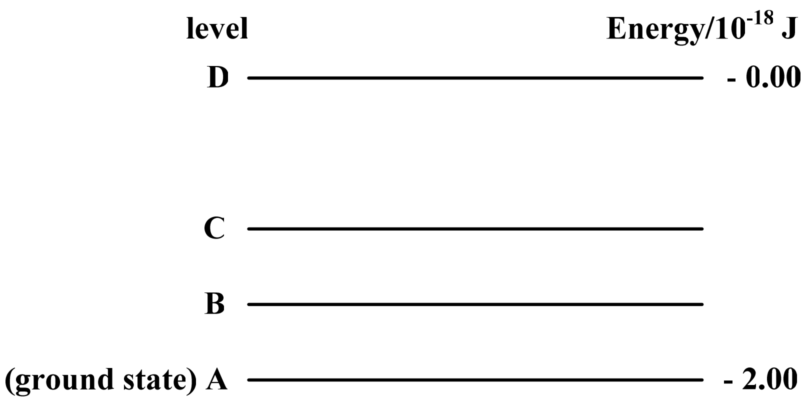


Fig. 17.1

When a current is passed through the gas at low pressure, a line spectrum is produced. Two of these lines, which correspond to transitions from levels B and C respectively to the ground state, are shown in **Fig. 17.2.**

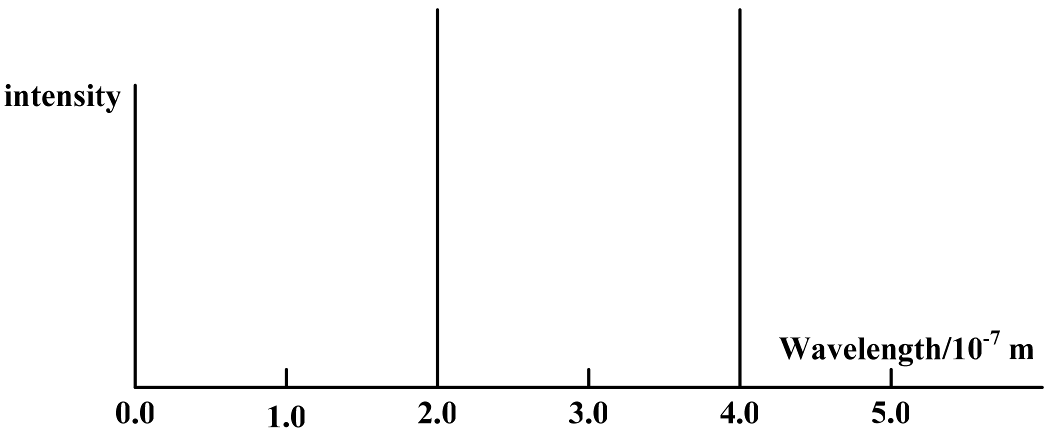


Fig. 17.2

(a) Describe what happens to an electron in an atom in the ground state in

order for the atom to emit light of wavelength 4.0×10^{-7} m.
You may be awarded marks for the quality of written communication in your answer.
Solutions:
The electrons in the ground state excite to higher energy level by electron collision or photon absorption; and then electrons in the higher energy level de-excite to the ground state, emitting photons, and the photon energy depends on the energy change between the energy level that is discrete.
(b) Determine the energy, in J, of
(i) The photons responsible for each of the two lines shown in **Fig. 17.2**,
Line 1, wavelength, $\lambda = 2.0\times10^{-7} m$,

$$\text{energy } E_1 = hf = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}\times3\times10^{8}}{2\times10^{-7}} = 9.9\times10^{-19} J$$

Line 2, wavelength, $\lambda = 4.0\times10^{-7} m$,

$$\text{energy } E_2 = hf = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}\times3\times10^{8}}{4\times10^{-7}} = 5.0\times10^{-19} J$$

(ii) Levels B and C in **Fig. 17.1**.
Energy of level B $= -1.5\times10^{-18} J$
Energy of level C $= -1.0\times10^{-18} J$
Solutions: in **Fig. 17.1**

$$\begin{aligned} E_B - E_A = 5.0\times10^{-19} J \Rightarrow E_B &= 5.0\times10^{-19} + E_A \\ &= 5.0\times10^{-19} + (-2.0\times10^{-18}) \\ &= -1.5\times10^{-18} J \end{aligned}$$

$$\begin{aligned} E_C - E_A = 1.0\times10^{-18} J \Rightarrow E_C &= 1.0\times10^{-18} + E_A \\ &= 1.0\times10^{-18} + (-2.0\times10^{-18}) \\ &= -1.0\times10^{-18} J \end{aligned}$$

18. (a) Explain what is meant by the term *work function* of a metal.
Solution:
The work function of the metal is the minimum energy needed by the conduction electrons to escape from the metal surface.
(b) In an experiment on the photoelectric effect, the maximum kinetic energy of the emitted photoelectrons is measured over a range of incident light frequencies. The results obtained are shown in **Fig. 18.1**.

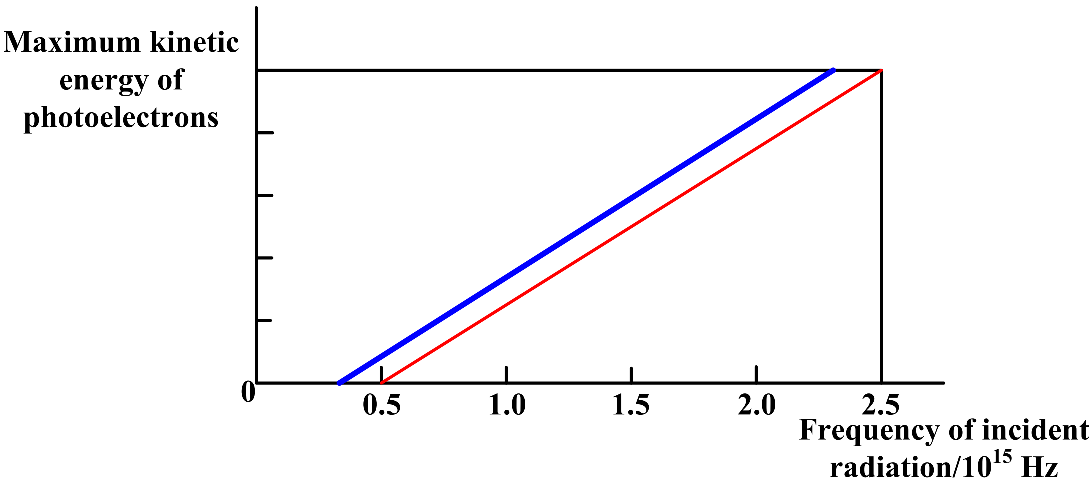


Fig. 18.1

(i) A metal of work function ϕ is illuminated with light of frequency f.
Write down the equation giving the maximum kinetic energy, E_K, of the photoelectrons emitted in terms of ϕ and f.

$$E_k = hf - \phi$$

(ii) Use the data in Figure 4 to determine the work function of the metal.

Solutions:

In Figure 4, we can get threshold frequency $f_0 = 0.5 \times 10^{15} Hz$

Work function $\phi = hf_0 = 6.63 \times 10^{-34} \times 0.5 \times 10^{15} = 3.3 \times 10^{-19} J$

(iii) Determine the maximum kinetic energy of the photoelectrons when the frequency of the incident radiation is 2.5×10^{15} Hz.

Solutions:

$$E_{kmas} = hf - \phi = 6.63 \times 10^{-34} \times 2.5 \times 10^{15} - 3.3 \times 10^{-19} = 1.33 \times 10^{-18} J$$

(c) The experiment is repeated but with the light incident on a metal of lower work function.
Draw a new line on **Fig. 18.1** that results from this change.

19. (a) one quantity in the photoelectric equation is a characteristic property of the metal that emits photoelectrons. Name and define this quantity.

Solution:

Work function, Φ, of the metal, which is the minimum energy needed by the conduction electrons to escape from the metal surface.

(b) A metal is illuminated with monochromatic light. Explain why the kinetic energy of the photoelectrons emitted has a range of values up to a certain maximum.

You may be awarded marks for the quality of written communication in your answer.

Solution:

$E_{k\max} = hf - \Phi$

For the monochromatic light, its photon energy is fixed, and the photoelectrons receive a fixed amount of energy, electron can lose various amounts of energy to escape from the metal.

(c) A gold surface is illuminated with monochromatic ultraviolet light of frequency $1.8\times10^{15}Hz$. The maximum kinetic energy of the emitted photoelectrons is $4.2\times10^{-19}J$.

Calculate, for gold,

(i) The work function, in J,

Given: incident light frequency $f = 1.8\times10^{15}Hz$, maximum kinetic energy $E_{k\max} = 4.2\times10^{-19}J$

Strategy: $E_{k\max} = hf - \Phi \Rightarrow \text{work function}, \Phi = hf - E_{k\max}$

$$\Phi = hf - E_{k\max} = 6.63\times10^{-34}\times1.8\times10^{15} - 4.2\times10^{-19}J$$
$$= 7.7\times10^{-19}J$$

(ii) The threshold frequency.

Strategy: Thus the threshold frequency of the metal:

$$f_0 = \frac{\phi}{h} = \frac{7.7\times10^{-19}J}{6.63\times10^{-34}} = 1.2\times10^{15}Hz$$

20. (i) A negative muon, μ^-, is 207 times more massive than an electron. Calculate the de Broglie wavelength of a negative muon traveling at $3.0\times10^{6}ms^{-1}$.

Given: $mass, m = 207\times9.11\times10^{-31}kg = 1.9\times10^{-28}kg$

$v = 3.0\times10^{6}ms^{-1}$

Strategy: de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{mv}$

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6.63\times10^{-34}}{1.9\times10^{-28}\times3.0\times10^{6}} = 1.2\times10^{-12}m$$

(ii) Using values from the data sheet calculate the ratio $\frac{\text{rest mass of } \pi^0}{\text{rest mass of } \mu^-}$, where

π^0 is a neutral pion.

Solution:

$$\frac{rest\ energy\ of\ \pi^0}{rest\ energy\ of\ \mu^-} = \frac{m_{\pi^0}\cdot c^2}{m_{\mu^-}\cdot c^2} = \frac{135MeV}{106MeV}$$

$$that\ is\ \ \frac{m_{\pi^0}}{m_{\mu^-}} = \frac{135MeV}{106MeV}$$

$$so\ \ \frac{rest\ mass\ of\ \pi^0}{rest\ mass\ of\ \mu^-} = \frac{135MeV}{106MeV} = 1.27$$

(iii) Calculate the speed necessary for a π^0 to have the same de Broglie wavelength as that of the μ^- in part (i).

Given: de Broglie wavelength $of\ \pi^0, \lambda = 1.2\times10^{-12}m$

$$\frac{rest\ mass\ of\ \pi^0}{rest\ mass\ of\ \mu^-} = \frac{135MeV}{106MeV} = 1.27$$

$$rest\ mass\ of\ \mu^-, m_{\mu^-} = 207\times9.11\times10^{-31}kg = 1.9\times10^{-28}kg$$

$$\text{Strategy}: de\ Broglie\ wavelength\ \lambda = \frac{h}{p} = \frac{h}{mv}$$

$$\Rightarrow v = \frac{h}{m_{\mu^-}\lambda}$$

$$m_{\mu^-} = 1.27\times1.9\times10^{-28}kg = 2.4\times10^{-28}kg$$

So $v = \frac{h}{m_{\mu^-}\lambda} = \frac{6.63\times10^{-34}}{2.4\times10^{-28}\times1.2\times10^{-12}} = 2.3\times10^{6}ms^{-1}$

21. Some of the energy levels of an atom are shown in **Fig. 21.1**. The atom may be ionised by electron impact.

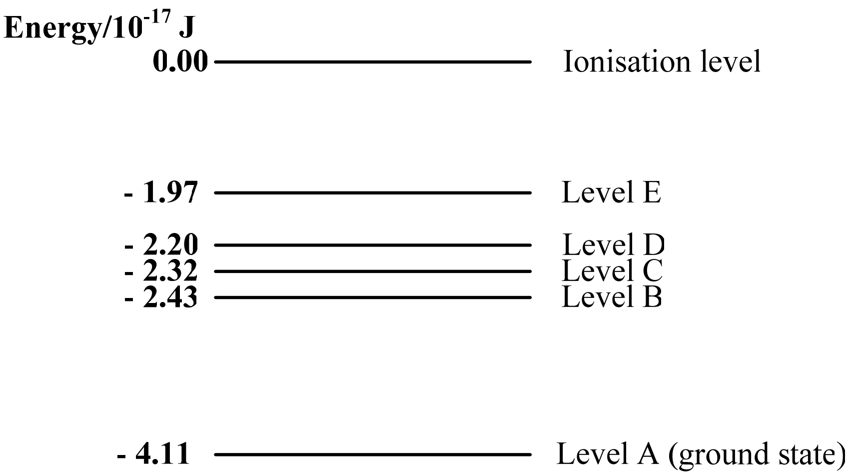


Fig. 21.1

(a) (i) State what is meant by the ionisation of an atom.
Ionization: any process of creating ions is called ionization.
(ii) Calculate the minimum kinetic energy, in eV, of an incident electron that could ionise the atom from its ground state.
Solution:
Energy needed to ionise the atom from its ground state needs:
$0-(-4.11\times10^{-17})=4.11\times10^{-17}J$, and

$$4.11\times10^{-17}J=\frac{4.11\times10^{-17}}{1.60\times10^{-19}}eV=2.6\times10^{2}eV$$

(b) You may be awarded marks for the quality of written communication in your answer to parts (b)(i) and (b)(ii).
The atom in the ground state is given $5.00\times10^{-17}J$ of energy by electron impact.
(i) State what happens to this energy.
Solution:
The atom is ionized, and electron escapes from the ground state with kinetic energy $0.89\times10^{-17}J$
(ii) Describe and explain what could happen subsequently to the electrons in the higher energy levels.
Answers:
The orbiting electrons fall down to fill the vacancy in the lower levels, emitting photons, and various routes down are possible.
(c) Identify two transitions between energy levels that would give off electromagnetic radiation of the same frequency.
Note: level E to level D, and level D to level B all gives off the same photon energy $0.23\times10^{-17}J$, that is, give off the same frequency.

22. The apparatus shown in **Fig. 22.1** can be used to demonstrate the photoelectric effect. Photoelectrons are emitted from the metal cathode when it is illuminated with white light which has passed through a blue filter.

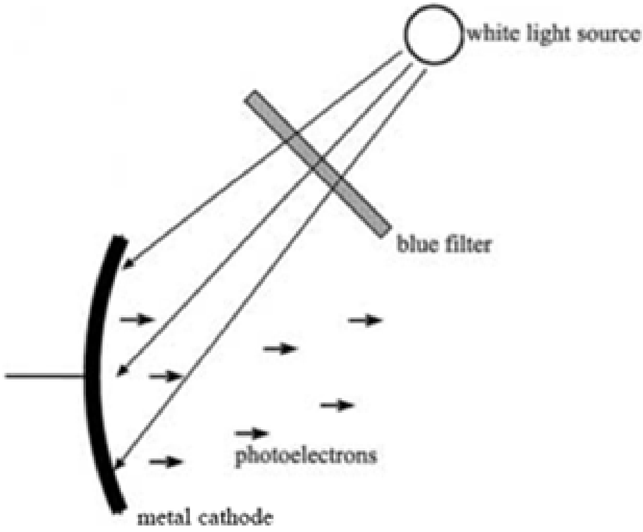


Fig. 22.1

You may be awarded additional marks to those shown in brackets for the quality of written communication in your answers to parts (a) and (b).

(a) The intensity of the light source is reduced. State and explain the effect of this on the emitted photoelectrons.

Answers:

The intensity determines the number of photons emitted per second, and the number of photons reduces per second, but the photon energy keep the same.

(b) Explain why no photoelectrons are emitted when the blue filter is replaced by a red filter.

Answers:

Wavelength of red light is greater than that of blue light, $\lambda_{red} > \lambda_{blue}$, that is,

$f_{red} < f_{blue}$, and $photon \quad energy, E = hf$

So, $E_{red} < E_{blue}$, the frequency of red light is below the threshold frequency of the metal.

(c) When a metal of work function 2.30×10^{-19} J is illuminated with ultraviolet radiation of wavelength 200 nm, photoelectrons are emitted.

Calculate

(i) The frequency of the ultraviolet radiation,

Solution:

$200nm = 200 \times 10^{-9} m$

$$f = \frac{c}{\lambda} = \frac{3 \times 10^{8}}{200 \times 10^{-9}} = 1.5 \times 10^{15} Hz$$

(ii) The threshold frequency of the metal,

Solution:

threshold frequency, $f_0 = \frac{\phi}{h} = \frac{2.30\times10^{-19}}{6.63\times10^{-34}} = 0.35\times10^{19}\,Hz$

(iii) The maximum kinetic energy of the photoelectrons, in J.

Solution:

$E_{k\max} = hf - \phi$

$= 6.63\times10^{-34}\times1.5\times10^{15} - 2.30\times10^{-19} \;\; = 7.6\times10^{-19}\,J$

23. Fig. 23.1 shows the energy level diagram of a hydrogen atom. Its associated spectrum is shown in **Fig. 23.2**.

The transition labeled **A** in **Fig. 23.1** gives the spectral line labeled **B** in **Fig. 23.2**.

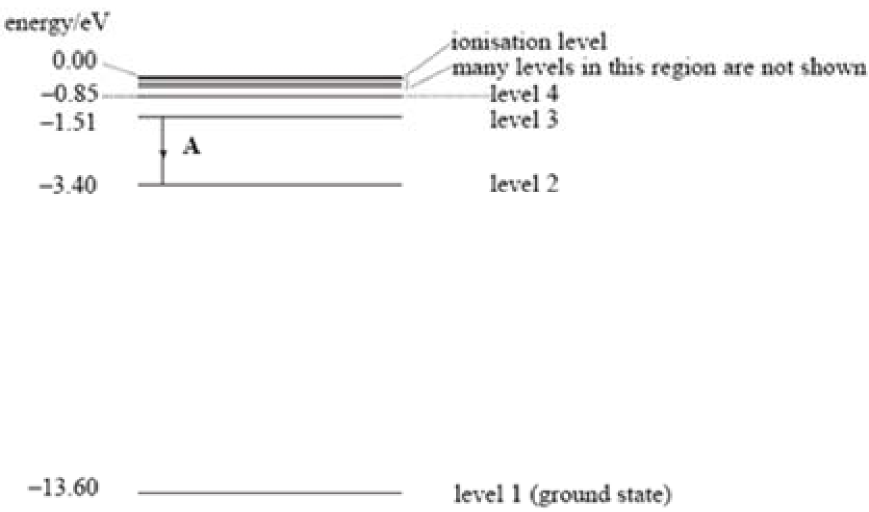


Fig. 23.1

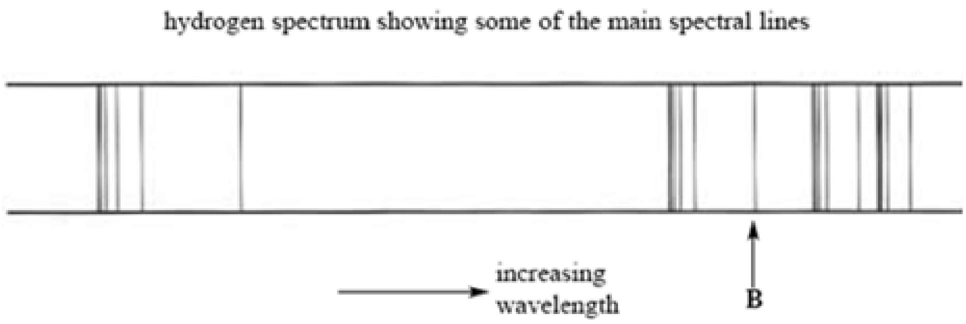


Fig. 23.2

(a) (i) Show that the frequency of spectral line B is about 4.6×10^{14} Hz.

Solution:

The transition from level 3 to level 2 gives the spectral line labeled **B** in **Fig. 23.2**.

That is

$$E_3 - E_2 = -1.51 - (-3.4) = hf$$

$$\Rightarrow f = \frac{-1.51eV - (-3.4eV)}{6.63\times10^{-34}Js} = \frac{1.89\times1.6\times10^{-19}J}{6.63\times10^{-34}Js} = 4.6\times10^{14}Hz$$

(ii) Calculate the wavelength represented by line B.

Solution:

$$\lambda = \frac{c}{f} = \frac{3\times10^{8}}{4.6\times10^{14}} = 6.5\times10^{-7}m$$

(b) The hydrogen atom is excited and its electron moves to level 4.

(i) How many different wavelengths of electromagnetic radiation may be emitted as the atom returns to its ground state?

Answers: 6 wavelengths

(ii) Calculate the energy, in eV, of the longest wavelength of electromagnetic radiation emitted during this process.

Solution: the longest wavelength means the minimum energy

Then by figure 4, we get $-0.85 - (-1.51) = 0.66eV$

(c) In a fluorescent tube, explain how the mercury vapour and the coating of its inner surface contribute to the production of visible light.

You may be awarded additional marks to those shown in brackets for the quality of written communication in your answer.

Answers:

Mercury vapour at low pressure is conducting, the atom of mercury was excited by electron impact, and then de-excitation happens, producing ultraviolet radiation, which is absorbed by the coating, then excitation and de-excitation happens in the atom of the coating, that is, the production of visible light.

24. (a) State what is meant by the duality of electrons. Give one example of each type of behavior.

You may be awarded additional marks to those shown in brackets for the quality of written communication in your answer.

Solution:

Electrons behave as waves and as particles.

Wave nature: diffraction of electrons

Particle nature: electrons can be deflected in the magnetic field.

(b) (i) Calculate the speed of an electron which has a de Broglie wavelength of $1.3\times10^{-10}m$

Solution:

The wave-like behaviour of a matter particle is characterized by a wavelength, its **de Broglie wavelength**, λ, which is related to the momentum, p, of the particle by means of the equation

$$de\ Broglie\ wavelength\ \lambda=\frac{h}{p}=\frac{h}{mv}$$

Where m is mass of particle, v is velocity of the particle.

Thus

$$v=\frac{h}{m\lambda}=\frac{6.63\times10^{-34}Js}{(9.11\times10^{-31}kg)(1.3\times10^{-10}m)}=5.60\times10^{6}m/s$$

(ii) A particle when travelling at the speed calculated in (b) (i) has a de Broglie wavelength of $8.6\times10^{-14}m$.

Solution:

Using the equation $\lambda=\frac{h}{p}=\frac{h}{mv}$, gives

$$m=\frac{h}{\lambda v}=\frac{6.63\times10^{-34}Js}{(8.36\times10^{-14}m)(5.60\times10^{6}m/s)}=1.42\times10^{-27}kg$$

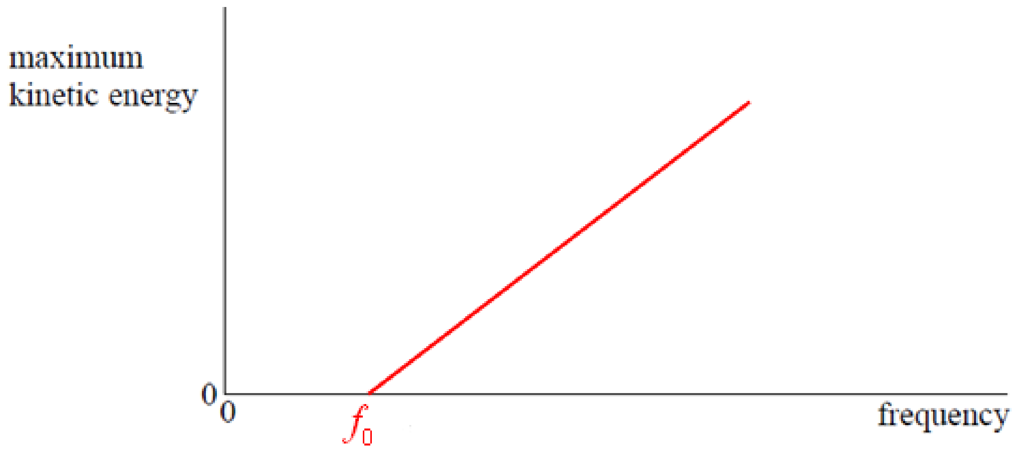
25. (a) (i) In relation to the photoelectric effect explain the meaning of the term threshold frequency.

Solution:

The minimum frequency of electromagnetic radiation required to eject photoelectrons from a metal surface.

(ii) Sketch on the axes a graph of the maximum kinetic energy of photoelectrons against the frequency of the incident electromagnetic radiation. Label the position of the threshold frequency, f_0.

Values are not required on the axes.



Solution:

The maximum kinetic energy of the emitted electrons is given by

$E_{k\max} = hf - \phi$, thus the maximum kinetic energy of photoelectrons against the frequency is a straight line.

So $hf = E_{k\max} + \phi$, where f is the frequency of directed light.

When $E_{k\max} = 0$, work function $\phi = hf$,

Thus the threshold frequency of the metal: $f_0 = \dfrac{\phi}{h}$

(b) The table gives the work function of some metals.

metal	Work function/$10^{-19}\,J$
Caesium	3.0
Lithium	3.7
Beryllium	6.2
Mercury	7.2
tungsten	7.4

(i) Calculate the threshold frequency for caesium.

Solution:

The threshold frequency of the metal:

$$f_0 = \frac{\phi}{h} = \frac{3.0\times10^{-19}\,J}{6.63\times10^{-34}\,Js} = 4.52\times10^{14}\,Hz$$

(ii) A caesium surface is illuminated with electromagnetic radiation of wavelength $3.0\times10^{-7}\,m$. Determine the maximum kinetic energy of the ejected photoelectrons.

Solution:

The maximum kinetic energy of the emitted electrons is given by

$$E_{k\max} = hf - \phi = h\frac{c}{\lambda} - \phi = 6.63\times10^{-34}\,Js \times \frac{3\times10^{8}\,m/s}{3\times10^{-7}\,m} - 3.0\times10^{-19}\,J = 3.63\times10^{-19}\,J$$

(iii) State which metals listed in the table will not emit photoelectrons when illuminated with electromagnetic radiation of wavelength $3.0\times10^{-7}\,m$.

Solution:

Mercury and tungsten will not emit photoelectrons, since their work function is greater than the incident energy ($E = h\frac{c}{\lambda} = 6.63\times10^{-19}\,J$).

26. Fig. 26.1 represents energy levels of the hydrogen atom.

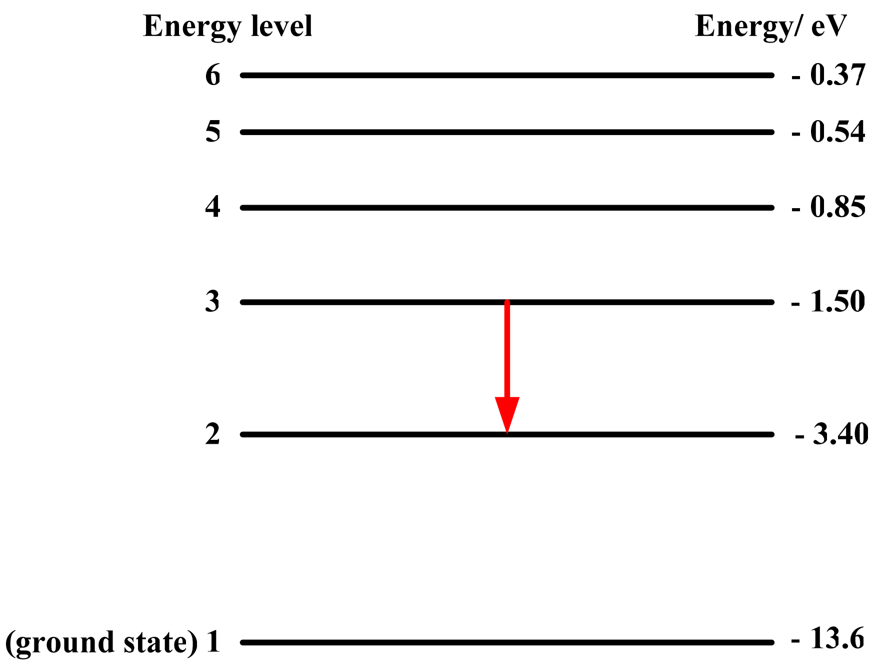


Fig. 26.1

(a) (i) state a similarity in the physical processes of excitation and ionisation.

Solution:

Ionization: any process of creating ions is called ionization.

Excitation: Any process that electrons moved from lower energy level (inner shell) to higher energy level (outer shell) in the atom.

Thus

In both cases an electron gains energy.

(ii) State how these two processes differ from each other.

Solution:

In excitation electrons stay in the atom, whereas in ionization an electron leaves the atom.

(b) (i) One of the emitted spectral lines of hydrogen has a frequency of $4.6\times10^{14}\,Hz$.

Calculate the energy, in eV, of a photon of this frequency.

Solution:

Photon energy is given by

$$E = hf = (6.63\times10^{-34}\,Js)\times4.6\times10^{14}\,Hz = 3.04\times10^{-19}\,J = \frac{3.04\times10^{-19}}{1.60\times10^{-19}}eV = 1.9eV$$

(ii) On the diagram draw an arrow to indicate the transition responsible for this spectral line.

Solution:

Draw the arrow from level 3 to level 2.

(c) An electron in the ground state of a hydrogen atom is struck by a photon. State and explain what happens to the electron, and what happens to the photon, when the energy of the photon is (i) 10 eV and (ii) 20 eV.

You may be awarded additional marks to those shown in brackets for the quality of written communication in your answer.

(i) Photon energy is 10 eV.

(ii) Photon energy is 20 eV.

Solution:

Excitation by: (1) electron collision. (2) Photon absorption.

(1) Electron collision: kinetic energy of the electrons must be greater than or equal to the excitation energy.

(2) Photon absorption: kinetic energy of the photons must be just equal to the excitation energy.

Thus:

(i) Energy of photon remains the same. The electron remains in its ground state.

(ii) Ionization happens. The photon is absorbed; the electron is removed from the atom with kinetic energy of 6.4 eV.

27. (a) Describe and explain the principal features of the spectrum from excited gas atoms.

You may be awarded additional marks to those shown in brackets for the quality of written communication in your answer.

Solution:

Photons are emitted when electrons move down from one level to another. And photons have definite frequency, so photons have discrete energies.
The energy gaps between energy levels are fixed.
(b) The energy levels of atomic hydrogen, in J, are given by the equation:

$$E_n = -\frac{22\times10^{-19}}{n^2}$$

Where n is a whole number corresponding to the energy level. Therefore the ground state, level 1, has energy $E_1 = -22\times10^{-19}\,J$ and level 2 has energy

$$E_2 = -\frac{22\times10^{-19}}{2^2} = -5.5\times10^{-19}\,J$$

A photon is emitted from atomic hydrogen as the atom undergoes a transition from level 4 to level 2.
Calculate
(i) The energy of the emitted photon,
Solution:
The energy of the emitted photon is the energy difference between level 4 and level 2.
And

$$E_4 = -\frac{22\times10^{-19}}{4^2} = -1.375\times10^{-19}\,J$$

Thus, the energy of the emitted photon is

$$\Delta E = E_4 - E_2 = -1.375\times10^{-19}\,J - (-5.5\times10^{-19}\,J) = 4.1\times10^{-19}\,J$$

(ii) The frequency of the photon.
Solution:
The frequency of the photon can be gained by $E = hf$

$$f = \frac{\Delta E}{h} = \frac{4.1\times10^{-19}\,J}{6.63\times10^{-34}\,Js} = 6.2\times10^{14}\,Hz$$

(c) How many different wavelengths of electromagnetic radiation can be emitted after atomic hydrogen is excited to level 4?
Solution:
The transition may be:
Level 4 to level 3. Level 4 to level 2. Level 4 to level 1.
Level 3 to level 2. Level 3 to level 1. Level 2 to level 1.
Thus, it has 6 different wavelengths.

28. (a) Explain the term work function.

Solution:

The work function, ϕ of a metal, which is the minimum energy needed by the conduction electrons to escape from the metal surface

(b) When a clean lithium surface is illuminated with ultraviolet radiation of photon energy $7.9\times10^{-19}J$, photoelectrons of energies up to $4.2\times10^{-19}J$ are emitted.

Calculate

(i) The wavelength of the ultraviolet radiation,

Solution:

Photon energy is given by $E = hf = h\frac{c}{\lambda}$

Thus

$$\lambda = \frac{hc}{E} = \frac{(6.63\times10^{-34}Js)(3\times10^{8}m/s)}{7.9\times10^{-19}J} = 2.5\times10^{-7}m$$

(ii) The work function of lithium, in J,

Solution:

From the equation $E_{k\max} = hf - \phi$, we can get the work function:

$$\phi = hf - E_{k\max} = h\frac{c}{\lambda} - E_{k\max} = 7.9\times10^{-19}J - 4.2\times10^{-19}J = 3.7\times10^{-19}J$$

(iii) The work function of lithium, in eV.

Solution:

$$\phi = \frac{3.7\times10^{-19}}{1.60\times10^{-19}}eV = 2.3eV$$

(c) Describe and explain the effect of increasing the intensity of the incident ultraviolet radiation on the emitted photoelectrons.

You may be awarded additional marks to those shown in brackets for the quality of written communication in your answer.

Solution:

The maximum kinetic energy depends on the frequency of the incident radiation, so the maximum kinetic energy remains unchanged.

But double the intensity means doubling the number of photons per second which doubles the number of photoelectrons per second.

29. When a metal plate is illuminated with electromagnetic radiation of wavelength $1.5\times10^{-7}\,m$, the maximum kinetic energy of the emitted photoelectrons is $1.2\times10^{-19}\,J$.

(a) State what is meant by the *work function* of the metal.

Solution:

(a) The work function, ϕ of a metal, which is the minimum energy needed by the conduction electrons to escape from the metal surface.

(b) (i) Show that the work function of the metal is $1.2\times10^{-18}\,J$.

(ii) Calculate the threshold frequency for the metal.

Solution:

(i) From the equation $E_{k\max} = hf - \phi$, we can get the work function:

$$\phi = hf - E_{k\max} = h\frac{c}{\lambda} - E_{k\max} = (6.63\times10^{-34}\,Js)\cdot\frac{3\times10^{8}\,m/s}{1.5\times10^{-7}\,m} - 1.2\times10^{-19}\,J = 1.2\times10^{-18}\,J$$

(ii) The threshold frequency of the metal:

$$f_0 = \frac{\phi}{h} = \frac{1.2\times10^{-18}\,J}{6.63\times10^{-34}\,Js} = 1.81\times10^{15}\,Hz$$

(c) The wavelength of the incident electromagnetic radiation remains at $1.5\times10^{-7}\,m$ but its intensity is doubled.

State and explain what changes occur, if any, to the maximum kinetic energy of each photoelectron and to the number emitted per second.

You may be awarded additional marks for the quality of written communication in your answer.

Solution:

The maximum kinetic energy depends on the frequency of the incident radiation, so the maximum kinetic energy remains unchanged.

But double the intensity means doubling the number of photons per second which doubles the number of photoelectrons per second.

30. Fig. 30.1 shows five electron energy levels of an isolated atom.

The ground state and the ionisation level are included.

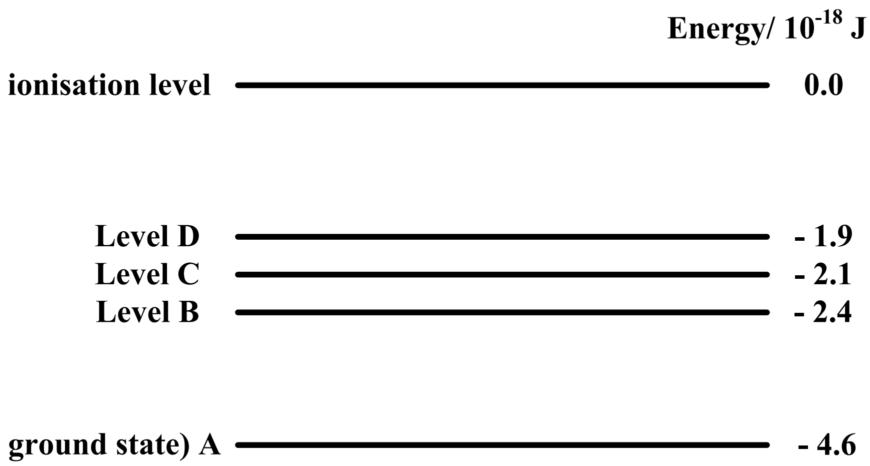


Fig. 30.1

(a) (i) Explain what is meant by ***ionisation***.

Solution:

Ionisation: any process of creating ions is called ionization.

(ii) Ionisation may be caused by electron impact.

Explain how else might an atom be ionised.

(iii) Calculate the ground state energy in eV.

Solution:

(ii) Photon absorption or ionizing radiation.

(iii) $-4.6\times10^{-18}J=-\frac{4.6\times10^{-18}}{1.6\times10^{-19}}eV=-28.75eV$

(b) (i) An electron with kinetic energy $2.6\times10^{-18}J$ collides inelastically with an electron in the ground state.

State which energy levels may be occupied following this collision.

(ii) A photon of energy $2.6\times10^{-18}J$ is incident on an electron in the ground state.

State and explain what would happen.

Solution:

Review:

Excitation can be caused by (i) electron collision. (ii) Photon absorption.

(i) Electron collision: kinetic energy of the electrons must be greater than or equal to the excitation energy.

(ii) Photon absorption: kinetic energy of the photons must be just equal to the excitation energy.

So

(i) B and C energy levels may be occupied following the electron collision.

(ii) Nothing would be absorbed, as the photons may lose all their energy but cannot lose part of their energy.

(c) After a separate excitation process, level D is occupied.

Calculate the longest possible wavelength of electromagnetic radiation emitted as the atom de-excites.

Solution:

The longest possible wavelength of electromagnetic radiation emitted means that minimum change in de-excitation energy. Thus the electrons de-excite from level D to level C.

And $\Delta E = hf = h\dfrac{c}{\lambda}$

$$\lambda = \frac{hc}{\Delta E} = \frac{(6.63\times10^{-34}\,Js)(3\times10^{8}\,m/s)}{-1.9\times10^{-18}\,J-(-2.1\times10^{-18}\,J)} = 9.9\times10^{-7}\,m$$

31. The tube in a fluorescent lamp contains mercury vapour at low pressure. When connected to a suitable power supply the lamp emits light.

You may be awarded additional marks to those shown in brackets for the quality of written communication in your answer to this question.

(i) Describe what happens in the fluorescent tube to excite the mercury atoms.

(ii) What is emitted from the mercury atoms when they de-excite?

(iii) Describe the purpose of the coating on the inside surface of the fluorescent tube.

Answers:

The fluorescent tube is a glass tube with a fluorescent coating on its inner surface. The tube contains mercury vapour at low pressure. When the tube is on, it emits visible light because:

i : Ionization and excitation of the mercury atoms occurs as they collide with each other and with electrons in the tube.

ii : The mercury atoms emit ultraviolet photons, as well as visible photons and photons of much less energy when they de-excite.

iii: The ultraviolet photons are absorbed by the atoms of the fluorescent coating, causing excitation of the atoms.

iv: The coating atoms de-excite and emit visible photons.

32. (a) (i) State what is meant by the dual nature of electrons.

(a) (ii) Give one example of each type of behaviour of electrons.

Solutions:

(i) The electrons behave like particles and like waves.

(ii) Evidence of particle-like nature of electrons: electrons can be deflected in the magnetic field.

Evidence of wave-like nature of electrons: diffraction of electrons.

(b) (i) Calculate the speed of an electron whose de Broglie wavelength is $1.50\times10^{-6}m$.

(b) (ii) Calculate the momentum of a proton that would have the same de Broglie wavelength as the electron in part (b)(i).

(b) (iii) Explain why electrons in part (b)(i) cannot be diffracted significantly by a crystal in which the atomic spacing is $1.0\times10^{-10}m$.

Solutions:

(i) $de\ Broglie\ wavelength\ \lambda = \frac{h}{p} = \frac{h}{mv}$

Thus

$$v = \frac{h}{m\lambda} = \frac{6.63\times10^{-34}}{9.11\times10^{-31}\times1.50\times10^{-6}} = 485m/s$$

(ii) The momentum of the proton p is given by

$$p = \frac{h}{\lambda} = \frac{6.63\times10^{-34}}{1.50\times10^{-6}} = 4.42\times10^{-28}kg\cdot m/s$$

(iii) Because the diffraction occurs when the wavelength is of similar size to the separation. And the wavelength of the electron is much larger than the separation.

33. Fig. 33.1 shows part of an energy level diagram for a hydrogen atom.

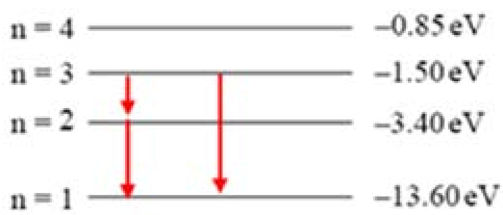


Fig. 33.1

(a) The level, n = 1, is the ground state of the atom. State the ionisation energy of the atom in eV.

Solution:

Ionization: any process of creating ions is called ionization.

Ionization energy: the energy needed for ionization.

Thus the energy (Ionization energy) for the electrons in level 1 to escape is given by

$$E = 0 - (-13.6eV) = 13.6eV$$

(b) When an electron of energy 12.1 eV collides with the atom, photons of three different energies are emitted.

(b) (i) On Figure 1 show with arrows the transitions responsible for these photons.

Solution:

The energy needed for electrons in level 1 excite to level 3 is $E = -1.50 - (-13.6eV) = 12.1eV$, which equals collision energy of the electron. And then de-excitation happens.

Therefore, de-excitation: level 3 to level 1, level 3 to level 2, level 2 to level 1.

1 (b) (ii) Calculate the wavelength of the photon with the smallest energy. Give your answer to an appropriate number of significant figures.

Solution:

The smallest energy is given by

$$E = -1.50 - (-3.40eV) = 1.9eV$$

And the photon energy is given by

$$E = hf = h\frac{c}{\lambda} = 1.9eV = 1.9 \times 1.60 \times 10^{-19} J = 3.04 \times 10^{-19} J$$

Gives

$$\lambda = \frac{hc}{E} = \frac{(6.63 \times 10^{-34} Js)(3 \times 10^{8} ms^{-1})}{3.04 \times 10^{-19} J} = 6.5 \times 10^{-7} m$$

34. When light of a certain frequency is shone on a particular metal surface, electrons are emitted with a range of kinetic energies.

(a) Explain

• In terms of photons why electrons are released from the metal surface, and

• Why the kinetic energy of the emitted electrons varies up to a maximum value.

The quality of your written communication will be assessed in this question.

Solution:

Einstein's explanation of photoelectricity:

i : light is composed of wave packets or photons, each photon of energy is equal to hf, where f is frequency, $h = 6.63\times10^{-34}\,Js$ is Planck constant,. So the intensity of light depends on the number of photons; and the energy of each photon depends only on the frequency.

$$energy\ of\ a\ photon = hf = h\frac{c}{\lambda}$$

Where c is speed of light, λ is wavelength of light.

Note: photon energy is proportional to frequency, inversely proportional to wavelength.

ii : An electron can leave the metal surface if the energy gained from a single photon exceeds the work function, ϕ of the metal, which is the minimum energy needed by the conduction electrons to escape from the metal surface.

Hence the maximum kinetic energy of the emitted electrons

$$E_{k\max} = hf - \phi$$

So $hf = E_{k\max} + \phi$, where f is the frequency of directed light.

$E_{k\max} = 0$, work function $\phi = hf$,

Thus the threshold frequency of the metal:

$$f_0 = \frac{\phi}{h}$$

Conditions for photoelectricity emission:

$$E_{k\max} > 0 \quad or \quad hf > \phi = hf_0$$

Where f is the frequency of directed light, f_0 is the threshold frequency.

(b) The graph below (**Fig. 34.1**) shows how the maximum kinetic energy of the electrons varies with the frequency of the light shining on the metal surface.

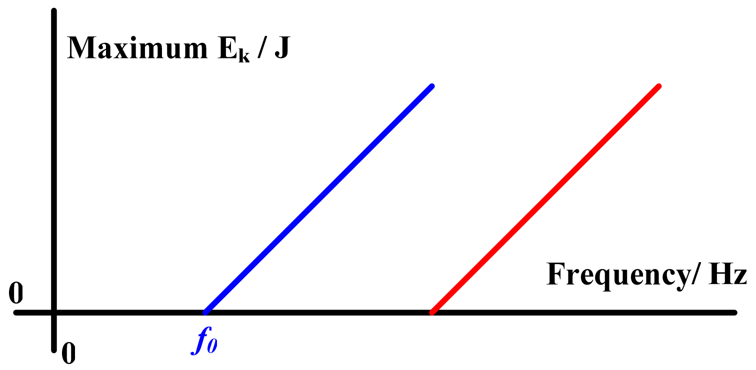


Fig. 34.1

(b) (i) On the graph mark the ***threshold frequency*** and label it f_0.

Solution:

When $E_{k\max} = 0$, work function $\phi = hf$,

Thus the threshold frequency of the metal:

$$f_0 = \frac{\phi}{h}$$

(b) (ii) On the graph draw a line for a metal which has a higher threshold frequency.

Solution:

The maximum kinetic energy of the emitted electrons is given by

$E_{k\max} = hf - \phi$, and the threshold frequency is higher now.

Therefore, it is a parallel line with higher threshold frequency.

(b) (iii) State what is represented by the gradient of the graph.

Solution:

The maximum kinetic energy of the emitted electrons is given by

$E_{k\max} = hf - \phi$

Thus, the gradient represents the Planck constant $h = 6.63\times10^{-34}\,Js$.

(c) The threshold frequency of a particular metal surface is $5.6\times10^{14}\,Hz$. Calculate the maximum kinetic energy of emitted electrons if the frequency of the light striking the metal surface is double the threshold frequency.

Solution:

The threshold frequency $f_0 = 5.6\times10^{14}\,Hz$, thus work function is given by

$\phi = hf_0 = 6.63\times10^{-34}\times5.6\times10^{14} = 3.7\times10^{-19}\,J$

The frequency of incident light $f = 2f_0 = 2\times5.6\times10^{14}\,Hz$

Thus

$E_{k\max} = hf - \phi = 6.63\times10^{-34}\times2\times5.6\times10^{14} - 3.7\times10^{-19} = 3.7\times10^{-19}\,J$

35. (a) State what is meant by the wave-particle duality of electrons.

Solution:

Electrons can have wavelike properties and particle like properties.

(b) Electrons of wavelength $1.2\times10^{-10}\,m$ are required to investigate the spacing between planes of atoms in a crystal.

(b) (i) Calculate the momentum of an electron of this wavelength stating an appropriate unit.

Solution:

The wave-like behaviour of a matter particle is characterized by a wavelength, its **de Broglie wavelength**, λ, which is related to the momentum, p, of the particle by means of the equation

$$de\ Broglie\ wavelength\ \lambda = \frac{h}{p} = \frac{h}{mv}$$

Where m is mass of particle, v is velocity of the particle.

Thus,

The momentum is given by

$$p = \frac{h}{\lambda} = \frac{6.63\times10^{-34}}{1.2\times10^{-10}} = 5.53\times10^{-24}\,kg\cdot m/s$$

(b) (ii) Calculate the speed of such an electron.

Solution:

Momentum $p = mv$, gives

$$v = \frac{p}{m} = \frac{5.53\times10^{-24}\,kg\cdot m/s}{9.11\times10^{-31}\,kg} = 6.0\times10^{6}\,m/s$$

(b) (iii) Calculate the kinetic energy of such an electron.

Solution:

Kinetic energy $E_k = \frac{1}{2}mv^2 = \frac{1}{2}\times9.11\times10^{-31}\times\left(6.0\times10^{6}\right)^2 = 1.64\times10^{-17}\,J$

36. Electrons with a range of kinetic energies strike atoms of a particular element which are in their ground state. As a result of these collisions photons of various frequencies are emitted by some of the atoms.

(a) Explain what is meant by the ground state of an atom and describe the process that is taking place in the atoms emitting photons.
The quality of your written communication will be assessed in this question.
Solution:
Ground state: Electron in atoms can only occupy certain energy levels, and the ground state is the lowest energy state an electron can occupy.
Process:
Electrons collide with orbital electrons, giving the electrons the energy necessary to move to a higher energy level (Excitation), electrons later return to a lower level emitting photons (de-excitation). And the photon energy is given by $E = hf$, where $h = 6.63\times10^{-34}\ Js$ is Planck constant.
(b) The table below shows how the kinetic energies of electrons with different incident energies may change after collisions with atoms.

	Kinetic energy of electron before collision/eV	Kinetic energy of electron after collision/eV
First electron	5.5	5.5
Second electron	9.0	1.0

(b) (i) Explain why one of the electrons loses energy while the other does not.
Solution:
Review:
Excitation: Any process that electrons moved from lower energy level (inner shell) to higher energy level (outer shell) in the atom.
Excitation energy: the energy absorbed by the atom for excitation.
Excitation by: (1) electron collision. (2) Photon absorption.
(1) Electron collision: kinetic energy of the electrons must be greater than or equal to the excitation energy.
(2) Photon absorption: kinetic energy of the photons must be just equal to the excitation energy.
De-excite (de-excitation): electrons in the atom moved from the higher energy level to lower energy level, emitting photons.
Therefore,
The 5.5 eV electron does not have enough energy to excite an orbital electron.
The 9.0 eV electron provide enough energy to excite an orbital electron.
(b) (ii) Convert the energy of 9.0 eV into joules

Solution:

Review:

$1eV = 1.60 \times 10^{-19} J$

$1MeV = 1.60 \times 10^{-13} J$

Therefore,

$9.0eV = 9.0 \times 1.60 \times 10^{-19} J = 1.44 \times 10^{-18} J$

(b) (iii) Calculate the **maximum** frequency of the photon emitted when the 9.0 eV electron collides with an atom.

Solution:

The maximum kinetic energy lost by the electron is given by

$\Delta E_k = 9.0eV - 1.0eV = 8.0eV = 8.0 \times 1.60 \times 10^{-19} J = 1.28 \times 10^{-18} J$

And the lost kinetic energy is totally converted to photon energy, thus photon energy $E = \Delta E_k = 1.28 \times 10^{-18} J$

And photon energy $E = hf$, gives

$$f = \frac{E}{h} = \frac{1.28 \times 10^{-18} J}{6.63 \times 10^{-34} Js} = 1.9 \times 10^{15} Hz$$

37. When monochromatic light is shone on a clean metal surface, electrons are emitted from the surface due to the photoelectric effect.

(a) State and explain the effect on the emitted electrons of

(a) (i) increasing the frequency of the light,

Solution:

The maximum kinetic energy of released electrons increases, this is because increasing the frequency of the photons increases their energy.

(a) (ii) increasing the intensity of the light.

Solution:

The number of electrons emitted per second increases, because there are now more photons striking the metal surface per second.

(b) The wave model was once an accepted explanation for the nature of light. It was rejected when validated evidence was used to support a particle model of the nature of light. Explain what is meant by ***validated evidence***.

Solution:

Experiment needs to be performed to test a theory, and the results of the experiment need to be proved.

(c) The threshold frequency of lithium is $5.5\times10^{14}\,Hz$.

(c) (i) Calculate the work function of lithium, stating an appropriate unit,

Solution:

Review:

The maximum kinetic energy of the emitted electrons

$$E_{k\max} = hf - \phi$$

So, $hf = E_{k\max} + \phi$, where f is the frequency of directed light.

$E_{k\max} = 0$, work function $\phi = hf$,

Thus the threshold frequency of the metal:

$$f_0 = \frac{\phi}{h}$$

Therefore,

Work function $\phi = hf = 6.63\times10^{-34}\,Js\times5.5\times10^{14}\,Hz = 3.65\times10^{-19}\,J$

(c) (ii) Calculate the maximum kinetic energy of the emitted electrons when light of frequency $6.2\times10^{14}\,Hz$ is incident on the surface of a sample of lithium.

Solution:

$$E_{k\max} = hf - \phi = 6.63\times10^{-34}\times6.2\times10^{14} - 3.65\times10^{-19} = 4.6\times10^{-20}\,J$$

38. (a) A fluorescent tube is filled with mercury vapour at low pressure. In order to emit electromagnetic radiation the mercury atoms must first be excited.

(a) (i) What is meant by an excited atom?

Solution:

Excitation: Any process that electrons moved from lower energy level (inner shell) to higher energy level (outer shell) in the atom.

Note:

Excitation energy: the energy absorbed by the atom for excitation.

Excitation by: (1) electron collision. (2) Photon absorption.

(1) Electron collision: kinetic energy of the electrons must be greater than or equal to the excitation energy.

(2) Photon absorption: kinetic energy of the photons must be just equal to the excitation energy.

(a) (ii) Describe the process by which mercury atoms become excited in a fluorescent tube.

(a) (iii) What is the purpose of the coating on the inside surface of the glass in a fluorescent tube?

Solution:

The fluorescent tube is a glass tube with a fluorescent coating on its inner surface. The tube contains mercury vapour at low pressure. When the tube is on, it emits visible light because:

i : Ionization and excitation of the mercury atoms occurs as they collide with each other and with electrons in the tube.

ii : The mercury atoms emit ultraviolet photons, as well as visible photons and photons of much less energy when they de-excite.

iii: The ultraviolet photons are absorbed by the atoms of the fluorescent coating, causing excitation of the atoms.

iv: The coating atoms de-excite and emit visible photons.

(b) The lowest energy levels of a mercury atom are shown in **Fig. 38.1**. The diagram is not to scale.

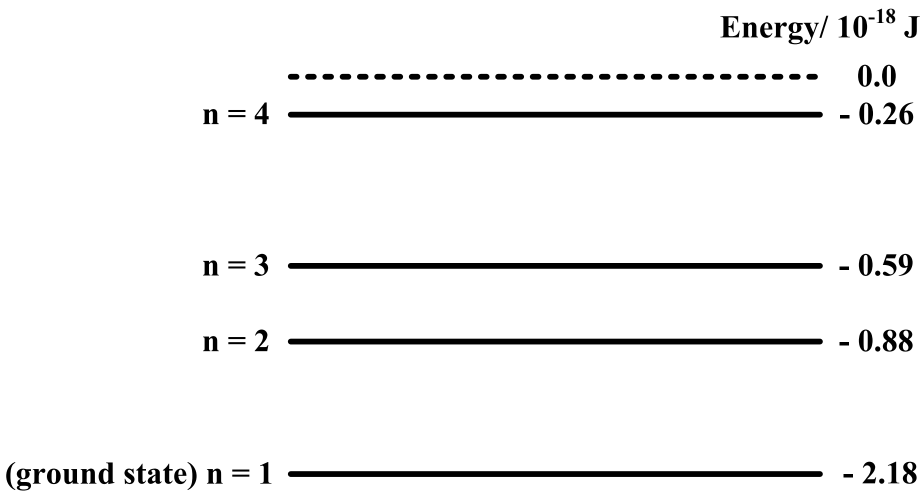


Fig. 38.1

(b) (i) Calculate the frequency of an emitted photon due to the transition level n = 4 to level n = 3.

Solution:

The photon energy released from level 4 to level 3 is given by

$E = -0.26\times10^{-18} - (-0.59\times10^{-18}) = 0.33\times10^{-18}\,J$

And it can use the equation $E = hf$ to find the frequency of the photon:

$f = \frac{E}{h} = \frac{0.33\times10^{-18}\,J}{6.63\times10^{-34}\,Js} = 5.0\times10^{14}\,Hz$

(b) (ii) Draw an arrow on the Figure 1 to show a transition which emits a photon of a longer wavelength than that emitted in the transition from level n = 4 to level n = 3.

Solution:

A longer wavelength means the lower photon energy released, thus it is from level 3 to level 2.

39. (a) Experiments based on the photoelectric effect support the particle nature of light. In such experiments light is directed at a metal surface.

(a) (i) State what is meant by the threshold frequency of the incident light.

Solution:

The threshold frequency is the minimum frequency for the electrons to overcome work function of a metal.

(a) (ii) Explain why the photoelectric effect is not observed below the threshold frequency.

Solution:

Below the threshold frequency does not have enough energy to liberate an electron as the energy of a photon depends on frequency.

(b) Monochromatic light of wavelength $5.40\times10^{-7}\,m$ is incident on a metal surface which has a work function of $1.40\times10^{-19}\,J$.

(b) (i) Calculate the energy of a single photon of this light.

Solution:

Photon energy:

$E = hf = h\frac{c}{\lambda} = (6.63\times10^{-34}\,Js)\times\frac{3\times10^{8}\,m/s}{5.4\times10^{-7}\,m} = 3.68\times10^{-19}\,J$

(b) (ii) Calculate the maximum kinetic energy of an electron emitted from the surface.

Solution:

The maximum kinetic energy of the emitted electrons is given by

$E_{k\max} = hf - \phi = 3.68\times10^{-19}\,J - 1.40\times10^{-19}\,J = 2.28\times10^{-19}\,J$

(b) (iii) Calculate the maximum speed of the emitted electron.

Solution: