Topic 7 – Atomic and Nuclear Physics

Atomic Structure

Nuclear Model

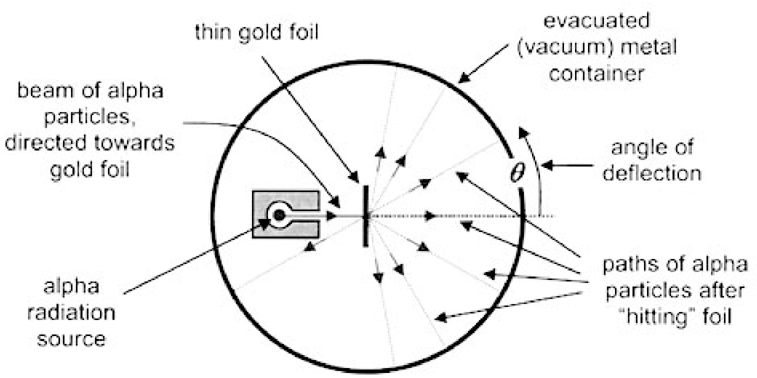
The currently accepted model of the atom is that it is spherical and composed of a central, very small and dense nucleus that is surrounded by "shells" of electrons, orbiting the nucleus.

The nucleus contains protons (positively charged) and neutrons (no charge – neutral), of approximately equal mass. The electrons are negative and are therefore attracted to the positively charged nucleus. This attraction, together with the momentum of the electrons, causes the electrons to orbit the nucleus in the same way that planets orbit stars. Electrons are virtually massless, and are considered to occupy no volume.

Evidence for this model was first provided by Geiger and Marsden, in the early 20th century.

Rutherford's/Geiger & Marsden's Alpha scattering Experiment

Experimental:



Note: *Alpha particles are helium nuclei (He^{2+}), which are very small, positively charged particles.*

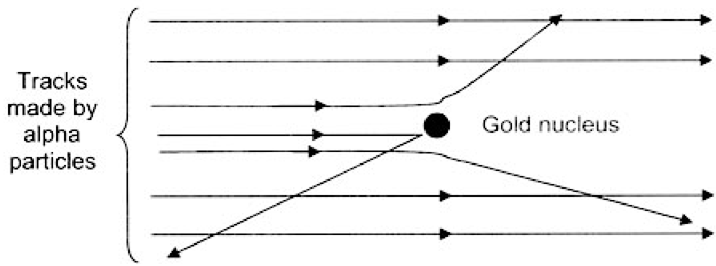
Results:

1. most particles passed straight through the foil, with no significant deflection
2. about 1 in 1800 particles was deflected by angles between 0° and 90°
3. about 1 in 8000 particles "bounced" backwards, at an angle greater than 90°

Explanation of results

1. given that the foil was around 400 layers of gold atoms thick, from result 1 above, it was concluded that the atom must be composed mostly of space (calculations show that an atom is about 10,000 times larger than its nucleus: atomic diameter $\approx 10^{-10}\ \boldsymbol{m}$, nuclear diameter $\approx 10^{-14}\ \boldsymbol{m}$)
2. these deflections were attributed to the fact that the gold nuclei are positive, and so are the alpha particles – so, when an alpha particle passes close to a gold nucleus (not very often, due to 1, above) it is repelled, and deflected. The amount by which it is deflected depends on how close it passes by the gold nucleus.
3. These deflections were explained by the fact that in a very few cases, the alpha particle actually collides with a gold nucleus, and therefore bounces back.

These observations and explanations can be summarized using the following diagram (which is worth drawing in most exam questions referring to this experiment)



Follow up calculations:

Size of atom: $\approx 10^{-10}\ \boldsymbol{m}$

Size of nucleus $\approx 10^{-14}\ \boldsymbol{m}$

Limitation of the model of the atom as a small nucleus surrounded by orbiting electrons

The model does not account for how the protons and neutrons stay together in the nucleus: at such short ranges the protons should repel each other enormously and fly apart.

Atomic Energy Levels

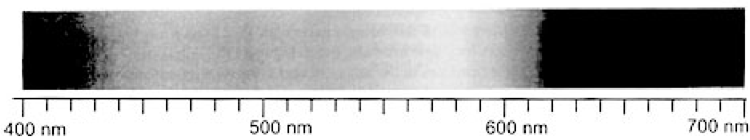
It is now accepted that electrons occupy "shells" surrounding the nucleus. Each shell corresponds to a certain energy level that the electrons occupying the shell have. An energy level of zero corresponds to the electron escaping from the atom. Electrons "attached" to an atom have energy levels with negative values. The further away the electron from the nucleus, the higher the energy level. Thus, to promote an electron from one shell to a shell further from the nucleus, i.e. to move it from one energy level to a higher energy level, energy must be put in. Conversely, if an electron relaxes back, dropping to a lower energy level, energy is released.

Atomic emission and absorption spectra provide us with experimental evidence for these atomic energy levels.

Emission Spectra:

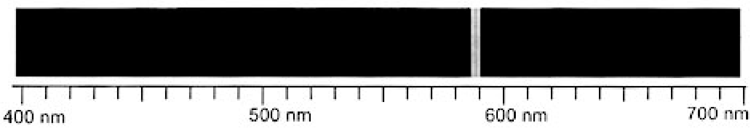
When certain substances are excited by some external source of energy, e.g. heat, light or electricity, they can become illuminated. For example, Neon tubes glow when stimulated by electricity. Sodium lamps appear yellow. An emission spectrum is a spectrum showing wavelengths (and frequencies) of light emitted. The light emitted is usually split up (dispersed) using a prism or diffraction grating.

When tungsten is heated strongly it emits a white light. White light consists of a continuous spectrum of all the colours in the visible spectrum (red, orange, yellow, etc). So if the light from a tungsten filament is dispersed using a prism and viewed on a screen, the following is observed:

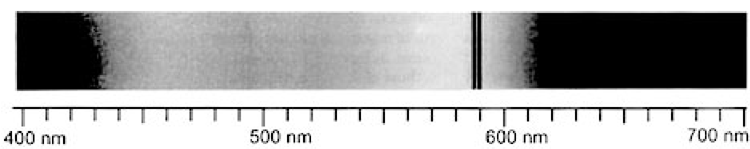


The scale shows the how the wavelength of light varies with colour.

Sodium vapour in a gas discharge tube (vapour is excited by high voltage) results in the following emission spectrum:



If white light is shone through sodium vapour, the following absorption spectrum results:



The last two spectra above are called line spectra, because lines of light are emitted or absorbed. It is no coincidence that the lines for the two spectra above correspond to the same wavelengths – it is because they originate from the same energy level jump in the same atom. The wavelength is the wavelength of light emitted or absorbed when electrons jump from one particular energy level to another. If they jump to a higher level, they absorb the light; if they jump to a lower level they emit light (there are many other, less distinct and bright lines for sodium corresponding to jumps to and from different energy levels)

Different elements have different energy levels corresponding to particular "shells" and require different amounts of energy to jump from one level to the next. Therefore line spectra provide a very accurate way of identifying the presence of a minute amount of a particular element in a sample.

Photons

Experimentation shows that light behaves not only as a wave-like energy, but also as a particle beam. A particle of light is called a photon. In an emission line spectrum, for example, like the one shown above, only light photons with the exact same energy as the energy involved in the electron jump will be emitted. The energy of a photon depends on the frequency of light, and the colour of light depends on the frequency, so a line with a certain colour will be emitted.

Energy of a photon

The energy of a photon depends on the frequency (and, therefore wavelength). The higher the frequency (lower the wavelength) the greater the photon-energy.

Equation: $E = hf$ where

$$E = photon\ energy\ (J)$$
$$h = Planck's\ constant\ (6.63\times10^{-34}\ Js)$$
$$f = frequency\ of\ light\ (Hz)$$

Nuclear Structure

As stated earlier, an atom is made up of a central nucleus and surrounding electrons. The nucleus is composed of protons and neutrons.

- The number of protons is called the atomic number (sometimes also called proton number)
- Nucleons is the collective term for protons and/or neutrons. So the number of nucleons in an atom is the total number (sum) of protons and neutrons.
- The number of nucleons (protons + neutrons) is called the mass number (also sometimes called the nucleon number)
- A nuclide refers to an atom with a particular nucleus configuration – referring simply to an atom is ambiguous because it could be one of two or more possible isotopes. It is common to refer to nuclides using their chemical symbol followed by their mass number. For example the nuclide with 53 protons and 74 neutrons is I-127 (Iodine 127).

General Symbol of the nuclide:

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

$$X = the\ element$$
$$A = nucleon\ number\ (protons + neutrons)$$
$$Z = protons$$

So neutron number N is equal to $A - Z$

Elements are defined by their atomic number. For any particular element, the atomic number does not change (for example, it is possible for an atom of the element oxygen to have 8 electrons or 10 electrons and it is possible for an atom of oxygen to have 8 neutrons, 9 neutrons or 10 neutrons, but, to be an oxygen atom, it must have 8 protons. An oxygen atom is defined to be an atom of the element with atomic number 8.

Some atoms of the same element have different masses. This mass difference is attributed to the fact that they contain different numbers of neutrons.

Atoms with the same atomic number (i.e. atoms of the same element) but different mass numbers are called isotopes. Two different isotopes of the same element therefore are different because they contain different numbers of neutrons.

Example T7.1

Uranium is an element with chemical symbol U, and it has an atomic number of 92. Two common isotopes of uranium have 145 and 146 neutrons in their nuclei.

(a) Name the two nuclides in this example
(b) For the nuclide with the greatest atomic mass, state its atomic mass, and nucleon number and how many protons and neutrons it has

Nuclear Forces

It may seem surprising that a nucleus stays together, given that it is composed only of positive and neutral particles. To understand why this is so, it is necessary to outline the forces that exist in a nucleus. Three types of force exist in a nucleus:

Gravitational force – an attractive force between particles with masses. Very weak compared to the other two

Electrical force – the repulsive force that the protons exert on each other. This force is immense compared to the gravitational force of attraction and would, without the existence of another attractive force, cause the nucleus to fly apart

Strong force – simply called "strong force" or "strong nuclear force" this force is about 100 times as strong as the electrical force in the nucleus. Unlike the electrical and gravitational forces, it has a very short range, reaching only as far as from one nucleon to its neighbour.

Radioactive Decay

Chemical reactions involve the electrons within an atom. The nuclei of the atoms taking part in chemical reactions never change.
Nuclear reactions, however, involve one or more nucleus changing.

Some nuclei are more stable than others. When an unstable nucleus disintegrates (breaks apart) to acquire a more stable state, radiations are emitted. This phenomenon is called radioactivity or radioactive decay. This reaction is spontaneous and most commonly involves the emission of an alpha particle (α particle) or beta particle (β particle).

In both α emission and β emission the parent nucleus undergoes a change of atomic number and therefore becomes the nucleus of a different element. This new nucleus is called the daughter nucleus or the decay product. It often happens that the daughter nucleus is in an excited state when it is formed, in which case it reaches its ground state by emitting a third type of radiation called a gamma ray (γ ray)

Beta decay: the antineutrino

When a nuclide undergoes beta decay two particles are observed products of the reaction: the daughter nucleus and the β^- particle.

In such reactions, the β^- particles emitted have a range of energies, up to a certain maximum energy.

Based on these observations alone, this should not be possible: if the daughter nuclide has a certain energy, the β^- particle should then take the remainder of the energy and all beta particles, therefore, should have the same energy, corresponding to the maximum β^- particle energy actually observed.

The observations, then, leave us to question where the missing energy has gone. This question was answered very recently. There is in fact a third particle emitted in β^- decay reactions: the antineutrino ($\bar{\nu}$).

Example: The β^- decay of chlorine-36:

First suggestion: $^{36}_{17}Cl \longrightarrow {}^{36}_{18}Ar + {}^{0}_{-1}\beta$

This reaction is balanced in terms of mass and proton number. However, as discussed, the β^- particles have a range of energies up to a certain maximum value, rather than all having the expected maximum value.

The correct reaction is thus: $^{36}_{17}Cl \longrightarrow {}^{36}_{18}Ar + {}^{0}_{-1}\beta + \bar{\nu}$

Properties of the Radiations

Property	α-particle	β-particle	γ-ray
Symbol	$^{4}_{2}\alpha$	$^{0}_{-1}\beta$	γ **or** $^{0}_{0}\gamma$
Production	loss of 2p+2n from Parent	Parent n → p+e (e emitted)	daughter nucleus relaxes → energy
Nature	Helium nucleus	Fast electron	EMR
Charge	+2e	-e	0
Rest Mass	4.0015u	.00055u	0
Velocity	≈ .06c	Up to 0.98c	c
Energy	≈ 6MeV	≈1 MeV	≈ 0.1MeV
Ionization power	≈ 10^5	10^3	10
Path through matter	straight	tortuous – (not at all straight!)	Straight
Deflection by a magnetic field	deflected	deflected strongly	not deflected
Penetration	≈ 5cm air	≈ 500cm air ≈ 0.1cm aluminium	≈ 4cm of lead reduces intensity to 10%

Note c = speed of light   EMR = Electro-Magnetic-Radiation

Ionizing properties of radiation

These radiations are able to ionize matter as they pass through it. They do this by knocking electrons off of atoms in the matter through which they pass. α-particles are so strongly ionizing because they are not only charged, but they also are quite massive – certainly compared to electrons (β-particles) and γ-rays.

The ability for these radiations to ionize matter makes it possible to detect them. The ionization chamber (cloud chamber) contains a gas that when ionized shows causes condensation of a vapour also contained in the chamber – so when radiation passes through it the tracks can be seen, rather like miniature clouds as left behind an aeroplane flying through the air.

The Geiger-Muller tube (GM tube) also relies on the ionization of a gas in an electric field, connected to a high voltage circuit. The ions so created move, effectively completing the circuit and allow current to flow in the circuit. The current created works an electronic counter, connected to the circuit. A GM tube is therefore a good means of measuring the level of radiation emitted from a radioactive sample.

Biological Effects of Ionising Radiation

When an ionising radiation is exposed to animal tissue, electrons can be knocked off tissue cells. This can cause atoms to be broken off of molecules. The structure of cells can thus be changed. This can then result in abnormal functioning of the cell (for example zero reproduction, or uncontrolled reproduction of the cell – cancer) or cell death.

Examples of radiation damage include: skin burns, ulceration, sterility, cataracts, cancer, decreased life expectancy.

Stability of Nuclei

The stability of a nucleus depends on the number of protons compared to neutrons. Iron-56 is one of the most stable nuclei. Nuclei lighter than iron-56 therefore tend to increase their stability by increasing in mass (i.e. undergoing nuclear fusion reactions) and those heavier than iron-56 tend to split apart, undergoing fission. Note that in both cases net energy is released, but a large amount of energy is often required to initiate the reaction – particularly in fusion reactions.

Radioactive nuclei disintegrate spontaneously; the process cannot be speeded up or slowed down. It follows that for large numbers of any particular species of nuclei the rate of decay is proportional to the number of parent nuclei present. (the parent nucleus is the original nucleus, before the nuclear reaction and the (one or more) nucleus produced is called the daughter nucleus or decay product(s)).

It is impossible to predict when any particular nucleus will disintegrate, but it is possible to say what proportion of a large number of nuclei will disintegrate at any given time.

For any particular nuclide, radioactive life = infinity

Half-Life

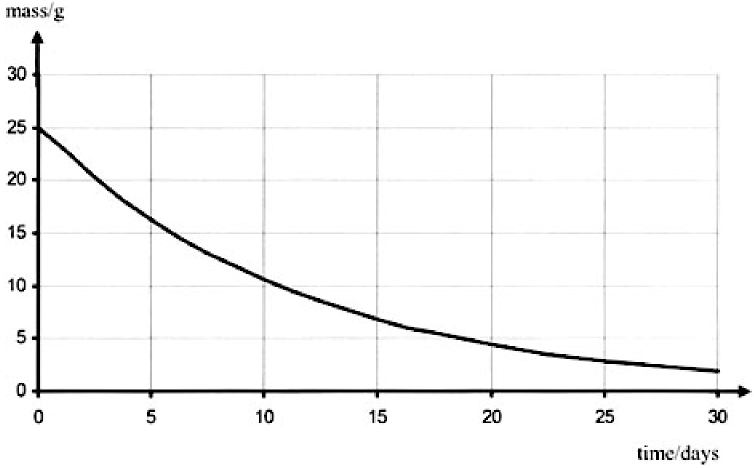
The half life of a radioactive substance is the time taken for the number (or mass) of radioactive nuclei present to fall to half its value. This length of time is constant at any point in time – showing that radioactive decay is exponential.

Example T7.2

The half-life of a certain radioactive material is 6 minutes. What fraction of a sample of the material will decay in half an hour?

Example T7.3

The following decay shows how the mass of a particular radioactive sample varies with time. Use the graph to find the half-life of the sample.



Note that to find the half-life from a decay curve, the time taken for the mass or activity of the sample to half is found – ANY starting point can be used. For example, try finding the time taken for the mass of the above sample to decrease from 10g to 5g – you should get the same answer, 8 days (approximately).

Radioactive decay curves such as the one above show exponential decay – the quantity reduces to half its value in constant time.

Nuclear Reactions

Artificial Transmutation

This is the name given to the process whereby a nucleus is artificially made from another nucleus (or nuclei). It is different from regular radioactivity, or radioactive decay, in that the reaction is not spontaneous; it is made to happen (hence artificial). It was discovered in 1918 (by Rutherford) in the following experiment:

When nitrogen gas was bombarded by α-particles it was found that there were two products: oxygen gas and positively charged particles, which were lighter than α-particles.

It was proposed and later proved that the second product consisted of protons.

Thus: $${}^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}P$$

This experiment was famous since it was responsible for the discovery of the proton as part of the nucleus (and for the discovery of artificial transmutation!)

Balancing Nuclear Reaction Equations

Balancing chemical reactions involves balancing the number of each type of atom (element) on the left and right hand side of the equation.
However, with nuclear reactions elements can change but the total mass (i.e. all mass numbers added up) and total atomic number are the same on both sides of the equation.

Example T7.4

In the following decay reaction, find the values of ***a,b,c,d,e,f***.

$$ {}^{a}_{b}Po \rightarrow {}^{c}_{d}\alpha + {}^{206}_{82}Pb + {}^{e}_{f}\gamma $$

Example T7.5

Complete the following nuclear reactions by adding in any mass or proton numbers and any other products.

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

b) ${}^{14}_{6}C \rightarrow {}^{14}_{7}N +$

c) $$\begin{array}{lll} {}^{60}_{27}Co \rightarrow & Ni^{*} & + \ \beta \\ & \downarrow & \\ & Ni & + \ \gamma \end{array}$$

Unified Mass Unit

In chemistry, masses of nucleons are expressed in atomic mass units. In physics, we need to be more precise (for example, we shall see that protons and neutrons have slightly different masses) and to use S.I. units for mass. Nucleons are therefore measured in terms of the unified mass unit, u, as follows:

$$\left.\begin{array}{l} 1u = 1.661\times10^{-27}\,\text{kg} \\ \text{mass of an electron, } m_e = 0.000549u \\ \text{mass of a proton, } m_p = 1.007276u \\ \text{mass of a neutron, } m_n = 1.008665u \end{array}\right\} \text{all given in data book}$$

Mass – Energy Equivalence

If an object increases in energy – for example, gets hotter, or moves more quickly, then its mass also increases. The effect is not noticeable on an "every-day" scale but, on a nuclear scale this effect becomes significant.
The relationship between mass and energy is described by Einstein's famous equation:

$E = mc^2$ where : E = energy, in joules

m = mass, in kilograms

c = speed of light $= 3.00 \times 10^8 ms^{-1}$

When energy is released, for example by a nuclear reactor, there is also a decrease in mass of the products, compared with reactants.

Example T7.6

Calculate the amount of energy accompanying a 1.00 gram fuel mass-loss in a reactor.

Mass Defect and Binding Energy

Since energy is required to break up a nucleus into its constituent parts (protons and neutrons), energy must be added. This energy is called binding energy since it is the energy associated with the binding together of the nucleons – and numerically equal to the energy required to separate them. Using the above idea of mass energy equivalence, mass is also therefore added when energy is added.

It follows that the mass of a nucleus is less than the total mass of all the separate protons and neutrons making it up. This difference in mass is called the mass defect of the nucleus.

Mass defect (for a nucleus) = total mass of separate nucleons – mass of nucleus

Mass defect (for an atom) = total mass of separate nucleons + electrons – mass of nucleus

Example T7.7

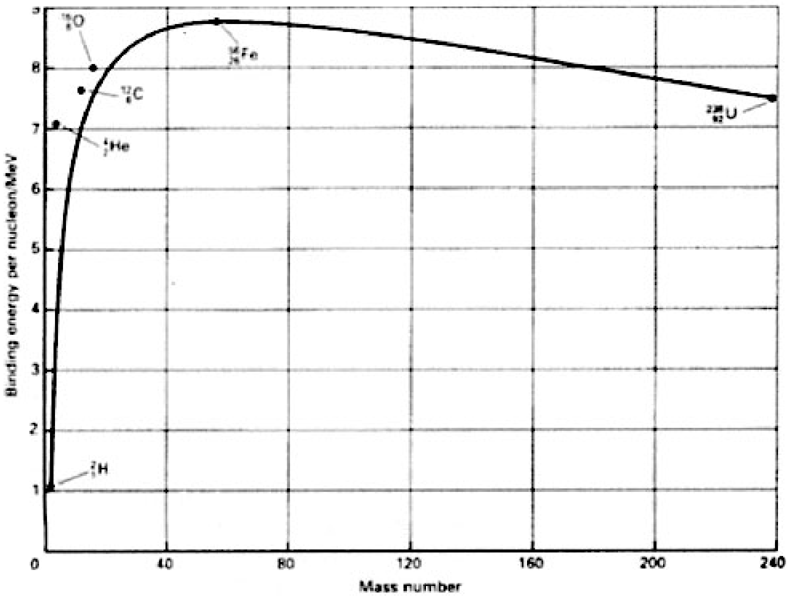
A helium atom has a mass of 4.00260u. Find the mass defect and the binding energy of a helium atom.

Fission and Fusion

A useful measure of the stability of a nucleus is its binding energy per nucleon. This is the energy that needs to be supplied to remove a nucleon from the nucleus. Nuclides that have the largest binding energy per nucleon are therefore the most stable.

The following graph shows how binding energy per nucleon varies with the mass number (nucleon number)

Binding Energy per nucleon graph



Nucleons in iron have the most binding energy, so are the most stable. Therefore iron (iron-56) is the most stable nuclide. As can be seen from the graph, the further either side of iron you go, the less stable the nuclide. Nuclides therefore become more stable if they change in mass closer to that of the mass of iron. Therefore nuclides heavier than iron tend to break apart (undergo fission reactions) and nuclides lighter than iron tend to join (fuse) with other light nuclides, undergoing fusion reactions.

When nuclides undergo fission or fusion reactions to produce more stable nuclides, energy is always released. This can be a little confusing, so to explain, remember:

Binding energy = energy you have to put in to break nucleus apart

Hence: High binding energy nuclide → low binding energy nuclide
(put energy in)

and Low binding energy nuclide → high binding energy nuclide
(energy is released)

This is the theory that allows us to release energy in nuclear reactions, e.g. in nuclear power stations.

Example T7.8

Using the graph above, predict which is the most stable nuclide: Pb-206 or Po-210, and whether energy will be released or absorbed in the following reaction. Find the quantity of this energy release/absorption

$${}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}He$$

Mass of ${}^{210}_{84}Po = 209.983u$

Mass of ${}^{206}_{82}Pb = 205.974u$

Mass of ${}^{4}_{2}He = 4.003u$

Further Notes

In order to make a nuclear fusion reaction take place, the reacting nuclei must approach each other at incredibly high speeds (to overcome electrostatic repulsion). One way of attaining these speeds is to use very high temperatures (about 100 million °C) – ***thermo***nuclear fusion reactions. So far, no one has managed to produce a controlled thermonuclear fusion reaction – bombs have been made using thermonuclear reactions – but these involve chain reactions, which are not controlled.

The sun's energy comes from fusion reactions, and many heavier nuclei are produced from fusion of hydrogen nuclei.