ATOMIC AND NUCLEAR PHYSICS

7

CORE

7.1 The atom

7.2 Radioactivity

7.3 Nuclear reactions, fission and fusion

7.1 THE ATOM

ATOMIC STRUCTURE

7.1.1 Describe a model of the atom that features a small nucleus surrounded by electrons.

7.1.2 Outline the evidence that supports a nuclear model of the atom.

7.1.3 Outline one limitation of the simple model of the nuclear atom.

7.1.4 Outline evidence for the existence of atomic energy levels.

7.1.1 A simple atomic model

Between 1911 and 1913, *Ernest Rutherford*, a New Zealander working at Cambridge University in England, developed a model of the atom that in essence, was not replaced until 1926. In this model, the electrons orbit a positively charged nucleus. In a neutral atom, the number of orbital electrons is the same as the number of protons in the nucleus. The simplest atom, that of the element hydrogen, consists of a single electron orbiting a single proton. The centripetal force keeping the electron is orbit is provided by the Coulomb attraction between proton and electron, the proton being positively charged and the electron negatively charged. The magnitude of the charge on the electron is equal to the magnitude of the charge on the proton. In 1910, the American physicist, *Robert Millikan* made the first precise determination of the charge on an electron as 1.602×10^{-19} C (The current value is $1.60217733 \times 10^{-19}$ C). Earlier, in 1987, the English physicist *J. J. Thomson* had measured the ratio of the electron charge to its mass, $\frac{e}{m_e}$. From the value of $\frac{e}{m_e}$ found by *Thomson*, *Millikan's* determination of e enabled the mass of the electron to be determined. The current value for the electron mass m_e is $9.10938188 \times 10^{-31}$ kg. The current value for mass of the proton m_p is $1.67262158 \times 10^{-27}$ kg.

7.1.2 Evidence for the Rutherford nuclear atom

The work of *J. J. Thomson* had indicated that the atom consists of a mixture of heavy positive particles, protons, and light negative particles, electrons. As suggested above, *Rutherford* devised an experiment to find out how the particles of the atom might be "mixed. The experiment was carried out by *Geiger* and *Marsden* and in order to outline the experiment, we must anticipate work discussed in Topic 7.2. Certain elements are unstable and disintegrate spontaneously. Such an element is radium and one of the products of the so-called **radioactive decay** of a radium atom, is a helium nucleus. Helium nuclei emitted as the result of radioactive decay are called alpha-particles (α). When α-particles strike a fluorescent screen, a pinpoint flash of light is seen.

Rutherford studied how α-particles were absorbed by matter and found that they were readily absorbed by thin sheets of metal. However, he found that they were able to penetrate gold-foil which, due to the malleable nature of gold, can be made very thin.

Figure 701 illustrates the principle of the experiment carried out by *Gieger* and *Marsden*.

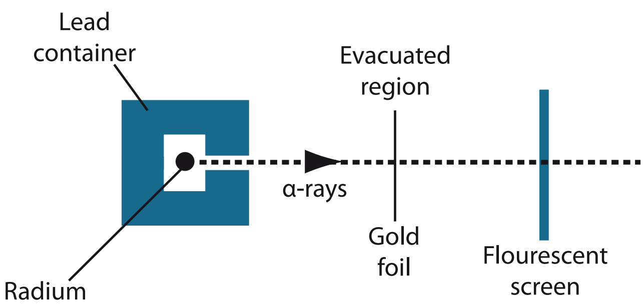

Figure 701 Geiger and Marsden's experiment

A piece of radium is placed in a lead casket such that a narrow beam of particles emerge from the tunnel in the casket The particle beam is incident on a piece of gold-foil behind which is placed a fluorescent screen. The whole apparatus is sealed in a vacuum.

The result is rather surprising. Most of the α-**particles** go straight through, but a few are scattered through quite large angle whilst some are even turned back on themselves. *Rutherford* was led to the conclusion that most of the gold-foil was empty space. However, to account for the scattering, some of the particles must encounter a relative massive object which deflects them from their path. Imagine firing a stream of bullets at a bale of hay in which is embedded a few stones. Most of the bullets go straight through but the ones which strike a stone will ricochet at varying angles depending on how they hit the stone. *Rutherford* suggested that the atom consisted of a positively charged centre (the stones) about which there was a mist of electrons (the straw). He neglected the interaction of the α-particles with the electrons because of the latter's tiny mass and diffuse distribution. The significant reaction was between the massive positively charged centre of the gold atoms and the incoming α-particles. *Rutherford* was in fact quoted as saying "It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you had fired a 15–inch shell at a piece of tissue paper and it came back and hit you."

Figure 702 illustrates the paths that might be followed as the α-particles pass through the gold-foil.

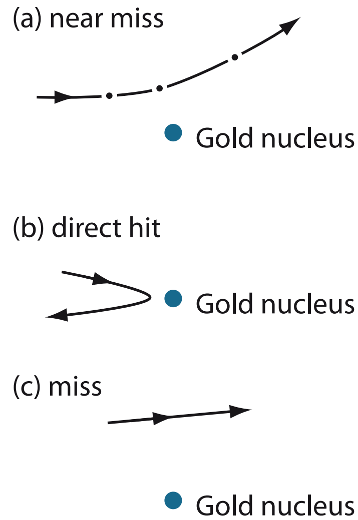

Figure 702 The paths of alpha particles through gold foil

It is the results of the Geiger-Marsden experiment that led to the atomic model outlined in 7.1.1 above. Detailed analysis of their results indicated that the gold atoms had a nuclear diameter of the order of 10^{-14} m, which meant that the radius of a proton is the order of 10^{-15} m. Work contemporary to that of *Geiger* and *Marsden*, using X-rays, had shown the atomic radius to be of the order of 10^{-10} m. To give some understanding to the meaning of the expression 'an atom is mainly empty space', consider the nucleus of the hydrogen atom to be the size of a tennis ball, then the radial orbit of the electron would be about 2 km.

7.1.3 Limitations of the simple nuclear model of the atom

The atomic model proposed by *Rutherford* has certain problems associated with it. In particular, Maxwell's theory of electromagnetic radiation (see 4.4.9) demonstrated that accelerated electric charges emit em radiation. It is difficult therefore to see how the Rutherford atom could be stable since the orbiting electrons would be losing their energy by emitting radiation and as such, would soon spiral into the nucleus. Furthermore, how could the nucleus be stable; what was there to stop the protons flying apart from each other due to Coulomb repulsion?

The model was also unable to account for that the fact that many elements exhibited a range of atomic weights. For example, J.J. Thomson had shown that neon is made up of atoms some of whose atomic weight is 20 and others whose atomic weight is 22.

Rutherford recognised that his new model had these limitations and he actually made some predictions about an improved model of the atom, even hypothesising the existence of the neutron. However, it was *Neils Bohr* who in 1914 proposed a model that went some way to answering the electron radiation conundrum.

7.1.4 EVIDENCE FOR ATOMIC ENERGY LEVELS

Emission spectra

If a sufficiently high potential difference is applied between the ends of a glass tube that is evacuated apart from the presence of a small amount of mercury vapour, the tube will glow. To study the radiation emitted by the tube, the emitted radiation could be passed through a slit and then through a dispersive medium such as a prism. The prism splits the radiation into its component wavelengths. If the light emerging from the prism is brought to a focus, an image of the slit will be formed for each wavelength present in the radiation. Whereas the radiation from an incandescent solid (e.g the filament of a lit lamp) produces a continuous spectrum of colours, the mercury source produces a **line spectrum.** Each line in this spectrum is an image of the slit and in the visible region, mercury gives rise to three distinct lines- red, green and blue.

The study of line spectra is of great interest as it is found that all the elements in the gaseous phase give rise to a line spectrum that is characteristic of the particular element. In fact elements can be identified by their characteristic spectrum and is one way that astronomers are able to determine the elements present in the surface of a star (*see Option E*). Also, the spectrum of an element provides clues as to the atomic structure of the atoms of the element.

In 1905, based on the work of *Max Planck*, Einstein proposed that light is made of small packets of energy called *photons*. Each photon has an energy E given by $E = hf$, where h is a constant known as the **Planck constant** and has a value 6.6×10^{-34} J s. The photon model of light suggests an atomic model that accounts for the existence of the line spectra of the elements. If it is assumed that the electrons in atoms can only have certain discrete energies or, looking at it another way, can only occupy certain allowed energy levels within an atom, then when an electron moves from one energy level to a lower energy level, it emits a photon whose energy is equal to the difference in the energy of the two levels. The situation is somewhat analogous to a ball bouncing down a flight of stairs; instead of the ball losing energy continuously when rolling down the banisters, it loses it in discrete amounts. *(The photon model of light and atomic energy levels are discussed in much more detail in Topic 13.1).*

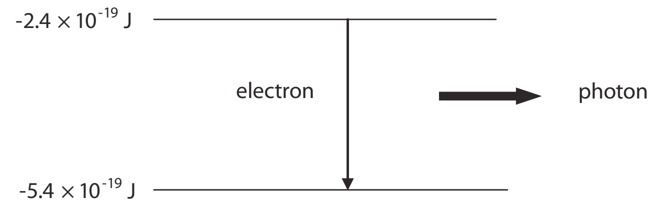

Figure 703 Shows two of the allowed energy levels of atomic hydrogen.

When the electron makes the transition as shown in Figure 703, it emits a photon whose frequency is given by the Planck formula i.e

$$f = \frac{E}{h} = \frac{3.0 \times 10^{-19}}{6.6 \times 10^{-34}} = 4.5 \times 10^{14} \text{ Hz}$$

The associated wavelength is given by

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{8}}{4.5 \times 10^{14}} = 6.6 \times 10^{-7} \text{ m}$$

This is in fact the measured value of the wavelength of the red line in the visible spectrum of atomic hydrogen.

In most situations, the electrons in an atom will occupy the lowest possible energy states. Electrons will only move to higher energy levels if they obtain energy from somewhere such as when the element is heated or, as mentioned above, when subjected to an electrical discharge. When the electrons are in their lowest allowed levels, the atom is said to be 'unexcited' and when electrons are in higher energy levels, the atom is said to be 'excited'. To move from a lower level to a higher energy level, an electron must absorb an amount of energy exactly equal to the difference in the energy between the levels.

(For IBO reference, carrying out calculations using the Planck relationship will not be expected; the above is just to try and help explain how the existence of line spectra strongly supports the existence of atomic energy levels).

Absorption spectra

Atomic line spectra can be obtained in another way. If the radiation from a filament lamp passes through a slit and then a tube containing unexcited mercury vapour and is then focussed after passing through a prism, the resulting spectrum is continuous but is crossed with dark lines. These lines correspond exactly to the lines in the emission spectrum of mercury. To understand this, suppose the difference in energy between the lowest energy level and the next highest level in mercury atoms is E, then to make the transition between these levels, an electron must absorb a photon of energy E. There are many such photons of this energy present in the radiation from the filament. On absorbing one of these photons, the electron will move to the higher level but then almost immediately fall back to the lower level and in doing so, will emit a photon also of energy E. However, the direction in which this photon is emitted will not necessarily in the direction of the incident radiation. The result of this absorption and re-emission is therefore, a sharp drop in intensity in the incident radiation that has a wavelength determined by the photon energy E. The phenomenon of absorption spectra is of great importance in the study of molecular structure since excitation of molecules will often cause them to dissociate before they reach excitation energies.

NUCLEAR STRUCTURE

7.1.5 Explain the terms nuclide, isotope and nucleon.

7.1.6 Define *nucleon number A*, *proton number Z* and *neutron number N*.

7.1.7 Describe the interactions in a nucleus.

7.1.5-7 NUCLEAR STRUCTURE

Isotopes

Many elements have forms that are chemically identical but each form has a different mass. These forms are called **isotopes**. The existence of isotopes explains why the chemical weights of elements do not have integral values since a sample of an element will consist of a mixture of isotopes present in the sample in different proportions.

The neutron

The explanation for the existence of isotopes did not come until 1932 when *James Chadwick* an English physicist, isolated an uncharged particle that has a mass very nearly the same as the proton mass. Since 1920 both *Rutherford* and *Chadwick* has believed that an electrically neutral particle existed. An uncharged particle will not interact with the electric fields of the nuclei of matter through which it is passing and will therefore have considerable penetrating ability. In 1930 *Bothe* and *Becke* found that when beryllium is bombarded with α-particles a very penetrating radiation was produced. It is this radiation that *Chadwick* showed to consist of identical uncharged particles. These particles he called **neutrons** and the current value of the neutron mass m_n is $1.67262158 \times 10^{-27}$ kg.

The neutron explains the existence of isotopes in the respect that a nucleus is regarded as being made up of protons and neutrons. The nuclei of the different isotopes of an element have the same number of protons but have different numbers of neutrons. For example, there are three stable isotopes of oxygen; each nucleus has eight protons but the nuclei of the three isotopes have eight, nine and ten neutrons respectively.

In the study of particle physics, the proton and neutron are regarded as different charge states of the same particle called the **nucleon**. (*Particle physics is studied in depth in Options D –SL, and Option J-HL*).

Nuclide, nucleon number, proton number and neutron number

The three isotopes of oxygen mentioned above are expressed symbolically as ${}^{16}_{8}O$, ${}^{17}_{8}O$ and ${}^{18}_{8}O$ respectively. The "O" is the chemical symbol for oxygen, the subscript is the number of protons in the nucleus of an atom of the isotope and the superscript, the number of protons plus neutrons. Each symbol therefore refers to a single nucleus and when expressed in this form, the nucleus is referred to as a **nuclide**. In general, any nuclide X is expressed as ${}^{A}_{Z}X$

A is the **nucleon number**

Z is the **proton number**

We also define the **neutron number** N as $N = A - Z$.

It should be mentioned that it is the proton number that identifies a particular element and hence the electron configuration of the atoms of the element. And it is the electron configuration that determines the chemical properties of the element and also many of the element's physical properties such as electrical conductivity and tensile strength.

Nuclear interactions

Shortly after the discovery of the neutron, *Hideki Yukawa*, a Japanese physicist, postulated a strong force of attraction between nucleons that overcomes the Coulomb repulsion between protons. The existence of the force postulated by Yukawa is now well established and is known as the **strong nuclear interaction**. The force is independent of whether the particles involved are protons or neutrons and at nucleon separations of about 1.3 fm, the force is some 100 times stronger than the Coulomb force between protons. At separation greater than 1.3 fm, the force falls rapidly to zero. At smaller separations the force is strongly repulsive thereby keeping the nucleons at an average separation of about 1.3 fm. (*1 femtometre = 10^{-15} m*)

7.2 RADIOACTIVE DECAY

7.2.1 Describe the phenomenon of natural radioactive decay.

7.2.2 Describe the properties of α and β particles and γ radiation.

7.2.3 Describe the ionizing properties of α and β particles and γ radiation.

7.2.4 Outline the biological effects of ionizing radiation.

7.2.5 Explain why some nuclei are stable while others are unstable.

7.2.1 NATURAL RADIOACTIVE DECAY

Certain elements emit radiation spontaneously, i.e. without any external excitation; this phenomenon is called **radioactivity**. It was first discovered by the Austrian physicist *Henri Becquerel* in 1896, who found that uranium salts which had been protected from exciting radiations for several months still emitted penetrating radiation seemingly without any loss in intensity. Becquerel discovered that the uranium itself was responsible for this radiation and also that the radiation was independent of pressure, temperature and chemical combination.

This indicated that the radioactive properties of uranium were due to the nucleus of the atom and not to the electronic structure.

7.2.2 THE RADIATIONS (α, β, γ)

Shortly after Becquerel's discovery two physicists working in France, *Pierre and Marie Curie* isolated two other radioactive elements, polonium and radium each of which is several million times more active than uranium. An extremely good account of the Curies' heroic experiments can be found in Madame Curie's biography written by her daughter, Irene. At first it was thought that the radiation emitted by radioactive elements were of the same nature as the X-rays that had been discovered the previous year. However, in 1897, *Rutherford* found that two types of radiation occurred in radioactivity, some of the rays being much more penetrating than the others. He called the less penetrating rays alpha (α) rays and the more penetrating ones beta (β) rays.

In 1900 *Villiard*, also French, detected a third type radiation which was even more penetrating than β-rays. Naturally enough he called this third type gamma (γ) radiation.

Madame Curie deduced from their absorption properties that α-rays consisted of material particles and *Rutherford* showed that these particles carried a positive charge equal to about twice the electron charge but that they were very much more massive than electrons. Then in 1909, in conjunction with *Royds*, *Rutherford* identified α-particles as helium nuclei.

α-**particles** have a range in air at STP of about 5 cm and are readily stopped by a few sheets thickness of writing paper.

β-**particles** were soon identified as electrons that have considerable energy. They travel several metres in air before being absorbed. They can also penetrate thin sheets of aluminium.

In 1928 the English physicist *Paul Dirac* predicted the existence of a positively charged electron and in 1932 this particle was found by the American physicist *Carl Anderson*, to be present in cosmic radiation. Then in 1934, the Curie's daughter Irene, along with her husband *Frederic Joliot*, discovered the positively charged electron, now called the **positron** (e+, β^+) , to be present in certain radioactive decay.

γ-**rays** are not influenced by electric or magnetic fields but can be diffracted by crystals. This indicates that γ-rays consist of short wavelength electromagnetic radiation typically in the range 5-0.05 nm. From the Planck relation, $E = hf$, this means that the photons associated with γ-radiation have very high energies and are therefore