APPLIED ATOMIC ENERGY

EDITED BY

FEARNSIDE, JONES & SHAW

TECHNICAL TRENDS SERIES

APPLIED ATOMIC ENERGY

By K. Fearnside, M.A., A.M.I.E.E.,
E. W. Jones, B.Sc., A.Inst.P., and E. N. Shaw, B.Sc.

1951

INTRODUCTION

SINCE the detonation of the first atomic bomb the attention of the public has been deflected more and more to the warlike potentialities of the discovery of atomic energy. The original atomic bombs have recently been superseded in the public imagination by the more powerful hydrogen bomb and the interest now lies in a race between America and Russia to stockpile larger and larger numbers of one type or another of bomb which may be used in a potential conflict. The peaceful uses of atomic energy have so far been almost neglected by the public. The use of atomic energy to provide power which will compete with coal and other present sources is a very long-term project and according to a recent speech by Sir John Cockcroft is unlikely to reach an economic level in this country for at least ten years. On the other hand, the production of the atomic pile has made possible the very wide-spread use of radioactive isotopes. Their uses in medicine have been developed with tremendous energy in America, in this country and on the Continent, and their uses in industry are only now beginning to be realised.

Although America had a very long start in the use of radioactive isotopes owing to the fact that the first atomic piles were built in that country, the production and uses in Britain have made great strides in the past eighteen months and it is believed that in some respects Britain is now ahead of America. This result is almost entirely due to the freedom with which isotopes are obtainable from Harwell by properly accredited scientific workers and to the encouragement given to scientists to use radioactive isotopes by the Isotope Division at Harwell. Dr. Seligman, head of this division, has pursued, under the direction of Sir John Cockcroft, an energetic policy of popularizing the use of isotopes and of advising potential users on the best approach to their problems. A counterpart to this service on an industrial basis has been created by the formation of a public company—Isotope Developments Limited—backed by a number of large industrial interests with the primary purpose of developing the use of radioactive techniques in industry. This is the first company in the world to be formed with this specific object, and although it is still very young there is no doubt that this company has a significant function in our industrial life before it.

This book endeavours to present to the layman and to the scientific workers specialising in fields other than nuclear physics or nuclear chemistry, an outline of the basis on which the development of atomic energy has been made and to indicate very briefly the fields of scientific knowledge in which new advances have been made by the use of radioactive materials. It is not, however, a complete handbook, and workers with radioactive isotopes are advised to obtain details of the necessary regulations from the appropriate authority. References to these regulations are given in the Bibliography. In particular, the question of health hazard, which is one of the most important aspects of the use of radioactive materials, has been excellently dealt with by the Medical Research Council in their *Introductory Manual on the Control of Health Hazards from Radioactive Materials.* Those intending to work with such materials are strongly recommended to obtain a copy from the Medical Research Council. It is hoped that the omission of such regulations will in no way prevent the interested layman from obtaining a complete picture from this book, while those who wish to go further into the subject will find the regulations easily obtainable.

CONTENTS

		Page
	INTRODUCTION	vii
Chapter 1	MODERN NUCLEAR PHYSICS	1
Chapter 2	NUCLEAR REACTORS	12
Chapter 3	THE PREPARATION AND DISTRIBUTION OF RADIO-ISOTOPES	23
Chapter 4	STABLE ISOTOPES	33
Chapter 5	LEGAL ASPECTS OF ATOMIC ENERGY .	47
Chapter 6	TECHNIQUES	54
Chapter 7	ISOTOPES IN PURE RESEARCH . .	70
Chapter 8	RADIO-ISOTOPES IN BIOLOGY . . .	86
Chapter 9	RADIO-ISOTOPES IN MEDICINE . .	97
Chapter 10	RADIO-ISOTOPES IN AGRICULTURE .	112
Chapter 11	RADIO-ISOTOPES IN INDUSTRY . .	122
Appendix	ISOTOPES AVAILABLE FROM HARWELL	148
	BIBLIOGRAPHY	153
	INDEX	154

LIST OF PLATES

			Between pages
Frontispiece		Dr. Henry Seligman	
Plate I		Experimental Face of BEPO	8–9
Plate II		Isotope loading machine in position on BEPO	8–9
Plate III	(a)	Mass Spectrometer	56–57
	(b)	Geiger Counter	56–57
Plate IV		H.G.^{198} Interferometer photo	56–57
Plate V	(a)	Apparatus for friction experiments	72–73
	(b)	Friction track	72–73
Plate VI		Iodine Separation Plant	72–73
Plate VII	(a)	Arrangement for locating counter for I^{131} measurements	88–89
	(b)	Patient treated with Au^{198}	88–89
Plate VIII	(a)	Reversed radioautograph of a tomato leaf one day after fumigation with sulphur dioxide	88–89
	(b)	Reversed sulphur radioautograph of tomato fruit	88–89
Plate IX	(a)	Radioautograph of tomato seed	104–105
	(b)	Reversed arsenic radioautograph of a young radish plant	104–105
Plate X	(a)	Radioactive mosquitoes on pool	104–105
	(b)	Microinjection of a cockroach	104–105
Plate XI	(a)	Distribution of Ca^{45} in leather	120–121
	(b)	Auto-radiograph showing distribution of wear debris from wire drawing die on copper wire	120–121
Plate XII	(a) & (b)	Auto-radiograph of end-mill tool after cutting radioactive steel	120–121

Between pages

Plate XIII (a) Auto-radiograph showing the distribution of "tagged" oil on textile fibres. . . 136–137

(b) A beta thickness gauge installed on a cardboard machine 136–137

Plate XIV Gamma-radiograph of steam valve . . 136–137

ACKNOWLEDGEMENT

THE authors gratefully acknowledge the co-operation and assistance they have received from Dr. Seligman and the staff of the Atomic Energy Research Establishment, their colleagues of Isotope Developments Limited, and all those who have kindly given permission for the results of their work to be quoted and their diagrams to be reproduced in this book.

K. FEARNSIDE
E. N. SHAW
E. W. JONES

Chapter I

MODERN NUCLEAR PHYSICS

BEFORE we proceed with a description of the nuclear reactor and the radioactive isotopes which it produces, it is essential that the reader should be familiar with the basic ideas of modern nuclear physics. These ideas, which are now universally accepted as correct beyond reasonable doubt, owe their inception to the researches of Sir J. J. Thomson in the Cavendish laboratory at Cambridge. He was the first to show that atoms were not, as was previously believed, indivisible, but that they contained small negatively charged particles which he termed "electrons" which could be removed from their parent atoms by a number of processes, including large electric fields and other shocks. The Cavendish laboratory continued the work started by Sir J. J. Thomson, under the leadership of Professor Sir Ernest Rutherford, later Lord Rutherford, whose school included such well-known names as Cockcroft, Chadwick, Ellis and Oliphant. The British work was supplemented by the work of scientists in many countries in the early stages—Becquerel and Curie of France, and, in the later stages, Hahn, Meitner and Frisch in Germany. These scientists, working on parallel lines in many cases, produced the finished picture of the atom which we can now present to you, and which enabled the British and American scientists during the late war to bring to perfection the nuclear reactor, and the atomic bomb, which wrought such spectacular and widespread damage in Japan.

The old definition of the atom was that it was the smallest and indivisible unit of a chemical element. That is to say, of a substance such as oxygen, sulphur, iron, lead, uranium or any of the other chemical. elements. This picture is still true. The particles into which the atom may be broken down are not particular to the element from which they come, but are common to all elements. The three fundamental particles of which all atoms are composed are, in the order of their discovery, the electron, the proton and the neutron. The electron is a small particle with a mass of $9{\cdot}01 \times 10^{-28}$ grammes and carrying a negative charge of $4{\cdot}77 \times 10^{-10}$ electrostatic units. The proton can similarly be considered as a particle having a mass of $1{\cdot}66 \times 10^{-24}$ grammes and carrying a positive charge of the same value as that of the electron. The neutron has a similar mass very close to that of the proton, but carries no charge whatsoever. The radii of the neutron and proton are about 2×10^{-13} centimetres and that of the electron somewhat bigger at 5×10^{-11} centimetres. The size of the hydrogen atom is approximately 10^{-8} centimetres, so that it will be seen that the majority of the atom consists of empty space. The atom is, in fact, composed of a nucleus in which are the protons and neutrons and in which therefore reside the great majority of the mass and a number of electrons which circulate round this nucleus, filling the volume of the atom. Since the atom is electrically neutral, the number of planetary electrons, as they are called, is equal to the number of protons in the nucleus. The number of neutrons does not affect the issue.

The chemical nature of the atom depends only on the number of planetary electrons, and all atoms having the same number of planetary electrons have the same chemical properties, irrespective of the state of their nuclei. It is therefore possible for atoms to have the same chemical properties, that is, to be atoms of the same chemical element, but to have different numbers of neutrons in their nucleus. Such atoms are known as isotopes, one of another. Every element, therefore, may consist of a number of isotopes, or, in other words, of a mixture of atoms which

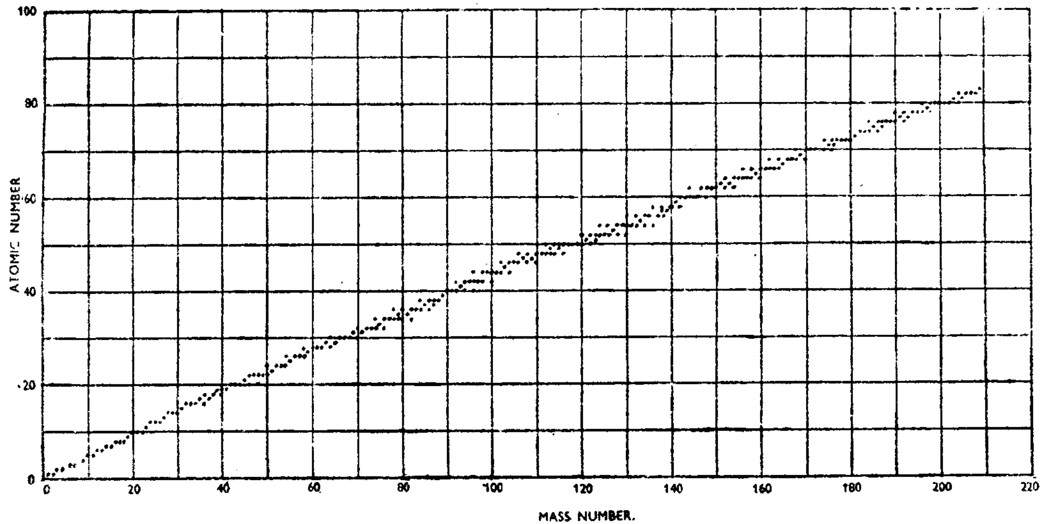

Fig. 1. Plot of Atomic Number against Mass Number for Stable Nuclei.

have the same number of protons in their nuclei, but different numbers of neutrons. It is not, however, found that all combinations of protons and neutrons are stable. The number of stable combinations is, in fact, much smaller than the number of known unstable ones.

Figure 1 shows the stable isotopes and indicates over what a narrow range of neutron-proton ratio stability can be achieved. A table of some common isotopes with their characteristics is given in the Appendix and should be consulted for further details.

The number of particles in the nucleus is known as the mass number, and the number of protons is known as the atomic number. For convenience in nuclear calculations, the mass of the proton or neutron is taken as unit mass, and the charge on the proton or electron as unit charge.

When a nucleus is in an unstable state, for any reason whatsoever, it has a definite probability per second of returning to a stable state. At the end of a given time, it will have had an even chance of returning to this stable state, and this time lapse is known as the half life. It can be visualised in another way by considering a large number of unstable nuclei. A number of these will return to the stable state each second, and at the end of a number of seconds, one half will remain in the unstable state. This lapse of time will be the same as that considered in the first example, and is again the half life. This half life is a characteristic only of the particular nucleus concerned, and is unaffected by any physical means which have so far been brought to bear. There is, however, an interesting exception to this rule which will be discussed later.

When a nucleus is unstable, and seeks to become stable, it may do so in a number of ways. The first way is by the emission of an alpha particle. The alpha particle is a nucleus of helium and consists of two protons and two neutrons. Its emission, therefore, causes the emitting atom to decrease in mass number by four units, and in charge by two units. This mode of radioactive decay is almost entirely confined to very heavy nuclei which occur naturally and on which a great deal of the early work on radioactive decay was done. The second way in which an unstable nucleus may decay is by emission of a beta particle. This is simply an electron moving with a velocity close to that of light. The emission of an electron, therefore, causes no change in the mass number of the emitting nucleus, but causes its positive charge to increase by one unit since the electron carries away with it a negative charge of one unit. The emission of beta radiation is one of the commonest modes of decay, and is not confined to any class of isotope. A third method of decay is by the emission of a positron or positive electron. This particle is exactly similar to the normal electron, save that it carries a positive charge. Its emission, therefore, causes no difference in mass to the emitting nucleus but decreases its positive charge by one unit. The fourth mode of decay, most recently discovered, is known as "K" capture. The shell of electrons nearest to the nucleus is known as the "K" shell, and it sometimes happens that a nucleus will capture an electron from the "K" shell, and incorporate it into the nucleus, using it to turn a proton into a neutron. The effect of this process is therefore similar to positron emission, to which it often occurs as an alternative. Any of these modes of decay may be accompanied by the emission of gamma radiation, that is to say, electromagnetic radiation of a very high frequency, which causes no change in either mass number or charge number but merely gets rid of surplus energy.

It will also be clear from a consideration of the Appendix that an unstable nucleus may very often have a choice of two stable configurations into which it can decay. This is the case, for example, with silver 110, which can decay either into cadmium 110 by beta emission or into palladium 110 by "K" capture. For practical results, it is important to know what proportion of atoms decay by each mode, and in the case of silver 110 only 10 per cent decay by beta emission. The exception to the rule that the radioactive decay is unaffected by physical or chemical means is beryllium 7, which decays by "K" capture. In the case of beryllium, the "K" shell of two electrons is complete, and the second shell, the "L" shell, contains two electrons. In the "K" capture process, the electron which is captured may sometimes belong to the "L" shell, not to the "K" shell, and it therefore follows that the rate of decay by "K" capture will depend on the number of electrons in the "L" shell, at any rate to a small extent. If, therefore, the decay constant or half-life of beryllium 9 is determined in the form of metallic beryllium, the half-life will have one value. If, on the other hand, the half-life is determined with a beryllium salt in solution, one or two electrons will have been removed from the "L" shell in the process of forming the ion, and the electron density will therefore be slightly smaller. It follows that the half-life will be appreciably longer and this has been found in practice, thereby confirming the theory of "K" capture.

The radiations emitted by unstable nuclei are themselves of considerable interest. The properties of alpha radiation have been known since 1890, and it was the first radiation to be studied in detail. It consists, as we have said above, of helium nuclei (two protons and two neutrons). When an alpha particle travels through matter, since it is a heavy body, it strikes away a number of the planetary electrons from the atoms it encounters and its track is therefore heavily ionised. This means also that it loses energy in these collisions and its track is a short one; in fact, the majority of alpha particle tracks are of length 4–5 centimetres in air. The rate of loss of energy is almost uniform along the track except at the very end, so that if the track were visible it would give the impression of being a pencil stroke. The number of ions formed is very large, and may be as many as 150,000 from a single alpha particle. Since these ions are formed within a distance of 5 centimetres from the source, the immediate neighbourhood of a source of alpha particles is very strongly ionised. This property of alpha particle sources has an important practical use which will be discussed in a later chapter. It has also a practical disadvantage in that the weight of air required to stop an alpha particle is about 6 milligrammes. Since the detection of these particles by counters depends on their penetrating the wall of the counter, this fact is extremely inconvenient, and makes necessary the construction of special alpha particle counters.

Beta radiation, in which for this purpose we may include positron radiation, consists of fast-moving electrons. The range of these particles in air is of the order of 1–2 metres and the tracks along which they move are only slightly ionised. The number of ions per centimetre path length is about one-hundredth of that of the alpha particles, and it follows, therefore, that the air in the neighbourhood of a beta particle source is much less strongly ionised. On the other hand, the total volume over which the ionisation is spread is very much larger and, in addition, the penetrating power of the beta radiation is a good deal greater. Except for very soft beta radiation, such as that from carbon 14, there is no difficulty in constructing counters with windows thin enough to allow the majority of radiation to penetrate them. The beta radiation from phosphorus 32, which is a fairly typical example, will penetrate up to 500 milligrammes per square centimetre of aluminium, which is considerably thicker than any counter wall normally made.

Gamma radiation is very different in properties from the two foregoing: the alpha particle and the beta particle both have a definite path length, at the end of which they stop. This is not the case with gamma radiation. In passing through matter, a definite proportion of the gamma energy is removed per centimetre by ionisation and collision processes, but, none the less, some remains however long the path. The effect of matter upon gamma rays is therefore expressed by means of an attenuation constant which shows the proportion of incoming gamma rays attenuated by 1 centimetre thickness of material or, more usually, by 1 gramme of material per square centimetre. The attenuation constant for gamma radiation depends on the chemical nature of the material and on the energy of the gamma radiation in a very complex fashion. The effect of the gamma radiation is to strike out electrons from the atoms with which hey collide and these electrons which have considerable energy in turn ionise other atoms, so that the path of the gamma ray is marked by secondary tracks, rather than by the ionisation along the original path. For this reason, in passing through a counter, gamma rays create very few ions and to count them is therefore a much more difficult business than the counting of beta radiation or alpha radiation.

For the sake of completeness we must consider the secondary processes incidental to "K" capture. When the "K" electron has been captured there remains a space in the "K" shell; this space is filled by an electron falling from a further orbit outside the "K" shell, and this change results in the emission of an X-ray. This X-ray can be detected by its ionising power and counted.

So far, we have been considering the decay of unstable nuclei without considering the methods by which the nuclei become unstable. These can be divided into the following headings: firstly, collision with other fundamental particles; and secondly, the formation of the nucleus by decay of another unstable nucleus.

The first heading covers a great variety of nuclear reactions. It is believed, for example, that when a nitrogen nucleus collides with an alpha particle, yielding oxygen and a proton, there is an intermediate stage which consists of the nucleus fluorine 19. Such intermediate nuclei are a feature of all nuclear reactions, though in writing down the equation for the reaction they are not normally shown. In the shorthand normally used in nuclear physics, the above reaction would be written:

$$N^{14} + He^{4} = O^{17} + H^{1}$$

This was the first nuclear reaction to be studied, and the second was the reaction of protons on lithium. In the first case, the alpha particles were obtained from a naturally alpha active substance, but in the second case, the protons were produced at very high energies by an electrical accelerating machine. The use of accelerating machines to produce protons, neutrons and alpha particles at high energies has grown very greatly, and a great many nuclear reactions have been studied in this way. Electrons and gamma rays have also been used for the production of nuclear reactions, but by far the most common nuclear projectile these days is the neutron.

As will be seen later, the atomic pile results in the production of a great number of neutrons at all speeds from very fast to very slow. The reaction of neutrons with nuclei is essentially different from that of the other particles. Whereas a minimum energy, usually quite high, is required to bring about a nuclear reaction, using a proton or other charged particle, a neutron may be absorbed by a nucleus at very low energies indeed, and all nuclei will absorb neutrons to some extent, though some of course absorb them more strongly than others. The probability of absorption is expressed by a cross-section, which is that area over which an atom will capture a passing neutron of the energy considered. These are expressed in terms of the "barn"—10^{-24} square centimetres. The absorption cross-sections for thermal neutrons, that is, those in equilibrium with the material in which they are found at room temperatures, will be found in the Appendix with other data on the isotopes concerned. The importance of this absorption is, however, that when material is placed in an atomic pile its nuclei will absorb neutrons and may become radioactive. It will be seen from the Appendix that a great many radioactive nuclei can be formed simply by the addition of one neutron to the normal nucleus, and the atomic pile, therefore, provides a convenient means of producing radioactive material artificially.

The second cause of instability is also very widespread. For example, when a fast neutron strikes a nucleus and becomes absorbed, the nucleus is left in a state of having surplus energy and must emit a gamma ray to return to a state of lower energy. This lower state may, however, not be stable. The nucleus formed by the emission of the gamma ray may be unstable and require to go through another radioactive decay before reaching a stable state. Another class of cases appears after the capture of slow neutrons in the atomic pile. An example is tin 124. This is a stable nucleus which. when placed in the pile, captures a neutron and becomes tin 125. The tin 125 decays by beta emission resulting in the nucleus antimony 125, which is still unstable and decays in its turn by beta emission to form tellurium 125. Such cases are quite common, and were originally known in the naturally radioactive series. One series, for example, starts at uranium and goes through a series of transitions, thirteen in number, to finish with an isotope of lead. Similar series start with actinium and thorium and finish again in lead isotopes.

Another nuclear reaction which was discovered just before the war is fission. It was found that when uranium is bombarded with neutrons a number of other elements are formed. A common one had the chemical characteristics of barium, and it was at first thought that the addition of successive neutrons to the uranium nucleus resulted in the formation of a heavier nucleus, known as eka-barium. A