An introduction to Radiation Protection

SECOND EDITION

ALAN MARTIN &
SAMUEL A. HARBISON

Science Paperbacks

An Introduction to
Radiation Protection

An Introduction to Radiation Protection

ALAN MARTIN
Associated Nuclear Services, Epsom

and

SAMUEL A. HARBISON
Nuclear Installations Inspectorate,
Health and Safety Executive, London

SECOND EDITION

SPRINGER-SCIENCE+BUSINESS MEDIA, B.V.

First published 1972

Second edition 1979

Photosetting by Thomson Press (India) Ltd, New Delhi,

British Library Cataloguing in Publication Data

Martin, Alan
An introduction to radiation protection. –
2nd ed., revised.
1. Ionizing radiation – Safety measures
I. Title II. Harbison, Samuel A
614.8′39 RA1231.R2 79–42847

ISBN 978-0-412-16230-5 ISBN 978-1-4899-6940-8 (eBook)
DOI 10.1007/978-1-4899-6940-8

Contents

Preface to First Edition

An Introduction to Radiation Protection is a comprehensive account of radiation hazards and their control. The presentation, which assumes no previous knowledge of the subject, is based on methods which the authors have found, over a number of years of teaching radiation protection at all levels, to be most easily understood by students. It is hoped that the book will meet the requirements of a wide range of readers who are involved, directly or indirectly, with ionizing radiation, including doctors, dentists, research workers, nuclear plant designers and operators. In particular we believe that the work is suitable for the health physics monitors and technicians who are concerned with the day-to-day control of radiation hazards in nuclear power stations, research establishments, hospitals and in industry. The generally accepted standard of training in this type of work is that set by the City and Guilds of London Institute courses in Radiation Safety Practice which are held in various centres throughout the UK. The chapters of the book dealing with the general aspects of health physics are aimed at this standard. Later chapters dealing with particular aspects of the subject are more detailed so that, for example, a health physics monitor in a nuclear power station or a technician in a hospital can get a deeper understanding of the problems in his own area.

Every attempt has been made to avoid detailed mathematical treatment but it has been necessary, in some areas, to use some simple mathematics. This includes squares, square roots, exponentials, logarithms and the plotting of graphs on logarithmic scales. Where a mathematical treatment is used we have tried to present it in such a way that, if the mathematics is not fully understood, it does not preclude an understanding of the chapter in general.

As far as possible each chapter is self-contained so that the reader can find all the information on a particular aspect without having to search through several chapters. The early chapters deal with basic physical principles, the nature of the hazard arising from the interaction of ionizing radiation with biological systems and the levels of radiation which are regarded as acceptable. Later chapters deal with the methods of measurement and control which are applied to attain these levels. In the second half of the book there are individual chapters on the more specialized topics of nuclear reactor health physics, problems associated with X-rays and radiography, health physics in medicine, the disposal of radioactive waste and radiological emergencies. Chapters are also presented on legislation and on the organization of health physics. Each chapter is followed by a summary in note form, in which the major points are reiterated. In addition, a number of revision questions requiring both descriptive and numerical answers are provided for the majority of chapters.

We have been greatly assisted in the preparation of this book by detailed criticisms and suggestions on various chapters by Miss B. E. Stern, Dr J. Vennart, Mr H. M. Carruthers and Mr D. Sykes to whom we are indebted. In writing Chapter 14, which deals with atomic energy legislation, we have leaned heavily on the excellent reviews by Mr D. F. Sim, Legal Adviser to UKAEA. In particular we are grateful to Surgeon Commander Michael Hatfield, RN, for a critical review of the draft manuscript and many helpful suggestions. We also have much pleasure in thanking Mrs Peggy Byford for her meticulous typing of the manuscript. The opinions and conclusions expressed in the book are those of the authors and have no official sanction.

Finally, we are especially grateful to our wives Linda and Joyce for their patience and encouragement during the writing of the book.

London AM
February 1972 SAH

Preface to the Second Edition

Since the publication of the first edition, a number of fundamental changes have taken place in certain aspects of radiation protection. The two most important relate to the SI system of units in radiation protection, and the revised system of dose limitation recommended by the International Commission on Radiological Protection (ICRP) in its Publication 26. It is generally accepted that it will be a number of years before the new SI units have completely replaced the existing ones. To cover this intervening period we have felt it necessary to define and discuss both sets of units in the early chapters. In subsequent chapters, where it seemed useful, we have used both sets of units, the new SI units being followed by the old unit in parentheses. We hope that by doing this we will help readers to become accustomed to the SI units.

To take account of the most recent recommendations of the ICRP, we have completely revised Chapter 6 and have also made major changes in Chapter 9. It has also been found necessary to rewrite much of Chapter 14 to reflect the changes which have taken place in the legislation and regulations dealing with radiation protection during the last few years. The UK regulatory position is treated in detail, to illustrate principles common to many national systems, but we also give a less detailed discussion of the position in four other nuclear countries and of the role of international organizations in setting radiation protection standards.

Substantial revisions have been made to Chapters 3, 4, 10 and 11 to take account of advances in the relevant technologies over the past six or seven years. Certain sections of Chapters 12 and 13 have been rewritten to take account of advances in these fields. In the remaining chapters a number of updating and editorial changes have been made.

We have extended the list of questions at the end of most of the chapters and updated the Bibliography as appropriate. Finally, an Appendix has been included, giving a detailed list of conversion factors relating the SI units to the former ones.

London AM
March 1979 SAH

Authors' Note

The figures quoted in Table 9.1 refer to the characteristics of reference man from ICRP Publication 2 and not to those from ICRP Publication 23, as stated in the footnote to the table. The characteristics of reference man are slightly different in Publication 23 and the reader should consult it for more up-to-date values. For the purposes of this book, these changes have no significant effect as rounded values have been used in calculations.

1 *The Structure of Matter*

1.1 Introduction

Matter is the name given to the materials of which the Universe is composed. It exists in three physical forms: solid, liquid and gas. All matter is found to consist of a number of simple substances called elements.

An *element* is a substance which cannot be broken down by ordinary chemical processes into simpler substances. There are 92 naturally occurring elements, e.g. oxygen, and another dozen or so have been produced artificially in recent years, e.g. plutonium. In nature, elements are usually chemically linked to other elements in the form of compounds.

A *compound* consists of two or more elements chemically linked in definite proportions, e.g. water, H_2O, which consists of two atoms of hydrogen and one atom of oxygen.

1.2 The atom

Consider an amount of some element and subject it to repeated subdivisions. Using ordinary optical instruments a stage will eventually be reached when the fragments cease to be visible. Supposing, however, that suitable tools and viewing apparatus were available, would it be possible to repeat the divisions of the original element indefinitely or would a stage be reached where the matter can no longer be subdivided?

More than 2000 years ago, the Greek philosophers considered this question. They did not have any viewing apparatus with which to observe the actual division of an element into vanishingly-small fragments. All they could do was to think about the problem in a logical manner. From this philosophical approach some of them decided that eventually a limit must be reached. They called the individual particles of matter, which could not be further subdivided, *atoms.* It was also postulated by some of the philosophers that all substances consist of these same atoms. Different arrangements of the constituent atoms give the different properties of the substances and the density is determined by how tightly the atoms are packed.

The theories mentioned above were based on logical and philosophical considerations. Early in the nineteenth century, an atomic theory with a scientific basis was advanced which confirmed many of the views held by the ancient philosophers. This was the atomic theory of Dalton which was able to explain the well established but little understood chemical laws. Modern theory has diverged somewhat from Dalton's, but he did establish the principle that matter consists of atoms, each element having its own characteristic atom.

1.3 The structure of the atom

Modern research has shown that atoms are not solid, indivisible objects as the Greek philosophers believed but are composed of even smaller particles. These fundamental particles, from which all atoms are constructed, are called *protons, neutrons* and *electrons.*

The *proton* (p) carries a positive electrical charge of magnitude one unit on the nuclear scale, and a mass of approximately one *atomic mass unit* (u).

The *electron* (e^-) has a negative electrical charge of the same magnitude as the proton's positive charge. It has a mass of 1/1840 u, which for most purposes is neglected in considering the mass of the atom.

The *neutron* (n) is often regarded as a close combination of a proton and an electron. It is electrically *neutral* and, neglecting the mass of the electron, has a mass of approximately one atomic mass unit. In the text and in illustrations the neutron will generally be treated as a fundamental particle, in common with normal usage.

The neutrons and protons of an atom form a central core or *nucleus* around which the electrons rotate in various orbits. It is found that the orbit closest to the nucleus can contain a maximum of *2* electrons, while the second can have up to *8* electrons, and so on for the outer orbits. The inner orbit is called the *K orbit* (or K shell), the second orbit is called the *L shell,* the third the *M shell,* and so on. The maximum numbers of electrons in the K, L, M, N shells are 2, 8, 18, 32 respectively. For example, the atomic system

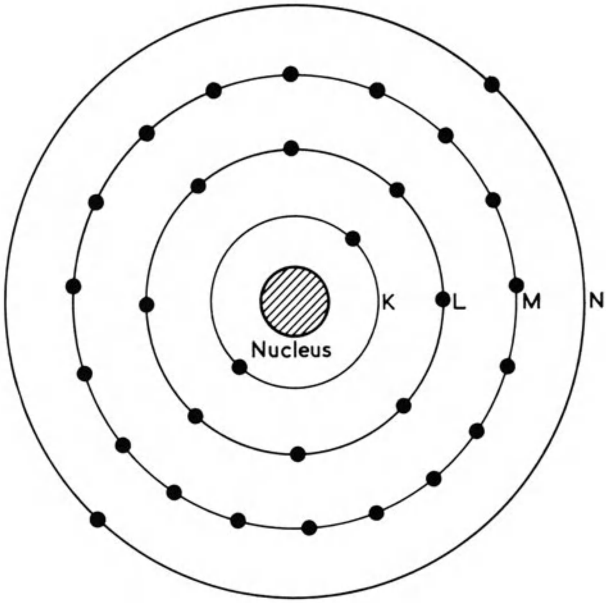

Figure 1.1 The atomic system of zinc.

of zinc, illustrated in Fig. 1.1 has 30 electrons arranged in 4 shells.

Each atom normally has the same number of protons as electrons. This means that the total positive charge on the nucleus is equal to the total negative charge due to the atomic electrons and so the atom is normally electrically neutral. Two simple atoms are illustrated in Fig. 1.2. The hydrogen atom is the simplest of all atoms and is the only atom which does not contain neutrons.

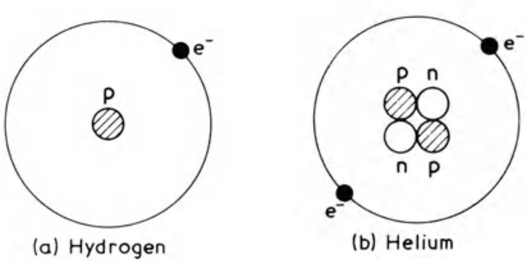

Figure 1.2 Atomic systems of hydrogen and helium.

1.4 Mass number

The mass of an atom is fixed by the number of protons and neutrons, if the very small mass of the atomic electrons is neglected. The sum of the number of protons plus the number of neutrons is called the *mass number* and is represented by the symbol A:

mass number (A) = number of protons + number of neutrons
For example, consider the helium atom in Fig. 1.2(b)

2 protons		2
2 neutrons		2
2 electrons (neglect)		–
mass number (A)	=	4

In the case of the hydrogen atom (Fig. 1.2(a))

1 proton		1
0 neutrons		0
1 electron (neglect)		–
mass number (A)	=	1

1.5 Atomic number

The number of protons in an atom is called the *atomic number*, represented by the symbol Z:

Atomic number (Z) = number of protons
e.g.
helium has 2 protons, $Z = 2$
hydrogen has 1 proton, $Z = 1$

The chemical symbol for helium is He and helium atoms of the type mentioned above would be designated $^4_2$He, and the hydrogen atoms (symbol H), $^1_1$H.

The number of protons, that is the atomic number, determines the chemical properties of the atom and so defines the element.

Thus:

all atoms with an atomic number of 1 are hydrogen atoms
all atoms with an atomic number of 2 are helium atoms
all atoms with an atomic number of 3 are lithium atoms
all atoms with an atomic number of 4 are beryllium atoms
all atoms with an atomic number of 5 are boron atoms
all atoms with an atomic number of 6 are carbon atoms..., etc.,

up to the heaviest naturally-occurring element, uranium, which has an atomic number of 92. About a dozen or so elements of higher atomic number have been artificially produced in recent years. They are all unstable and can only be made under special conditions which are not found naturally on Earth.

1.6 **Isotopes**

Although all the atoms of a particular element contain the same number of protons, they may occur with different numbers of neutrons. This means that an element can have several types of atom. For example, the element phosphorus (P) has an atomic number of 15 (i.e. each atom contains 15 protons), but it can occur with different numbers of neutrons:

$^{28}_{15}P$	15 protons, 13 neutrons	$(Z = 15, A = 28)$
$^{29}_{15}P$	15 protons, 14 neutrons	$(Z = 15, A = 29)$
$^{30}_{15}P$	15 protons, 15 neutrons	$(Z = 15, A = 30)$
$^{31}_{15}P$	15 protons, 16 neutrons	$(Z = 15, A = 31)$
$^{32}_{15}P$	15 protons, 17 neutrons	$(Z = 15, A = 32)$
$^{33}_{15}P$	15 protons, 18 neutrons	$(Z = 15, A = 33)$
$^{34}_{15}P$	15 protons, 19 neutrons	$(Z = 15, A = 34)$

These different forms are called *isotopes* of the element. Thus, for example, $^{32}_{15}P$ is an isotope of phosphorus. The three isotopes of helium ($Z = 2$) are illustrated in Fig. 1.3. These isotopes are normally referred to as helium-3, helium-4 and helium-5, respectively (^{3}He, ^{4}He, ^{5}He).

It is important to note that all the isotopes of a given element are *chemically* identical, since the chemical properties are determined by the atomic number of the element.

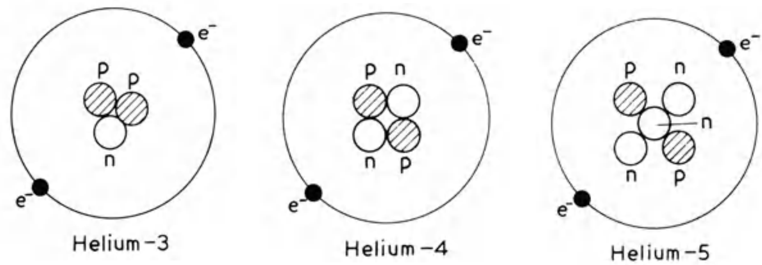

Figure 1.3 The three isotopes of helium.

Most elements occur naturally as a mixture of isotopes and other isotopes may be produced by bombarding a naturally occurring isotope with nuclear particles, for example by neutrons in a nuclear reactor. These artificially produced isotopes are unstable and will eventually disintegrate with the emission of a secondary particle or γ-ray photon (see Chapter 2).

Apart from the few lightest elements the number of neutrons exceeds the number of protons in an atom. The difference becomes greater as Z increases, e.g.

$^{4}_{2}He$	2 protons + 2 neutrons
$^{31}_{15}P$	15 protons + 16 neutrons
$^{65}_{30}Zn$	30 protons + 35 neutrons
$^{238}_{92}U$	92 protons + 146 neutrons

The known isotopes of all the elements, both naturally occurring and artificially produced, have been arranged systematically in a table known as the *chart of the nuclides* and this will be discussed in more detail in Chapter 2. The term *nuclide* means any isotope of any element.

1.7 Ancient and modern theories

It will now be seen that the ancient Greek philosophers were remarkably close to the truth in their theory that all substances are constituted from the same basic particles. However, instead of being different arrangements of only one type of particle, different substances appear to result from various combinations of three 'fundamental' particles: protons, neutrons and electrons. Nuclear physicists are still finding other apparently more fundamental particles, so that the Ancient Greeks may yet prove to have been correct.

Summary of chapter

Element: material whose atoms all have the same number of protons.
u: atomic mass unit.
Proton: fundamental particle, mass 1 u, charge +1 unit.
Electron: fundamental particle, mass 1/1840 u, charge −1 unit.
Neutron: close combination of proton and electron, mass 1 u, electrically neutral.
Atom: central nucleus of protons and neutrons, around which electrons rotate in orbits.
Mass number (A): number of protons + number of neutrons.
Atomic number (Z): number of protons.
Isotope: one of several nuclides with the same atomic number.
Nuclide: a nuclear species.

Revision questions

1. Using a billiard ball technique, draw an atom of each of the following nuclides:

$$^{4}_{2}\mathrm{He}, \quad ^{6}_{3}\mathrm{Li}, \quad ^{7}_{3}\mathrm{Li}, \quad ^{8}_{4}\mathrm{Be}$$

2. The nuclide cobalt 60 may be written $^{60}_{27}\mathrm{Co}$. How many protons, electrons and neutrons are there in this type of atom?

3. What are the masses and charges on the atomic scale of protons, electrons and neutrons?

4. Which atomic property determines the chemical behaviour of an element?

5. Explain what is meant by the term *isotope*. Give some examples.