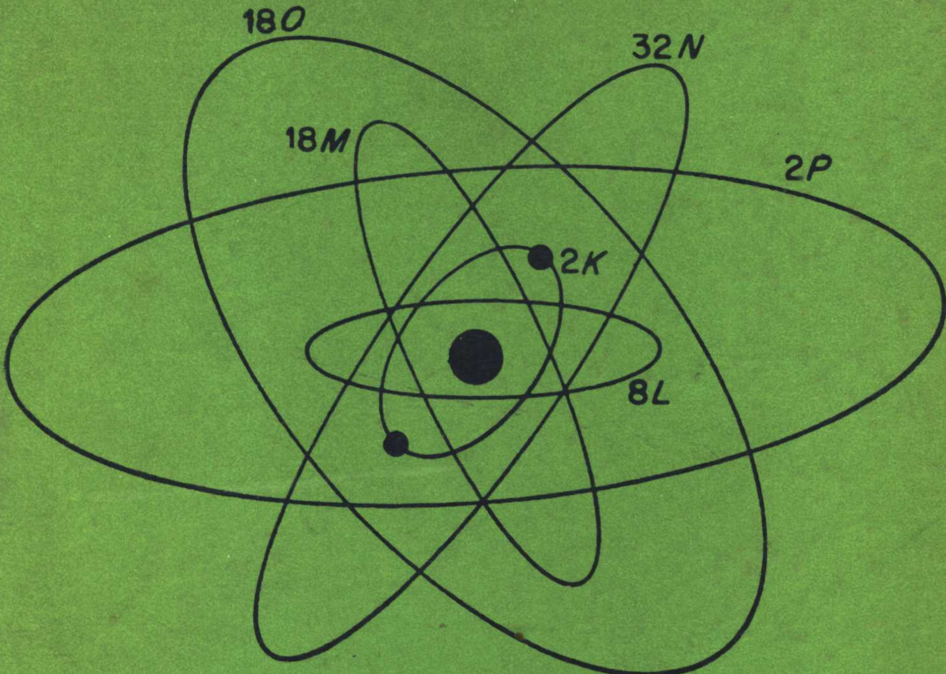

principles of radiological health

PRINCIPLES OF RADIOLOGICAL HEALTH

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PREFACE

The principles of radiological health are applied by the engineer or the health physicist to provide a healthful environment for people living in the nuclear age. This text is an outgrowth of the authors' recent experiences in classroom teaching, practical field applications, and advanced research. Thirty-five years of combined experience by the authors in teaching graduate radiological health courses, special radiation protection courses for engineers, scientists, and practicing physicians, and consulting in both radiation protection and radioactive waste management have provided the necessary basis for a definitive treatment of radiation protection and radioactive wastes management.

This basic textbook presents the problems and applications approach toward radiation safety. The specific premise underlying the book is that the practitioner should be able to measure the radiation exposure and/or dosage; to evaluate the hazards from the radiation; to design control methods, equipment, and procedures; to institute the controls; and to check the effectiveness of the measures initiated.

In order to be able to perform these actions effectively, one needs to have certain background information and theory. It is the authors' belief that no other book in existence fills the need of a text which prepares the engineer or other technical person to carry out these functions.

The first three chapters introduce the reader to nuclear reactions and the resultant energy releases. Chapter 4 lays the groundwork for interactions of radiations with matter, an understanding which is requisite for satisfactory measurements and evaluation of radiation effects. Chapter 5 defines the nomenclature and methodology for specifying radiation dosages. Formulas and their applications for calculating radiation dose for varying geometries, types of radiations, and modes of bodily intake are presented in a readily usable form.

The next three chapters are concerned with measurement of radiation. All current radiation measurement techniques are described. Successful measurements are those which are made with the minimum effort necessary to obtain the desired accuracy. Accomplishing this task requires a knowledge of not only the radiation measurement methods but also the principles and statistics of such measurements. The treatment of statistics is brief, but it includes example problems covering the full range of counting statistics.

Evaluations of radiation hazards are made from dosages and effects data derived from texts and incidental exposure experiences. Radiation effects include physical, chemical, and biological—all of these are described in Chapter 9.

The subject of environmental transport, Chapter 10, is developed around the three spheres of man's environment, namely, air, water, and soil. The movement of radionuclides through the environment deals with their continual uptake and release by specific chemical, physical, and biological processes.

Chapter 11, Radiation Protection Methods, provides a practical treatment of the subject matter. The breadth of coverage is wide ranging and includes topics from laboratory procedures to detailed shielding analyses.

The area of wastes management, the topic of Chapter 12, considers the various aspects of handling, treating, and disposal for liquid, solid, and gaseous wastes. Information is provided on the present practices of storage, concentration, and containment of high-level and intermediate-level wastes, as well as the dilution to the environment of low-level wastes. Descriptions are included of the various methods of offgas handling, containerization, and ultimate storage. Ways of dissipating waste heat generated by decaying radionuclides are also discussed.

Today X rays are the major source of ionizing radiation exposure to the population. Consequently, a detailed chapter on X rays is included. In Chapter 13, the subjects treated are (a) generation, (b) usage, (c) exposure, and (d) shielding. This information is particularly applicable for X-ray technicians, public health workers, and various professionals.

Nonionizing radiations are causing increased concern. Increasingly powerful sources such as radar and lasers are presenting new and potential health hazards. This topic is introduced in Chapter 14, because the principles of control are closely related to those for ionizing radiation. Recent legislation has treated these two subjects together and an introduction to this text is justified.

Ionizing radiation is an integral part of modern science and technology. The use of nuclear energy in modern industry is of considerable importance today, but the major impact is still to come. Man's daily experiences with ionizing radiation, whether through medicine, engineering applications, or scientific research, will increase. While the nuclear power industry is expected to increase a hundredfold by the year 2000, the acceptance of ionizing radiation to drive chemical reactions must not be underestimated.

Those of us engaged in teaching and research have observed the development and growth of problems associated with radiological health. The need for a textbook emphasizing radiological health principles, particularly as these basic concepts can be used in modern technology, is apparent. Similarly, there is an obvious need for a useful reference source which illustrates the practical problems of ionizing radiation control.

Acknowledgments are extended to those many students who have assisted in the development of this text.

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CONTENTS

CHAPTER 1 ATOMIC STRUCTURE

The atom may be viewed as having two principal parts—the extremely dense nucleus and the electron field that surrounds the nucleus. Each of these provides the basis for a whole, complex area of study. Nuclear physicists and chemists are concerned with the characteristics of the nucleus and its parts, while the study of the electron field has moved beyond the determination of chemical valence to quantum mechanical considerations. By definition the *atom* is the smallest unit of an element which exhibits all the chemical properties of the element.

1-1. Historical Concepts

Many scientific and philosophical hurdles had to be overcome before the atomic-molecular theory of structure was generally accepted. The concept of matter and atoms can be traced to antiquity; however, the nuclear concept was introduced by Rutherford only within this century.

The early Greek philosophers sought to develop a connection between their philosophies on matter, being, and becoming, and the material world. Democritus and his teacher Leucippus in the fifth century B.C. postulated that all matter was composed of very small, but finite, particles that could not be cut, *atomos*. Democritus' theories went even further and described compounds. However, owing to the strong influence of the mistaken beliefs of Aristotle, the atomic-molecular theory was dormant for 2000 years. The natural atomic sciences began to develop along the lines that they are known today after chemist and physicist Robert Boyle (1627–1691) produced his theories on the behavior and composition of gases. Through these efforts and those of Bacon, Newton, and others, the theories of Democritus finally prevailed. Then Lavoisier, the acknowledged "father of chemistry," interpreted the process of combustion. Richter (1792) and Dalton (1803) proposed the ideas that chemical elements always combine in definite quantitative proportions to give compounds. Dalton's atoms were followed by Avogadro's molecules (1811). Avogadro maintained that, at the same temperature and pressure, equal volumes of all gases contained the same number of molecules. The relationships between Avogadro's number (N_a) and mass are shown by

$$N_a = 6.025 \times 10^{23} \text{ atoms/gram atomic weight (also molecules/gram molecular weight)} \quad (1\text{-}1)$$

and a term defined as the atomic mass unit (amu)†:

$$\text{amu} = (1/N_a)\text{ g} = 1.66 \times 10^{-24}\text{ g} \quad (1\text{-}2)$$

Using Dalton's concepts, Berzelius turned to laboratory experimentation to establish combining weights which he believed to be atomic weights. He changed the basis of atomic weights from hydrogen equal to 1, as Dalton used, to oxygen equal to 16, because oxygen is more reactive than hydrogen. Berzelius furthered the concept of valence in chemical bonds and started the shorthand element and compound notation that is used today. Another step toward understanding the atom was made by Faraday (1791–1867), who proved that there is a relationship between the amount of substance transformed electrically and the amount of electricity required to induce the transformation. This relation is now known to be 96,514 coulombs (C) per gram mole equivalent, Faraday's constant (F_a); e.g., a sodium chloride solution would liberate 1 g mole of sodium (univalent) at the cathode for each 96,514 C of electricity applied.

Advances made by Maxwell, Clausius, and Boltzmann showed that gases did indeed consist of molecules in rapid motion, as Boyle had postulated. In 1865 Loschmidt determined the approximate size of molecules and the number present in 1 cm^3 of gas. A more nearly accurate size of about 10^{-8} cm for the diameter of an atom was set by Lord Kelvin in 1870, but Loschmidt had shown the way. The very small size of the atom may be better illustrated by stating that 10 million atoms placed in a line would extend only 1 mm.

Shortly prior to 1900, the work of Hittorf and J. J. Thomson led to the conclusion that the atomistic behavior of an ionic charge varies only in

† For complete information regarding abbreviations, see Appendix A.

multiples of a basic unit, indicating that the charge is carried by some kind of indivisible particle. Several years before, Stoney had suggested the name *electron* for the elementary unit of electrical charge and the term was adopted for the particle. Of considerable importance is the fact that electrons are always associated with the same mass of 9.107×10^{-28} g (when at rest). The significance of the electron to an overall understanding of the atom is illustrated by pointing out that conventional chemistry and atomic physics are primarily studies of the behavior of electrons with respect to atoms.

Millikan showed by measuring the terminal settling velocities of oil drops in different electrical fields (1911) that the electric charge in atoms really does occur only in multiples of an elementary unit (ϵ).

$$\epsilon = \frac{F_a}{N_a} = \frac{(96{,}514 \text{ C/gmole equivalent})}{6.025 \times 10^{23} \text{ molecules/gmole}}$$
$$= 1.60 \times 10^{-19} \text{ C} = 4.80 \times 10^{-10} \text{ electrostatic units (esu)} \quad (1\text{-}3)$$

Oil droplets suspended in an electric field make possible the equating of the gravitational force ($m \cdot g$) with the electrical force ($q \cdot E$); i.e.,

$$\text{force} = m \cdot g = q \cdot E \quad (1\text{-}4)$$

where m = mass
g = acceleration of gravity
q = total charge on drop = number of electrons $\times\ \epsilon$
E = electrical field strength (potential/distance)

The movement of a charged particle across an electrical potential also forms the basis for defining the elemental unit of energy used in radiological health—the *electron volt* (eV). An electron volt is the amount of energy gained by an electron moving across a potential of 1 V, as shown in Fig. 1-1.

1-2. Periodic Table of the Elements

Although Döbereiner and others had noted a relationship between the chemical properties of atoms and their atomic weights as early as 1829, it remained for Mendeleev to systematize this connection into the periodic law in 1870, a law which states that the properties of the elements are periodic functions of their atomic weights. Mendeleev was so confident in his scheme that he left blanks for some undiscovered elements and claimed that some of the measured atomic weights were in error—he was