RADIATION BIOPHYSICS

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PREFACE

THE DISCOVERY and exploitation of the self-sustaining nuclear chain reaction has had an explosive impact upon all facets of human existence. On the one hand nuclear detonations of fantastic power can be readily produced, so that all living things are potentially exposed to radiation from such detonations. On the other hand nuclear power is becoming increasingly available both in fixed installations and for vehicle propulsion. Hundreds of varieties of radioactive nuclides have been added to those few formerly available in minute amounts from natural sources.

These new radiation sources carry both a promise and a threat. The promise includes improvements in medical diagnosis and treatment, and the unknown future benefits to be derived from improved research methods. The threat includes the possibility of causing, through careless use today, injury to presently unborn thousands, through an accumulation of an undesirable genetic burden. Obviously, both the potentialities and the hazards of these new substances must be thoroughly understood by all who use them.

In the early days detailed knowledge of the physical and biological properties of penetrating radiation resided largely with those who were collaterally increasing that knowledge. Today such an enormous body of literature is available that it is sometimes difficult to separate the pertinent from the relatively less important.

The present book is aimed at presenting a working knowledge of radiation fundamentals to those just making its acquaintance. No apology is made for what may seem to be an overemphasis on physical principles. Without an understanding of these principles one can hardly expect to explain chemical and biological actions, or to use effectively and safely any of the wide variety of radiation sources presently available. Large numbers of disconnected bits of biological information exist, but there seems little to gain by a routine description of many of them. A detailed treatment must await the discovery of some unifying principles not now available. It is this philosophy which has led to what may seem like a casual treatment of the phenomenological aspect of radiation injury.

This book, like almost any other, comes from the work of so many investigators and teachers that complete acknowledgment is impossible. I am particularly indebted to Drs. W. W. Smith and F. Smith for much invaluable advice and counsel. To Jean and Alice Andrews, who participated in all of the tedious phases of manuscript preparation, my gratitude for a job well done.

H. L. A.

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BASIC PRINCIPLES

1.01 ELEMENTARY PARTICLES

The production of X-rays in 1895 and the discovery of radioactivity in 1896 inaugurated an era of most intensive research into the nature of matter and energy, and the interactions between them. Experiment and theory agreed that matter is made up of various combinations of a relatively few types of elementary particles. As research in nuclear physics intensified, and more refined equipment became available, more and more particles were discovered, and at present the list of identified types is a formidable one. The roles played by some of these particles are quite clear but the function of others is obscure.

Some of the elementary particles interact very weakly with the matter through which they pass, or appear as free particles only rarely. These play no direct, major role in the reactions of radiation with chemical systems or living tissue. For present purposes we can confine our attention to those particles listed in the upper section of Table 1-1.

Table 1-1. PROPERTIES OF ELEMENTARY PARTICLES

Name	Symbol	MASS amu	MASS m_e	Charge	Comments
Electron	e^-	0.000549	1	-1	Stable
Positron	e^+	0.000549	1	$+1$	Lifetime 10^{-6} sec
Proton	p	1.007593	1,836	$+1$	Nucleus of hydrogen
Neutron	n	1.008982	1,838	0	Lifetime 13 min
Neutrino	ν	Less than $0.01 m_e$		0	Accompanies β decay
L meson	π, μ	$(206\text{–}273)m_e$		$+1, -1, 0$	Lifetime 10^{-6} sec
K meson	$\tau, \theta, \chi, \varkappa$	$(960\text{–}965)m_e$		$+1, -1, 0$	or less
Hyperon	Λ, Σ, Ξ	$(2{,}180\text{–}2{,}580)m_e$		$+1, -1, 0$	

Particle masses are given in Table 1-1 in terms of *atomic mass units* (amu) and as multiples of the electron mass, m_e. By definition one amu is equal to $\frac{1}{16}$ the mass of one atom of the most common form or *isotope* of oxygen. In the physical system of atomic weights this oxygen isotope is assigned the value 16.0000 to form the basis for the system. Since one gram-atom of any element contains 6.02×10^{23} atoms,* a single atom of the common isotope of oxygen will have a mass of $16/6.02 \times 10^{23} = 2.66 \times 10^{-23}$ gm. Hence 1 amu $= 1.66 \times 10^{-24}$ gram. The amu is very nearly, but not quite equal to the chemical atomic weight unit, which is obtained by assigning 16.0000 to naturally occurring oxygen instead of to the common isotope.

The values of electric charge listed in Table 1-1 are obtained by assigning to the electron the value of -1. The magnitude of this charge is the smallest amount of free electric charge known to exist. In general, electrical quantities are expressed in one of three systems of units derived from the basic definitions of mass, length, and time. We shall occasionally make use of these three systems, but for most calculations shall find the electron unit to be preferred. The systems are interrelated as shown below.

$$\text{one electron charge} \begin{cases} 1.6 \times 10^{-20} \text{ electromagnetic units (emu)}\dagger \\ 1.6 \times 10^{-19} \text{ practical units (coulombs)} \\ 4.8 \times 10^{-10} \text{ electrostatic units (esu)} \end{cases} \qquad (1\text{-}1)$$

* Avogadro's number. More accurate values of this and other constants will be found in the Appendix.

† The notation and abbreviations used in this book are in accord with the Style Manual, 2nd ed., American Institute of Physics, New York, 1959.

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In the domain of these elementary particles size cannot be uniquely defined. Fortunately, exact sizes are of little consequence for present purposes—it is sufficient to think of the elementary particles as spheres with radii of the order of 10^{-13} cm.

1.02 ELECTROMAGNETIC RADIATION

Long before substantial progress was made in identifying the elementary particles, physicists had recognized that energy could be transmitted through space by *electromagnetic radiation*. The nature of visible light, one of the many manifestations of electromagnetic radiation, had been intensively investigated. It was known that electromagnetic radiation was propagated like a wave motion, and methods were devised for measuring wavelengths with extraordinary accuracy.

Theoretical studies by Maxwell showed that electromagnetic radiation consisted of interdependent electric and magnetic fields vibrating at a frequency ν which is related to the wavelength λ and the velocity of propagation c by the basic wave equation

$$\lambda\nu = c \tag{1-2}$$

In free space the velocity of propagation of any electromagnetic wave is nearly 3×10^{10} cm/sec. In a ponderable medium the velocity may be considerably less than c, $\cong$ (2×10^{10} cm/sec), and this results in a phenomenon known as Cerenkov radiation, to be discussed later.

At the turn of the century it was becoming evident that wave properties would not serve to explain energy interchanges between radiation and matter. In 1901 Max Planck made the then startling assumption that in energy exchanges radiation does not behave like a continuously distributed wave, but rather like an energy package of discrete size, the size being given by

$$E = h\nu \tag{1-3}$$

where E = energy in ergs
h = Planck's constant, 6.62×10^{-27} erg sec
ν = number of vibrations per second.

Each energy package is known as a *photon*, or *quantum*.

The dual nature of electromagnetic radiation has been demonstrated repeatedly. Since we will be concerned primarily with energy exchanges there will be little occasion to consider the wave properties, and quantum concepts will be used almost exclusively.

Known electromagnetic radiations cover an enormous wavelength range, Fig. 1-1, and have strikingly different properties. Although

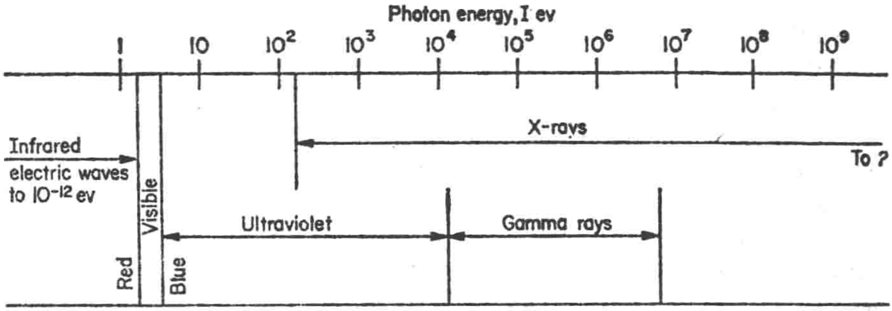

Fig. 1-1. The electromagnetic spectrum plotted on a logarithmic energy scale.

methods of generation differ, all the various electromagnetic radiations are basically similar, differing only in wavelength and hence in photon energy. In particular, as we shall see later, X-rays and gamma rays are produced by quite different processes, but once emitted are indistinguishable if the photon energies are equal.

Because of the enormous range of the electromagnetic spectrum, a variety of units has been found useful in measuring wavelength. In the radio region the meter or centimeter is the usual unit. The centimeter is an inconveniently large unit in the domain of X-rays and gamma rays, where the *Angstrom*, A, is customarily used

$$1\text{ A} = 10^{-8}\text{ cm} = 10^{-10}\text{ m}$$

Some older wavelength data are given in x units where

$$1\text{ xu} = 10^{-11}\text{ cm} = 10^{-3}\text{ A}$$

1.03 THE ELECTRON VOLT

Consider an evacuated tube, Fig. 1-2, containing a fine wire filament F, and a cold metal anode A. If the filament is heated by passing an electric current through it, free electrons will be emitted by the hot wire into the surrounding space. If the anode is positively charged to potential difference V above the filament, each emitted

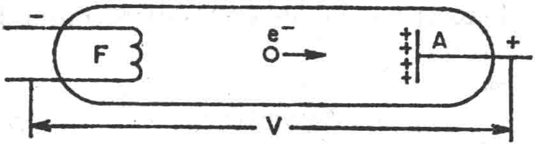

Fig. 1-2. Kinetic energy acquired by an electron as work is done on it by an electrical potential.

electron will experience an attractive force and will move toward the anode. Just before striking the anode each electron will have a kinetic energy equal to the work done by the potential V on the electric charge e, carried by the electron.

The principle of conversion of work by an electric potential into kinetic energy is simple but the application is complicated by the various systems of electrical units. To avoid restriction to the electronic charge e, consider the general case of any electric charge Q moving through a potential difference V. The various systems of units are arranged to satisfy the following relations:

$$V\ (\text{esu}) \times Q\ (\text{esu}) = W\ (\text{ergs})$$
$$V\ (\text{emu}) \times Q\ (\text{emu}) = W\ (\text{ergs})$$
$$V\ (\text{volts}) \times Q\ (\text{coulombs}) = W\ (\text{ergs} \times 10^7)\ \text{or joules.}$$

Now let V, Fig. 1-2, equal one volt and consider an electron which, from Eq. (1-1) has a charge of 1.6×10^{-19} coulomb. Then

$$W\ (\text{electron volts}) = 1 \times 1.6 \times 10^{-19}\ \text{joule} = 1.6 \times 10^{-12}\ \text{erg} \quad (1\text{-}4)$$

The *electron volt*, ev, defined by Eq. (1-4) is the basic unit of energy used in most radiation studies. Natural extensions are:

10^3 ev = 1 Kilo electron volt, Kev
10^6 ev = 1 Mega electron volt, Mev = 1.6×10^{-6} erg
10^9 ev = 1 Billion electron volt, Bev

Careless application of these terms may lead to confusion between units of electrical potential and units of energy. When, for example, 250 kilovolts (250 kv) is applied to an X-ray tube, each electron striking the target has an energy of 250 Kev. The numerical agreement comes about because the accelerated particles have a single charge. The same potential would impart twice the energy to doubly charged particles, and so on.

Equation (1-3) may now be put in a form more useful for numerical calculations. This is best done in terms of λ since this is a quantity capable of experimental determination. From Eqs. (1-2) and (1-3)

$$E\ (\text{ergs}) = \frac{hc}{\lambda} \tag{1-5}$$

$$E\ (\text{ev}) = \frac{6.62 \times 10^{-27} \times 3 \times 10^{10}}{1.6 \times 10^{-12}\,\lambda} = \frac{1.24 \times 10^{-4}}{\lambda}$$

If λ is expressed in Angstroms instead of centimeters and E is in Kev

$$E\ (\text{Kev}) = \frac{12.4}{\lambda_A} \tag{1-5A}$$

Illustrative Example

Radioactive cobalt, Co^{60} emits a gamma ray whose wavelength is measured as 0.01060 A. Calculate the energy of this gamma-ray photon.

$$E = \frac{12.4}{0.01060} = 1170\ \text{Kev} = 1.17\ \text{Mev}$$

1.04 THE BOHR ATOM

In 1910, Rutherford reported the results of a series of experiments which demonstrated that matter consists essentially of empty space with particles separated by distances which are large compared to their own size. The Rutherford model was extended and put on a quantitative basis by Niels Bohr, who in 1913 announced the theory of atomic structure now bearing his name. The Bohr theory was based on a simple physical picture of atomic structure and gave surprisingly accurate predictions of the spectral lines emitted by atomic hydrogen.

According to the Bohr theory an atom of hydrogen appears as in Fig. 1-3. The *nucleus* of the atom is a single proton which is very massive when compared to the electron revolving around it. An electrostatic force of attraction exists between the two unlike charges, and indeed such a force is required to maintain the electron in uniform circular motion. The attractive force follows an *inverse square law*

$$F = \frac{e \times e}{r^2} \tag{1-6}$$

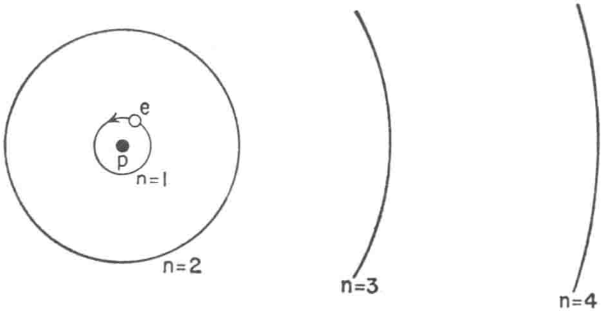

Fig. 1-3. The Bohr model of hydrogen in its ground state. The proton and electron are enlarged 10^5 times in relation to the radii of the orbits.

where F is the force in dynes, e the electric charge in esu, and r the orbital radius in cm. Conditions imposed by the theory restrict the electron to a series of *allowable* orbits whose radii can be calculated from well-known physical constants. These radii are of the order of 10^{-8} cm so the Bohr model is in accord with the empty-space requirements of the Rutherford experiments.

Each allowable orbit has an associated energy content and it is actually more precise to think of a series of allowable *energy levels* rather than a series of orbits. Normally the electron remains in the state of lowest possible energy, or *ground state,* corresponding to the innermost orbit. This orbit or energy level is designated by a *principal quantum number* $n = 1$.

In an electric discharge, or at high temperatures where energetic collisions can occur, the electron may receive sufficient energy to raise it to a higher energy level $n = 2, 3 \ldots$ and then the atom is said to be in an *excited state.* Note that energy must be put *into* the electron to raise it from the ground state against the electrostatic force of attraction. After perhaps 10^{-12} sec the electron will return spontaneously to the ground state and will get rid of the excess energy by the emission of a photon of electromagnetic radiation. The return to the ground state may take place in a single step or as a series of transitions through intermediate allowed states, each accompanied by the emission of a photon.

Each photon emission obeys the relation

$$h\nu = E' - E \tag{1-7}$$

where E' is the energy of the state preceding radiation and E is the energy of the state following. In the case of hydrogen the emitted frequencies lie in the visible and ultraviolet regions of the electromagnetic spectrum, Fig. 1-4.

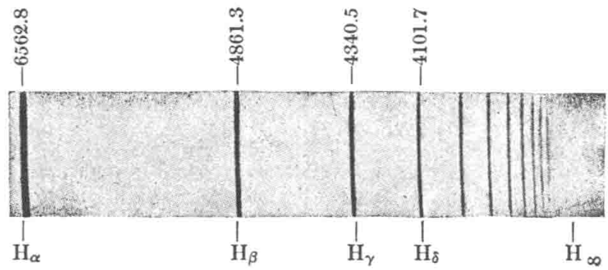

Fig. 1-4. Emission spectrum of atomic hydrogen in the visible and near ultraviolet. Wavelengths in Angstroms. From Herzberg, *Atomic Spectra and Atomic Structure.* Prentice-Hall, Englewood Cliffs, N. J., 1937.

Values of E corresponding to values of the principal quantum number 1, 2, 3 . . . can be readily calculated from known physical constants and so predicted values of $h\nu$ can be compared with those actually observed in the emission spectrum of atomic hydrogen. The close correspondence shows that at worst the Bohr model is a good approximation to the true situation. Later theories have reduced the physical reality of the orbits, but the concept of energy levels is retained, as is the relation between radiated energy and energy-level transitions.

1.05 THE FOUR QUANTUM NUMBERS

Although the original Bohr theory gave wavelength predictions in remarkable agreement with observation, there were discrepancies well outside the experimental errors, and many physicists attempted to modify the theory to obtain closer agreement. As a result of this work it appears that four quantum numbers rather than one are needed to specify the energy state of an electron.

The principal quantum number n, which can take on integral values 1, 2, 3, . . . has been used in referring to circular orbits. The laws of mechanics governing planetary motion permit elliptical as well as circular orbits, but quantum restrictions allow only certain

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