RADIATION HAZARDS and PROTECTION

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FOREWORD

By Sir Ernest Rock Carling, F.R.C.S.

This book appears at a particularly opportune moment. There is every justification for present preoccupation over the Country's training resources for educating all those whose services will shortly be needed to ensure safe exploitation of the potentials for public good that lie in nuclear energy.

Courses of instruction will be needed at all levels: for those whose duties demand no more than "orientation" in the nuclear field; for those whose knowledge must be highly expert and only to be completed by experience "on the job"; and for intermediate groups who must themselves, or through their staffs, be sufficiently informed to co-operate effectively with the highly qualified officers of Ministries, Local Authorities, Industrial Establishments and major autonomous bodies.

The Authors have both of them personal experience of radiation hazards and of methods of protection. They know what must be taught and how the knowledge acquired should be applied. They seem to me to have supplied just such a book as very many of those entering for any but the extremely advanced course of instruction will need to have always at hand. The text is not all of it simple, but it is understandable even by those who are not well versed in mathematics or physics. It does not deal exhaustively with the biological or medical aspects of the problems, but it says enough for those who, while concerned more particularly with the material aspects, ought also to know of the human implications if they are to appreciate to the full what protection and safety mean. To ensure safety, measurement of the hazard is a fundamental requisite. The book's strongest recommendation is the excellent account of instrumentation to that end.

E. Rock Carling

PREFACE

DURING the past ten years or so there has been a rapid growth of interest in radioactivity and of work with radioactive substances. Many people are concerned as to the possible hazards of such work and as to whether the dangers can be avoided.

There have, of course, been many articles published in specialist journals which deal with different branches of this subject but there has been little attempt to present a comprehensive survey of the whole subject in a readily accessible form. In this volume we have tried to bring together such of the available data and current practice as our experience leads us to believe will be of assistance not only to all those who have to work with radioactive materials or radiation generators but also to many others, not necessarily scientists, who are interested to know what all this business of radiation is about.

The plan of the book is to explain first the nature of the hazard, then to state the levels of radiation which are accepted as safe and to describe the protective methods by which these safe levels can be attained and the measurements which will show whether satisfactory conditions have been achieved. In the last chapter the radiological hazards arising from atomic warfare are discussed together with the protective measures which are possible.

So far as is practicable, we have tried to make each chapter largely self-contained so that the reader in referring to a particular aspect is sufficiently reminded of the basic information without having to search for it. This has meant a certain amount of duplication, but we hope that it will make the book more valuable to those who wish to use it as a work of reference.

Some readers may wish to purchase apparatus for making health physics measurements. We have not attempted to single out any of the many excellent instruments which are now on the market, but we have tried to explain the types of instrument required and their important characteristics. For detailed information as to what is currently available the reader is advised to study the Buyers' Guides published from time to time in magazines such as *Nuclear Power* and *Nuclear Engineering* (for British instruments) and *Nucleonics* (for American instruments). A wide range of apparatus, including protective and handling devices, is also described in the catalogue of *British Nucleonic Instruments* published by the Scientific Instrument

Manufacturers Association and obtainable from their offices at 20 Queen Anne Street, London, W.1.

Most of the figures have been specially drawn for this book, but in a number of cases we have been allowed to reproduce drawings from earlier publications by the authors. We are indebted to the Institution of Electrical Engineers for allowing us to reproduce Figs. 18, 19, 37, 43 and 44 which have previously appeared in their Proceedings, the *Journal of Scientific Instruments* for the republication of Fig. 30 and the journal *Nuclear Power* for the republication of Figs. 31 and 32. In addition we acknowledge the assistance of the U.K.A.E.A. in allowing us to reproduce Figs. 21, 27, 33, 34, 39, 40, 42, 50 and 51, also Plates II, IV, V and VIII, the Plessey Co. for Fig. 49 and Plate III, Messrs. E. K. Cole for Plate VII and R. A. Stephens & Co. for Plate I. Also Dr. Anderson of the Los Alamos Scientific Laboratory for Plate VI.

It would not be possible in a book of this size to include all that it is necessary for a Health Physicist to know, indeed we would not encourage anyone to think that the practice of Health Physics could be learned from a book for there is too much that only training and experience can teach; nevertheless we hope that it will prove adequate to solve the day-to-day problems of those who do not have a trained Health Physicist to advise them. In addition, persons who are responsible for work involving radiation and who feel in need of advice on specific problems may obtain assistance, including a film dosage service, from the Radiological Protection Service (Ministry of Health and Medical Research Council), Clifton Avenue, Sutton, Surrey.

D. E. Barnes
Denis Taylor

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CHAPTER 1

NATURE AND PROPERTIES OF RADIATION

RADIATION AND ENERGY

RADIATION is a form of energy and this energy may exist as an electromagnetic wave or as the mass and momentum of a particle. It is usual to consider a particular type of radiation as taking one or other of these forms, but by de Broglie's theory the two are interchangeable and a moving particle may be regarded as a wave of frequency depending on the momentum of the particle, or conversely a quantum of electromagnetic radiation may equally well be regarded as a particle and is then known as a photon. This dual nature of radiations is illustrated by the fact that electrons, which are normally thought of as particles, can be diffracted by a crystal lattice in much the same way as can X-rays; and again X-rays when they undergo Compton scattering behave like a particle in collision with another particle, the electron.

In radiation work the energy of photons, electrons and other particles is generally measured in electron-volts (eV) which is the amount of energy gained by an electron when it falls through a potential difference of one volt. This is equivalent to $1{\cdot}60 \times 10^{-12}$ erg.* The electron-volt is a small unit so that multiples of a thousand (keV) and a million (MeV) are commonly used and a thousand million (BeV) occasionally.

As well as the kinetic energy due to their motion, particles have mass which in certain circumstances is converted into energy in the form of electromagnetic radiation. The energy equivalent of mass is given by the Einstein equation, $E = m_0c^2$, when E is the energy in ergs, m_0 is the rest mass of the particle in grams and c is the velocity of light in cm/sec.

The velocity of propagation of all electromagnetic radiation is the same as that of light and has a constant value (3×10^{10} cm/sec) irrespective of the energy of the radiation. The velocity of particles, other than photons, depends on their energy and is given by $E_k = \frac{1}{2}mv^2$. The mass (m) may be taken as the rest mass except when the velocity approaches that of light when there is a significant relativistic increase of mass.

* Potential difference is work done in carrying unit charge from one point to the other. Charge on electron is $4{\cdot}80 \times 10^{-10}$ e.s.u. and one volt is $\frac{1}{300}$ e.s.u.

X-RAYS AND GAMMA-RAYS

The discovery of X-rays by Röntgen in the year 1895 marked the beginning of radiation physics. It was soon found that this radiation would penetrate considerable thicknesses of light materials such as cardboard and wood and small thicknesses of metals. By modern standards these were very low energy or *soft* X-rays and their penetrating power was small.

X-rays are produced in two ways, either by the sudden stoppage of fast-moving electrons or by a change of level among the orbital electrons of an atom. The latter gives rise to a line spectrum, the energies of the lines corresponding to the energy difference between the levels in the atomic structure; it is called *characteristic* radiation because the energies of the radiation are characteristic of the atom in which it arises. The stopping of electrons, such as occurs at the anode of an X-ray tube, causes a broad continuous spectrum. Its maximum energy is that of the electrons producing it, but the intensity here is very low because very few of the electrons lose all their energy in a single collision; the intensity rises rapidly to a maximum at about two-thirds of the electron energy and then falls away more slowly, tailing off to zero at very low energies.

Superimposed on this will be sharp peaks of characteristic radiation due to the excitation of the atoms of the target (Fig. 1). The

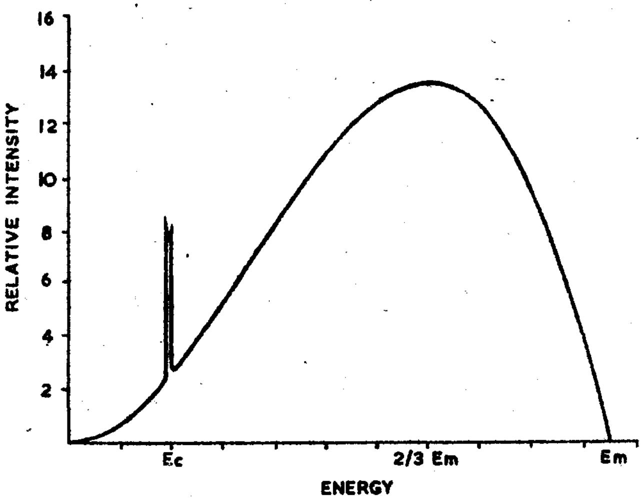

FIG. 1. TYPICAL X-RAY SPECTRUM

E_m is maximum energy of electrons. Peak intensity is at about two-thirds of E_m. E_c is energy of characteristic radiation continuous spectrum of X-rays is sometimes called *white radiation* by analogy with white light and sometimes *bremsstrahlung* from the German for *braking radiation*. As noted above the maximum energy of the radiation corresponds to the maximum energy of the electrons and this, in the case of an X-ray tube, will equal the maximum potential applied to the tube which is commonly expressed as kilovolts peak (kVp). The wavelength of this maximum energy radiation is given by the relations:

$$E = h\nu \quad \text{and} \quad \nu = c/\lambda$$

where E = energy in ergs,
h = Planck's constant,
ν = frequency,
λ = wavelength in cm.

The wavelength is usually measured in Ångström units (Å) which are 10^{-8} cm, so that converting to these and to energy in keV:

$$E\,(\text{keV}) = \frac{1}{\lambda\,(\text{Å})}\,\frac{6{\cdot}62\times10^{-27}\times3\times10^{10}\times10^{8}}{1{\cdot}6\times10^{-12}\times10^{3}} = \frac{12{\cdot}4}{\lambda\,(\text{Å})}$$

X-ray energies range from a few keV up to tens of MeV, giving wavelengths from around 10 Å down to less than 10^{-3} Å.

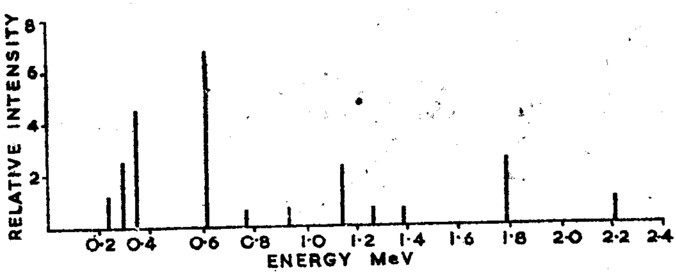

FIG. 2. LINE SPECTRUM OF γ-RAYS FROM RADIUM (RaB + RaC)

Gamma-rays differ from X-rays only in their origin. They come from a rearrangement of the nucleus of an atom and, as in the case of characteristic X-rays, the spectrum consists of a series of lines (Fig. 2) the energies of the γ-ray lines being associated with differences in energy levels in the nucleus. Many γ-ray emitters have only a single line, others two or more, while a few have a complex spectrum. Energies mostly lie in the range 0·1 MeV to 3 MeV with a relatively small number above and below.

Various types of events give rise to γ-rays, the most important being:

(a) radioactive disintegration, when there is usually accompanying beta radiation,
(b) nuclear fission, when there is an instantaneous emission of γ-radiation followed at a later stage by disintegration of the fission fragments,
(c) capture reactions in which a neutron enters into the nucleus and a gamma photon is emitted.

The penetration of X- and γ-rays is illustrated by the table of thicknesses (Table 1) which will reduce the intensity to approximately one-half.

TABLE 1.—HALF-VALUE THICKNESSES IN CM

Energy	100 keV	1 MeV	10 MeV
Aluminium	1·5	4·3	11·0
Iron	0·25	1·5	2·9
Lead	0·01	0·9	1·2

ALPHA RADIATION

Alpha particles are emitted on the disintegration of certain radioactive isotopes, principally those of heavy elements. They are identical with helium nuclei, having a mass of four atomic mass units (a.m.u.)* and a positive charge of two units (the charge on an electron being taken as one unit).

Because of their relatively large size they have little penetrating power and are completely stopped by paper, thin metal foil or even a few centimetres of air (Fig. 3).

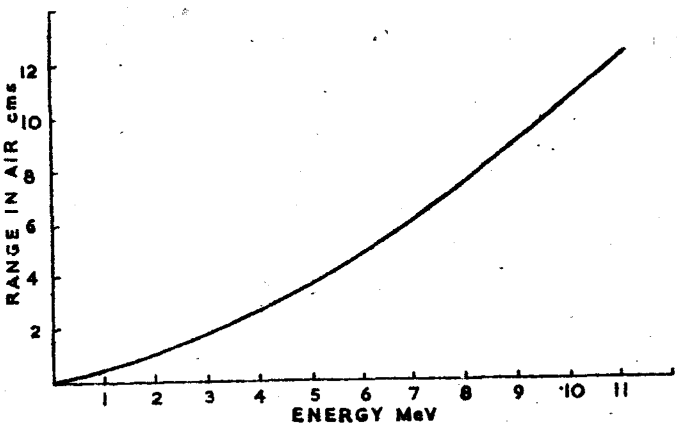

FIG. 3. RANGE OF α-PARTICLES IN AIR

* An a.m.u. is one-sixteenth of the mass of the oxygen atom.

The energies of α-rays lie in a limited band from about 4 to 9 MeV with corresponding approximate range in air of 2·5 to 8·5 cm.

BETA RADIATION

Beta particles are given out by the majority of radioactive isotopes, sometimes alone but more often accompanied by gamma rays. They can be either negatively or positively charged, but usually a reference to beta particles means the negatively charged type. These negative β particles are identical with electrons and after emission when they have lost their energy become part of the free electron population. The positive particles are the same as positrons and are usually referred to in that way or as β^+. The positrons have a very short life, of the order of a micro-second, before meeting with a free electron when both are annihilated with the emission of two photons of 0·5 MeV energy.

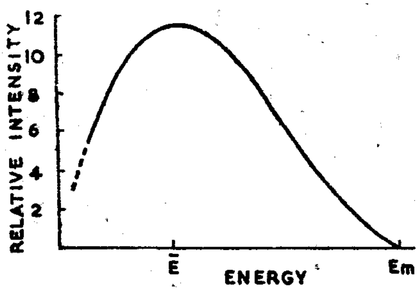

FIG. 4. TYPICAL SPECTRUM OF β-RADIATION
E_m is maximum energy emitted by the nuclide. $\bar{E}$ is mean energy and is about one-third of E_m

Whereas γ-rays and α-particles are emitted with discrete energies corresponding to differences between energy levels in the nucleus, it is found that β-rays are emitted with a spread of energy from almost zero up to a maximum value which depends on the isotope (Fig. 4). These maxima correspond to energy levels, but for many years there was no satisfactory explanation for the lower energies since it was felt that the whole of the energy must be emitted from the nucleus and the difference could not be accounted for. Pauli suggested, in 1931, that the remaining energy might be taken by a small uncharged particle; this particle was later called a neutrino. There is considerable support for this theory and it may be said to be well established now.

It is the maximum energy of the β-particle which is characteristic of the isotope and it is this which is given in reference tables. Very few are emitted with this maximum energy and the greatest number have energies around one-third of the maximum.

The maximum energy of β-radiation from the majority of isotopes lies between 0·5 and 3·5 MeV, but a number are found above and below these values.

The maximum range of β-rays is the range of those of maximum energy and, since there are few of these, the absolute range is somewhat indeterminate. With elements of low atomic weight the range is independent of material and is a function of thickness and density. Because of this it is generally measured in milligrams per square

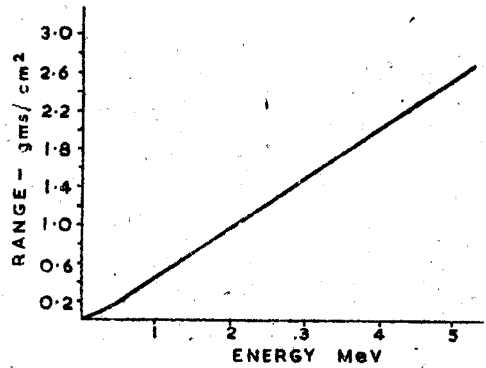

FIG. 5. RANGE OF β-PARTICLES IN LOW ATOMIC NUMBER MATERIALS

centimetre (mg/cm²). The majority lie between 1 and 2000 mg/cm² (Fig. 5).

When β-particles are stopped they give rise to bremsstrahlung in much the same way as do the electrons in an X-ray tube. The energy distribution of the β-radiation will, of course, be superimposed on that of the normal X-ray production so that the peak of the latter will be broadened and moved to an energy about one-quarter the maximum β energy.

NEUTRONS

Neutrons are uncharged particles having a mass of one a.m.u. The most important sources of neutrons are nuclear fission, alpha bombardment of certain light elements and the bombardment of a deuterium or tritium loaded target by protons or deutrons in an accelerator. In spite of their comparatively large size, the absence of charge enables them to pass readily through the electron structure of an atom and they are stopped or deflected only when they come close to a nucleus, so that they have considerable ranges in all materials.

In passing through any material, neutrons lose energy by collisions with the nuclei and, as in collisions between larger bodies, the energy lost by the neutron depends on the mass of the other nucleus. The greatest loss of energy occurs with hydrogen where the two masses are equal and so the neutron can lose all of its energy in a single head-on collision, whereas with heavy elements neutrons will be scattered but there will be little loss of energy by elastic collision.

Energy can also be lost in inelastic collisions. These are of the nature of a reaction with the nucleus whereby the neutron enters into combination with the nucleus which then undergoes internal rearrangement and the neutron is ejected with lower energy, the difference in energy appearing as a γ-photon.

Other reactions, known as capture reactions, result in the complete assimilation of the neutron by a nucleus and the emission of a totally different particle; this may be an α-particle ((n, α) reaction), a γ-photon (n, γ), or a proton (n, p). There is also a reaction where one neutron enters and two neutrons are emitted $(n, 2n)$.

If a neutron were to escape all these capture reactions, it would disintegrate like a radioactive nucleus by emission of a β-particle, leaving a proton as the stable product. However, the half-life is about 12 minutes and this is long compared with the probable lifetime before capture, so that disintegration is only observed under careful experimental conditions.

Neutron energies cover a wide range and for convenience in description they are usually divided into four bands:

Slow	up to 100 eV
Intermediate	100 eV to 100 keV
Fast	100 keV to 10 MeV
High energy	over 10 MeV

When neutrons have been slowed down by multiple collisions they will finally move randomly with a velocity due to the thermal movement of the molecules around them. They are then said to be thermalised or of thermal energy. This thermal energy lies in the region of 0·03 eV.

PROTONS

Protons are particles of mass one a.m.u. with a positive charge of one unit. They are thus the same as the hydrogen nucleus. Protons are produced by (n, p) reactions, acceleration of hydrogen ions or by the collision action of neutrons in hydrogenous materials; these latter are known as *knock-on* protons.

The penetrating power of protons is much less than that of neutrons and is intermediate between that of α-particles and β-particles. For protons of 1 to 10 MeV energy the range lies between 3 and 150 mg/cm^2 in light elements.

When a proton has lost its energy by collisions it will quickly acquire an electron and revert to a hydrogen atom.

CHAPTER 2

UNITS OF RADIATION AND RADIOACTIVITY

GENERAL

The fundamental units of physics such as ergs/cm² and calories/sec can be used as measures of radiation and of radioactivity. It may in some circumstances be convenient to make use of such units and they certainly have advantages in being well understood and not liable to cause confusion as to what is meant. Nevertheless they are not in practice a measure of the phenomenon which is generally observed and consequently units were introduced which were based directly on the observable effects without the introduction of factors of proportionality which were either unknown or not well determined.

One of the earliest of such units was the *pastille unit* developed by Holzknecht and others. This was a tablet about one cm in diameter of barium platino-cyanide which with increasing dosage changed in colour from green through a range of tints to orange. The various intermediate tints could be matched with steps in a comparator to find the number of units of dose which had been delivered. This system was not reliable and ultimately gave way to a system based on the ionisation produced in air.

RÖNTGEN

In 1928 the International Congress of Radiology meeting in Stockholm gave the first internationally agreed definition of a unit of dose of X-radiation. Their definition was extended at the Chicago Congress in 1937 so as to include γ-radiation and the wording was slightly altered to the form still in use today:

> "The röntgen shall be that quantity of X- or γ-radiation such that the associated corpuscular emission per 0·001293 gramme of air produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign."

The mass quoted is that of one c.c of dry air at a temperature of 0°C and a pressure of 760 mm of mercury.

There has sometimes been a certain confusion as to whether the röntgen referred to the total radiation flux which gives rise to the ionisation during its passage through the volume or to the quantity of the radiation which is actually absorbed. The latter view is the one now generally held. The importance of the quantity absorbed is that it is this part of the radiation which is giving the effect whether it be in air or in the tissue of the body.

The energy required to produce one ion-pair in air is about 32·5 eV, the charge so liberated is $4{\cdot}80 \times 10^{-10}$ e.s.u. whence the energy equivalent of the röntgen is:

$$\frac{32{\cdot}5 \times 1{\cdot}6 \times 10^{-12}}{4{\cdot}8 \times 10^{-10} \times 1{\cdot}293 \times 10^{-3}} = 83 \text{ ergs/g of air}$$

The absorption of energy in tissue is somewhat greater than in the same mass of air and a value of 93 ergs/g is generally taken.

REP

By definition the röntgen can be used only for X- and γ-radiation. In order to have a similar unit for particulate radiations, Parker proposed in 1942 a unit called the röntgen-equivalent-physical or rep, which he defined as the dose producing an energy absorption of 83 ergs/cm³ of tissue irrespective of the radiation. Some years later the constant was altered to 93 ergs/cm³ at which value it has remained. Since the density of muscle tissue is very close to unity, the röntgen and the rep represent the same energy absorption in tissue.

REM

The same dose in rep given by different types of radiation does not produce the same biological effect, and Parker therefore suggested a further unit to be known as the röntgen-equivalent-man or rem which should be the dose of any radiation which produces the same biological effect as one röntgen of X- or γ-radiation.

The ratio between the energy in a rep and a rem for any kind of radiation is a measure of the efficiency of the radiation in causing biological change and is known as the relative biological effectiveness or R.B.E.

RAD

At the Seventh International Congress of Radiology at Copenhagen in 1953, the confusion between radiation flux and absorbed energy was dealt with specifically and a new unit known as the rad was introduced which is unambiguous. The following are definitions which were recommended:

Intensity of radiation: energy flowing per unit time through unit area perpendicular to the beam at the point in question. Expressed in ergs/cm²/sec or in watts/cm².