SAFETY SERIES No. 38

Radiation Protection Procedures

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1973

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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RADIATION PROTECTION PROCEDURES

THIS SAFETY SERIES WILL ALSO BE PUBLISHED
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FOREWORD

The International Atomic Energy Agency published in 1960 a manual, Safety Series No.2, entitled "Safe Handling of Radioisotopes: Health Physics Addendum", which was prepared by two authors, the late G.J. Appleton of the United Kingdom Atomic Energy Authority and P.N. Krishnamoorthy of the Directorate of Radiation Protection, Department of Atomic Energy, Trombay, India. The Addendum contained technical information necessary for the implementation of the controls given in the code of practice entitled "Safe Handling of Radioisotopes", IAEA Safety Series No.1. In addition, it was intended to serve as a brief introduction to the technical problems encountered in radiological protection work and to the methods of resolving them.

During the past twelve years considerable developments have taken place on various aspects of radiation protection, especially on measuring techniques and instruments. The manual has therefore been thoroughly revised and brought up to date, jointly by P.N. Krishnamoorthy, who was appointed as the consultant, and J.U. Ahmed of the IAEA. The revised manual has been expanded by the inclusion of new chapters, tables and figures. It has thus become a complete guide in itself and is now published under the title "Radiation Protection Procedures".

CONTENTS

Annex: A collection of useful health physics data

1. INTRODUCTION

All radioactive materials and radiation are potentially hazardous. They can give rise, when outside the body, to external radiation exposure of personnel, and when inside the body, to the irradiation of certain organs. The health physicist must therefore be capable of advising the user of the radioactive material or other radiation sources on the methods necessary for the prevention and control of these hazards.

Evidence and experience indicate that limited exposure to external radiation, or the intake of small amounts of radioactive material into the body, are associated with a negligible probability of severe somatic or genetic injury. This has led to the concept of the maximum permissible levels of exposure for personnel working with radioactive materials or radiation sources. In addition to the exposure of radiation workers, there is also the possibility of exposure of the general public. The health physicist must therefore bear in mind two main aspects of radiological protection: (a) protection of radiation workers; and (b) protection of the general public. The large number involved and the impracticability of large-scale medical supervision necessitates even more stringent precautions for the protection of the general public than for the protection of radiation workers.

There are three principles which can be applied to prevent or control the exposure of personnel to radiation hazards:

(a) Remove the hazard
(b) Guard the hazard
(c) Guard the worker.

These principles should be applied in the above order for personnel protection. The first is an obvious one, the second implies the proper design of work places and the provision of appropriate equipment and shielding to ensure the maximum amount of protection, and the third refers to the measures required to make a periodic check on the continuing adequacy of the controls, the personal protection measures and the equipment. The procedures necessary for the implementation of these three principles for radiological protection in any specific situation can be assessed only after a proper evaluation of the technical and other aspects involved. Such a review, which takes into account the requirements of radiation and non-radiation workers, has been presented in tabular form in the annex at the end of this book.

2. FUNDAMENTALS OF NUCLEAR PHYSICS

2.1. The atom

2.1.1. Structure

The atom is the smallest part of an element which can participate in any chemical reaction. It is so small (about 10^{-8} cm in diam.) that in a gram atomic weight of any substance (e.g. 1 g of hydrogen or 12 g of carbon) there are 6.02×10^{23} atoms of the element. The atom consists of a small positively charged central nucleus (about 10^{-12} cm in diam.), in which most of its mass is concentrated. The volume of the nucleus, however, is only a small fraction of the volume of the atom. The nucleus, in turn, consists of positively charged particles called protons and uncharged particles called neutrons. Particles inside a nucleus are also referred to as nucleons. The positive charge of the nucleus results from the presence of protons in it. Negatively charged particles called electrons whirl around the nucleus in well-defined orbits or shells at different radial distances from the nucleus (see Fig.2.1). The simplest atom is that of hydrogen which consists of a proton as its nucleus and an electron in the orbit. The helium atom has 2 protons and 2 neutrons in the nucleus and 2 orbital electrons. Similarly ^{238}U has 92 protons and 146 neutrons in the nucleus and 92 orbital electrons.

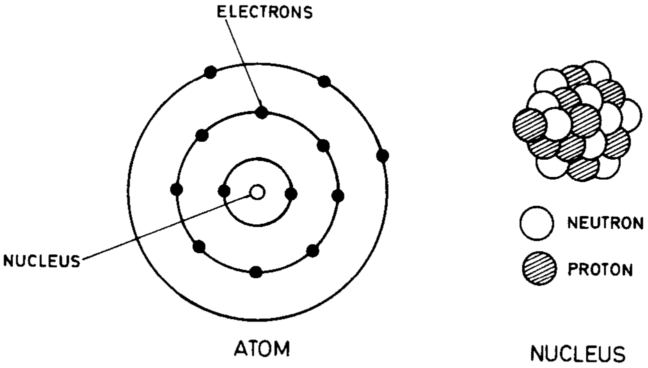

FIG. 2. 1. Schematic visualization of an atom and a nucleus.

The proton is 1837 times heavier than the electron while the mass of the neutron is slightly greater than that of a proton. The charge of an electron is 4.8×10^{-10} electrostatic units (esu) and is the smallest charge known to exist. The proton carries a charge equal to that of an electron but of opposite sign.

2.1.2. Atomic number and mass number

The atom as a whole is electrically neutral and hence the number of protons in the nucleus is equal to the number of orbital electrons. Thus the total number of protons in the nucleus or the total number of orbital electrons characterizes an element and is known as the "atomic number" - denoted by the symbol Z. The sum of the numbers of protons and neutrons is called the "mass number" - denoted by the symbol A and is an index of the mass of the atom. The number of neutrons in the nucleus is thus given by A-Z. Any individual atom, with its characteristic number of protons and neutrons, is called a nuclide.

2.1.3. Isotopes

The atomic number Z is the index of an element. Therefore, nuclides having the same Z but different mass number A are called the isotopes of the element of atomic number Z. The isotopes of the same element have identical chemical properties, but generally highly dissimilar nuclear properties. The nuclide of an element X of atomic number Z and mass number A is represented as $^{A}_{Z}X$ (e.g., $^{4}_{2}He$ denotes the nucleus of helium atom consisting of 2 protons and 2 neutrons), but in practice Z is usually omitted, since the use of the chemical symbol and mass number is sufficient identification. In Table 2.1, examples of nuclides and isotopes are shown.

TABLE 2.1. EXAMPLES OF NUCLIDES AND ISOTOPES

Term	Characterized by	Examples	Remarks
Nuclide	Z, A	$^{1}_{1}H$, $^{12}_{6}C$, $^{238}_{92}U$	More than 700 nuclides known
Isotope	Constant Z	$^{1}_{1}H$, $^{2}_{1}H$, $^{3}_{1}H$	3 to 19 isotopes known per element

TABLE 2.2. SOME COMMON TYPES OF RADIATION

Type of radiation	Symbol	Charge	Rest mass (amu)
Alpha particle	α	+2	4.002777
Beta particle			
(a) electron	β^-, e^-	-1	0.000549
(b) positron	β^+, e^+	+1	0.000549
Proton	p	+1	1.007593
Neutron	n	0	1.008982
Electromagnetic radiations			
(a) X-rays	X	0	
(b) Gamma-rays	γ	0	

2.2. Nuclear radiation

2.2.1. Types of nuclear radiation

The term *nuclear radiation* commonly refers to the wide variety of emanations associated with systems undergoing nuclear transformation. In this group are also included sub-atomic and atomic particles as well as X- and gamma radiation. Since a discussion of all types of nuclear radiation is beyond the scope of this manual, only a few common types presented in Table 2.2 will be discussed.

2.2.1.1. Alpha particles: Alpha particles are the helium nuclei (^4_2He) emitted by radionuclides, mainly by heavy nuclei such as polonium, radium, thorium, uranium, etc. In alpha decay the mass of the parent nucleus is greater than the sum of the masses of the products, and this mass difference is released as the kinetic energy of the alpha particle. The alpha particles emitted by any radionuclide have generally one or two, and rarely more, discrete energies, which are characteristic of the radionuclide.

2.2.1.2. Beta particles: Beta particles are high-energy electrons or positrons created and emitted by certain radionuclides.

Unlike alpha particles, beta particles are not monoenergetic but are emitted with a continuous spectrum of energy. Beta particles emitted by radionuclides are of two kinds – the negative electron and the positive electron resulting from neutron or proton excess respectively in the parent radionuclide. The emission of the positive electron is called positron decay. (A process equivalent in effect to positron decay is electron capture, in which the nucleus captures an inner orbital electron.) Owing to the emission of a beta particle, the mass of the nucleus remains practically unchanged but the atomic number is changed by one unit. As mentioned earlier, beta particles from radionuclides are emitted in a continuous energy spectrum, and hence tables of beta energies always list the maximum energy of emission which is characteristic of each radionuclide. For many purposes, however, a mean energy equal to one-third of the maximum energy is taken.

2.2.1.3. Protons: Protons are hydrogen nuclei and are therefore positively charged. Proton beams are produced in accelerators of different types and may have energies of several hundreds of mega electron volts or more. Protons are also emitted in the interactions of fast neutrons with hydrogen atoms.

2.2.1.4. Neutrons: The neutron is an uncharged particle having a mass slightly greater than that of a proton. It suffers no Coulomb interaction with either the orbital electrons or the nucleus of the atom. Neutrons are generally classified according to their energies under four broad categories.

(a) Thermal neutrons are those which are in thermal equilibrium with the surrounding matter, so that on the average there is no net exchange of kinetic energy between the neutrons and the thermally agitated atoms of the surrounding matter. The neutrons in this case will have a Maxwellian distribution of velocities with a most probable velocity of 2.2×10^5 cm/s which corresponds to a kinetic energy of 0.025 eV.
(b) Intermediate neutrons are those falling in the energy range of 0.5 eV to 10 keV. Neutrons having energies less than 100 eV are also referred to as slow neutrons.
(c) Fast neutrons have energies between 10 keV and 10 MeV.
(d) Relativistic neutrons have energies greater than 10 MeV. In this range the kinetic energy becomes a significant fraction of the total energy of the neutrons, so that relativistic corrections should be applied in analyses of neutron interactions.

2.2.1.5. X- and gamma-rays: X- and gamma-rays are electromagnetic radiation of very short wavelength. There is no difference between X- and gamma-rays except in their origin. While gamma rays are emitted with discrete energies characteristic of the nuclide formed, X-ray emission is of two types, characteristic radiation (discrete energies) and bremsstrahlung (continuous spectrum of energies). Characteristic X-rays are produced from transitions between energy levels of inner electrons in an atom, while gamma rays are emitted because of transitions of the nucleus from higher to lower energy states. The nucleus is left unchanged by gamma emission. Pure gamma emission is unknown in natural radioactivity; it frequently follows alpha or beta decay.

2.3. Radioactivity

It has been mentioned earlier that, except for the simplest nucleus, that of hydrogen, all other nuclei consist of neutrons and protons. The ratio of neutrons to protons is unity for lighter isotopes and increases gradually as one approaches the heavier elements at the end of the periodic table. As this ratio increases, a stage is reached where the nuclide is no longer stable. The heaviest stable nuclide is $^{209}_{83}Bi$. Nuclides heavier than this are unstable because they have excess energy to dissipate. Such unstable nuclides are called radionuclides and they dissipate their surplus energy by the emission of radiation. This process is called radioactivity or radioactive decay. The more frequent modes of decay of radionuclides are alpha, beta and gamma decays.

Radioactivity can be of two types: (1) natural radioactivity exhibited by more than 50 naturally occurring isotopes (e.g., ^{238}U, ^{226}Ra, ^{40}K, etc.), and (2) artificial radioactivity which is the radioactivity induced in some elements by bombarding them with neutrons, charged particles or photons. The resultant nuclei (e.g., ^{137}Cs, ^{60}Co, ^{32}P, etc.) could be in excited states and will therefore decay by one of the modes described above. Most radionuclides currently in use are artificially produced.

The decay of a radionuclide is a statistical process in the sense that it is not possible to predict exactly when a particular nucleus will disintegrate. One may, however, ascribe a probability that a nucleus will decay in unit time. This probability is known as the radioactive decay constant (transformation constant), λ, of the radionuclide. The number of atoms of a radioactive substance disintegrating per unit time, dN/dt, which is referred to as the activity of the substance, is proportional to the total number, N, of radioactive atoms present at time t; the constant of proportionality being λ.

Thus,

$$-\frac{dN}{dt} = \lambda N \qquad (1)$$

Integrating this equation, one has

$$N = N_0 e^{-\lambda t} \qquad (2)$$

where N_0 is the initial number of radioactive atoms present, and N, as already stated, the number of radioactive atoms at time t. Rewriting Eq.(1), one has

$$-\frac{dN}{dt} = \lambda N = \lambda N_0 e^{-\lambda t} \qquad (3)$$

Equation (3) indicates that the number of radioactive atoms present as well as the disintegration rate (activity) decrease exponentially with time.

The time taken for half the radioactive atoms originally present to decay is called the half-life of the radionuclide.

Substituting $N = N_0/2$ and $t = t_{\frac{1}{2}}$ in Eq.(2), one has

$$N_0/2 = N_0 e^{-\lambda t_{\frac{1}{2}}}$$

or

$$\lambda t_{\frac{1}{2}} = \ln 2 = 0.693$$

or

$$t_{\frac{1}{2}} = 0.693/\lambda \qquad (4)$$

The number of radioactive atoms present and hence the rate of disintegration decreases to one-half in one half-life, to one-quarter in two half-lives, to one-eighth in three half-lives, and so on. The half-life is characteristic of any particular radioisotope. Another useful quantity is the mean life or the average life of a radionuclide which is the reciprocal of the decay constant, ($t_m = 1/\lambda$).

2.3.1. Radioactive equilibrium

A radionuclide upon undergoing disintegration of a particular type yields a specified nuclide. The original radionuclide is called the parent and the decay product is called the daughter. The daughter may also be a radionuclide. A succession of nuclides, each of which transforms by radioactive disintegration into the next until a stable nuclide results, is called a radioactive series. Examples of such series are the uranium series and the thorium series.

Radioactive equilibrium refers to that state in which the ratios between the amounts of successive members of the series remain constant. Under these conditions the disintegration rates of the parent and all the subsequent radioactive daughters will be the same.

2.4. Unit of radiation energy

The energy of atomic radiation is expressed in units of electron volts (eV). The electron volt is defined as the kinetic energy acquired by an electron when it falls through a potential difference of one volt. Expressed in terms of ergs, one has

$$\text{One electron volt, } 1 \text{ eV} = 1.6 \times 10^{-12} \text{ erg}$$

$$\text{One million electron volts, } 1 \text{ MeV} = 1.6 \times 10^{-6} \text{ erg}$$

As already stated, the energy released in a decay process occurs as a result of the difference in mass of the parent nucleus and the sum of the masses of the products. The magnitude of this energy is given by Einstein's mass (m)-energy (E) relation

$$E = mc^2$$

where c is the velocity of light, which is constant and equal to 3×10^{10} cm/s. From this relationship one can easily see that 1 atomic mass unit = 931 MeV. Also, the rest mass of an electron can be seen to be 0.51 MeV.