SAFETY SERIES

No. 2

Safe Handling of Radioisotopes

Health Physics Addendum

INTERNATIONAL ATOMIC ENERGY AGENCY

VIENNA 1960

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SAFE HANDLING OF RADIOISOTOPES

HEALTH PHYSICS ADDENDUM

by

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INTERNATIONAL ATOMIC ENERGY AGENCY
Kärntner Ring, Vienna I, Austria
1960

THIS ADDENDUM IS ALSO PUBLISHED
IN FRENCH, RUSSIAN AND SPANISH

SAFE HANDLING OF RADIOISOTOPES: HEALTH PHYSICS ADDENDUM,
IAEA, VIENNA, 1960

STI/PUB/10

FOREWORD

The International Atomic Energy Agency published in 1958 a Manual entitled "Safe Handling of Radioisotopes" (Safety Series No. 1 — STI/PUB/1), based on the work of an international panel convened by the Agency. As recommended by that panel and approved by the Agency's Board of Governors, this Addendum has now been prepared, primarily as a supplement to the Manual. It contains technical information necessary for the implementation of the controls given in the Manual. In addition, it is intended to serve as a brief introduction to the technical problems encountered in radiological protection work and to the methods of resolving them.

As in the case of the Manual itself, the information given in this Addendum is particularly relevant to the problems encountered by the small user of radioisotopes. Although the basic principles set forth in it apply to all work with radiation sources, the Addendum is not intended to serve as a radiological protection manual for use in reactor installations or large-scale nuclear industry, where more specialized techniques and information are required.

The Addendum has been prepared by the Secretariat with the assistance of two consultants appointed by the Agency, Mr. G. J. Appleton (United Kingdom Atomic Energy Authority) and Dr. P. N. Krishnamoorthy (Atomic Energy Establishment, Trombay, India), both of whom were among the experts forming the international panel mentioned above. The Agency believes that this Addendum will provide information of great value and publishes it for whatever use Member States and others may wish to make of it. However, it should not be regarded as representing the Agency's official judgment or policy on the matter.

July, 1960

Director General

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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 injuries. 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 non-radiation workers and the general public. The large number involved and the impracticability of large-scale medical supervision necessitate more stringent precautions for the protection of non-radiation workers and 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 equipment 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 perspective of 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 perspective, which takes into account the requirements of radiation and non-radiation workers, has been presented in a tabular form towards the end of this publication.

2. FUNDAMENTALS OF NUCLEAR PHYSICS

The world around us consists of chemical combinations of various elements. Ninety-two such elements occur in nature, and about a dozen more have been produced artificially. The smallest part of an element which can participate in any chemical reaction is an atom. The atom is so small (about 10^{-8} cm in diameter) that in a gramme atomic weight of any substance (e. g. 1 g of hydrogen or 16 g of oxygen) there are 6.0×10^{23} atoms of the element. Each atom has a central nucleus, in which most of its mass is concentrated. The volume of the nucleus, however, is only a very small fraction of the volume of the atom. The nucleus consists of positively charged particles called protons and uncharged particles called neutrons. Negatively charged particles called electrons whirl around the nucleus in well-defined orbits or shells at different radial distances from the nucleus.

The unit of charge, or the elementary charge, is the charge on an electron or proton and is the smallest charge known to exist:

$$e = 4.8 \times 10^{-10} \text{ electrostatic units (esu).}$$

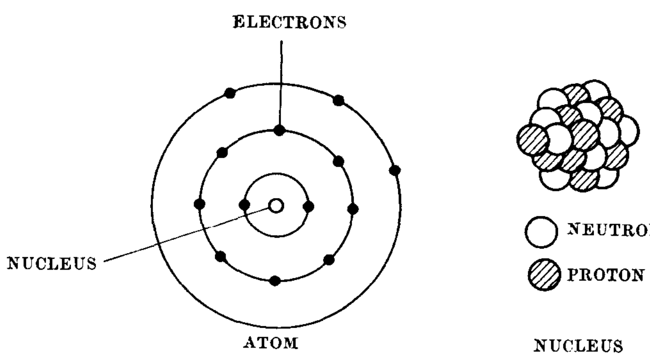

Fig. 2.1.

The proton is nearly 2,000 times heavier than the electron and the neutron mass is slightly greater than that of a proton. The atom as a whole is uncharged and hence the number of protons is equal to the number of orbital electrons. Thus the total number of electrons or protons 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. 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. Atoms of an element with the same Z but different A are called isotopes of the element. These different 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 $_{Z}X^{A}$ (e. g. $_{2}He^{4}$ denotes the nucleus of a helium atom consisting of 2 protons and 2 neutrons), but in practice Z is usually omitted, since the use of the chemical symbol and the mass number is sufficient identification.

TABLE 2.1

Term	Characterized by	Examples	Remarks
Nuclide	Z, A	$_{1}H^{1}$, $_{8}O^{16}$, $_{92}U^{238}$	More than 700 nuclides known
Isotope	Constant Z	$_{1}H^{1}$, $_{1}H^{2}$, $_{1}H^{3}$	3 to 19 isotopes known per element

The simplest nucleus is that of hydrogen and consists of a single proton. All other nuclei consist of neutrons and protons, the ratio of neutrons to protons being unity for the lighter isotopes and increasing 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 $_{83}Bi^{209}$. Nuclides heavier than this are unstable because they have excess energy to dissipate. Such unstable nuclides are called radionuclides and they dissipate the surplus energy by the emission of radiations. This process is called natural radioactivity or radioactive decay. The more frequent modes of decay of radionuclides are named alpha, beta and gamma decay:

(a) Alpha decay is the emission of a helium nucleus ($_{2}He^{4}$), called an alpha particle, by the radionuclide. In this mode of 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.

(b) Beta decay is the creation and emission of a positive or negative electron from the nucleus, resulting from neutron or proton excess. The emission of a 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. Beta particles are emitted in a broad energy spectrum. The maximum beta energy is characteristic of each radionuclide.

(c) Gamma decay is the creation and ejection of a photon (unit of quantity of electromagnetic radiation). The photon is electrically uncharged, has no mass and always travels with the velocity of light. The nucleus is left unchanged by gamma emission. Pure gamma emission is unknown in natural radioactivity; it frequently follows alpha or beta decay.

Apart from naturally occurring radionuclides, any non-radioactive nuclide can be made radioactive by inducing artificial changes in the nucleus. When particles and/or energy are transferred to a stable nucleus by bombarding it with neutrons, charged particles or photons, the resultant nucleus or nuclei may be in an excited state and will therefore decay by any one of the modes described above. Most of the radioisotopes currently in use are artificially produced.

The decay of a radioisotope 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 the nucleus will decay in unit time. This probability is known as the radioactive decay constant λ of the radioisotope. Statistical studies of radioactive decay show that the number of disintegrations per unit time, $\frac{Nd}{dt}$, of a radioactive substance is proportional to N, the total number of radioactive atoms present at time t, the constant of proportionality being λ, the decay constant. Thus,

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

Integrating this equation, we have:

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

where N_0 is the initial number of radioactive atoms present, and N, as already stated, the number of radioactive atoms at time t.

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

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

Substituting $N = \frac{N_0}{2}$ and $t = t_{½}$ in equation (2), we have:

$$\frac{N_0}{2} = N_0 e^{-\lambda t_{½}}$$

$$\lambda t_{½} = \ln 2 = 0.693$$

$$\text{or } t_{½} = \frac{0.693}{\lambda}$$

The number of radioactive atoms present, and hence the rate of disintegration, decreases to one half in a 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.

The energy of these radiations 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 1 volt. Expressed in terms of energy,

$$1 \text{ eV} = 1.6 \times 10^{-12} \text{ erg}, \; 1 \text{ MeV} = 10^6 \text{ eV} = 1.6 \times 10^{-6} \text{ erg}.$$

As already stated, energy released in decay processes 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 relationship between mass (m) and energy (E),

$$E = mc^2,$$

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

3. INTERACTION OF RADIATION WITH MATTER

The radiations encountered in radiation work may be divided into two broad classes — directly ionizing radiations and indirectly ionizing radiations. Directly ionizing radiations include all charged particles, such as alpha particles and heavier ions and beta particles. Indirectly ionizing radiations include some types of electromagnetic radiations and neutrons. These radiations interact with matter by giving rise to secondary radiation which is ionizing. Although all radiations interact with matter, an important factor to be borne in mind while considering radiation protection is the fact that radiations do not produce any readily perceptible stimuli in man except in the case of very high doses. Hence the presence of these radiations has to be detected by using suitable sensitive devices, which depend for their functioning on the nature of the interaction of these radiations with matter.

The intensity of radiation (or radiant energy flux density) at a given point is defined as the energy per unit time entering a small sphere of unit cross-sectional area centred at that point. It is measured in terms of ergs per square centimetre per second or watts per square centimetre. When radiation passes through matter it suffers a reduction in intensity as a result of complex interactions between the radiation and the material concerned. This reduction in intensity is called attenuation. The degree of attenuation depends upon the type of radiation and the material used. Materials used for purposes of radiation attenuation are called shielding materials and in this connexion the terms "half-value layer" and "1/10-value layer" are often used. The half-value layer of a material for a certain quality of radiation is the thickness required to reduce the intensity by one half — similarly the "1/10-value layer" implies an intensity reduction by a factor of 10.

The exact specification of "quality" of radiation is possible in the case of a monoenergetic beam, or in the case of heterogeneous beams where the spectral distributions of energies present are known. Fortunately, however, in the case of heterogeneous beams it is not necessary to specify the "quality" for most applications. In such cases, an "effective energy" of the heterogeneous beam is specified, which is the energy of a monoenergetic beam having the same half-value layer as the heterogeneous beam in question. However, the effective energy of a beam derived from the half-value layer does not coincide with and is invariably lower than the mean energy more correctly deduced from the detailed spectrum.

Directly ionizing radiations lose energy by interaction with the orbital electrons of atoms in the material they traverse. Indirectly ionizing radiations lose energy by collisions with electrons or atomic nuclei, and the charged particles, thus set into motion, interact in turn with orbital electrons or nuclei.

The mechanisms of energy loss for various types of radiations will now be discussed in some detail. All charged corpuscular particles lose energy by:

(a) atomic or molecular excitation, with the emission of light resulting from subsequent de-excitation; and
(b) ionization, which involves the ejection of an orbital electron, resulting in the creation of an ion pair.

It has been determined that on the average about 34 eV is expended in the creation of each ion pair in air. The ionization of an atom which forms part of a molecule could result in the dissociation of the molecule.

Alpha particles emitted from radionuclides have well-defined and characteristic energies. As they are doubly charged, they are densely ionizing and hence their penetrating power or range is extremely limited. In fact, alpha particles of energies up to 7.5 MeV are incapable of penetrating the protective layer of the skin on most parts of the body (e. g. the hand). Their range in air is only a few centimetres. Thus, shielding against this type of radiation presents no problem.

Beta particles of energies up to about 1 MeV lose energy through ionization. In the case of higher-energy beta particles, an additional mechanism of energy loss (bremsstrahlung) is involved. Since beta particles are much lighter than other charged particles, their velocity for a given energy is much higher and their specific ionization much smaller. Thus, for a given energy, beta particles have a much larger range than alpha particles. In addition, because of their small mass, beta particles undergo frequent scattering with little loss of energy, and thus follow tortuous paths. This can cause a process analogous to reflection from surfaces. This process is referred to as back-scattering, and the extent of back-scattering increases with the atomic number of the surface material. The beta particles from radionuclides are emitted with a continuous energy spectrum and are attenuated exponentially for the greater part of their maximum range. Tables of beta energies always list the maximum energy of emission. but for many purposes a mean energy of 1/3 the maximum is taken. It has further been observed that for light elements the absorpticn thickness for beta particles (measured in mg/cm^2) is almost independent of the nature of the absorber.

Beta particles of energies higher than about 1 MeV lose energy also by the emission of electromagnetic radiation called bremsstrahlung (braking radiation). The intensity of bremsstrahlung depends upon the atomic number of the absorber. This process is similar to the process involved in the production of X-rays by bombarding a heavy-metal target with high-energy electrons. Thus, in the design of shielding for pure beta emitters particular attention has to be paid to the bremsstrahlung.

Electromagnetic radiation is classified according to its origin, independently of its energy. Thus we could have, for example, gamma rays and X-rays of the same energy. Gamma rays are the electromagnetic radiations or photons emitted by a nucleus in an excited state. Following the emission of the gamma radiation the nucleus returns to its lowest energy or ground state. The production of continuous X-rays or bremsstrahlung has been described earlier. Characteristic X-rays are emitted in atomic transitions of bound electrons between the various electronic shells in the atom. Annihilation radiation is produced by the interaction of positrons and electrons, whereby the masses of the two particles are completely converted into energy in accordance with Einstein's mass-energy relationship. The mechanism of interaction of radiations of the above-mentioned types with matter, however, are dependent only on their energy and not on their origin. This is an important factor to be borne in mind while planning radiation protection.

There are a number of ways in which electromagnetic radiation may interact with matter. The modes of interaction and their possible effects are listed in the table below.

TABLE 3.1

Kinds of interaction	Effects of interaction
1. Interaction with atomic electrons. 2. Interaction with nucleons. 3. Interaction with the electric field surrounding the nuclei or electrons. 4. Interaction with the nuclear field.	a. Complete absorption. b. Elastic scattering. c. Inelastic scattering.

The two columns in the above table can be combined in twelve different ways. However, only three of these processes are of importance in the interaction of gamma rays with matter. These are the photoelectric effect (1 a), the Compton effect (1 b) and pair production (3 a).

Photo-electric effect

The most important mechanism of energy loss for low-energy photons in the range of 10 KeV to 500 KeV is the photoelectric effect. In this process, a low-energy photon collides with an electron in one of the various shells of the atom and transfers its entire energy to the electron, which is then ejected from the atom as a photoelectron. The kinetic energy T of the electron is given by

$$T = h\nu - \Phi,$$

where $h\nu$ is the photon energy and Φ the binding energy of the electron. Thus, for the photoelectric effect to occur, the photon energy must be greater than the binding energy. The important features of the photoelectric effect are the following:

(a) The cross-section for this process decreases with increase in photon energy and at higher energies this process plays an insignificant role, other processes like the Compton effect being more important. Further, the cross-section for this process increases with increasing atomic number of the absorber. For lead, the photoelectric effect is significant up to about 1 MeV.

(b) The process is most likely to occur when the photon energy is slightly higher than the binding energy.

Compton effect

Whereas the photoelectric effect occurs in the case of a bound electron, the Compton effect can occur with a free or loosely-bound electron. In this process, the incident photon makes an elastic collision with a free or loosely-bound electron and loses part of its energy. Compton scattering cannot be characterized exclusively as an absorption process since the scattered photons may not be appreciably deflected or degraded in energy.

The Compton effect depends only on the number of electrons present in the material which the photons traverse and is the dominant absorption process for intermediate gamma-ray energies. In the case of lead, this process predominates in the energy range $1-5$ MeV; the corresponding energy range for aluminium is $0.1-15$ MeV.

Pair production

At photon energies exceeding 1.02 MeV, the photon interacts either with the coulomb field of the nucleus or, less frequently, with that of an electron to produce a positron-electron pair. This process can be regarded as the inverse of the annihilation process described earlier. Any energy of the photon in excess of 1.02 MeV appears as kinetic energy of the two particles created. For purposes of shielding, pair production is considered to be a true absorption process, since any annihilation radiation resulting from the annihilation of the positrons produced in this process is of relatively low energy and is emitted isotropically.

In the case of alpha and beta particles, definite thicknesses of shielding materials are sufficient to stop these particles completely. However, for gamma rays, the radiation is absorbed exponentially and the intensity I at any point is given by the relation:

$$I = I_0 e^{-\mu x}$$