3. Radiation Protection. Biological Effects of Radiation

That radiation can be hazardous to living organisms is well-known to any informed person today. However, except for this simple fact, further knowledge of just how and why this is so appears to be rare even among those who work with radiation professionally. Indeed, it behooves anyone handling radioactive material or working in a radiation environment to have at least a few elementary ideas concerning the effects of exposure to radiation, the permissible limits and the safety precautions to be taken. The nuclear physicist is, of course, no exception. In this chapter, therefore, we will briefly survey the dosimetric units used for discussing the effects of irradiation, and some simple safety precautions to be followed in the nuclear physics laboratory.

3.1 Dosimetric Units

The quantity of radiation received by an object is measured by several different units. Since radiation interacts with matter by ionizing or exciting the atoms and molecules making up the material, these units are either a measure of the quantity of ionization produced or the amount of energy deposited in the material.

3.1.1 The Roentgen

The oldest unit is the *Roentgen*, which is a measure of *exposure* and is defined as

$$1\ \text{Roentgen (R)} = \text{the quantity of x-rays producing an ionization of } 1\ \text{esu/cm}^3 = (2.58 \times 10^{-4}\ \text{Coul/kg}) \text{ in air at STP.} \tag{3.1}$$

Note that the definition refers specifically to x-rays and γ-rays in air. As such, it is an easy quantity to measure with ionization chambers, however, it becomes inconvenient when the irradiated object is living tissue or some other material.

In air, ionization is produced primarily by the slowing down of the recoil electrons resulting from the Compton scattering of the γ-rays and x-rays. The amount of ionization produced, therefore, depends on both the absorption coefficient for γ-rays and the specific ionization of electrons. If isotropic radiation from a point is assumed and attenuation from air is ignored, the ionization per unit time or *exposure rate* due to a given source may be found from the formula

$$\text{Exposure rate} = \frac{\Gamma \cdot A}{d^2}\ , \tag{3.2}$$

where A is the activity, d the distance to the source and Γ is an *exposure rate constant* dependent on the decay scheme of the particular source, the energy of the γ's, the ab-

sorption coefficient in air and the specific ionization of electrons. This constant has been calculated for a number of common γ-sources and a short list is given in Table 3.1. A more complete list is given in [3.1].

Table 3.1. Short list of exposure rate constants [3.1]

Source	Γ[R-cm^2/hr-mCi]
^{137}Cs	3.3
^{57}Co	13.2
^{22}Na	12.0
^{60}Co	13.2
^{222}Ra	8.25

3.1.2 Absorbed Dose

A more relevant quantity for discussing the effects of irradiation is the *absorbed dose*, D. This is a quantity which measures the total energy absorbed per unit mass and is the fundamental parameter in radiological protection. Its unit of measurement is the *Gray* which is defined as

$$1 \text{ Gray (Gy)} = 1 \text{ Joule/kg} \ . \tag{3.3}$$

A somewhat older unit for the absorbed dose, which is no longer actively used, is the *rad* where

$$1 \text{ rad} = 100 \text{ erg/g} = 0.01 \text{ Gy} \ . \tag{3.4}$$

It should be noted that the absorbed dose gives no indication of the rate at which the irradiation occurred nor the specific type of radiation, factors which play an important role when considering the biological effects of radiation.

Example 3.1 Calculate the absorbed dose in air for 1 Roentgen of γ-rays. Assume that for electrons, the average energy to create an ion-electron pair in air is 33.7 eV.

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ Coul/kg} \times \frac{1}{1.6 \times 10^{-19} \text{ Coul/elect}} = 1.61 \times 10^{15} \text{ ion-pairs/kg} \ .$$

The energy expended in creating the ion-pairs is thus

$$33.7 \text{ eV/ion-pr} \times 1.61 \times 10^{15} \text{ ion-pr/kg} = 5.42 \times 10^{10} \text{ MeV/kg} \ .$$

Since $1 \text{ MeV} = 1.6 \times 10^{-13}$ J, we then find

$$D = (5.42 \times 10^{10}) \times (1.6 \times 10^{-13}) = 0.00867 \text{ Gy} \ .$$

Example 3.2 Assuming soft living tissue absorbs ≈ 93 erg/g for 1 R of γ radiation what is the dose rate received from working at an average distance of 50 cm from a 100 μCi (3.7 MBq) ^{22}Na source?

Using Table 3.1, the exposure rate is

$$\text{Exposure rate} = \frac{12.0 \times 0.1 \text{ mCi}}{50^2} = 0.48 \text{ mR/hr} \ .$$

$$\text{Dose rate} = 93 \times 0.48 \times 10^{-3} = 0.045 \text{ erg/g-hr} = 0.045 \text{ mGy/hr} \ .$$

3.1.3 Relative Biological Effectiveness (RBE)

When considering biological effects, the nonspecificity of the absorbed dose proves to be inadequate. Indeed, studies show that the biological damage caused by radiation is a strong function of the specific radiation type and its energy. An absorbed dose of α-particles, for example, produces more damage than an equal dose of protons and this, more damage than a similar dose of electrons or γ-rays. The difference lies in the *linear energy transfer* (LET) of the different particles, i.e., the energy locally deposited per unit path length[1]. Thus, the more ionizing the particle the greater the local biological damage.

To account for this effect, each radiation type is assigned a *radiation weighting factor*, w_R, (or *quality factor*) which indicates its *relative biological effectiveness* (RBE). Table 3.2 lists this factor for several different types of radiation. Thus, for equal absorbed doses, α-particles may be considered as about 4 times more damaging than protons, and these 5 times more damaging than electrons or photons, etc.

Table 3.2. Radiation weighting factors [3.2]

Radiation type and energy	Radiation weighting factor, w_R
Photons, all energies	1
Electrons and muons, all energies[†]	1
Neutrons	
< 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, energy > 2 MeV	5
α-particles, fission fragments, heavy nuclei	20

[†] Excluding Auger electrons emitted from nuclei bound to DNA

[1] For most purposes, this is the same as dE/dx. The only difference is the emission of bremsstrahlung, which generally escapes from the region of the particle path. This energy loss is included in the dE/dx, but not in the LET.

3.1.4 Equivalent Dose

To obtain a normalized measure of the biological effect suffered by a tissue or organ due to irradiation, the *equivalent dose*[2], H_T is calculated by multiplying the value of the absorbed dose, averaged over the entire tissue or organ, by the radiation weighting factor, i.e.,

$$\text{Equivalent dose} = H_T = w_R \times D_R \tag{3.5}$$

where D_R is the average absorbed dose received by organ R. If more than one radiation type is present, the sum of the absorbed doses for each radiation type weighted by the corresponding w_R factor is calculated instead. Thus

$$H_T = \sum_R w_R D_{T,R} \tag{3.6}$$

where $D_{T,R}$ is the average absorbed dose received by organ T from the radiation type R.

The unit of equivalent dose is the Sievert (Sv) which has the same dimensions as the Gray (J/kg). The use of the Sievert, however, indicates that the dose is normalized by the RBE, so that 1 Sv of α-particles produces approximately the same effect as 1 Sv of γ-rays, etc. It should be kept in mind, however, that the equivalent dose is *not* a directly measurable quantity whereas the absorbed dose is.

A much older unit, no longer in active use but which appears in the literature, is the *rem*. The relation between the two units is given by

$$1\ \text{Sv} = 100\ \text{rem}\ . \tag{3.7}$$

Table 3.3. Tissue weighting factors [3.2]

Tissue or organ	Tissue weighting factor, w_T
Gonads	0.20
Bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

[2] Prior to the 1990 ICRP recommendations [3.2], a quantity known as the *dose equivalent* was used instead. This quantity is almost identical to the *equivalent dose* except that the *dose equivalent* refers to the dose as measured at a *point* on the irradiated tissue.

3.1.5 Effective Dose

The relation between the probability of developing biological effects such as cancer or genetic anomalies due to radiation is also found to depend on the specific organ or tissue receiving the radiation. To account for this, a *tissue weighting factor*, w_T is defined for the different organs of the body. These are given in Table 3.3. Note that the tissue weighting factors are totally independent of the radiation type and energy (just as the radiation weighting factors are independent of tissue type.)

Using these factors, the *effective dose*, E, is defined as

$$E = \sum_{\mathrm{T}} w_{\mathrm{T}} H_{\mathrm{T}} \ , \tag{3.8}$$

where the sum is over the different tissues and organs exposed. The effective dose has been found to better correlate with the probabilities of developing effects such as cancer, and it, like the equivalent dose, is measured in units of Sieverts.

Note that the definition of the tissue weighting factors is such that their sum is normalized to 1. For a uniform equivalent dose over the whole body, the effective dose is then numerically equal to the equivalent dose.

3.2 Typical Doses from Sources in the Environment

As is well known, we are constantly bathed in radiation coming from a variety of natural and artificial sources. These include cosmic rays, radioactive isotopes found naturally in the environment (e.g., the ground, building materials, etc.), nuclear fallout, medical diagnostics, and radioactive sources used in industry. To get an idea of the magnitude of these doses, Table 3.4 lists the typical doses received from some of these natural and artificial sources.

These values may vary by as much as a factor 2 or 3 depending on the region in which the individual lives. At an altitude of 2000 meters, for example, the cosmic ray

Table 3.4. Estimates of effective doses from some common sources

Source	Average dose per person (mSv/yr)		
	World population [3.3]	USA [3.4]	Germany [3.5]
Natural sources			
Overall	2.4	2.95	2 – 2.5
Cosmic rays	0.37	0.27	
Terrestial		0.28	≈0.1
Inhaled radon		2.0	0.8 – 1.6
Environmental sources			
Nuclear power	0.002		
Baggage check at airport		7 nSv/trip	
Subsonic airplane flight at 8000 m		2 μSv/hr	
Medical exposures			
Diagnosis	0.4 – 1	0.53	0.5 – 1.5
(e.g. 1 chest x-ray)		0.1 mSv/x-ray	
Occupational	0.002	0.1 – 3	

dose is practically double that at sea level. Similarly, the natural background dose may also be larger or smaller depending on the mineral and geological structure of the region. The natural background, in fact, is the major source of radiation exposure for the general public followed by irradiation from medical diagnosis.

3.3 Biological Effects

Radiation is harmful to living tissue because of its ionizing power in matter. This ionization can damage living cells directly by breaking the chemical bonds of important biological molecules (particularly DNA), or indirectly by creating chemical radicals from water molecules in the cells which then attack the biological molecules chemically. To a certain extent, these molecules are repaired by natural biological processes; however, the effectiveness of this repair depends on the extent of the damage. Obviously, if the repair is successful then no effect is observed, however, if the repair is faulty or not made at all, the cell may then suffer three possible fates:

1. Death (of the cell).
2. An impairment in the natural functioning of the cell leading to somatic effects (i.e., physical effects suffered by the irradiated individual only) such as cancer.
3. A permanent alteration of the cell which is transmitted to later generations, i.e., a genetic effect.

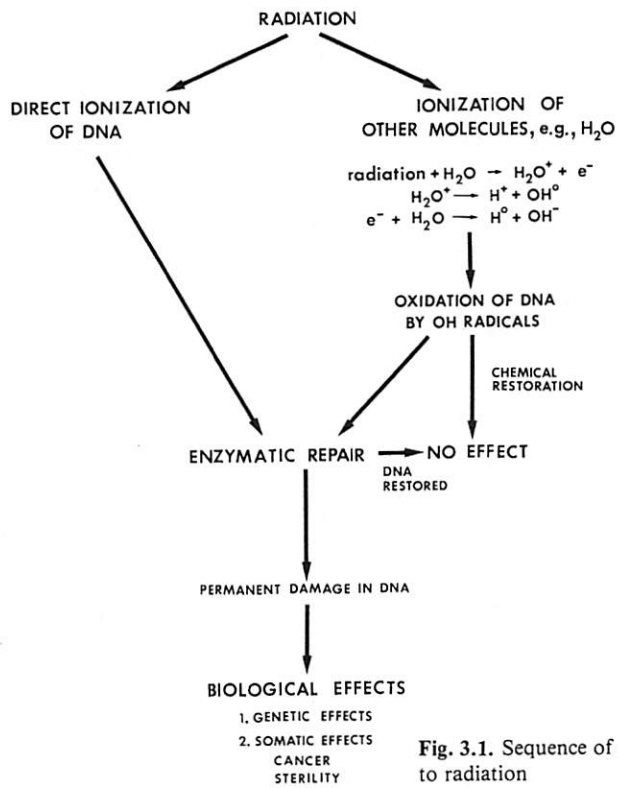

Fig. 3.1. Sequence of events occurring in living matter exposed to radiation

The sequence of events is outlined in Fig. 3.1.

Let us now consider the specific biological consequences which may result in humans. Depending on the dose, these consequences may be immediate or delayed by many years.

3.3.1 High Doses Received in a Short Time

The effects of high doses of radiation (≥ 1 Gy) received in a short time period ($\leq$ few hours) are generally well known. The immediate effect is a disruption of the reproductive process in mitotic cells leading to their depletion. The most important of these are the white blood cells, the bone marrow and the cells lining the intestine. The first consequences of a high dose of radiation will thus be noticed in the blood of an individual. If the dose is greater than 2 – 3 Sv, death may occur either due to the radiation itself or to complications arising from the depletion of the mitotic cells, e.g., infections. An outline of the possible sequence of events which might occur after exposure to a dose of several Sievert is given in Table 3.5.

Table 3.5. Symptoms after receiving 4 – 6 Sv in a short time

0 – 48 hrs	Loss of appetite, nausea, vomiting, fatigue and prostration
2 days to 6 – 8 wks	Above symptoms disappear, patient feels better
2 – 3 wks to 6 – 8 wks	Purpura and hemorrhage, diarrhea, loss of hair, fever, lethargy, death
6 – 8 wks	Recovery stage

If the patient survives, a number of other effects may develop at a later time, for example, reddening of the skin, sterility, cataracts, and birth defects. These effects, including death, all exhibit a threshold characteristic, i.e., there exists a safe minimum dose below which these effects do not appear. Above this threshold, there is a certain chance of developing one or more of the effects with the probability increasing with increasing dose. This threshold characteristic appears reasonable as, in general, a minimum number of cells must be damaged before impairment of an organ is affected. As

Table 3.6. Threshold doses for several effects [3.6]

Stage of development	Effect	Threshold dose (Sv)
Embryo	Small head circumference	0.04
Fetus	Diminished body growth Increased infant mortality	0.2
Child	Hypothyroidism	5
Adult	Opacity of the eye lens	2.5
Adult	Death	2 – 3
Adult	Aging	3
Adult	Erythema (reddening of the skin)	3 – 10
Male adult	Temporary sterility	0.5 – 1
	Permanent sterility	> 5
Female adult	Permanent sterility	3 – 4

well, this also explains the dependence on the dose rate. A summary of some of these effects (known as *deterministic* or *non-stochastic effects*) and their threshold doses is given in Table 3.6.

It is perhaps important to note here the relative sensitivity of the fetus to radiation. Prenatal irradiation with doses as small as 0.25 Sv at critical stages of embryo development (between the 8^{th} to 15^{th} week) can cause abnormal growth and development at later stages. Indeed, effects such as mental retardation, lower IQ scores, etc. have been observed in the children of atomic bomb survivors.

3.3.2 Low-Level Doses

Low-level doses are taken to be doses of 0.2 Gy or less, or higher doses received at the maximum permissible rates as described in the next section. Here the principal effects are cancer and genetic effects. In contrast to the high dose situation, however, very little is known about the relation of radiation to the occurrence of these two diseases. For cancer, this is due in part to the long delay between irradiation and the appearance of the effect, and in part, to the difficulty of isolating radiation from other possible causes such as drugs, cigarettes, chemicals, etc. In the case of genetic effects, no radiation-induced genetic defect in humans (including the Hiroshima-Nagasaki survivors) has ever been *significantly* demonstrated, although laboratory experiments on mice and other animals have shown such injuries. Present knowledge of the genetic effects of radiation on man, in fact, is based entirely upon extrapolation from these experiments.

Nevertheless, it is generally accepted that these effects:

1. do *not* exhibit a threshold, that is, there is *no safe* level of radiation below which these effects are not observed, and
2. that they do *not* depend on the dose rate, but rather on the total accumulated dose.

Indeed, for a given total dose, one has a certain non-zero probability of developing one or the other of these effects. For this reason, these effects are usually referred to as *stochastic effects* to indicate their probabilistic nature. In general, a linear relation between the total dose and the risk of developing cancer or a genetic effect is assumed, although there may be deviations from this model at higher doses. Current estimates of the probability from [3.4] are given in Table 3.7. These values vary somewhat depending on the source and should be taken as order of magnitude estimates. Moreover, they should be put into perspective by comparing them with the risks taken in some common, everyday occupations. This is shown in Table 3.8 where the risk has been transformed into an average loss in life expectancy.

Table 3.7. Risk of radiation-induced cancer [3.4]

Radiation exposure	Excess fatal cancers (per 10^5 persons exposed)
Single, brief exposure to 0.1 Sv	790
Continuous lifetime exposure to 1 mSv/yr	560
Continuous exposure to 0.01 Sv/yr from age 18 until age 65	3000

Table 3.8. Comparison of risk from radiation with risk from other occupations. Normal life expectancy is taken as 73 years. (from [3.6])

Occupation	Average loss of life expectancy (months)
0.20 Sv (typical dose of radiation worker in research lab after 47 yrs, i.e. from age 18 until 65)	0.4
0.5 Sv (typical dose of worker in nuclear power plant after 47 yrs)	1
2.35 Sv	5
Trade	1
Service industries	1.2
Transportation and public utilities	5
Off-the-job accidents	7.5
Construction	10
Mining and quarrying	11

3.4 Dose Limits

We now turn to a question important for anyone handling radioactive materials: What is the maximum dose an individual can be permitted to receive in addition to the natural background dose? This is a difficult question to answer. Indeed, as we have seen, no safe level of radiation exists and, moreover, the effects are cumulative. Nevertheless, certain benefits are derived from radiation, e.g. medical diagnosis or cancer therapy, so that abandoning the use of radiation altogether would also result in a net loss to society. The setting of maximum dose limits thus implies establishing a balance between the benefits to be gained versus the risks incurred. This is obviously a subjective question and indeed the equilibrium point may be different for different people, localities, etc.

The only internationally recognized body for setting these limits is the International Commission on Radiological Protection (ICRP). Because of the possible differences mentioned above, the ICRP presents its limits as recommendations only. Each country is then free to accept, reject or modify these values as it feels fit.

Two sets of limits are defined: one for individuals exposed occupationally and one for the general public. Within each set, dose limits for different parts of the body are given, since some organs are more sensitive than others, as well as for the whole body.

Table 3.9. Dose limits as recommended by the ICRP [3.2]

	Occupational	General public
Whole body	100 mSv in 5 yrs, but not more than 50 mSv in any year	1 mSv/yr averaged over any consecutive 5 years
Single organs		
Lens of eye	150 mSv/yr	15 mSv/yr
Skin (100 cm^2)	500 mSv/yr	50 mSv/yr
Other organs or tissues	500 mSv/yr	50 mSv/yr

It should be stressed that these are allowable doses *in addition* to the natural background dose. Table 3.9 summarizes some of the dose limits for various organs.

Note that these limits are approximately 2.5 times lower than the recommended limits prior to 1990. This is due mostly to a readjustment of the doses received by the Hiroshima-Nagasaki atomic bomb survivors to lower levels.

3.5 Shielding

To ensure total safety, all radioactive materials in the laboratory or place of work should be surrounded by sufficiently thick shielding material such that the radiation in neighboring work areas is kept at minimum permissible levels. This quantity of shielding is determined by the material chosen, the distance of the work area from the source and the maximum time it is inhabited.

The choice of shielding materials and the design of the shield depend on the type of radiation and its intensity. Gamma rays, for example, are best attenuated by materials with a high atomic number, as we have seen in Chap. 2. Materials such as Pb or iron, therefore, would be more stable than, say, plastic or water. Similarly, for stopping charged particles, dense materials would be preferred because of their higher dE/dx. For neutron shielding, on the other hand, hydrogenous materials should be chosen in order to facilitate moderation. In these choices, the possibility of secondary radiation from interactions in the shield should also be considered. For example, positrons are easily stopped by a very thin layer of Pb, however, once at rest they annihilate with electrons resulting in the emission of even more penetrating annihilation radiation. The shield, then, must not only be designed for stopping positrons but also for absorbing 511 keV photons! A summary of the recommended shielding schemes for various radiations found in the nuclear physics laboratory is given in Table 3.10.

Table 3.10. Shielding materials for various radiations

Radiation	Shielding
Gamma-rays	High-Z material, e.g. Pb
Electrons	Low-Z materials, e.g., polystyrene or lucite. High-Z materials should be avoided because of bremsstrahlung production. For intense electron sources, a double layer shield consisting of an inner layer of low-Z material followed by a layer of Pb (or some other high-Z material) to absorb bremsstrahlung should be used. The inner layer should, of course, be sufficiently thick to stop the electrons while the outer layer should provide sufficient attenuation of bremsstrahlung.
Positrons	High-Z material. Since the stopping of positrons is always accompanied by annihilation radiation, the shield should be designed for absorbing this radiation. A double layer design, here, is usually not necessary.
Charged particles	High density materials in order to maximize dE/dx
Neutrons	Hydrogenous materials such as water or paraffin. As for electrons, this shielding should also be followed by a layer of Pb or other high-Z material in order to absorb γ's from neutron capture reactions.

While certain materials are better suited than others for a given type of radiation, cost usually limits the choice of shielding to a few readily available materials. The most used are lead, iron and steel, water, paraffin and concrete. Lead is often used because

of its high atomic number and density. As well, it is soft and malleable and easily cast into various forms. When large amounts of Pb are required, it is usually cheaper to use scrap iron or steel. For very large volumes, concrete blocks are generally the most advantageous as far as cost is concerned. In accelerator laboratories, concrete is, in fact, the standard shielding material.

3.6 Radiation Safety in the Nuclear Physics Laboratory

Since our text is concerned with experimental nuclear physics, it behooves us to say a few words concerning safety in the nuclear physics lab. In general, the risks of working in a student nuclear physics laboratory are very small. The radioactive sources are of relatively low intensity and are all normally sealed against any "rubbing off" of radioactive material. Nevertheless, needless exposure should be avoided and to ensure that this risk be kept at a minimum, a few safety precautions should be followed.

1. Do not eat or smoke in the laboratory. The most dangerous situation, even with a low intensity source, is when radioactive material is ingested. Vital organs, which are otherwise protected by clothing, skin and muscle, would then be exposed.
2. For the same reason as above, always wash hands after handling radioactive material.
3. Wear your dosimeter!