3

Units of radiation measurements and radiation sources

Ketchup left overnight on dinner plates has a longer half-life than radioactive waste.

Wes Smith

3.1 Units of radiation measurement

Many measurements and tests with detectors are made with radioactive sources. Radiation aspects are also an issue at any accelerator and, in particular, at hadron colliders. Even at neutrino factories the radiation levels can be quite high. Basic knowledge of the units of radiation measurement and the biological effects of radiation are therefore useful [1–5].

Let us assume that there are initially N_0 nuclei of a certain radioactive element. The number will decrease in the course of time t due to decay according to

$$N = N_0 \, \mathrm{e}^{-t/\tau} \ , \tag{3.1}$$

where τ is the *lifetime* of the radioisotope. One has to distinguish between the lifetime and the *half-life* $T_{1/2}$. The half-life can be calculated from Eq. (3.1) as

$$N(t = T_{1/2}) = \frac{N_0}{2} = N_0 \, \mathrm{e}^{-T_{1/2}/\tau} \ , \tag{3.2}$$

$$T_{1/2} = \tau \cdot \ln 2 \ . \tag{3.3}$$

The decay constant of the radioactive element is

$$\lambda = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}} \ . \tag{3.4}$$

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The activity of a source gives the number of decays per unit time,

$$A = -\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{1}{\tau}N = \lambda N \ . \tag{3.5}$$

The unit of the activity is *Becquerel* (Bq). 1 Bq means 1 decay per second. (In passing it should be mentioned that the physical quantity with the dimension s^{-1} already has a name: Hertz! However, this unit Hz is mostly used for periodic phenomena, while Bq is used for statistically distributed events.) The unit Bq supersedes the old unit Curie (Ci). Historically 1 Ci was the activity of 1 g of radium,

$$1\,\mathrm{Ci} = 3.7 \cdot 10^{10}\,\mathrm{Bq} \tag{3.6}$$

or

$$1\,\mathrm{Bq} = 27 \cdot 10^{-12}\,\mathrm{Ci} = 27\,\mathrm{pCi} \ . \tag{3.7}$$

1 Bq is a very small unit of the activity. The radioactivity of the human body amounts to about 7500 Bq, mainly due to ^{14}C, ^{40}K and ^{232}Th.

The activity in Bq does not say very much about possible biological effects. These are related to the energy which is deposited per unit mass by a radioactive source.

The *absorbed dose* D (absorbed energy per mass unit)

$$D = \frac{1}{\varrho}\frac{\mathrm{d}W}{\mathrm{d}V} \tag{3.8}$$

($\mathrm{d}W$ – absorbed energy; ϱ – density; $\mathrm{d}V$ – unit of volume) is measured in *Grays* (1 Gray = 1 J/kg). The old cgs unit rad (**r**öntgen **a**bsorbed **d**ose, 1 rad = 100 erg/g) is related to Gray according to

$$1\,\mathrm{Gy} = 100\,\mathrm{rad} \ . \tag{3.9}$$

Gray and rad describe only the physical energy absorption, and do not take into account any biological effect. Since, however, α-, β-, γ- and neutron-emitting sources have different biological effects for the same energy absorption, a ***r**elative **b**iological **e**ffectiveness* (RBE) is defined. The absorbed dose D_γ obtained from the exposure to γ or X rays serves as reference. The absorbed dose of an arbitrary radiation which yields the same biological effect as D_γ leads to the definition of the relative biological effectiveness as

$$D_\gamma = RBE \cdot D \ . \tag{3.10}$$

The RBE factor has a complicated dependence on the radiation field, the radiation energy and the dose rate. For practical reasons, therefore,

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Table 3.1. *Radiation weighting factors* w_R

Radiation and energy range	Radiation weighting factor w_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons $E_n < 10\,\mathrm{keV}$	5
$10\,\mathrm{keV} \le E_n \le 100\,\mathrm{keV}$	10
$100\,\mathrm{keV} < E_n \le 2\,\mathrm{MeV}$	20
$2\,\mathrm{MeV} < E_n \le 20\,\mathrm{MeV}$	10
$E_n > 20\,\mathrm{MeV}$	5
Protons, except recoil protons, $E > 2\,\mathrm{MeV}$	5
α particles, nuclear fragments, heavy nuclei	20

a *radiation weighting factor* w_R (formerly called *quality factor*) is introduced. The absorbed dose D multiplied by this weighting factor is called *equivalent dose* H. The unit of the equivalent dose is 1 *Sievert* (Sv),

$$H\{\mathrm{Sv}\} = w_R \cdot D\,\{\mathrm{Gy}\} \ . \tag{3.11}$$

The weighting factor has the unit Sv/Gy. The old cgs unit rem ($H\{\mathrm{rem}\} = w_R \cdot D\{\mathrm{rad}\}$, rem = **r**öntgen **e**quivalent **m**an) is related to Sievert according to

$$1\,\mathrm{Sv} = 100\,\mathrm{rem} \ . \tag{3.12}$$

The radiation weighting factors w_R are listed in Table 3.1.

According to Table 3.1, neutrinos do not present a radiation hazard. This is certainly true for natural neutrino sources, however, the high flux of energetic neutrinos from future neutrino factories might present a radiation problem.

It should be mentioned that the biological effect of radiation is also influenced by, for example, the time sequence of absorption (e.g. fractionated irradiation), the energy spectrum of radiation, or the question whether the irradiated person has been sensitised or desensitised by a pharmaceutical drug.

The biological effect also depends on which particular part of the human body is irradiated. To take account of this effect a further *tissue weighting factor* w_T is introduced leading to a general expression for the effective equivalent dose

$$H_{\mathrm{eff}} = \sum_T w_T\, H_T \ , \tag{3.13}$$

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Table 3.2. *Tissue weighting factors* w_R

Organ or tissue	Tissue weighting factor w_T
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Chest	0.05
Liver	0.05
Oesophagus	0.05
Thyroid gland	0.05
Skin	0.01
Bone surface	0.01
Other organs or tissue	0.05

where the sum extends over those irradiated parts of the human body which have received the doses H_T. The tissue weighting factors are listed in Table 3.2.

The most general form of the effective equivalent dose is therefore

$$H_{\text{eff}} = \sum_T w_T \sum_R w_R \, D_{T,R} \ , \tag{3.14}$$

where the sums run over the partial body doses received in different radiation fields properly weighted by the radiation and tissue weighting factors.

The *equivalent whole-body dose rate* from pointlike radiation sources can be calculated from the relation

$$\dot{H} = \Gamma \, \frac{A}{r^2} \ , \tag{3.15}$$

where A is the activity (in Bq) and r the distance from the source in metres. Γ is the dose constant which depends on the radiation field and the radioisotope. Specific γ-ray dose constants ($\Gamma_\gamma = 8.46 \cdot 10^{-14} \, \frac{\text{Sv}\cdot\text{m}^2}{\text{Bq}\cdot\text{h}}$ for ^{137}Cs) and β-ray dose constants ($\Gamma_\beta = 2.00 \cdot 10^{-11} \, \frac{\text{Sv}\cdot\text{m}^2}{\text{Bq}\cdot\text{h}}$ for ^{90}Sr) are listed in the literature [4].

Apart from these units, there is still another one describing the quantity of produced charge, which is the *Röntgen* (R). One Röntgen is the

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radiation dose for X-ray or γ radiation which produces, under normal conditions, one electrostatic charge unit (esu) of electrons and ions in $1\,\mathrm{cm}^3$ of dry air.

The charge of an electron is $1.6 \cdot 10^{-19}\,\mathrm{C}$ or $4.8 \cdot 10^{-10}\,\mathrm{esu}$. (The esu is a cgs unit with $1\,\mathrm{esu} = \frac{1}{3 \cdot 10^9}\,\mathrm{C}$.) If one electrostatic charge unit is produced, the number of generated electrons per cm^3 is given by

$$N = \frac{1}{4.8 \cdot 10^{-10}} = 2.08 \cdot 10^9 \ . \tag{3.16}$$

If the unit Röntgen is transformed into an ion charge per kg, it gives

$$1\,\mathrm{R} = \frac{N \cdot q_e\ \{\mathrm{C}\}}{m_{\mathrm{air}}(1\,\mathrm{cm}^3)\ \{\mathrm{kg}\}} = \frac{1\,\mathrm{esu}}{m_{\mathrm{air}}(1\,\mathrm{cm}^3)\ \{\mathrm{kg}\}} \ , \tag{3.17}$$

where q_e is the electron charge in Coulomb, $m_{\mathrm{air}}(1\,\mathrm{cm}^3)$ is the mass of $1\,\mathrm{cm}^3$ air; consequently

$$1\,\mathrm{R} = 2.58 \cdot 10^{-4}\,\mathrm{C/\,kg} \quad \text{for air} \ . \tag{3.18}$$

If Röntgen has to be converted to an absorbed dose, one has to consider that the production of an electron–ion pair in air requires an energy of about $W = 34\,\mathrm{eV}$,

$$1\,\mathrm{R} = N \cdot \frac{W}{m_{\mathrm{air}}} = 0.88\,\mathrm{rad} = 8.8\,\mathrm{mGy} \ . \tag{3.19}$$

To obtain a feeling for these abstract units, it is quite useful to establish a natural scale by considering the radiation load from the environment.

The radioactivity of the human body amounts to about 7500 Bq, mainly caused by the radioisotope $^{14}\mathrm{C}$ and the potassium isotope $^{40}\mathrm{K}$. The average radioactive load (at sea level) by cosmic radiation ($\approx 0.3\,\mathrm{mSv/a}$)*, by terrestrial radiation ($\approx 0.5\,\mathrm{mSv/a}$) and by incorporation of radioisotopes (inhalation $\approx 1.1\,\mathrm{mSv/a}$, ingestion $\approx 0.3\,\mathrm{mSv/a}$) are all of approximately the same order of magnitude, just as the radiation load caused by civilisation ($\approx 1.0\,\mathrm{mSv/a}$), which is mainly caused by X-ray diagnostics and treatment and by exposures in nuclear medicine. The total annual per capita dose consequently is about 3 mSv.

The natural radiation load, of course, depends on the place where one lives; it has a typical fluctuation corresponding to a factor of two. The radiation load caused by civilisation naturally has a much larger fluctuation. The average value in this case results from relatively high doses obtained by few persons.

* a (Latin) = annum = year.

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The *lethal whole-body dose* (50% mortality in 30 days without medical treatment) is 4 Sv (= 400 rem).

The International Commission for Radiological Protection (ICRP) has recommended a limit for the whole-body dose for persons working in controlled areas of 20 mSv/a (=2 rem/a) which has been adopted in most national radiation protection regulations. The ICRP has also proposed *exemption limits* for the handling of radioactive sources (e.g. 10^4 Bq for ^{137}Cs) and *clearance levels* for discharging radioactive material from radiation areas (e.g. 0.5 Bq/g for solid or liquid material containing ^{137}Cs). A radiation officer has to be installed whose responsibility is to watch that the various radiation protection regulations are respected.

3.2 Radiation sources

There is a large variety of radiation sources which can be used for detector tests. Historically, radioactive sources were the first ones to be employed. In β decay electrons or positrons with continuous energy spectra are produced. In β^- decay a neutron inside the nucleus decays according to

$$n \rightarrow p + e^- + \bar{\nu}_e \tag{3.20}$$

while in positron decay a proton of the radioactive element undergoes the transformation

$$p \rightarrow n + e^+ + \nu_e \ . \tag{3.21}$$

The electron-capture reaction

$$p + e^- \rightarrow n + \nu_e \tag{3.22}$$

mostly leads to excited states in the daughter nucleus. The excited nucleus is a source of monochromatic γ rays or monoenergetic electrons which originate from the K or the L shell if the nuclear excitation energy is directly transferred to atomic electrons. The energies of these *conversion electrons* are $E_{\mathrm{ex}} - E_{\mathrm{binding}}$ where E_{ex} is the nuclear excitation energy and E_{binding} the binding energy in the respective atomic shell. As a consequence of internal conversion or other processes which liberate electrons from atomic shells, *Auger electrons* may be emitted. This happens when the excitation energy of the atomic shell is transferred to an electron of the outer shells, which then can leave the atom. If, e.g., the excitation energy of a nucleus liberates a K-shell electron, the free electron state can

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be filled up by an L-shell electron. The excitation-energy difference of the atomic shells, $E_K - E_L$, can be emitted as either characteristic K_α X ray or can directly be transferred to an L electron which then gets the energy $E_K - 2 \cdot E_L$. Such an electron is called an Auger electron. Conversion electrons are typically in the MeV range while Auger electrons are in the keV region.

In most cases β decays do not reach the ground state of the daughter nucleus. The excited daughter nucleus de-excites by γ-ray emission. There is a large selection of γ-ray emitters covering the energy region from keV to several MeV. γ rays can also come from *annihilation*

$$e^+ + e^- \rightarrow \gamma + \gamma \tag{3.23}$$

which provides monoenergetic γ rays of 511 keV or from other annihilation reactions.

γ rays from a wide energy spectrum or X rays can be produced in bremsstrahlung reactions where a charged particle (mostly electrons) is decelerated in the Coulomb potential of a nucleus, as it is typical in an X-ray tube. If charged particles are deflected in a magnetic field, synchrotron photons (*magnetic bremsstrahlung*) are emitted.

Sometimes, also heavily ionising particles are required for detector tests. For this purpose α rays from radioactive sources can be used. Because of the short range of α particles (≈ 4 cm in air), the sources must be very close to the detector or even integrated into the sensitive volume of the detector.

For tests of radiation hardness of detectors one frequently also has to use neutron beams. *Radium–beryllium sources* provide neutrons in the MeV region. In these sources α particles from ^{226}Ra decay interact with beryllium according to

$$\alpha + {}^9\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + n \ . \tag{3.24}$$

Neutrons can also be produced in photonuclear reactions.

In Table 3.3 some α-, β- and γ-ray emitters, which are found to be quite useful for detector tests, are listed [6–8]. (For β-ray emitters the maximum energies of the continuous energy spectra are given; *EC* means electron capture, mostly from the K shell.)

If gaseous detectors are to be tested, an ^{55}Fe source is very convenient. The ^{55}Fe nucleus captures an electron from the K shell leading to the emission of characteristic X rays of manganese of 5.89 keV. X rays or γ rays do not provide a trigger. If one wants to test gaseous detectors with triggered signals, one should look for electron emitters with an electron energy as high as possible. Energetic electrons have a high range making

Table 3.3. *A compilation of useful radioactive sources along with their characteristic properties [5–12]*

Radio-isotope	Decay mode/ branching fraction	$T_{1/2}$	Energy of radiation	
			β, α	γ
$^{22}_{11}$Na	β^+ (89%)	2.6 a	β_1^+ 1.83 MeV (0.05%)	1.28 MeV
	EC (11%)		β_2^+ 0.54 MeV (90%)	0.511 MeV (annihilation)
$^{55}_{26}$Fe	*EC*	2.7 a		Mn X rays 5.89 keV (24%) 6.49 keV (2.9%)
$^{57}_{27}$Co	*EC*	267 d		14 keV (10%) 122 keV (86%) 136 keV (11%)
$^{60}_{27}$Co	β^-	5.27 a	β^- 0.316 MeV (100%)	1.173 MeV (100%) 1.333 MeV (100%)
$^{90}_{38}$Sr	β^-	28.5 a	β^- 0.546 MeV (100%)	
$\rightarrow$ $^{90}_{39}$Y	β^-	64.8 h	β^- 2.283 MeV (100%)	
$^{106}_{44}$Ru	β^-	1.0 a	β^- 0.039 MeV (100%)	
$\rightarrow$ $^{106}_{45}$Rh	β^-	30 s	β_1^- 3.54 MeV (79%) β_2^- 2.41 MeV (10%) β_3^- 3.05 MeV (8%)	0.512 MeV (21%) 0.62 MeV (11%)
$^{109}_{48}$Cd	*EC*	1.27 a	monoenergetic conversion electrons 63 keV (41%) 84 keV (45%)	88 keV (3.6%) Ag X rays
$^{137}_{55}$Cs	β^-	30 a	β_1^- 0.514 MeV (94%) β_2^- 1.176 MeV (6%)	0.662 MeV (85%)
$^{207}_{83}$Bi	*EC*	32.2 a	monoenergetic conversion electrons 0.482 MeV (2%) 0.554 MeV (1%) 0.976 MeV (7%) 1.048 MeV (2%)	 0.570 MeV (98%) 1.063 MeV (75%) 1.770 MeV (7%)
$^{241}_{95}$Am	α	433 a	α 5.443 MeV (13%) α 5.486 MeV (85%)	60 keV (36%) Np X rays

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it possible to penetrate the detector and also a trigger counter. ^{90}Y produced in the course of ^{90}Sr decay has a maximum energy of 2.28 MeV (corresponding to $\approx$ 4 mm aluminium). An Sr/Y radioactive source has the convenient property that almost no γ rays, which are hard to shield, are emitted. If one wants to achieve even higher electron energies, one can use a ^{106}Rh source, it being a daughter element of ^{106}Ru. The electrons of this source with a maximum energy of 3.54 MeV have a range of $\approx$ 6.5 mm in aluminium. The *electron capture* (*EC*) emitter ^{207}Bi emits monoenergetic conversion electrons, and is therefore particularly well suited for an energy calibration and a study of the energy resolution of detectors. A compilation of commonly used radioactive sources along with their characteristic properties is given in Table 3.3. The *decay-level schemes* of these sources are presented in Appendix 5.

If higher energies are required, or more penetrating radiation, one can take advantage of test beams at accelerators or use muons from cosmic radiation.

In these test beams almost any particle with well-defined momentum and charge (electrons, muons, pions, kaons, protons, ...) can be provided. These beams are mostly produced in interactions of energetic protons in a target. A suitable test-beam equipment consisting of momentum-selection magnets, beam-defining scintillators and Cherenkov counters for tagging special particle species can tailor the secondary beam to the needs of the experimenter. If no particle accelerator is at hand, the omnipresent cosmic rays provide an attractive alternative – albeit at relatively low rates – for detector tests.

The flux of cosmic-ray muons through a horizontal area amounts to approximately $1/(\mathrm{cm}^2 \cdot \mathrm{min})$ at sea level. The muon flux per solid angle from near vertical directions through a horizontal area is $8 \cdot 10^{-3}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ [6, 13].

The angular distribution of muons roughly follows a $\cos^2\theta$ law, where θ is the zenith angle measured with respect to the vertical direction. Muons account for 80% of all charged cosmic-ray particles at sea level.

3.3 Problems

3.1 Assume that some piece of radioactive material has a nearly constant gamma activity of 1 GBq. Per decay a total energy of 1.5 MeV is liberated. Work out the daily absorbed dose, if the ionising radiation is absorbed in a mass of $m = 10$ kg?

3.2 In an accident in a nuclear physics laboratory a researcher has inhaled dust containing the radioactive isotope ^{90}Sr, which led to

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a dose rate of 1 µSv/h in his body. The physical half-life of ^{90}Sr is 28.5 years, the biological half-life is only 80 days. How long does it take this dose rate to decay to a level of 0.1 µSv/h?

3.3 Consider a pocket dosimeter with a chamber volume of 2.5 cm^3 and a capacitance of 7 pF. Originally it had been charged to a voltage of 200 V. After a visit in a nuclear power plant it only showed a voltage of 170 V. What was the received dose?

The density of air is $\varrho_{\mathrm{L}} = 1.29 \cdot 10^{-3}\,\mathrm{g/cm^3}$.

3.4 In a reactor building (volume $V_1 = 4000\,\mathrm{m^3}$) a tritium concentration of 100 Bq/m^3 has been measured. The tritium originated from the containment area of volume 500 m^3. Work out the original tritium concentration and the total activity.

3.5 Assume that in a certain working area a ^{60}Co concentration in the air of 1 Bq/m^3 exists. Based on a respiratory annual volume of 8000 m^3 this would lead to an intake of 8000 Bq in this environment. What sort of amount of ^{60}Co would this cobalt activity correspond to ($T_{1/2}(^{60}\mathrm{Co}) = 5.24\,\mathrm{a}$, mass of a ^{60}Co nucleus $m_{\mathrm{Co}} = 1 \cdot 10^{-22}\,\mathrm{g}$)?

3.6 A large shielded shipping container (mass $m = 120$ tons) with an inventory activity of 10^{17} Bq will warm up as a consequence of the emitted ionising radiation. Assume that 10 MeV are liberated per decay which is transferred to the container for a period of 24 hours without any losses. What would be the corresponding temperature increase if the shipping container is made from iron, and if it had originally a temperature of 20 °C (specific heat of iron: $c = 0.452\,\mathrm{kJ/(kg\,K)}$)?

3.7 The absorption coefficient for 50 keV X rays in aluminium is $\mu = 0.3\,(\mathrm{g/cm^2})^{-1}$. Work out the thickness of an aluminium shielding which reduces the radiation level by a factor of 10 000.

3.8 How does the radiation dose received in a four-week holiday in the high mountains (3000 m) compare to the radiation load caused by an X-ray of the human chest in an X-ray mass screening?

3.9 ^{137}Cs is stored in a human with a biological half-life of about 111 days ($T_{1/2}^{\mathrm{phys}} = 30\,\mathrm{a}$). Assume that a certain quantity of ^{137}Cs corresponding to an activity of $4 \cdot 10^6$ Bq is incorporated due to a radiation accident. Work out the ^{137}Cs content of the radiation worker after a period of three years.

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3.10 Assume that during the mounting of a radiation facility for medical tumour irradiation a 10 Ci ^{60}Co source falls down and is almost immediately recovered by a technician with his naked, unprotected hand. Work out the partial body dose and also estimate a value for the whole-body dose (exposure time $\approx$ 60 seconds for the hands and 5 minutes for the whole body).

3.11 A nuclear physics laboratory had been contaminated with a radioactive isotope. The *decontamination procedure* had an efficiency of $\varepsilon = 80\%$. After three decontamination procedures a remaining *surface contamination* of 512 Bq/cm^2 was still measured. Work out the initial contamination! By how much did the third decontamination procedure reduce the surface contamination?

If the level of contamination had to be suppressed to 1 Bq/cm^2, how many procedures would have been required?

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