# 1. RADIOACTIVITY AND RADIATION PROTECTION

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## 1.1. Definitions

The International Commission on Radiation Units and Measurements (ICRU) recommends the use of SI units. Therefore we list SI units first, followed by cgs (or other common) units in parentheses, where they differ.

• **Activity** (unit: Becquerel):

1 Bq = 1 disintegration per second (= 27 pCi).

• **Absorbed dose** (unit: Gray): The absorbed dose is the energy imparted by ionizing radiation in a volume element of a specified material divided by the mass of this volume element.

1 Gy = 1 J/kg (= $10^4$ erg/g = 100 rad)
 = $6.24 \times 10^{12}$ MeV/kg deposited energy.

• **Kerma** (unit: Gray): Kerma is the sum of the initial kinetic energies of all charged particles liberated by indirectly ionizing particles in a volume element of the specified material divided by the mass of this volume element.

• **Exposure** (unit: C/kg of air [= 3880 Roentgen†]): The exposure is a measure of photon fluence at a certain point in space integrated over time, in terms of ion charge of either sign produced by secondary electrons in a small volume of air about the point. Implicit in the definition is the assumption that the small test volume is embedded in a sufficiently large uniformly irradiated volume that the number of secondary electrons entering the volume equals the number leaving (so-called charged particle equilibrium).

• **Equivalent dose** (unit: Sievert [= 100 rem (roentgen equivalent in man)]): The equivalent dose $H_T$ in an organ or tissue $T$ is equal to the sum of the absorbed doses $D_{T,R}$ in the organ or tissue caused by different radiation types $R$ weighted with so-called radiation weighting factors $w_R$:

$$H_T = \sum_R w_R \times D_{T,R} \ . \tag{1.1}$$

It expresses long-term risks (primarily cancer and leukemia) from low-level chronic exposure. The values for $w_R$ recommended recently by ICRP [1] are given in the following table:

† This unit is somewhat historical, but appears on some measuring instruments. One R is the amount of radiation required to liberate positive and negative charges of one electrostatic unit of charge in 1 $cm^3$ of air at standard temperature and pressure (STP)

**Table 1.1:** Radiation weighting factors, $w_R$.

| Radiation type | $w_R$ |
|---|---|
| Photons | 1 |
| Electrons and muons | 1 |
| Neutrons, $E_n < 1$ MeV | $2.5 + 18.2 \times \exp[-(\ln E_n)^2/6]$ |
| $1 \text{ MeV} \leq E_n \leq 50$ MeV | $5.0 + 17.0 \times \exp[-(\ln(2E_n))^2/6]$ |
| $E_n > 50$ MeV | $2.5 + 3.25 \times \exp[-(\ln(0.04E_n))^2/6]$ |
| Protons and charged pions | 2 |
| Alpha particles, fission fragments, heavy ions | 20 |

• **Effective dose** (unit: Sievert): The sum of the equivalent doses, weighted by the tissue weighting factors $w_T$ ($\sum_T w_T = 1$) of several organs and tissues $T$ of the body that are considered to be most sensitive [2], is called "effective dose" $E$:

$$E = \sum_T w_T \times H_T \ . \tag{1.2}$$

## 1.2. Radiation levels [3]

• **Natural annual background**, all sources: Most world areas, whole-body equivalent dose rate $\approx$ (0.4–4) mSv (40–400 mrem). Can range up to 50 mSv (5 rem) in certain areas. U.S. average $\approx$ 3.6 mSv, including $\approx$ 2 mSv ($\approx$ 200 mrem) from inhaled natural radioactivity, mostly radon and radon daughters. (Average is for a typical house and varies by more than an order of magnitude. It can be more than two orders of magnitude higher in poorly ventilated mines. 0.1–0.2 mSv in open areas.)

• **Cosmic ray background** (sea level, mostly muons): $\sim 1 \text{ min}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$. For more accurate estimates and details, see the Cosmic Rays section (Sec. 24 of this *Review*).

• **Fluence** (per cm$^2$) to deposit one Gy, assuming uniform irradiation:

$\approx$ (**charged particles**) $6.24{\times}10^9/(dE/dx)$, where $dE/dx$ (MeV g$^{-1}$ cm$^2$), the energy loss per unit length, may be obtained from Figs. 27.3 and 27.4 in Sec. 27 of this *Review*, and `pdg.lbl.gov/AtomicNuclearProperties`.

$\approx 3.5 \times 10^9$ cm$^{-2}$ minimum-ionizing singly-charged particles in carbon.

$\approx$ (**photons**) $6.24{\times}10^9/[Ef/\ell]$, for photons of energy $E$ (MeV), attenuation length $\ell$ (g cm$^{-2}$), and fraction $f \lesssim 1$ expressing the fraction of the photon's energy deposited in a small volume of thickness $\ll \ell$ but large enough to contain the secondary electrons.

$\approx 2 \times 10^{11}$ photons cm$^{-2}$ for 1 MeV photons on carbon ($f \approx 1/2$).

• **Recommended limits of effective dose to radiation workers (whole-body dose):**$^*$

**EU/Switzerland:** 20 mSv yr$^{-1}$

**U.S.:** 50 mSv yr$^{-1}$ (5 rem yr$^{-1}$)$^\dagger$

• **Lethal dose**: The whole-body dose from penetrating ionizing radiation resulting in 50% mortality in 30 days (assuming no medical treatment) is 2.5–4.5 Gy (250–450 rad), as measured internally on body longitudinal center line. Surface dose varies due to variable body attenuation and may be a strong function of energy.

• **Cancer induction by low LET radiation**: The cancer induction probability is about 5% per Sv on average for the entire population [2].

**Footnotes:**

$^*$ The ICRP recommendation [2] is 20 mSv yr$^{-1}$ averaged over 5 years, with the dose in any one year $\leq$ 50 mSv.

$^\dagger$ Many laboratories in the U.S. and elsewhere set lower limits.

See full *Review* for references and further details.