29. RADIOACTIVITY & RADIATION PROTECTION

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29.1. 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)
  = 6.24×10^{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:

$$H_T = \sum_R w_R \times D_{T,R} \ . \tag{29.1}$$

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 29.1: 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:

$$E = \sum_T w_T \times H_T \ . \tag{29.2}$$

29.2. Radiation levels [3]

- **Natural annual background**, all sources: Most world areas, whole-body equivalent dose rate ≈ (0.4–4) mSv (40–400 mrem). Can range up to 50 mSv (5 rem) in certain areas. U.S. average ≈ 3.6 mSv, including ≈ 2 mSv (≈ 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:

≈ (**charged particles**) $6.24\times10^9/(dE/dx)$, 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`.

≈ 3.5×10^9 cm^{-2} minimum-ionizing singly-charged particles in carbon.

≈ (**photons**) $6.24\times10^9/[Ef/\ell]$, for photons of energy E (MeV), attenuation length ℓ (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.

≈ 2×10^{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})†

- **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].

29.3. Prompt neutrons at accelerators

Neutrons dominate the particle environment outside thick shielding (*e.g.*, > 1 m of concrete) for high energy (> a few hundred MeV) electron and hadron accelerators.

29.3.1. ***Electron beams*** : At electron accelerators, neutrons are generated via photonuclear reactions from bremsstrahlung photons. Neutron yields from semi-infinite targets per unit electron beam power are plotted in Fig. 29.1 as a function of electron beam energy [4]. In the photon energy range 10–30 MeV, neutron production results from the giant photonuclear resonance mechanism. Neutrons are produced roughly isotropically (within a factor of 2) and with a Maxwellian energy distribution described as:

$$\frac{dN}{dE_n} = \frac{E_n}{T^2} e^{-E_n/T} \ , \tag{29.3}$$

where T is the nuclear temperature characteristic of the target nucleus, generally in the range of $T = 0.5$–1.0 MeV. For higher energy photons, the quasi-deuteron and photo-pion production mechanisms become important.

29.3.2. ***Proton beams*** : At proton accelerators, neutron yields emitted per incident proton by different target materials are roughly independent [5] of proton energy between 20 MeV and 1 GeV, and are given by the ratio C:Al:Cu-Fe:Sn:Ta-Pb $=$ $0.3 : 0.6 : 1.0 : 1.5 : 1.7$. Above 1 GeV, the neutron yield [6] is proportional to E^m, where $0.80 \leq m \leq 0.85$.

A typical neutron spectrum [7] outside a proton accelerator concrete shield is shown in Fig. 29.2. The shape of these spectra are generally characterized as having a low-energy evaporation peak around $1 - 2$ MeV, and a high-energy spallation shoulder at around $70 - 80$ MeV.

The neutron-attenuation length, is shown in Fig. 29.3 for concrete and mono-energetic broad-beam conditions.

Letaw's [8] formula for the energy-dependence of the inelastic proton cross-section for $E < 2$ GeV is:

$$\sigma(E) = \sigma_{\text{asympt}} \left[1 - 0.62 e^{-E/200} \sin(10.9 E^{-0.28})\right] \ , \tag{29.4}$$

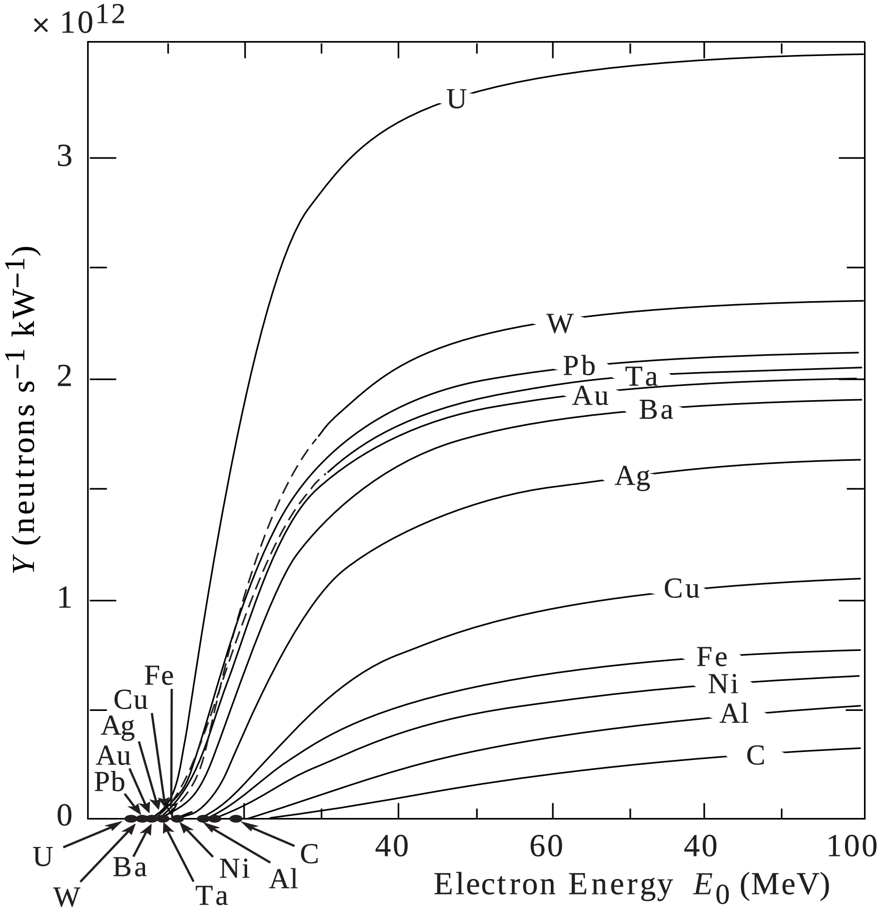

Figure 29.1: Neutron yields from semi-infinite targets, per kW of electron beam power, as a function of electron beam energy, disregarding target self-shielding.

and for $E > 2$ GeV:

$$\sigma_{\text{asympt}} = 45A^{0.7}\left[1 + 0.016\sin(5.3 - 2.63\ln\ A)\right] \ , \qquad (29.5)$$

where σ is in mb, E is the proton energy in MeV and A is the mass number.

29.4. Dose conversion factors

Conversion coefficients from fluence to effective dose are given for anterior-posterior irradiation and various particles in Fig. 29.4 [9]. These factors can be used for converting particle fluence to dose for personnel protection purposes. For example, the effective dose from an anterior-posterior irradiation in a field of 1-MeV neutrons with a fluence of 1 neutron / cm^2 is about 290 pSv.

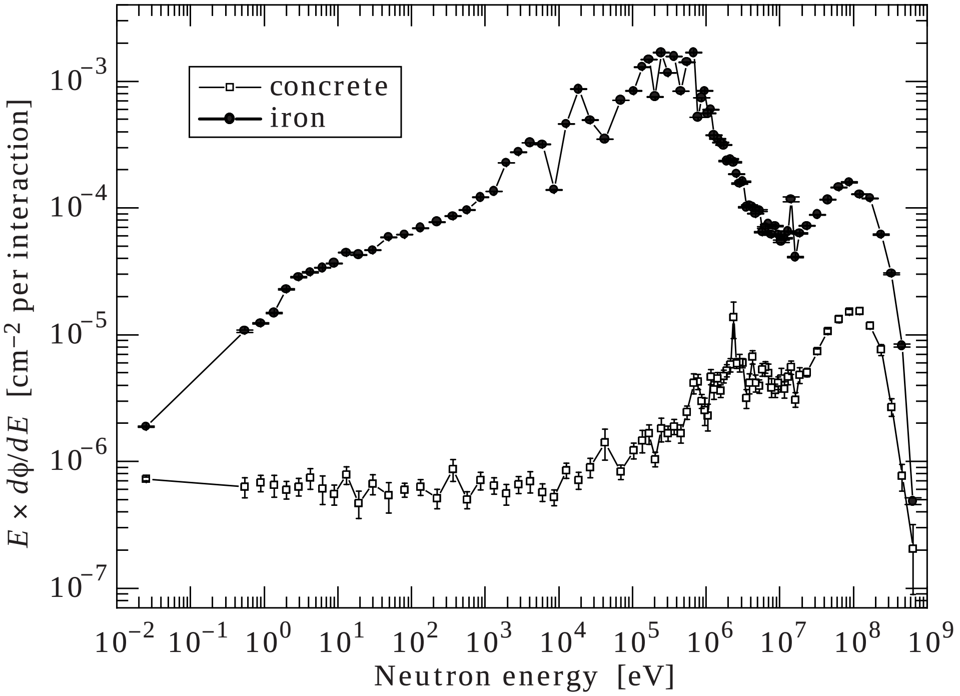

Figure 29.2: Calculated neutron spectrum from 205 GeV/c hadrons (2/3 protons and 1/3 π^+) on a thick copper target [7]. Spectra are evaluated at 90° to beam and through 80 cm of normal density concrete or 40 cm of iron.

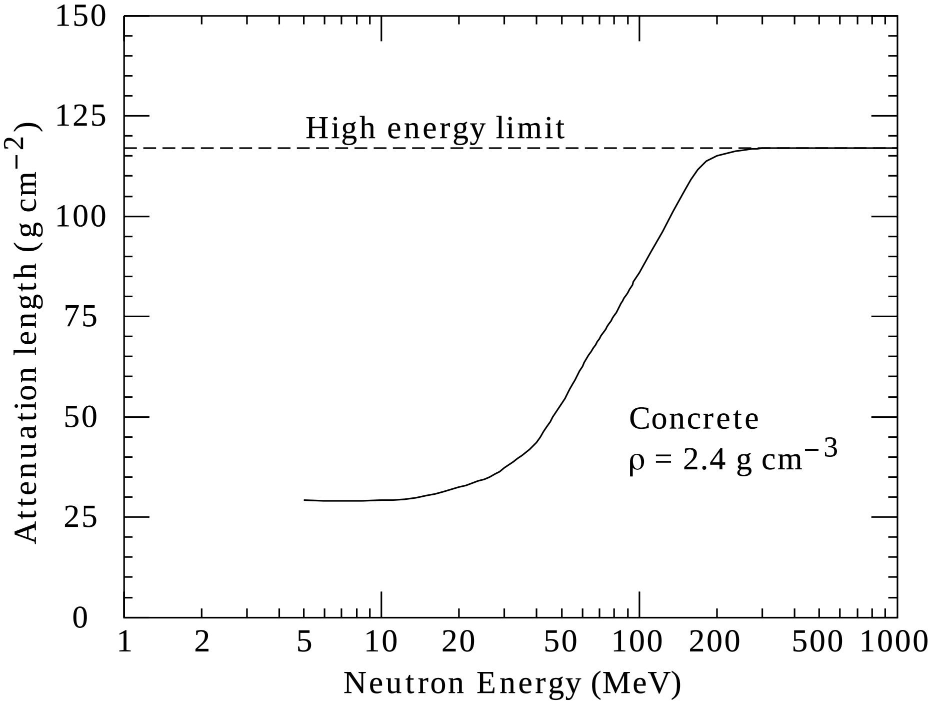

Figure 29.3: The variation of the attenuation length for mono-energetic neutrons in concrete as a function of neutron energy [5].

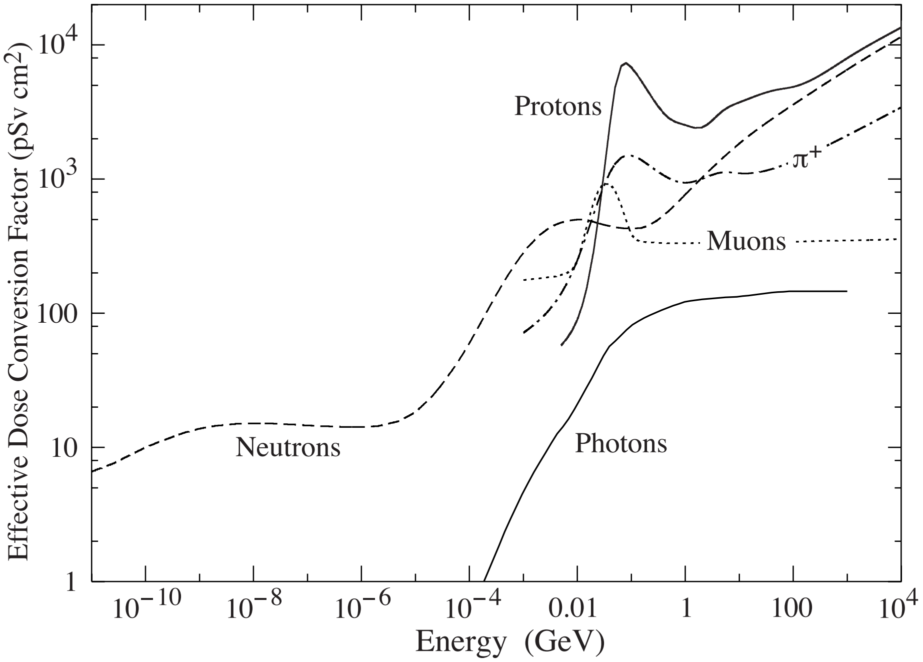

Figure 29.4: Fluence to effective dose conversion factors for anterior-posterior irradiation and various particles [9].

29.5. Accelerator-induced activity

The dose rate at 1 m due to spallation-induced activity by high energy hadrons in a 1 g medium atomic weight target can be estimated [10] from the following expression:

$$D = D_0\, \Phi\, \ln[(T+t)/t] \,, \tag{29.6}$$

where T is the irradiation time, t is the decay time since irradiation, Φ is the flux of irradiating hadrons (hadrons cm^{-2} s^{-1}), and D_0 has a value of 5.2×10^{-17} [(Sv hr^{-1})/(hadron cm^{-2} s^{-1})]. This relation is essentially independent of hadron energy above 200 MeV.

Dose due to accelerator-produced induced activity can also be estimated with the use of "ω factors" [5]. These factors give the dose rate per unit star density (inelastic reaction for $E > 50$ MeV) after a 30-day irradiation and 1-day decay. The ω factor for steel or iron is $\simeq 3 \times 10^{-12}$ (Sv cm^3/star). This does not include possible contributions from thermal-neutron activation. Induced activity in concrete can vary widely depending on concrete composition, particularly with the concentration of trace quantities such as sodium. Additional information can be found in Barbier [11].

29.6. Photon sources

The dose rate in air from a gamma point source of C Curies emitting one photon of energy $0.07 < E < 4$ MeV per disintegration at a distance of 30 cm is about $6\,C\,E$ (rem/hr), or $60\,C\,E$ (mSv/hr), ±20%. In general, the dependence of the dose rate from a point source on the distance r follows a $1/r^2$ behaviour

$$D(r) = \frac{D(r_0)}{(r/r_0)^2}. \tag{29.7}$$

The dose rate in air from a semi-infinite uniform photon source of specific activity C (μCi/g) and gamma energy E (MeV) is about $1.07CE$ (rem/hr), or $10.7CE$ (mSv/hr).

Footnotes:

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

[†] Many laboratories in the U.S. and elsewhere set lower limits.

References:

1. *Recommendation of the International Commission on Radiological Protection,* (2007), (in press).
2. ICRP Publication 60, *1990 Recommendation of the International Commission on Radiological Protection*, Pergamon Press (1991).
3. See E. Pochin, *Nuclear Radiation: Risks and Benefits*, Clarendon Press, Oxford, 1983.
4. W.P. Swanson, *Radiological Safety Aspects of the operation of Electron Linear Accelerators,* IAEA Technical Reports Series No. 188 (1979).
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6. T.A. Gabriel *et al.*, Nucl. Instrum. Methods **A338**, 336 (1994).
7. C. Birattari *et al.*, Nucl. Instrum. Methods **A338**, 534 (1994).
8. J.R. Letaw, R. Silberberg, and C.H. Tsao, *Astrophysical Journal Supplement Series,* **51**, 271 (1983);
   For improvements to this formula see Shen Qing-bang, “Systematics of intermediate energy proton nonelastic and neutron total cross section,” International Nuclear Data Committee INDC(CPR)-020 (July 1991).
9. M. Pelliccioni, “Overview of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients for high energy radiation calculated using the FLUKA code,” Radiation Protection Dosimetry **88**, 279 (2000).
10. A.H. Sullivan *A Guide To Radiation and Radioactivity Levels Near High Energy Particle Accelerators,* Nuclear Technology Publishing, Ashford, Kent, England (1992).
11. M. Barbier, *Induced Activity,* North-Holland, Amsterdam (1969).