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.

• **Unit of activity** = becquerel (curie):

$1\ \mathrm{Bq} = 1$ disintegration s^{-1} $[= 1/(3.7 \times 10^{10})\ \mathrm{Ci}]$

• **Unit of absorbed dose** = gray (rad):

$1\ \mathrm{Gy} = 1$ joule kg^{-1} $(= 10^4\ \mathrm{erg\ g}^{-1} = 100\ \mathrm{rad})$

$= 6.24 \times 10^{12}\ \mathrm{MeV\ kg}^{-1}$ deposited energy

• **Unit of exposure**, the quantity of x- or γ- radiation at a point in space integrated over time, in terms of charge of either sign produced by showering electrons in a small volume of air about the point:

$= 1\ \mathrm{coul\ kg}^{-1}$ of air (roentgen; $1\ R = 2.58 \times 10^{-4}\ \mathrm{coul\ kg}^{-1}$)

$= 1\ \mathrm{esu\ cm}^{-3}$(= 87.8 erg released energy per g of air)

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. This unit is somewhat historical, but appears on many measuring instruments.

• **Unit of equivalent dose** (for biological damage) = sievert [= 100 rem (**r**oentgen **e**quivalent for **m**an)]: Equivalent dose in Sv = absorbed dose in grays × w_R, where w_R (radiation weighting factor, formerly the quality factor Q) expresses long-term risk (primarily cancer and leukemia) from low-level chronic exposure. It depends upon the type of radiation and other factors, as follows [2]:

Table 29.1: Radiation weighting factors.

Radiation	w_R
X- and γ-rays, all energies	1
Electrons and muons, all energies	1
Neutrons < 10 keV	5
10–100 keV	10
> 100 keV to 2 MeV	20
2–20 MeV	10
> 20 MeV	5
Protons (other than recoils) > 2 MeV	5
Alphas, fission fragments, & heavy nuclei	20

29.2. Radiation levels [3]

• **Natural annual background**, all sources: Most world areas, whole-body equivalent dose rate $\approx$ (0.4–4) mSv (40–400 millirems). Can range up to 50 mSv (5 rems) 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 (0.1–0.2 mSv in open areas. 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).

• **Cosmic ray background** in counters (Earth's surface): $\sim 1\ \mathrm{min}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}$. For more accurate estimates and details, see the Cosmic Rays section (Sec. 24 of this *Review*).

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

$\approx$ (**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 the Mean Range and Energy Loss figures.

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

$\approx$ (**photons**) $6.24\times10^9/[Ef/\lambda]$, for photons of energy E (MeV), attenuation length λ (g cm^{-2}) (see Photon Attenuation Length figure), and fraction $f \lesssim 1$ expressing the fraction of the photon's energy deposited in a small volume of thickness $\ll \lambda$ but large enough to contain the secondary electrons.

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

(Quoted fluxes are good to about a factor of 2 for all materials.)

• **Recommended limits to exposure of radiation workers (whole-body dose):***

CERN: 15 mSv yr^{-1}

U.K.: 15 mSv yr^{-1}

U.S.: 50 mSv yr^{-1} (5 rem yr^{-1})†

• **Lethal dose**: Whole-body dose from penetrating ionizing radiation resulting in 50% mortality in 30 days (assuming no medical treatment) 2.5–3.0 Gy (250–300 rads), as measured internally on body longitudinal center line. Surface dose varies due to variable body attenuation and may be a strong function of energy.

29.3. Prompt neutrons at 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:

$$\frac{dN}{dE_n} = \frac{E_n}{T^2} e^{-E_n/T} \ , \tag{29.1}$$

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 photopion production mechanisms become important.

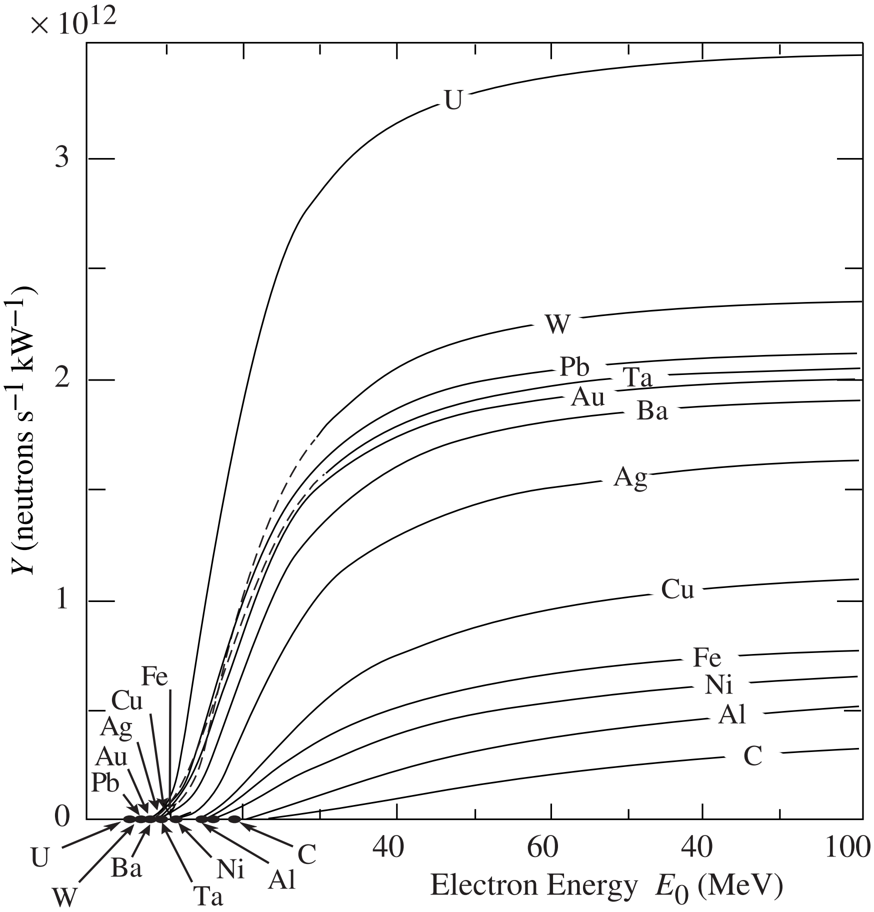

Figure 29.1: Neutron yields from semi-infinite targets, per kW of electron beam power, as a function of electron beam energy, disregarding target self-shielding.

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 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 thermal-energy peak which is very dependent on geometry and the presence of hydrogenic material, a low-energy evaporation peak around 2 MeV, and a high-energy spallation shoulder.

The neutron-attenuation length, λ, is shown in Fig. 29.3 for monoenergetic broad-beam conditions. These values give a satisfactory representation at depths greater than 1 m in concrete.

Letaw's [8] formula for the energy dependence of the inelastic proton cross-section (asymptotic values given in Table 6.1) for $E < 2$ GeV is:

$$\sigma(E) = \sigma_{\rm asympt} \left[1 - 0.62 e^{-E/200} \sin(10.9 E^{-0.28})\right] \ , \qquad (29.2)$$

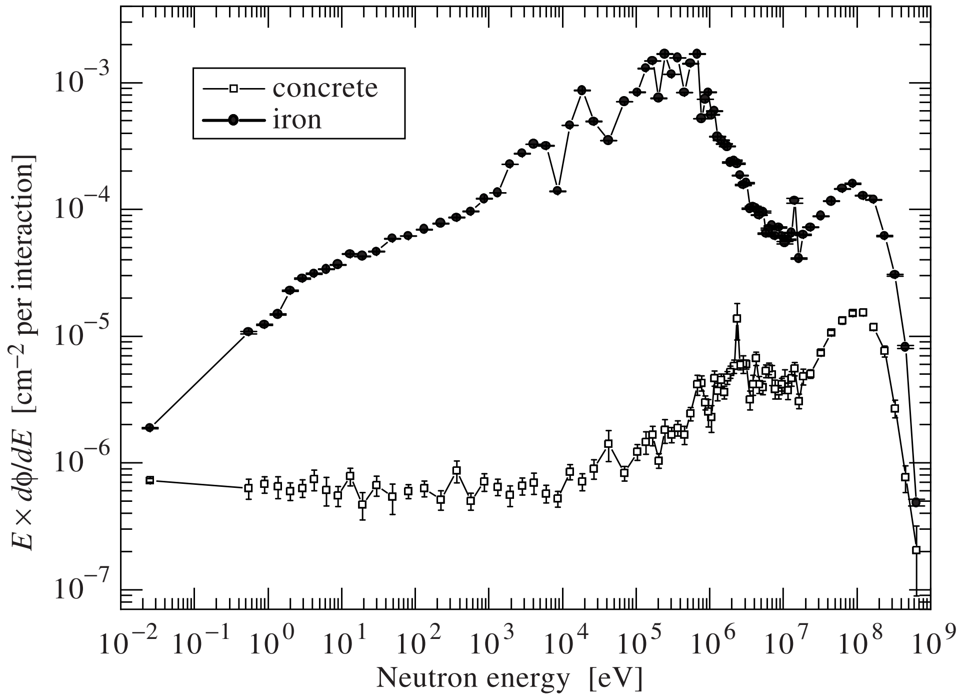

Figure 29.2: Calculated neutron spectrum from 205 GeV/c hadrons (2/3 protons and 1/3 π^+) on a thick copper target. Spectra are evaluated at 90° to beam and through 80 cm of normal density concrete or 40 cm of iron.

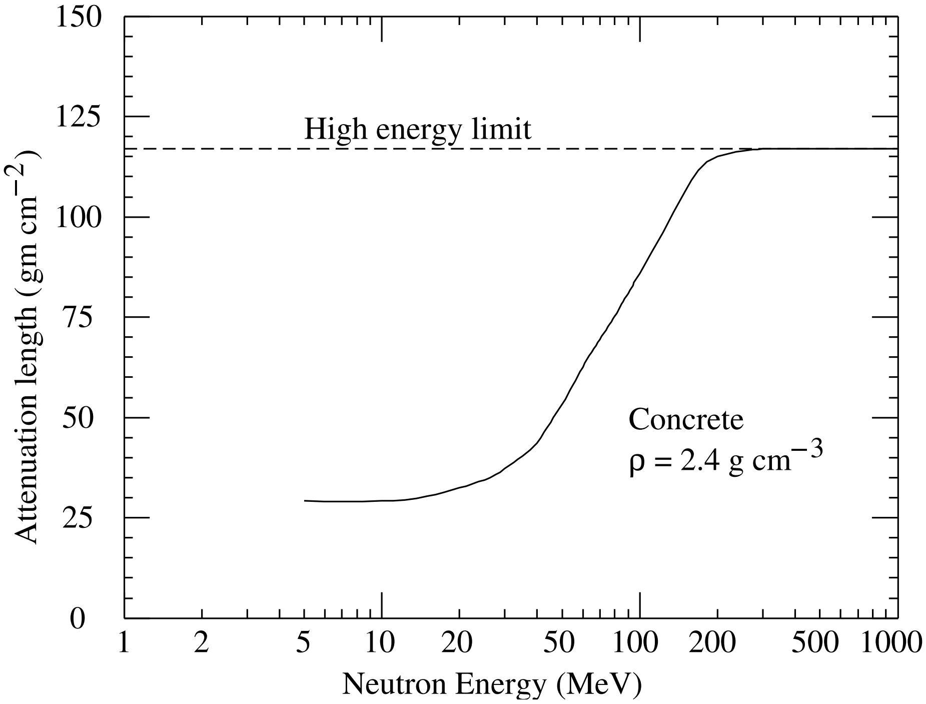

Figure 29.3: The variation of the attenuation length for monoenergetic neutrons in concrete as a function of neutron energy [5].

and for $E > 2$ GeV:

$$\sigma_{\rm asympt} = 45 A^{0.7} \left[1 + 0.016 \sin(5.3 - 2.63 \ln\ A)\right] \ , \tag{29.3}$$

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

29.4. Dose conversion factors

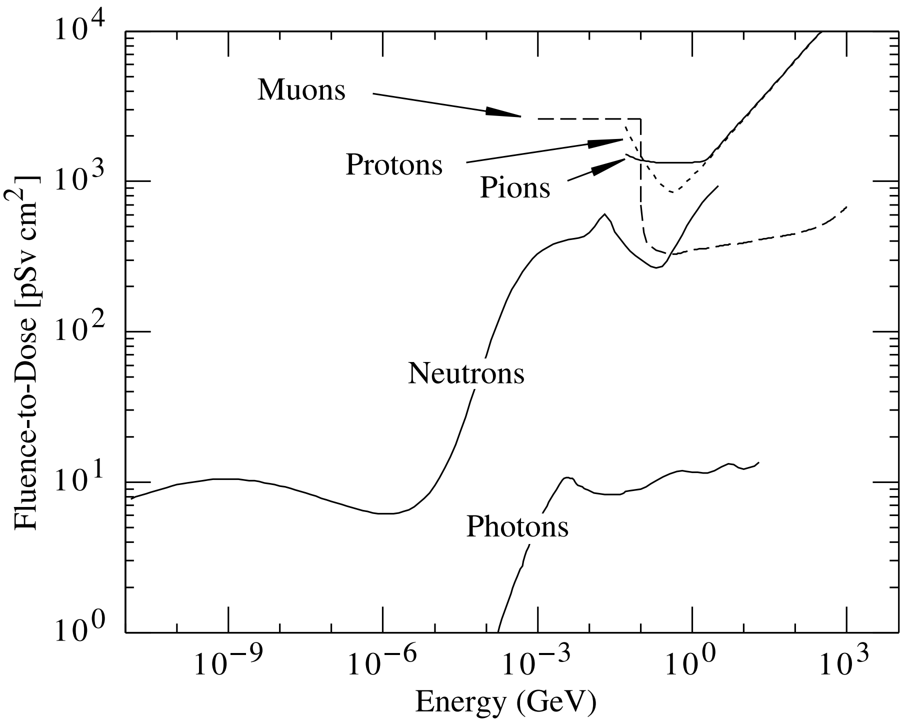

Figure 29.4: Fluence to dose equivalent conversion factors for various particles.

Fluence to dose equivalent factors are given in Fig. 29.4 for photons [9], neutrons [10], muons [11], protons and pions [12]. These factors can be used for converting particle fluence to dose for personnel protection purposes.

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 [13] from the following expression:

$$D = D_0 \ \Phi \ \ln[(T + t)/t] \ , \tag{29.4}$$

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 [14].

29.6. Photon sources

The dose rate 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 6CE (rem/hr), or 60CE (mSv/hr), $\pm 20\%$.

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

Footnotes:

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

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

‡ *Dose* is the time integral of *dose rate*, and *fluence* is the time integral of *flux*.

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