25. RADIOACTIVITY & RADIATION PROTECTION

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

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

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

= 6.24×10^{12} 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 coul kg^{-1} of air (roentgen; 1 $R = 2.58\times10^{-4}$ coul kg^{-1})

= 1 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 25.1: 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

25.2. Radiation levels [3]

• **Natural annual background**, all sources: Most world areas, whole-body equivalent dose rate ≈ (0.4–4) mSv (40–400 millirems). Can range up to 50 mSv (5 rems) in certain areas. U.S. average ≈ 3.6 mSv, including ≈ 2 mSv (≈ 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): ~ 1 min^{-1} cm^{-2} sr^{-1}. For more accurate estimates and details, see the Cosmic Rays section (Sec. 20 of this *Review*).

• **Fluxes** (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 the Mean Range and Energy Loss figures.

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

≈ (**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.

≈ 2×10^{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.

25.3. Prompt neutrons at accelerators

25.3.1. ***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. 25.1 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:

$$\frac{dN}{dE_n} = \frac{E_n}{T^2} e^{-E_n/T} \;, \tag{25.1}$$

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.

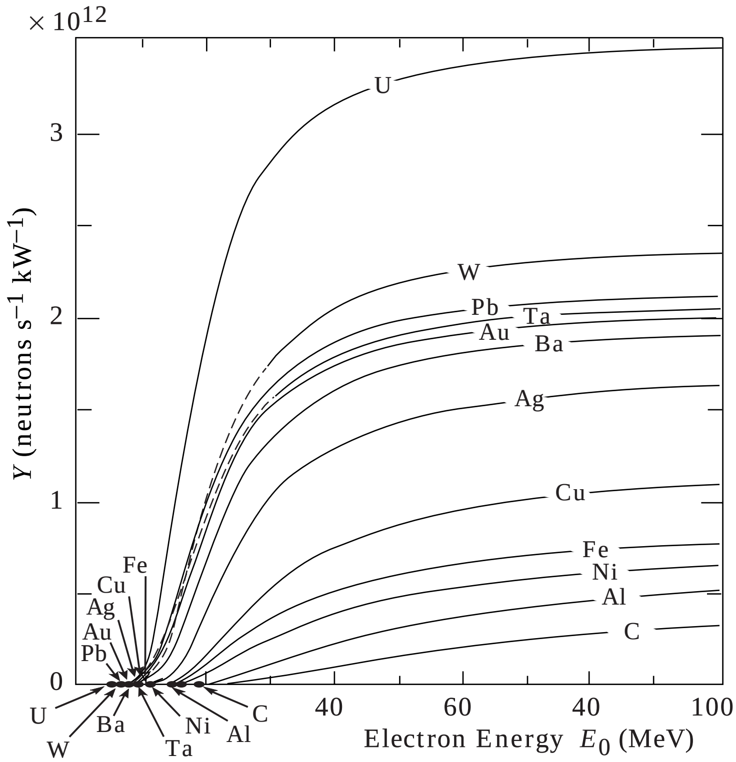

Figure 25.1: Neutron yields from semi-infinite targets, per kW of electron beam power, as a function of electron beam energy, disregarding target self-shielding.

25.3.2. ***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. 25.2. 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.

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:

$$\sigma(E) = \sigma_{\rm asympt}\left[1 - 0.62 e^{-E/200} \sin(10.9 E^{-0.28})\right] , \qquad (25.2)$$

and for $E > 2$ GeV:

$$\sigma_{\rm asympt} = 45 A^{0.7} \left[1 + 0.016 \sin(5.3 - 2.63 \ln\ A)\right] , \qquad (25.3)$$

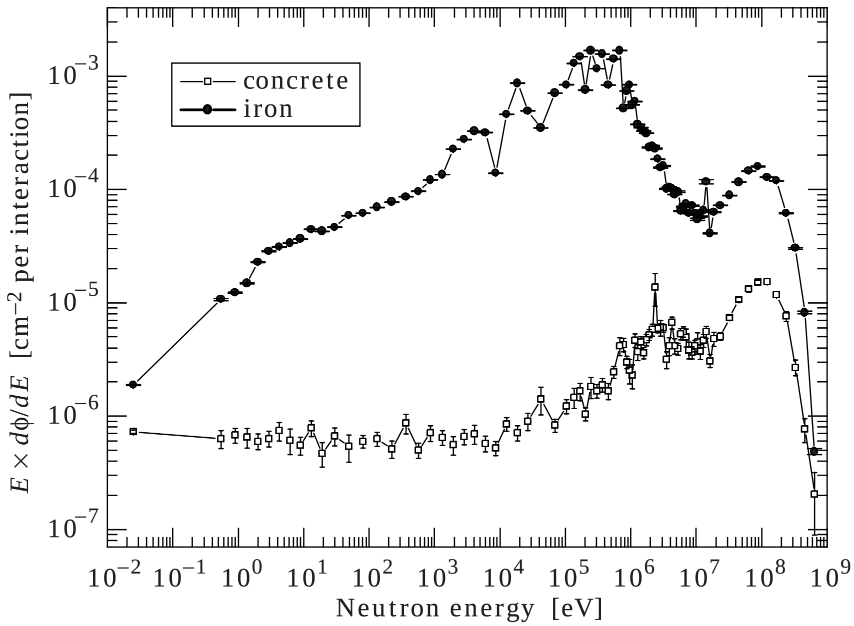

Figure 25.2: Calculated neutron spectrum from 205 GeV/c hadrons (2/3 protons and 1/3 π^+) on a thick copper target. Spectra are evaluated at 90° to beam and through 80 cm of normal density concrete or 40 cm of iron.

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

The neutron-attenuation length, λ, is shown in Fig. 25.3 for monoenergetic broad-beam conditions. These values give a satisfactory representation at depths greater than 1 m in concrete.

25.4. Dose conversion factors

Fluence to dose equivalent factors are given in Fig. 25.4 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.

25.5. 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:

$$D = D_0 \ \Phi \ \ln[(T + t)/t] \ , \tag{25.4}$$

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.

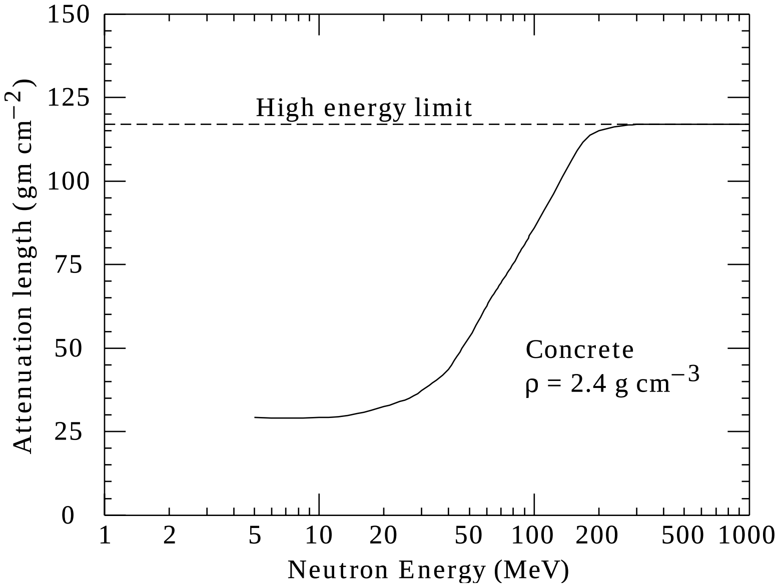

Figure 25.3: The variation of the attenuation length for monoenergetic neutrons in concrete as a function of neutron energy [5].

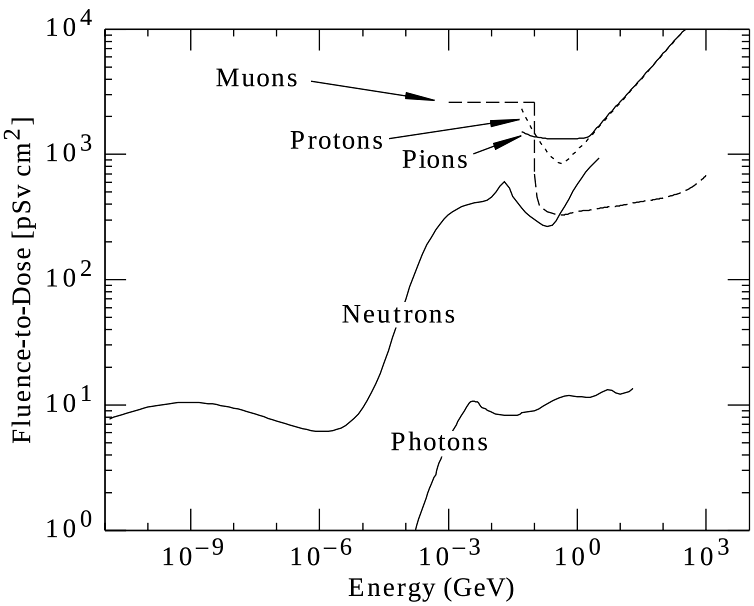

Figure 25.4: Fluence to dose equivalent conversion factors for various particles.

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].

25.6. 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), ±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).

25.7. Radiation levels in detectors at hadron colliders

An SSC Central Design Group task force studied the radiation levels to be expected in SSC detectors [15]. The study focused on scaling with energy, distance, and angle. As such, it is applicable to future detectors such as those at the LHC. Although superior detector-specific calculations have since been made, the scaling is in most cases not evident, and so the SSC results have some relevance. The SSC/CDG model assumed

- The machine luminosity at $\sqrt{s} = 40$ TeV is $\mathscr{L} = 10^{33}$ cm^{-2}s^{-1}, and the pp inelastic cross section is $\sigma_{\rm inel} = 100$ mb. This luminosity is effectively achieved for 10^7 s yr^{-1}. The interaction rate is thus 10^8 s^{-1}, or 10^{15} yr^{-1};
- All radiation comes from pp collisions at the interaction point;
- The charged particle distribution is (a) flat in pseudorapidity for $|\eta| < 6$ and (b) has a momentum distribution whose perpendicular component is independent of rapidity, which is taken as independent of pseudorapidity:

$$\frac{d^2 N_{\rm ch}}{d\eta dp_\perp} = H\ f(p_\perp) \tag{25.5}$$

  (where $p_\perp = p \sin\theta$). Integrals involving $f(p_\perp)$ are simplified by replacing $f(p_\perp)$ by $\delta(p_\perp - \langle p_\perp \rangle)$; in the worst case this approximation introduces an error of less than 10%;
- Gamma rays from π^0 decay are as abundant as charged particles. They have approximately the same η distribution, but half the mean momentum;
- At the SSC ($\sqrt{s} = 40$ TeV), $H \approx 7.5$ and $\langle p_\perp \rangle \approx 0.6$ GeV/c; assumed values at other energies are given in Table 25.3. Together with the model discussed above, these values are thought to describe particle production to within a factor of two or better.

It then follows that the flux of charged particles from the interaction point passing through a normal area da located a distance $r_\perp$ from the beam line is given by

$$\frac{dN_{\rm ch}}{da} = \frac{1.2 \times 10^8\,{\rm s}^{-1}}{r_\perp^2}\ . \tag{25.6}$$

In a typical organic material, a relativistic charged particle flux of 3×10^9 cm^{-2} produces an ionizing radiation dose of 1 Gy, where 1 Gy $\equiv$ 1 joule kg^{-1} (= 100 rads). The above result may thus be rewritten as dose rate,

$$\dot{D} = \frac{0.4\ \ {\rm MGy\ yr}^{-1}}{(r_\perp/1\ {\rm cm})^2}\ . \tag{25.7}$$

If a magnetic field is present, "loopers" may increase this dose rate by a factor of two ore more.

In a medium in which cascades can develop, the ionizing dose or neutron fluence is proportional to $dN_{\rm ch}/da$ multiplied by $\langle E\rangle^\alpha$, where $\langle E\rangle$ is the mean energy of the particles going through da and the power α is slightly less than unity. Since $E \approx p = p_\perp/\sin\theta$ and $r_\perp = r\sin\theta$, the above expression for $dN_{\rm ch}/da$ becomes

$$\text{Dose or fluence}^\ddagger = \frac{A}{r^2}\cosh^{2+\alpha}\eta = \frac{A}{r^2\sin^{2+\alpha}\theta}\ . \tag{25.8}$$

The constant A contains the total number of interactions $\sigma_{\rm inel}\int \mathscr{L}\,dt$, so the ionizing dose or neutron fluence at another accelerator scales as $\sigma_{\rm inel}\int \mathscr{L}\,dt\,H\,\langle p_\perp\rangle^\alpha$.

The dose or fluence in a calorimeter scales as $1/r^2$, as does the neutron fluence inside a central cavity with characteristic dimension r.

Under all conditions so far studied, the neutron spectrum shows a broad log-normal distribution peaking at just under 1 MeV. In a 2 m radius central cavity of a detector with coverage down to $|\eta| = 3$, the average neutron flux is 2×10^{12} cm^{-2}yr^{-1}, including secondary scattering contributions.

Values of A and α are given in Table 25.2 for several relevant situations. Examples of scaling to other accelerators are given in Table 25.3. It should be noted that the assumption that all radiation comes from the interaction point does not apply to the present generation of accelerators.

The constant A includes factors evaluated with cascade simulation programs as well as constants describing particle production at the interaction point. It is felt that each could introduce an error as large as a factor of two in the results.

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.

Table 25.2: Coefficients $A/(100\ \text{cm})^2$ and α for the evaluation of calorimeter radiation levels at cascade maxima under SSC nominal operating conditions. At a distance r and angle θ from the interaction point the annual fluence or dose is $A/(r^2 \sin^{2+\alpha}\theta)$.

Quantity	$A/(100\ \text{cm})^2$	Units	$\langle p_\perp \rangle$	α
Neutron flux	1.5×10^{12}	$\text{cm}^{-2}\text{yr}^{-1}$	0.6 GeV/c	0.67
Dose rate from photons	124	Gy yr^{-1}	0.3 GeV/c	0.93
Dose rate from hadrons	29	Gy yr^{-1}	0.6 GeV/c	0.89

Table 25.3: A rough comparison of beam-collision induced radiation levels at the Tevatron, high-luminosity LHC, SSC, and a possible 100 TeV machine [16].

	Tevatron	LHC	SSC	100 TeV
$\sqrt{s}$ (TeV)	1.8	15.4	40	100
$\mathscr{L}_{\text{nom}}$ ($\text{cm}^{-2}\text{s}^{-1}$)	2×10^{30}	1.7×10^{34}[a]	1×10^{33}	1×10^{34}
σ_{inel}	56 mb	84 mb	100 mb	134 mb
H	3.9	6.2	7.5	10.6
$\langle p_\perp \rangle$ (GeV/c)	0.46	0.55	0.60	0.70
Relative dose rate[b]	5×10^{-4}	11	1	20

[a] High-luminosity option.
[b] Proportional to $\mathscr{L}_{\text{nom}}\, \sigma_{\text{inel}}\, H\ \langle p_\perp \rangle^{0.7}$

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

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