Chem 481 Lecture Material

2/25/09

Characteristics of Ionizing Radiation

Interactions of Radiation with Matter

Understanding how various forms of ionizing radiation interact with matter is important for the design of detectors, selection of appropriate radiation shielding, for medical applications and for the labeling of molecules.

Ionizing radiation consists of charged particles (α, e^-, p^+, etc.), high energy photons and neutrons. The passage of radiation through matter results in the transfer of energy from the radiation to atoms and molecules of the absorber material. This continues until the radiation undergoes a reaction with an absorber nucleus or atomic electrons, or until the impinging particle reaches the same average energy as the atoms in the absorber (becomes thermalized). The probability for interaction with electrons is considerably greater, except for the uncharged neutron which must interact with a nucleus. Neutron capture or scattering can result in charged particle emission or nuclear recoil which can cause ionization and excitation. Most ionization processes require less than 15 eV so many ion-electron pairs form as radiation transfers its energy to an absorber. Electrons from the primary ionization events may have enough energy to cause secondary ionization or excitation. The table below summarizes the important characteristics of the interactions of radiation with matter.

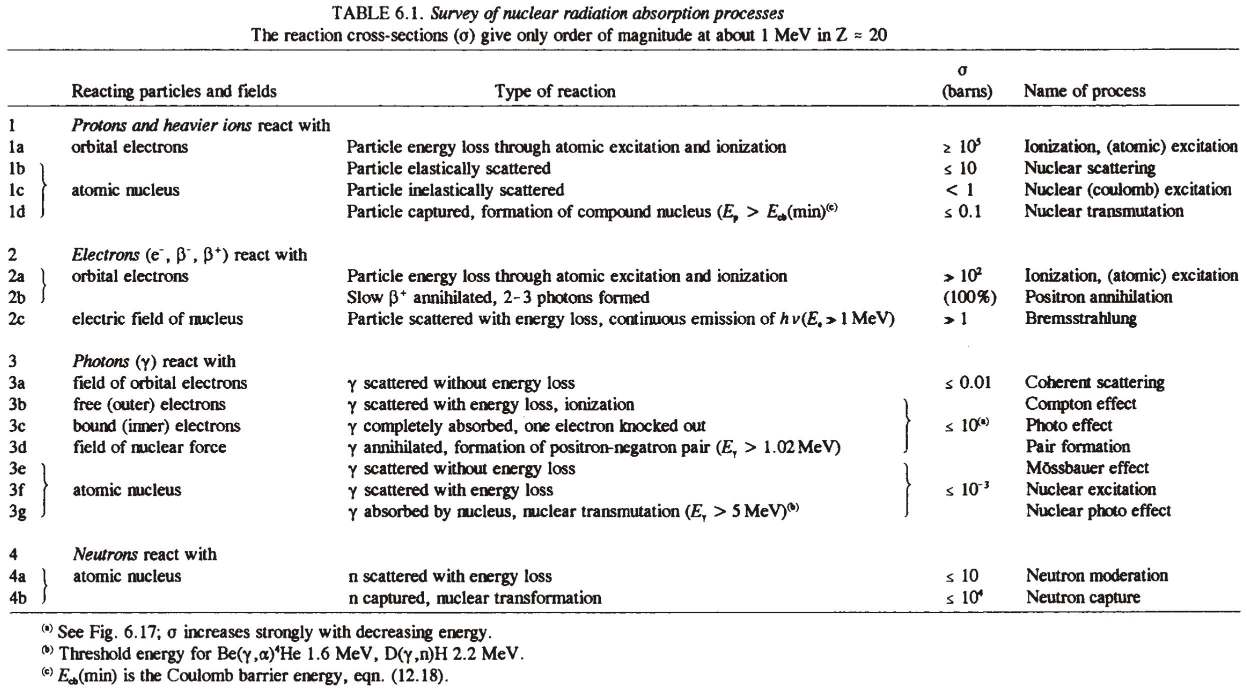


TABLE 6.1. *Survey of nuclear radiation absorption processes*
The reaction cross-sections (σ) give only order of magnitude at about 1 MeV in $Z \approx 20$

	Reacting particles and fields	Type of reaction	σ (barns)	Name of process
1	*Protons and heavier ions* react with			
1a	orbital electrons	Particle energy loss through atomic excitation and ionization	$\geq 10^5$	Ionization, (atomic) excitation
1b	atomic nucleus	Particle elastically scattered	≤ 10	Nuclear scattering
1c		Particle inelastically scattered	< 1	Nuclear (coulomb) excitation
1d		Particle captured, formation of compound nucleus ($E_p > E_{cb}(\min)$(c)	≤ 0.1	Nuclear transmutation
2	*Electrons* (e^-, β^-, β^+) react with			
2a	orbital electrons	Particle energy loss through atomic excitation and ionization	$> 10^2$	Ionization, (atomic) excitation
2b		Slow β^+ annihilated, 2-3 photons formed	(100%)	Positron annihilation
2c	electric field of nucleus	Particle scattered with energy loss, continuous emission of $h\nu(E_e > 1\text{ MeV})$	> 1	Bremsstrahlung
3	*Photons* (γ) react with			
3a	field of orbital electrons	γ scattered without energy loss	≤ 0.01	Coherent scattering
3b	free (outer) electrons	γ scattered with energy loss, ionization	≤ 10(a)	Compton effect
3c	bound (inner) electrons	γ completely absorbed, one electron knocked out		Photo effect
3d	field of nuclear force	γ annihilated, formation of positron-negatron pair ($E_\gamma > 1.02\text{ MeV}$)		Pair formation
3e	atomic nucleus	γ scattered without energy loss	$\leq 10^{-3}$	Mössbauer effect
3f		γ scattered with energy loss		Nuclear excitation
3g		γ absorbed by nucleus, nuclear transmutation ($E_\gamma > 5\text{ MeV}$)(b)		Nuclear photo effect
4	*Neutrons* react with			
4a	atomic nucleus	n scattered with energy loss	≤ 10	Neutron moderation
4b		n captured, nuclear transformation	$\leq 10^4$	Neutron capture

(a) See Fig. 6.17; σ increases strongly with decreasing energy.
(b) Threshold energy for $Be(\gamma,\alpha)^4He$ 1.6 MeV, $D(\gamma,n)H$ 2.2 MeV.
(c) $E_{cb}(\min)$ is the Coulomb barrier energy, eqn. (12.18).

Absorption Measurements

Ideally, radiation absorption measurements are made with a well-collimated beam, a point source with no self-absorption and a sensitive detector. The narrow beam geometry shown below is the preferred arrangement for making absorption measurements.

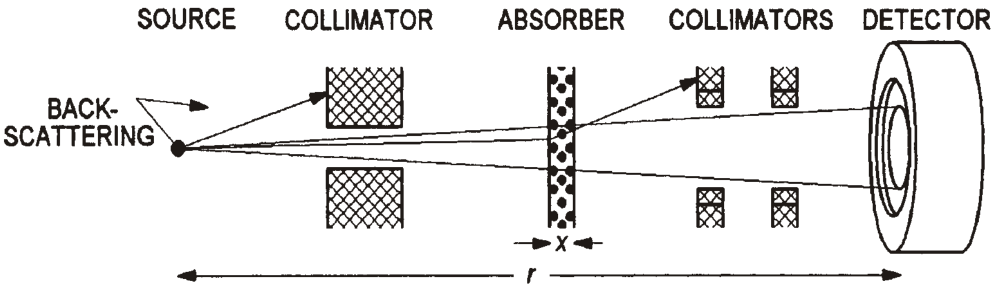


FIG. 6.1. Geometrical arrangement for measuring absorption curves.

The count rate (R) in such an absorption measurement is related to the sample activity (A) by $R = \varepsilon A n$ where ε is the counting efficiency and n is the number of detectable particles emitted per decay. The counting efficiency depends on a number of factors

$$\varepsilon = \varepsilon_{sam} \cdot \varepsilon_{abs} \cdot \varepsilon_{\mathrm{det}} \cdot \varepsilon_{geom}$$

where ε_{sam} is the self-absorption and scattering in the sample;

ε_{abs} is the absorption of the radiation between the source and detector;

ε_{det} is the sensitivity of the detector to the radiation;

ε_{geom} is the geometric efficiency.

Ideally, there is no self-absorption or scattering ($\varepsilon_{sam} = 1$), no air or other absorber absorption ($\varepsilon_{abs} = 1$) and 100% detector sensitivity ($\varepsilon_{det} = 1$). The geometric efficiency is 1 if the point source is at the center of a spherical detector (known as "4π" counting geometry). Otherwise, as in the absorption measurement depicted above, if the detector is placed a distance r from a point source and has a window of area S_{det}, then the solid angle subtended by the detector is approximately S_{det}/r^2 and

$$\varepsilon_{geom} \simeq \frac{S_{\mathrm{det}}}{4\pi r^2}$$

As the thickness of an absorber increases the amount of radiation reaching the detector decreases, resulting in an absorption curve (see figure below). Charged particles (α, e^-, p^+, etc.) have a finite range. However, the reduction in intensity of a beam of unchanged particles like photons and neutrons follows an exponential form

$$\varphi = \varphi_0 e^{-\mu x}$$

where φ is the beam intensity (particles/cm^2·s) reaching the detector;

φ_0 is the beam intensity (particles/cm^2·s) originating at the source;

μ is the linear absorption coefficient (cm^{-1});

x is the absorber thickness (cm).

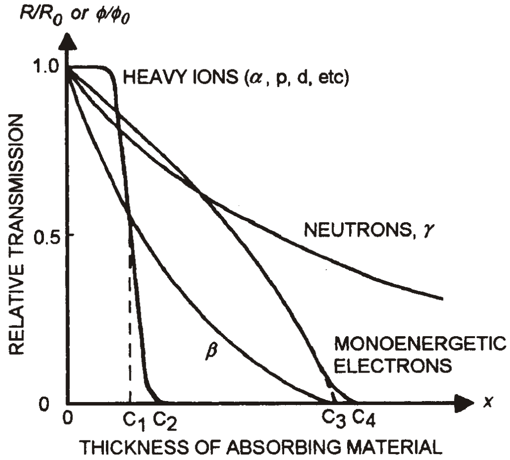


FIG. 6.3. Curves showing relative transmission ϕ/ϕ_0 (or R/R_0) as function of absorber thickness x. C_1 and C_3 are average, C_2 and C_4 maximum range.

Alpha Radiation

Alpha particles are emitted at discrete energies (typically 5-7 MeV). Since they are much heavier than electrons, they are deflected only slightly as they interact with atomic electron clouds to form ion pairs. Consequently, they travel in rather straight lines. For a gas, the energy loss per ion pair formed (W-value) is typically 25-35 eV. Ion-pair formation can produce electrons with sufficient energy (~100 eV) to cause secondary ionization.

The range of alpha particles is usually given in mass thickness (surface density) units such as mg/cm^2. A linear absorber thickness (cm) is converted to its equivalent surface density thickness by multiplying by the absorber density (mg/cm^3). The range of an alpha particle in air is given by

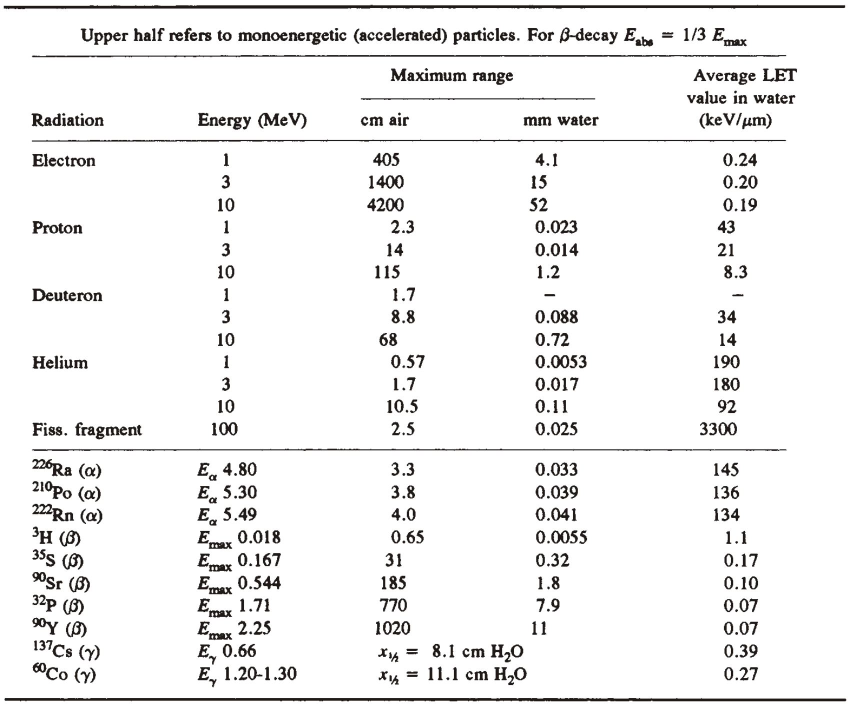
$$R_{air}(mg/cm^2) = 0.40\, E_\alpha^{3/2}$$

For other absorbers the alpha range can be gotten by

$$R_Z(mg/cm^2) = 0.17\, E_\alpha^{3/2}\, A_{abs}^{1/3}$$

where A$_{abs}$ is the mass number of the absorber. In gases at typical room temperature and pressure, the range of alpha particles is several cm. In water the range would be only 0.03-0.04 mm (see table below).

TABLE 6.2. *Range in water, and average linear energy transfer (LET) values for different radiation*



Upper half refers to monoenergetic (accelerated) particles. For β-decay $E_{abs} = 1/3\ E_{max}$

Radiation	Energy (MeV)	Maximum range cm air	 mm water	Average LET value in water (keV/μm)
Electron	1	405	4.1	0.24
	3	1400	15	0.20
	10	4200	52	0.19
Proton	1	2.3	0.023	43
	3	14	0.014	21
	10	115	1.2	8.3
Deuteron	1	1.7	–	–
	3	8.8	0.088	34
	10	68	0.72	14
Helium	1	0.57	0.0053	190
	3	1.7	0.017	180
	10	10.5	0.11	92
Fiss. fragment	100	2.5	0.025	3300
^{226}Ra (α)	E_α 4.80	3.3	0.033	145
^{210}Po (α)	E_α 5.30	3.8	0.039	136
^{222}Rn (α)	E_α 5.49	4.0	0.041	134
^{3}H (β)	E_{max} 0.018	0.65	0.0055	1.1
^{35}S (β)	E_{max} 0.167	31	0.32	0.17
^{90}Sr (β)	E_{max} 0.544	185	1.8	0.10
^{32}P (β)	E_{max} 1.71	770	7.9	0.07
^{90}Y (β)	E_{max} 2.25	1020	11	0.07
^{137}Cs (γ)	E_γ 0.66	$x_{1/2}$ = 8.1 cm H_2O		0.39
^{60}Co (γ)	E_γ 1.20-1.30	$x_{1/2}$ = 11.1 cm H_2O		0.27

Because alpha particles have high charge (+2) and a relatively low velocity they interact strongly with atomic electron clouds and have a large specific ionization (number of ion pairs formed per unit path length). The specific ionization of an alpha particle increases as it slows down and interacts more strongly (see figure below).