University of Pittsburgh

ME/ENGR 2100 Fundamentals of Nuclear Engineering

Radiation Protection:

Radiation Terminology and Units

Dr. Daniel F. Gill

Stephen R. Tritch Program in Nuclear Engineering
Swanson School of Engineering
University of Pittsburgh

Relevant Reading Assignments

- Chapter 9 of "Introduction to Nuclear Engineering," Lamarsh and Baratta, 3rd edition, Prentice-Hall (2001)
- Chapter 3 of "Nuclear Engineering: Theory and Technology of Commercial Nuclear Power," Knief, 2nd edition, American Nuclear Society (1992, reprint by ANS 2008)

Learning Objectives

- Explain basic radiation terminology, radiation interactions with matter, and common radiation dose units.

The basic physics of radiation: terminology

- Radiation: energy emitted from a nucleus or atom (typically, gamma-rays or x-rays, electrons, neutrons, alpha-particles)
- Radioactivity: the process of emission of radiation due to nuclear instability
- Radiation is energy; radioactive material is matter that emits radiation
- Activity is measured in disintegrations per unit time. The historical unit is the Curie, defined as 3.7×10^{10} disintegrations per second (= 2.22×10^{12} disintegrations per minute). The SI unit is the Becquerel: 1Bq=1dps.

Macroscopic Effects of Radiation

- Ionization events are the root cause behind **ALL** observable effects of radiation [except neutron disruption of material lattices (e.g., in steels), and even there one finds ionizations]
  - Ionization reactions damage materials by breaking chemical bonds and disrupting normal chemical processes (material embrittlement [e.g., in polymers], biological damage, etc.)
- The rate of ionization (damage) depends on the type and energy of the radiation, as well as the constituent atoms in the target material.
- Note that radiation "damage" can also be beneficial – e.g., hardening of tool steel surfaces using ion beams

Ionization Density

- The number of ionization events that a single particle of radiation can produce is determined by the energy of the radiation.
- The ionization density is determined by the LET (linear energy transfer, in units of energy per unit length)

Radiation	Relative Range	Relative LET
Alpha	1	10,000
Beta	100	100
Gamma	10,000	1

Ionization Density

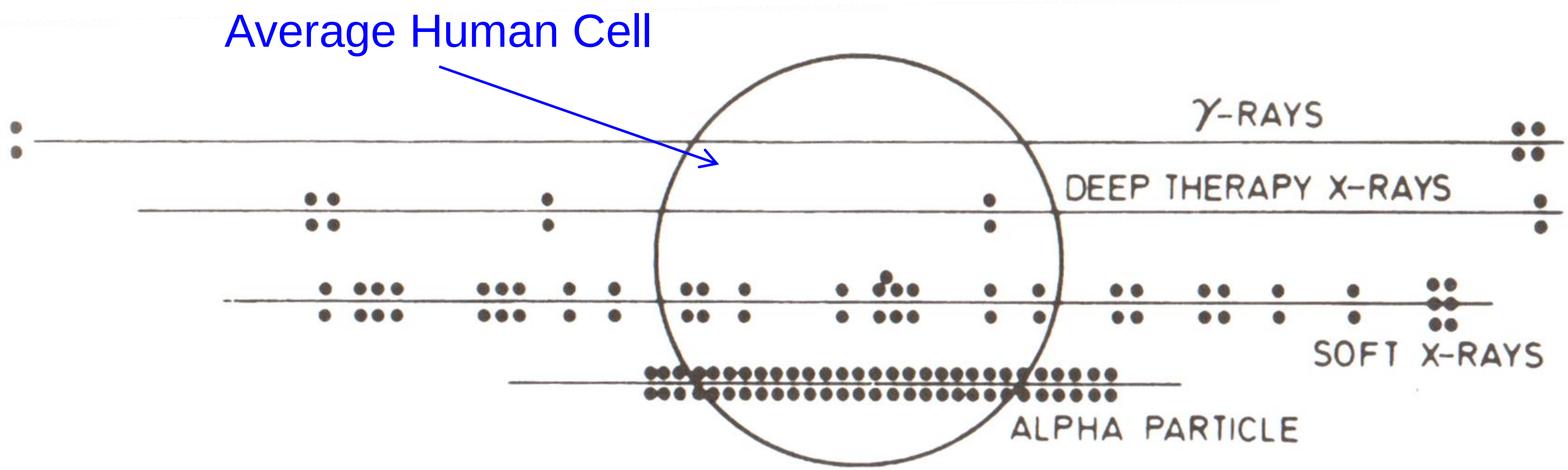
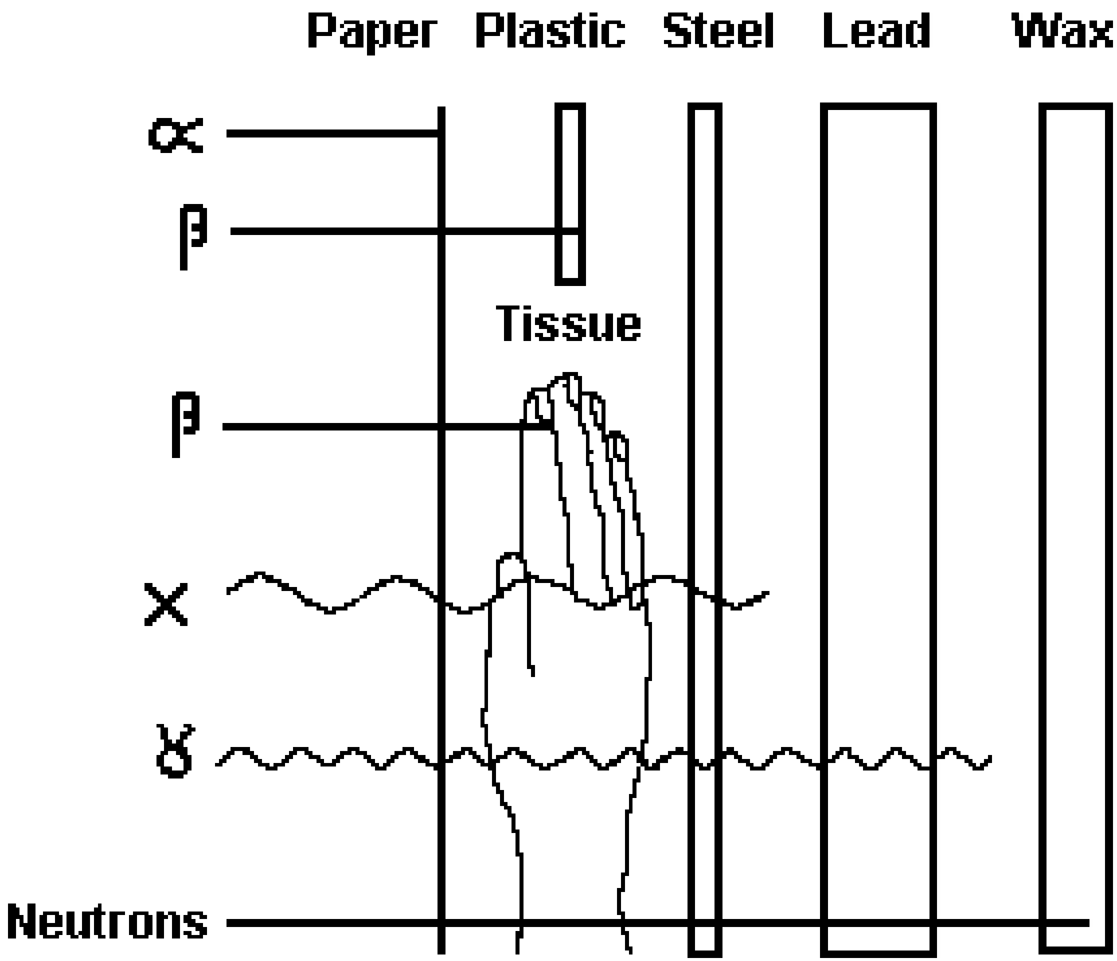


Figure 4.4. Separation of ion clusters in relation to the size of a biological target. (Reproduced from Gray, 1946, *Br. Med. Bull.* by permission of the author.)

Figure taken from Nias, 1997, *An Introduction to Radiobiology, 2nd Ed.*

Penetrating Properties of Radiation



Reproduced from Knief, 1992, *Nuclear Engineering*

Student Question

- Q. The range of a charged particle may be characterized by its LET (Linear Energy Transfer) or the energy deposition per unit distance of travel. Which of the following charged particles has the largest LET and hence the shortest range in material?

a) Fission fragments
b) Alpha particles
c) Beta particles (i.e., electrons)
d) Cannot be estimated

Student Question

- The range of a charged particle may be characterized by its LET (Linear Energy Transfer) or the energy deposition per unit distance of travel. Which of the following charged particles has the largest LET and hence the shortest range in material?

a) Fission fragments

b) Alpha particles

c) Beta particles (i.e., electrons)

d) Cannot be estimated

Question: Multiple Choice

- A rule of thumb for the penetrating power of radiation is that the relative range for radiation in a specified material decrease from high to low as:

a) Gamma, Beta, Alpha
b) Alpha, Beta, Gamma
c) Alpha, Gamma Beta
d) Beta, Gamma, Alpha

Question: Multiple Choice

- A rule of thumb for the penetrating power of radiation is that the relative range for radiation in a specified material decrease from high to low as:

a) Gamma, Beta, Alpha
b) Alpha, Beta, Gamma
c) Alpha, Gamma Beta
d) Beta, Gamma, Alpha

Behaviors of some key radiation modes

- γ-rays and x-rays are photons, and undergo:
  - Compton scattering: scattering off an electron, in the presence of a nuclear mass to carry off momentum
  - The photoelectric effect: delivering energy greater or equal to the "work function" of a material liberating an electron from its surface
  - Pair production – a photon of energy greater or equal to twice the rest mass of a particle (e.g., 1.022 MeV for electrons) spontaneously converts to the particle-antiparticle pair

Depending on energy, photon fields can require thick metallic or other shielding for protection

Behaviors of some key radiation modes

- Electrons (β-particles) undergo:
  - Electromagnetic interactions with photons, charged particles (Coulomb force) or magnetic fields
  - The weak interaction: e.g., a neutron spontaneously decays to a proton, an electron and an antineutrino

Electrons of MeV energies can typically be stopped by a few centimeters of plastic

Behaviors of some key radiation modes

- α-particles (helium-4 nuclei) undergo:
  - Electromagnetic interactions, through the Coulomb force with photons, charged particles or magnetic fields
  - The strong (or nuclear) interaction: they participate in nuclear reactions
  - When naturally emitted, their kinetic energy tends to be 5 to 7 MeV

α-particles can be stopped by a thin sheet of paper, or the layer of dead cells on the surface of living skin

Behaviors of some key radiation modes

- Neutrons undergo:
  - the strong (or nuclear) interaction: they scatter off other nuclear particles or participate in nuclear transmutation reactions
  - the weak interaction: e.g., a neutron spontaneously decays to a proton, an electron and an antineutrino

Shielding against energetic neutrons requires significant quantities of hydrogenous material (plastic, paraffin, water) and often absorbers such as boron.

Exposure: symbol “X”

- Exposure: This (γ-ray or x-ray only) concept is the *γ- or x-ray radiation field* incident on a body, measured by the specific ionization produced by it in the neighboring air.

- The unit of exposure is a measure of photon flux through the amount of energy transferred from the photons to a unit mass of air; viz., the flux of photon radiation that produces in air ions carrying 1 C of charge.

Exposure (cont.)

- Traditional unit for exposure is roentgen (R)
- 1 R is the amount of γ- or x-radiation required to liberate positive or negative charges of one electrostatic unit of charge (esu, =3.33 x 10^{-10} coulomb) in 1 cm^3 of dry air at standard temperature and pressure (“STP”: 0° C and 1 atmosphere pressure).
- 1R = 1 esu/cm^3 where ρ = 1.293 kg/m^3
  - Also note 1 “X unit” = 1 C/kg of air, and **1 C/kg of air = 3876 R**
- Legacy unit, among first attempt at standardizing field of radiation measurement

Absorbed dose

- Radiation damage to matter results from the absorption of energy from radiation.
- The *absorbed dose* is described by the ***deposited energy per unit mass*** of material.
- Applicable to all ionizing radiation, from external or internal sources.

- The cgs unit is the rad, for "*radiation absorbed dose*": 1 rad = 100 ergs/gm

SI units for radiation quantities

- In the late 1980's, Standard International units for radiation were introduced by the European community, which were based on the original units of Curie (radioactive decay rate), rad (deposited energy) and rem (radiation effects in "man").

- Decay rate: Becquerel (Bq): 1Bq = 1 disintegration/second (dps), whereas 1 Curie = 3.7 x 10^{10} dps
- Deposited energy: Gray (Gy): 1 Gy = 100 rads = 1 joule/kg *
- Biological radiation effect: Sievert (Sv): 1 Sv = 100 rem

* Recall 1 erg = 10^{-7} joule

Biological Effect

- For biological damage, concentrations of ionizations within a single cell are more damaging than the same number of ionizations spread over many cells.
- Therefore, biological damage is proportional to both the absorbed dose or radiation, as well as the LET for the type and energy of radiation.

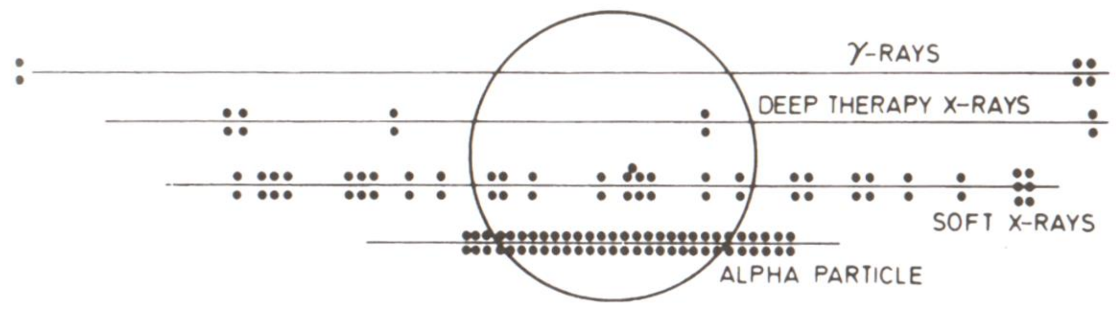


Figure 4.4. Separation of ion clusters in relation to the size of a biological target. (Reproduced from Gray, 1946, *Br. Med. Bull.* by permission of the author.)

Figure taken from Nias, 1997, *An Introduction to Radiobiology, 2nd Ed.*

Biological Effectiveness

- In order to have a common basis for comparing biological effects due to different types of radiation, we define a **relative biological effectiveness** (RBE); for example:

$$\text{RBE} = \frac{\text{Dose of 250-keV X-rays producing given effect}}{\text{Dose of reference radiation for same effect}}$$

- The RBE is highly dependent on the type and energy of radiation.

Equivalent Dose

- The upper limit of the RBE for a specific type of radiation is called the **quality factor** (QF) for the radiation.
- Multiplying absorbed dose by the quality factor for the type of radiation gives the effective or **equivalent** dose.

$$\text{equivalent dose (rem)} = \text{QF} \times \text{absorbed dose (rad)}$$

- Equivalent dose in rem is a common unit of measurement for comparing unique exposure events.
- In SI and traditional units:
  - 1Sv (sievert) = D (Gy) x QF
  - 1 rem = D (rad)x QF, where 1 Sv = 100 rem and 1 Gy = 100 rad

Equivalent Dose

- Because the quality factor is an upper limit, equivalent dose is considered a measure of the potential damage from a radiation exposure.
- Simultaneous doses from multiple types of radiation are additive.
- The weighting factor, determined by the International Commission on Radiation Protection (ICRP), is closely related to the "Quality Factor".

TABLE 9.2 QUALITY FACTORS FOR VARIOUS TYPES OF RADIATION*

Type of radiation	Q	W_R
x-rays and γ-rays	1	1
β-rays, $E_{max} > 0.03$ MeV	1†	
β-rays, $E_{max} < 0.03$ MeV	1.7†	
Naturally occurring α-particles	10	
Heavy recoil nuclei	20	20
Neutrons:		
Thermal to 1 keV	2	5
10 keV	2.5	10
100 keV	7.5	10
500 keV	11	20
1 MeV	11	20
2.5 MeV	9	5
5 MeV	8	5
7 MeV	7	5
10 MeV	6.5	5
14 MeV	7.5	5
20 MeV	8	5
Energy not specified	10	

*Based on 10CFR20 (Q) and ICRP 60 (W_R).
†Recommended in ICRP Publication 9.