Radiological Sciences @ OUHSC

Radiation Detection and Measurement

Lecture 5

Chapter 2: Radiation Interactions

Interactions of neutrons: general

- like γ's , neutrons carry no charge and do not interact via the coulombic force
- may travel quite far into a material before interacting with a nucleus
- interaction may absorb neutron and produce secondary radiation or just change the energy / direction of the neutron
- secondary radiations are generally charged particles
- neutron energy is key to type of reactions and we will simplify by dividing into “fast” and “slow” neutrons at the point 0.5 eV (the cadmium cut off energy – the abrupt drop in absorption cross section in cadmium

Interactions of neutrons: slow

- Elastic scattering where little energy is transferred to the absorber nucleus, which does not make a useful means for detection
- Majority of slow neutrons are thermal neutrons with E ~0.025 eV at room temperature, which are produced after elastic collision
- Important reactions are neutron induced with (+) Q values:
- Radiative capture (n, γ)- important in attenuation and shielding
- Others (better for detecting) (n, α), (n, p) and $(n, \text{fission})$

Interactions of neutrons: fast

- Probability of interaction drops sharply with increasing energy and elastic scattering increases importance producing the secondary radiation of recoil nuclei
- After each reaction the neutron is modulated or slowed
- ^{1}H is the most effective moderator due to its similar mass to the neutron, n can deliver all its energy in one reaction
- With high enough energy, inelastic scattering can occur exciting the nucleus of the absorber
- The nucleus then de excites via γ emission
- This is not a beneficial reaction for fast neutron detectors based on elastic collisions

Neutron cross-sections

- σ is the cross section per nucleus for a type of reaction and is measured in barns ($1 \times 10^{-28}m^2$)
- each nuclear species will have a cross section for elastic scattering , radioactive capture , etc.
- macroscopic cross section (Σ) is the cross section per nucleus times the number of nuclei per unit volume *N*

$$\Sigma = N\sigma$$

Neutron cross sections

- The total cross section is then

$$\Sigma_{tot} = \Sigma_{scatter} + \Sigma_{radcapture} + \ldots\ldots\ldots$$

  - where Σ_{tot} is the probability per unit path length that any interaction will occur

Neutron attenuation

- For attenuation we then get:

$$\frac{I}{I_0} = e^{-\Sigma_{tot} t}$$

- with a MFP = $$\frac{1}{\Sigma_{tot}} = \lambda$$

- For slow neutrons λ ~ < 1 cm, for fast neutrons λ ~ 10 cm

Neutron flux rate

- Neutrons flux is the rate of neutrons at a given energy (or velocity) *v* times the number density at a vector *r*

$$\psi(r) = n(r)v$$

- We can then find a reaction rate density by multiplying by Σ

$$reaction \quad rate \quad density = \psi(r)\Sigma$$

- The reaction rate density can be generalized to an energy independent expression:

$$reaction \quad rate \quad density = \int_0^\infty \psi(r,E)\Sigma(E)dE$$

Radiation exposure

- The charge (*dQ*) due to ionization created by secondary electrons (negative electron and positive positron (β^+)) formed in a volume of air *dm*, when the secondary electrons are completely stopped in air is the exposure

$$X=dQ/dm$$

- SI unit of measure is the [C/kg]
- The historical unit, the Roentgen [R] is the exposure that results in the generation of one electrostatic charge (~2.08 x 10^9 pairs) per 0.001293 gm (1 cm^3 STP) of air.
- The relation is then : 1 R = 2.58 x 10^{-4} C/kg

Exposure rate

- We can determine the exposure rate $\dot{X}$ by

$$\dot{X} = \Gamma_\delta \frac{\alpha}{d^2}$$

  - where Γ_δ is the exposure rate constant for specific radioisotope of interest, where δ indicates the minimum energy penetrating the detector
  - α is the activity and
  - d the distance from the source.

Exposure rate

- The rate equation holds only under the following assumptions or conditions:
  - the source is small enough to be considered a point source and spherical geometry holds (where the flux diminishes in a $1/d^2$ fashion).
  - there is no attenuation of the x- or γ- rays between the source and the measuring point
  - only γ's passing directly from the source to the detector contribute to the exposure (good collimation), and γ-rays scattered from nearby materials are neglected.
- Note the Γ values listed in table 2.1 are Γ_0 (δ=0).

Absorbed dose

- Traditional units 1 rad = 100 ergs/gm
- SI unit is the gray [J/kg] : 1 Gy = 100 rad
- The exposure of 1 [C/kg] of γ-rays amounts to 33.8 [Gy], which is about the same for water due to similar average atomic numbers
- Measurements of absorbed dose are not common (difficult to do), so the absorbed dose is inferred from an exposure measurement. Calorimetric testing is a way to measure an absorbed dose

Dose equivalent

- Takes into account the relative biological damage done by a type of radiation through its ionizing potential
- This is related to the local rate of energy deposition along a radiation track called the linear energy transfer (L).
- The linear energy transfer is almost identical to the specific energy loss (-dE/dx), only L does not include bremsstrahlung energy losses (which may deposit energy relatively far from the particle track).

Dose equivalent

- The dose equivalent H=DQ , where D is the absorbed dose and Q the quality factor increases with L.
- Table 2.2 shows the relation of Q to L
- Units of H are SI – Sievert, traditional – rem. 1 Sv=100 rem

Quality factors

Table 2.2 Quality Factors for Different Radiations

L in Water (keV/μm)	Q
< 10	1
10–100	$0.32L - 2.2$
> 100	$300/\sqrt{L}$

From ICRP Publication 60.

Fluence to dose conversion

- Fluence is the number of particles incident per unit area:

$$\Phi = dN/da,$$

  - dN is the differential number of γ ray photons or neutrons
  - da is the differential cross sectional area
- For a point source one can assume the effect of air to be negligible in attenuation and the fluence over short distances to be $\Phi = N/4\pi d^2$

Fluence to dose conversion

- Taking into account the differing radio sensitivities of various organs and tissues, the individual dose components can be combined into an effective dose equivalent H_E, which represents an estimate of the overall biological effect of a uniform, whole body exposure to the assumed fluence

$$H_E = h_E \, \Phi,$$

- where h_E is a fluence to dose factor seen plotted for various energies in Fig 2.22

h_E factors

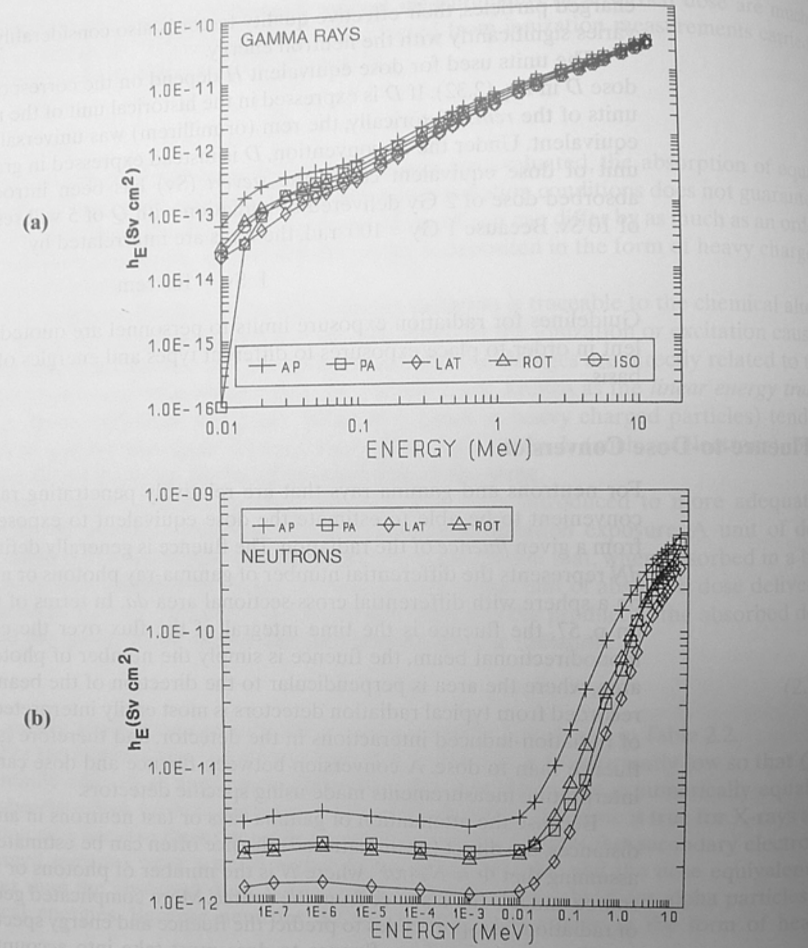

Figure 2.22 Fluence-to-dose conversion factors h_E for uniform whole body exposures to (*a*) gamma rays and (*b*) neutrons. The labels refer to different assumed directions of the incident particle flux: AP for frontal exposure of the body, PA for rear exposure, LAT for exposure from the side, ROT for uniform rotation of the body about its axis, perpendicular to the directional flux, and ISO for an isotropic incident flux. Tabulated data and additional details are given in Ref. 31, which is the source of these data. (Copyright 1992 by the American Nuclear Society, LaGrange Park, Illinois.)

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ICRP dose units

- The international commission on Radiation Protection (ICRP) has defined a measure called equivalent dose *($H_{T,R}$)* which is calculated by multiplying the absorbed dose $D_{T,R}$ averaged over a tissue or organ times a radiation weighting factor, w_R, which takes into account the biological effectiveness of radiation

$$H_{T,R} = w_R \, D_{T,R}$$

- w_R is listed in table 2.3

ICRP dose units

- For a mix of radiations:

$$H_T = \sum_R w_R D_{TR} = \sum_R H_{TR}$$

- To account for varying radio sensitivities of various tissues or organs

$$E = \sum_T w_T H_T$$

  - where w_T are a set of tissue weighting factors
- *E* is called the effective dose, and the w_T's sum to **1** over the whole body, and the units are again in Sieverts.

Radiation weighting factors

Table 2.3 Radiation Weighting Factors

Type and Energy Range	Radiation Weighting Factor, w_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, energy < 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 Me V	5
Protons, other than recoil protons, energy > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

From ICRP Publication 60.