Lecture 22: Biological Effects of Radiation

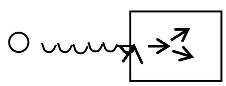
I. Radiation Chemistry

Interaction of Radiation with Matter:

Emphasis on effect of medium on incident radiation

Biological Effects of Radiation:

Emphasis on effect of radiation on medium



$dE/dx \propto AZ^2/E$ for charged particles

$dE/dx \propto \mu E_\gamma$ for photons

A. Chemical Species Formed in Medium

1. Cation-Electron Pairs

a. Gases and Liquids ⇒ mobile ions – facilitates detection

e.g., $CH_4 \xrightarrow{hv} CH_4^+ + e^-$

biological systems: alters electrolyte balance

b. Solids ⇒ trapped electrons and lattice defects
modified conduction bands: impurities, Si bit upsets

2. Free Radicals

Bond cleavage $CH_4 \xrightarrow[hv]{} \bullet CH_3 + \bullet H$

a. Radioalysis: Decomposition of compounds; esp. H_2O, by radiation

$H_2O \longrightarrow \bullet H + \bullet OH$

$\bullet H + \bullet H \rightarrow H_2$ (reducing agent)

$\bullet OH + \bullet OH \rightarrow H_2O$ (oxidizing agent)

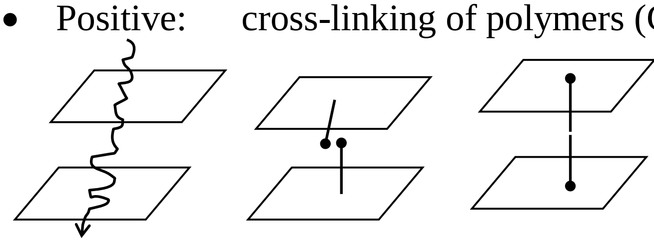
} Body mostly H_2O TMI

b. Compounds

$C_xH_yO_z \xrightarrow{hv} CO_2, H_2O, H_2,$ etc.

recombinants may alter properties – negative or positive

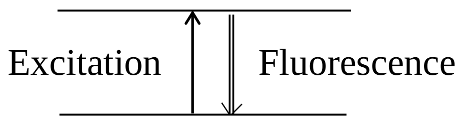
- Negative: biological alterations (DNA)
- Positive: cross-linking of polymers (Cook, Inc.)



can improve qualities of polymers

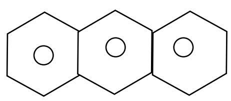
3. Excited Atoms and Molecules

a.

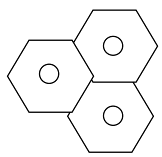


Resonance stabilization ; aromatic hydrocarbons highly susceptible to excitation (good scintillators)

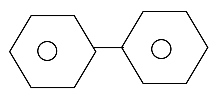
b. Application
Scintillation detectors (both liquid and solid)
Widely used in biochemistry and medical sciences
for counting ^{3}H, ^{14}C, ^{32}P



anthracene



phenathrene



stilbene

and derivatives

B. Radiation Dosimetry

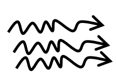
DOSE – Quantity of Radiation Exposure

1. Rad – Basic unit of radiation dose measurement
(Gray – SI unit) = Gy

a. Definition:

$$\boxed{1 \text{ rad} = 10^{-2} \text{ J/kg}} \text{ of absorbed material} = \boxed{100 \text{ ergs/g}} = \frac{\Delta E}{\text{mass}}$$

10^{-2}J



1 kg

$1 \text{ eV} = 1.60 \times 10^{-19}$J

1 Gy = 1 J/kg = 100 rads

(1) Charged particles
E = energy of particle if stopped
(dE/dx)(Δx) if transmitted

(2) Photons

$\{ \Delta E = \mu E_\gamma/cm^2 \}$

b. Example: {A 2.0 g sample absorbs 1.0 μ Ci of 100 keV electrons in 10.0 min. What is the dose in rads?}

$$\Delta E = \underbrace{(1.00 \times 10^5 eV)(1.60 \times 10^{-19} J/eV)}_{\text{Energy/particle}}\underbrace{(3.70 \times 10^4 dps)(600 s)}_{\text{Number of particles}}$$

$\Delta E = 3.6 \times 10^{-7}$ J

$$\text{Dose} = \frac{\Delta E}{\text{mass}} = \frac{3.6\times10^{-7}\ J}{2.0\times10^{-3} kg} \times \underbrace{\frac{kg}{10^{-2} J}}_{\text{Rad}} = \boxed{1.8 \times 10^{-2}\text{ rads}} = 18 \text{ mrads} = 1.8 \times 10^{-4} Gy$$

⇑

2. Biologically Permissible Doses

a. Depends on type of radiation
- charged ions: dE/dx high ; range low
- β±: dE/dx intermediate ; same for range
- γ, n: low dE/dx ; long range

} Bottom Line: identical doses may not induce the same biological damage

b. Quality Factor (QF), or Relative Biological Effectiveness (RBE)

x-rays, γ-rays = 1	protons = 1-10 (depending on energy)
β± = 1	α's = 1-20 (depending on energy)
thermal neutrons = 5	heavy ions ($Z \geq 3$) or fission fragments } = 20
fast neutrons = 10	

TAKE UPPER LIMIT TO BE SAFE

c. Dose Equivalent

$\boxed{\text{rem} = \text{rads} \times QF}$ ⇐ We'll use these,

d. SI Unit: Sievert SV

$\boxed{1\ SV = 100\ \text{rems} = \text{Gray} \times RBE}$ ← Not these,

e. Previous Example: apply to other particles

dose (e^-)	$= 18$ mrads $\times 1 =$	18 mrem
dose (γ)	$= 18$ mrads $\times 1 =$	18 mrem
dose (slow n)	$= 18$ mrads $\times 5 =$	90 mrem
dose (fast n)	$= 18$ mrads $\times 10 =$	180 mrem
dose (α's)	$= 18$ mrads $\times 20 =$	360 mrem

3. Radiation in the Environment

Basis for setting standards ; easy to measure

a. Natural Average ≈ 360 mrem/y at sea level

Sources:

b. National Background

- Cosmic rays:
  Altitude-dependent; increases with elevation
- $^{40}K(^{87}Rb)$:
  Ubiquitous (and it's everywhere, too!)
- U/Th and decay products (esp. Rn gas):
  Geology-dependent (Rockies, Sri Lanka, Brazil)

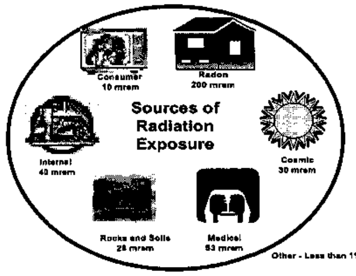
c. Anthropogenic

- Medical and diagnostic
- Fallout from nuclear weapons tests
- Jet Travel (enhanced cosmic-ray exposure)
- Nuclear applications: TV, smoke detectors, (Fiesta ware), cigarette smoke [archaic: Ra dial watches, shoe x-rays]

d. Dose Computation Table

➡ CONCERNS ABOUT RADIATION MUST BE TAKEN IN THIS CONTEXT ⬅

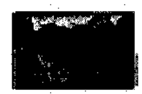
Radiation is in every part of our lives. It occurs naturally in the earth and can reach us through cosmic rays from outer space. Radiation may also occur naturally in the water we drink or the soils in our backyard. It even exists in food, building materials, and in our own human bodies. Fill out the chart below to see how much radiation you receive in a year.



Cosmic radiation at sea level (from outer space) 26

What is the elevation (in feet) of your town? ***Idaho Falls 4736 feet***

Up to 1000 (add 2 mrem) 1000-2000 (add 5 mrem) 2000-3000 (add9 mrem) 3000-4000 (add 15 mrem) 4000-5000 (add 21 mrem) 5000-6000 (add 29 mrem) 6000-7000 (add 40 mrem) 7000-8000 (add 53 mrem) above 8000 (add 70 mrem) ---------



Terrestrial (from the ground):

What region of the US do you live in? ---------

Gulf Coast (23 mrem) Atlantic Coast (23 mrem) The Colorado Plateau (90 mrem) Elsewhere in the US (46 mrem)

Internal radiation (in your body):

From food and water, (e.g. potassium) 40

From air, (radon) 200

Do you wear a plutonium powered pacemaker? No (0 mrem) Yes (100 mrem) ---------

Do you have porcelain crowns or false teeth? No (0 mrem) Yes (.07 mrem) ---------

Travel Related Sources:

Add 1 for each 1000 miles traveled by jet this year: ---------

Are X-ray luggage inspection machines used at your airport?
No (0 mrem) Yes (.002 mrem) ---------

Do you use gas lantern mantles when camping? No (0 mrem) Yes (.003 mrem) ---------

Miscellaneous Sources:

Weapons test fallout 1

Do you live in a stone, brick, or concrete building? No (0 mrem) Yes (7 mrem) ---------

Do you wear a luminous wristwatch (LCD)? No (0 mrem) Yes (.06 mrem) ---------

Do you watch TV? No (0 mrem) Yes (1 mrem) ---------

Do you use a computer monitor? No (0 mrem) Yes (.1 mrem) ---------

Do you have a smoke detector in your home? No (0 mrem) Yes (.008 mrem) ---------

How many medical x-rays do you receive per year? (40 mrem each) ---------

How many nuclear medical procedures do you receive per year? (14 mrem each) ---------

Do you live within 50 miles of a nuclear power plant?
No (0 mrem) Yes (.009 mrem) ---------

Do you live within 50 miles of a coal fired power plant? ---------
No (0 mrem) Yes (.03 mrem)

****TOTAL YEARLY DOSE (in mrem):** ---------

**In the United States, the annual average dose per person from all sources is about 360 mrems, but it isn't uncommon for any of us to receive far more than that in a given year (largely due to medical procedures we may have done).

American Nuclear Society Annual Radiation Dose Chart

4. Exposure Limits

a. General Population: 500 mr/y

b. Workers in Radiation-Related Fields

(1) Periodic: 100 mr/week

(2) Annually: 5 r/y

(3) Lifetime: 5 (N–18)r where N = age

c. Previous Example: How long can one work with a 1.8 mr/min β^- source before using up the weekly limit?

(Time)(1.8 mr/min) = 100 mr $\Leftarrow$ LIMITING DOSE

time = 55 minutes

5. Dose Reduction

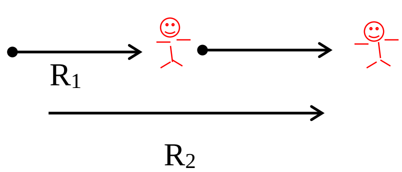
a. Attenuate with absorbers (good for α, β ; less so for γ, n

b. Geometry: (i.e., back away).

$$\% \text{ exposure} = \frac{(\text{Area exposed})(100\%)}{4\pi R^2}$$

, where R is distance from the source

Source



$$\frac{\text{Dose (2)}}{\text{Dose (1)}} = \frac{\text{Area} / 4\pi\ R_2^2}{\text{Area} / 4\pi\ R_1^2} = \left(\frac{R_1}{R_2}\right)^2$$

i.e., exposure decreases as the square of the separation distance

c. Earlier Problem:

If the dose rate of 1.8 mr/min is measured at 20.0 cm, what will the dose rate be at a distance of 40.0 cm?

$$\frac{\text{Dose (40 cm)}}{\text{Dose (20cm)}} = \frac{(20)^2}{(40)^2} = \frac{1}{4}$$

∴ Dose (40 cm) = ¼ (1.8 mr/min) = 0.45 mr/min

6. Radiation Dose Monitoring

a. Dosimeter: Device for measuring total integrated doses; depends on calibrated, radiation-sensitive chemical reaction (redox)

$$\left.\begin{array}{l} H_2O \xrightarrow{hv} H_2O_2 \\ Fe^{2+}(aq) \xrightarrow{hv} Fe^{+3}(aq) \end{array}\right\} \text{instantaneous, but integral}$$

b. Film Badge: Integrated dose for long-term monitoring; x-ray film; Boron-loaded for neutron sensitivity.
integral, requires processing

c. Survey Meter – differential, instantaneous, audio, doesn't integrate
d. Common sense

C. Biological Effects of Radiation

Depends on:

1. Properties of Radiation
   - QF
   - Energy – E, dE/dx, μE_γ
   - Amount –dN/dt
   - Half-life – $t_{1/2}$

2. Nature of Exposure
   a. External – burns (esp. uv) ; skin cancer; extremities vs. torso; SF and α negligible (air stops); γ, β , n penetrate

b. Internal

Ingestion, Inhalation; all types dangerous, esp. α (large dE/dx)

Depends on:

(1) Rate of Excretion (e.g. 18 y ^{244}Cm)

(2) Biological Distribution: concentrated or dispersed?

e.g., $^{131}I \rightarrow$ thyroid ; $^{90}Sr \rightarrow$ bones ; $^{40}K \rightarrow$ all body fluids

(3) Biological Susceptibility; genetic differences (e.g., suntans)

D. Clinical Effects: High Levels

1. Somatic vs. Genetic Effects

a. Somatic Effects: Damage to individual irradiated (including fetus in case of pregnancy).

Short Term – fatal if large enough

Long Term – positive correlation with leukemia and skin cancer;
slight(very) negative correlation with other cancer types

b. Genetic Effects: Alterations to genetic material that are transferred to later generations ; DNA alteration

Hiroshima – Nagasaki survivors – no evidence to support

2. Symptoms: Function of Dose and Dose Rate

a. Leukopenia: serious deficiency of leucocytes in blood; leucocytes maintain the immune system.

b. $LD_{50} = 450$ rem ; Exposure time $\lesssim$ 1 day

LD = lethal dose: dose at which 50% of people will die in a few months

3. Hiroshima – Nagasaki

a. Most deaths caused by fire, not radiation

BIOLOGICAL EFFECTS OF RADIATIO

Large Doses

Short Term

Long Term

Small Doses ~ 100 mrem/year

Difficult to assess

Statistics

Radiation Hormesis

Risk Estimates

b. Leukemia statistics confirmed

c. No evidence for genetic effects in 2^{nd} and 3^{rd} generations

d. Correlations

II. Risk Estimates: Dangers of LOW LEVELS of Radiation

A. Fatality Estimates

1. Case: Add 100 mr to average annual exposure for general population
   - a. Equivalent to: > 100-fold increase in nuclear power generation
     spending the entire year in Vail, CO;
     << one thermonuclear explosion
   - b. Model estimates of death rate due to 100 mr/yr increase:
     Absolute risk method: ~ 1500 /yr
     Relative risk method: ~ 8300/yr
     } delay time ~ 20 yr

2. Environmental Factors
   - a. Example: CO – <bkg> ~ 500 mr/yr; cancer rate 46/50
     (50 = lowest)

     PA – <bkg. ~ 360 mr/yr; cancer rate 10/50
     (1 = highest)

   Points out synergistic effects due to air and water quality
   - b. Kerala Coast (West India): <bkg> ~ 1–1.5 r/yr. (Th in soil)
     cancer rates normal
     Swiss Alpine villages – same effect

3. Radiation Hormesis

   Theory that small amounts of radiation are beneficial; Mechanism: radiation damage stimulates immune system, leaves the body better prepared to deal with invading organisms.

B. Statistical Significance and the Press

1. Utah: "epidemiological studies show leukemia rates 50% higher down stream from 1950's test site"

   Actual numbers:

cases reported:	29 (± 5.4)	i.e., identical at 67% confidence level.
cases expected:	19 (± 4.4)	

In addition, same population sample experienced lower than normal incidence of other types of cancer. Net cancer rate effect ~0

2. Recent reports of "unethical experiments with radiation in the 40's and 50's." Certainly true by today's standards, but concerns for nuclear war created need to know what to expect.

3. Electromagnetic radiation: 36,000 electrical workers in southern California – normal cancer rates; similar Swedish study – same result

C. Relative Risks in Context

1. Major causes of death due to cancer
2. Total risk tables

Hiroshima-Nagasaki Survivor Leukemia Statistics
(18 year study)

Dose (rems)	No of Cases	Deaths	Person-Yrs ÷ 1000	Rate (per 10^5 p-yrs)
200 +	1460	22	26.7	81.6
100-199	1677	10	30.2	33.1
50-99	2665	7	48.3	14.5
10-49	10,707	17	195.4	8.7
0-9	43,830	34	795.6	4.3

LD_{50} = 450 rem

No detectable genetic effects

Clinical Effects of High-Level Radiation

Subclinical			Therapeutic		Lethal	
Dose (rems)	0-100	100 – 200	200 – 600	600 – 1000	1000 – 5000	> 5000
Symptoms	none		leukopenia hemorrhage infection		Diarrhea fever electrolyte imbalance	Convulsions
Critical Period	none	none	4-6 weeks		5-14 days	
Therapy	7 Reassurance 6 surveillance		Blood transfusions; Bone marrow transplant		Balance electrolytes	Sedation
Prognosis	7 Excellent 6		Good	Guarded	Unfavorable	
Recovery Time	—	weeks	1-12 mo.	long	rare	
Death Rate	none	none	0 - 80%	80- 100%	90 - 100%	
			∅∪∩ 2 mo.		2 wk	2 D

RISK FACTOR	ANNUAL DEATHS*
Smoking (1E)	434,000
Alcohol	105,000
Secondary Smoke	53,000
Motor Vehicles	49,000
AIDS	31,000
Homicides	22,000
Electric Power	14,000
Cocaine/Crack	3,300
Motorcycles	3,000
Swimming	3,000
Surgery	2,800
Heroin/Morphine	2,400
x-rays	2,300
Railroads	1,900
Aviation (not commercial)	1,400
Large Construction	1,000
Bicycles	1,000
Hunting	800
⋮ ⋮	
Nuclear Power	100
⋮	
Skiing	20

*Sources: US Center for Disease Control; National Safety Council, National Center for Health Statistics; Insurance Actuarial Tables