Illinois Institute of Technology

PHYSICS 561
RADIATION BIOPHYSICS

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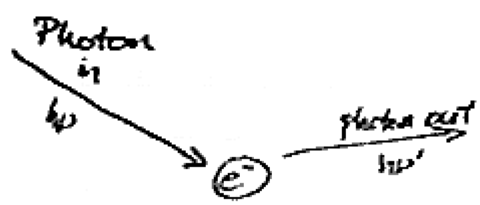
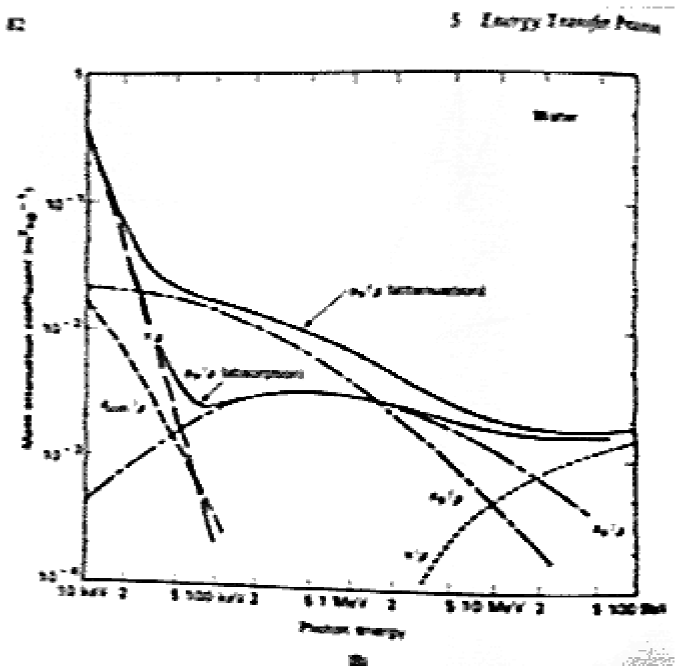
Compton processes
in tissue :



for water: fig. 5.2(b) in text
shows that Compton scattering
(μ_{ab}/ρ) predominates above 100KeV



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Interaction of photons with matter

Attenuation coefficients for molecules and mixtures:

- Calculate mole fraction f_M for each atom in molecule or mixture ($\Sigma f_{Mi} = 1$)
- Calculate $\frac{\sigma}{\rho}$ for mixture as

$$\left(\frac{\sigma}{\rho}\right)_{Tot} = \sum_i \left(\frac{\sigma}{\rho}\right)_i f_{Mi}$$

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Example:

water, $f_m(H) = \frac{2}{18}$, $f_m(O) = \frac{16}{18}$

→ In a molecule, the mole fraction associated with a particular atom type is proportional to the product of the number of atoms of that type in the molecule × the atomic weight of that atom ...

H_2 : $2 \cdot 1 = 2$

O : $1 \cdot 16 = 16$

normalize $\Sigma f_{mi} = 1$ so $\frac{2}{N} + \frac{16}{N} = 1$

$N = 18$, ∴ $f_m(H) = \frac{2}{18}$, $f_m(O) = \frac{16}{18}$

C_6H_6 (benzene) : $f_m(C) = \frac{12 \cdot 6}{N}$, $f_m(H) = \frac{1 \cdot 6}{N}$

$\frac{72}{N} + \frac{6}{N} = 1$, $N = 78$, $f_m(C) = \frac{72}{78}$, $f_m(H) = \frac{6}{78}$

Interaction of charged particles with matter

with matter: recall diagram 5.3, p. 87

crucial equation is

$$\Delta E(b) = \text{energy taken from heavy particle}$$

$$= \frac{z^2 r_0^2 m c^4 M}{b^2 E}$$

where E = kinetic energy of moving particle = $\frac{1}{2} M v^2$

big issue:

$\Delta E \propto \frac{1}{E}$!

¶2, p 87:

principal, not principle

¶1, new section, p 79:

"the the" → "to the"

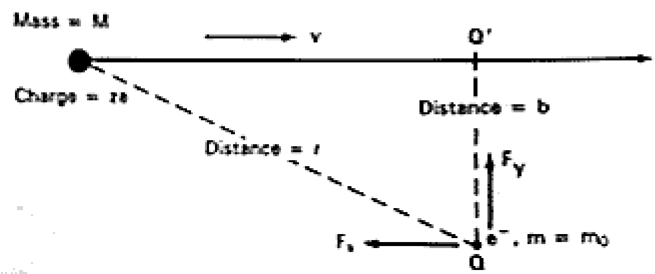

Figure 5.3 Interaction of a moving heavy particle of mass M passing an electro
the medium.

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If Eq. (5.3) is written with all variables in terms of θ and the defi
r_0 is taken from Eq. (5.4), the simplification can be written

$$\Delta p = \frac{zke^2}{vb}\int_{-\pi/2}^{+\pi/2}\cos\theta\,d\theta = \frac{2zke^2}{vb} = \frac{2zr_0 m_0 c^2}{vb}.$$

Δp is the momentum transferred to the resting electron. The ener
from the heavy particle is

$$\Delta E(b) = \frac{(\Delta p^2)}{2m_0} = \frac{2z^2 r_0^2 m_0 c^4}{v^2 b^2} = \frac{z^2 r_0^2 m_0 c^4 M}{b^2 E},$$

where E, the kinetic energy of the moving particle, is $\frac{1}{2}Mv^2$.

The parameter b, which is the distance of closest approach of
is called the impact parameter. *A very important point must be m*

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The derivations given in Eqs. (5.2)–(5.6) are not complete. The rea referred to any textbook of modern physics for a complete derivatio for example; Attix *et al.* in Suggested Additional Reading).

The special case given in Fig. 5.3 is for a moving heavy particle Fermi energy electron of the medium. The special case has g applicability. There are several possibilities:

1. M is large compared to m_0; that is, M is a charged nucleus nucleon.
2. M is the same as m_0; that is, M is an electron.
3. Either M or m_0 is at rest.

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2. M is the same as m_0; that is, M is an electron.
3. Either M or m_0 is at rest.

Case 1. This case is assumed in the preceding model. The details the expressions in Eqs. (5.2)–(5.6) are not important, nor are their deriv tions, for the applications of radiation biophysics. The important conside ation is to examine the denominator of the expression. To restate a poi made previously, the impact parameter b will vary stochastically, but th important determinant of the rate of energy loss is the squared veloci term, which appears in the denominator. Most of the moving particle energy will be given up as it begins to approach the rest state.

Case 2. In the case of two electron masses interacting, we can n longer assume that the trajectory of either is unaffected. The calculation classically the same, but complicated. The important point is that the pat of both the projectile electron and the target electron are affected. Ener loss is still inversely proportional to the velocity of the projectile electr squared, but the track of the projectile electron will be unpredictable a

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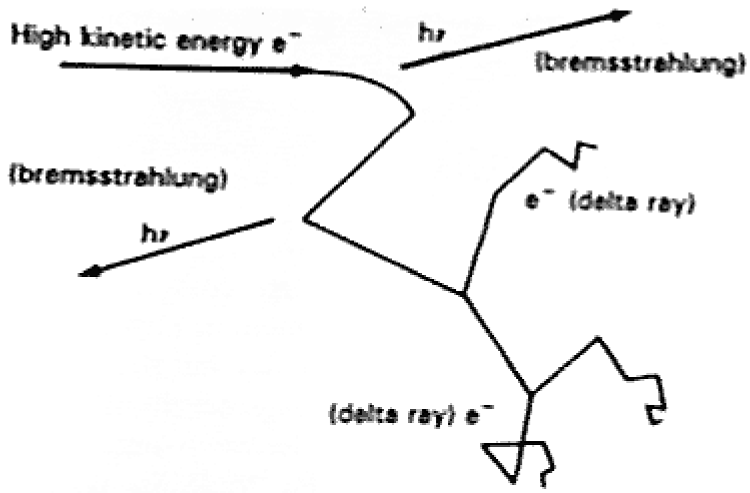


Figure 5.4 Life history of a fast electron.

Homework For 2/14

1. Alpen, Ch. 6, #3
2. Why is cancer more likely to occur in individuals deficient in DNA repair enzymes?
   (2 - 3 paragraphs)
3. Would you expect that the rate of restitution of an altered molecule to be temperature-dependent? Why?

Schedule Issues

- 1st two assignments will be graded by Monday 2/12.
- 3rd assignment by Friday 2/16

Outline of Session

- Energy Deposition at different physical scales (ch.5)
- Types of energy transfer from electrons (ch.6)
- Free Radicals
- Radiation Chemistry of water
- Break
- Recombination, Restitution, Repair
- Molecular Biology 101

Dose

$$\left[\frac{\text{Energy deposited}}{\text{Unit mass}}\right]$$

size scales $\sim 1\mu m$

$\rho \sim 1$ g/cm^3 for water or soft tissue

mass of $(1\mu m)^3 \cdot \rho = (10^{-4}cm)^3 \cdot \rho$

$= 10^{-12}cm^3 \cdot 1g/cm^3$

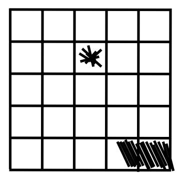
$= 10^{-12}g = 10^{-15}kg$

Energy Absorbed in a Cell

- Suppose *N* Joules of energy are deposited in a 70 kg human. Nominally the dose is *N*/70 Gy.
- How much energy is deposited in a single $(1\mu m)^3$ cell? (*N*/70)Gy * 10^{-15} kg
  = (*N*/70)*10^{-15} J= (1.3*10^{-17})**N* J
  = [(1.3*10^{-17})**N*]/1.609*10^{-19} J
  = 85**N* eV. So it's a lot of energy!
- Is the Bethe-Blocke continuous slowing-down approximation applicable here? No! Too much energy is being stopped per cell for it to be applicable. But we try to use it anyway.

Mozumder & Magee

[1 MeV "typical" electron]		Portion of energy deposited
◆ Spurs	6 - 100 eV	65%
◆ Blobs	100 - 500 eV	15%
◆ Tracks	500 - 5000 eV	20%



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Demonstration That Events Don't Interact Much

Spurs are 400 nm apart

1 nm = 10^{-9} m

400 nm = 0.4 μm

H radical diffusion

8×10^{-5}cm^{2}s^{-1} diffusion constant for H•

Typical lifetime ~ 10^{-6}s

Typical diffusion dist. = 180 nm

This is smaller than the distance between spurs!

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Free Radicals - Definitions and Illustrations

A free radical is defined as molecular species containing an unpaired electron. It may be charged or uncharged.

Most biological free radicals are uncharged

Exception: superoxide ($O_2^-\bullet$)

- OH^- Hydroxide ion -9 protons, 10 electrons
- $OH\bullet$ Hydroxyl Radical -9 protons, 9 electrons

Free radicals are reactive because the unpaired electrons tend to seek out targets, either other unpaired electrons:

$H\bullet + H\bullet \rightarrow H_2$

. . . Or other acceptors of the unpaired electron

Cartoons of Electron Distributions: Ions and Radicals


Hydroxyl Radical
9 electrons (one unpaired), 9 protons


Hydroxide Ion
10 electrons (all paired), 9 protons


Molecular Oxygen
16 electrons, neutral


Superoxide radical
17 electrons, one unpaired

10^{-16} - 10^{-12} s Scale Events and After

Ionization:

$$e_{fast} + \boxed{H_2O} \rightarrow \underset{\downarrow}{H_2O^{+}\bullet} + \underset{(<100\ eV)}{e^-} + e^-_{fast}$$

$H_2O^{+}\bullet \rightarrow H^+ + OH\bullet$

$e^- \xrightarrow{H_2O} H_2O^{-}\bullet$

$e^- \xrightarrow{nH_2O} e^-_{aq}$ Solvated aqueous hydrated $(10^{-4}s)$

$e^- \xrightarrow[H^+]{Acid} H\bullet \rightarrow H_2$

Activation:

$$e^-_{fast} + \boxed{H_2O} \rightarrow e^-_{fast} + H_2O^* \rightarrow H\bullet + OH\bullet$$

$H_2O^* \xrightarrow{\sim 10^{-11}s} H_2O$

$H\bullet$, $OH\bullet$, e^-_{aq}
$O\bullet \rightarrow O_2$
$O_2^-\bullet$, H_2O_2

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Radiation Chemistry of Water

- Since biological tissue is mostly water, we're very interested in the products produced when water absorbs ionizing radiation.
- The reactive species formed out of water are responsible for a large fraction of the biological activities of radiation.
- Ordinary ions (H^+, OH^-, H_3O^+,) are among these species, as is hydrogen peroxide (H_2O_2);
- So are free radicals: $H\bullet$, $OH\bullet$, $O_2^-\bullet$, $HO_2\bullet$, $O_2^-\bullet$
- Often discuss "solvated electron", e_{aq}^-.

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Fricke Dosimeter

- Bookkeeping tool for aqueous radical chemistr

$Fe^{2+} \rightarrow Fe^{3+} + e^-$

ferrous ferric

$H\bullet + O_2 \rightarrow HO_2\bullet$ H-O=O

$HO_2\bullet + Fe^{2+} \rightarrow HO_2^- + Fe^{3+}$

$HO_2^- + H^+ \rightarrow H_2O_2$

$OH\bullet + Fe^{2+} \rightarrow Fe^{3+} + OH^-$

$H_2O_2 + Fe^{2+} \rightarrow Fe^{3+} + OH^- + OH\bullet$

$H\bullet + H_2O \rightarrow OH\bullet + H_2$ (only in absence of O_2)

Fricke Dosimeter: bookkeeping

- Each hydrogen radical causes the oxidation of three molecules of errous ion
- H_2O_2 produced by radiolysis will oxidize two ferrous ions--one direct, one indirect.
- A radiolytically-produced $OH\bullet$ radical gives rise to one more oxidation.
- Therefore at acidic pH with oxygen: $G(Fe^{3+}) = 2G(H_2O_2) + 3G(H) + G(OH\bullet)$

Definition of Yield

G = Yield $\equiv$ Number of events produced per 100 eV energy deposition

Yield is either unitless or has units of $(\text{energy})^{-1}$ depending on your perspective

Fricke dosimeter provides a way of measuring yield

Interactions of Energetic Electrons With Biological Tissue

- Direct

$e^-_{fast} + DNA \rightarrow DNA_{broken} + e^-_{fast}$ (biol response)

$e^-_{fast} + Protein \rightarrow Protein_{broken} + e^-_{fast}$

log - linear dose - response

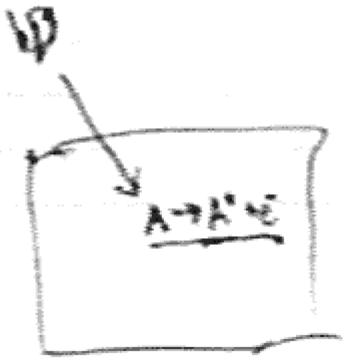
$$\frac{dN}{N} = \text{constant} \bullet D \qquad N_{undamaged} = N_o e^{-kD}$$

- Indirect Action

$$e^-_{fast} + H_2O \rightarrow H_2O^* + e^-_{fast} \rightarrow \text{further radical chemistry}$$

$$e^-_{fast} + H_2O \rightarrow H_2O^{+\bullet} + e^-_{H2O} + e^-_{fast} \rightarrow \text{further radical chemistry}$$

$$\begin{pmatrix}\text{water}\\ \text{molecules}\end{pmatrix} + \text{biomolecules} \rightarrow (\text{biomolecules})^* + H_2O \text{ products}$$



more radiation dose ⇒ more response

let N = number of undamaged molecules after irradiation with dose D

$$dN \propto N\,dD$$

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let N = number of undamaged molecules after irradiation with dose D

$$dN \propto N\,dD$$

$$\boxed{dN = -kN\,dD}$$

k = inactivation constant

$$\frac{dN}{N} = -k\,dD$$

$$\ln N = -kD + \text{constant}$$

$$e^{\ln N} = e^{-kD} \cdot \underbrace{e^{\text{constant}}}_{N_0}$$

$$N = e^{-kD} \cdot N_0$$

$$N = N_0 e^{-kD}$$

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Indirect Action

initial absorption of radiation energy gives rise to secondary chemical events

Specifically in biological tissue:

$$R + H_2O \rightarrow H_2O^*$$

radiation

$\downarrow$ biological macromolecules

damaged biological macromolecules

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Radical Fates/ Damaged Biomolecule Fates

- Recombination $A\bullet + B\bullet \rightarrow A - B$ (timescale 10^{-11}s)

  Generally A = B i.e. $A\bullet + \bullet A \rightarrow A - A$
- Restitution: Non catalyzed regeneration of non-radical species

  $$\underset{\text{biol molecule}}{A\bullet} + \underset{\text{diffuseable}}{X} \rightarrow \underset{\text{biol}}{A} + X\bullet \searrow \text{out}$$
- Repair: Catalyzed regeneration of undamaged species

  $\underset{\text{biol}}{A\bullet} + E + R \rightarrow \underset{\text{biol}}{A^{mod}} + E + R\bullet$ where E is enzyme

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Some biochemistry definitions

Enzyme: biological macromolecule capable of catalysis

Catalyst : a species that increases the rate of a reaction without ultimately being changed

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Enzyme: biological macromolecule capable of catalysis (E)

Catalyst : a species that increases the rate of a reaction without ultimately being changed

$A \rightarrow B$ uncatalyzed

$$A + \underset{\text{catalyst}}{C} \rightarrow A\text{-}C \rightarrow B\text{-}C$$ catalyzed

$$\downarrow$$

$$B + \underline{C}$$

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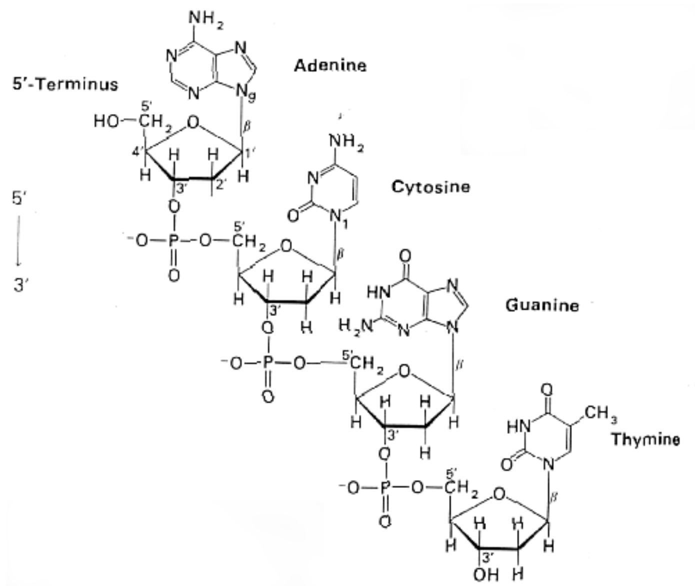

W. H. Brown & J. A. McClarin, Introduction to Organic and Biochemistry, 3rd Ed., 1981

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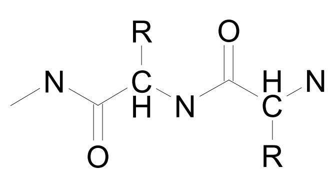
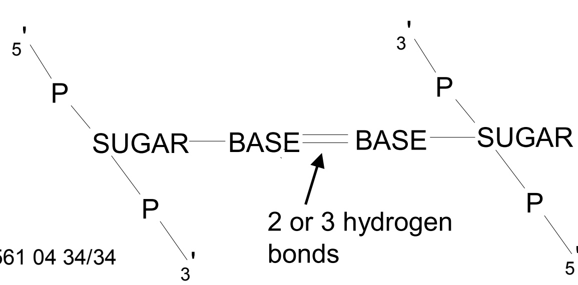
Protein Backbones and Nucleic Acid Backbones



R = 20 amino acid sidechain
(Alanine, Glycine,...)



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