NATIONAL UNIVERSITY OF PHARMACY
Department of Educational and Information Technologies

BIOPHYSICS, PHYSICAL METHODS OF ANALYSIS

Lecture 8

Nuclear physics. The action of physical factors on biological objects. Own physical fields of human.

Plan of the Lecture

1. The atomic structure.
2. The Bohr Model of the Hydrogen Atom.
3. Rydberg Equation.
4. Radioactivity.
5. Nuclide Transmutation.
6. Photoelectric Effect.
7. Compton scattering.
8. Pair production.

Purpose of the lecture is

- to form knowledge about the possible effects of electromagnetic radiation on the human body; to master the basic provisions of atomic physics and quantum mechanics and learn how to use this knowledge to create new dosage forms.

Introduction to Nuclear Physics

We are interested in the sources and the types of radiation. We have to consider what happens when this radiation interacts with matter (mechanisms of energy transfer and its effects on the physical-chemical- and biological level)

Our main reason for doing this is to find out what happens to the radiation as it passes through matter and also to set ourselves up for considering how it interacts with living tissue and understand the chain of events leading to radiation injury. This knowledge also forms the bases of **radiation therapy** and **diagnostic radiology**.

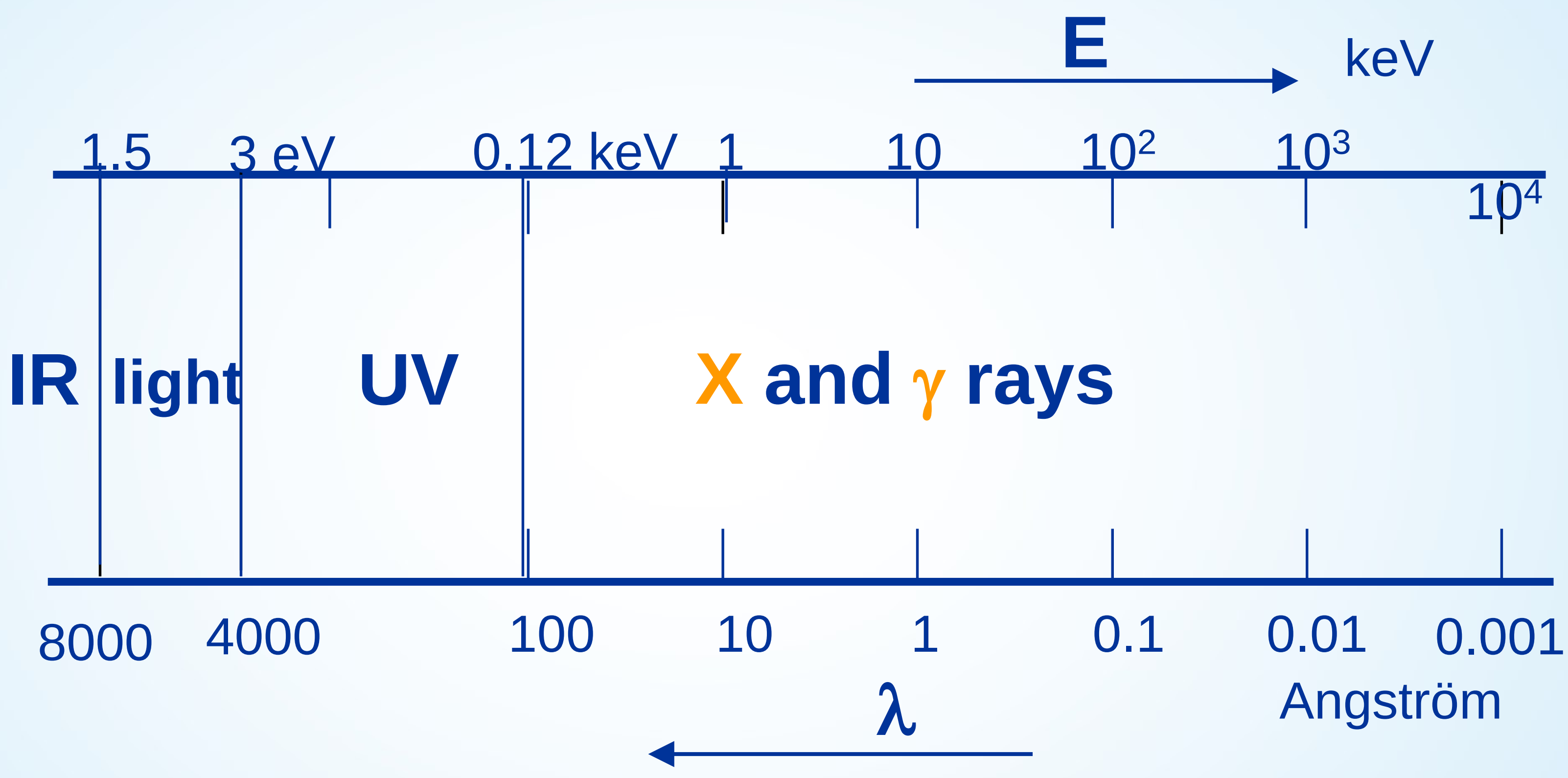
Also, since all **radiation detectors** are made from some form of matter it is useful to first of all know how radiation interacts so that we can exploit the effects in the design of such detectors and know how it works.

Radiation therapy is based on the exposure of malign tumor cells to significant but well localized doses of radiation to destroy the tumor cells. The goal is to maximize the dose at the tumor location while minimizing the exposure of the surrounding body tissue.

Radiation therapy can be performed by using external radiation sources (charged particle exposure by accelerator beams, neutron exposure by reactor beams - **EXTERNAL BEAM THERAPY**) or by using internal radiation sources (long-lived radioactive sources in close vicinity of the tumor - **BRACHYTHERAPY**).

Parameters of radiation need to be carefully studied for planning the radiation treatment to maximize the damage for the tumor while minimizing the potential damage to the normal body tissue. An insufficient amount of radiation dose does not kill the tumor, while too much of a dose may produce serious complications in the normal tissue, may in fact be carcinerous .

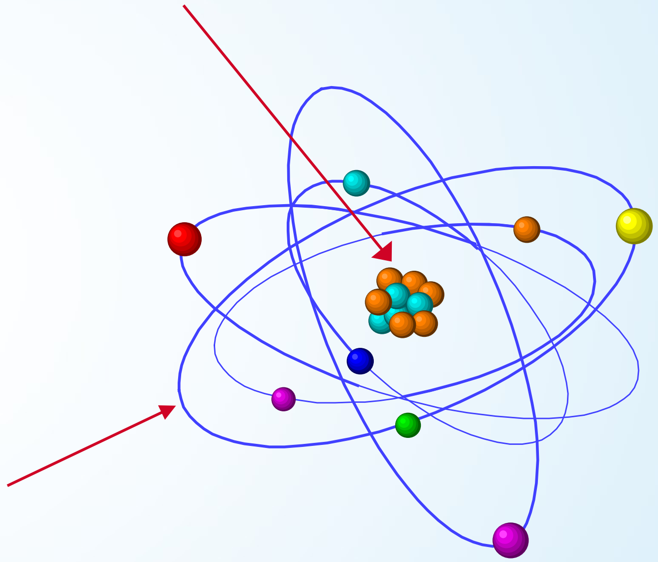
Electromagnetic spectrum



IR: infrared, UV = ultraviolet

The atomic structure

- The nuclear structure
  - protons and neutrons = nucleons
  - Z protons with a positive electric charge
    - ($1.6\ 10^{-19}$ C)
  - neutrons with no charge (neutral)
  - number of nucleons = mass number A
- The extranuclear structure
  - Z electrons (light particles with electric charge)
    - equal to proton charge but negative
- The atom is normally electrically neutral



The Classical/solar system Atomic Model is doomed

Let’s consider atoms as a quasi sun/planet model (only one planet so that it is just a two body problem.

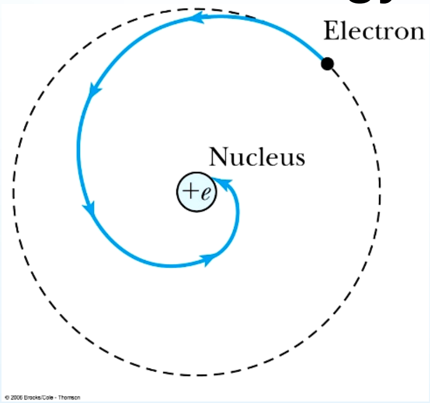
The force balance of circular orbits for an electron “going around” a stationary nucleolus

$$\vec{F}_e = \frac{-1}{4\pi\varepsilon_0}\frac{e^2}{r^2}\hat{e}_r = \frac{mv^2}{r}$$

For the centripetal force in a circular orbit

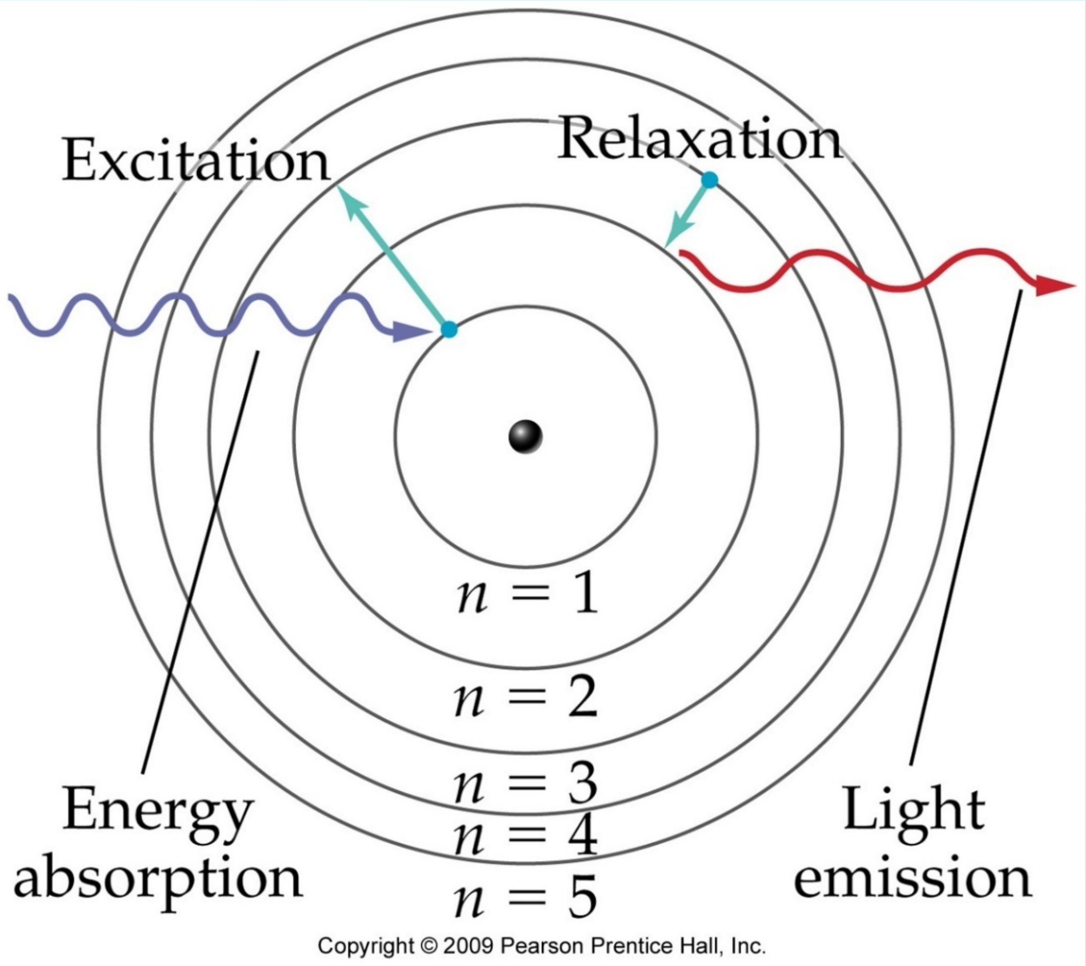
where *v* is the tangential velocity of the electron.

Circular motion is accelerated, accelerated charges need to radiate energy off according to Maxwell, loosing kinetic energy



Bohr's Model of the Atom (1913)

1. e^- can have only specific (quantized) energy values
2. light is emitted as e^- moves from one energy level to a lower energy level



$$E_n = -R_H\left(\frac{1}{n^2}\right)$$

n (principal quantum number) = 1,2,3,…

R_H (Rydberg constant) = 2.18×10^{-18}J

The Bohr Model of the Hydrogen Atom

Niels Bohr’s general assumptions:

1) “Stationary states” (orbiting electron does not radiate energy) exist in the hydrogen atom.
2) $\Delta E = E_1 - E_2 = hf$
3) Classical laws of physics do not apply to transitions between stationary states, the electron just “jumps” makes a “quantum leap”
4) Angular momentum is quantized in units of $^h/_{2\pi}$, in the future simply called h-bar $\hbar$
5) One form of the correspondence principle, at very high quantum numbers binding energies become so low that transitions between stationary states can be achieved without us noticing their discrete quantum nature, energy changes seem to be continuous again

Bohr model: radius

- Quantized angular momentum $mvr = nh/2p$
- But this is associated with coulombic attraction for which the centripetal force must equal the coulombic force:

  $F = mv^2/r = kZe^2/r^2$, so $r = kZe^2/mv^2$
- Thus $v = nh/(2pmr) = 2pkZe^2/nh$

  so $r = n^2h^2/(4p^2kZe^2m)$
- For $n=Z=1$,

  $r = h^2/(4p^2ke^2m) = 0.529*10^{-10}$ m = *Bohr radius*

Bohr model: Electron Energies

Velocity = $v = 2\text{p}kZe^2/(nh)$

Kinetic energy = $1/2mv^2 = 2\text{p}^2k^2Z^2e^4m/(n^2h^2)$

Potential energy = $-kZe^2/r = -4\text{p}^2k^2Z^2e^4m/(n^2h^2)$

Total energy = KE + PE = $-2\text{p}^2k^2Z^2e^4m/(n^2h^2)$

Photons emerge from transitions from one value of *n* to another.

Transition from $n = 3$ to $n = 2$ gives
photon energy = $-2\text{p}^2k^2Z^2e^4m$ / $[(1/9 - 1/4)\ h^2]$= 1.89 eV

- In the Bohr model of hydrogen, the lowest amount of energy hydrogen's one electron can have corresponds to being in the ***n*** = 1 orbit. We call this its **ground state.**
- When the atom gains energy, the electron leaps to a higher energy orbit. We call this an **excited state**.
- The atom is less stable in an excited state and so it will release the extra energy to return to the ground state.

Rydberg Equation

- As more scientists discovered emission lines at infrared and ultraviolet wavelengths, the Balmer series equation was extended to the Rydberg equation, actually on the basis of this equation, people went out looking for more lines :

$$\frac{1}{\lambda} = R_H \left(\frac{1}{n^2} - \frac{1}{k^2} \right) \qquad R_H = 1.096776 \times 10^7 \ \mathrm{m}^{-1}$$

Table 3.2 Hydrogen Series of Spectral Lines

Discoverer (year)	Wavelength	n	k
Lyman (1916)	Ultraviolet	1	>1
Balmer (1885)	Visible, ultraviolet	2	>2
Paschen (1908)	Infrared	3	>3
Brackett (1922)	Infrared	4	>4
Pfund (1924)	Infrared	5	>5

Aside:

$$R_H = \frac{\mu}{m_e} R_\infty$$

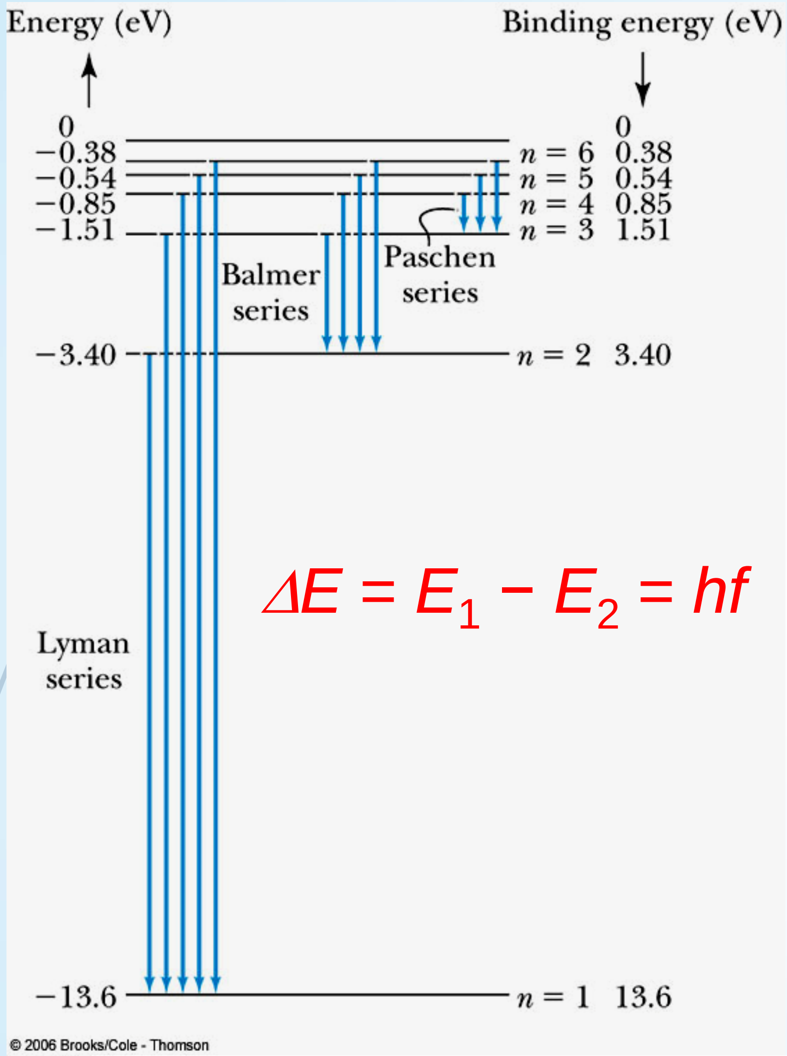
$$R_\infty = \frac{\alpha^2 m_e c}{2h} =$$

$$1.09737 \cdot 10^7 \_ m^{-1}$$

$$\mu = \frac{m_e \cdot M}{m_e + M}$$

with μ as reduced mass of the elecron, α as fine structure constant, and M mass of the nucleus

Transitions in the Hydrogen Atom



$\Delta E = E_1 - E_2 = hf$

$$E_n = -\frac{ke^2}{2a_0}\left(\frac{1}{n^2}\right) \qquad n = 1, 2, 3, \ldots$$

Lyman series

The atom will remain in the excited state for a short time before emitting a photon and returning to a lower stationary state. Most hydrogen atoms exist in *n* = 1 at room temperature.

Balmer series (of formula fame)

When sunlight passes through the atmosphere, hydrogen atoms in water vapor absorb the wavelengths (visible), seen as dark lines in absorption spectrum.

DeBroglie Wave Theory

- So: we've allowed electromagnetic radiation to behave as a wave and a particle. We can express momentum of light as
  $P = E/c = hn/c = h/\lambda$
- Can we also talk about matter behaving both as a wave and a particle? *Yes.*
- Particles can exhibit interference effects associated with wave behavior.

Wavelength $\lambda = h/P = h/(mv)$

Wave Behavior in electrons

- Nonrelativistic approximation:
  $KE = (1/2)mv^2$ so $\lambda = h/(mv) = h(2(KE)m)^{-1/2}$
- Further, since the angular momentum *mvr* is quantized ($mvr = nh/(2\pi)$), we can say $2\pi r = n\lambda$
- So we can say that the circumference of the electron's orbit is an integer multiple of the electron's wavelength! Standing waves!

Radioactivity

Radioactivity is the property of some atoms that cause them to spontaneously give off energy as particles or rays. **Radioactivity** is the process by which unstable nuclei change state in order to arrive at a lower-energy configuration

Radioactive atoms emit ionizing radiation when they decay

- **Ionizing radiation** is radiation that has sufficient energy to remove electrons from atoms, creating ions.
- **Ionizing radiation** can be classified into two groups: photons (gamma and X-rays) and particles (alpha, beta, and neutrons)

- In nature there are about 300 nuclides
- Majority of naturally occurring elements aye stable
- A few of high atomic weight, from polonium (Z =84) onward Radium (88), Thorium (90), Uranium (92) consists entirely of unstable nuclides
- The unstable substances undergo spontaneous change, radioactive disintegration or radioactive decay at definite rates.

Transmutation of gamma decay

Nuclide: a type of atoms with a certain number of protons, say *Z*, and mass number *M*, usually represented by $^{M}E^{Z}$, *E* be the symbol of element *Z*.

Periodic table of elements organizes chemical properties of elements.

Nuclide chart organizes unique nuclear properties of nuclides (isotopes).

In the radioactive process, the nuclide undergoes a transmutation, converting to another nuclide.

Gamma decay emits energy from atomic nucleus as photons. Gamma, γ, decay follows α and β decay or from isomers.

Nuclide Transmutation of a Decay

$$^{A}P^{Z} \longrightarrow \ ^{A-4}D^{Z-2} + \ ^{4}He^{2}$$

Nuclide Transmutation of b Decay

Beta decay consists of three processes: emitting an electron, emitting a positron, or capturing an electron from the atomic orbital.

Electron emission

$$^{A}P^{Z} + \nu \rightarrow \ ^{A}D^{Z+1} + \beta^{-} \quad \text{(absorbs a neutrino)}$$

or

$$^{A}P^{Z} \rightarrow \ ^{A}D^{Z+1} + \beta^{-} + \underline{\nu} \quad \text{(emit antineutrino, } \underline{\nu}\text{)}$$

Positron emission

$$^{A}P^{Z} \rightarrow \ ^{A}D^{Z-1} + \beta^{+} + \nu$$

or

$$^{A}P^{Z} + \underline{\nu} \rightarrow \ ^{A}D^{Z-1} + \beta^{+}.$$

Electron capture

$$^{A}P^{Z} + e^{-} \rightarrow \ ^{A}D^{Z-1} + \nu$$

or

$$^{A}P^{Z} + e^{-} + \underline{\nu} \rightarrow \ ^{A}D^{Z-1}$$

The shell model

Quantum mechanics treats nucleons in a nucleus as waves.

Each particle is represented by a wavefunction.

The wavefunctions are obtained by solving a differential equation.

Each wavefunction has a unique set of quantum numbers.

The energy of the state (function) depends on the quantum numbers.

Quantum numbers are:

n = any integer, the principle q.n.
l = 0, 1, 2, ..., n-1, the orbital quantum number
s = $^1/_2$ or $-^1/_2$ the spin q.n.
J = vector sum of l and s

The wavefunction $\Psi_{n,l}$ is even or odd parity.

A Summary of Radioactive Decay Kinetics

Radioactivity or decay rate A is the rate of disintegration of nuclei. Initially (at t = 0), we have N_o nuclei, and at time t, we have N nuclei. This rate is proportional to N, and the proportional constant is called decay constant λ.

$$A = -\frac{dN}{dt} = \lambda N$$

Integration gives

$$\ln N = \ln N_o - \lambda t \qquad or \qquad N = N_o\, e^{-\lambda t}$$

Also

$$A = A_o\, e^{-\lambda t}$$

Activity

The amount of a radionuclide present

SI unit is the Becquerel (Bq)   1 Bq = 1 disintegration per second

Curie (Ci) = 3.7×10^{10} dps

Becquerel (Bq) = 1 dps   1 Ci = 3.7×10^{10} Bq

$$A = \lambda N$$

where "A = activity" has units of disintegrations per second (dps or Bq)

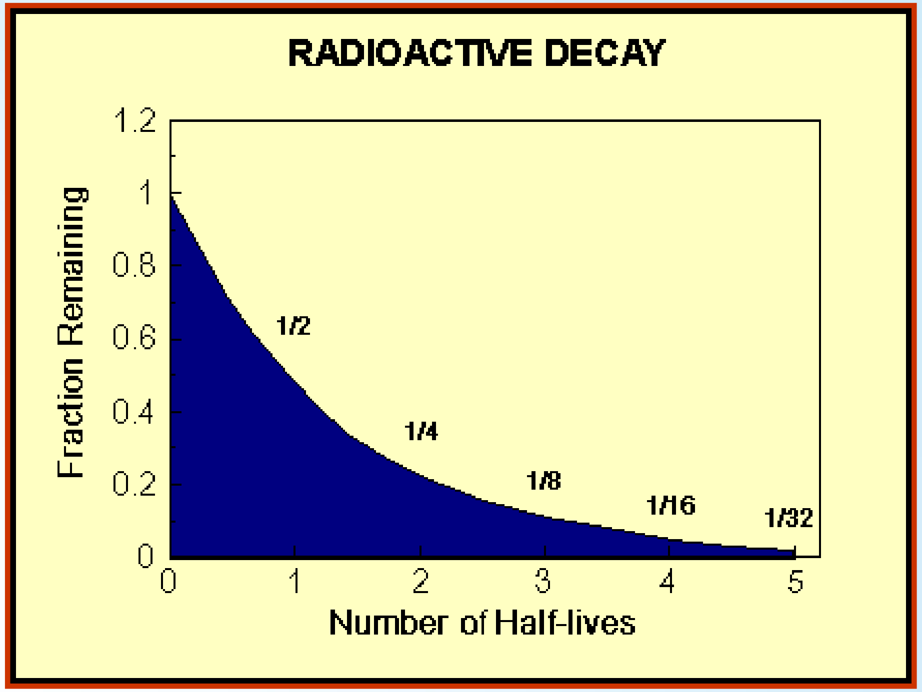
If we have N atoms of a given radioisotope and the radioisotope has a known decay constant, the activity of this sample is given by the simple product of the number of atoms and the decay constant.

Decay Constant

The Decay Constant is denoted by λ

NOTE: Units on λ are $\frac{1}{\text{time}}$

Typically $\frac{1}{\text{sec}}$ or sec^{-1} or "per second"



Half-Life and Decay Constant

The relationship between half-life and decay constant is:

$$T_{1/2} = \frac{0.693}{\lambda}$$

Mean Life

For some applications, as in the case of dosimetry of internally deposited radioactive material, it is convenient to use the average life of the radioisotope.

$$T_M = 1.44\ T_{1/2}$$

Energy - Wavelength Relationship for Photons

- The general relation connecting wavelength to energy is $E = hc / \lambda$
- Specifically, for energy in eV and wavelength in Å: $E = 12398.4 / \lambda$
- For energy in MeV and wavelength in Å: $E = 0.0123984 / \lambda$
- for either of the photons emitted in a positron-electron annihilation: $E = 0.511$ MeV so $\lambda = 0.0123984 / 0.511 = 0.02426$ Å $= 2.426$ pm.

Quantities, Units, and Definitions

The world of radiation research has gone through a major change in the units that it uses to express quantities. As recently as the 1970's when I was learning radiation quantitation, the traditional units for activity, dose, energy imparted, and equivalent dose were still in common use. In this course we will use the more modern units except in dealing with older research papers.

Additional Quantities: Equivalent Dose

Effects of a dose depend on how much energy is deposited per unit mass and on how influential that energy is in the medium:

$H_{T,R} = D_R W_{T,R}$

(D_R=dose, $W_{T,R}$= weight factor)

for tissue T, radiation type R.

If R is ^{60}Co photons, W_R=1 (reference type)

Unit: Sievert (1 J/kg)

Quantities, Units, and Definitions

Quantity	Exposure (em only)	Dose	Energy Imparted
Definition	$\Delta Q/\Delta m$	$\Delta E_d/\Delta m$	E_d
SI Unit	C kg^{-1}	Gray	Joule
Unit definition		J kg^{-1}	kg $m^2 s^{-2}$
Old Unit	Röntgen	Rad	Erg
Definition	1 esu cm^{-3}	100 erg g^{-1}	g $cm^2 s^{-2}$
Conversion	1 R = 2.58 * 10^{-4} C kg^{-1}	1 Gy = 100 Rad	1 J = 10^7 erg

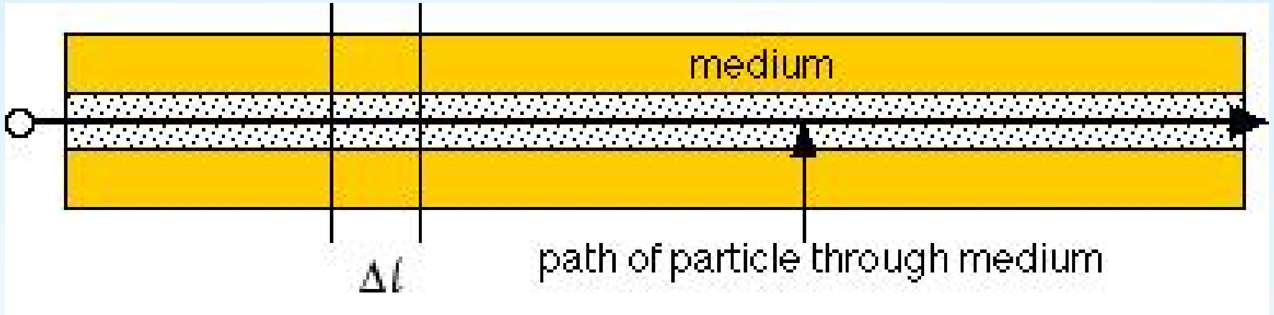
RBE and Kerma

RBE (relative biological effectiveness):

- describes weight factors for specific biological endpoints (e.g. carcinogenesis) as well as specific radiation types.
- Often used in context of radiation-induced tumors and other long-term problems.

- Kerma: *K*inetic *E*nergy *R*eleased to the *M*edium
  - Let ΔE_K =initial kinetic energy of all charged particles liberated. Then Kerma $K = \Delta E_K / \Delta m$
  - Dimensions of dose (book says energy—that's wrong)
  - Units: Gy or rad.

Linear Energy Transfer (LET)



- LET defined as dE_L/dl, where dE_L is the energy locally imparted to the medium over the length interval *dl*.
- Dimensions: Energy / length; units: J/m
- *restricted range stopping power*: don't look for energy deposited far from path.

LET depends on

Nature of radiation

- Alpha particles can be stopped by paper
- Betas can be stopped by aluminum
- Photons can get through almost anything

Nature of medium (density, chemistry)

Energy of radiation

The Three main Interactions Of X and Gamma Rays With Matter

- **Photoelectric effect**
  - **Very important in diagnostic radiology**

- **Compton scatter**
  - **Very important in diagnostic radiology**

- **Pair production**
  - **Very important in therapeutic & diagnostic radiology**

Photoelectric effect

- Incident photon with energy $h\nu$
- $\approx$ all photon energy absorbed by a tightly bound orbital electron
  - ejection of electron from the atom
  - Kinetic energy of ejected electron: $E = h\nu - E_B$
- Condition: $h\nu$ > EB (electron binding energy)
- Recoil of the residual atom
- Attenuation (or interaction) coefficient
  - ↓ photoelectric absorption coefficient

The Byproducts of the Photoelectric Effect

- Photoelectrons
- Characteristic photons

Compton scattering

- Interaction between photon and electron
- $h\nu = E_a + E_s$ (energy is conserved)
  - E_a: energy transferred to the atom
  - E_s: energy of the scattered photon
  - momentum is conserved in angular distributions
- At low energy, most of initial energy is scattered
  - ex: $E_s > 80\% (h\nu)$ if $h\nu < 1$ keV
- Increasing Z ↓ increasing probability of interaction. Compton is practically independent of Z in diagnostic range
- The probability of interaction decreases as $h\nu$ increases

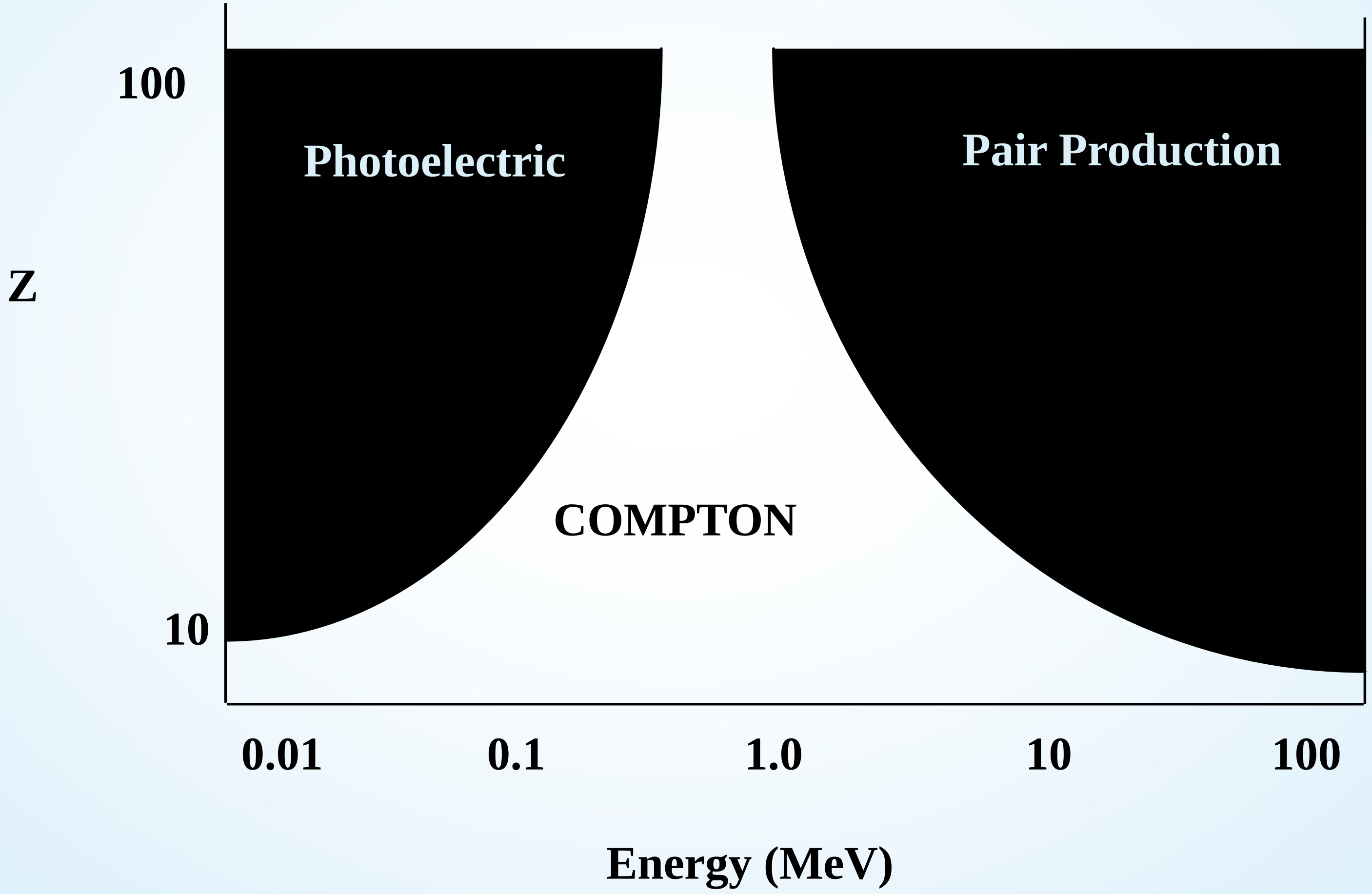
Pair Production

- The produced gamma photons may interact with matter through pair production or Compton scatter
- Pair production is used for positron emission tomography, a nuclear medicine imaging procedure
- It is also used in radiation therapy
- Incoming photon must have an energy of at least 1.02 MeV
- This process is a conversion of energy into matter and then matter back into energy
- Two electrons are produced in this interaction

Exponential attenuation law of photons (I)

- Any interaction $\Rightarrow$ change in photon energy and or direction
- Accounts for all effects: Compton, photoelectric,…
  - $dI/I = - \mu \, dx$
  - $I_x = I_0 \exp(-\mu x)$
    - I: number of photons per unit area per second [s^{-1}]
    - μ: the linear attenuation coefficient [m^{-1}]
    - μ / ρ [$m^2.kg^{-1}$]: mass attenuation coefficient
    - ρ [$kg.m^{-3}$]: material density

Photon Interaction Probabilities



Control Questions

1. Bohr model.
2. The Shell Model.
3. Radioactive Decay Kinetics.
4. Quantities, Units and Definitions.
5. Three Main Interactions Of X and Gamma Rays With Matter.
6. Attenuation Law.

Recommended literature:

Basic:

1. Vladimir Timanyuk, Elena Zhivotova, Igor Storozhenko. Biophysics: Textbook for students of higher schools / Kh.: NUPh, Golden Pages, 2011.- 576p.
2. Vladimir Timaniuk, Marina Kaydash, Ella Romodanova. Physical methods of analysis / Manual for students of higher schools/– Kharkiv: NUPh: Golden Pages, 2012. – 192 p.
3. Philip Nelson. Biological Physics. – W. H. Freeman, 1st Edition, 2007. – 600 p.
4. Biophysics, physical methods of analysis. Workbook: Study guide for the students of higher pharmaceutical educational institutions / Pogorelov S. V., Krasovskyi I. V., Kaydash M. V., Sheykina N. V., Frolova N. O., Timaniuk V. O., Romodanova E.O., Kokodii M.H. – Kharkiv., – 2018. – 130 p.
5. Center for distance learning technologies of NPhaU. Access mode: http://nuph.edu.ua/centr-distancijjnih-tehnologijj-navcha/

Support:

1. Eduard Lychkovsky. Physical methods of analysis and metrology: tutorial / Eduard Lychkovsky, Zoryana Fedorovych. – Lviv, 2012. – 107 p.
2. Daniel Goldfarb. Biophysics DeMYSTiFied. – McGraw-Hill Professional, 1st Edition, 2010. – 400 p.


Thanks for
your attention