## Basic Radiation Physics

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## Outline





## 1.1 INTRODUCTION
### 1.1.3 Physical quantities and units

- Physical quantities are characterized by their numerical value (magnitude) and associated unit.
- Symbols for physical quantities are set in *italic type*, while symbols for units are set in roman type.

  *For example*: $m = 21\ \mathrm{kg}$; $E = 15\ \mathrm{MeV}$

## 1.1 INTRODUCTION
### 1.1.4 Classification of forces in nature

There are four distinct forces observed in interaction between various types of particles

| Force | Source | Transmitted particle | Relative strength |
|---|---|---|---|
| Strong | Strong charge | Gluon | 1 |
| EM | Electric charge | Photon | 1/137 |
| Weak | Weak charge | $W^+$, $W^-$, and $Z^o$ | $10^{-6}$ |
| Gravitational | Energy | Graviton | $10^{-39}$ |



## 1.1 INTRODUCTION
### 1.1.5 Classification of fundamental particles

Two classes of fundamental particles are known:

- Quarks are particles that exhibit strong interactions

  Quarks are constituents of hadrons with a fractional electric charge (2/3 or -1/3) and are characterized by one of three types of strong charge called color (red, blue, green).

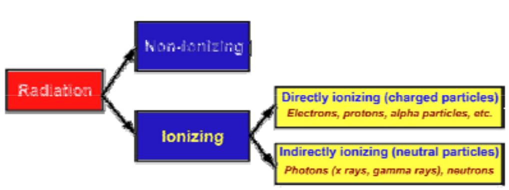
- Leptons are particles that do not interact strongly.

  Electron, muon, tau, and their corresponding neutrinos



## 1.1 INTRODUCTION
### 1.1.6 Classification of radiation

Radiation is classified into two main categories:



## 1.1 INTRODUCTION
### 1.1.7 Classification of ionizing photon radiation

Ionizing photon radiation is classified into four categories:

- Characteristic x ray
  - Results from electronic transitions between atomic shells.
- Bremsstrahlung
  - Results mainly from electron-nucleus Coulomb interactions.
- Gamma ray
  - Results from nuclear transitions.
- Annihilation quantum (annihilation radiation)
  - Results from positron-electron annihilation.



## 1.1 INTRODUCTION
### 1.1.9 Radiation quantities and units

| *Quantity* | *Definition* | *SI unit* | *Old unit* | *Conversion* |
|---|---|---|---|---|
| Exposure $X$ | $X = \frac{\Delta Q}{\Delta m_{air}}$ | $2.58 \times \frac{10^{-4}\,\text{C}}{\text{kg air}}$ | $1\,\text{R} = \frac{1\,\text{esu}}{\text{cm}^3\,\text{air}_{STP}}$ | $1\,\text{R} = 2.58 \times \frac{10^{-4}\,\text{C}}{\text{kg air}}$ |
| Dose $D$ | $D = \frac{\Delta E_{ab}}{\Delta m}$ | $1\,\text{Gy} = 1\frac{\text{J}}{\text{kg}}$ | $1\,\text{rad} = 100\,\frac{\text{erg}}{\text{g}}$ | $1\,\text{Gy} = 100\,\text{rad}$ |
| Equivalent dose $H$ | $H = D w_R$ | $1\,\text{Sv}$ | $1\,\text{rem}$ | $1\,\text{Sv} = 100\,\text{rem}$ |
| Activity $\mathcal{A}$ | $\mathcal{A} = \lambda N$ | $1\,\text{Bq} = 1\,\text{s}^{-1}$ | $1\,\text{Ci} = 3.7 \times 10^{10}\,\text{s}^{-1}$ | $1\,\text{Bq} = \frac{1\,\text{Ci}}{3.7 \times 10^{10}}$ |



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.1 Basic definitions for atomic structure

- The constituent particles forming an atom are:
  - Proton
  - Neutron
  - Electron

  Protons and neutrons are known as nucleons and form the nucleus.
- Atomic number $Z$
  - Number of protons and number of electrons in an atom.

## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.1 Basic definitions for atomic structure

- Atomic mass number *A*

  Number of nucleons $A = Z + N$ in an atom,

  where

  - $Z$ is the number of protons (atomic number) in an atom.
  - $N$ is the number of neutrons in an atom.



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.1 Basic definitions for atomic structure

- Atomic gram-atom is defined as the number of grams of an atomic compound that contains exactly one Avogadro's number of atoms, i.e.,

$$N_A = 6.022 \times 10^{23} \text{ atom/g-atom}$$

- Atomic mass numbers *A* of all elements are defined so that *A* grams of every element contain exactly $N_A$ atoms.

- *For example*:
  - 1 gram-atom of cobalt-60 is 60 g of cobalt-60.
  - 1 gram-atom of radium-226 is 226 g of radium-226.



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.1 Basic definitions for atomic structure

- Molecular gram-mole is defined as the number of grams of a molecular compound that contains exactly one Avogadro's number of molecules, i.e.,

$$N_A = 6.022 \times 10^{23} \text{ molecule/g-mole}$$

- The mass of a molecule is the sum of the masses of the atoms that make up the molecule.

- *For example:*
  - 1 gram-mole of water is 18 g of water.
  - 1 gram-mole of carbon dioxide is 44 g of carbon dioxide.

## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.1 Basic definition for atomic structure

- The atomic mass $\mathcal{M}$ is expressed in atomic mass units $u$
  - 1 $u$ is equal to 1/12th of the mass of the carbon-12 atom or to 931.5 MeV/$c^2$.
  - The atomic mass $\mathcal{M}$ is smaller than the sum of the individual masses of constituent particles because of the intrinsic energy associated with binding the particles (nucleons) within the nucleus.



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.1 Basic definition for atomic structure

- The nuclear mass $M$ is defined as the atomic mass with the mass of atomic orbital electrons subtracted, i.e.,

$$M = \mathcal{M} - Zm_e$$

The binding energy of orbital electrons to the nucleus is neglected.



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.1 Basic definitions for atomic structure

In nuclear physics the convention is to designate a nucleus X as ${}^{A}_{Z}\mathrm{X}$,

where

$A$ is the atomic mass number

$Z$ is the atomic number

For example:

- Cobalt-60 nucleus with $Z$ = 27 protons and $N$ = 33 neutrons is identified as ${}^{60}_{27}\mathrm{Co}$.
- Radium-226 nucleus with $Z$ = 88 protons and $N$ = 138 neutrons is identified as ${}^{226}_{88}\mathrm{Ra}$.

## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.1 Basic definitions for atomic structure

- Number of atoms $N_a$ per mass $m$ of an element:
  $$\frac{N_a}{m} = \frac{N_A}{A}$$
- Number of electrons $N_e$ per mass $m$ of an element:
  $$\frac{N_e}{m} = Z\frac{N_a}{m} = Z\frac{N_A}{A}$$
- Number of electrons $N_e$ per volume $V$ of an element:
  $$\frac{N_e}{V} = \rho Z\frac{N_a}{m} = \rho Z\frac{N_A}{A}$$



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.1 Basic definitions for atomic structure

- For all elements $Z/A \approx 0.5$ with two notable exceptions:
  - Hydrogen-1 for which $Z/A = 1.0$
  - Helium-3 for which $Z/A = 0.67$.
- Actually, $Z/A$ gradually decreases:
  - from 0.5 for low atomic number $Z$ elements
  - to □ 0.4 for high atomic number $Z$ elements.
- For example: $Z/A = 0.50$ for ${}^{4}_{2}\text{He}$
  $Z/A = 0.45$ for ${}^{60}_{27}\text{Co}$
  $Z/A = 0.39$ for ${}^{235}_{92}\text{U}$

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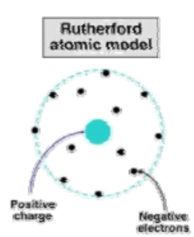
## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.2 Rutherford's model of the atom

- Ernest Rutherford concluded that the peculiar results of the Geiger-Marsden experiment did not support the Thomson's atomic model and proposed the currently accepted atomic model in which:
  - Mass and positive charge of the atom are concentrated in the nucleus the size of which is of the order of $10^{-15}$ m.
  - Negatively charged electrons revolve about the nucleus in a spherical cloud on the periphery of the Rutherford atom with a radius of the order of $10^{-10}$ m.

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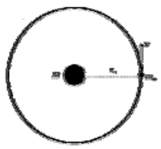
## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.3 Bohr's model of the hydrogen atom

- Niels Bohr in 1913 combined
  - Rutherford's concept of the nuclear atom

  and
  - Planck's idea of the quantized nature of the radiation process

  to develop an atomic model that successfully deals with one-electron structures, such as the hydrogen atom, singly ionized helium, etc.

  - *M* nucleus with mass *M*
  - $m_e$ electron with mass $m_e$
  - $r_n$ radius of electron orbit



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## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.3 Bohr's model of the hydrogen atom

- Bohr's atomic model is based on four postulates:
  - *Postulate* 1: Electrons revolve about the Rutherford nucleus in well-defined, allowed orbits (planetary-like motion).
  - *Postulate* 2: While in orbit, the electron does not lose any energy despite being constantly accelerated (no energy loss while electron is in allowed orbit).
  - *Postulate* 3: The angular momentum of the electron in an allowed orbit is quantized (quantization of angular momentum).
  - *Postulate* 4: An atom emits radiation only when an electron makes a transition from one orbit to another (energy emission during orbital transitions).

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## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.4 Multi-electron atom

- Bohr theory works well for one-electron structures, however, it does not apply directly to multi-electron atoms because of the repulsive Coulomb interactions among the atomic electrons.
  - Electrons occupy allowed shells; however, the number of electrons per shell is limited to $2n^2$.
  - Energy level diagrams of multi-electron atoms resemble those of one-electron structures, except that inner shell electrons are bound with much larger energies than $E_R$.

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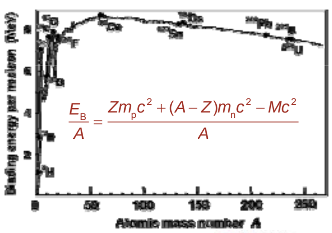
## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.5 Nuclear structure

- Most of the atomic mass is concentrated in the atomic nucleus consisting of $Z$ protons and $A$-$Z$ neutrons where $Z$ is the atomic number and $A$ the atomic mass number (Rutherford-Bohr atomic model).
- Protons and neutrons are commonly called nucleons and are bound to the nucleus with the strong force.



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.5 Nuclear structure

The binding energy per nucleon ($E_B/A$) in a nucleus varies with the number of nucleons $A$ and is of the order of 8 MeV per nucleon.




$$\frac{E_B}{A} = \frac{Zm_pc^2 + (A-Z)m_nc^2 - Mc^2}{A}$$

| Nucleus | $E_B/A$ (MeV) |
|---|---|
| $^{2}_{1}H$ | 1.1 |
| $^{3}_{1}H$ | 2.8 |
| $^{3}_{1}He$ | 2.6 |
| $^{4}_{1}He$ | 7.1 |
| $^{60}_{27}Co$ | 8.8 |
| $^{238}_{92}U$ | 7.3 |



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.6 Nuclear reactions

- Nuclear reaction: $A + a = B + b$ or A(a,b)B
  Projectile (a) bombards target (A)
  which is transformed into nuclei (B) and (b).
- The most important physical quantities that are conserved in a nuclear reaction are:
  - Charge
  - Mass number
  - Linear momentum
  - Mass-energy

## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.7 Radioactivity

- Radioactivity is a process by which an unstable nucleus (parent nucleus) decays into a new nuclear configuration (daughter nucleus) that may be stable or unstable.
- If the daughter is unstable it will decay further through a chain of decays until a stable configuration is attained.



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.7 Radioactivity

- Radioactive decay involves a transition from the quantum state of the parent P to a quantum state of the daughter D.
- The energy difference between the two quantum states is called the decay energy $Q$
- The decay energy $Q$ is emitted:
  - in the form of electromagnetic radiation (gamma rays)

    or
  - in the form of kinetic energy of the reaction products.



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.7 Radioactivity

- All radioactive processes are governed by the same formalism based on:
  - Characteristic parameter called the decay constant $\lambda$.
  - Activity $\mathcal{A}(t)$ defined as $\lambda N(t)$ where $N(t)$ is the number of radioactive nuclei at time $t$

    $\mathcal{A}(t) = \lambda N(t).$
- Specific activity $a$ is the parent's activity per unit mass:

$$a = \frac{\mathcal{A}(t)}{M} = \frac{\lambda N(t)}{M} = \frac{\lambda N_A}{A}$$

$N_A$ Avogadro's number

$A$ Atomic mass number

## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.7 Radioactivity

- Activity represents the total number of disintegrations (decays) of parent nuclei per unit time.
- The SI unit of activity is the becquerel (1 Bq = 1 $s^{-1}$).
  Both becquerel and hertz correspond to $s^{-1}$, however, hertz expresses frequency of periodic motion, while becquerel expresses activity.
- The older unit of activity is the curie $(1\ \text{Ci} = 3.7 \times 10^{10}\ \text{s}^{-1})$, originally defined as the activity of 1 g of radium-226.
  Currently, the activity of 1 g of radium-226 is 0.988 Ci.

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## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.7 Radioactivity

- Decay of radioactive parent P into stable daughter D:

$$\text{P} \xrightarrow{\lambda_\text{P}} \text{D}$$

- The rate of depletion of the number of radioactive parent nuclei $N_\text{P}(t)$ is equal to the activity $\mathcal{A}_\text{P}(t)$ at time $t$:

$$\frac{\text{d}N_\text{P}(t)}{\text{d}t} = -\mathcal{A}_\text{P}(t) = -\lambda_\text{P} N_\text{P}(t), \qquad \int_{N_\text{P}(0)}^{N_\text{P}(t)} \frac{\text{d}N_\text{P}(t)}{N_\text{P}} = -\int_0^t \lambda_\text{P} \text{d}t$$

where $N_\text{P}(0)$ is the initial number of parent nuclei at time $t$ = 0.

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## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.7 Radioactivity

- The number of radioactive parent nuclei $N_\text{P}(t)$ as a function of time $t$ is:

$$N_\text{P}(t) = N_\text{P}(0) e^{-\lambda_\text{P} t}$$

- The activity of the radioactive parent $\mathcal{A}_\text{P}(t)$ as a function of time $t$ is:

$$\mathcal{A}_\text{P}(t) = \lambda_\text{P} N_\text{P}(t) = \lambda_\text{P} N_\text{P}(0) e^{-\lambda_\text{P} t} = \mathcal{A}_\text{P}(0) e^{-\lambda_\text{P} t},$$

where $\mathcal{A}_\text{P}(0)$ is the initial activity at time $t$ = 0.

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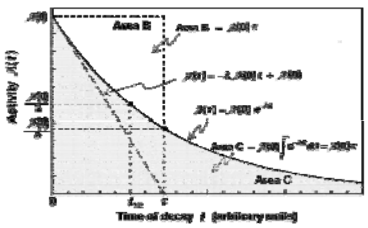
## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.7 Radioactivity

Parent activity $\mathcal{A}_P(t)$ plotted against time $t$ illustrating:

- Exponential decay of the activity
- Concept of half life
- Concept of mean life





## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.7 Radioactivity

- Half life $(t_{1/2})_P$ of radioactive parent P is the time during which the number of radioactive parent nuclei decays from the initial value $N_P(0)$ at time $t = 0$ to half the initial value:

$$N_P(t = t_{1/2}) = (1/2)N_P(0) = N_P(0)e^{-\lambda_P (t_{1/2})_P}$$

- The decay constant $\lambda_P$ and the half life $(t_{1/2})_P$ are related as follows:

$$\lambda_P = \frac{\ln 2}{(t_{1/2})_P}$$



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.7 Radioactivity

Special considerations for the $P \xrightarrow{\lambda_P} D \xrightarrow{\lambda_D} G$ relationship:

- For $\lambda_D < \lambda_P$ or $(t_{1/2})_D > (t_{1/2})_P$
  General relationship (no equilibrium)
  $$\frac{\mathcal{A}_D}{\mathcal{A}_P} = \frac{\lambda_D}{\lambda_D - \lambda_P}\left\{1 - e^{-(\lambda_D - \lambda_P)t}\right\}$$

- For $\lambda_D > \lambda_P$ or $(t_{1/2})_D < (t_{1/2})_P$
  Transient equilibrium for $t >> t_{max}$
  $$\frac{\mathcal{A}_D}{\mathcal{A}_P} = \frac{\lambda_D}{\lambda_D - \lambda_P}$$

- For $\lambda_D >> \lambda_P$ or $(t_{1/2})_D << (t_{1/2})_P$
  Secular equilibrium
  $$\frac{\mathcal{A}_D}{\mathcal{A}_P} \approx 1$$

## 1.2.8 Activation of nuclides

- Radioactivation of nuclides occurs when a parent nuclide P is bombarded with thermal neutrons in a nuclear reactor and transforms into a radioactive daughter nuclide D that decays into a granddaughter nuclide G.

$$P \xrightarrow{\sigma\dot{\varphi}} D \xrightarrow{\lambda_D} G$$

- The probability for radioactivation to occur is governed by the cross section $\sigma$ for the nuclear reaction and the neutron fluence rate $\dot{\varphi}$.
  - The unit of $\sigma$ is barn per atom where $1 \text{ barn} = 1 \text{ b} = 10^{-24} \text{ cm}^2$.
  - The unit of $\dot{\varphi}$ is $\text{cm}^{-2} \cdot \text{s}^{-1}$.



1.2 ATOMIC AND NUCLEAR STRUCTURE

## 1.2.8 Activation of nuclides

- An important example of nuclear activation is the production of the cobalt-60 radionuclide through bombarding stable cobalt-59 with thermal neutrons

$${}^{59}_{27}\text{Co} + \text{n} \rightarrow {}^{60}_{27}\text{Co} + \gamma \quad \text{or} \quad {}^{59}_{27}\text{Co}(\text{n},\gamma){}^{60}_{27}\text{Co}$$

  - For cobalt-59 the cross section $\sigma$ is 37 b/atom
  - Typical reactor fluence rates $\dot{\varphi}$ are of the order of $10^{14} \text{ cm}^{-2} \cdot \text{s}^{-1}$.

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1.2 ATOMIC AND NUCLEAR STRUCTURE

## 1.2.9 Modes of radioactive decay

- Nuclear transformations are usually accompanied by emission of energetic particles (charged particles, neutral particles, photons, neutrinos)

| Radioactive decay | Emitted particles |
|---|---|
| Alpha decay | $\alpha$ particle |
| Beta plus decay | $\beta^+$ particle (positron), neutrino |
| Beta minus decay | $\beta^-$ particle (electron), antineutrino |
| Electron capture | neutrino |
| Pure gamma decay | photon |
| Internal conversion | orbital electron |
| Spontaneous fission | fission products |

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## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

- In each nuclear transformation a number of physical quantities must be conserved.
- The most important conserved physical quantities are:
  - Total energy
  - Momentum
  - Charge
  - Atomic number
  - Atomic mass number (number of nucleons)



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

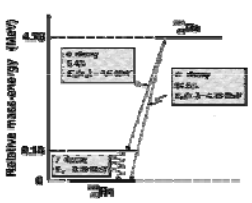
- Alpha decay is a nuclear transformation in which:
  - An energetic alpha particle (helium-4 ion) is emitted.
  - The atomic number *Z* of the parent decreases by 2.
  - The atomic mass number *A* of the parent decreases by 4.

$${}^{A}_{Z}\mathrm{P} \rightarrow {}^{A-4}_{Z-2}\mathrm{D} + {}^{4}_{2}\mathrm{He}$$



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

- Best known example of alpha decay is the transformation of radium-226 into radon-222 with a half life of 1600 y.




$${}^{A}_{Z}\mathrm{P} \rightarrow {}^{A-4}_{Z-2}\mathrm{D} + {}^{4}_{2}\mathrm{He}$$

$${}^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + \alpha$$

# 1.2 ATOMIC AND NUCLEAR STRUCTURE
## 1.2.9 Modes of radioactive decay

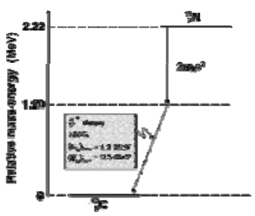
- Beta plus decay is a nuclear transformation in which:
  - A proton-rich radioactive parent nucleus transforms a proton into a neutron.
  - A positron and neutrino, sharing the available energy, are ejected from the parent nucleus.
  - The atomic number *Z* of the parent decreases by one; the atomic mass number *A* remains the same.
  - The number of nucleons and total charge are conserved in the beta decay process and the daughter D can be referred to as an isobar of the parent P.

$$p \rightarrow n + e^{+} + \nu_{e} \qquad {}^{A}_{Z}P \rightarrow {}^{A}_{Z-1}D + e^{+} + \nu_{e}$$



# 1.2 ATOMIC AND NUCLEAR STRUCTURE
## 1.2.9 Modes of radioactive decay

- An example of a beta plus decay is the transformation of nitrogen-13 into carbon-13 with a half life of 10 min.



$$p \rightarrow n + e^{+} + \nu_{e}$$

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

$${}^{13}_{7}N \rightarrow {}^{13}_{6}C + e^{+} + \nu_{e}$$



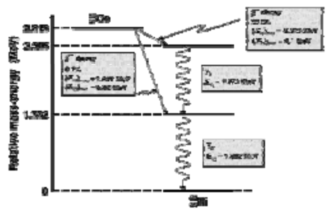
# 1.2 ATOMIC AND NUCLEAR STRUCTURE
## 1.2.9 Modes of radioactive decay

- Beta minus decay is a nuclear transformation in which:
  - A neutron-rich radioactive parent nucleus transforms a neutron into a proton.
  - An electron and anti-neutrino, sharing the available energy, are ejected from the parent nucleus.
  - The atomic number *Z* of the parent increases by one; the atomic mass number *A* remains the same.
  - The number of nucleons and total charge are conserved in the beta decay process and the daughter D can be referred to as an isobar of the parent P.

$$n \rightarrow p + e^{-} + \bar{\nu}_{e} \qquad {}^{A}_{Z}P \rightarrow {}^{A}_{Z+1}D + e^{-} + \bar{\nu}_{e}$$

## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

- An example of beta minus decay is the transformation of cobalt-60 into nickel-60 with a half life of 5.26 y.



$$n \rightarrow p + e^- + \bar{\nu}_e$$

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

$$^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + e^- + \bar{\nu}_e$$



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

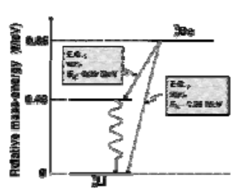
- Electron capture decay is a nuclear transformation in which:
  - A nucleus captures an atomic orbital electron (usually K shell).
  - A proton transforms into a neutron.
  - A neutrino is ejected.
  - The atomic number *Z* of the parent decreases by one; the atomic mass number *A* remains the same.
  - The number of nucleons and total charge are conserved in the beta decay process and the daughter D can be referred to as an isobar of the parent P.

$$p + e^- = n + \nu_e \qquad {}^{A}_{Z}P + e^- = {}^{A}_{Z-1}D + \nu_e$$



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

- An example of nuclear decay by electron capture is the transformation of berillium-7 into lithium-7



$$p + e^- = n + \nu_e$$

$$^{A}_{Z}P + e^- = {}^{A}_{Z+1}D + \nu_e$$

$$^{7}_{4}Be + e^- = {}^{7}_{3}Li + \nu_e$$

## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

- Gamma decay is a nuclear transformation in which an excited parent nucleus P, generally produced through alpha decay, beta minus decay or beta plus decay, attains its ground state through emission of one or several gamma photons.
- The atomic number *Z* and atomic mass number *A* do not change in gamma decay.



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

- In most alpha and beta decays the daughter de-excitation occurs instantaneously, so that we refer to the emitted gamma rays as if they were produced by the parent nucleus.
- If the daughter nucleus de-excites with a time delay, the excited state of the daughter is referred to as a meta-stable state and process of de-excitation is called an isomeric transition.



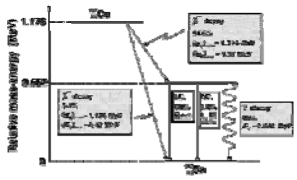
## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

- Internal conversion is a nuclear transformation in which:
  - The nuclear de-excitation energy is transferred to an orbital electron (usually K shell) .
  - The electron is emitted form the atom with a kinetic energy equal to the de-excitation energy less the electron binding energy.
  - The resulting shell vacancy is filled with a higher-level orbital electron and the transition energy is emitted in the form of characteristic photons or Auger electrons.

$$ {}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X^{+} + e^{-} $$

## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

- An example for both the emission of gamma photons and emission of conversion electrons is the beta minus decay of cesium-137 into barium-137 with a half life of 30 y.



$$n \rightarrow p + e^- + \bar{\nu}_e$$

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

$$^{137}_{55}Cs \rightarrow {}^{137}_{56}Ba + e^- + \bar{\nu}_e$$



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

- Spontaneous fission is a nuclear transformation by which a high atomic mass nucleus spontaneously splits into two nearly equal fission fragments.
  - Two to four neutrons are emitted during the spontaneous fission process.
  - Spontaneous fission follows the same process as nuclear fission except that it is not self-sustaining, since it does not generate the neutron fluence rate required to sustain a “chain reaction”.



## 1.2 ATOMIC AND NUCLEAR STRUCTURE
### 1.2.9 Modes of radioactive decay

- In practice, spontaneous fission is only energetically feasible for nuclides with atomic masses above 230 u or with $(Z^2/A) \geq 235$
- The spontaneous fission is a competing process to alpha decay; the higher is A above uranium-238, the more prominent is the spontaneous fission in comparison with the alpha decay and the shorter is the half-life for spontaneous fission.

## 1.4 PHOTON INTERACTIONS
### 1.4.1 Types of indirectly ionizing photon irradiations

Ionizing photon radiation is classified into four categories:

- Characteristic x ray
  - Results from electronic transitions between atomic shells
- Bremsstrahlung
  - Results mainly from electron-nucleus Coulomb interactions
- Gamma ray
  - Results from nuclear transitions
- Annihilation quantum (annihilation radiation)
  - Results from positron-electron annihilation



## 1.4 PHOTON INTERACTIONS
### 1.4.1 Types of indirectly ionizing photon irradiations

- In penetrating an absorbing medium, photons may experience various interactions with the atoms of the medium, involving:
  - Absorbing atom as a whole
  - Nuclei of the absorbing medium
  - Orbital electrons of the absorbing medium.



## 1.4 PHOTON INTERACTIONS
### 1.4.1 Types of indirectly ionizing photon irradiations

- Interactions of photons with nuclei may be:
  - Direct photon-nucleus interactions (photodisintegration)

    or
  - Interactions between the photon and the electrostatic field of the nucleus (pair production).
- Photon-orbital electron interactions are characterized as interactions between the photon and either
  - A loosely bound electron (Compton effect, triplet production)

    or
  - A tightly bound electron (photoelectric effect).

## 1.4 PHOTON INTERACTIONS
### 1.4.1 Types of indirectly ionizing photon irradiations

- A loosely bound electron is an electron whose binding energy $E_B$ to the nucleus is small compared to the photon energy $h\nu$.

$$E_B << h\nu$$

- An interaction between a photon and a loosely bound electron is considered to be an interaction between a photon and a free (unbound) electron.



## 1.4 PHOTON INTERACTIONS
### 1.4.1 Types of indirectly ionizing photon irradiations

- A tightly bound electron is an electron whose binding energy $E_B$ is comparable to, larger than, or slightly smaller than the photon energy $h\nu$.
  - For a photon interaction to occur with a tightly bound electron, the binding energy $E_B$ of the electron must be of the order of, but slightly smaller, than the photon energy.

$$E_B \le h\nu$$

  - An interaction between a photon and a tightly bound electron is considered an interaction between a photon and the atom as a whole.



## 1.4 PHOTON INTERACTIONS
### 1.4.1 Types of indirectly ionizing photon irradiations

- As far as the photon fate after the interaction with an atom is concerned there are two possible outcomes:
  - Photon disappears (i.e., is absorbed completely) and a portion of its energy is transferred to light charged particles (electrons and positrons in the absorbing medium).
  - Photon is scattered and two outcomes are possible:
    - The resulting photon has the same energy as the incident photon and no light charged particles are released in the interaction.
    - The resulting scattered photon has a lower energy than the incident photon and the energy excess is transferred to a light charged particle (electron).

## 1.4 PHOTON INTERACTIONS
### 1.4.1 Types of indirectly ionizing photon irradiations

- The light charged particles produced in the absorbing medium through photon interactions will:
  - Deposit their energy to the medium through Coulomb interactions with orbital electrons of the absorbing medium (collision loss also referred to as ionization loss).

    or
  - Radiate their kinetic energy away through Coulomb interactions with the nuclei of the absorbing medium (radiation loss).



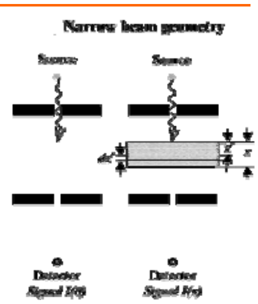
## 1.4 PHOTON INTERACTIONS
### 1.4.2 Photon beam attenuation

- The most important parameter used for characterization of x-ray or gamma ray penetration into absorbing media is the linear attenuation coefficient $\mu$.
- The linear attenuation coefficient $\mu$ depends on:
  - Energy $h\nu$ of the photon beam
  - Atomic number $Z$ of the absorber
- The linear attenuation coefficient may be described as the probability per unit path length that a photon will have an interaction with the absorber.



## 1.4 PHOTON INTERACTIONS
### 1.4.2 Photon beam attenuation

- A slab of absorber material of thickness $x$ decreases the detector signal intensity from $I(0)$ to $I(x)$.
- A layer of thickness d$x'$ reduces the beam intensity by d$I$ and the fractional reduction in intensity, -d$I/I$ is proportional to
  - Attenuation coefficient $\mu$
  - Layer thickness d$x'$



## 1.4 PHOTON INTERACTIONS
### 1.4.2 Photon beam attenuation

- For a homogeneous medium $\mu = \text{const.}$ and one gets the standard exponential relationship valid for monoenergetic photon beams:

$$I(x) = I(0)e^{-\mu x}$$

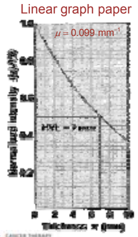
or

$$I(x)/I(0) = e^{-\mu x}$$

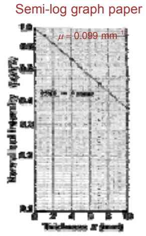
For $x$ = HVL

$$\frac{I(x)}{I(0)} = 0.5$$

Linear graph paper




Semi-log graph paper






## 1.4 PHOTON INTERACTIONS
### 1.4.2 Photon beam attenuation

- Several thicknesses of special interest are defined as parameters for mono-energetic photon beam characterization in narrow beam geometry:
  - Half-value layer (HVL$_1$ or $x_{1/2}$)
    Absorber thickness that attenuates the original intensity to 50%.
  - Mean free path (MFP or $\bar{x}$)
    Absorber thickness which attenuates the beam intensity to 1/e = 36.8%.
  - Tenth-value layer (TVL or $x_{1/10}$)
    Absorber thickness which attenuates the beam intensity to 10%.



## 1.4 PHOTON INTERACTIONS
### 1.4.2 Photon beam attenuation

- The half-value layer $x_{1/2}$, mean free path $\bar{x}$, and tenth-value layer $x_{1/10}$ are related by the following:

$$\mu = \frac{\ln 2}{x_{1/2}} = \frac{1}{\bar{x}} = \frac{\ln 10}{x_{1/10}}$$

or

$$x_{1/2} = (\ln 2)\bar{x} = \frac{\ln 2}{\ln 10} x_{1/10} \approx 0.3 x_{1/10}$$

## 1.4 PHOTON INTERACTIONS
### 1.4.2 Photon beam attenuation

- In addition to the linear attenuation coefficient $\mu$ other related attenuation coefficients and cross sections are in use for describing photon beam attenuation:
  - Mass attenuation coefficient $\mu_m$
  - Atomic cross section ${}_a\mu$
  - Electronic cross section ${}_e\mu$



## 1.4 PHOTON INTERACTIONS
### 1.4.2 Photon beam attenuation

| | Symbol | Relationship to $\mu$ | Units |
|---|---|---|---|
| Linear attenuation coefficient | $\mu$ | $\mu$ | $cm^{-1}$ |
| Mass attenuation coefficient | $\mu_m$ | $\frac{\mu}{\rho}$ | $cm^2/g$ |
| Atomic cross section | ${}_a\mu$ | $\frac{\mu}{n^a}$ | $cm^2/atom$ |
| Electronic cross section | ${}_e\mu$ | $\frac{\mu}{Zn^a}$ | $cm^2/electron$ |



## 1.4 PHOTON INTERACTIONS
### 1.4.2 Photon beam attenuation

- Energy transfer coefficient $\mu_{tr} = \mu \frac{\bar{E}_{tr}}{h\nu}$

  with $\bar{E}_{tr}$ the average energy transferred from the primary photon with energy $h\nu$ to kinetic energy of charged particles ($e^-$ and $e^+$).

- Energy absorption coefficient $\mu_{ab} = \mu \frac{\bar{E}_{ab}}{h\nu}$

  with $\bar{E}_{ab}$ the average energy absorbed in the volume of interest in the absorbing medium.

  In the literature $\mu_{en}$ is usually used instead of $\mu_{ab}$, however, the the use of subscript "ab" for energy absorbed compared to the subscript "tr" for energy transferred seems more logical.

## 1.4 PHOTON INTERACTIONS
### 1.4.2 Photon beam attenuation

- The average energy absorbed in the volume of interest

$$\bar{E}_{ab} = \bar{E}_{tr} - \bar{E}_{rad}$$

with $\bar{E}_{rad}$ the average energy component of $\bar{E}_{tr}$ which the charged particles lose in the form of radiation collisions (bremsstrahlung) and is not absorbed in the volume of interest.



## 1.4 PHOTON INTERACTIONS
### 1.4.2 Photon beam attenuation

- The mass attenuation coefficient of a compound or a mixture is approximated by a summation of a weighted average of its constituents:

$$\frac{\mu}{\rho} = \sum_i w_i \frac{\mu_i}{\rho}$$

  - $w_i$ is the proportion by weight of the i-th constituent
  - $\mu_i/\rho$ is the mass attenuation coefficient of the i-th constituent



## 1.4 PHOTON INTERACTIONS
### 1.4.2 Photon beam attenuation

- The attenuation coefficient $\mu$ has a specific value for a given photon energy $h\nu$ and absorber atomic number $Z$.
- The value for the attenuation coefficient $\mu(h\nu,Z)$ for a given photon energy $h\nu$ and absorber atomic number $Z$ represents a sum of values for all individual interactions that a photon may have with an atom:

$$\mu = \sum_i \mu_i$$

## 1.4 PHOTON INTERACTIONS
### 1.4.3 Types of photon interactions with absorber

- According to the type of target there are two possibilities for photon interaction with an atom:
  - Photon - orbital electron interaction
  - Photon - nucleus interaction
- According to the type of event there are two possibilities for photon interaction with an atom:
  - Complete absorption of the photon
  - Scattering of the photon



## 1.4 PHOTON INTERACTIONS
### 1.4.3 Types of photon interactions with absorber

- In medical physics photon interactions fall into four groups:
  - Interactions of major importance
    - Photoelectric effect
    - Compton scattering by free electron
    - Pair production (including triplet production)
  - Interactions of moderate importance
    - Rayleigh scattering
    - Thomson scattering by free electron
  - Interactions of minor importance
    - Photonuclear reactions
  - Negligible interactions
    - Thomson and Compton scattering by the nucleus
    - Meson production,
    - Delbrück scattering



## 1.4 PHOTON INTERACTIONS
### 1.4.3 Types of photon interactions with absorber

| Interaction | Symbol for electronic cross section | Symbol for atomic cross section | Symbol for linear attenuation coefficient |
|---|---|---|---|
| Thomson scattering | ${}_e\sigma_{Th}$ | ${}_a\sigma_{Th}$ | $\sigma_{Th}$ |
| Rayleigh scattering | - | ${}_a\sigma_R$ | $\sigma_R$ |
| Compton scattering | ${}_e\sigma_c$ | ${}_a\sigma_c$ | $\sigma_C$ |
| Photoelectric effect | - | ${}_a\tau$ | $\tau$ |
| Pair production | - | ${}_a\kappa_{pp}$ | $\kappa_p$ |
| Triplet production | ${}_e\kappa_{tp}$ | ${}_a\kappa_{tp}$ | $\kappa_t$ |
| Photodisintegration | - | ${}_a\sigma_{pn}$ | $\sigma_{pn}$ |

## 1.4 PHOTON INTERACTIONS
### 1.4.3 Types of photon interactions with absorber

- TYPES OF TARGETS IN PHOTON INTERACTIONS

**Photon-orbital electron interaction**

- with bound electron
  - Photoelectric effect
  - Rayleigh scattering
- with "free" electrons
  - Thomson scattering
  - Compton scattering
- with Coulomb field of electron
  - Triplet production

**Photon-nucleus interaction**

- with nucleus directly
  - Photodisintegration
- with Coulomb field of nucleus
  - Pair production



## 1.4 PHOTON INTERACTIONS
### 1.4.3 Types of photon interactions with absorber

- Types of photon-atom interactions

**Complete absorption of photon**

- Photoelectric effect
- Pair production
- Triplet production
- Photodisintegration

**Photon scattering**

- Thomson scattering
- Rayleigh scattering
- Compton scattering



## 1.4 PHOTON INTERACTIONS
### 1.4.4 Photoelectric effect

- In the photoelectric effect a photon of energy $h\nu$ interacts with tightly bound orbital electron, i.e., with the whole atom.
- The photon disappears and the orbital electron is ejected from the atom.
- Conservation of energy and momentum considerations show that photoelectric effect can occur only on a tightly bound electron rather than on a loosely bound ("free") electron.

## 1.4 PHOTON INTERACTIONS
### 1.4.4 Photoelectric effect

- The orbital electron is ejected from the atom with kinetic energy

$$E_K = h\nu - E_B,$$

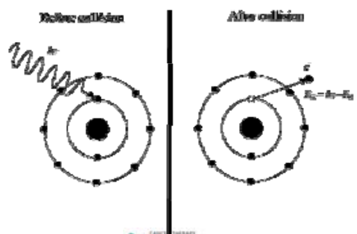
where $E_B$ is the binding energy of the orbital electron.

- The ejected orbital electron is called a photoelectron.
- When the photon energy $h\nu$ exceeds the K-shell binding energy $E_B(K)$ of the absorber atom, the photoelectric effect is most likely to occur with a K-shell electron in comparison with higher shell electrons.



## 1.4 PHOTON INTERACTIONS
### 1.4.4 Photoelectric effect

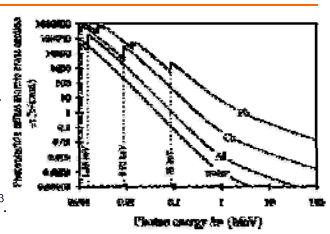
- Schematic diagram of the photoelectric effect
  - A photon with energy $h\nu$ interacts with a K-shell electron
  - The orbital electron is emitted from the atom as a photoelectron





## 1.4 PHOTON INTERACTIONS
### 1.4.4 Photoelectric effect

- The atomic attenuation coefficient $_a\tau$ for photoelectric effect is proportional to $Z^4/(h\nu)^3$.
- The mass attenuation coefficient $\tau_m$ for photoelectric effect is proportional to $Z^3/(h\nu)^3$.



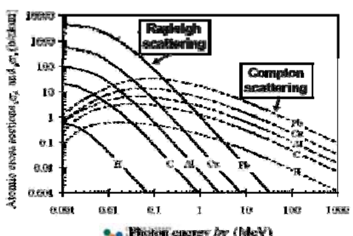
## 1.4 PHOTON INTERACTIONS
### 1.4.5 Coherent (Rayleigh) scattering

- In coherent (Rayleigh) scattering the photon interacts with a bound orbital electron, i.e., with the combined action of the whole atom.
  - The event is elastic and the photon loses essentially none of its energy and is scattered through only a small angle.
  - No energy transfer occurs from the photon to charged particles in the absorber; thus Rayleigh scattering plays no role in the energy transfer coefficient but it contributes to the attenuation coefficient.



## 1.4 PHOTON INTERACTIONS
### 1.4.5 Coherent (Rayleigh) scattering

- Coefficients for coherent (Rayleigh) scattering
  - The atomic cross section is proportional to $(Z/h\nu)^2$
  - The mass attenuation coefficient is proportional to $Z/(h\nu)^2$

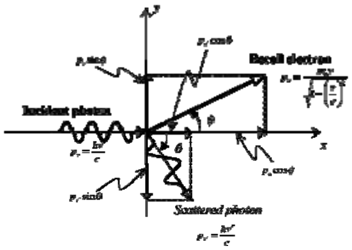





## 1.4 PHOTON INTERACTIONS
### 1.4.6 Compton (Incoherent) scattering

- In Compton effect (incoherent scattering) a photon with energy $h\nu$ interacts with a loosely bound ("free") electron.
  - Part of the incident photon energy is transferred to the "free" orbital electron which is emitted from the atom as the Compton (recoil) electron.
  - The photon is scattered through a scattering angle $\theta$ and its energy $h\nu'$ is lower than the incident photon energy $h\nu$.
  - Angle $\phi$ represents the angle between the incident photon direction and the direction of the recoil electron.

## 1.4 PHOTON INTERACTIONS
### 1.4.6 Compton scattering




Conservation of energy

$$h\nu + m_e c^2 = h\nu' + m_e c^2 + E_K$$

Conservation of momentum (x axis)

$$p_\nu = p_{\nu'} \cos\theta + p_e \cos\phi$$

Conservation of momentum (y axis)

$$0 = -p_{\nu'} \sin\theta + p_e \sin\phi$$

Compton expression:

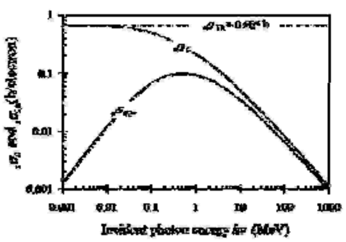
$$\Delta\lambda = \lambda_c (1 - \cos\theta)$$

$$\lambda_c = \frac{h}{m_e c} = 0.24 \; □$$



## 1.4 PHOTON INTERACTIONS
### 1.4.6 Compton scattering

- The electronic Compton attenuation coefficient ${}_e\sigma_c$ steadily decreases with increasing photon energy $h\nu$




$$({}_e\sigma_c)_{tr} = {}_e\sigma_c \times f_c$$

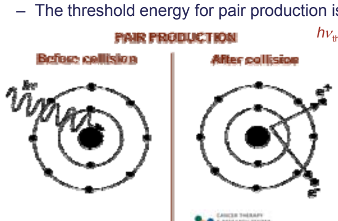
$$f_c = \frac{\bar{E}_K}{h\nu}$$



## 1.4 PHOTON INTERACTIONS
### 1.4.7 Pair production

- In pair production
  - The photon disappears.
  - An electron-positron pair with a combined kinetic energy equal to $h\nu - 2m_e c^2$ is produced in the nuclear Coulomb field.
  - The threshold energy for pair production is:

$$h\nu_{thr} = 2m_e c^2 \left\{1 + \frac{m_e c^2}{M_A c^2}\right\} \approx 2m_e c^2$$



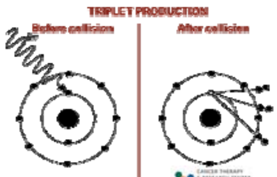

$m_e$ electron mass

$M_A$ mass of nucleus

$m_e c^2 = 0.511$ MeV

## 1.4 PHOTON INTERACTIONS
### 1.4.7 Pair production

- In triplet production:
  - The photon disappears.
  - An electron-positron pair is produced in the Coulomb field of an orbital electron, and a triplet (two electrons and one positron) leave the site of interaction.
  - The threshold energy for triplet production is: $h\nu_{thr} = 4m_e c^2$

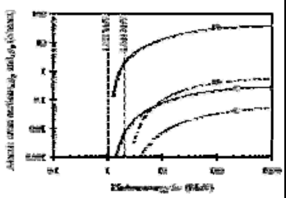



$m_e c^2 = 0.511\ \text{MeV}$



## 1.4 PHOTON INTERACTIONS
### 1.4.7 Pair production

- The atomic cross sections for pair production and triplet production equal zero for photon energies below the threshold energy.
- The atomic cross section for pair production and triplet production increase rapidly with photon energy above the threshold energy.



Atomic cross sections for pair production: **solid curves**

Atomic cross sections for triplet production: **dashed curves**



## 1.4 PHOTON INTERACTIONS
### 1.4.7 Pair production

- The mass attenuation coefficient for pair production $(\kappa/\rho)^{pp}$ varies approximately linearly with $Z$, the atomic number of the absorber.
- The mass attenuation coefficient for triplet production $(\kappa/\rho)^{tp}$ is essentially independent of the atomic number $Z$ of the absorber.

## 1.4 PHOTON INTERACTIONS
### 1.4.7 Pair production

- The attenuation coefficient for pair production exceeds significantly the attenuation coefficient for triplet production at same photon energy and atomic number of absorber.
- ${}_a\kappa^{\text{tp}}$ is at most about 30% of ${}_a\kappa^{\text{pp}}$ for $Z$ = 1 and less than 1% for high Z absorbers.
- Usually, the tabulated values for pair production include both the pair production in the field of the nucleus and the pair production in the field of electron.



## 1.4 PHOTON INTERACTIONS
### 1.4.7 Pair production

- The total kinetic energy transferred from the photon to charged particles (electron and positron) in pair production is $h\nu - 2m_ec^2$
- The mass attenuation coefficient $\kappa/\rho$ is calculated from the atomic cross section ${}_a\kappa$

$$\frac{\kappa}{\rho} = {}_a\kappa \frac{N_A}{A}$$

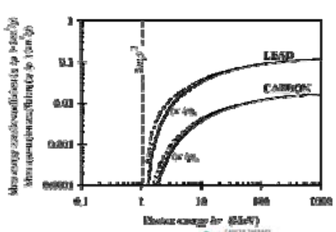
- The mass energy transfer coefficient $(\kappa/\rho)_{tr}$ is:

$$\left(\frac{\kappa}{\rho}\right)_{tr} = f_\kappa \frac{\kappa}{\rho} = \frac{\kappa}{\rho}\left(1 - \frac{2m_ec^2}{h\nu}\right)$$



## 1.4 PHOTON INTERACTIONS
### 1.4.7 Pair production

- The mass attenuation coefficient $\kappa/\rho$ and the mass energy transfer coefficient $(\kappa/\rho)_{tr}$ for pair production against photon energy $h\nu$.




Mass attenuation coefficient: **dashed curves**

Mass energy transfer coefficient: **solid curves**

## 1.4 PHOTON INTERACTIONS
### 1.4.8 Photonuclear reactions

- Photonuclear reactions (photodisintegration):
  - A high energy photon is absorbed by the nucleus of the absorber.
  - A neutron or a proton is emitted.
  - The absorber atom is transformed into a radioactive reaction product.
- The threshold is of the order of ≈10 MeV or higher, with the exception of the deuteron and beryllium-9 (≈2 MeV).
- The probability for photonuclear reactions is much smaller than that for other photon atomic interactions; photonuclear reactions are thus usually neglected in medical physics.



## 1.4 PHOTON INTERACTIONS
### 1.4.9 Contribution to attenuation coefficients

- For a given $h\nu$ and $Z$:
  - the linear attenuation coefficient $\mu$
  - the linear energy transfer coefficient $\mu_{tr}$
  - the linear energy absorption coefficient $\mu_{ab}$ (often designated $\mu_{en}$)

  are given as a sum of coefficients for individual photon interactions.

$$\mu = \tau + \sigma_R + \sigma_c + \kappa$$

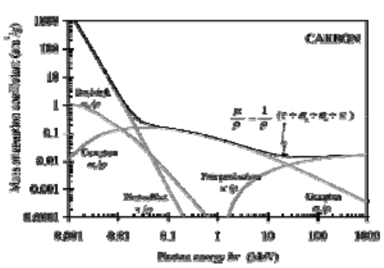
$$\mu_{tr} = \tau_{tr} + (\sigma_R)_{tr} + (\sigma_c)_{tr} + \kappa_{tr} = f_\tau \, \tau + f_c \, \sigma_c + f_\kappa \, \kappa$$

$$\mu_{ab} \equiv \mu_{en} = \mu_{tr}(1 - \bar{g})$$



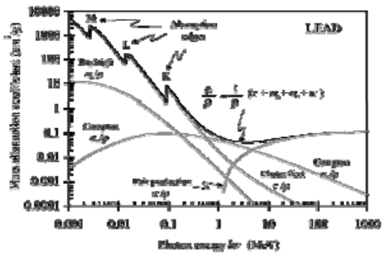
## 1.4 PHOTON INTERACTIONS
### 1.4.9 Contribution to attenuation coefficients

Mass attenuation coefficient against photon energy for carbon



## 1.4 PHOTON INTERACTIONS
### 1.4.9 Contribution to attenuation coefficients

- Mass attenuation coefficient against photon energy for lead





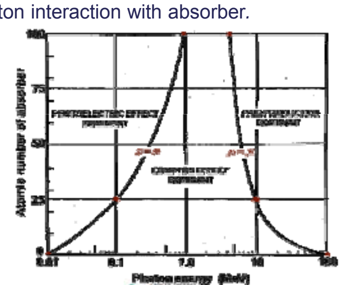

## 1.4 PHOTON INTERACTIONS
### 1.4.10 Relative predominance of individual effects

- The probability for a photon to undergo any one of the various interaction phenomena with an atom of the absorber depends:
- On the energy $h\nu$ of the photon
  - On the atomic number *Z* of the absorber
- In general,
  - Photoelectric effect predominates at low photon energies.
  - Compton effect predominates at intermediate photon energies.
  - Pair production predominates at high photon energies.



## 1.4 PHOTON INTERACTIONS
### 1.4.10 Relative predominance of individual effects

- Regions of relative predominance of the three main forms of photon interaction with absorber.



## 1.4 PHOTON INTERACTIONS

### 1.4.11 Effects following photon interactions

- In photoelectric effect, Compton scattering and triplet production vacancies are produced in atomic shells through ejection of an orbital electron.
  - The vacancies are filled with orbital electrons making transitions from higher to lower level atomic shells.
  - The electronic transitions are followed by emission of characteristic x rays or Auger electrons; the proportion governed by the fluorescent yield.



## 1.4 PHOTON INTERACTIONS

### 1.4.11 Effects following photon interactions

- Pair production and triplet production are followed by the annihilation of the positron, which lost almost all its kinetic energy through Coulomb interactions with absorber atoms, with a "free" electron producing two annihilation quanta.
  - The two annihilation quanta have most commonly an energy of 0.511 MeV each, and are emitted at approx-imately 180º to each other to satisfy the conservation of momentum and energy.
  - Annihilation may also occur of an energetic positron with an electron and this rare event is referred to as annihilation-in-flight.



## 1.4 PHOTON INTERACTIONS

### 1.4.12 Summary of photon interactions

| | *Photoelectric effect* | *Rayleigh scattering* | *Compton effect* | *Pair production* |
|---|---|---|---|---|
| *Photon interaction* | With whole atom (bound electron) | With bound electrons | With free electrons | With nuclear Coulomb field |
| *Mode of photon interaction* | Photon disappears | Photon scattered | Photon scattered | Photon disappears |
| *Energy dependence* | $\frac{1}{(h\nu)^3}$ | $\frac{1}{(h\nu)^2}$ | Decreases with energy | Increases with energy |
| *Threshold* | Shell binding energy | No | Shell binding energy | $\approx 2m_ec^2$ |
| *Linear attenuation coefficient* | $\tau$ | $\sigma_R$ | $\sigma_c$ | $\kappa$ |
| *Atomic coefficient dependence on Z* | ${}_a\tau \propto Z^4$ | ${}_a\sigma_R \propto Z^2$ | ${}_a\sigma_c \propto Z$ | ${}_a\kappa \propto Z^2$ |
| *Mass coefficient dependence on Z* | $\frac{\tau}{\rho} \propto Z^3$ | $\frac{\sigma_R}{\rho} \propto Z$ | Independent of Z | $\frac{\kappa}{\rho} \propto Z$ |

## 1.4 PHOTON INTERACTIONS
### 1.4.12 Summary of photon interactions

| | Photoelectric effect | Rayleigh scattering | Compton effect | Pair production |
|---|---|---|---|---|
| Particles released in absorber | Photoelectron | None | Compton (recoil) electron | Electron-positron pair |
| Average energy transferred to charged particles | $h\nu - P_K \omega_K E_B(K)$ | 0 | $\bar{E}_{tr}^{C}$ (from the Graph) | $h\nu - 2m_ec^2$ |
| Fraction of energy $f$ transferred | $f = 1 - \frac{P_K \omega_K \overline{h\nu}_K}{h\nu}$ | 0 | $f = \frac{\bar{E}_{tr}^{C}}{h\nu}$ | $f = 1 - \frac{2m_ec^2}{h\nu}$ |
| Subsequent effect | Characteristic x ray, Auger effect | None | Characteristic x ray, Auger effect | Annihilation radiation |
| Significant energy region for water | < 20 keV | < 20 keV | 20 keV – 10 MeV | > 10 MeV |



## 1.4 PHOTON INTERACTIONS
### 1.4.14 Production of vacancies in atomic shells

- There are 8 main means for producing vacancies in atomic shells and transforming the atom from a neutral state into an excited positive ion:
  - Coulomb interaction (1) of energetic charged particle with orbital electron
  - Photon interactions
    - Photoelectric effect (2)
    - Compton effect (3)
    - Triplet production (4)
  - Nuclear decay
    - Electron capture (5)
    - Internal conversion (6)
  - Positron annihilation (7)
  - Auger effect (8)



## 1.4 PHOTON INTERACTIONS
### 1.4.14 Production of vacancies in atomic shells

- Pair production does not produce shell vacancies, because the electron-positron pair is produced in the field of the nucleus.
- Vacancies in inner atomic shells are not stable; they are followed by emission of:
  - Characteristic photons
    
    or
  - Auger electrons

  and cascade to the outer shell of the ionized atom.
- The ion eventually attracts an electron from its surroundings and reverts to a neutral atom.