CHAPTER 1.

BASIC RADIATION PHYSICS

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1.1. INTRODUCTION

1.1.1. Fundamental physical constants

- Avogadro's number : N_A = 6.022×10^{23} atoms/g-atom
- Avogadro's number : N_A = 6.022×10^{23} molecules/g-mole
- speed of light in vacuum : c = 299 792 458 m/s ($\approx 3\times10^8$ m/s)
- electron charge : e = 1.602×10^{-19} C
- electron rest mass : m_{e^-} = 0.511 MeV/c^2
- positron rest mass : m_{e^+} = 0.511 MeV/c^2
- proton rest mass : m_p = 938.3 MeV/c^2
- neutron rest mass : m_n = 939.6 MeV/c^2
- atomic mass unit : u = 931.5 MeV/c^2
- Planck's constant : h = 6.626×10^{-34} J·s
- permittivity of vacuum : ε_o = 8.854×10^{-12} C/(V·m)
- permeability of vacuum : μ_o = $4\pi\times10^{-7}$ (V·s)/(A·m)
- Newtonian gravitation constant : G = 6.672×10^{-11} $m^3\cdot kg^{-1}\cdot s^{-2}$
- proton mass / electron mass : m_p / m_e = 1837
- specific charge of electron : e / m_e = 1.758×10^{11} C·kg^{-1}

1.1.2. Important derived physical constants and relationships

- Speed of light in vacuum:

$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}} \approx 3 \times 10^8 \text{ m/s} \tag{1.1}$$

- Planck's constant × speed of light in vacuum:

$$\hbar c = \frac{h}{2\pi} c = 197 \text{ MeV} \cdot \text{fm} \approx 200 \text{ MeV} \cdot \text{fm} \tag{1.2}$$

- Fine structure constant:

$$\alpha = \frac{e^2}{4\pi\varepsilon_o} \frac{1}{\hbar c} = \frac{1}{137} \tag{1.3}$$

- Bohr radius:

$$r_H = \frac{\hbar c}{\alpha \, m_e c^2} = \frac{4\pi\varepsilon_o}{e^2} \frac{(\hbar c)^2}{m_e c^2} = 0.529 \text{ Å} \tag{1.4}$$

- Bohr energy:

$$E_H = \frac{1}{2} m_e c^2 \alpha^2 = \frac{1}{2} \left[\frac{e^2}{4\pi\varepsilon_o} \right]^2 \frac{m_e c^2}{(\hbar c)^2} = 13.61 \text{ eV} \tag{1.5}$$

- Rydberg constant:

$$R_\infty = \frac{E_H}{2\pi\hbar c} \frac{m_e c^2 \ \alpha^2}{4\pi \ \hbar c} = \frac{1}{4\pi} \left[\frac{e^2}{4\pi\varepsilon_o} \right]^2 \frac{m_e c^2}{(\hbar c)^3} = 109\ 737 \text{ cm}^{-1} \tag{1.6}$$

- Classical electron radius:

$$r_e = \frac{e^2}{4\pi\varepsilon_o m_e c^2} = 2.818 \text{ fm} \tag{1.7}$$

- Compton wavelength of the electron:

$$\lambda_C = \frac{h}{m_e c} = 0.0243 \text{ Å} \tag{1.8}$$

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 kg; *E* = 15 MeV**).

- The numerical value and the unit of a physical quantity must be separated by space (for example: **21 kg and not 21kg; 15 MeV and not 15MeV**).

- The currently used metric system of units is known as the Système International d'Unités (International System of Units) with the international abbreviation SI. The system is founded on base units for seven basic physical quantities:

Length ℓ	:	meter (m)
Mass m	:	kilogram (kg)
Time t	:	second (s)
Electric current I	:	ampere (A)
Temperature T	:	kelvin (K)
Amount of substance	:	mole (mol)
Luminous intensity	:	candela (cd)

All other quantities and units are derived from the seven base quantities and units.

TABLE 1.I. BASIC AND DERIVED PHYSICAL QUANTITIES AND THEIR UNITS IN *SYSTÈME INTERNATIONAL (SI)* AND IN RADIATION PHYSICS.

Physical quantity	*Symbol*	*Units in SI*	*Units used in radiation physics*	*Conversion*
Length	ℓ	m	nm, Å, fm	$1\ \text{m} = 10^9\ \text{nm} = 10^{10}\ \text{Å} = 10^{15}\ \text{fm}$
Mass	m	kg	MeV/c^2	$1\ \text{MeV}/c^2 = 1.78\times10^{-30}\ \text{kg}$
Time	t	s	ms, μs, ns, ps	$1\ \text{s} = 10^3\ \text{ms} = 10^6\ \mu\text{s} = 10^9\ \text{ns} = 10^{12}\ \text{ps}$
Current	I	A	mA, μA, nA, pA	$1\ \text{A} = 10^3\ \text{mA} = 10^6\ \mu\text{A} = 10^9\ \text{nA}$
Charge	Q	C	e	$1\ \text{e} = 1.602\times10^{-19}\ \text{C}$
Force	F	N		$1\ \text{N} = 1\ \text{kg}\cdot\text{m}\cdot\text{s}^{-2}$
Momentum	p	$\text{N}\cdot\text{s}$		$1\ \text{N}\cdot\text{s} = 1\ \text{kg}\cdot\text{m}\cdot\text{s}^{-1}$
Energy	E	J	eV, keV, MeV	$1\ \text{eV} = 1.602\times10^{-19}\ \text{J} = 10^{-3}\ \text{keV}$

1.1.4. Classification of forces in nature

There are four distinct forces observed in the interaction between various types of particles (see Table 1.II). These forces, listed in decreasing order of strength, are the *strong*, *electromagnetic (EM), weak* and *gravitational* force with relative strengths of 1, 1/137, 10^{-6}, and 10^{-39}, respectively.

- The ranges of the EM and gravitational forces are infinite ($1/r^2$ dependence where r is the separation between two interacting particles).

- The ranges of the strong and weak forces are extremely short (on the order of a few fm).

Each force results from a particular intrinsic property of the particles, such as:

- strong charge for the strong force transmitted by mass-less particles called gluons;
- electric charge for the EM force transmitted by photons;
- weak charge for the weak force transmitted by particles called W and Z^o;
- energy for the gravitational force transmitted by a hypothetical particles called gravitons.

1.1.5. Classification of fundamental particles

Two classes of fundamental particles are known: *quarks* and *leptons.*

- *Quarks* are particles that exhibit strong interactions. They are constituents of hadrons (protons and neutrons) with a fractional electric charge (2/3 or – 1/3) and are characterized by one of three types of strong charge called colour (red, blue, green). Currently there are five known quarks: up, down, strange, charm, bottom.

- *Leptons* are particles that do not interact strongly. Electron, muon, tau and their corresponding neutrinos are in this category.

TABLE 1.II. THE FOUR FUNDAMENTAL FORCES IN NATURE

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

1.1.6. Classification of radiation

Radiation is classified into two main categories: *non-ionizing* and *ionizing*, depending on its ability to ionize matter. The ionisation potential of atoms, *i.e*., the minimum energy required to ionize an atom, ranges from a few eV for alkali elements to 24.5 eV for helium (noble gas).

- *Non-ionizing radiation* (cannot ionize matter)
- *Ionizing radiation* (can ionize matter either directly or indirectly)
  - Directly ionizing radiation (charged particles)
    electrons, protons, alpha particles, heavy ions
  - Indirectly ionizing radiation (neutral particles)
    photons (x rays, gamma rays), neutrons

Directly ionizing radiation deposits energy in the medium through direct Coulomb interactions between the directly ionizing charged particle and orbital electrons of atoms in the medium.

Indirectly ionizing radiation (photons or neutrons) deposits energy in the medium through a two step process:

- In the first step a charged particle is released in the medium (photons release electrons or positrons, neutrons release protons or heavier ions).
- In the second step, the released charged particles deposit energy to the medium through direct Coulomb interactions with orbital electrons of the atoms in the medium.

Both directly and indirectly ionizing radiations are used in treatment of disease, mainly but not exclusively malignant disease. The branch of medicine that uses radiation in treatment of disease is called *radiotherapy*, *therapeutic radiology* or *radiation oncology*. Diagnostic radiology and nuclear medicine are branches of medicine that use ionizing radiation in diagnosis of disease.

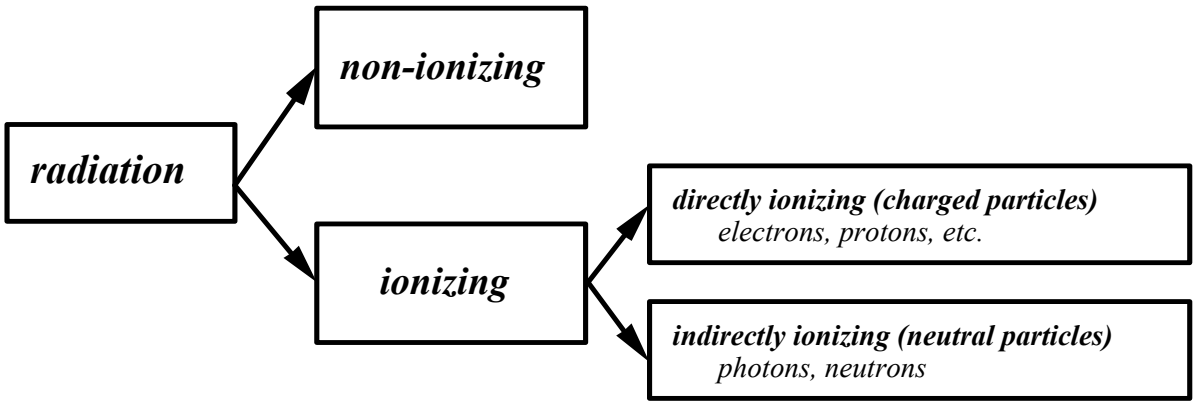

FIG. 1.1. Classification of radiation.

1.1.7. Classification of ionizing photon radiation

- *Characteristic x rays:*
  result from electron transitions between atomic shells

- *Bremsstrahlung:*
  results from electron-nucleus Coulomb interactions

- *Gamma rays:*
  result from nuclear transitions

- *Annihilation quanta:*
  result from positron-electron annihilation

1.1.8. Einstein's relativistic mass, energy, and momentum relationships:

- $$m(v) = \frac{m_o}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{m_o}{\sqrt{1-\beta^2}} = \gamma\, m_o \quad , \tag{1.9}$$

- $$E = m(v)c^2 \quad , \tag{1.10}$$

- $$E_o = m_o c^2 \quad , \tag{1.11}$$

- $$KE = E - E_o = (\gamma - 1) E_o \quad , \tag{1.12}$$

- $$E^2 = E_o^2 + p^2 c^2 \quad , \tag{1.13}$$

  where

  v is the particle velocity,
  c is the speed of light in vacuum,
  $m(v)$ is the particle mass at velocity v,
  m_o is the particle rest mass (at velocity $v = 0$),
  E is the total energy of the particle,
  E_o is the rest energy of the particle,
  KE is the kinetic energy of the particle,
  p is the momentum of the particle.

- For photons $E = h\nu$ and $E_o = 0$, thus using E. (1.13) we get $p = h\nu / c = h / \lambda$, with ν and λ the photon frequency and wavelength, respectively.

1.1.9. Radiation quantities and units

The most important radiation quantities and their units are listed in Table 1.III. Also listed are the definitions for the various quantities and the relationships between the old and the SI units for these quantities.

TABLE 1.III. RADIATION QUANTITIES, UNITS, AND CONVERSION BETWEEN OLD AND SI UNITS.

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

where

ΔQ	is the charge of either sign collected,
Δm_{air}	is the mass of air,
ΔE_{ab}	is the absorbed energy,
Δm	is the mass of medium,
w_{R}	is the radiation weighing factor,
λ	is the the decay constant,
N	is the number of radioactive atoms,
R	stands for roentgen,
Gy	stands for for gray,
Sv	stands for for sievert,
Bq	stands for for becquerel,
Ci	stands for curie,
STP	stands for standard temperature (273.2 K) and standard pressure (101.3 kPa).

1.2. ATOMIC AND NUCLEAR STRUCTURE

1.2.1. Basic definitions for atomic structure

- The constituent particles forming an atom are protons, neutrons and electrons. Protons and neutrons are known as nucleons and form the nucleus of the atom.

- ***Atomic number*** *Z:* number of protons and number of electrons in an atom.

- ***Atomic mass number*** *A:* number of nucleons in an atom, *i.e.*, number of protons Z plus number of neutrons N in an atom; *i.e.*, $A = Z + N$

- There is no basic relation between A and Z, but the empirical relationship

$$Z = \frac{A}{1.98 + 0.0155A^{2/3}} \tag{1.14}$$

furnishes a good approximation for stable nuclei.

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

- ***Atomic g-atom*** *(gram-atom):* number of grams that correspond to N_A atoms of an element, where $N_A = 6.022 \times 10^{23}$ atoms/g-atom (Avogadro's number). The atomic mass numbers of all elements are defined so that A grams of every element contain exactly N_A atoms.

  For example: 1 g-atom of cobalt-60 is 60 g of cobalt-60 or in 60 g of cobalt-60 there is Avogadro's number of atoms.

- Number of atoms N_a per mass of an element: $\frac{N_a}{m} = \frac{N_A}{A}$

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

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

  Note that $(Z/A) \approx 0.5$ for all elements with one notable exception of hydrogen for which $(Z/A) = 1$. Actually, Z/A slowly decreases from 0.5 for low Z elements to 0.4 for high Z elements.

- In nuclear physics the convention is to designate a nucleus X as ${}^{A}_{Z}\mathrm{X}$, where A is the atomic mass number and Z the atomic number. For example, the cobalt-60 nucleus is identified as ${}^{60}_{27}\mathrm{Co}$, the radium-226 nucleus as ${}^{226}_{88}\mathrm{Ra}$.

- In ion physics the convention is to designate ions with + or – superscripts. For example, ${}^{4}_{2}\mathrm{He}^{+}$ stands for a singly ionized helium-4 atom and ${}^{4}_{2}\mathrm{He}^{2+}$ stands for a doubly ionized helium-4 atom which is the alpha particle.

- If we assume that the mass of a molecule is equal to the sum of the masses of the atoms that make up the molecule, then for any molecular compound there are N_A molecules per g-mole of the compound where the ***g-mole*** (gram-mole or *mole*) in grams is defined as the sum of the atomic mass numbers of the atoms making up the molecule. For example, a g-mole of water H_2O is 18 g of water and a g-mole of carbon dioxide CO_2 is 44 g of carbon dioxide. Thus, 18 g of water or 44 g of carbon dioxide contain exactly N_A molecules (or $3N_A$ atoms, since each molecule of water and carbon dioxide contains three atoms).

1.2.2. Rutherford's model of the atom

- The model is based on results of an experiment, carried out by Geiger and Marsden in 1912, with alpha particles scattered on thin gold foils. The experiment tested the validity of the Thomson atomic model which postulated that the positive charges and negative electrons were uniformly distributed over the spherical atomic volume, the radius of which was on the order of a few Å. Theoretical calculations predict that the probability for an alpha particle to be scattered on such an atom with a scattering angle exceeding 90^o is of the order of 10^{-3500}, while the Geiger-Marsden experiment showed that approximately 1 in 10^4 alpha particles was scattered with a scattering angle $\theta > 90^o$ (probability 10^{-4}).

- From the findings of the Geiger-Marsden experiment Rutherford concluded that the positive charge and most of the mass of the atom are concentrated in the atomic nucleus (diameter: few fm) and negative electrons are smeared over on the periphery of the atom (diameter: few Å).

- In α particle scattering the positively charged α particle has a repulsive Coulomb interaction with the more massive and positively charged nucleus. The interaction produces a hyperbolic trajectory of the α particle and the scattering angle θ is a function of the impact parameter b. The limiting case is a direct hit with $b = 0$ and $\theta = \pi$ (backscattering), that, assuming conservation of energy, determines the distance of closest approach $D_{\alpha\text{-N}}$ in the backscattering interaction:

$$KE_\alpha = \frac{z_\alpha Z_N e^2}{4\pi\varepsilon_o D_{\alpha-N}} \quad \Rightarrow \quad D_{\alpha-N} = \frac{z_\alpha Z_N e^2}{4\pi\varepsilon_o KE_\alpha} \quad , \tag{1.15}$$

where

z_α is the atomic number of the α particle,
Z_N is the atomic number of the scattering material, and
KE_α is the initial kinetic energy of the alpha particle.

- The repulsive Coulomb force between the α particle (charge +2e) and the nucleus (charge +Ze) is governed by $1/r^2$ as follows:

$$F_{Coul} = \frac{2Ze^2}{4\pi\varepsilon_o r^2} \quad , \tag{1.16}$$

resulting in the following b *vs* θ relationship:

$$b = \frac{1}{2} D_{\alpha-N} \cot\frac{\theta}{2} \quad . \tag{1.17}$$

- The differential Rutherford scattering cross-section is then expressed as follows:

$$\left(\frac{d\sigma}{d\Omega}\right)_R = \left[\frac{D_{\alpha-N}}{4}\right]^2 \frac{1}{\sin^4(\theta/2)} \quad . \tag{1.18}$$

1.2.3. Bohr's model of hydrogen atom

- Bohr expanded Rutherford's atomic model in 1913 and based it on four postulates that combine classical, non-relativistic mechanics with the concept of angular momentum quantization. Bohr's model successfully deals with one-electron entities, such as the hydrogen atom, singly ionized helium atom, doubly ionized lithium atom, etc.

- The four Bohr postulates are as follows:

  - *Postulate* 1:
    Electrons revolve about the Rutherford nucleus in well-defined, allowed orbits (shells). The Coulomb force of attraction $F_{\text{Coul}} = Ze^2/(4\pi\varepsilon_o r^2)$ between the negative electrons and the positively charged nucleus is balanced by the centrifugal force $F_{\text{cent}} = m_e v^2/r$, where Z is the number of protons in the nucleus (atomic number); r the radius of the orbit; m_e the electron mass; and v the velocity of the electron in the orbit.

  - *Postulate* 2:
    While in orbit, the electron does not lose any energy despite being constantly accelerated (this postulate is in contravention of the basic law of nature which states that an accelerated charged particle will lose part of its energy in the form of radiation).

  - *Postulate* 3:
    The angular momentum $L = m_e vr$ of the electron in an allowed orbit is quantized and given as $L = n\hbar$, where n is an integer referred to as the principal quantum number and $\hbar = h/(2\pi)$ with h the Planck's constant. The simple quantization of angular momentum stipulates that the angular momentum can have only integral multiples of a basic value ($\hbar$).

  - *Postulate* 4:
    An atom or ion emits radiation when an electron makes a transition from an initial orbit with quantum number n_i to a final orbit with quantum number n_f for $n_i > n_f$.

- *Radius* of a one-electron Bohr atom is given by:

$$r_n = r_H\left(\frac{n^2}{Z}\right) = 0.53 \text{ Å}\left(\frac{n^2}{Z}\right). \tag{1.19}$$

- *Velocity* of the electron in a one-electron Bohr atom is:

$$v_n = \alpha c\left(\frac{Z}{n}\right) = \frac{c}{137}\left(\frac{Z}{n}\right), \tag{1.20}$$

where α is the fine structure constant.

- *Energy levels* for orbital electron shells in mono-electronic atoms (for example: hydrogen, singly-ionized helium, doubly-ionized lithium, etc.) are given by:

$$E_{\mathrm{n}} = -E_{\mathrm{H}}\left(\frac{Z}{n}\right)^2 = -13.6\ \mathrm{eV}\left(\frac{Z}{n}\right)^2 \quad , \tag{1.21}$$

where

n is the principal quantum number (n = 1, ground state; n >1, excited state),
Z is the atomic number (Z = 1 for hydrogen atom, Z = 2 for singly-ionized helium, Z = 3 for doubly-ionized lithium, etc.).

- The *wave-number k* of the emitted photon is given by:

$$k = \frac{1}{\lambda} = R_\infty Z^2\left(\frac{1}{n_{\mathrm{f}}^2} - \frac{1}{n_{\mathrm{i}}^2}\right) = 109\ 737\ \mathrm{cm}^{-1}\ Z^2\left(\frac{1}{n_{\mathrm{f}}^2} - \frac{1}{n_{\mathrm{i}}^2}\right) \quad , \tag{1.22}$$

where R_∞ is the Rydberg constant.

- Bohr's model results in the following energy level diagram for the hydrogen atom.

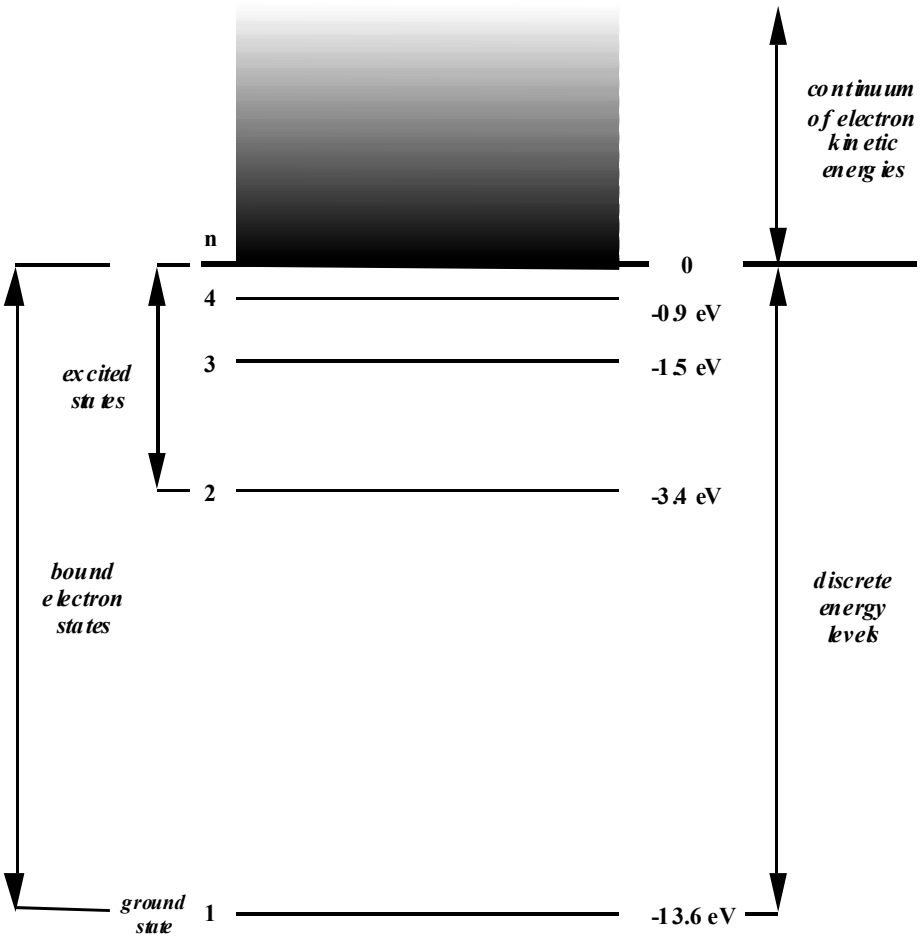

FIG. 1.2. Energy level diagram for hydrogen atom (ground state: n=1, excited state: n > 1).

1.2.4. Multi-electron atoms

- For multi-electron atoms the fundamental concepts of the Bohr atomic theory provide qualitative data for orbital electron binding energies and electron transitions resulting in emission of photons.

- Electrons occupy allowed shells, but the number of electrons per shell is limited to $2n^2$ where n is the shell number (principal quantum number).

- The K-shell binding energies BE_K for atoms with $Z > 20$ may be estimated with the following relationship:

$$BE_K(Z) = E_H Z_{eff}^2 = E_H(Z-s)^2 = E_H(Z-2)^2 \quad , \tag{1.23}$$

where Z_{eff}, the effective atomic number, is given by $Z_{eff} = Z - s$, with s the screening constant equal to 2 for K-shell electrons.

- Excitation of an atom occurs when an electron is moved from a given shell to a higher n shell that is either empty or does not contain a full complement of electrons.

- Ionisation of an atom occurs when an electron is removed from the atom, *i.e*., the electron is supplied with enough energy to overcome its binding energy in a shell.

- Excitation and ionisation processes occur in an atom through various possible interactions in which orbital electrons are supplied a given amount of energy. Some of these interactions are: (1) *Coulomb interaction* with a charged particle; (2) *photoeffect*; (3) *Compton effect*; (4) *triplet production*; (5) *internal conversion*; (6) *electron capture*; (7) *Auger effect*; and (8) *positron annihilation*.

- An orbital electron from a higher n shell will fill an electron vacancy in a lower n atomic shell. The energy difference between the two shells will be either emitted in the form of a *characteristic photon* or it will be transferred to a higher n shell electron that will be ejected from the atom as an *Auger electron*.

- Energy level diagrams of multi-electron atoms resemble those of one-electron structures, except that inner shell electrons are bound with much larger energies, as shown for a lead atom in Fig. 1.3.

- The number of characteristic photons (sometimes called fluorescent photons) emitted per orbital electron shell vacancy is referred to as *fluorescent yield* ω, while the number of Auger electrons emitted per orbital electron vacancy is equal to $(1-\omega)$. The fluorescent yield depends on the atomic number Z of the atom and on the principal quantum number of a shell. For atoms with $Z < 10$ the fluorescent yield $\omega_K = 0$; for $Z \approx 30$ the fluorescent yield $\omega_K \approx 0.5$; and for high atomic number atoms $\omega_K = 0.96$, where ω_K refers to the fluorescent yield for the K shell (see Fig. 1.9 in Section 1.4.11).

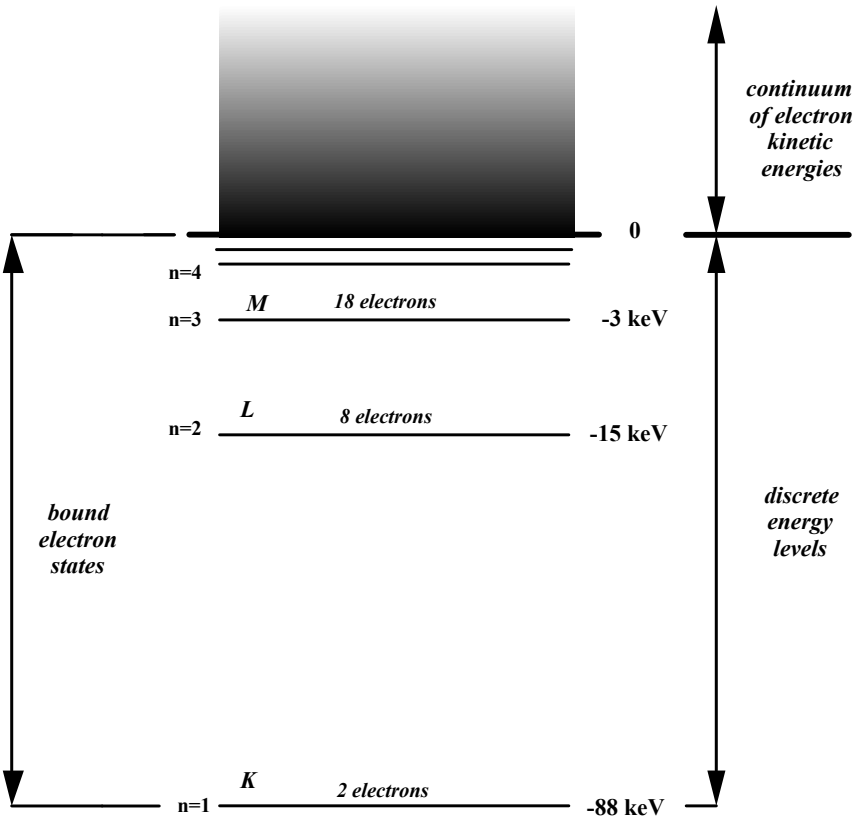

FIG. 1.3. Energy level diagram for a multi-electron atom (lead). The n = 1, 2, 3, 4..... shells are referred to as the K, L, M, O.... shells, respectively. Electronic transitions that end in low n shells are referred to as x-ray transitions because the resulting photons are in the x-ray energy range. Electronic transitions that end in high n shells are referred to as optical transitions because they result in ultraviolet, visible or infrared photons.

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 of a given nucleus.

- *Radius r* of the nucleus is estimated from:

$$r = r_o \sqrt[3]{A} \quad , \tag{1.24}$$

  with r_o a constant (~ 1.2 fm).

- Protons and neutrons are commonly referred to as nucleons and are bound to the nucleus with the *strong force*. In contrast to electrostatic and gravitational forces that are inversely proportional to the square of the distance between two particles, the strong force between two nucleons is a very short-range force, active only at distances on the order of a few fm. At these short distances the strong force is the predominant force exceeding other forces by several orders of magnitude.

- The *binding energy BE* per nucleon in a nucleus varies with the number of nucleons A and is on the order of ~8 MeV/nucleon. It may be calculated from the energy equivalent of the mass deficit Δm as follows:

$$\frac{BE}{\text{nucleon}} = \Delta mc^2 / A = \left[Zm_{\text{p}}c^2 + (A-Z)m_{\text{n}}c^2 - Mc^2 \right] / A \ , \tag{1.25}$$

where

M is the nuclear mass in atomic mass units u,
$m_{\text{p}}c^2$ is the proton rest energy,
$m_{\text{n}}c^2$ is the neutron rest energy.

1.2.6. Nuclear reactions

Much of the present knowledge of the structure of nuclei comes from experiments in which a particular nuclide A is bombarded with a projectile a. The projectile undergoes one of three possible interactions: (i) *elastic scattering* - no energy transfer occurs, however, the projectile changes trajectory; (ii) *inelastic scattering* - the projectile enters the nucleus and is re-emitted with less energy and in a different direction; and (iii) *nuclear reaction* - the projectile a enters the nucleus A which is transformed into nucleus B and a different particle b is emitted.

- Nuclear reactions are designated as follows:

$$a + A \rightarrow B + b \qquad \text{or} \qquad A(a,b)B \ , \tag{1.26}$$

- A number of physical quantities are rigorously conserved in all nuclear reactions. The most important of these quantities are: charge, mass number, linear momentum, and mass-energy.

- Threshold energy for a nuclear reaction is defined as the smallest value of projectile's kinetic energy at which a nuclear reaction can take place. The threshold kinetic energy of projectile a is derived from relativistic conservation of energy and momentum as:

$$KE_{\text{thr}}(a) = \frac{(m_{\text{B}}c^2 + m_{\text{b}}c^2)^2 - (m_{\text{A}}c^2 + m_{\text{a}}c^2)^2}{2m_{\text{A}}c^2}, \tag{1.27}$$

with m_{A}, m_{a}, m_{B}, and m_{b} the rest masses of the target A, projectile a, and products B and b, respectively.

1.2.7. Radioactivity

Radioactivity is characterized by a transformation of an unstable nucleus into a more stable entity that itself may be unstable and will decay further through a chain of decays until a stable nuclear configuration is reached. The exponential laws that govern the decay and growth of radioactive substances were first formulated by Rutherford and Soddy in 1902 and then refined by Bateman in 1910.

- Activity $\mathcal{A}(t)$ of a radioactive substance at time t is defined as the product of the decay constant λ and the number of radioactive nuclei $N(t)$, i.e.,

$$\mathcal{A}(t) = \lambda N(t) . \tag{1.28}$$

- The simplest radioactive decay is characterized by a radioactive parent nucleus P decaying with a decay constant λ_P into a stable daughter nucleus D, *i.e.*,

$$P \xrightarrow{\lambda_P} D . \tag{1.29}$$

  - The number of radioactive parent nuclei $N_P(t)$ as a function of time t is governed by the following relationship:

$$N_P(t) = N_P(0)\, e^{-\lambda_P t} , \tag{1.30}$$

    where $N_P(0)$ is the initial number of parent nuclei at time $t = 0$.

  - Similarly, the activity of parent nuclei $\mathcal{A}_P(t)$ at time t is given as:

$$\mathcal{A}_P(t) = \mathcal{A}_P(0)\, e^{-\lambda_P t} , \tag{1.31}$$

    where $\mathcal{A}_P(0)$ is the initial activity of parent nuclei at time $t = 0$.

- Half-life $t_{1/2}$ of a radioactive substance is the time during which the number of radioactive nuclei decays to half of the initial value $N(0)$ present at time $t = 0$, *i.e.*,

$$N(t = t_{1/2}) = \frac{1}{2} N(0) = N(0) e^{-\lambda_P t_{1/2}} . \tag{1.32}$$

- The *decay constant* λ and half-life $t_{1/2}$ are thus related as follows:

$$\lambda = \frac{\ln 2}{t_{1/2}} . \tag{1.33}$$

- *Specific activity* a is defined as the activity per unit mass, i.e.,

$$a = \frac{\mathcal{A}}{m} = \frac{\lambda N}{m} = \lambda \frac{N_A}{A} = \frac{N_A \ln 2}{A\, t_{1/2}} , \tag{1.34}$$

  where N_A is Avogadro's number and A is the atomic mass number.

- *Average (mean) life* τ of a radioactive substance represents the average life expectancy of all radioactive atoms in the substance at time $t = 0$; *i.e.*,

$$\mathcal{A}(0)\tau = \int_o^\infty \mathcal{A}(0) e^{-\lambda t} dt = \frac{\mathcal{A}(0)}{\lambda} . \tag{1.35}$$

- The decay constant λ and average life τ are thus related as follows:

$$\lambda = 1/\tau \quad , \tag{1.36}$$

resulting in the following relationship between $t_{1/2}$ and τ:

$$t_{1/2} = \tau \ \ln 2 \ . \tag{1.37}$$

- A more complicated radioactive decay occurs when a radioactive parent nucleus *P* decays with a decay constant λ_P into a daughter nucleus *D* which in turn is radioactive and decays with a decay constant λ_D into a stable grand-daughter *G*, *i.e.*,

$$P \ \overset{\lambda_P}{\rightarrow} \ D \ \overset{\lambda_D}{\rightarrow} \ G \ . \tag{1.38}$$

  - The activity of the daughter $\mathcal{A}_D(t)$ may then be expressed as follows:

$$\mathcal{A}_D(t) = \frac{\lambda_D}{\lambda_D - \lambda_P} \mathcal{A}_P(0) \left\{ e^{-\lambda_P t} - e^{-\lambda_D t} \right\} \quad , \tag{1.39}$$

    where $\mathcal{A}_P(0)$ is the initial activity of the parent nuclei present at time $t = 0$, *i.e.*, $\mathcal{A}_P(0) = \lambda_P N_P(0)$ with $N_P(0)$ the number of parent nuclei at $t = 0$.

  - The maximum activity of daughter nuclei occurs at time t_{max} given by:

$$t_{max} = \frac{\ln \frac{\lambda_D}{\lambda_P}}{\lambda_D - \lambda_P} \quad , \tag{1.40}$$

    under the condition that $N_D = 0$ at time $t = 0$.

- Special considerations in *parent* $\rightarrow$ *daughter* $\rightarrow$ *grand-daughter* relationships:

  - For $\lambda_D < \lambda_P$ or $(t_{1/2})_D > (t_{1/2})_P$ we get the following general relationship:

$$\frac{\mathcal{A}_D}{\mathcal{A}_P} = \frac{\lambda_D}{\lambda_D - \lambda_P} \left\{ 1 - \ e^{-(\lambda_D - \lambda_P)t} \right\} \quad . \tag{1.41}$$

  - For $\lambda_D > \lambda_P$ or $(t_{1/2})_D < (t_{1/2})_P$ we get *transient equilibrium* with

$$\frac{\mathcal{A}_D}{\mathcal{A}_P} = \frac{\lambda_D}{\lambda_D - \lambda_P} \quad \text{for} \ \ t >> t_{max} \ . \tag{1.42}$$

  - For $\lambda_D >> \lambda_P$ or $(t_{1/2})_D << (t_{1/2})_P$ we get *secular equilibrium* and

$$\frac{\mathcal{A}_D}{\mathcal{A}_P} \approx 1 \quad . \tag{1.43}$$

1.2.8. Activation of isotopes

Activation of isotopes occurs when a stable parent isotope *P* is bombarded with neutrons in a nuclear reactor and transforms into a radioactive daughter *D* which decays into a grand-daughter *G*, *i.e.*,

$$P \xrightarrow{\sigma\phi} D \xrightarrow{\lambda_D} \mathrm{G} \quad . \tag{1.44}$$

The probability for activation is determined by the cross section for the nuclear reaction usually expressed in barns per atom where 1 barn = 10^{-24} cm^2.

- Activity of the daughter $\mathcal{A}_D(t)$ is expressed as:

$$\mathcal{A}_D(t) = \frac{\sigma\ \phi\ \lambda_D}{\lambda_D - \sigma\phi} N_P(0)\left[e^{-\sigma\phi t} - e^{-\lambda_D t}\right] \quad , \tag{1.45}$$

  where $N_P(0)$ is the initial number of parent nuclei.

- This result is similar to the $P \rightarrow D \rightarrow G$ relationship above (Eq. (1.39)) in which an unstable parent *P* decays into an unstable daughter *D* which in turn decays into grand-daughter *G*. However, the decay constant λ_P in the $P \rightarrow D \rightarrow G$ decay relationship is replaced by $\sigma\phi$, where σ is the cross-section for activation of parent nuclei (in cm^2/atom) and ϕ is the fluence rate of neutrons in the reactor (in neutrons$\cdot$cm$^{-2}\cdot$s^{-1}).

- The time t_{max} at which the maximum activity $\mathcal{A}_D$ occurs in the activation process is then, similarly to Eq. (1.40), given by:

$$t_{max} = \frac{\ln \frac{\lambda_D}{\sigma\phi}}{\lambda_D - \sigma\phi} \quad . \tag{1.46}$$

- In situations where $\sigma\phi << \lambda_D$, the daughter activity relationship transforms into a simple exponential growth relationship:

$$\mathcal{A}_D(t) = \sigma\ \phi\ N_P(0)\left[1 - e^{-\lambda_D t}\right] \quad . \tag{1.47}$$

- An important example of nuclear activation is the production of the cobalt-60 isotope through bombarding cobalt-59 with thermal neutrons in a nuclear reactor:

$$^{59}_{27}\mathrm{Co} + \mathrm{n} \rightarrow {}^{60}_{27}\mathrm{Co} + \gamma \quad , \tag{1.48}$$

  or in shorthand notation $^{59}_{27}\mathrm{Co}(\mathrm{n},\gamma)^{60}_{27}\mathrm{Co}$, with an activation cross-section σ of 37×10^{-24} cm^2/atom (37 barn/atom with 1 barn = 10^{-24} cm^2) and typical reactor neutron fluence rates ϕ on the order of 10^{13} neutrons$\cdot$cm$^{-2}\cdot$s^{-1}.

1.2.9. Modes of radioactive decay

Radioactive parent X with atomic number Z and atomic mass number A decays into a daughter Y through the following possible modes of decay: α, β^-, β^+, electron capture, γ, and internal conversion.

- *α decay*: $${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\mathrm{He}(\alpha) \ , \tag{1.49}$$

  where ${}^{4}_{2}\mathrm{He}(\alpha)$ is a helium-4 nucleus referred to as an α particle. An example of α decay is the decay of radium-226 into radon-222 with a half-life of 1600 years:

  $${}^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He} \ . \tag{1.50}$$

- *β^- decay:* $${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{Y} + \beta^- + \bar{\nu}_e \ : \tag{1.51}$$

  A neutron transforms into a proton, and an electron β^- and antineutrino $\bar{\nu}_e$, sharing the available energy, are ejected from the nucleus. An example of β^- decay is the decay of cobalt-60 nuclei into excited nickel-60 nuclei with a half-life of 5.26 years:

  $${}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni}^{*} + \beta^- + \bar{\nu}_e \ . \tag{1.52}$$

- *β^+ decay:* $${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + \beta^+ + \nu_e \ : \tag{1.53}$$

  A proton transforms into a neutron, and a positron β^+ and neutrino ν_e, sharing the available energy, are ejected from the nucleus. An example of β^+ decay is the decay of nitrogen-13 into carbon-13:

  $${}^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + \beta^+ + \nu_e \ . \tag{1.54}$$

- *Electron capture*: $${}^{A}_{Z}\mathrm{X} + e^-_{K} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + \nu_e : \tag{1.55}$$

  Nucleus captures one of its own K-shell orbital electrons, a proton transforms into a neutron, and a neutrino ν_e is ejected. An example of electron capture is the decay of iodine-125 into tellurium-125 in an excited state, which decays to tellurium-125 ground state through gamma decay and internal conversion:

  $${}^{125}_{53}\mathrm{I} + e^-_{K} \rightarrow {}^{125}_{52}\mathrm{Te}^{*} + \nu_e \ . \tag{1.56}$$

  The resulting K-shell vacancy is filled with a higher level orbital electron and the transition energy is emitted from the atom in the form of characteristic photons or Auger electrons.

- *γ decay*: $${}^{A}_{Z}\mathrm{X}^{*} \rightarrow {}^{A}_{Z}\mathrm{X} + \gamma \ : \tag{1.57}$$

  An excited nucleus ${}^{A}_{Z}\mathrm{X}^{*}$, generally produced through β^- or β^+ decay, attains its ground state ${}^{A}_{Z}\mathrm{X}$ through emission of one or several γ photons.

An example of gamma decay is the transition of the excited $^{60}_{28}Ni^{*}$, resulting from the β^- decay of cobalt-60, into stable $^{60}_{28}Ni$ through an emission of two gamma rays with energies of 1.17 and 1.33 MeV.

- *Internal conversion*: $^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + e^{-}_{K}$: (1.58)

  Rather than being emitted as a gamma photon, the nuclear excitation energy may be transferred to a K-shell orbital electron that is ejected with a kinetic energy equal to the excitation energy less the orbital electron binding energy. The resulting K-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. An example of internal conversion is the decay of excited tellurium-125, which results from an electron capture decay of iodine-125, into stable telurium-125 through emission of 35 keV gamma rays (7%) and internal conversion electrons (93%).

1.3. ELECTRON INTERACTIONS

As an energetic electron traverses matter, it interacts with matter through Coulomb interactions with atomic orbital electrons and atomic nuclei. Through these collisions the electrons may lose their kinetic energy (*collision* and *radiative losses*) or change their direction of travel (*scattering*). Energy losses are described by stopping power; scattering is described by scattering power.

The collisions between the incident electron and an orbital electron or nucleus of an atom may be elastic or inelastic. In an *elastic collision* the electron is deflected from its original path but no energy loss occurs, while in an *inelastic collision* the electron is deflected from its original path and some of its energy is transferred to an orbital electron or emitted in the form of bremsstrahlung. Energetic electrons experience thousands of collisions as they traverse an absorber; hence their behavior is described by a statistical theory of *multiple scattering* embracing the individual elastic and inelastic collisions with orbital electrons and nuclei.

The type of interaction that the electron undergoes with a particular atom of radius a depends on the impact parameter b of the interaction, defined as the perpendicular distance between the electron direction before the interaction and the atomic nucleus (see Fig. 1.4).

- For $b>>a$, the electron will undergo a *soft collision* with the whole atom and only a small amount of energy will be transferred from the incident electron to orbital electrons.

- For $b \approx a$, the electron will undergo a *hard collision* with an orbital electron and an appreciable fraction of the electron's kinetic energy will be transferred to the orbital electron.

- For $b<<a$, the incident electron undergoes a *radiative interaction (collision)* with the atomic nucleus. The electron will emit a photon (bremsstrahlung) with energy between zero and the incident electron kinetic energy. The energy of the emitted bremsstrahlung photon depends on the magnitude of the impact parameter b; the smaller the impact parameter, the higher the energy of the bremsstrahlung photon.

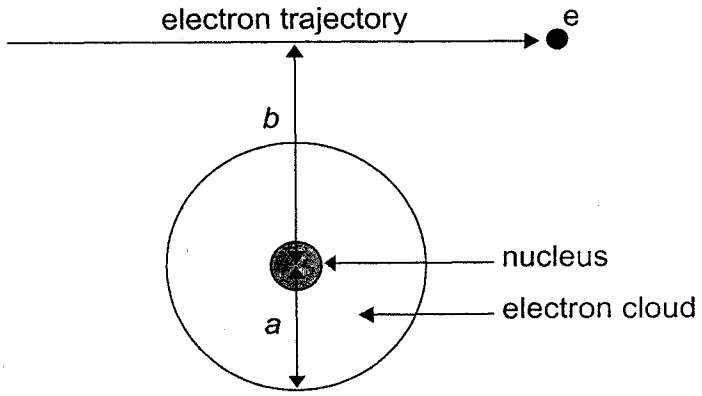

FIG. 1.4. Interaction of an electron with an atom, where a is the atomic radius and b the impact parameter.

1.3.1. Electron-orbital electron interactions

- Coulomb interactions between the incident electron and orbital electrons of an absorber result in ionisations and excitations of absorber atoms:

  - *Ionisation*: ejection of an orbital electron from absorber atom;

  - *Excitation*: transfer of an orbital electron of the absorber atom from an allowed orbit to a higher allowed orbit (shell);

- Atomic excitations and ionisations result in collisional energy losses and are characterized by *collision* (*ionisation*) *stopping powers*.

1.3.2. Electron-nucleus interactions

- Coulomb interactions between the incident electron and nuclei of the absorber atom result in electron scattering and energy loss of the electron through production of x-ray photons (bremsstrahlung). These types of energy losses are characterized by *radiative stopping powers.*

- Bremsstrahlung production is governed by the *Larmor relationship* which states that the power P emitted in the form of photons from an accelerated charged particle is proportional to the square of the particle acceleration a and the square of the particle charge q, or

$$P = \frac{q^2 a^2}{6\pi\varepsilon_o c^3} \quad . \tag{1.59}$$

- The angular distribution of the emitted photons (bremsstrahlung) is proportional to $\sin^2\theta/(1-\beta\cos\theta)^5$, where θ is the angle between the acceleration of the charged particle and a unit vector connecting the charge with the point of observation, and β is the standard relativistic v/c.

- At small velocities *v* of the charged particle ($\beta \to 0$) the angular distribution goes as $\sin^2\theta$ and exhibits a maximum at θ = 90°. However, as the velocity of the charged particle increases from 0 toward *c*, the angular distribution of the emitted photons becomes increasingly more forward-peaked.

- The angle at which the photon emission intensity is maximum can be calculated from the following relationship:

$$\theta_{\max} = \arccos\left[\frac{1}{3\beta}\left(\sqrt{1+15\beta}-1\right)\right] \quad , \tag{1.60}$$

  which for $\beta \to 0$ gives $\theta_{\max} = \pi/2$ and for $\beta \to 1$ gives $\theta_{\max} = 0$, indicating that in the diagnostic radiology energy range (orthovoltage beams) most x ray photons are emitted at 90° to the electron path, while in the megavoltage range (linac beams) most photons are emitted in the direction of the electron beam striking the target.

- The energy loss by radiation and the bremsstrahlung yield *g* increase directly with the absorber atomic number *Z* and the kinetic energy of electrons. The radiation yield for x-ray targets in the diagnostic radiology energy range (~100 keV) is of the order of 1%, while in the megavoltage energy range it amounts to 10-20%.

1.3.3. Stopping power

The inelastic energy losses by an electron moving through a medium with density ρ are described by the total mass energy stopping power $(S/\rho)_{\text{tot}}$ which represents the kinetic energy *KE* loss by the electron per unit path length *x*, or

$$(S/\rho)_{\text{tot}} = \frac{1}{\rho}\frac{d(KE)}{dx} \quad (\text{in MeV}\cdot\text{cm}^2/\text{g}) \quad . \tag{1.61}$$

$(S/\rho)_{\text{tot}}$ consists of two components: the *mass collision stopping power* $(S/\rho)_{\text{col}}$ resulting from electron-orbital electron interactions (atomic excitations and ionisations) and the *mass radiative stopping power* $(S/\rho)_{\text{rad}}$ resulting from electron-nucleus interactions (brems-strahlung production), *i.e.*,

$$(S/\rho)_{\text{tot}} = (S/\rho)_{\text{col}} + (S/\rho)_{\text{rad}} \quad . \tag{1.62}$$

- $(S/\rho)_{\text{col}}$ plays an important role in radiation dosimetry, since the dose *D* in the medium may be expressed as:

$$D = \phi\ (S/\rho)_{\text{col}} \quad , \tag{1.63}$$

  where ϕ is the fluence of electrons.

- $(S/\rho)_{\text{tot}}$ is used in the calculation of electron range R as follows:

$$R = \int_0^{KE_i} \left(\frac{S}{\rho}(KE) \right)_{\text{tot}}^{-1} d(KE), \tag{1.64}$$

where KE_i is the initial kinetic energy of the electron.

- Both $(S/\rho)_{\text{rad}}$ and $(S/\rho)_{\text{tot}}$ are used in the determination of radiation yield (also referred to as bremsstrahlung efficiency) Y as:

$$Y = \frac{1}{KE_i} \int_0^{KE_i} \frac{(S/\rho)_{\text{rad}}}{(S/\rho)_{\text{tot}}} d(KE) \quad . \tag{1.65}$$

- The stopping power focuses on the energy loss by an electron moving through a medium. When attention is focused on the absorbing medium, one is interested in the linear rate of energy absorption by the absorbing medium as the electron traverses the medium. The rate of energy absorption, called the *linear energy transfer (LET*), is defined as the average energy locally imparted to the absorbing medium by an electron of specified energy in traversing a given distance in the medium.

- In radiation dosimetry the concept of *restricted stopping power* (S_Δ/ρ) is introduced which accounts for that fraction of the collisional stopping power $(S/\rho)_{\text{col}}$ that includes all the soft collisions plus those hard collisions, which result in delta rays with energies less than a cut-off value Δ. In radiation dosimetry this cut-off energy is usually taken as 10 keV, an energy which allows an electron to just traverse an ionisation chamber gap of 1 mm in air. Delta rays are defined as electrons that acquire sufficiently high kinetic energies through hard collisions enabling them to carry this energy a significant distance away from the track of the primary particle and produce their own ionisations of absorber atoms.

1.3.4 Mass scattering power

When a beam of electrons passes through an absorbing medium, the electrons undergo multiple scattering through Coulomb interactions between the incident electrons and nuclei of the absorber. The angular and spatial spread of a pencil electron beam can be approximated by a Gaussian distribution. The multiple scattering of electrons traversing a path length ℓ through an absorbing medium is commonly described by the mean square angle of scattering $\overline{\theta^2}$ which is proportional to the mass thickness $\rho\ell$ of the absorber. Analogously to the definition of stopping power, the ICRU defines the *mass scattering power* T/ρ as:

$$\frac{T}{\rho} = \frac{1}{\rho}\frac{d\,\overline{\theta^2}}{d\ell} \quad \text{or} \quad \frac{T}{\rho} = \frac{\overline{\theta^2}}{\rho\ell} \quad . \tag{1.66}$$

The scattering power varies approximately as the square of the absorber atomic number and inversely as the square of the electron kinetic energy.

1.4. PHOTON INTERACTIONS

1.4.1. Types of indirectly ionizing photon radiations

Depending on their origin, the indirectly ionizing photon radiations fall into one of the following four categories:

- *Bremsstrahlung* (continuous x rays), emitted through electron-nucleus interactions.
- *Characteristic x-rays* (discrete), emitted in transitions of orbital electrons from one allowed orbit to a vacancy in another allowed orbit.
- *Gamma rays* (discrete), emitted through nuclear transitions in gamma decay.
- *Annihilation radiation* (discrete, typically 0.511 MeV), emitted through positron-orbital electron annihilation.

1.4.2. Photon beam attenuation

- The *intensity* $I(x)$ of a narrow monoenergetic photon beam, attenuated by an attenuator of thickness x, is given as:

$$I(x) = I(0)e^{-\mu(h\nu,Z)x} \quad , \tag{1.67}$$

where

$I(0)$ is the original intensity of the un-attenuated beam and
$\mu(h\nu,Z)$ is the linear attenuation coefficient that depends on photon energy $h\nu$ and attenuator atomic number Z.

- The *half-value layer* (*HVL* or $x_{1/2}$) is defined as that thickness of the attenuator that attenuates the photon beam intensity to 50% of its original value, *i.e.*:

$$x_{1/2} = HVL = \ln 2 / \mu \quad . \tag{1.68}$$

- Similarly, the *tenth-value layer* (*TVL* or $x_{1/10}$) is defined as that thickness of the attenuator that attenuates the photon beam intensity to 10% of its original value:

$$x_{1/10} = TVL = \ln 10 / \mu \quad . \tag{1.69}$$

- *HVL* and *TVL* are thus related as follows:

$$x_{1/10} = x_{1/2} \frac{\ln 10}{\ln 2} = 3.3\, x_{1/2} \quad . \tag{1.70}$$

- The *mass attenuation coefficient* μ_m, *atomic attenuation coefficient* ${}_a\mu$, and *electronic attenuation coefficient* ${}_e\mu$ are proportional to the linear attenuation coefficient μ through the following relationships:

$$\mu = \rho\mu_m = \frac{\rho N_A}{A}\,{}_a\mu = \frac{\rho N_A Z}{A}\,{}_e\mu \quad , \tag{1.71}$$

where ρ, Z, and A are the density, atomic number, and atomic mass number, respectively, of the attenuator.

- Typical units for the linear, mass, atomic, and electronic attenuation coefficients are: cm^{-1}; cm^{-2}/g; cm^2/atom; and cm^2/electron, respectively, implying that thickness x in the exponent $(-\mu x)$ must be given in: cm; g/cm^2; atoms/cm^2; and electrons/cm^2, respectively.

- For use in radiation dosimetry two additional attenuation coefficients are defined: *the energy transfer coefficient* μ_{tr} and the *energy absorption coefficient* μ_{ab} (often designated as μ_{en}). The two coefficients are related to μ as follows:

$$\mu_{tr} = \mu\frac{\bar{E}_{tr}}{h\nu} \tag{1.72}$$

and

$$\mu_{ab} = \mu\frac{\bar{E}_{ab}}{h\nu} \quad , \tag{1.73}$$

where

$\bar{E}_{tr}$ is the average energy transferred to charged particles (electrons and positrons) in the attenuator,

$\bar{E}_{ab}$ is the average energy deposited by charged particles in the attenuator.

- The energy transfer coefficient μ_{tr} and the energy absorption coefficient μ_{ab} are related through the radiation (bremsstrahlung) yield g as follows:

$$\mu_{ab} = \mu_{tr}(1-g) \quad . \tag{1.74}$$

1.4.3. Types of photon interactions

Photons may undergo various possible interactions with atoms of an attenuator; the probability or cross-section for each interaction depends on the energy $h\nu$ of the photon and on the atomic number Z of the attenuator.

- The photon interactions may be with a tightly bound electron, *i.e.*, with an atom as a whole (*photoelectric effect, coherent scattering*), with the field of the nucleus (*pair production*), or with a free orbital electron (*Compton effect, triplet production*).

- In the context of photon interactions, a tightly bound electron is an orbital electron with a binding energy of the order of, or slightly larger than, the photon energy, while a free electron is an electron with a binding energy that is much smaller than the photon energy.

- During the interaction the photon may completely disappear (photoeffect, pair production, triplet production) or it may be scattered coherently (coherent scattering) or incoherently (Compton effect).

1.4.4. Photoelectric effect

In photoelectric effect (sometimes referred to as photoeffect) the photon interacts with a tightly bound orbital electron of an attenuator and disappears, while the orbital electron is ejected from the atom as a photoelectron with a kinetic energy *KE* given as:

$$KE = h\nu - BE \quad , \tag{1.75}$$

where $h\nu$ is the incident photon energy and *BE* is the binding energy of the electron.

- The atomic attenuation coefficient for photoeffect ${}_{a}\tau$ is proportional to $Z^4/(h\nu)^3$, while the mass attenuation coefficient for photoeffect τ_m is proportional to $(Z/h\nu)^3$, with *Z* the atomic number of the attenuator and $h\nu$ the photon energy.

- In addition to a steady decrease in τ_m with an increasing $h\nu$, the plot of τ_m *vs.* $h\nu$ also shows sharp discontinuities in τ_m when $h\nu$ equals *BE* for a particular electronic shell of the attenuator. These discontinuities, called absorption edges, reflect the fact that for $h\nu < BE$ photons cannot undergo photoeffect with electrons in that particular shell, while for $h\nu \geq BE$ they can.

- The average energy transferred from the photon with energy $h\nu > BE_K$ to electrons $\overline{KE}_{tr}^{PE}$ in photoeffect is given as follows:

$$\overline{KE}_{tr}^{PE} = h\nu - P_K \ \omega_K \ BE_K \quad , \tag{1.76}$$

where BE_K is the binding energy of the K-shell orbital electron (photoelectron), P_K is the fraction of all photoeffect interactions that occur in the K-shell, and ω_K is the fluorescent yield for the K-shell. The range of P_K is from 1.0 at low atomic numbers *Z* to 0.8 at high atomic numbers (see Fig. 1.9 in Section 1.4.11).

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 in the sense that the photon loses essentially none of its energy and is scattered through only a small angle. Since no energy transfer occurs from the photon to charged particles, Rayleigh scattering plays no role in the energy transfer coefficient; however, it contributes to the attenuation coefficient.

- The atomic cross-section for Rayleigh scattering ${}_{a}\sigma_{R}$ is proportional to $(Z/h\nu)^2$ and the mass attenuation coefficient σ_R / ρ to $Z/(h\nu)^2$.

- In tissue and tissue-equivalent materials the relative importance of Rayleigh scattering in comparison to other photon interactions is small, as it contributes only a few percent or less to the total attenuation coefficient.

1.4.6. Compton effect (incoherent scattering)

Compton effect (incoherent scattering) represents a photon interaction with a free and stationary orbital electron. The incident photon with energy $h\nu$ loses part of its energy to the recoil (Compton) electron and is scattered as photon $h\nu'$ through a scattering angle θ, as shown schematically in Fig. 1.5. Angle ϕ represents the angle between the incident photon direction and the direction of the recoil electron.

- The change in photon wavelength $\Delta\lambda$ is given by the well-known Compton relationship:

$$\Delta\lambda = \lambda_C(1-\cos\theta) \quad , \tag{1.77}$$

where λ_C is the Compton wavelength of the electron, expressed as:

$$\lambda_C = \frac{h}{m_e c} = 0.024 \ \text{Å} \quad . \tag{1.78}$$

- The relationship for $\Delta\lambda$ is calculated from equations representing conservation of energy and momentum in the Compton process:

$$h\nu + m_e c^2 = h\nu' + m_e c^2 + KE \quad , \tag{1.79}$$

$$\frac{h\nu}{c} = \frac{h\nu'}{c}\cos\theta + \frac{m_e v}{\sqrt{1-\left(\frac{v}{c}\right)^2}}\cos\phi \quad , \tag{1.80}$$

and

$$0 = \frac{h\nu'}{c}\sin\theta - \frac{m_e v}{\sqrt{1-\left(\frac{v}{c}\right)^2}}\sin\phi \quad , \tag{1.81}$$

with ε the normalized incident photon energy, *i.e.*, $\varepsilon = \frac{h\nu}{m_e c^2}$. Equation (1.79) represents conservation of energy; Eq. (1.80) and Eq. (1.81) represent conservation of momentum along the x axis and y axis, respectively, of Fig. 1.5.

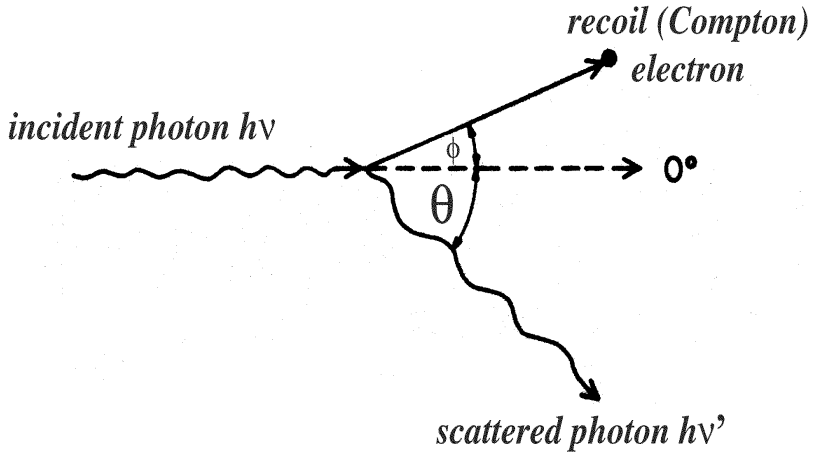

FIG. 1.5. Schematic diagram for Compton scattering.Incident photon with energy $h\nu$ interacts with a loosely-bound (essentially free) atomic electron. The electron is ejected from the atom as a recoil (Compton) electron with kinetic energy KE and a scattered photon with energy $h\nu' = h\nu - KE$ is produced.

- The scattering angle θ and the recoil electron angle ϕ are related through the following relationship:

$$\cot\phi = (1+\varepsilon)\tan(\theta/2) \tag{1.82}$$

From Eq. (1.82) it is evident that the range of angle ϕ is between 0 for $\theta = \pi$ (photon back-scattering) and $\pi/2$ for $\theta = 0$ (photon forward scattering) for any arbitrary photon energy. For a given θ, the higher the incident photon energy, the smaller is the recoil electron angle ϕ.

- The Compton interaction represents a photon interaction with an essentially free and stationary electron ($h\nu >> BE$). Consequently, the atomic Compton attenuation coefficient ${}_a\sigma_C$ depends linearly on the atomic number Z of the attenuator, while ${}_e\sigma_C$ and σ_C/ρ, the electronic and mass Compton attenuation coefficients, respectively, are independent of Z.

- The electronic Compton attenuation coefficient ${}_e\sigma_C$ steadily decreases with $h\nu$ from a value of 0.665×10^{-24} cm^2/electron at low photon energies to 0.21×10^{-24} cm^2/electron at $h\nu = 1$ MeV; 0.051×10^{-24} cm^2/electron at $h\nu$ = 10 MeV; and 0.008×10^{-24} cm^2/electron at $h\nu = 100$ MeV.

- The scattered photon energy $h\nu'$ and the kinetic energy of the Compton electron KE_C are given as follows:

$$h\nu' = h\nu\frac{1}{1+\varepsilon(1-\cos\theta)} \quad \text{and} \quad KE_C = h\nu\frac{\varepsilon(1-\cos\theta)}{1+\varepsilon(1-\cos\theta)} \quad . \tag{1.83}$$

- Energy of photons scattered at 90° and 180° is thus given as:

$$h\nu'(\theta = 90^o) = \frac{h\nu}{1+\varepsilon} \quad \text{and} \quad h\nu'(\theta = 180^o) = \frac{h\nu}{1+2\varepsilon} \quad , \tag{1.84}$$

which for large incident photon energies ($\varepsilon = h\nu/(m_e c^2) \to \infty$) results in $m_e c^2$ and 0.5 $m_e c^2$ for the $\theta = 90^o$ and $\theta = 180^o$, respectively.

- The maximum (for $\theta = 180^o$, *i.e.*, photon backscattering) and mean fractions of the incident photon energy transferred to the Compton recoil electron are given in Fig. 1.6. The mean fraction is used in the determination of the Compton effect contribution to the energy transfer coefficient.

- For example, from Fig. 1.6 we determine that a 1 MeV photon undergoing a Compton backscattering event would result in a recoil electron with a kinetic energy of 800 keV and a back-scattered photon with energy of 200 keV.

- On the average, a 1 MeV photon undergoing Compton scattering will produce a 440 keV recoil electron and a 560 keV scattered photon; a 100 keV photon will produce a 15 keV recoil electron and a 85 keV scattered photon; a 10 MeV photon will produce a 6.9 MeV recoil electron and a 3.1 MeV scattered photon; and a 100 MeV photon will produce an 80 MeV recoil electron and a 20 MeV scattered photon.

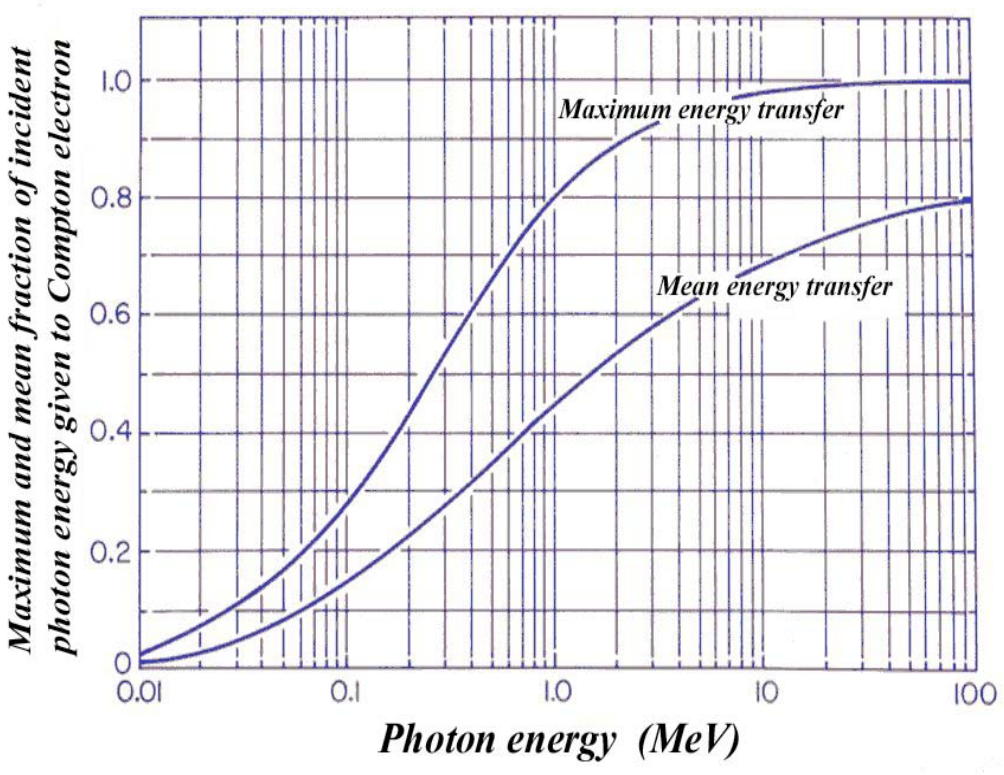

FIG. 1.6. Maximum and mean fraction of incident photon energy transferred to Compton recoil electron in the photon energy range from 10 keV to 100 MeV. (Reprinted from Johns, H.E. and Cunningham, J.R. with permission).

1.4.7. Pair production

In pair production the photon disappears and an electron-positron pair with a combined kinetic energy equal to $h\nu - 2\,m_e c^2$ is produced in the nuclear Coulomb field.

- Because mass is produced out of photon energy in the form of an electron-positron pair, pair production has an energy threshold (minimum photon energy required for the effect to happen) of $2m_e c^2 = 1.02$ MeV.

- When pair production occurs in the field of an orbital electron, the effect is referred to as *triplet production*, and three particles (electron-positron pair and the orbital electron) share the available energy. The threshold for this effect is 4 $m_e c^2$.

- The probability for pair production is zero for photon energies below the threshold energy and increases rapidly with photon energy above the threshold.

- The atomic attenuation coefficient for pair production ${}_a\kappa$ and the mass attenuation coefficient for pair production κ/ρ vary approximately as Z^2 and Z, respectively, where Z is the atomic number of the attenuator.

1.4.8. Photonuclear reactions

- Photonuclear reactions (also referred to as photodisintegration reactions) occur when a high energy photon is absorbed by the nucleus of an atom, resulting in an emission of a neutron [(x,n) reaction] or proton [(x,p) reaction] and a transformation of the nucleus into a radioactive reaction product.

- The threshold for a particular photonuclear reaction depends on the reaction and the nucleus and is of the order of 10 MeV or higher for most nuclei (with the exception of the deuteron and beryllium-9 nuclei for which the threshold is of the order of 2 MeV).

- The probability for photonuclear reactions is much smaller than that for other photon interactions and their contribution to the total attenuation coefficient amounts to only a few percent at photon energies above the reaction threshold.

- While photonuclear reactions do not play an active role in photon attenuation considerations, they are of concern in high energy radiotherapy treatment rooms because of the neutron production through the (x,n) reactions and because of the radioactivity that is induced in the treatment room air and in machine components through the (x,n) reaction. Both the neutrons and the radioactivity present a health hazard to personnel and must be dealt with in treatment room and treatment machine design. The neutron problem is handled with special treatment room doors incorporating borated hydrogeneous materials to thermalize and absorb the neutrons; the radioactivity with adequate room ventilation (6 to 8 air changes per hour) and use of machine components with low reaction cross-section and short half-life of the reaction product.

1.4.9. Contributions to attenuation coefficients

For a given photon energy $h\nu$ and attenuator *Z*, the attenuation coefficient μ, energy transfer coefficient μ_{tr} and energy absorption coefficient μ_{ab} are given as a sum of coefficients for individual photon interactions (energy transfer coefficient is often designated as μ_{en}):

$$\mu = \tau + \sigma_R + \sigma_C + \kappa \quad , \tag{1.85}$$

$$\mu_{tr} = \tau_{tr} + (\sigma_C)_{tr} + \kappa_{tr} = \tau \frac{\overline{KE}_{tr}^{PE}}{h\nu} + \sigma_C \frac{\overline{KE}_{tr}^{CE}}{h\nu} + \kappa \frac{\overline{KE}_{tr}^{PP}}{h\nu} \quad , \tag{1.86}$$

$$\mu_{ab} = \mu_{en} = \mu_{tr}(1-g) \quad , \tag{1.87}$$

where *g* is the bremsstrahlung fraction, and the average energies transferred to electrons for photoelectric effect, Compton effect, and pair production are designated as $\overline{KE}_{tr}^{PE}$, $\overline{KE}_{tr}^{CE}$ and $\overline{KE}_{tr}^{PP}$, respectively.

- $\overline{KE}_{tr}^{PE}$ may be approximated by $h\nu - P_K \omega_K BE_K$, with BE_K the binding energy of the K-shell electron, P_K the fraction of all photoelectric effect interactions that occur in the K-shell, and ω_K. the fluorescent yield for the K-shell.

- $\overline{KE}_{tr}^{CE}$ is obtained from tabulated values or from the graph given in Fig. 1.6.

- $\overline{KE}_{tr}^{PP} = h\nu - 2\, m_e c^2$.

- Note that in Rayleigh scattering no energy transfer occurs and therefore Rayleigh scattering contributes neither to the energy transfer coefficient nor to the energy absorption coefficient.

The individual components of the attenuation coefficients, when summed up, result in the total mass attenuation, mass energy transfer, and mass energy absorption coefficients as follows:

$$\frac{\mu}{\rho} = \frac{\tau}{\rho} + \frac{\sigma_R}{\rho} + \frac{\sigma_C}{\rho} + \frac{\kappa}{\rho} \quad , \tag{1.88}$$

$$\frac{\mu_{tr}}{\rho} = \frac{\tau_{tr}}{\rho} + \frac{(\sigma_C)_{tr}}{\rho} + \frac{\kappa_{tr}}{\rho} = \frac{1}{\rho}\left[\tau \frac{h\nu - P_K\ \omega_K\ BE_K}{h\nu} + \sigma_C \frac{\overline{KE}_{tr}^{CE}}{h\nu} + \kappa \frac{h\nu - 2m_e c^2}{h\nu} \right] \quad , \tag{1.89}$$

$$\frac{\mu_{ab}}{\rho} = \frac{\mu_{tr}}{\rho}(1-g) \ . \tag{1.90}$$

Figure 1.7 shows the mass attenuation coefficient μ/ρ on the left hand side, and the mass energy transfer coefficient (μ_{tr}/ρ) and mass energy absorption coefficient (μ_{ab}/ρ) on the right hand side for lead in the photon energy range from 10 keV to 100 MeV.

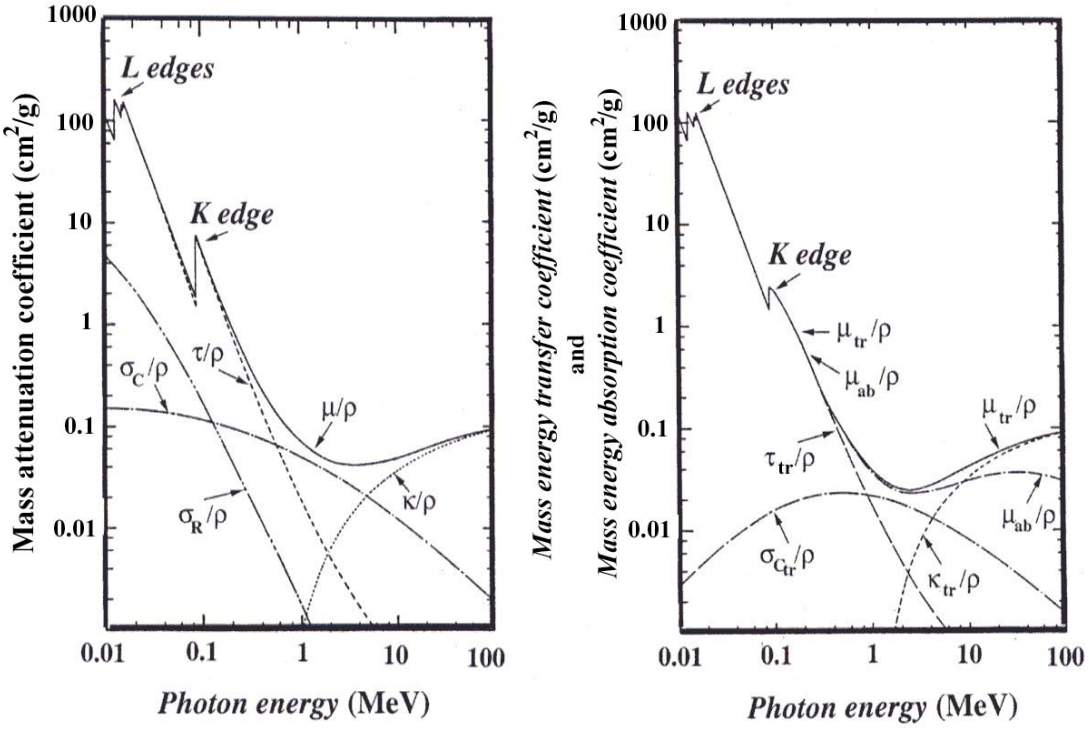

FIG. 1.7. Mass attenuation coefficient μ/ρ (left diagram); mass energy transfer coefficient μ_{tr}/ρ and mass energy absorption coefficient μ_{ab}/ρ (right diagram) ***for lead*** *in the photon energy range between 10 keV and 100 MeV. The dotted-dashed curves represent contributions of individual effects, while the solid curves represent the sum of the contributions of the individual effects as given by Eq. (1.88) for μ/ρ, Eq. (1.89) for μ_{tr}/ρ, and Eq. (1.90) for μ_{ab}/ρ. For photon energies below 2 MeV, $\mu_{tr}/\rho \approx \mu_{ab}/\rho$, because the bremsstrahlung fraction g in this energy region is negligible. Above 2 MeV, g increases with photon energy causing the divergence between the mass energy transfer and mass energy absorption coefficients.*

1.4.10. Relative predominance of individual effects

The probability for a photon to undergo any one of the various interaction phenomena with an attenuator depends on the energy $h\nu$ of the photon and on the atomic number Z of the attenuating material. In general, photoelectric effect predominates at low photon energies, Compton effect at intermediate energies, and pair production at high photon energies.

Figure 1.8 shows the regions of relative predominance of the three most important individual effects with $h\nu$ and Z as parameters. The two curves display the points in the $(h\nu, Z)$ diagram for which ${}_a\sigma_C = {}_a\tau$ or ${}_a\sigma_C = {}_a\kappa$ and thus delineate the regions of photoelectric effect predominance at low photon energies, Compton effect predominance at intermediate energies, and pair production predominance at high photon energies.

For example, a 100 keV photon will interact with lead (Z = 82) predominantly through photoeffect and with soft tissue (Z_{eff} = 7.5) predominantly through Compton effect. A 10 MeV photon, on the other hand, will interact with lead predominantly through pair production and with tissue predominantly through Compton effect.

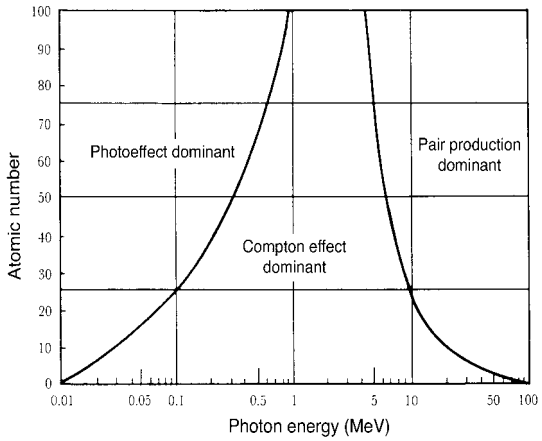

FIG. 1.8. Regions of relative predominance of the three main forms of photon interaction with matter. The left curve represents the region where the atomic coefficient for the photoeffect and Compton effect are equal ($_a\tau = _a\sigma_C$)*, the right curve is for the region where the atomic Compton coefficient equals the atomic pair production coefficient* ($_a\sigma_C = _a\kappa$).

1.4.11. Effects following photon interactions

In photoelectric effect, Compton effect, and triplet production vacancies are produced in atomic shells through the ejection of orbital electrons. For orthovoltage and megavoltage photons used in diagnosis and treatment of disease with radiation, the shell vacancies occur mainly in inner atomic shells and are followed by *characteristic x rays* or *Auger electrons*, the probability for the former given by the fluorescent yield ω, while the probability for Auger effect is $1 - \omega$ (see Fig. 1.9).

Pair production and triplet production are followed by the annihilation of the positron with a "free" and stationary electron producing two *annihilation quanta*, most commonly with energy of 0.511 MeV each and emitted at 180^o from each other to satisfy the conservation of charge, momentum and energy. An annihilation of a positron before it expended all of its kinetic energy is referred to as annihilation-in-flight and produces photons with energies exceeding 0.511 MeV.

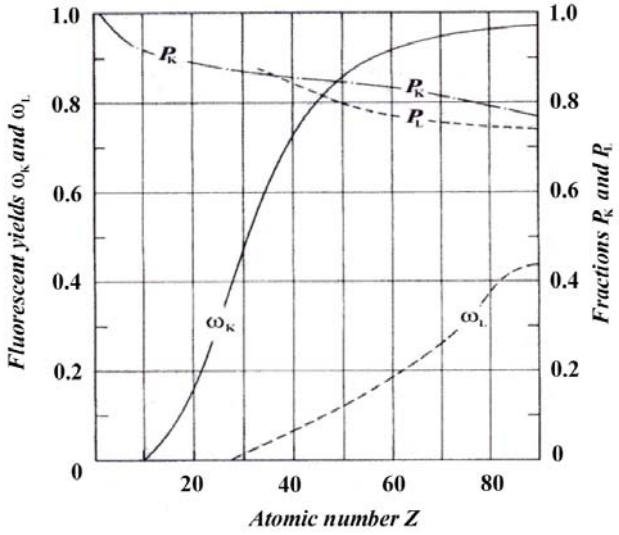

FIG. 1.9. Fluorescent yields ω_K *(for* $h\nu > BE_K$*) and* ω_L *(for* $BE_L < h\nu < BE_K$*) as well as fractions* P_K *(for* $h\nu > BE_K$*) and* P_L *(for* $BE_L < h\nu < BE_K$*) against the atomic number Z.*

1.4.12. Summary of photon interactions

TABLE 1.IV. MAIN CHARACTERISTICS OF PHOTOEFFECT, RAYLEIGH SCATTERING, COMPTON EFFECT, AND PAIR PRODUCTION.

	Photoeffect	***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	No	No	No	$2\,m_e c^2$
Attenuation coefficient	τ	σ_R	σ_C	κ
Particles released	Photoelectron	None	Compton (recoil) electron	Electron-positron pair
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	$\frac{\kappa}{\rho} \propto Z$
Average energy transferred	$h\nu - P_K \omega_K BE_K$	0	$\overline{KE}_{tr}^{CE}$ (see Fig. 1.6)	$h\nu - 2\,m_e c^2$
Subsequent effect	characteristic x ray, Auger effect	none	characteristic x ray, Auger effect	annihilation radiation
Significant energy region	0 to 0.5 MeV	< 1 MeV	around 1 MeV	> 1 MeV

1.4.13. Example

For 2 MeV photons in lead (Z = 82; A = 207.2 g/g-atom; ρ = 11.36 g/cm^3) the photoeffect, coherent scattering, Compton effect, and pair production linear attenuation coefficients are: τ = 0.055 cm^{-1}, σ_R = 0.008 cm^{-1}, σ_C = 0.395 cm^{-1}, and κ = 0.056 cm^{-1}. The average energy transferred to charged particles $\overline{KE}_{tr}$ = 1.13 MeV and the average energy absorbed in lead is $\overline{KE}_{ab}$ = 1.04 MeV.

Calculate the linear attenuation coefficient μ; mass attenuation coefficient μ_m; atomic attenuation coefficient ${}_a\mu$; mass energy transfer coefficient μ_{tr}; mass energy absorption coefficient μ_{ab}; and bremsstrahlung fraction g.:

$$\mu = \tau + \sigma_R + \sigma_C + \kappa = (0.055 + 0.008 + 0.395 + 0.056)\ \text{cm}^{-1} = 0.514\ \text{cm}^{-1} \tag{1.91}$$

$$\mu_m = \frac{\mu}{\rho} = \frac{0.514\ \text{cm}^{-1}}{11.36\ \text{g/cm}^3} = 0.0453\ \text{cm}^2/\text{g} \tag{1.92}$$

$${}_a\mu = \left(\frac{\rho N_A}{A}\right)^{-1}\mu = \frac{207.2\ (\text{g/g-atom})\ 0.514\ \text{cm}^{-1}}{11.36\ \text{g/cm}^3\ 6.022\times10^{23}(\text{atom/g-atom})} = 1.56\times10^{-23}\ \text{cm}^2/\text{atom} \tag{1.93}$$

$$\frac{\mu_{tr}}{\rho} = \frac{\overline{KE}_{tr}}{h\nu}\frac{\mu}{\rho} = \frac{1.13\ \text{MeV}\ 0.0453\ \text{cm}^2/\text{g}}{2\ \text{MeV}} = 0.0256\ \text{cm}^2/\text{g} \tag{1.94}$$

$$\frac{\mu_{ab}}{\rho} = \frac{\mu_{en}}{\rho} = \frac{\overline{KE}_{ab}}{h\nu}\frac{\mu}{\rho} = \frac{1.04\ \text{MeV}\ 0.0453\ \text{cm}^2/\text{g}}{2\ \text{MeV}} = 0.0236\ \text{cm}^2/\text{g} \tag{1.95}$$

$$g = \frac{\overline{KE}_{tr} - \overline{KE}_{ab}}{\overline{KE}_{tr}} = 1 - \frac{\overline{KE}_{ab}}{\overline{KE}_{tr}} = 1 - \frac{1.04\ \text{MeV}}{1.13\ \text{MeV}} = 0.08 \tag{1.96}$$

or

$$g = 1 - \frac{\mu_{ab}/\rho}{\mu_{tr}/\rho} = 1 - \frac{0.0236\ \text{cm}^2/\text{g}}{0.0256\ \text{cm}^2/\text{g}} = 0.08\,. \tag{1.97}$$

The mass energy transfer coefficient μ_{tr}/ρ can also be determined using Eq. (1.89) with:

$$h\nu - P_K\omega_K BE_K = 2\ \text{MeV} - 0.8\times0.96\times0.088\ \text{MeV} = 1.93\ \text{MeV} \quad (\textit{from Fig. 1.9}) \tag{1.98}$$

$$\overline{KE}_{tr}^{CE} = 0.53\times2\ \text{MeV} = 1.06\ \text{MeV} \qquad (\textit{from Fig. 1.6}) \tag{1.99}$$

$$h\nu - 2\,m_e c^2 = 2\ \text{MeV} - 1.02\ \text{MeV} = 0.98\ \text{MeV} \tag{1.100}$$

to get

$$\frac{\mu_{tr}}{\rho} = \frac{1}{11.36}\left(\frac{1.93}{2}\times0.055 + \frac{1.06}{2}\times0.395 + \frac{0.98}{2}\times0.056\right)\frac{\text{cm}^2}{\text{g}} = 0.0254\ \frac{\text{cm}^2}{\text{g}} \tag{1.101}$$

in good agreement with the result obtained in Eq. (1.94).

Thus, as shown schematically in Fig. 1.10, a 2 MeV photon in lead will on the average:

- Transfer 1.13 MeV to charged particles (electrons and positrons) and
- 0.87 MeV will be scattered through Rayleigh and Compton scattering.

Of the 1.13 MeV of energy transferred,

- 1.04 MeV will be absorbed in lead and
- 0.09 MeV will be re-emitted through bremsstrahlung radiative loss.

The bremsstrahlung fraction *g* for 2 MeV photons in lead is 0.08.

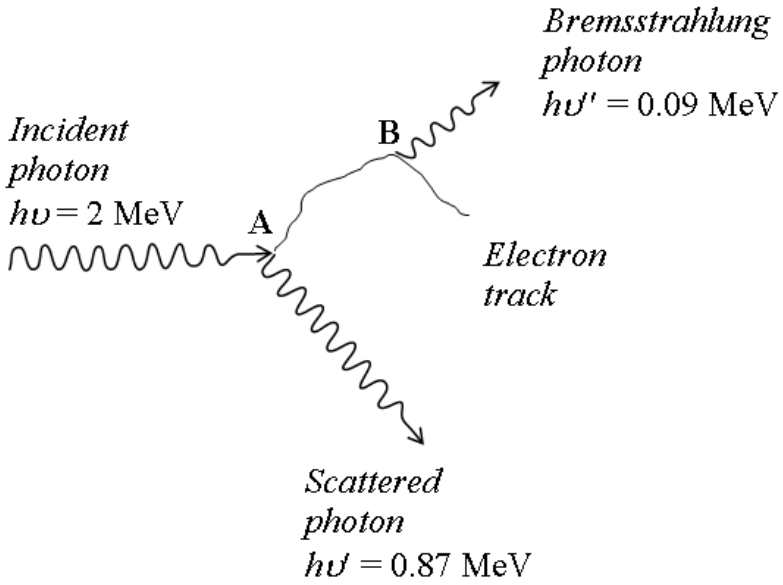

FIG. 1.10. Schematic diagram for general photon interactions with an atom. In this example a 2 MeV photon hν interacts with a lead atom. An individual 2 MeV photon, as it encounters a lead atom at point A, may interact with the atom through photoelectric effect, Rayleigh scattering, Compton effect or pair production, or it may not interact at all. However, for a large number of 2 MeV photons striking lead, we may state that on the average:

- *1.13 MeV will be transferred at point A to charged particles (mainly to fast energetic electrons, but possibly also to positrons if the interaction is pair production);*
- *0.87 MeV will be scattered through Rayleigh and Compton scattering (hν′).*

Of the 1.13 MeV transferred to charged particles:

- *1.04 MeV will be absorbed in lead over the fast charged particle tracks, and*
- *0.09 MeV will be emitted in the form of bremsstrahlung photons (hν″).*

1.4.14. Production of vacancies in atomic shells

There are eight main means for producing vacancies in inner atomic shells and transforming the atom from a neutral entity into an excited negative ion:

- *Coulomb interaction* (1) of an energetic charged particle with an orbital electron
- Photon interactions:
  - *photoeffect* (2),
  - *Compton effect* (3),
  - *triplet production* (4)
- Nuclear decay:
  - *electron capture* (5),
  - *internal conversion* (6)
- *Positron annihilation* (7)
- *Auger effect* (8)

Note: *pair production* does not produce shell vacancies. 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 ion. The ion eventually attracts an electron from its surroundings and reverts to a neutral atom.

BIBLIOGRAPHY

ATTIX, F.H., ROESCH, W.C., TOCHILIN, E., "Radiation dosimetry", Academic Press, New York, New York, U.S.A. (1968).

ATTIX, F.H.,"Introduction to radiological physics and radiation dosimetry", Wiley, New York, New York, U.S.A. (1986).

EVANS, R.D., "The atomic nucleus", McGraw Hill, New York, New York, U.S.A. (1955).

HALE, J.,"The fundamentals of radiological science", Thomas, Springfield, Illinois, U.S.A. (1974).

JOHNS, H.E., CUNNINGHAM, J.R, "The physics of radiology", Thomas, Springfield, Illinois, U.S.A. (1984).

KASE, K.R, BJARNGARD, B.E., ATTIX, F.H. (editors), "The dosimetry of ionizing radiation", Academic Press, San Diego, California, U.S.A. (1985).

KHAN, F., "The physics of radiation therapy", Williams and Wilkins, Baltimore, Maryland, U.S.A. (1994).

YAYARAMAN, S., LANZL, L.H., "Clinical radiotherapy physics", CRC Press, Boca Raton, Florida (1996).