Radiation Dosimetry

PHYS-H-500

Teacher: N. Pauly

References

- F.H. Attix, *Introduction to Radiological Physics and Radiation Dosimetry*, Wiley-VCH, 2004

- *Fundamental quantities and units for ionizing radiation (Revised)*. International Commission on Radiation Units and Measurements, ICRU Report n° 85, Journal of the ICRU 11 (2011) n° 1: http://jicru.oxfordjournals.org/content/11/1.toc

- *The 2007 Recommendations of the International Commission on Radiological Protection*. International Commission on Radiological Protection, ICRP Publication 103, Annals of the ICRP 37 (2007) 1-332: http://www.sciencedirect.com/science/journal/01466453/37/2-4
  Version in french: http://www.icrp.org/docs/P103_French.pdf

References (2)

- *Royal Decree of July 20, 2001:* General regulation for protection of the population, workers and environment against the danger of ionizing radiations (Moniteur Belge, august 30, 2001) + modifications: http://www.fanc.fgov.be/fr/page/introduction-arretes-royaux/446.aspx

Organization of teaching

- Theory: 2 ECTS (50% → Written examination) → Slides available on http://metronu.ulb.ac.be/pauly_cours.html

- Exercises (Assistant: M. Ciccarelli - Maureen.Ciccarelli@ulb.be):
  1 ECTS (25% → Written examination)

- Labs (Organization: M. Ciccarelli): 1 ECTS (25% → Exercises book)

  → - Erasme (S. Simon)

  - Bordet (S. Simon)

  - Isib (I. Gerardy)

January examination - 2013 (theory)

- Bragg-Grey relation :
  - Express the Bragg-Grey relation.
  - Give its mathematic form (and define terms of the equation).
  - Express the Bragg-Grey conditions.
  - Comment these conditions for γ radiations, for electrons and for incident heavy charged particles.
- Define the notions of narrow-beam attenuation, broad-beam attenuation, narrow-beam geometry and ideal broad-beam geometry.
- Define the notion of dose response for a thermoluminescent dosimeter and develop this notion for the particular case of LiF:Mg,Ti (explain the role of the Mg and Ti impurities).
- Radiophotoluminescence dosimetry:
  - Define the radiophotoluminescence.
  - Explain the mechanisms of luminescence for phosphate glass with Ag impurities.
  - Explain the build-up effect.

Contents

Part 1: Theoretical basis

I. Introduction and reminders
II. Radiometric and dosimetric quantities
III. Geometric configurations for non-charged particles
IV. Notion of equilibrium
V. Cavity theories

Part 2: Experimental Dosimetry

VI. Introduction
VII. Ionization Chambers
VIII. Photographic dosimetry
IX. Thermoluminescent dosimeters
X. Optically stimulated luminescence dosimeters
XI. Electronic dosimeters
XII. Chemical dosimeters

Chapter I:
Introduction and reminders

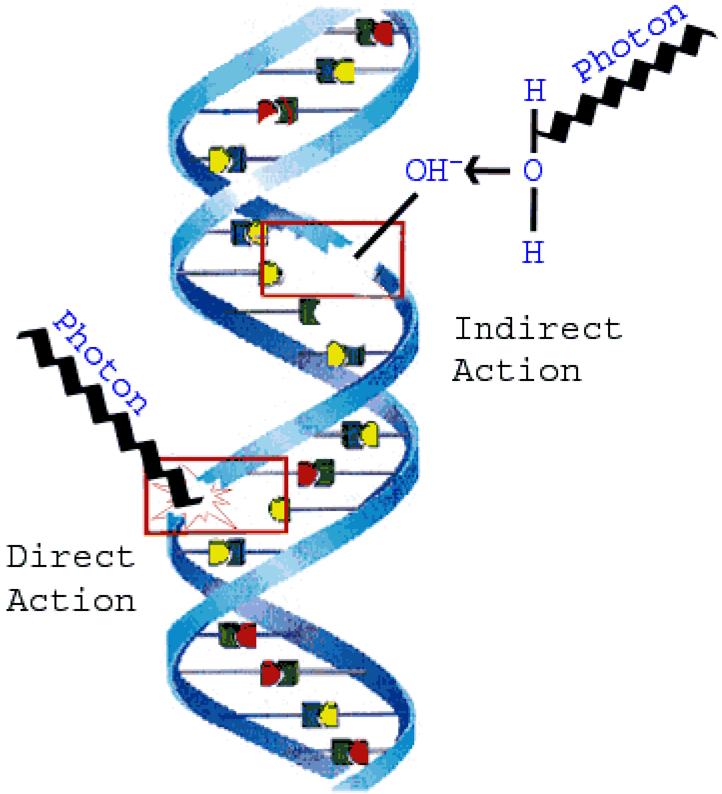
Dosimetry definition

- **Radiological physics is the science of ionizing radiation and its interaction with matter, with special interest in the absorbed energy**

- **Radiation dosimetry has to determine quantitatively this absorbed energy**

<u>Note</u>: Typical energy considered in radiation dosimetry is small (example: the semi-lethal dose to an uniform X-ray exposition: 4 Gy → 280 J) → The effects of ionizing radiations are explained because the energy is locally delivered (at molecular level)

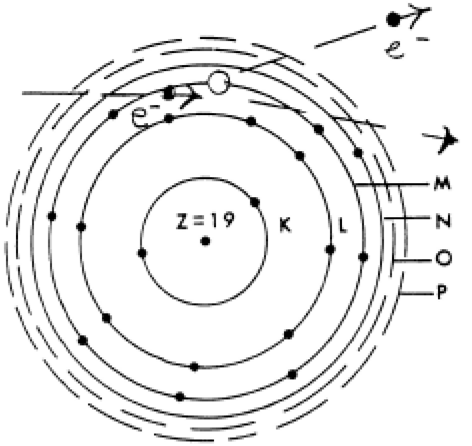
Direct and indirect damages



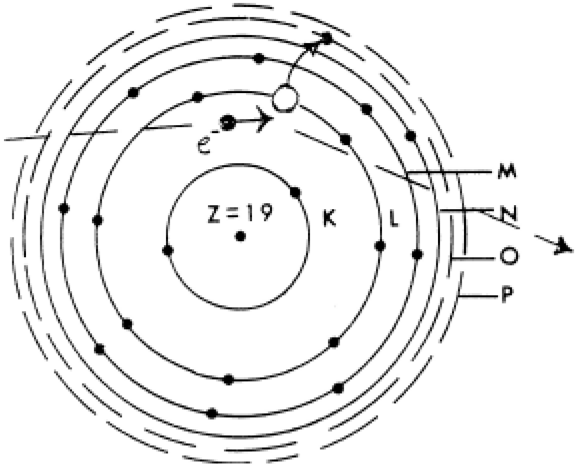
Interactions of ionizing radiations with matter

Energy transfer particles → matter:

- **Ionization**: one or more e^- are liberated during the collision between an incident particle and an atom or a molecule
- **Excitation**: Transfer of an e^- to a higher energy level in the atom or in the molecule



Ionization

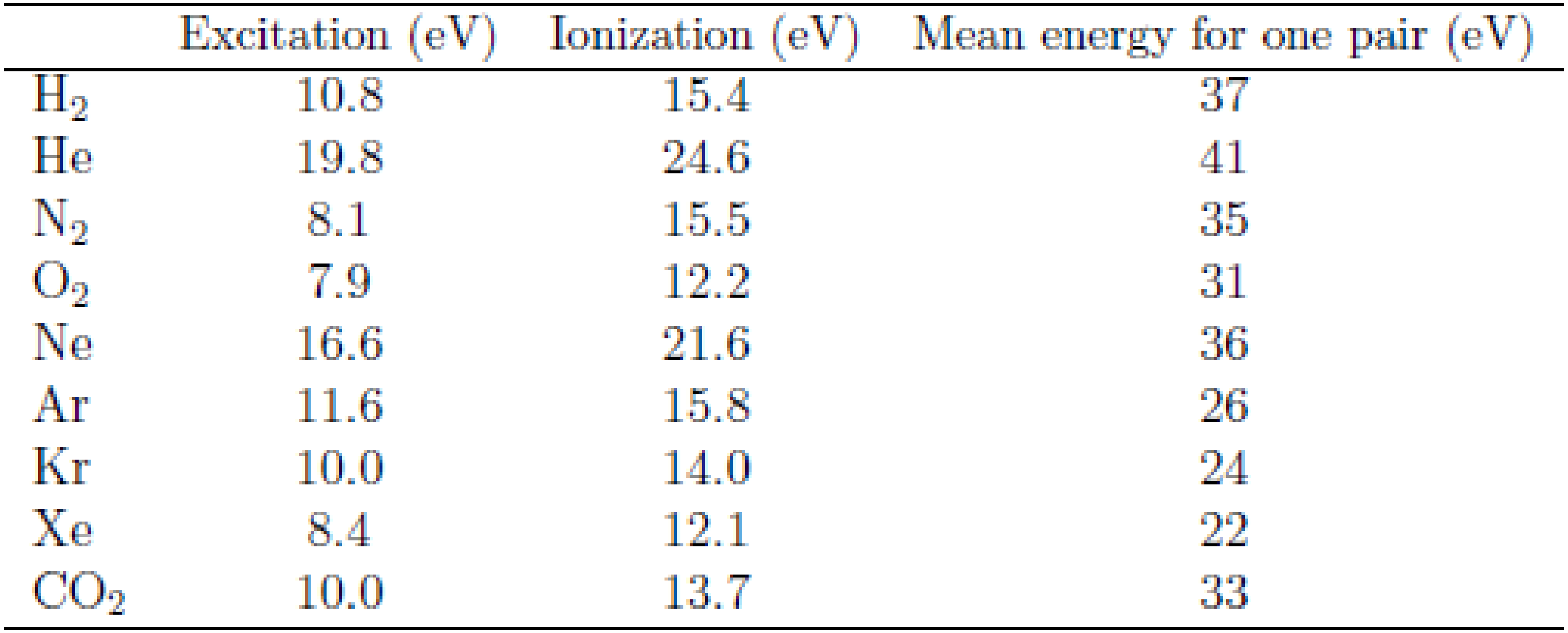


Excitation

Ionizations and excitations

- Typically: $\sigma_{\text{ionization}} > \sigma_{\text{excitation}}$ but for ionization → presence of $E_{threshold}$ → as transfers of small energies are the + probable → excitations reactions generally dominate
- Ions and e^- created by the incident ionizing radiation→ primary ionization
- If the e^- also creates other ions-e^- pairs→ secondary ionization
- We define *W* as the mean energy expended inside the medium by ions pair
- *W* is « relatively » independent on the incident particle and also on its energy → for gases $W \approx 30$ eV
- The distinction between ionization and excitation in a dense medium is blurred → pragmatic way: introduction of a threshold energy: if $E < E_{threshold}$ → the particle is no more ionizing → at the end of its travel a particle is no more ionizing

Excitation, ionization and mean energies: Example for gases



	Excitation (eV)	Ionization (eV)	Mean energy for one pair (eV)
H_2	10.8	15.4	37
He	19.8	24.6	41
N_2	8.1	15.5	35
O_2	7.9	12.2	31
Ne	16.6	21.6	36
Ar	11.6	15.8	26
Kr	10.0	14.0	24
Xe	8.4	12.1	22
CO_2	10.0	13.7	33

Ionizing radiations

- The term *ionizing radiation* relates to charged or uncharged which can produce ionizations inside a medium

- Ionizing radiations are characterized by their interaction coefficients

- Ionizing radiations are subdivided into 2 categories:
  - Directly ionizing radiations (e^-, heavy charged particles)
  - Indirectly ionizing radiations (photons, neutrons) which first transfer their energy to charged particles. Charged particles then in turn deliver the energy to the matter as above

Directly ionizing radiations

- Charged particles (e^-, e^+, α, p, ion,…) interact with the e^- and the nuclei of the medium via the Coulomb force → frequent interactions → the energy is lost in a quasi-continuous way → finite distance travelled inside the matter → definition of a total range
- **Stopping power (force)** → Quotient of the mean energy loss ΔE undergone by a charged particle along a part of its trajectory by the length Δx of this part → mean energy loss by unit of length of the charged particle along its trajectory (unit: Jm^{-1}) → for a « thick » target, weak fluctuations in energy and rectilinear trajectory (*continuous-slowing-down-approximation: CSDA*): $E = E(x)$ → dE/dx

Expression of the stopping force (within CSDA)

$$\frac{dE}{dx} = -NS(E)$$

N: atomic density

S: stopping cross section

$$S = \int T d\sigma$$

T: lost energy

σ: collision cross section

Stopping cross section

- $S = S_{elec} + S_{rad} + S_{nucl}$
- Ions: $S \approx S_{elec}$ (S_{nucl} to be considered only at small energies ≈ 1 keV)
- Electrons: $S = S_{elec} + S_{rad}$ (S_{rad} especially for Z ↗)
- For S_{elec} → corrected equation of Bethe-Bloch (ions), of Møller (e^-), of Bhabha (e^+)
- Standard expression for S:

$$S_{elec} = \frac{4\pi r_e^2 mc^2}{\beta^2} Z z^2 L(\beta)$$

with $\beta = v/c$, $z = e_{proj}/e$, $r_e = e^2/(mc^2)$ and $L(\beta)$ the stopping number

Restricted stopping power (linear energy transfer)

L_{Δ}: **Linear energy transfer** (LET) (or Restricted stopping power) →

$$L_\Delta = \frac{dE_\Delta}{dx}$$

$$L_\Delta = \frac{dE_{elec}}{dx} - \frac{dE_{KE>\Delta}}{dx}$$

with $dE_{\Delta} = dE_{elec} - dE_{KE>\Delta}$ et $dE_{KE>\Delta}$: sum of kinetic energies for secondary e^- (e^- δ) with kinetic energy > the Δ energy → dE_{Δ} is the locally transferred energy

L_{∞}: **Non-restricted stopping power** → $L_\infty = \frac{dE_{elec}}{dx}$

Determination of the maximal transferred energy: T_{max}

$$T_{max} = \gamma E$$

with

$$\gamma = \frac{4m_1 m_2}{(m_1 + m_2)^2}$$

m_1: incident charged particle
m_2: target charged particle

For $m_1 = m_2 \rightarrow \gamma = 1$
For $m_1 \ll$ or $\gg m_2 \rightarrow$ small γ

electron/electron: large transferred energy is possible
electron/ion or ion/electron: small transferred energy
ion/ion: large transferred energy is possible

Angular deviations

- If $m_2 \leq m_1$: θ_{max} is given by

$$\sin \theta_{max} = \frac{m_2}{m_1}$$

- Otherwise $\theta_{max} = \pi$

electron/electron: large deviations are possible $\theta_{max} = \pi/2$
electron/ion: very large deviations are possible $\theta_{max} = \pi$
ion/electron: small deviations
ion/ion: depends on the masses but large deviations are possible

Expression of the range

$$x = \int_{E(x)}^{E_0} \frac{dE'}{NS(E')}$$

➡ The total range *R* is obtained for *E(R)=0*

$$R_{CSDA} = \int_{0}^{E_0} \frac{dE'}{NS(E')}$$

This estimation of the range is based on the CSDA hypothesis!

Projected range R_p: Mean value of the depth reached by a charged particle at its stop (measured along the initial direction of the particle) → $R_P < R_{CSDA}$

Examples of CSDA ranges for ions

- 5.5 MeV α in air: R_{CSDA}= 4.2 cm
- 4.0 MeV α in air: R_{CSDA}= 2.6 cm
- 5.5 MeV α in aluminium: R_{CSDA}= 2.5 10^{-3} cm
- 5.5 MeV α in H_20: R_{CSDA}= 4.3 10^{-3} cm

- 1 MeV proton in air: R_{CSDA}= 2.4 cm
- 4 MeV proton in air: R_{CSDA}= 23.6 cm
- 5.5 MeV proton in aluminium: R_{CSDA}= 2.3 10^{-2} cm
- 5.5 MeV proton in H_20: R_{CSDA}= 4.3 10^{-2} cm

http://www.nist.gov/pml/data/star/index.cfm

Examples of CSDA ranges for e^-

- 5.5 MeV e^- in air: R_{CSDA}= 2500 cm
- 4.0 MeV e^- in air: R_{CSDA}= 1800 cm
- 1 MeV e^- in air: R_{CSDA}= 410 cm

- 5.5 MeV e^- in aluminium: R_{CSDA}= 1.2 cm
- 5.5 MeV e^- in H_20: R_{CSDA}= 2.8 cm
- 1 MeV e^- in H_20: R_{CSDA}= 0.44 cm

Indirectly ionizing radiations

- Photons (γ rays, characteristic X-rays, Bremsstrahlung) → interact with matter via successive unique events → between 2 evens: no interaction with matter
- Neutrons → carry no charge → no interaction with matter via the Coulomb force de → interact via nuclear force
- In 2 cases → can lose all their energy in only one interaction and conversely can cross a « large » quantity of matter without interaction
- After one interaction → emission of directly ionizing particles (electrons, positrons, protons, alphas, fission products,…)

Types of interactions for indirectly ionizing radiations

- Photons: photoelectric effect, Compton effect, pair or triplet creation, Rayleigh scattering,…
- Neutrons: elastic scattering, inelastic scattering, absorption
- Interaction cross section σ: (with *j* types of processes)

$$\sigma = \sum_j \sigma_j$$

- Example: photons → ${}_a\mu = {}_a\tau + {}_a\sigma + {}_a\kappa$ (photoelectric + Compton + pair creation)

Linear attenuation coefficient for indirectly ionizing radiations

- The probability for a indirectly ionizing radiation incident ($\perp$) on a medium with length *dl* and with atomic density *N* to undergo an interaction is ${}_a\mu N dl$ → for a monoenergetic beam of I particles (∥) by time unit the variation dI after crossing the target is (each particle is absorbed in a single interaction):

$$dI = -{}_a\mu N I dl$$

- For a thick target (thickness *l*) and an initial beam with I_0 particles, the intensity after crossing the target is:

$$I = I_0 \exp\left(-{}_a\mu N l\right)$$

- $\mu = {}_a\mu N$: **Linear attenuation coefficient** (unit: m^{-1}) → allows to evaluate the frequency of collisions

Alternative coefficients

- We van write (with *M,* the molar masse of the medium, ρ its density and N_A the Avogadro number):

$$\mu l = \left({}_a\mu \frac{N_A}{M}\right)(\rho l)$$

- (ρl): **Area density** (unit: kg m^{-2})
- μ/ρ: **Mass attenuation coefficient** (unit: m^2 kg^{-1}) →

$$\left(\frac{\mu}{\rho}\right) = \left({}_a\mu \frac{N_A}{M}\right)$$

- $\lambda = 1/\mu$: **Mean free path** (unit: m) → mean distance travelled by a photon between two collisions
- ρ/μ: **Mass attenuation length** (unit: kg m^{-2})

Mass attenuation coefficient

- μ/ρ: **Mass attenuation coefficient** (unit: m^2kg^{-1}) → ratio of dI/I by ρdl with dI/I, the fraction of indirectly ionizing radiations which undergo interactions along the distance *dl* travelled inside a medium of density ρ
- Global coefficient global → takes into account the interactions of particles in matter regardless of the nature of the interaction
- The mass coefficients are directly proportional to the cross section and do not depend on the physical nature of the target → these coefficients are displayed in databases

Mass attenuation coefficient : Examples

- 1 MeV photons in air: μ/ρ=0.064 cm^2/g with ρ(air)=0.001205 g/cm^3 → μ=7.71 10^{-5} cm^{-1} → after 1m → I/I_0= 99.2%
- 10 keV photons in air : μ/ρ=5.1 cm^2/g with ρ(air)=0.001205 g/cm^3 → μ=6.15 10^{-3} cm^{-1} → after 1m → I/I_0= 54.1%
- 1 MeV photons in Pb: μ/ρ=0.070 cm^2/g with ρ(lead)=11.35 g/cm^3 → μ=7.95 10^{-1} cm^{-1} → after 1m → I/I_0≈0%

  → after 1cm → I/I_0≈45.2%
- 1 MeV photons in H_20: μ/ρ=0.071 cm^2/g with ρ(H_20)=1.0 g/cm^3 → μ=7.7 10^{-2} cm^{-1} → after 1m → I/I_0≈0%

  → after 1cm → I/I_0≈92.5%

http://www.nist.gov/pml/data/xraycoef/index.cfm

Mass energy-transfer coefficient

- μ_{tr}/ρ: **Mass energy-transfer coefficient** (unit: m^2kg^{-1}) → quotient of $dE_{tr}/(EN)$ (with E the energy of all particles excluding rest energy) by ρdl where $dE_{tr}/(EN)$ is the fraction of energy of the incident particles transformed in kinetic energy of charged particles by interactions in a depth dl of the medium of density ρ → also: $\mu_{tr} = (E_{tr}/E)\mu$
- Also defined as →

$$\frac{\mu_{tr}}{\rho} = f_{ph}\frac{\tau}{\rho} + f_C\frac{\sigma}{\rho} + f_{pn}\frac{\kappa_n}{\rho} + f_{pe}\frac{\kappa_e}{\rho}$$

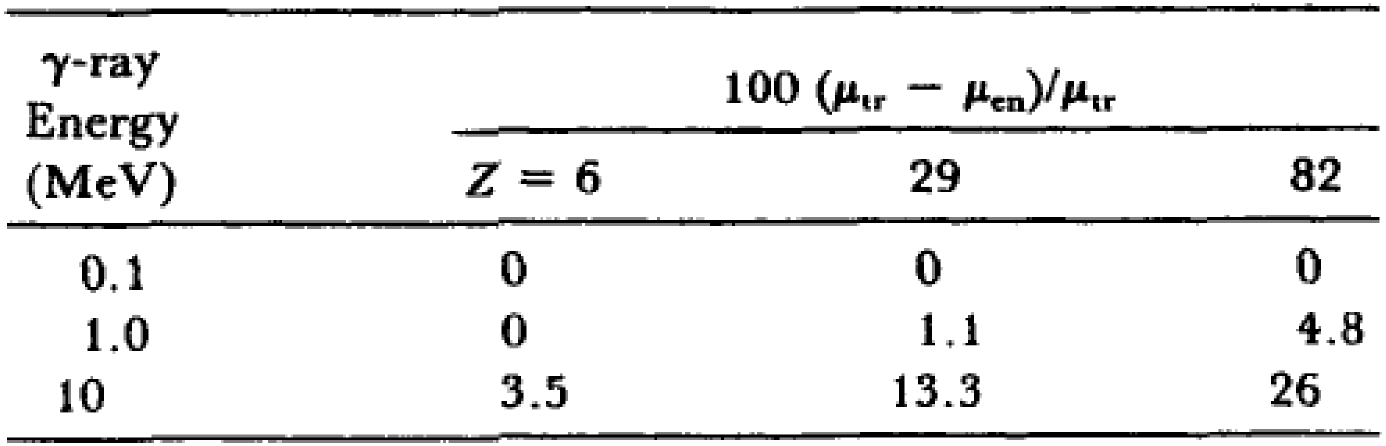
with f_i, the fractions of photon energy transferred to kinetic energy of charged particles for all processes

Mass energy-absorption coefficient

- A part of kinetic energy of charged particles set in motion can be absorbed no locally → a part of the energy can be lost in radiative processes (especially Bremsstrahlung but also in-flight annihilation or fluorescence radiations)
- μ_{en}/ρ: **Mass energy-absorption coefficient** (unit: m^2kg^{-1}) → product of the mass energy-transfer coefficient by *(1-g), with* g the fraction of energy lost on average in radiative processes as the charged particles slow to rest in the material
- *g* is specific to the material

$$\frac{\mu_{en}}{\rho} = (1-g)\frac{\mu_{tr}}{\rho}$$

Comparison $\mu_{\mathrm{tr}} \leftrightarrow \mu_{\mathrm{en}}$



γ-ray Energy (MeV)	$100\,(\mu_{\mathrm{tr}} - \mu_{\mathrm{en}})/\mu_{\mathrm{tr}}$		
	$Z = 6$	29	82
0.1	0	0	0
1.0	0	1.1	4.8
10	3.5	13.3	26