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Dosimetry for indirectly ionizing radiation

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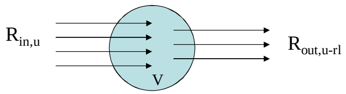
Indirectly ionizing radiation

- Indirectly ionizing radiation experience few interactions, but releases relatively large amounts of energy in each interaction
- Example: photons, neutrons
- Secondary charged particles (electrons most relevant) will deposit the transferred energy over a short distance
- How large are the energy transfers from e.g. photons to matter for a given volume element?
- The energy-mass budget is important!

Energy transferred, ε_{tr}

- A photon field with total energy $R_{in,u}$ enters a volume, while $R_{out,u\text{-}rl}$ is the energy leaving the volume:



- Energy transferred:

$$\varepsilon_{tr} = R_{in,u} - R_{out,u-rl} + \Sigma Q$$

- ε_{tr} is the total energy transferred from photons to electrons, and is the sum of all kinetic energy released

Energy transferred, ε_{tr} 2

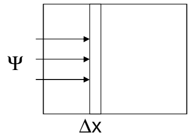
- u-rl: uncharged minus radiative losses; radiative losses by secondary electrons should not be included
- ε_{tr} is a stochastic quantity
- ΣQ: energy from conversion of rest mass or *vice versa*
- Example, pair production $\Sigma Q = -2m_e c^2$

KERMA

- Kinetic Energy Release per MAss:

$$K = \frac{d\varepsilon_{tr}}{dm} \quad \text{unit: [J/kg]}$$

- K is the expectation value of the energy transferred per unit mass in a point of interest
- Consider monoenergetic photons (quantum energy hν) passing a thin layer:



S: cross section of photon field

KERMA 2

- Probability per unit lenght for photon interaction multiplied with fraction of energy transferred: μ_{tr}
- Total energy transferred to electrons: $\varepsilon_{tr}=N(h\nu)\mu_{tr}\Delta x$
- Energy fluence for monoenergetic photons:

$$\Psi = (h\nu)\Phi = \frac{N(h\nu)}{S}$$

- KERMA becomes: $K = \frac{\varepsilon_{tr}}{m} = \frac{N(h\nu)\mu_{tr}\Delta x}{\rho V} = \frac{N(h\nu)\mu_{tr}\Delta x}{\rho S \Delta x}$

$$= \Psi \frac{\mu_{tr}}{\rho}$$

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KERMA 3

- KERMA is determined by the energy fluence and the mass energy transfer coeffecient
- For a distribution of photons:

$$K = \int_0^{h\nu_{max}} \Psi_{h\nu} \frac{\mu_{tr}}{\rho} d(h\nu)$$

- Remember that μ_{tr}/ρ is dependent on the photon energy and atomic number of the absorber

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Components of KERMA

- Kerma includes all kinetic energy given to secondary electrons, and this energy may be lost by:
  - Collisions
  - Radiative losses
- Kerma may be divided into two components:

  $K=K_c+K_r$

- K_c: collision Kerma; provides a measure of the energy loss per unit mass from photons resulting in collisional losses for secondary electrons!

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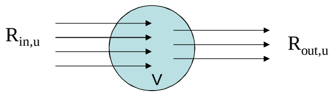
Net energy transferred ε_{tr}^{n}

- ε_{tr}^{n} is defined as:



$$\varepsilon_{tr}^{n} = R_{in,u} - R_{out,u} + \Sigma Q$$

- $R_{out,u}$ er is all photon energy leaving the volume element (including brehmsstrahlung)
- ε_{tr}^{n} is thus the total kinetic energy of secondary electrons which is not lost as brehmsstrahlung

Collision Kerma

- Is defined by:

$$K_c = \frac{d\varepsilon_{tr}^{n}}{dm}$$

- May take radiative losses into account by defining the qantity *g*; the fraction of kinetic energi lost as brehmsstrahlung

$$K_c = K(1-g) = \Psi \frac{\mu_{tr}}{\rho}(1-g)$$

- Definition: $\frac{\mu_{en}}{\rho} \equiv \frac{\mu_{tr}}{\rho}(1-g)$
- μ_{en}/ρ: mass energy absorption coeffecient

Collision Kerma 2

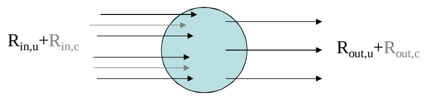
- K_c is thus:

$$K_c = \Psi \frac{\mu_{en}}{\rho}$$

- Generally: $K_c < K$
- Special case: Low energy photons releases low energy electrons in an absorber of low atomic number Z. Radiative losses are insignificant, and $g \approx 0$ and $K_c \approx K$

Energy imparted and absorbed dose

- Look at all energy transport (both charged and uncharged particles) through the volume of interest:



$$\varepsilon = R_{in,u} + R_{in,c} - R_{out,u} - R_{out,c} + \Sigma Q$$

- Absorbed dose is (at last) defined as:

$$\boxed{D = \frac{d\varepsilon}{dm}}$$

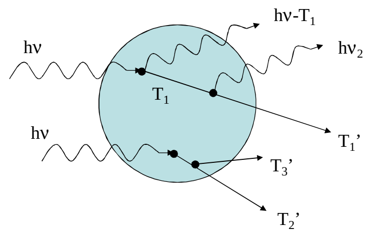
unit: [Gy] = [J/kg]

Absorbed dose

- The absorbed dose is all energy imparted to the volume per mass
- May not be directly related to photon interaction coefficients
- However, in some cases the dose may be approximated by K_c

ε_{tr} , ε_{tr}^{n} , ε : example

- Two photons interacts in a volume of interest ($\Sigma Q=0$):



ε_{tr} , ε_{tr}^{n} , ε : example 2

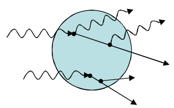
- Photon 1:

  $\varepsilon_{tr} = R_{in,u} - R_{out,u\text{-}rl} = h\nu - (h\nu - T_1) = T_1$

  $\varepsilon_{tr}^{n} = R_{in,u} - R_{out,u} = h\nu - (h\nu - T_1) - h\nu_2 = T_1 - h\nu_2$

  $\varepsilon = R_{in,u} + R_{in,c} - R_{out,u} - R_{out,c}$

  $= h\nu + 0 - (h\nu - T_1) - h\nu_2 - T_1' = T_1 - h\nu_2 - T_1'$



- Photon 2:

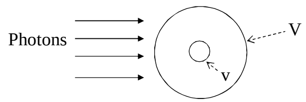
  $\varepsilon_{tr} = h\nu - 0 = h\nu$

  $\varepsilon_{tr}^{n} = h\nu - 0 = h\nu$

  $\varepsilon = h\nu + 0 - T_2 - T_3 = h\nu - T_2' - T_3'$

Charged particle equilibrium (CPE)

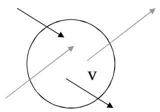
- Photons enter a volume V, which includes a smaller volume v:



- CPE: Number of charged particles of a given type and energy entering v is equal to the number of particles of the same type and energy leaving
- Certain conditions must be fullfilled:
  - V must be homogeneous
  - Photon attenuation must be negligible

CPE 2

CPE:



- If CPE is present, $R_{in,c} = R_{out,c}$
- Energy imparted:

$$\varepsilon = R_{in,u} + R_{in,c} - R_{out,u} - R_{out,c} = R_{in,u} - R_{out,u} = \varepsilon_{tr}^{n}$$

- In this case, absorbed dose equals collision Kerma:

$$D = \frac{\varepsilon}{m} \overset{CPE}{=} \frac{\varepsilon_{tr}^{n}}{m} = K_c = \Psi \frac{\mu_{en}}{\rho}$$

Absorbed doses under CPE

- K_c, and thus dose, is given by $\Psi\mu_{en}/\rho$, and is thus proportional to the interaction probability in a given absorber
- Two different absorbers A og B placed in the same point in a radiation field:

$$\frac{D_A}{D_B} = \frac{\Psi\left(\frac{\mu_{en}}{\rho}\right)_A}{\Psi\left(\frac{\mu_{en}}{\rho}\right)_B} = \frac{\left(\frac{\mu_{en}}{\rho}\right)_A}{\left(\frac{\mu_{en}}{\rho}\right)_B}$$

CPE, example

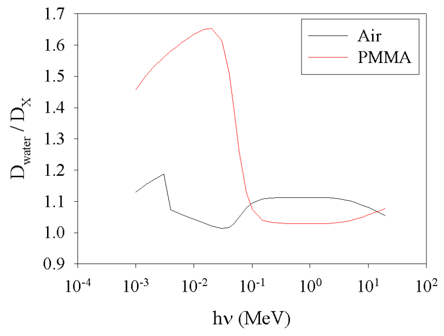
- Two small volumes of water and air is placed in same point in a radiation field (1 MeV photons) where CPE exists. What is the dose ratio?
- Use tabulated values for μ_{en}/ρ (Attix):

  μ_{en}/ρ(water) = 0.0309

  μ_{en}/ρ(air) = 0.0278

  $\rightarrow$ D(air) / D(water) = 0.90

CPE, example 2

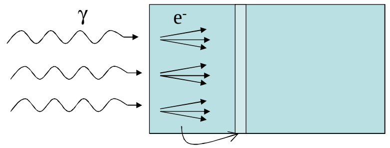


CPE, problems

- When the photon energy increases, the range of the secondary electrons increases more than the photon pathlenght

Photon energy(MeV)	Photon attenuation (%) in water within the range of a secondary electron
0.1	0
1	1
10	7
30	15

CPE, problems 2



e^- with long range contributes to the dose at the layer. Photon beam significantly attenuated between the interaction point and the layer – fewer electrons are generated in the layer than what was generated upstream.

- Thus: $R_{in,c} > R_{out,c}$ and:

$$\Rightarrow \varepsilon = R_{in,u} + R_{in,c} - R_{out,u} - R_{out,c} > \varepsilon_{tr}^{n}$$

$$\Rightarrow D > K_c$$

- Most relevant for high photon energies

TCPE

- Transient Charged Particle Equilibrium: electrons originating from upstream contributes to the dose, while the photon contribution ($R_{in,u}$-$R_{out,u}$) is given by the collision Kerma
- Assumption: absorbed dose propotional to K_c

$$\overset{TCPE}{D} = K_c(1+f_{TCPE})$$

$$f_{TCPE} \geq 0$$