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Dosimetry of indirectly ionizing radiation

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Indirectly ionizing radiation

- Indirectly ionizing radiation has relative few interactions with matter, but loses a relative large amount of the energy in each interaction
- Examples: photons, neutrons
- Secondary charged particles (often electrons) will then depose the energy in a relative small distance
- What is the *energy transferred* from interactions between photons and matter in a given volume?
- Energy accounting important?

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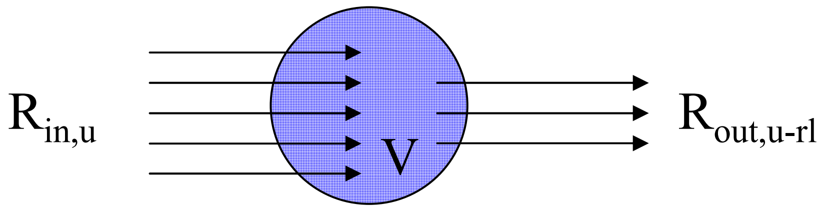
Energy transferred, ε_{tr} 1)

- A photon field of total energy $R_{in,u}$ entering a volume and $R_{out,u\text{-}rl}$ is the amount of photon energy of *interest* which leaving the volume:



- Energy transferred:

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

- ε_{tr} is the total energy transferred from the photons to the charged particles and the sum of all kinetic energy transferred to charged particles

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Energy transferred, ε_{tr} 2)

- u-rl: uncharged minus radiative loses; if the secondary electrons have lost energy by bremsstrahlung shall these photons not be included in the Rout,u-rl
- ε_{tr} is a stochastic value
- $\sum Q$: energy derived from rest mass in V (m→E positive, E→m negative)
- Ex: pair-production: $\sum Q = -2m_e c^2$

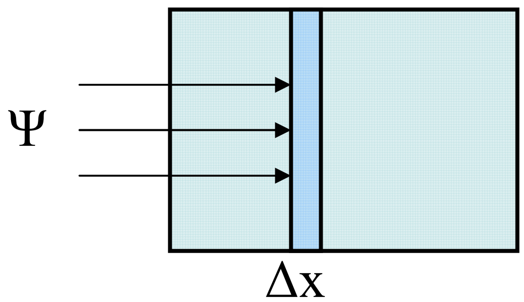
  annihilation: $\sum Q = +2m_e c^2$

KERMA 1)

- Kinetic Energy Release per Mass:

$$K \equiv \frac{d\varepsilon_{tr}}{dm} \qquad \text{unit [J/kg]}$$

- K is the energy transferred to charged particles per mass unit in a point of interest
- Consider a monoenergetic photon field (energy hν) which pass through a thin layer in a object



S: cross-area of photon field

KERMA 2)

- Probability per length unit of a photon interaction with a given fraction transferred to electrons is μ_{tr}
- Transferred energy to electrons: $\varepsilon_{tr} = N(h\nu)\mu_{tr}\Delta x$
- Energy fluence of monoenergetic photons:

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

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

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KERMA 3)

- Kerma is the dependent of the energy fluence and mass-energy transfer coefficient
- For a distribution (a spectrum) of photons are given:

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

- Remember that μ_{tr}/ρ dependent of atom number and photon energy

Kerma components

- Kerma includes all kinetic energy given to electrons and the energy will be lost by:
  - Collision
  - Radiation losses
- Kerma can be divided in components: $K = K_c + K_r$
- K_c: *collision kerma*; will give a value of the energy losses per mass unit from photons which results in collision losses of electrons!

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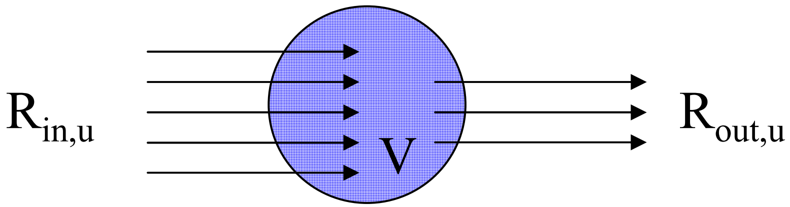
Net energy transferred, ε_{tr}^{n}

- ε_{tr}^{n} defined from a volume:



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

- $R_{out,u}$ is all energy emitted out of the volume as photons (also the bremsstrahlung)
- ε_{tr}^{n} is then the total kinetic energy past to electrons which is not lost in bremsstrahlung

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Collision kerma 1)

- Defined by:

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

- Account from the bremsstrahlung by introducing *g*; the fraction of kinetic energy resulting in bremsstrahlung:

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

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

- μ_{en}/ρ: mass energy-absorption coefficient

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Collision kerma 2)

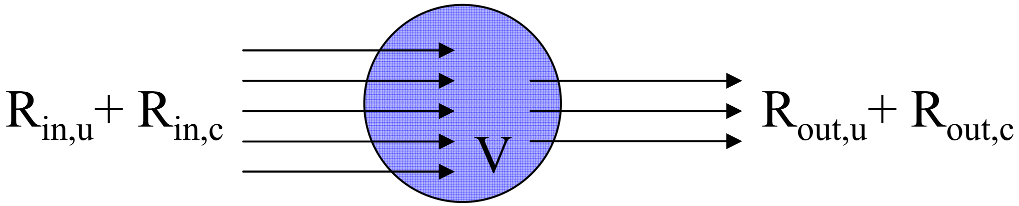
- K_c is then given as:

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

- Generally: $K_c < K$
- Special case: Low energetic photons give origin to low energetic secondary electrons in a substance of low Z. Bremsstrahlung is then nelectable, g=0 and $K_c = K$

Absorbed energy and dose, ε and D

- Consider all transport of energy (both charged and uncharged particles) trough a volume:



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

- Absorbed dose is defined (and only defined) as:

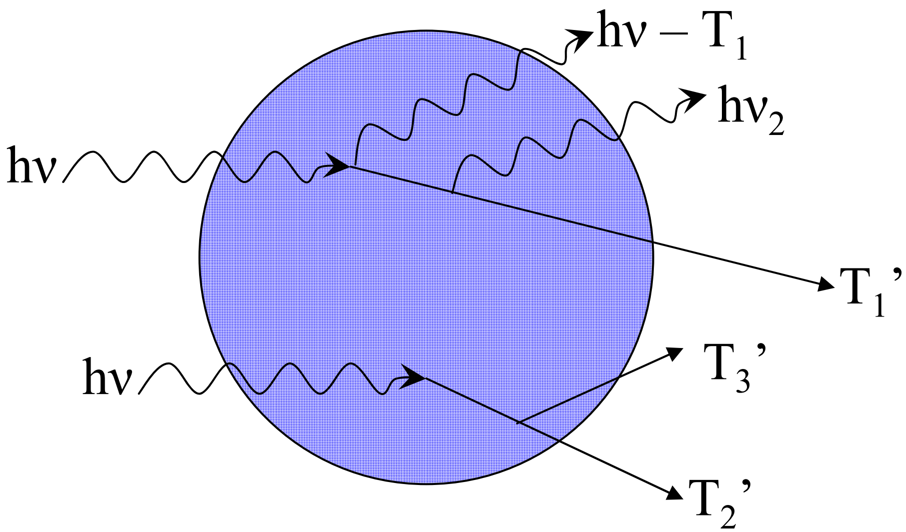
$$D = \frac{d\varepsilon}{dm} \qquad \text{unit: } [\text{Gy}] = [\text{J/kg}]$$

Dose

- The dose is all energy which stays in the volume per mass unit
- Can not be related to photon coefficients as K and K_c
- But: in some special cases can absorbed dose be approximated with K_c

ε_{tr} , ε_{tr}^{n} , ε: example

- Two photons interact in volume V (∑Q = 0):



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ε_{tr} , ε_{tr}^{n} , ε: example

- Score form photon 1:

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

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

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

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

- Score form photon 2:

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

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

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

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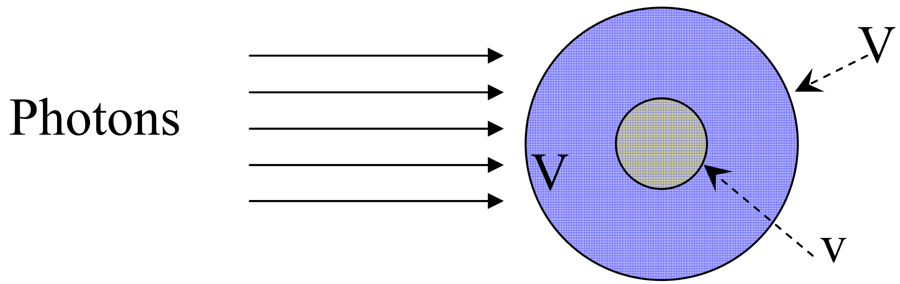
Charged Particle Equilibrium (CPE) 1)

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



- Charged particle equilibrium: The number of charged particles of given type and energy which entering v is equal the number of particles of same type and energy which leaves the volume v
- Certain conditions must be present to have CPE – the substance most be homogenous and *the photon field attenuation most be nelectable*

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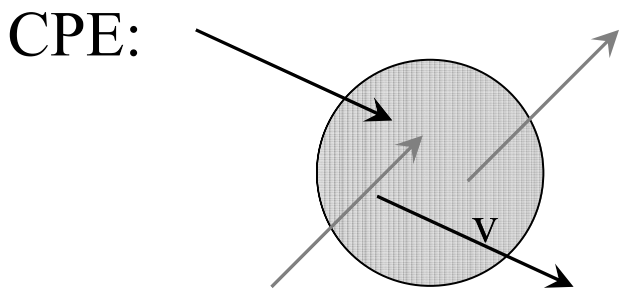
CPE 2)



- When CPE is present: $R_{in,u} = R_{out,u}$

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

- And the dose equals collision kerma:

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

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Dose at CPE

- The dose at CPE is $\Psi\mu_{en}/\rho$, and is then proportional with "the interaction probability" of the photons
- Two substances A and B is placed in the same point in a radiation field, will then get doses related to each other by:

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

CPE, example

- Two volumes of water and air is positioned in the same point in a radiation field (1 MeV photons) with CPE present. If the dose two the air is 1 Gy what is the dose to water?
- Use the tabulated values of μ_{en}/ρ (Attix) a get:

$(\mu_{en}/\rho)_{water} = 0.0309$

$(\mu_{en}/\rho)_{air} = 0.0278$

$\rightarrow D_{water} = D_{air} \cdot (\mu_{en}/\rho)_{water} / (\mu_{en}/\rho)_{air} = 1.11 Gy$

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CPE, problem 1)

- If the photon energy increase, will the penetration ability of the secondary electrons increase more than that of the photons
- Attenuation of the photon field trough the range of the secondary electrons:

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

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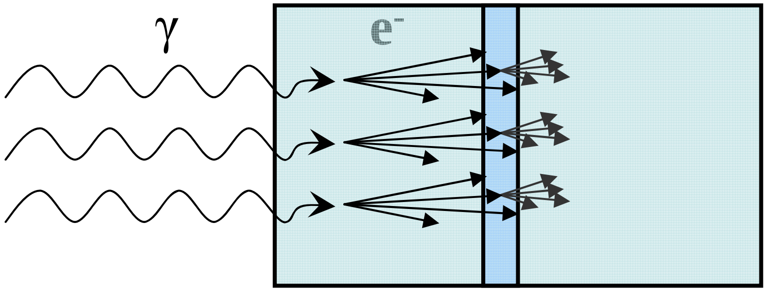
CPE, problem 2)



"upstream" e^- entering have higher energy then e^- emitted and leaving; due to the photon attenuation

- Then is $R_{in,c} > R_{out,c}$

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

$$\Rightarrow D > K_c$$

- The case of high photon energies

TCPE

- Transient Charged Particles Equilibrium: electrons from "upstream" contribute to the dose and the photon contribution ($R_{in,u} - R_{out,u}$) is the collision kerma
- Dose proportional with K_c:

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

$$f_{TCPE} \geq 0$$