Radiation Physics

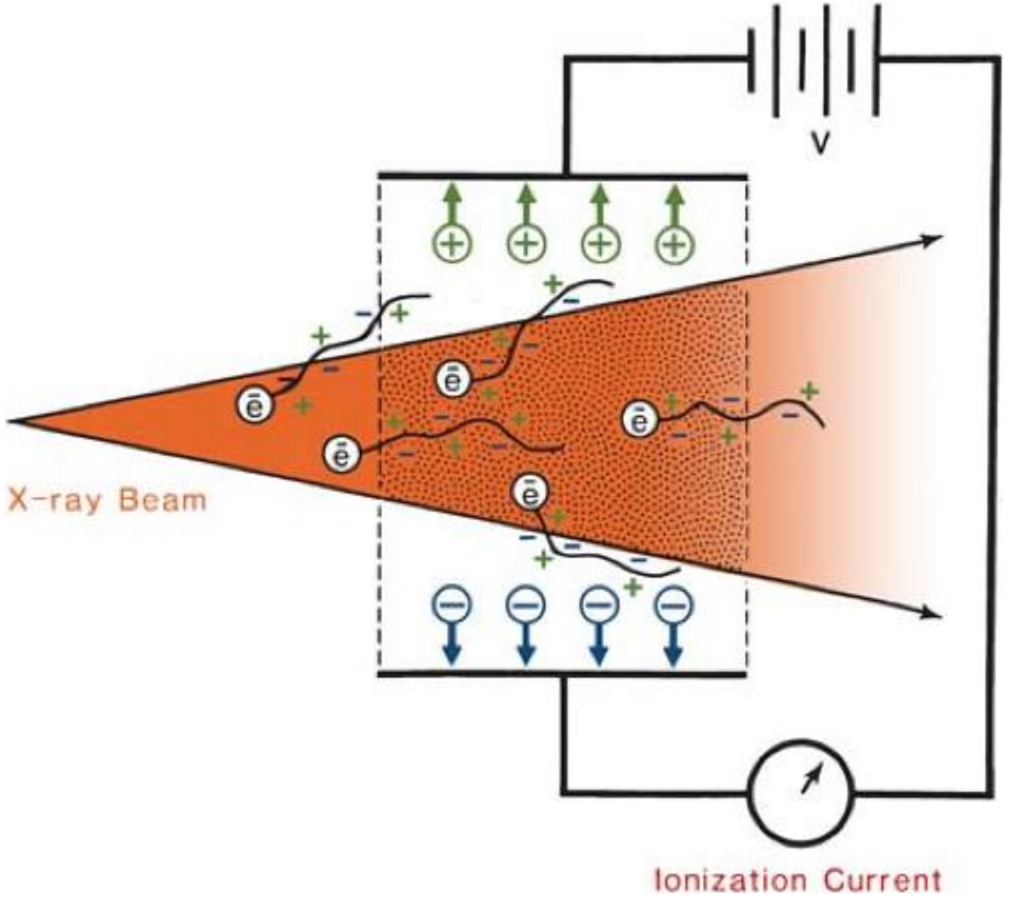
SEAN ZHANG, PH.D.

626-218-2160

SEANZHANG@COH.ORG

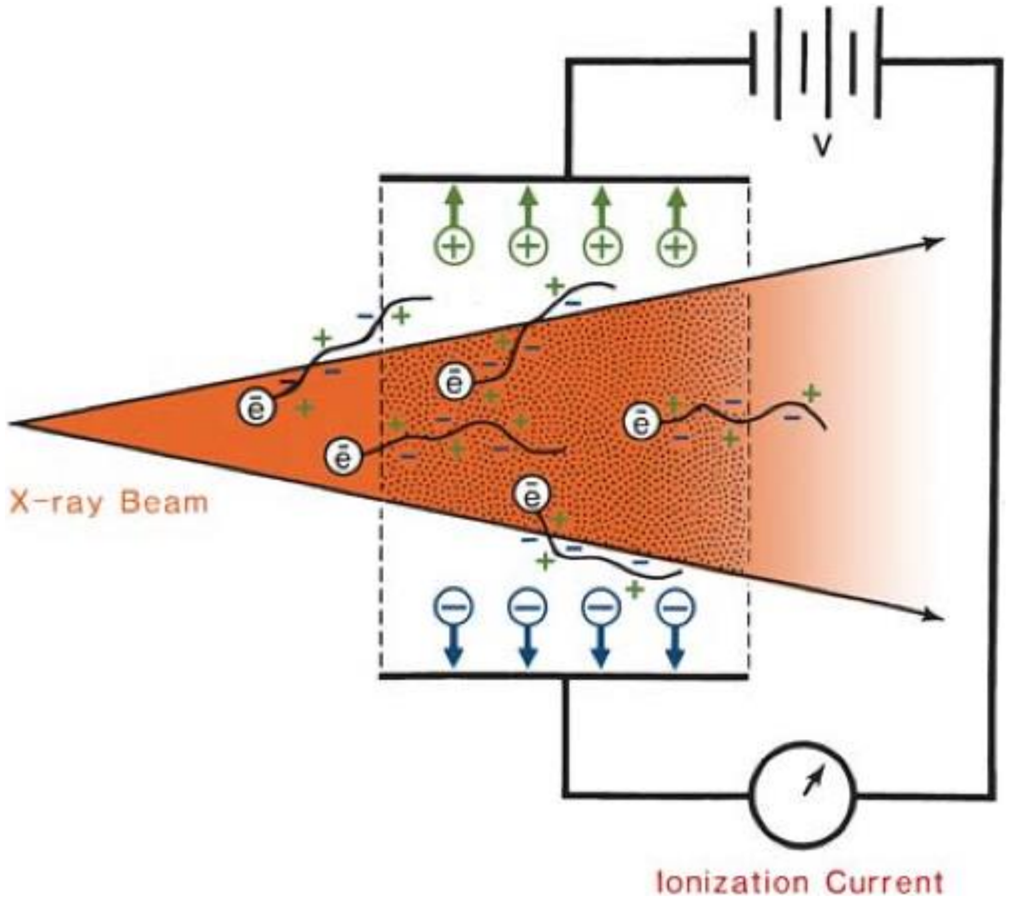
Measurement of Absorbed Dose

Chapter 8



Exposure

- Exposure (Chapter 6.2)
  - Measure of ionization produced in air by photons
  - X = dQ/dm
- Exposure unit
  - C/kg
  - Roentgen, R
    - 1R = 1 esu/cc of air at STP
      - 1 esu = 3.333×10^{-10} C
      - Density of air, ρ = 1.29 kg/m^3 and mass of 1 cc of air = 1.29 kg/m^3 x 10^{-6} m^3 = 1.29×10^{-6} kg
  - 1 R = 1 esu/ 1 cc of air = 3.333×10^{-10} C/1.29×10^{-6} kg = 2.58×10^{-4} C/kg



KERMA

- Kinetic energy released in the matter, KERMA
  - Measure of energy transfer from photons to charged particles in medium
  - $K = dE_{tr}/dm$
- KERMA unit (tip: same as dose)
  - J/kg
- Kerma is a quantity applicable to **indirectly ionizing** radiations, such as photons and neutrons.
- Kerma is directly proportional to the photon energy fluence, Ψ
  - $K = \Psi\ \mu_{tr}/\rho$
- The total kerma is divided into two components: collision kerma, K^{col} and radiation Kerma, K^{rad}
  - $K = K^{col} + K^{rad}$
  - $K^{col} = \Psi\ \mu_{en}/\rho$
    - under CPE (charged particle equilibrium): $D = K^{col} = \Psi\ \mu_{en}/\rho$

KERMA

What is the exact meaning of **"Energy Transfer "** ?

The term energy transfer refers to **uncharged particles**, e.g., photons, neutrons, etc.

The photon fate after an interaction with an atom includes two possible outcomes:

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

KERMA

Continued: What is the exact meaning of **"Energy Transfer "** ?

- The energy that is transferred in a photon interaction to a light charged particle (mostly a secondary electron) is called an energy transfer.
- This process is described by the **energy transfer coefficient**

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

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

KERMA

Relation between **"Energy Transfer"** and **"Energy Absorption"**

- For charged particles, most of the energy loss is directly absorbed $\Rightarrow$ **Energy Absorption**

- For uncharged particles, energy is transferred in a first step to (secondary) charged particles $\Rightarrow$ **Energy Transfer**.

  In a second step, the secondary charged particles lose their energy according to the general behavior of charged particles (again **Energy Absorption).**

  The energy of uncharged particles like photons or neutrons is imparted to matter in a two-stage process.

Absorbed Dose

- Absorbed dose is a quantity applicable to both indirectly and directly ionizing radiations.
- **Indirectly ionizing** radiation means:
  the energy is imparted to matter in a two-step process.
  - In the first step (resulting in kerma), the indirectly ionizing radiation transfers energy as kinetic energy to secondary charged particles.
  - In the second step, these charged particles transfer a major part of their kinetic energy to the medium (finally resulting in absorbed dose).
- **Directly ionizing** radiation means:
  - charged particles transfer a major part of their kinetic energy directly to the medium (resulting in absorbed dose).

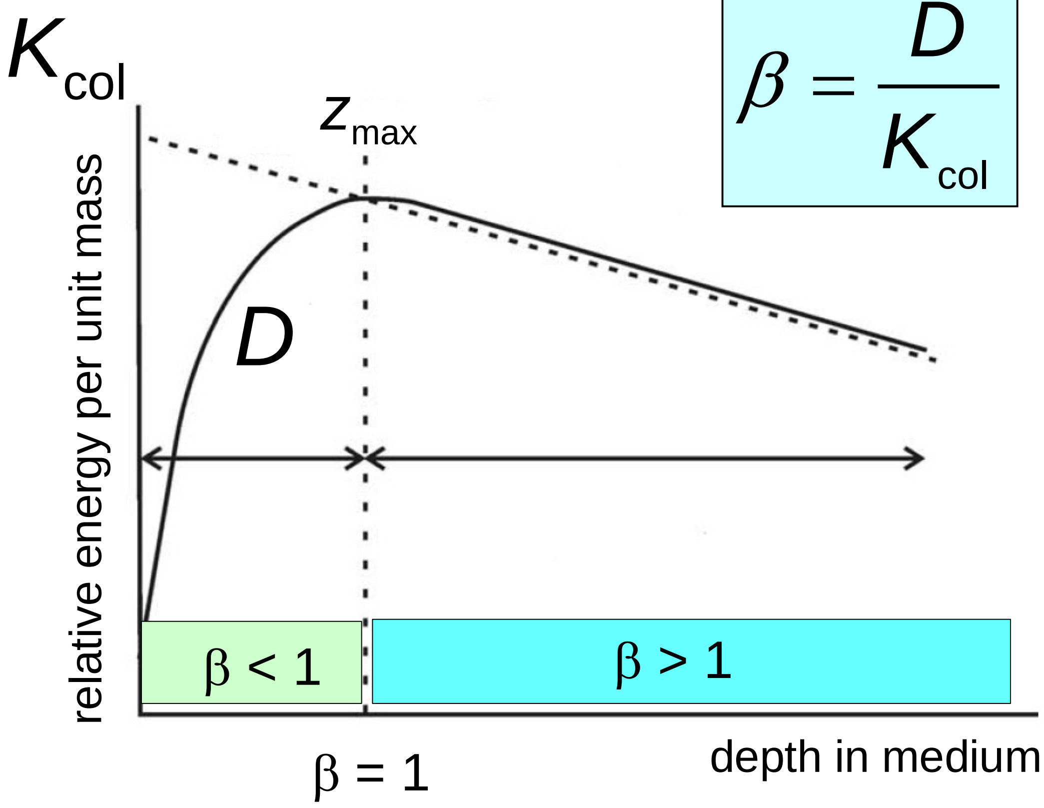
Dose

- Radiation absorbed dose, absorbed dose, or dose
  - Measure of energy deposited in a medium by ionizing radiation
  - D = dE/dm
- Dose unit
  - Gray (Gy), J/kg
  - rad
  - 1 rad = 1 cGy = 0.01 Gy
- $D = K^{col} = \Psi\ \mu_{en}/\rho$
  - under CPE (charged particle equilibrium)
  - Ψ : Energy fluence, J/ m^2
  - μ_{en}/ρ : Mass energy absorption coefficient, m^2/kg
- $$D_{med} = \Phi \cdot \left(\frac{S_{col}}{\rho}\right)_{med} \qquad \left(\frac{S}{\rho}\right)_{tot} = \left(\frac{S}{\rho}\right)_{col} + \left(\frac{S}{\rho}\right)_{rad}$$

  Φ : fluence, $1/m^2$

  S_{col}/ρ: collision stopping power, (**MeV** m^2/kg)

Relationship between collision kerma and absorbed dose



$$\beta = \frac{D}{K_{col}}$$

In the buildup region:
$\beta < 1$

In the region of a transient charged particle equilibrium:
$\beta > 1$

At the depth $z = z_{max}$, a true charged particle equilibrium exists.
$\beta = 1$

$$D = K_{col} = K \cdot (1 - \bar{g})$$

W/e and f factor

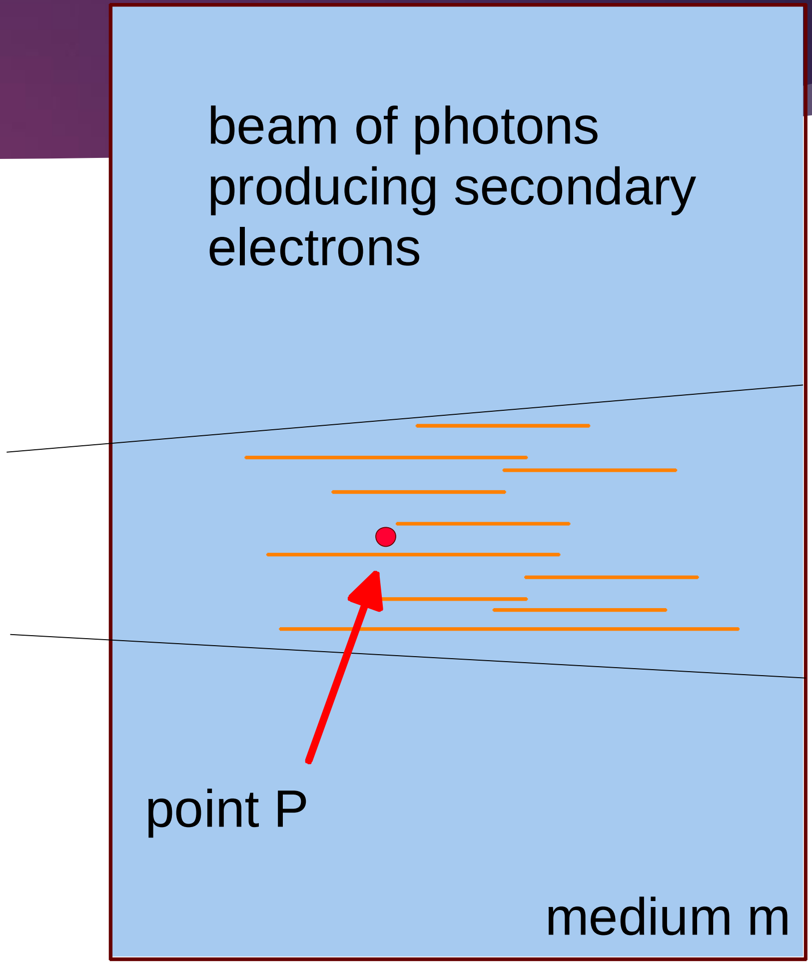
- W, Mean energy required to produce an ion pair in dry air
  - W = 33.97 eV/ion pair
  - W = 33.97 J/C
- Absorbed dose to air, D_{air}
  - $D_{air} = (K^{col})_{air} = X\ (W/e)$
- D_{air} (rad)= 0.876 (rad/R) X(R)
  - Roentgen-to-rad conversion factor
- **Dose to medium**
  - $D_{med}/\ D_{air} = (\mu_{en}/\rho\ )_{med\text{-}air}\ A,$ $\qquad A = \Psi_{med\text{-}air}$
  - $\mathbf{D_{med}} = D_{air}\ (\mu_{en}/\rho\ )_{med\text{-}air}\ A = \mathbf{X\ (W/e)\ (\mu_{en}/\rho\ )_{med\text{-}air}\ A}$
- f factor for MV beams, $f_{med} = [(W/e)\ (\mu_{en}/\rho\ )_{med\text{-}air}] = 0.876\ (\mu_{en}/\rho\ )_{med\text{-}air}$ if convert R to rad
  - $f_{air} = 0.876$ $\qquad f_{water} = 0.962$ $\qquad f_{tissue} = 0.971$

Cavity Theory

- Consider a point P within a medium m within a beam of photon radiation (right).

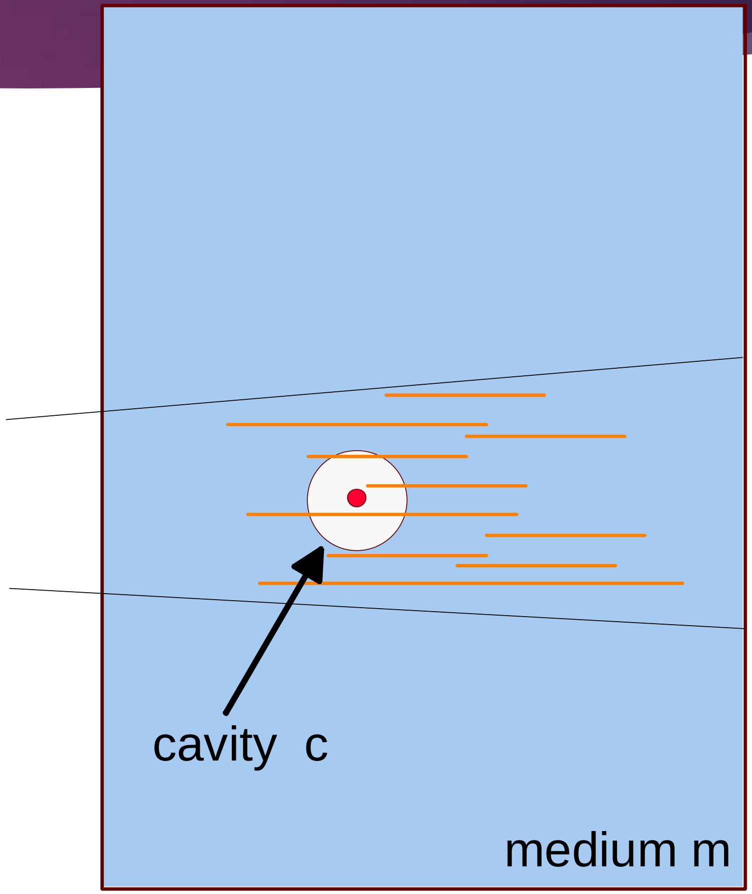
- The absorbed dose at point P can be calculated by:

$$D_{\text{med}}(\text{P}) = \Phi \cdot \left(\frac{\bar{S}}{\rho} \right)_{\text{med}}$$



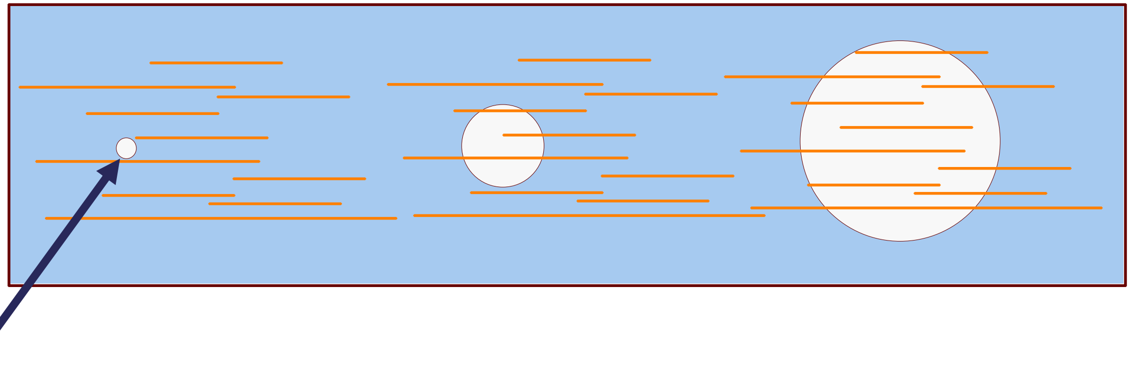
Cavity Theory

- In order to **measure** the absorbed dose at point P in the medium, it is necessary to introduce a radiation sensitive device (dosimeter) into the medium.
- The sensitive medium of the dosimeter is frequently called a **cavity**.
- Generally, the sensitive medium of the cavity will not be of the same material as the medium in which it is embedded.



Cavity Theory

- Cavity sizes are referred to as **small, intermediate or large** in comparison with the **ranges of secondary charged particles** produced by photons in the cavity medium.



- The case where the range of charged particles (electrons) is much larger than the cavity dimensions (i.e. the cavity is regarded as small) is of special interest.

Cavity Theory

- In order to determine D_m from D_c, various cavity theories have been developed depending on the size of the cavity.

Examples are:

- for small cavities:
  - **Bragg–Gray theory**
  - **Spencer–Attix theory**
- for cavities of intermediate sizes:
  - **Burlin theory**.

Cavity Theory

- The Bragg–Gray cavity theory was the first cavity theory developed to provide a relation between **the absorbed dose in a dosimeter** and the **absorbed dose in the medium** containing the dosimeter.

- There are **two conditions** for application of the Bragg–Gray cavity theory.
- **Condition (1):**
  The cavity must be **small** when compared with the range of charged particles incident on it, so that its presence does not perturb the fluence of charged particles in the medium;

Cavity Theory

- The result of condition (1) is that the electron fluences are almost the same and equal to the equilibrium fluence established in the surrounding medium.
- However:
  - This condition can only be valid in regions of **charged particle equilibrium** or **transient charged particle equilibrium**.
  - The presence of a cavity always causes some degree of **fluence perturbation** that requires the introduction of a fluence perturbation correction factor.

Cavity Theory

- **Condition (2):**
  The absorbed dose in the cavity is deposited solely by those electrons crossing the cavity.

- This implies that
  - Photon interactions in the cavity are assumed negligible and thus ignored.
  - All electrons depositing the dose inside the cavity are produced outside the cavity and **completely cross the cavity**. Such electrons can be called "**crossers**".
  - No secondary electrons are produced inside the cavity (starters) and no electrons stop within the cavity (stoppers).

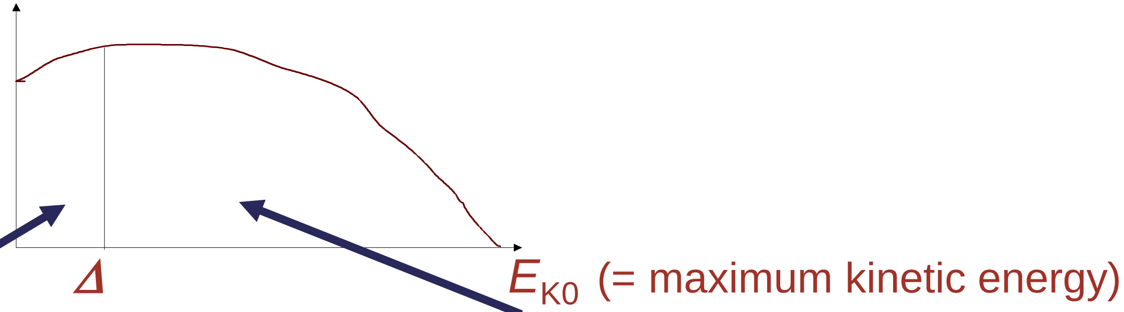
Cavity Theory

- Bragg-Gray cavity theory: The ionization produced in a gas-filled cavity placed in a medium is related to the energy absorbed in the surrounding medium
  - The absorbed dose to the medium at point P can be obtained from measured absorbed dose in the cavity by multiplication with the stopping power ratio
  - $\mathbf{D_{med} = J_g\ (W/e)\ (S/\rho)_{med\text{-}gas}}$
- Stopping power, S
  - The energy loss by electrons per unit length of a material
  - Spencer-Attix cavity theory
    - Restricted stopping power, L
    - cut off energy, δ: ~10-20 keV
    - $\mathbf{D_{med} = J_g\ (W/e)\ (L/\rho)_{med\text{-}gas}}$
- Dose calibration protocol, TG-51
  - $D_w = M\ k_Q\ N^{Co60}$
  - $M = P_{tp}\ P_{elec}\ P_{ion}\ P_{pol}\ M_{raw}$

Cavity Theory

The concept of the Spencer-Attix cavity theory:

The total secondary electron fluence (crossers and δ electrons) is divided into two components based on a user-defined **energy threshold Δ**.



Secondary electrons with kinetic energies E_K less than Δ are considered "slow" electrons. They deposit their energy locally.

Secondary electrons with energies larger than or equal to Δ are considered “fast” electrons. They all deposit their energy like crossers.

Other Dose Measurement Methods

- Calorimetry: temperature change due to ionizing radiation, limits to relatively large dose
- Chemical Dosimetry, Fricke Ferrous Sulfate dosimeter, limits in laboratory use due to storage
- Solid State Methods
  - TLD (**T**hermo**l**uminescence **d**osimetry)
  - OSLD (**O**ptically **S**timulated **L**uminescence **d**osimetry), nanodot
  - RPLD (**R**adio-**p**hoto**l**uminescence **d**osimetry)
    - The silver activated phosphate glass irradiated with ionizing radiations emits luminescence when exposed to UV lights
- Film Dosimetry
  - Characteristic curve: log (exposure) versus optical density
    - Gradient, gamma, slope = (D2-D1)/Log (E2-E1)
    - Speed (sensitivity) = 1/R for OD equal to unity
    - Latitude (contrast) = range of log exposure to give an acceptable density range)
  - Film badge dosimeter: personal dosimetry used for monitoring cumulative radiation dose
    - Tissue depth of interest include

      Skin: 0.07 cm

      Lens of the eye: 0.30 cm

      Deep dose, or dose to the whole body: 1.0 cm