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ICTP SChool On MEdical PHysics For RAdiation THerapy: DOsimetry And TReatment PLanning For BAsic And ADvanced APplications

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Dosimetry: Fundamentals

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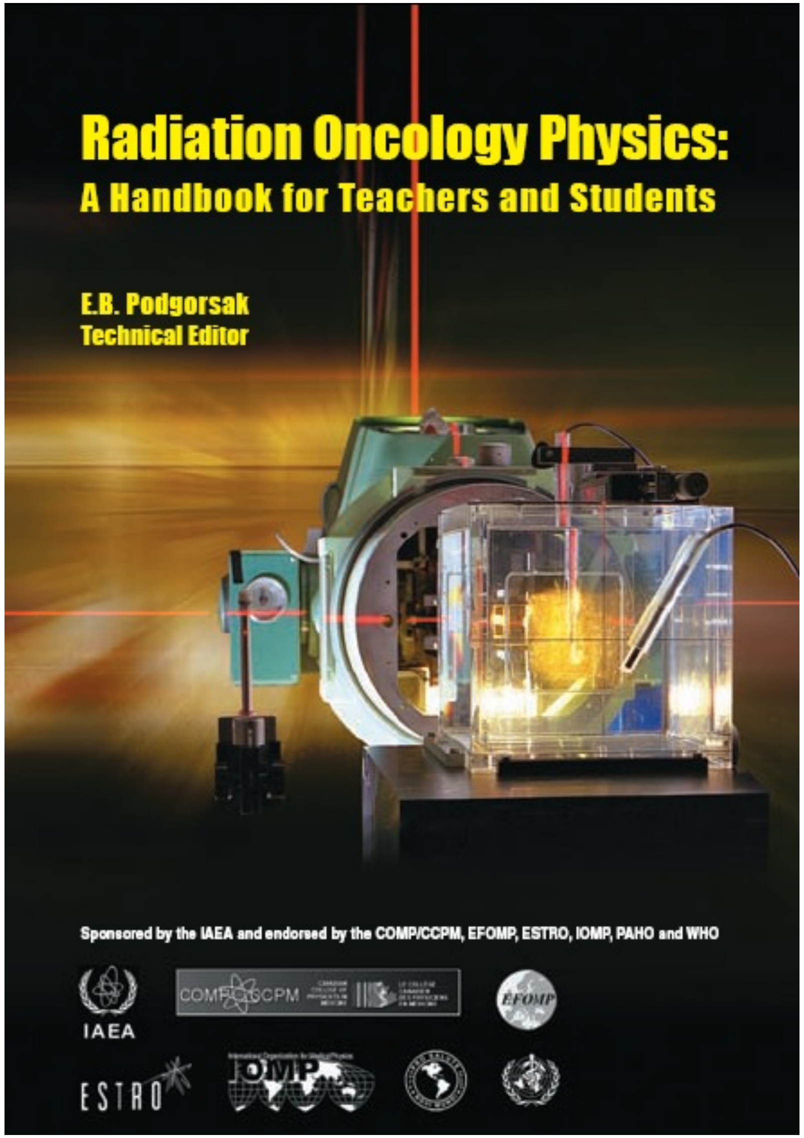
Content:

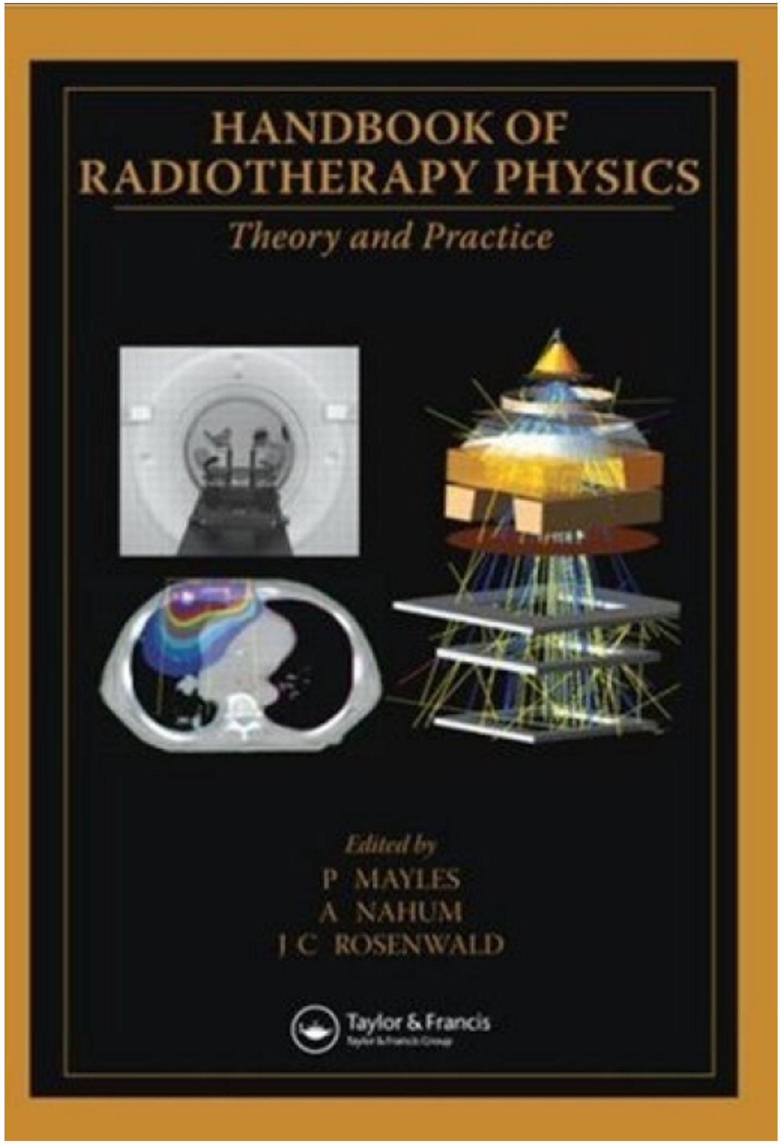
(1) Introduction: Definition of "radiation dose"

(2) General methods of dose measurement

(3) Principles of dosimetry with ionization chambers:
- Dose in air
- Stopping Power
- Conversion into dose in water, Bragg Gray Conditions
- Spencer-Attix Formulation

This lesson is partly based on:





IAEA Website:

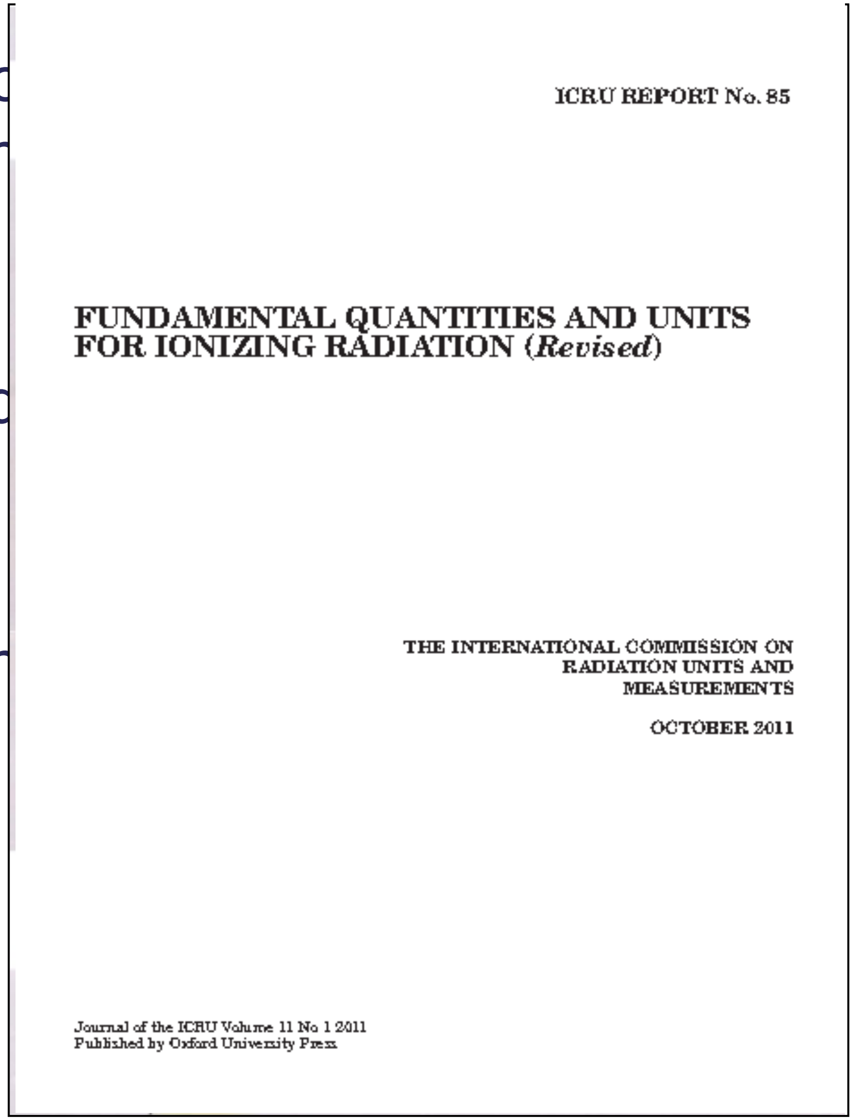
1. Introduction

Exact physical meaning of "dose of radiation"

"Dose" is a sloppy expression tc
radiation and should be used or
communication really knows its

A dose of radiation is correctly c
quantity of **absorbed dose,** *D*.

The most fundamental definitior
is given in Report ICRU 85a


ICRU REPORT No. 85

FUNDAMENTAL QUANTITIES AND UNITS FOR IONIZING RADIATION (*Revised*)

THE INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS

OCTOBER 2011

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1. Introduction

Exact physical meaning of "dose of radiation"

- According to ICRU Report 85a, the absorbed dose *D* is defined by:

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}$$

where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted to matter of mass

$\mathrm{d}m$ is a small element of mass

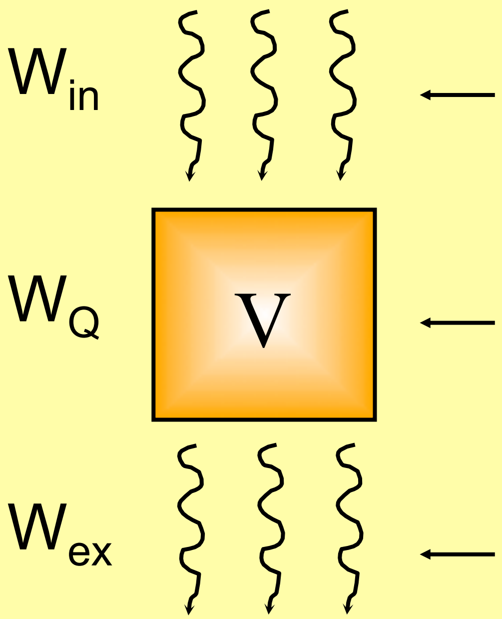
- The unit of absorbed dose is joule per kilogram (J/kg), the special name for this unit is gray (Gy).

1. Introduction

Exact physical meaning of "dose of radiation"

- 4 characteristics of absorbed dose:

  (1) The term "**energy imparted**" can be considered to be the radiation energy absorbed in a volume:



Energy coming in (electrons, photons)

Interactions + elementary particle processes (pairproduction, annihilation, nuclear reactions, radioaktive decay)

Energy going out

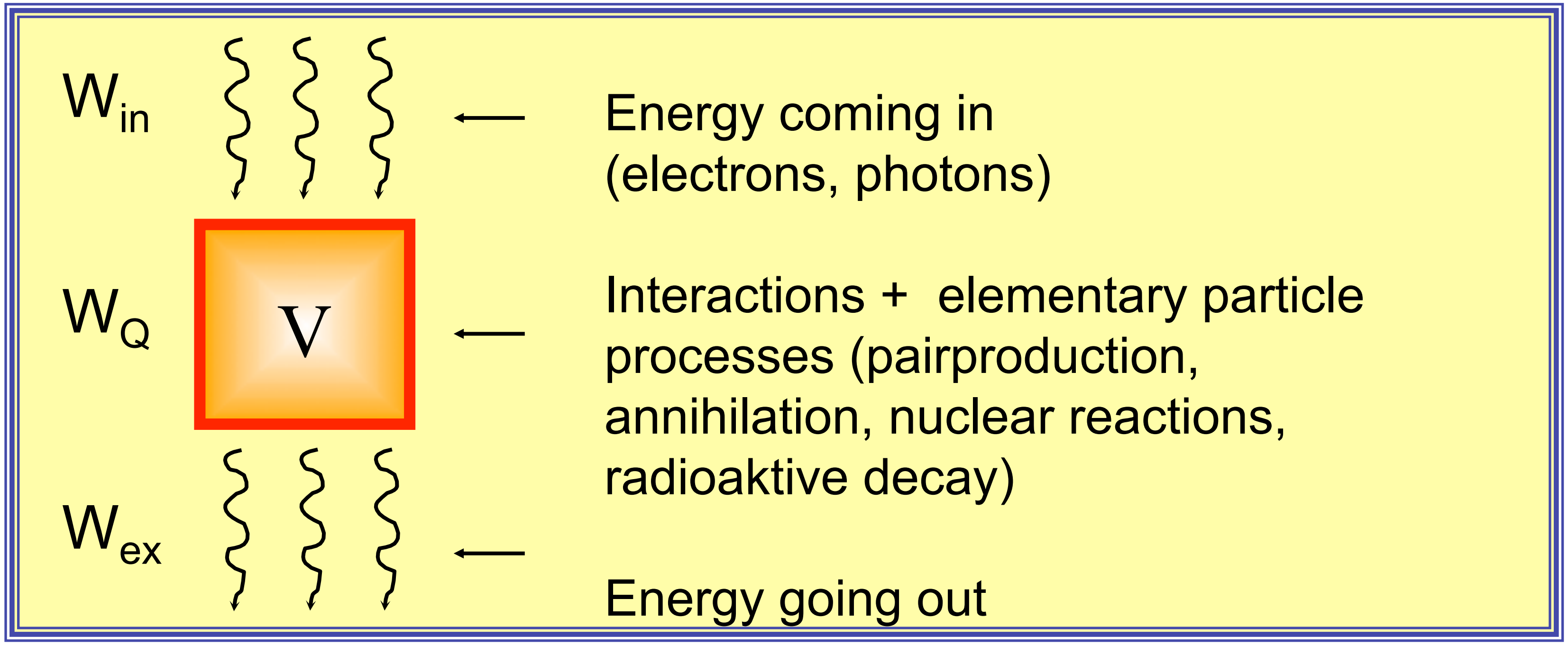
$$\text{Energy absorbed} = W_{in} - W_{ex} + W_Q$$

1. Introduction

Exact physical meaning of "dose of radiation"

- Four characteristics of absorbed dose :

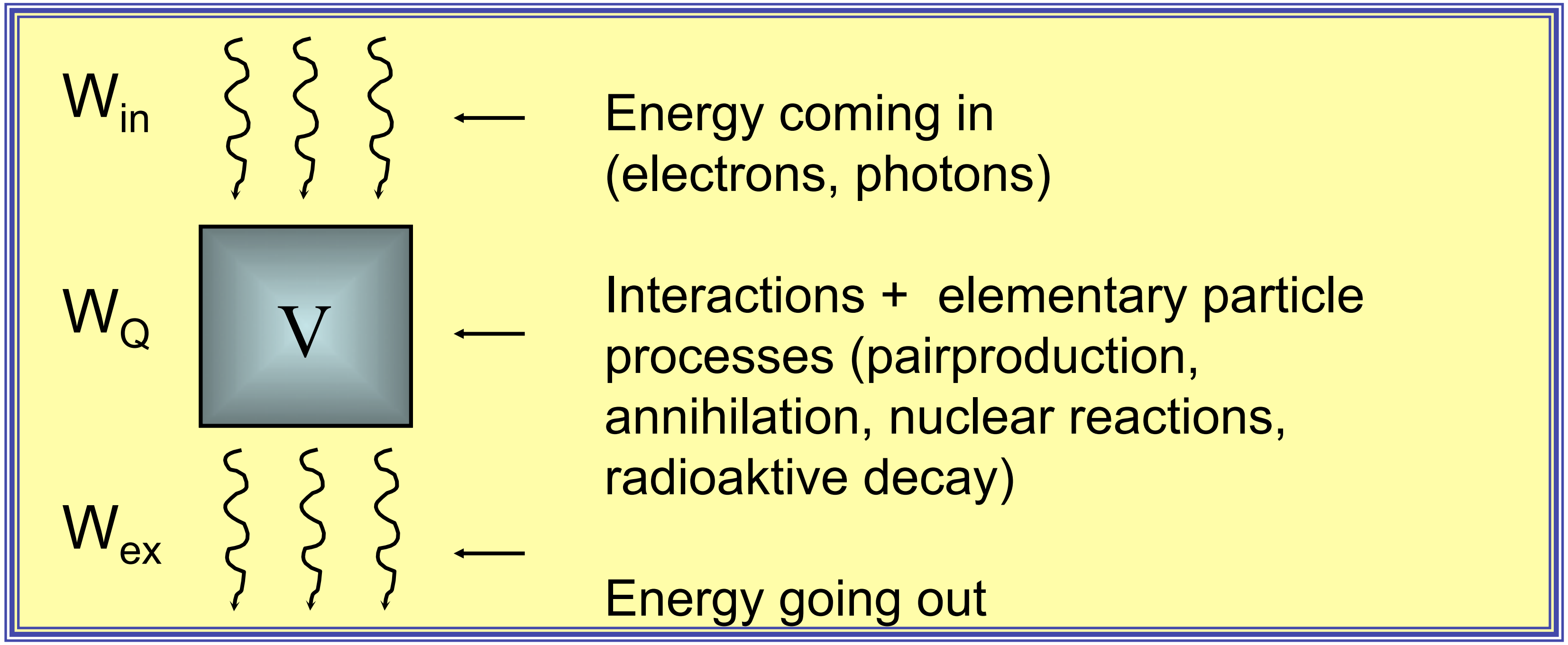
  (2) The term "**absorbed dose**" refers to an exactly defined volume and only to the volume V:



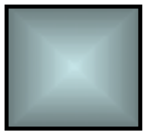
Exact physical meaning of "dose of radiation"

- Four characteristics of absorbed dose :

  (3) The term "**absorbed dose**" refers to the material of the volume :



 = air: D_{air}

 = water: D_{water}

1. Introduction

Exact physical meaning of "dose of radiation"

- Four characteristics of absorbed dose:

  (4) "**absorbed dose**" is a macroscopic quantity that refers to a point $\vec{r}$ in space:

$$D = D(\vec{r})$$

This is associated with:

(a) D is steadily in space and time

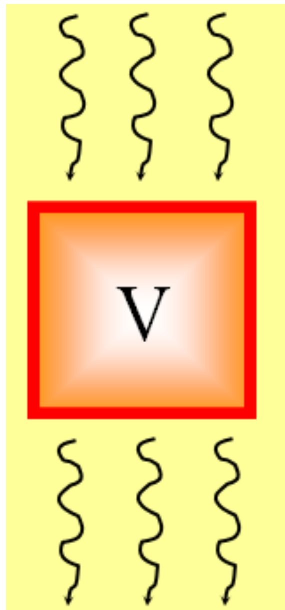
(b) D can be differentiated in space and time

This last statement on absorbed dose:

"absorbed dose is a macroscopic quantity that refers to a mathematical **point in space,** $\vec{r}$"

seems to be a contradiction to:

"The term absorbed dose refers to an exactly defined **volume**"



We need a closer look into:

What is happening in an irradiated volume?

In particular, facing our initial definition:

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}$$

this question is synonym to the question, what energy imparted really means !!!

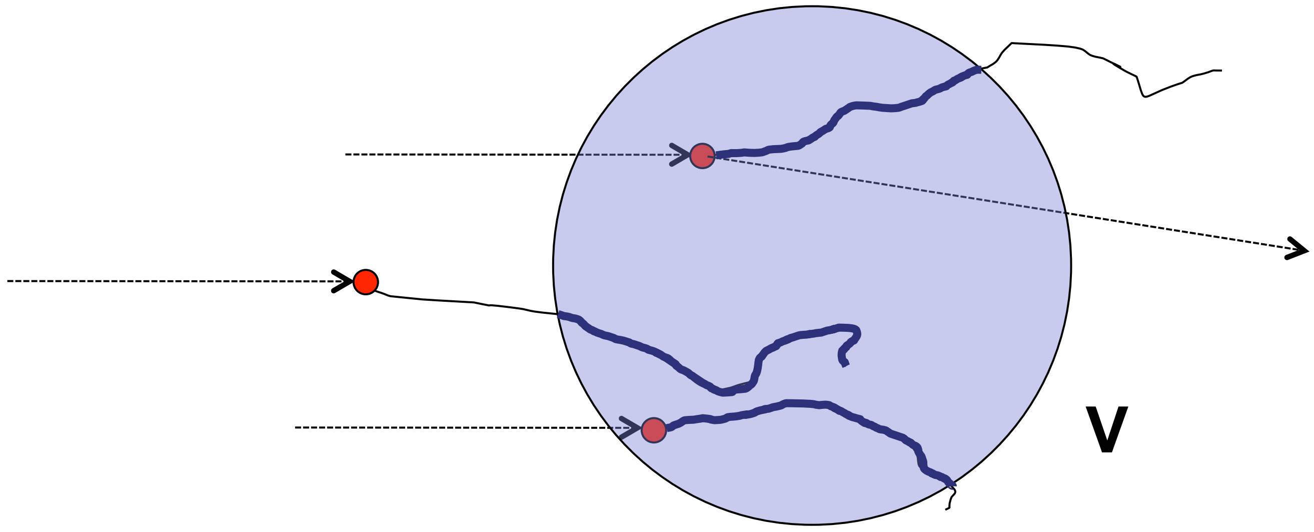
1. Introduction
"Absorbed dose" and "energy imparted"

The absorbed dose D is defined by:

$$D = \frac{d\bar{\varepsilon}}{dm}$$ ← energy imparted

We need a definition of energy imparted ε :

The energy imparted, ε, to matter in a given volume is the sum of all **energy deposits** in that volume.



1. Introduction

"Absorbed dose" and "energy imparted"

The energy imparted **ε** is the sum of all elemental **energy deposits** by those basic interaction processes which have occurred **in the volume** during a time interval considered:

$$\varepsilon = \sum_i \varepsilon_i$$

energy imparted

energy deposits

1. Introduction
"Absorbed dose" and "energy imparted"

Now we need a definition of an **energy deposit** (symbol: ε_i).
The **energy deposit** is the elemental absorption of radiation energy as

$$\varepsilon_i = \varepsilon_{in} - \varepsilon_{out} + Q$$

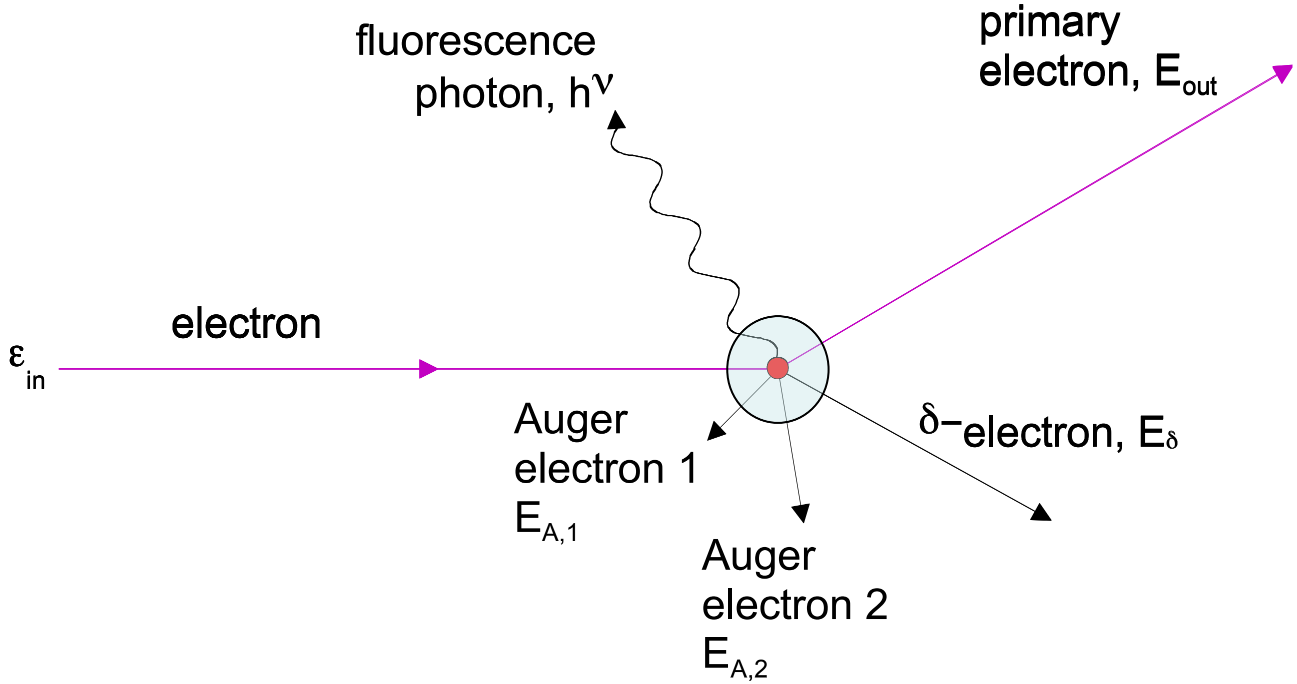
Unit: J

in a single interaction process.

- Three examples will be given for that:
  - electron knock-on interaction
  - pair production
  - positron annihilation

1. Introduction
"Absorbed dose" and "energy imparted"

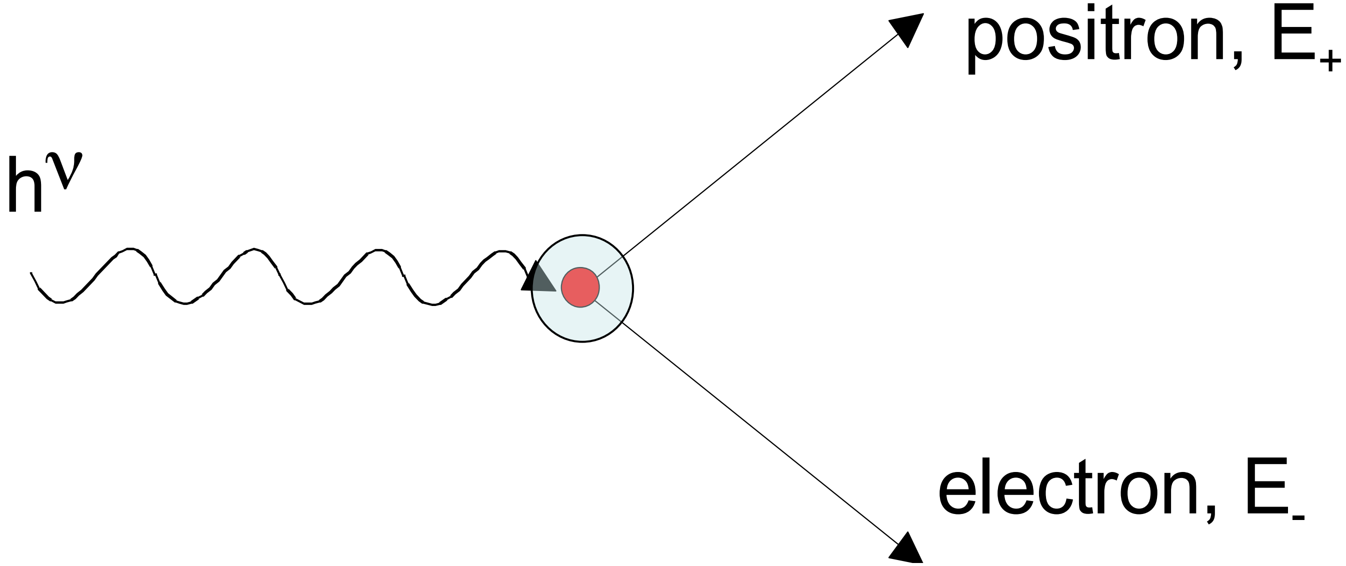
Energy deposit ε_i by electron knock-on interaction:



$$\varepsilon_i = \varepsilon_{in} - (E_{out} + E_\delta + h\nu + E_{A,1} + E_{A,2})$$

1. Introduction
"Absorbed dose" and "energy imparted"

Energy deposit ε_i by pair production:



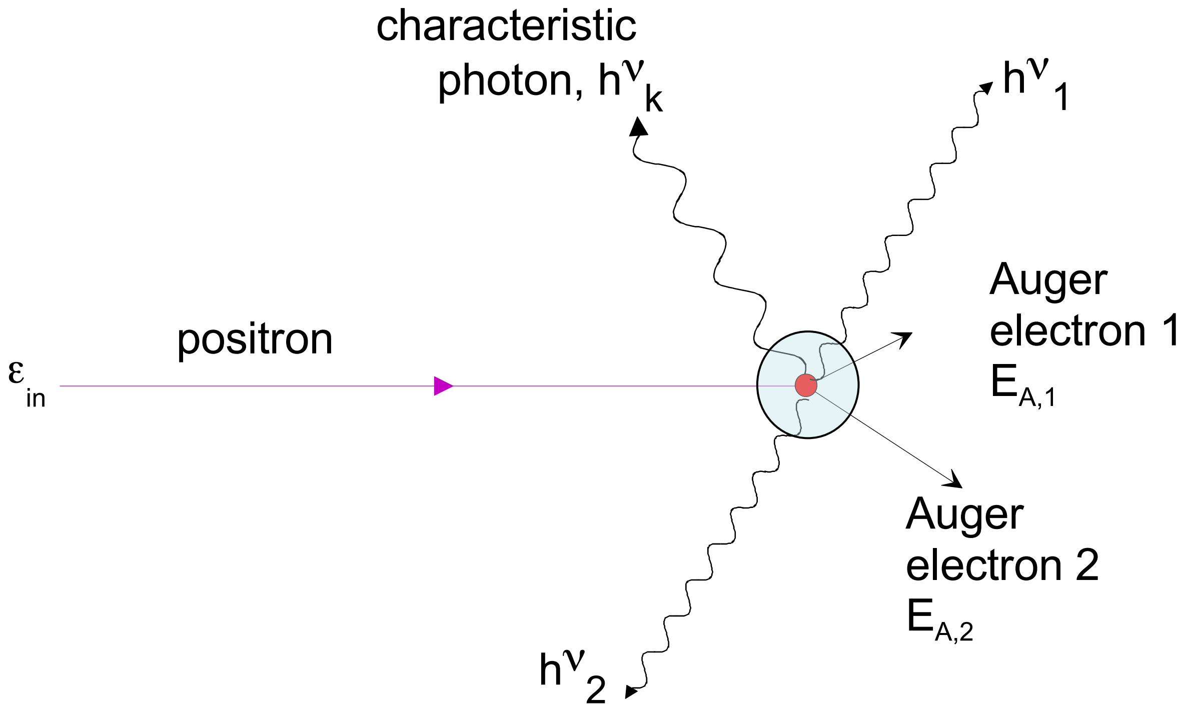
Note: **The rest energy of the positron and electron is also escaping!**

$$\varepsilon_i = h\nu - (E_+ + E_-) - 2m_0c^2$$

1. Introduction
"Absorbed dose" and "energy imparted"

Energy deposit ε_i by positron annihilation:

Note: The rest energies have to be added !



$$\varepsilon_i = \varepsilon_{in} - (h\nu_1 + h\nu_2 + h\nu_k + E_{A,1} + E_{A,2}) + 2m_0c^2$$

1. Introduction

Energy imparted and energy deposit

- The energy deposit ε_i is the energy deposited in a single interaction *i*

$$\varepsilon_i = \varepsilon_{in} - \varepsilon_{out} + Q$$ Unit: J

where

ε_{in} = the energy of the incident ionizing particle (excluding rest energy)

ε_{out} = the sum of energies of all ionizing particles leaving the interaction (excluding rest energy),

Q = is the change in the rest energies of the nucleus and of all particles involved in the interaction.

1. Introduction
Energy imparted and energy deposit

Application to dosimetry:

A radiation detector responds to irradiation with a signal ***M*** which is basically related to the energy imparted ε in the detector volume.

$$M \sim \varepsilon = \sum_i \varepsilon_i$$

1. Introduction
Stochastic of energy deposit events

By nature, a single energy deposit ε_i is a stochastic quantity.

$$\varepsilon = \sum_i \varepsilon_i$$

It follows:
energy imparted is **also** a stochastic quantity:

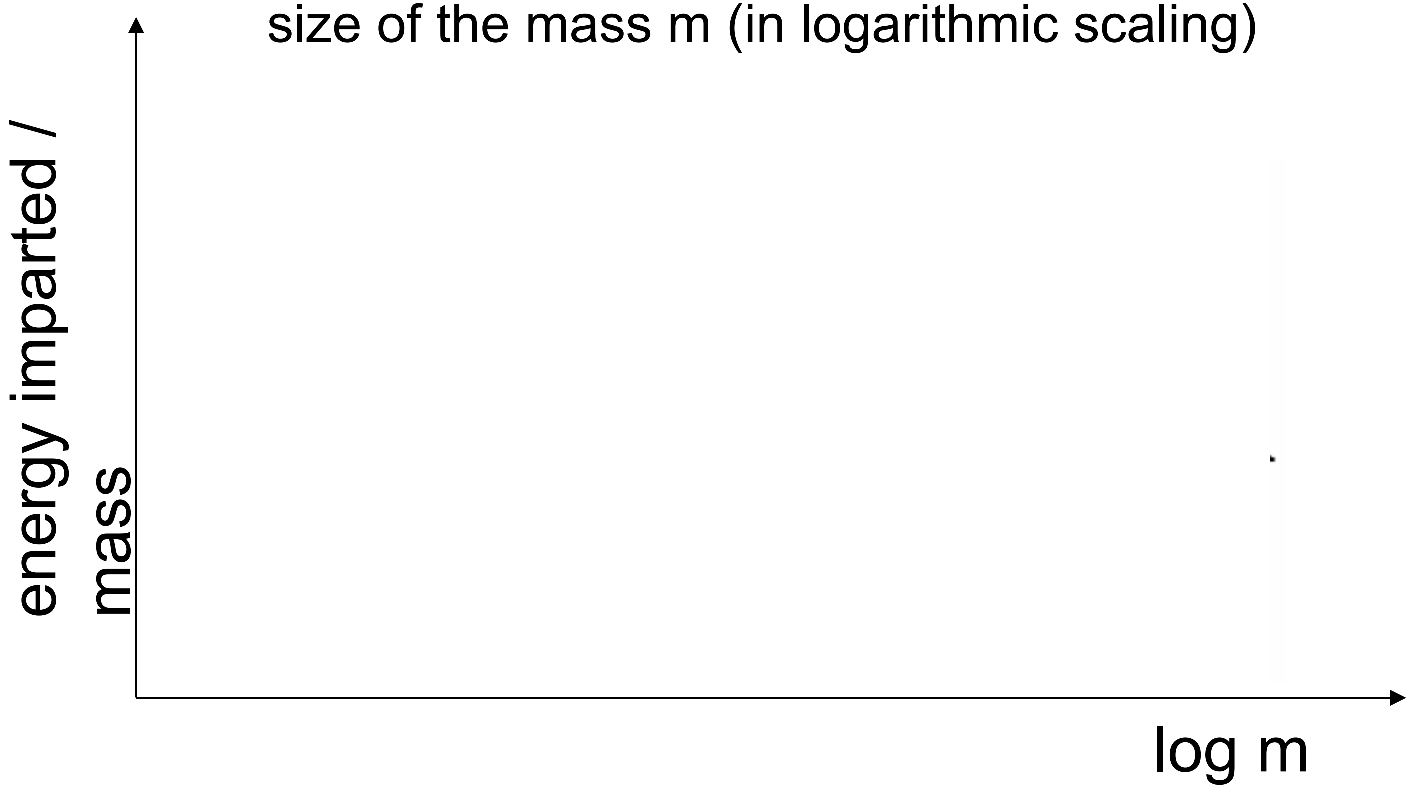
energy imparted (ε) — energy deposits (ε_i)

That means with respect to repeated measurements of energy imparted:

If the determination of ε is repeated, it will never will yield the same value.

As a consequence we can observe the following:

Shown below is the value of (**ε/m**) as a function of the size of the mass m (in logarithmic scaling)



The distribution of (**ε/m**) will be larger and larger with decreasing size of m !

1. Introduction

Exact physical meaning of "dose of radiation"

- That is the reason why the absorbed dose D is **not** defined by:

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

but by:

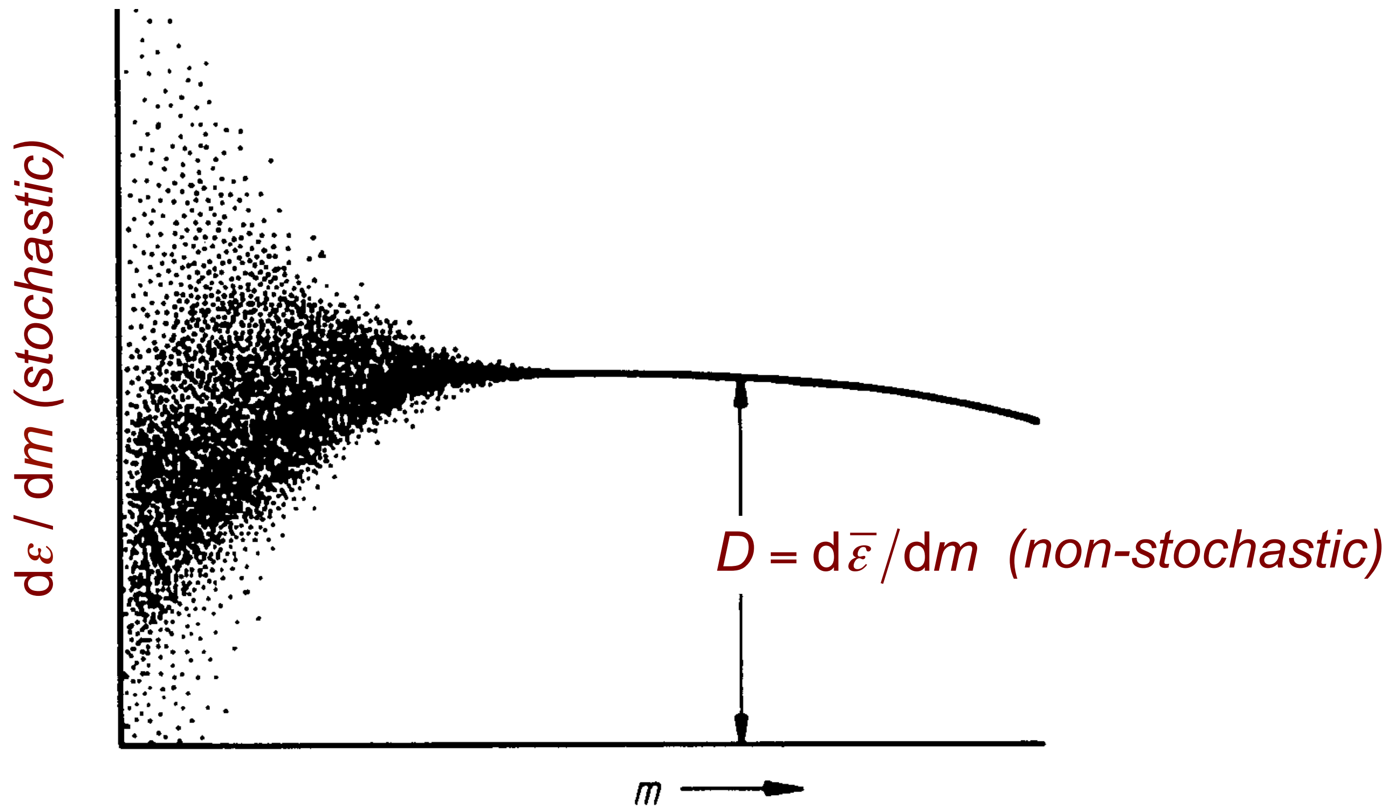
$$D = \frac{d\bar{\varepsilon}}{dm}$$

where $d\bar{\varepsilon}$ is the **mean** energy imparted

dm is a small element of mass

The difference between energy imparted and absorbed dose

- The energy imparted ε is a **stochastic quantity**
- The absorbed dose *D* is a **non-stochastic quantity**



1. Introduction

What is meant by "radiation dose"

- Often, the definition of absorbed dose is expressed in a simplified manner as:

$$D = \frac{\mathrm{d}E}{\mathrm{d}m}$$

- But remember:
  The correct definition of absorbed dose *D* as being a non-stochastic quantity is:

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}$$

Now we should have a precise idea of what is meant with a dose of radiation.

However, there are also further dose quantities which are frequently used.

One important example is the **KERMA.**

The **kerma**, K, is the quotient of $\mathrm{d}E_{\mathrm{tr}}$ by $\mathrm{d}m$, where $\mathrm{d}E_{\mathrm{tr}}$ is the sum of the initial kinetic energies of all the charged particles liberated by uncharged particles in a mass $\mathrm{d}m$ of material, thus

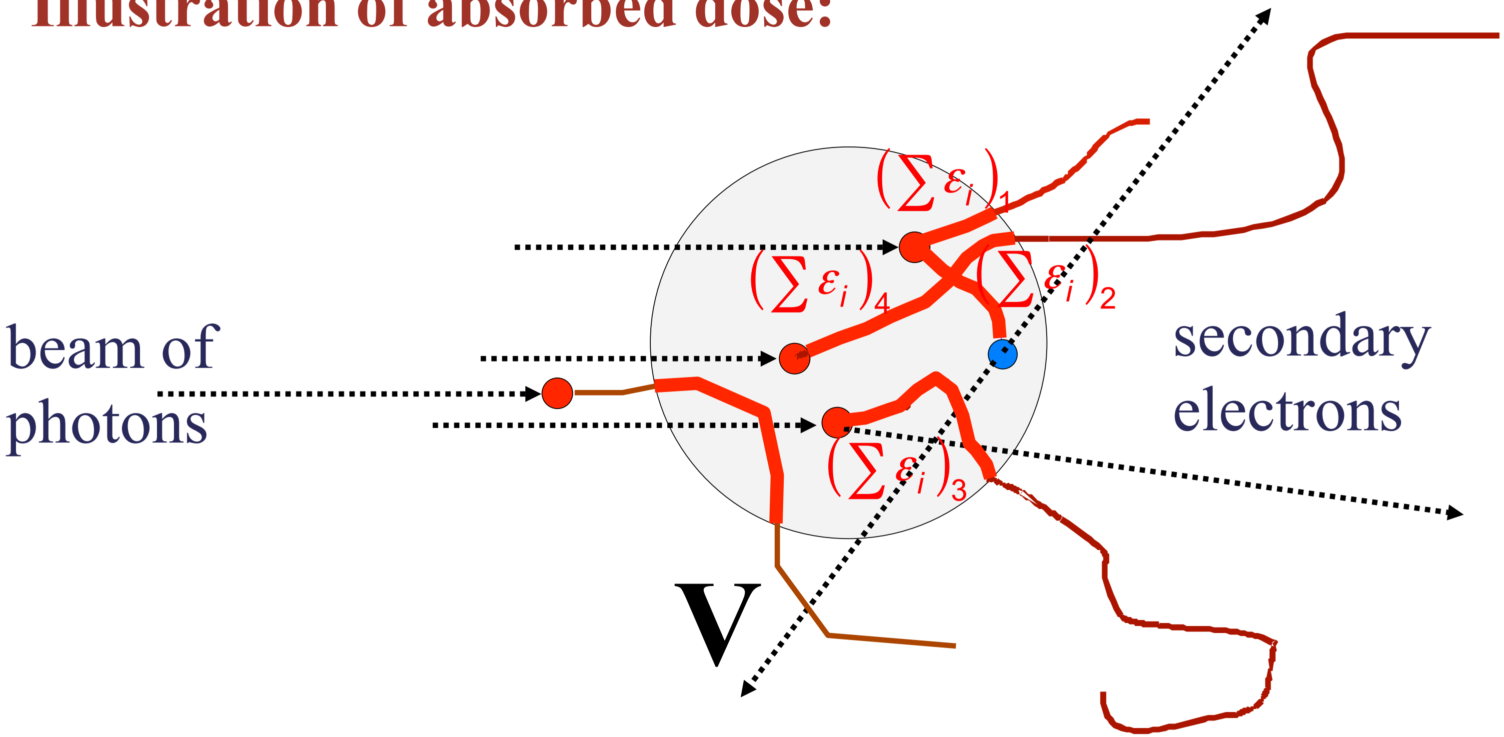
$$K = \frac{\mathrm{d}E_{\mathrm{tr}}}{\mathrm{d}m} \, .$$

Unit: $\mathrm{J\,kg^{-1}}$

The special name for the unit of kerma is gray (Gy).

Absorbed dose

Illustration of absorbed dose:

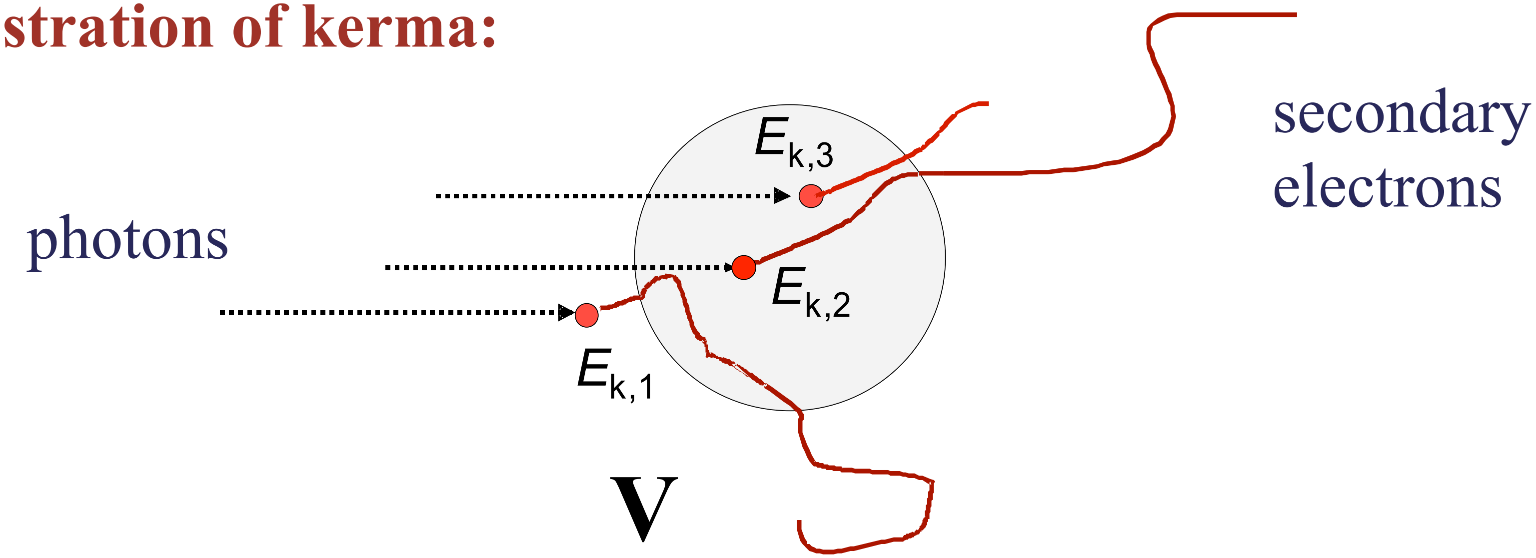


$(\sum \varepsilon_i)$ is the sum of energy losts by collisions along the track of the secondary particles **within the volume V**.

energy absorbed in the volume $= \quad (\sum \varepsilon_i)_1 + (\sum \varepsilon_i)_2 + (\sum \varepsilon_i)_3 + (\sum \varepsilon_i)_4$

Kerma

Illustration of kerma:



The collision energy transferred **within the volume** is:

$$E_{tr} = E_{k,2} + E_{k,3}$$

where E_k is the initial kinetic energy of the secondary electrons.

Note: $E_{k,1}$ is transferred **outside the volume** and is therefore not taken into account in the definition of kerma!

Kerma, as well as the following dosimetrical quantities can be calculated, if the energy fluence of photons is known:

Terma $\int \Phi_E \cdot \left(\frac{E\mu}{\rho} \right) \cdot dE \quad \left[\frac{J}{kg} \right]$

Kerma $\int \Phi_E \cdot \left(\frac{E\mu_{tr}}{\rho} \right) \cdot dE \quad \left[\frac{J}{kg} \right]$

Collision Kerma $\int \Phi_E \cdot \left(\frac{E\mu_{en}}{\rho} \right) \cdot dE \quad \left[\frac{J}{kg} \right]$

} for photons

A further difference between absorbed dose and KERMA

The absorbed dose D is a quantity which is accessible mainly by a measurement

KERMA is a dosimetrical quantity which cannot be measured but calculated only (based on the knowledge of photon fluence differential in energy)

Absorbed dose from charged particle:

This requires the introduction of the concept of stopping power

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4.4 Mass Stopping Power

The *mass stopping power*, S/ρ, of a material, for charged particles of a given type and energy, is the quotient of $\mathrm{d}E$ by $\rho\mathrm{d}l$, where $\mathrm{d}E$ is the mean energy lost by the charged particles in traversing a distance $\mathrm{d}l$ in the material of density ρ, thus

$$\frac{S}{\rho} = \frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}l}.$$

Unit: $\mathrm{J\ m^2\ kg^{-1}}$

Stopping Power and Mass Stopping Power

The mass stopping power can be expressed as a sum of independent components by

$$\frac{S}{\rho} = \frac{1}{\rho}\left(\frac{dE}{dl}\right)_{el} + \frac{1}{\rho}\left(\frac{dE}{dl}\right)_{rad} + \frac{1}{\rho}\left(\frac{dE}{dl}\right)_{nuc}, \qquad (4.4.1)$$

$\frac{1}{\rho}\left(\frac{dE}{dl}\right)_{el} = \frac{1}{\rho}S_{el}$ is the *mass electronic (or collision*[4]*) stopping power* due to interactions with atomic electrons resulting in ionization or excitation.

$\frac{1}{\rho}\left(\frac{dE}{dl}\right)_{rad} = \frac{1}{\rho}S_{rad}$ is the *mass radiative stopping power* due to emission of bremsstrahlung in the electric fields of atomic nuclei or atomic electrons, and

$\frac{1}{\rho}\left(\frac{dE}{dl}\right)_{nuc} = \frac{1}{\rho}S_{nuc}$ is the *mass nuclear stopping power*[5] due to elastic Coulomb interactions in which recoil energy is imparted to atoms.

Stopping Power and Mass Stopping Power

Why **stopping power, i.e.** the energy lost of electrons is such an important concept in dosimetry?

Answer 1: The energy lost is at the same time the energy absorbed

Answer 2: There is a fundamental relationship between the **absorbed dose from charged particles** and the mass electronic stopping power

Absorbed dose of charged particles is approximately equal to CEMA.
Exact definition of CEMA:
(CEMA = C onverted E nergy per Ma ss)

The *cema*, C, for ionizing charged particles, is the quotient of $\mathrm{d}E_{\mathrm{el}}$ by $\mathrm{d}m$, where $\mathrm{d}E_{\mathrm{el}}$ is the mean energy lost in electronic interactions in a mass $\mathrm{d}m$ of a material by the charged particles, except secondary electrons, incident on $\mathrm{d}m$, thus

$$C = \frac{\mathrm{d}E_{\mathrm{el}}}{\mathrm{d}m}. \quad = \int \Phi_E(E) \, \frac{S_{el}}{\rho} \, dE$$

Unit: J kg^{-1}

The special name of the unit of cema is gray (Gy).

Summary: Energy absorption and absorbed dose

- absorbed dose

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

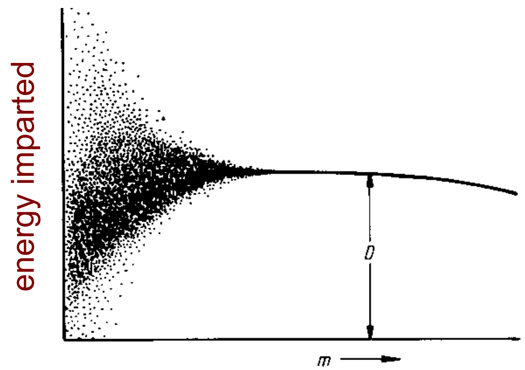
- energy imparted

$$\varepsilon = \sum_i \varepsilon_i$$

- energy deposit

$$\varepsilon_i = \varepsilon_{in} - \varepsilon_{out} + Q$$

- stochastic character of energy absorption



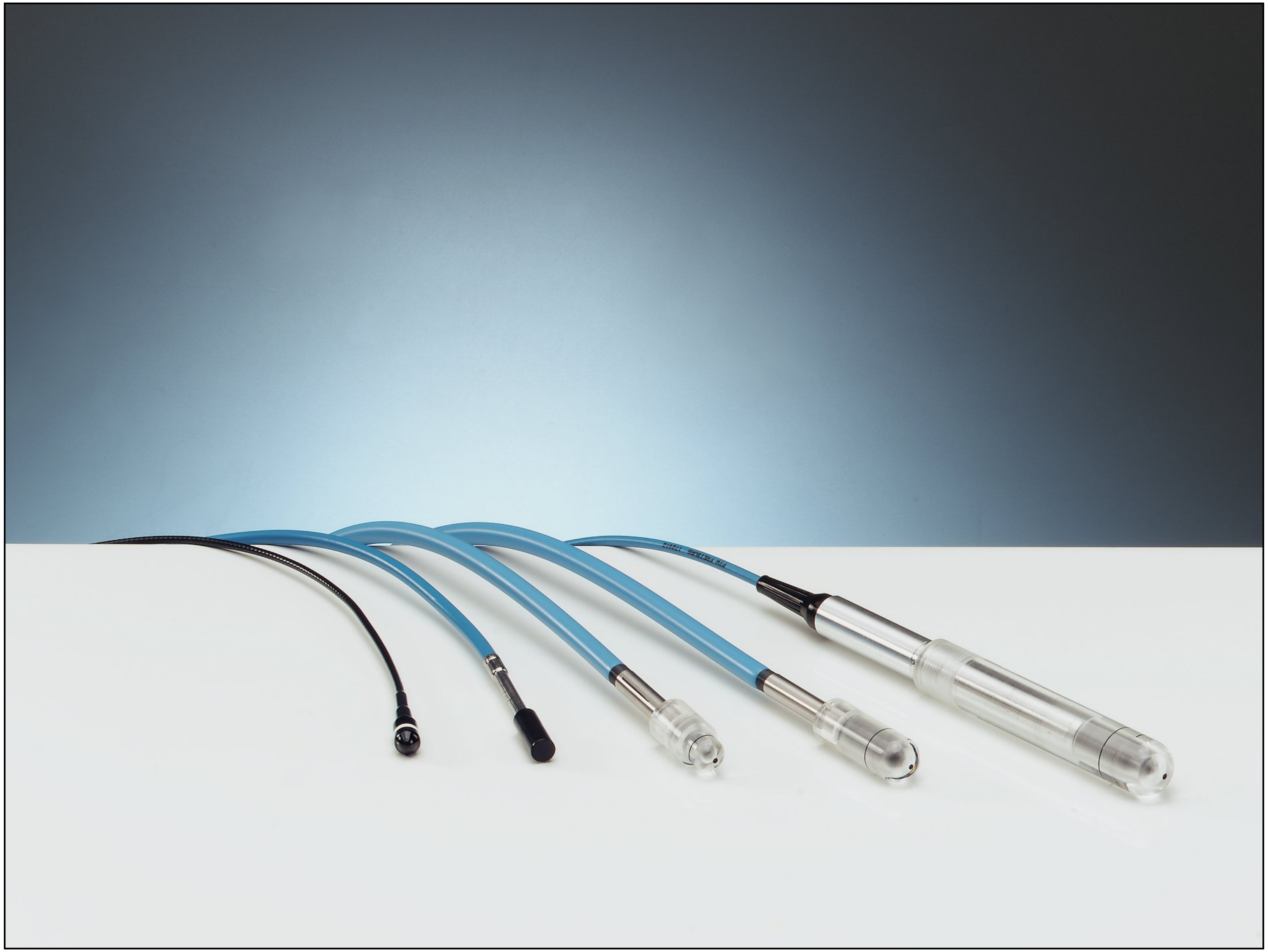
2. General methods of dose measurement

- ❑ Absorbed dose is measured with a (radiation) **dosimeter**

- ❑ The four most commonly used radiation dosimeters are:

  - **Ionization chambers**
  - **Radiographic films**
  - **TLDs**
  - **Diodes**

2. General methods of dose measurement:
Ionization chambers



2. General methods of dose measurement: Ionization chambers

Advantage	(small) Disadvantage
Accurate and precise	Connecting cables required
Recommended for beam calibration	High voltage supply required
Necessary corrections well understood	Many corrections required
Instant readout	

2. General methods of dose measurement: Film

Advantage	Disadvantage
❑ 2-D spatial resolution ❑ Very thin: does not perturb the beam	❑ Darkroom and processing facilities required ❑ Processing difficult to control ❑ Variation between films & batches ❑ Needs proper calibration against ionization chambers ❑ Energy dependence problems ❑ Cannot be used for beam calibration

2. General methods of dose measurement:
Radiochromic film

Advantage	Disadvantage
❑ 2-D spatial resolution ❑ Very thin: does not perturb the beam	❑ ~~Darkroom and processing facilities required~~ ❑ ~~Processing difficult to control~~ ❑ Variation between films & batches ❑ Needs proper calibration against ionization chambers ❑ Energy dependence problems ❑ ~~Needs an appropriate scanner!~~

2. General methods of dose measurement:
Thermo-Luminescence-Dosimeter (TLD)

Advantage	Disadvantage
❑ Small in size: point dose measurements possible	❑ Signal erased during readout
❑ Many TLDs can be exposed in a single exposure	❑ Easy to lose reading
❑ Available in various forms	❑ No instant readout
❑ Some are reasonably tissue equivalent	❑ Accurate results require care
❑ Not expensive	❑ Readout and calibration time consuming
	❑ Not recommended for beam calibration

2. General methods of dose measurement: Diode

Advantage	Disadvantage
❑ Small size	❑ Requires connecting cables
❑ High sensitivity	❑ Variability of calibration with temperature
❑ Instant readout	❑ Change in sensitivity with accumulated dose
❑ No external bias voltage	❑ Special care needed to ensure constancy of response
❑ Simple instrumentation	❑ Should not be used for beam calibration
❑ Good to measure relative distributions!	

2. General methods of dose measurement:

The remaining lesson is exclusively dedicated to the determination of "absorbed dose to water" by ionization chambers in terms of Gray!

3. Some principles of dosimetry with ionization chambers

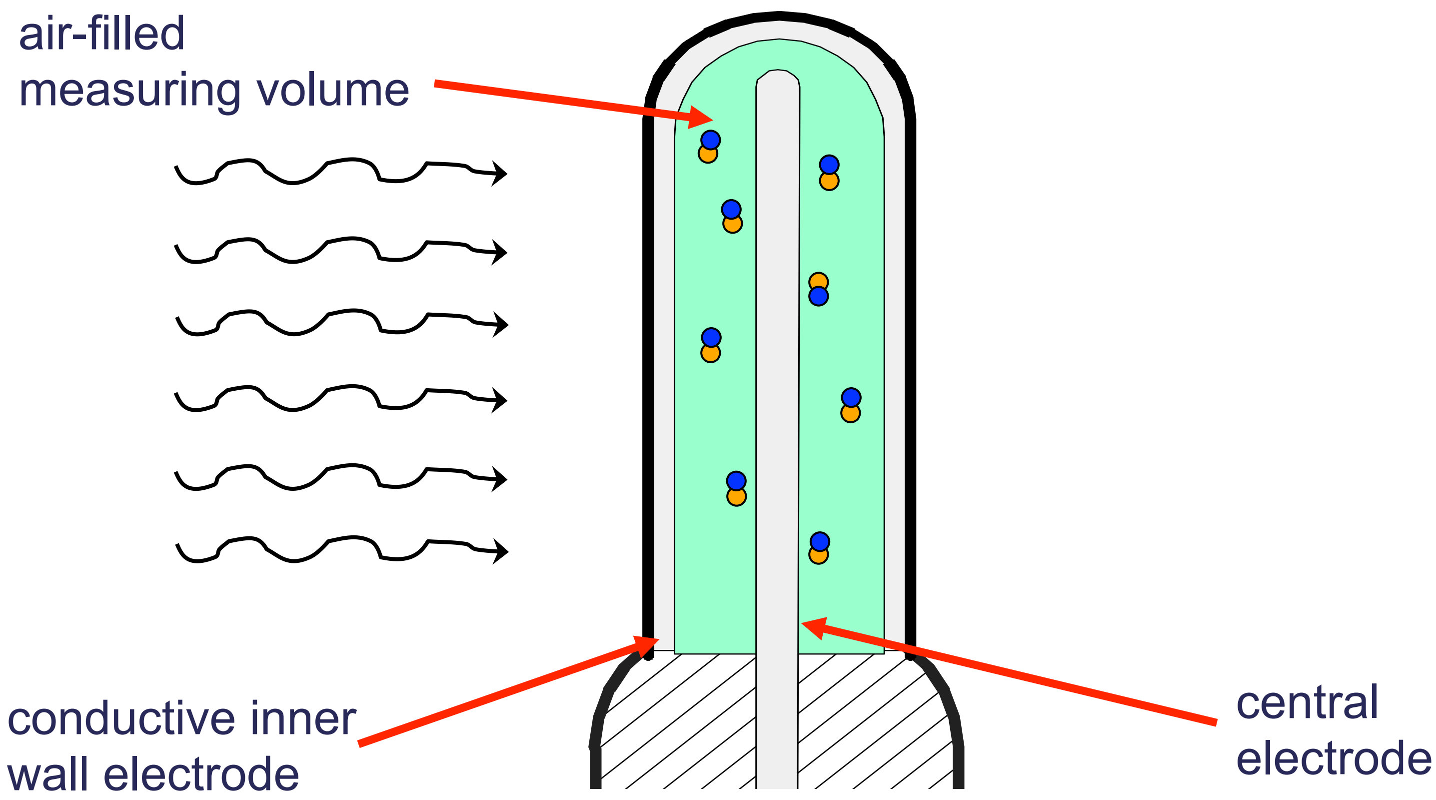
Ionization

- Measurement of absorbed dose requires the measurement of the mean energy imparted in small volume by various interaction processes.
- Such interaction processes normally result in the creation of ion pairs.

3. Some principles of dosimetry with ionization chambers

Ionization

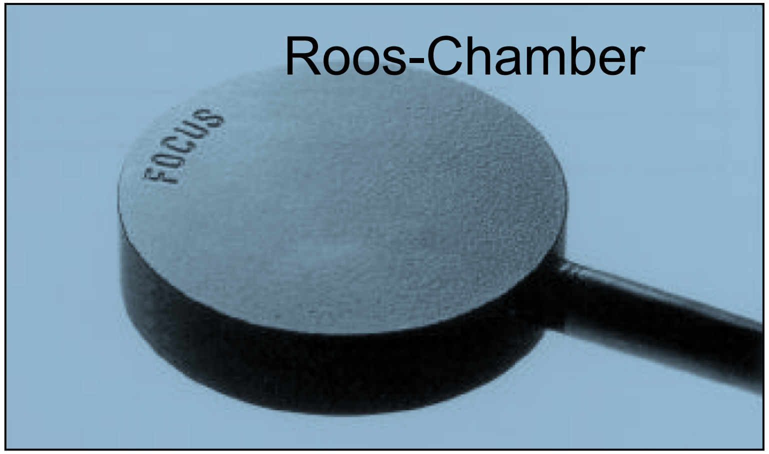
- Example: Creation of charge carriers in an ionization chamber



3. Some principles of dosimetry with ionization chambers

Ionization

- The creation and measurement of ionization in a gas is the basis for dosimetry with ionization chambers.



- **Because of the key role that ionization chambers play in radiotherapy dosimetry, it is vital that practizing physicists have a thorough knowledge of the characteristics of ionization chambers.**

3. Some principles of dosimetry with ionization chambers
Ionization chambers

- The Ionization chamber is the most practical and most widely used type of dosimeter for accurate measurement of machine output in radiotherapy.
- It may be used as an absolute or relative dosimeter.
- Its sensitive volume is usually filled with ambient air and:
  - The dose related measured quantity is charge *Q*,
  - The dose rate related measured quantity is current *I*,

  produced by radiation in the chamber sensitive volume.

3. Some principles of dosimetry with ionization chambers
Absorbed dose in air

- Measured charge Q and sensitive air mass m_{air} are related to absorbed dose in air D_{air} by:

$$D_{air} = \frac{Q}{m_{air}} \left(\frac{\overline{W}_{air}}{e} \right)$$

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

$\overline{W}_{air}/e$ is the mean energy required to produce an ion pair in air per unit charge e.

3. Some principles of dosimetry with ionization chambers

Values of $(\overline{W}_{air}/e)$

- It is generally assumed that for $\overline{W}_{air}/e$ a constant value can be used, valid for the complete photon and electron energy range used in radiotherapy dosimetry.

- $\overline{W}_{air}/e$ depends on relative humidity of air:
  - For air at relative humidity of 50%:

    $$(\overline{W}_{air}/e) = 33.77 \text{ J/C}$$ ←

  - For dry air:

    $$(\overline{W}_{air}/e) = 33.97 \text{ J/C}$$

3. Some principles of dosimetry with ionization chambers
Absorbed dose in water

- Thus the absorbed dose in air can be easily obtained by:

$$D_{air} = \frac{Q}{m_{air}} \left(\frac{\overline{W}_{air}}{e} \right)$$

- Next the measured absorbed dose in air of the ionization chamber D_{air} must be converted into absorbed dose in water D_w.

- This conversion depends on several conditions such as:
  - type and energy of radiation
  - type and volume of the ionization chamber

3. Some principles of dosimetry with ionization chambers
Absorbed dose in water

- For this conversion and for most cases of dosimetry in clinically applied radiation fields such as:
  - high energy photons (E > 1 MeV)
  - high energy electrons

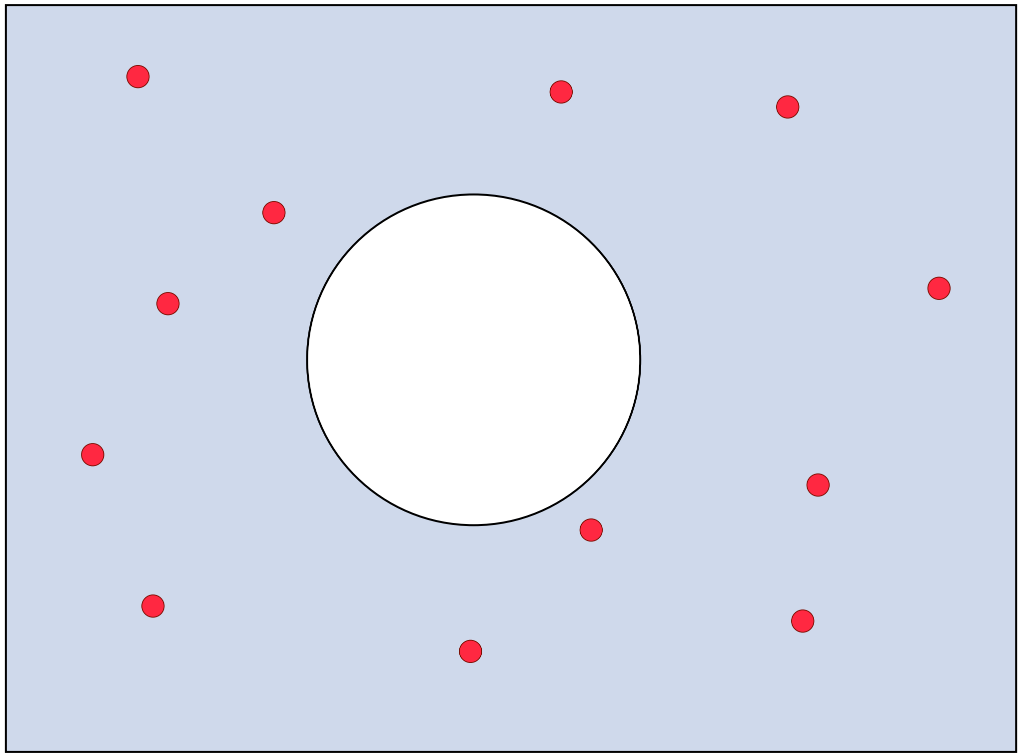
  the so-called **Bragg-Gray Cavity Theory** can be applied.

To enter the discussion of what is meant by:

Bragg-Gray Theory

we start to analyze the dose absorbed in the detector and assume, that the detector is an air-filled ionization chamber in water:

The primary interactions within a radiation field of photons then are photon interactions.

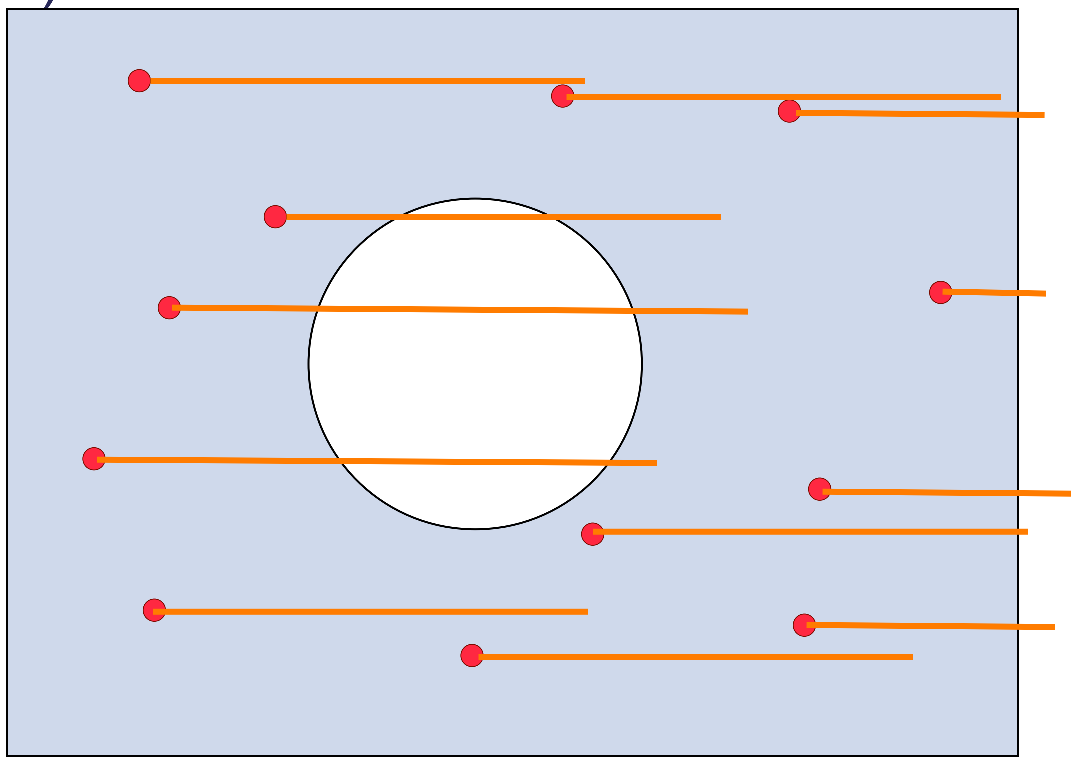


● photon interaction

Note:

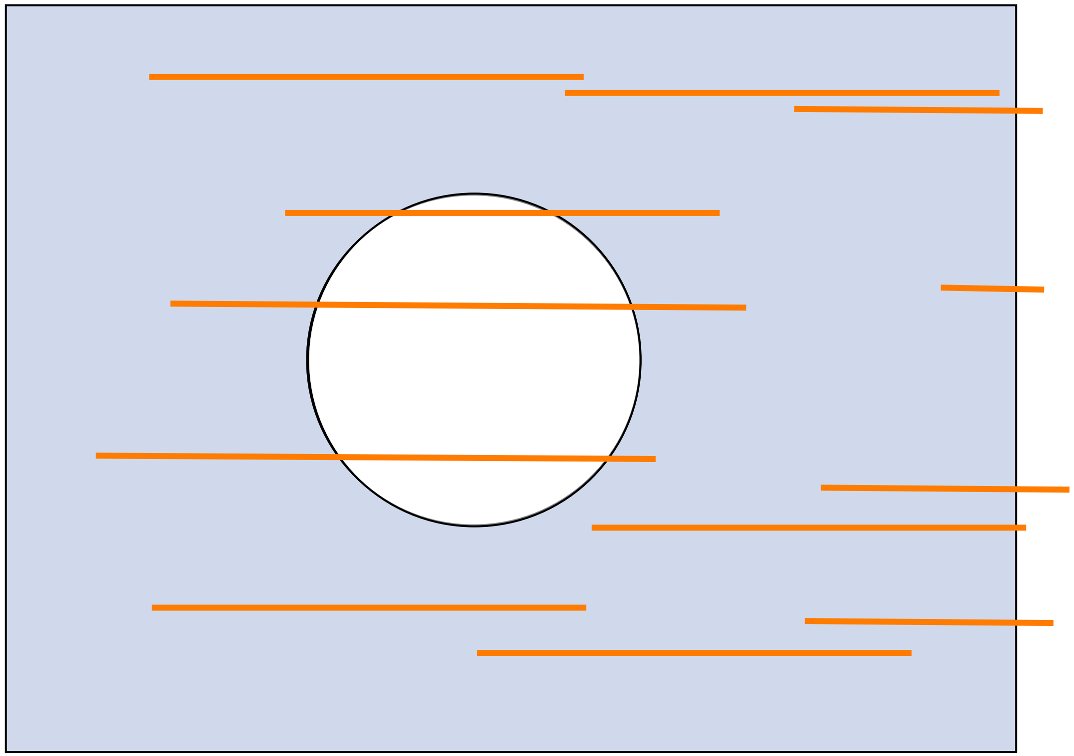
We assume that the number of interactions in the air cavity itself is negligible (due to the ratio of density between air and water)

The primary interactions of the photon radiation mainly consist of those producing secondary electrons



electron track

We know: Interactions of the secondary electrons in any medium are characterized by the **stopping power**.



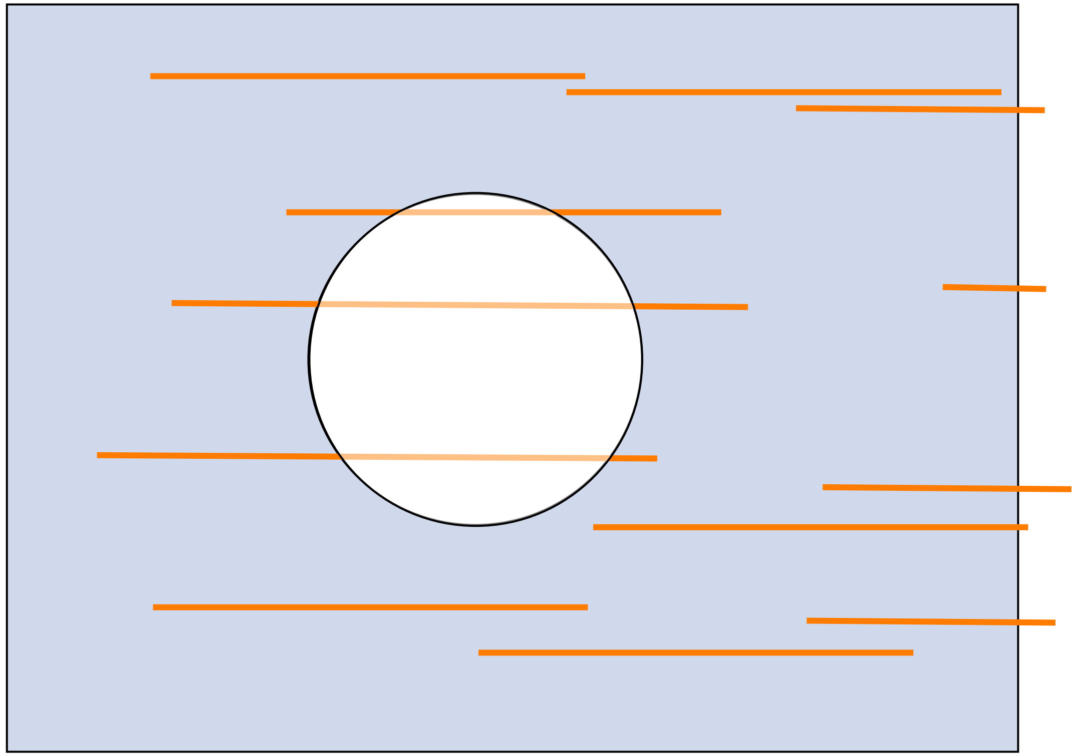
Consequently, the types of interactions

within the air cavity

are exclusively those of electrons characterized by stopping power.

Absorbed dose D in the air can be calculated D as:

$$D_{air} = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho} \right)_{air} \cdot dE$$



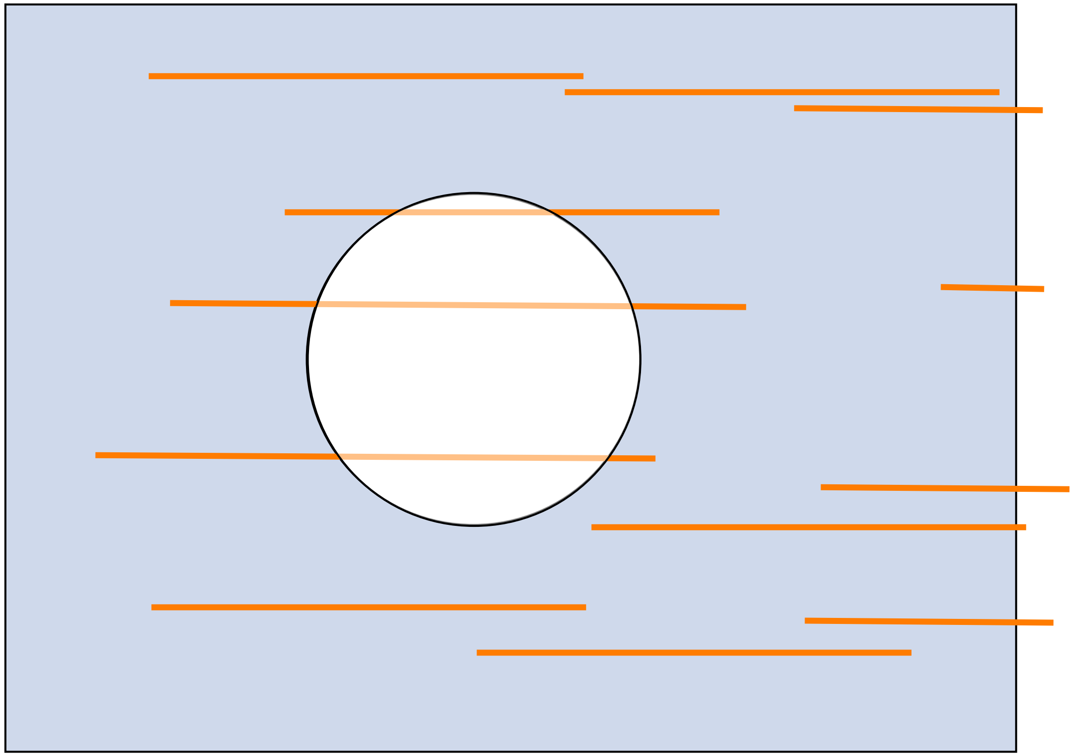
Let us further assume, that exactly the **same fluence** of the secondary electrons exists, independent from whether there is the **air cavity** or **water**.

We would have in air:

$$D_{air} = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho}\right)_{air} \cdot dE$$

and we would have in water:

$$D_{water} = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho}\right)_{water} \cdot dE$$



We further introduce the **mean mass stopping** power as:

$$\left(\frac{\overline{S}_{el}}{\rho}\right) = \frac{\int_0^{E_{max}} \Phi_E(E) \cdot \left(\frac{S_{el}}{\rho}\right) dE}{\int_0^{E_{max}} \Phi_E(E)\, dE}$$

Because of $\int_0^{E_{max}} \Phi_E(E)\, dE = \Phi$, we obtain:

absorbed dose in water $$D_{water} = \left(\frac{\overline{S}_{el}}{\rho}\right)_{water} \times \Phi$$

absorbed dose in air $$D_{air} = \left(\frac{\overline{S}_{el}}{\rho}\right)_{air} \times \Phi$$

- …and it follows from:

$$D_{water} = \left(\frac{\bar{S}_{el}}{\rho}\right)_{water} \Phi$$

$$D_{air} = \left(\frac{\bar{S}_{el}}{\rho}\right)_{air} \Phi$$

the relationship which is fundamental in dosimetry

$$D_{water} = D_{air} \cdot \frac{\left(\frac{\bar{S}_{el}}{\rho}\right)_{water}}{\left(\frac{\bar{S}_{el}}{\rho}\right)_{air}}$$

Summary of the derivation of the equation:

$$D_{water} = D_{air} \cdot \left(\frac{\bar{S}_{el}}{\rho} \right)_{water} \Bigg/ \left(\frac{\bar{S}_{el}}{\rho} \right)_{air}$$

This conversion formula is valid under the two conditions:

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 the electrons in the medium;

2) The absorbed dose in the cavity is deposited **solely by the electrons** crossing it (i.e. photon interactions in the cavity are assumed to be negligible and thus can be ignored).

Conversion of absorbed dose

- These considerations are the essence of the Bragg-Gray theory, and the two conditions are hence called the

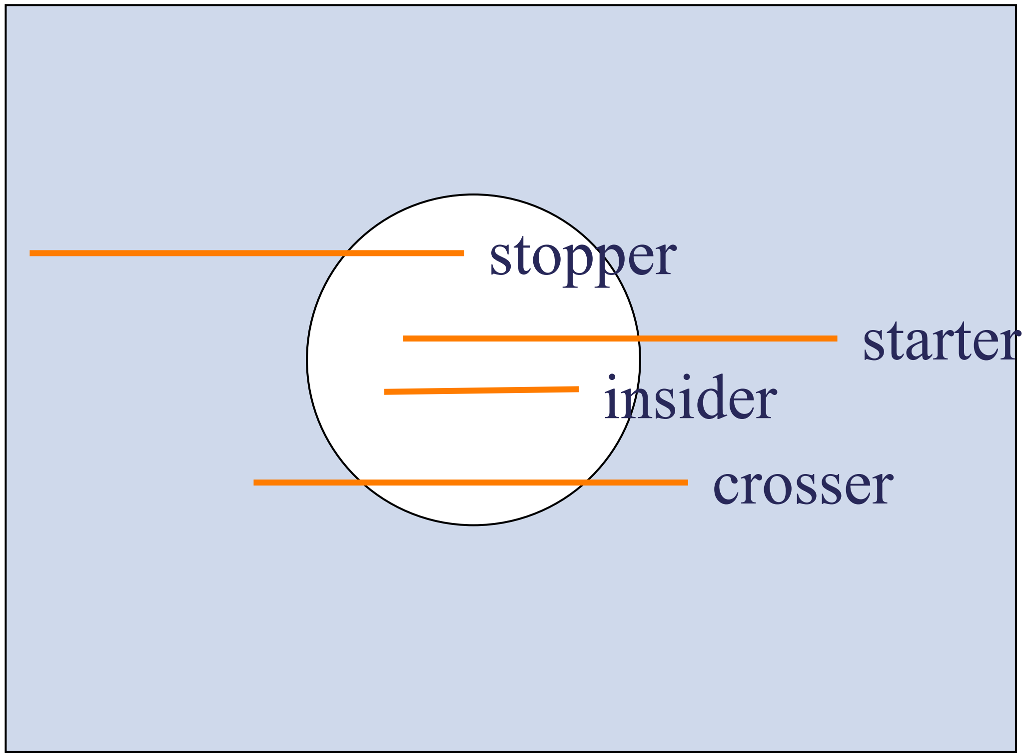
  two Bragg-Gray conditions.

- Thus Bragg-Gray theory provides the most important mean to determine water absorbed dose from a detector measurement which is not made of water:
- If the two Bragg-Gray conditions are fulfilled, the absorbed dose in water can be obtained by the absorbed dose measured in the detector using

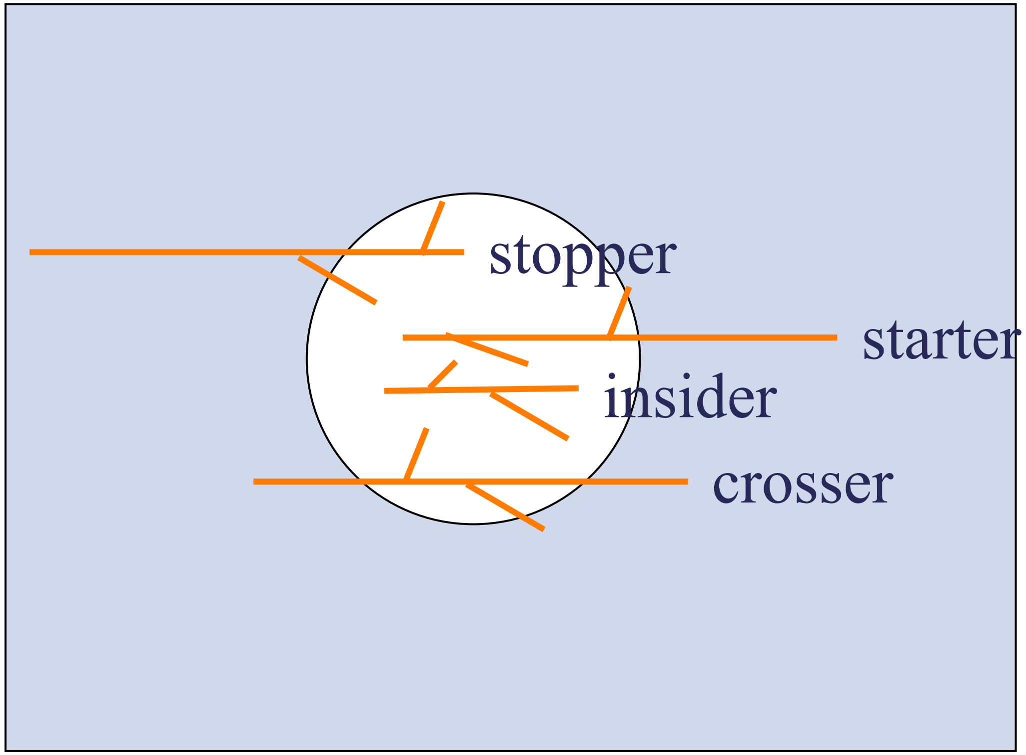
$$D_{water} = \frac{Q}{m_{air}} \cdot \left(\frac{\overline{W}_{air}}{e} \right) \cdot \frac{\left(S_{el}/\rho \right)_{water}}{\left(S_{el}/\rho \right)_{air}}$$

How well are the two Bragg-Gray conditions really fulfilled??

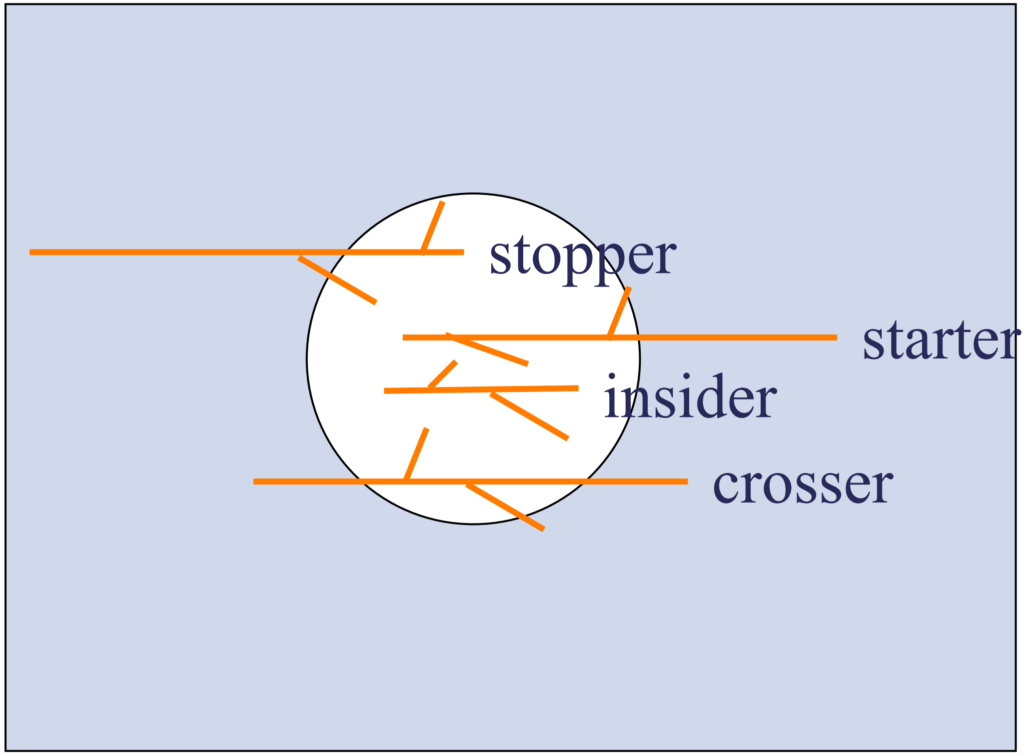
To discuss this question, we need a closer look on the cavity and all **possible electron tracks** in the following:



In addition, the electron tracks must also include the production of so-called δ electrons:

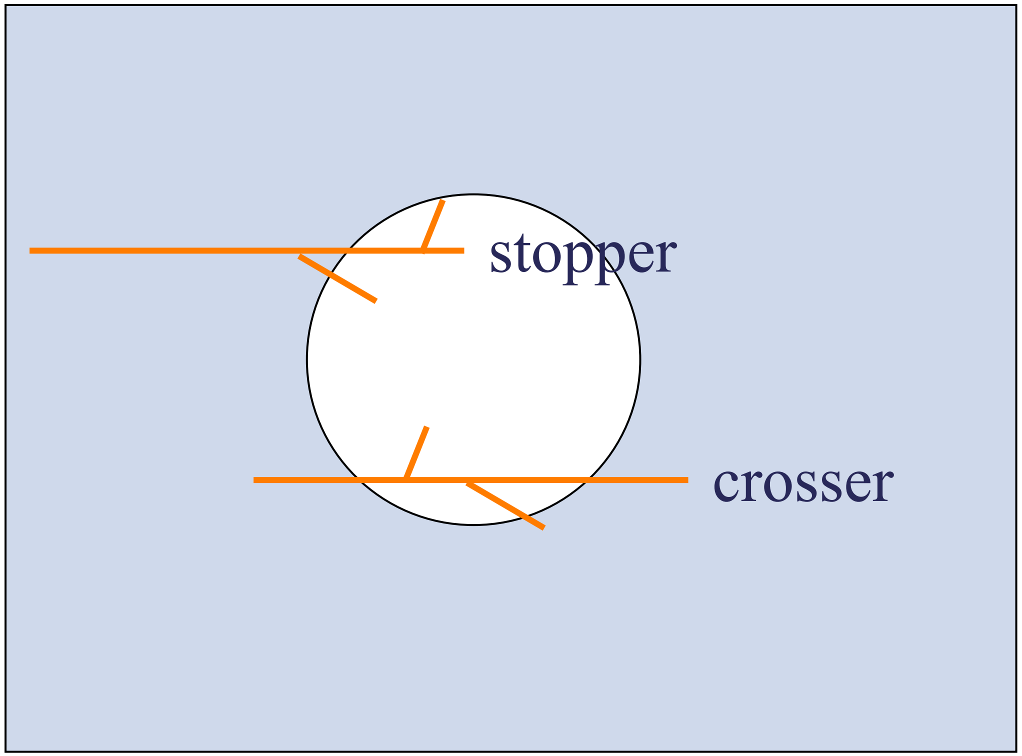


- In a very good approximation we can neglect photon interactions within the cavity.
- Thus we will neglect the starters and insiders!



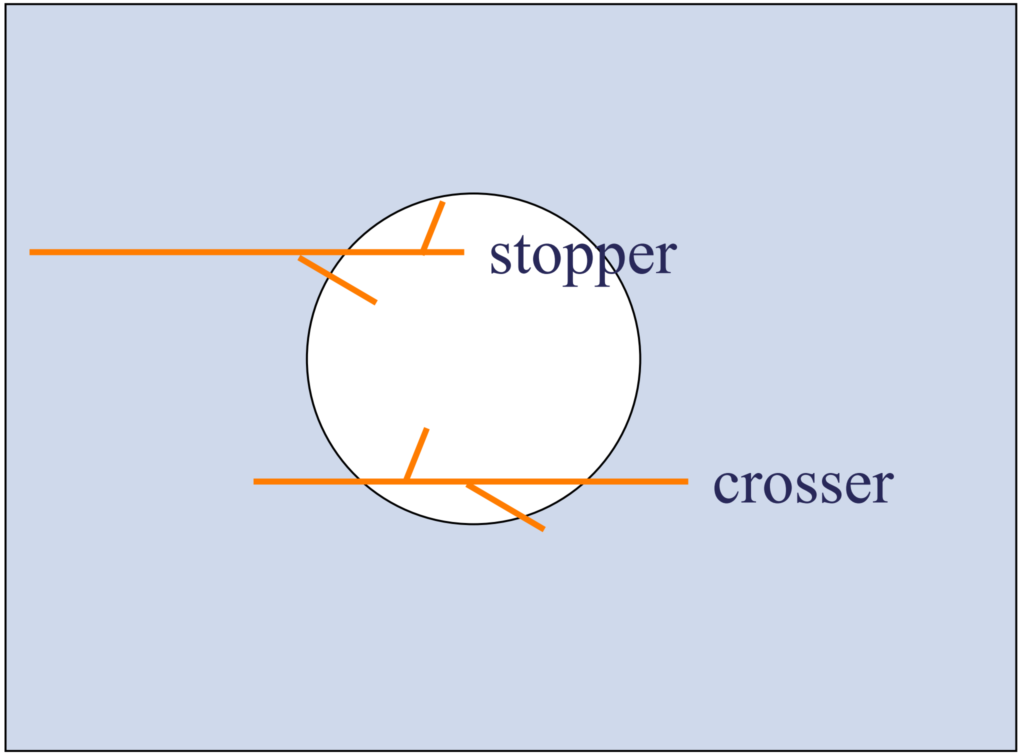
In a very good approximation, also the fluence of the pure crossers and stoppers is not changed (a density change does not change the fluence!).

However, the fluence of the δ electrons is slightly changed close to the border of the cavity (the number of δ electrons entering and leaving the cavity is unbalanced).



It follows:
Thus the Bragg-Gray condition, that the fluence of **all electrons** must not be disturbed, cannot be exactly fulfilled.

Hence this must be taken into account by a so-called perturbation factor when converting dose in air to that in water.

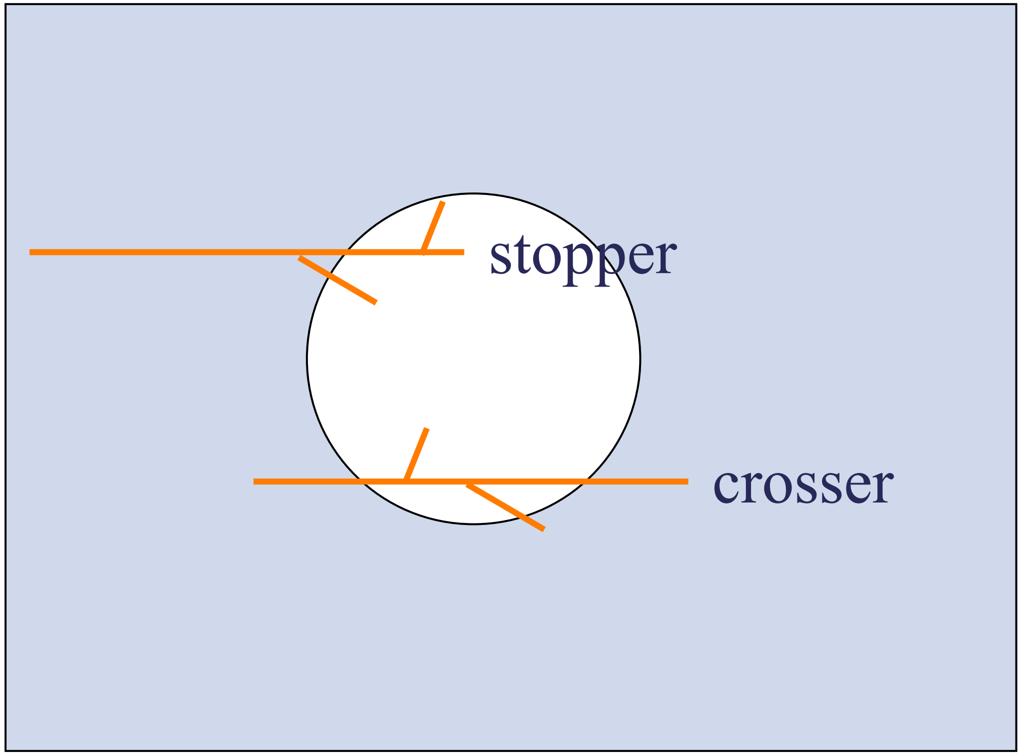


$$D_{water} = \frac{Q}{m_{air}} \cdot \left(\frac{\overline{W}_{air}}{e} \right) \cdot \frac{\left(S_{el}/\rho \right)_{water}}{\left(S_{el}/\rho \right)_{air}}$$

$$D_{water} = \frac{Q}{m_{air}} \cdot \left(\frac{\overline{W}_{air}}{e} \right) \cdot \frac{\left(S_{el}/\rho \right)_{water}}{\left(S_{el}/\rho \right)_{air}} \cdot p$$

- What about the stoppers ???? Do they create a problem???

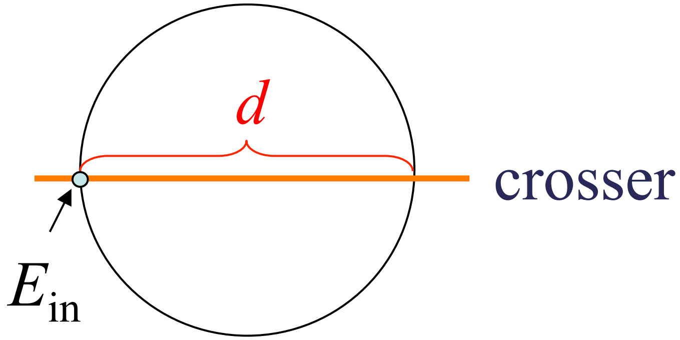
- The answer is: Yes, they do!



- Let us exactly analyze the process of energy absorption of a crosser:
- We assume that the energy E_{in} of the electron entering the cavity is almost not changed when moving along its track length *d* within the cavity.

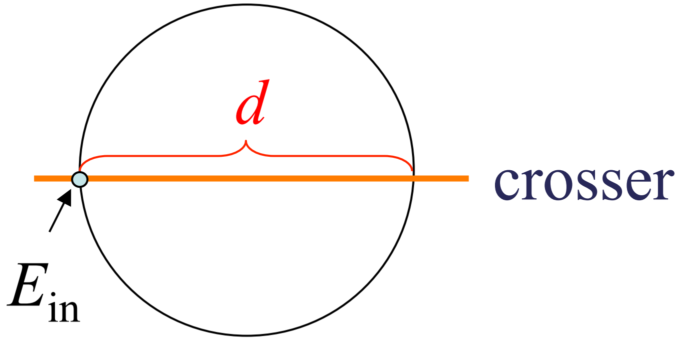
- Then the energy imparted ε is:

$$\varepsilon = S_{el}\left(E_{in}\right) \times d$$



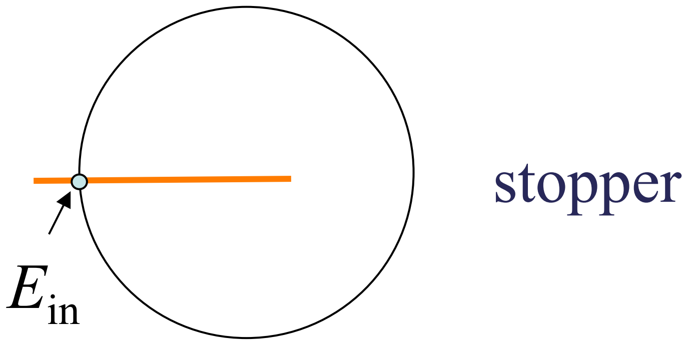
We compare this sitution:

$$\varepsilon = S_{el}(E_{in}) \times d$$



With the energy absorption of a stopper:

$$\varepsilon = E_{in}$$



- Therefore, the calculation of absorbed dose using the stopping power according to the formula:

$$D_{air} = \int \Phi_E \cdot \left(\frac{S_{el}}{\rho}\right)_{air} \cdot dE$$

only works for crossers!

As a consequence, the calculation of the ratio of the mean mass collision stopping power also works only for crossers

$$s_{water,air} = \left(\frac{\overline{S}_{el}}{\rho}\right)_{water} \Bigg/ \left(\frac{\overline{S}_{el}}{\rho}\right)_{air}$$

and hence needs some corrections for the stoppers!

Spencer-Attix stopping power ratio

- Spencer & Attix have developed a method in the calculation of the water to air stopping power ratio which explicitly takes into account the problem of the stoppers!

$$\left(\overline{S}/\rho\right)_{w,a}^{SA} = \frac{\displaystyle\int_{\Delta}^{E_{max}} \Phi_E^{w,\delta}(E)\cdot\frac{L_{\Delta,w}(E)}{\rho}\,dE + \Phi_E^{w,\delta}(\Delta)\cdot\frac{S_w(\Delta)}{\rho}\cdot\Delta}{\displaystyle\int_{\Delta}^{E_{max}} \Phi_E^{w,\delta}(E)\cdot\frac{L_{\Delta,air}(E)}{\rho}\,dE + \Phi_E^{w,\delta}(\Delta)\cdot\frac{S_{air}(\Delta)}{\rho}\cdot\Delta}$$

Summary: Determination of Absorbed dose in water

The absorbed dose in water is obtained from the measured charge in an ionization chamber by:

$$D_{water} = \frac{Q}{m_{air}} \cdot \left(\frac{\overline{W}_{air}}{e} \right) \cdot s_{w,a}^{SA} \cdot p$$

where:

- $s_{w,air}^{SA}$ is now the water to air ratio of the mean mass **Spencer-Attix stopping power**
- p is for all perturbation correction factors required to take into account deviations from BG-conditions.