FUNDAMENTAL QUANTITIES & UNITS FOR IONIZING RADIATION

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INTRODUCTION

- A unit is necessary for the measurement of any physical quantity.
- International Commission of Radiation Units and Measurements (ICRU)
  - Reviews and updates the concepts related to quantities and their units in radiation physics, dosimetry and radiological protection.

CLASSIFICATION

- Dosimetric Quantities
- Radioactivity
- Protectional Quantities
- Operational Quantities
- Radiometric Quantities
- Interaction Coefficients

DOSIMETRIC QUANTITIES
EXPOSURE

- Exposure is a quantity which measures the photon (X or γ radiation) flux at any point in air.
- It is defined as that quantity of x or γ radiation that produces in air, ions carrying 1 coulomb (C) of charge of either sign per kg of air.
- The S.I. unit of exposure is CKg^{-1}.
- The old unit of exposure is Roentgen (R).

DOSIMETRIC QUANTITIES
EXPOSURE (X)

- Measurement of ionization produced in air by photons
- Quotient of **dQ** by dm

dQ- The absolute value of the total charge of ions of one sign produced air, when all the electrons liberated by the photons in a volume of element of air having mass dm are completely stopped in air

$$\boxed{X = \left(\frac{dQ}{dm}\right)}$$

Unit: C.kg $^{-1}$

DOSIMETRIC QUANTITIES
EXPOSURE

- *One roentgen* is defined as the amount of X or γ radiation which would liberate 1 e.s.u of charge of either sign in 1cc of air at STP.
  - 1 R = 1 esu per cc of air at STP
  - 1 R = 2.58×10^{-4} CKg^{-1}
- Exposure is not defined above photon energies of <u>3 MeV.</u>

DOSIMETRIC QUANTITIES
ABSORBED DOSE

- The effects of radiation depends (physical, chemical and biological) not so much on the energy transferred to the medium, but on the energy absorbed by it.
- Absorbed dose (simply dose) is defined as the amount of energy absorbed per unit mass of the matter at the point of interest.

DOSIMETRIC QUANTITIES
ABSORBED DOSE (D)

Energy absorbed from ionizing radiation per unit mass

Quotient of **dE** by **dm**

dE- Mean energy imparted by the ionizing radiation to the mass dm

$$\boxed{D = \left(\frac{dE}{dm}\right)}$$

Unit: J.kg $^{-1}$

The quantity absorbed dose has been defined to describe the quantity of radiation for all types of ionizing radiation including charged and uncharged particles

DOSIMETRIC QUANTITIES
ABSORBED DOSE

- The special name of the unit of dose is Gray (Gy).
  - 1 Gy = 1 Jkg^{-1}
- The old Unit of absorbed dose is rad.
  - Energy absorption of 100 erg per gram of material
  - 1rad = 100 ergs/gm
  - 1rad = 1 cGy=10^{-2} Jkg^{-1} = 10^{-2} Gy
  - 1Gy = 100 rads

DOSIMETRIC QUANTITIES
KERMA

- The field of indirectly ionizing radiations at any point in matter is given by the quantity “Kerma”.

- **K**inetic **E**nergy **R**eleased in a **M**edium

- It is defined as the sum of initial kinetic energies of all charged particles liberated by radiation (uncharged particles) in a material of mass 1 kg.

DOSIMETRIC QUANTITIES

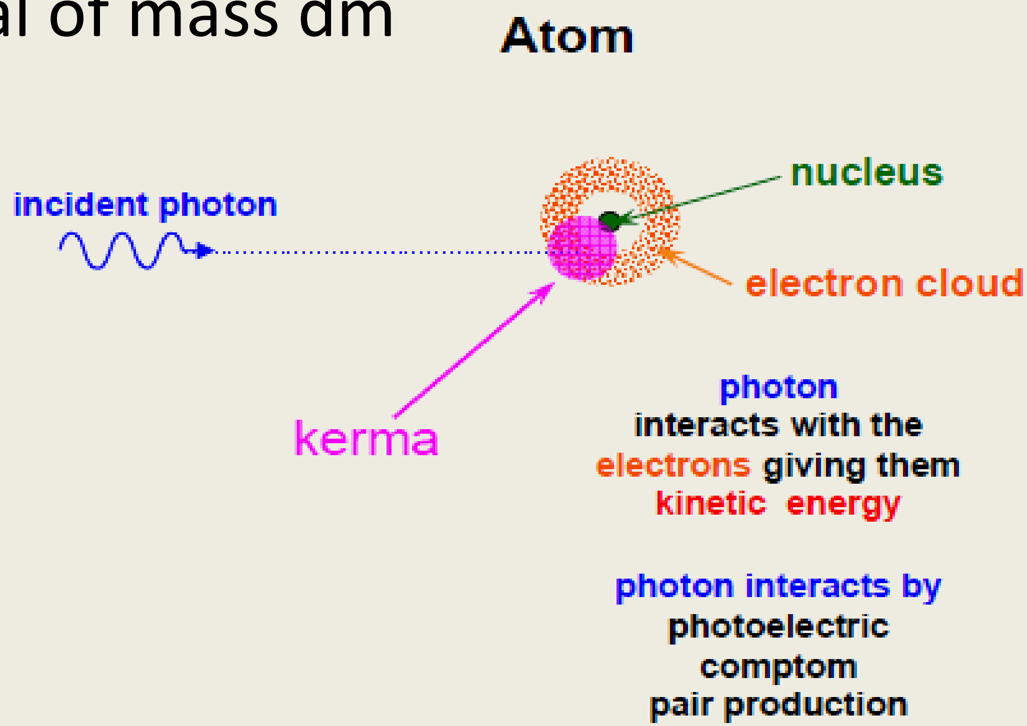
KERMA (KINETIC ENERGY RELEASED IN THE MEDIUM)

Quotient of **dE_{tr}** by **dm**

dE_{tr}- the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged particles in the material of mass dm

$$\boxed{K = \left(\frac{dE_{tr}}{dm}\right)}$$

Unit: J.kg $^{-1}$



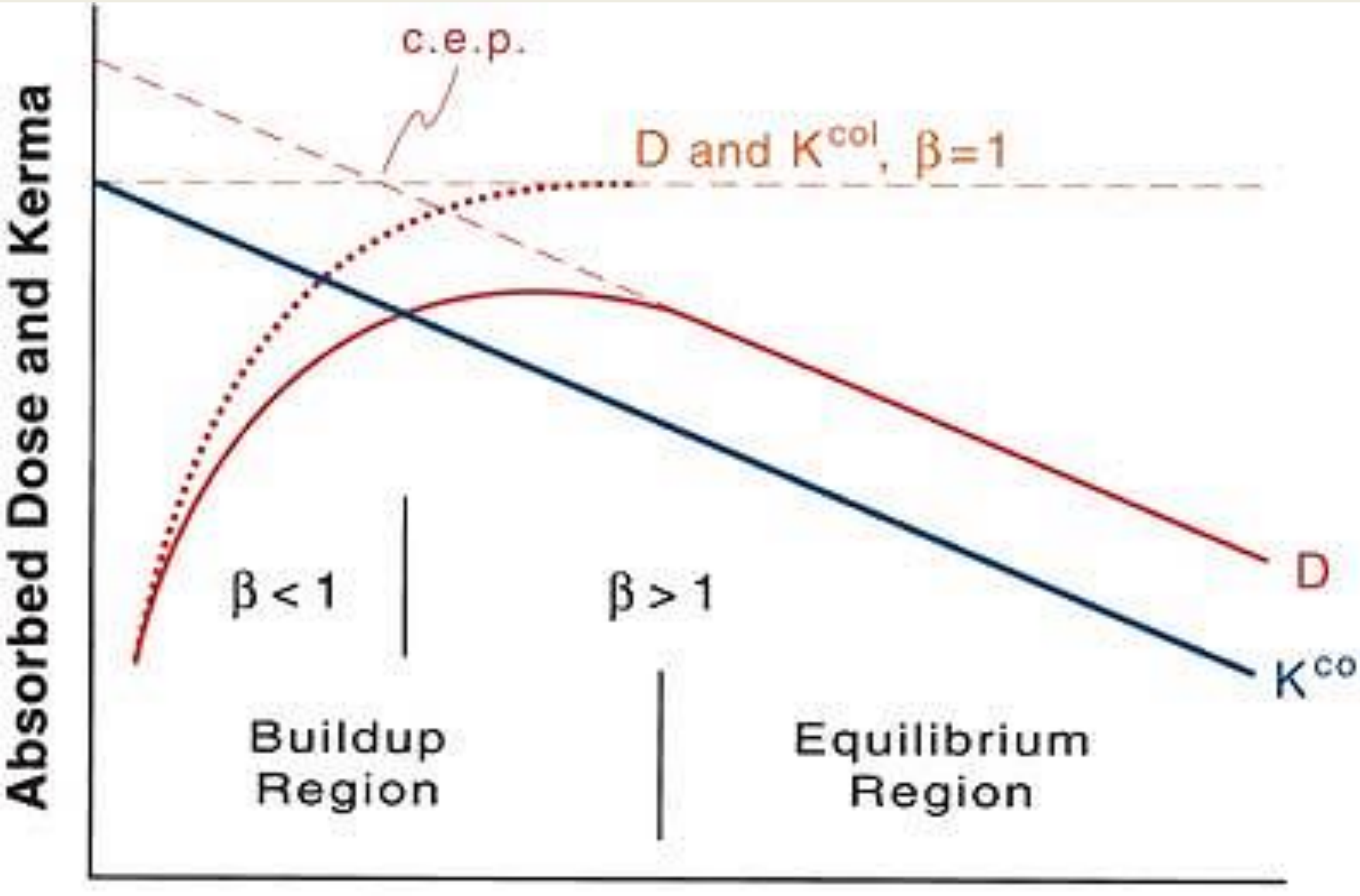
DOSIMETRIC QUANTITIES
KERMA

- The SI unit is Joules per kilogram (Jkg^{-1}).

- The special name of the unit is Gray (Gy).
  - 1 Gy = 1 Jkg^{-1}

- If the reference material is air, the quantity is called "air kerma".

DOSIMETRIC QUANTITIES
KERMA & ABSORBED DOSE RELATION



DOSIMETRIC QUANTITIES
KERMA & ABSORBED DOSE RELATION

- Kerma is maximum at surface and decreases with depth.
- Dose initially buildup to a maximum value and decreases at the same rate as kerma
- Because of the increasing range of electrons complete electronic equilibrium does not exist within MV photon beam.
- At depth greater than the maximum range of electrons, there is a region of Transient electronic equilibrium

CLASSIFICATION

- Dosimetric Quantities
- Radioactivity
- Protectional Quantities
- Operational Quantities
- Radiometric Quantities
- Interaction Coefficients

RADIOACTIVITY QUANTITIES

- Radioactivity refers to the phenomena associated with spontaneous transformations that involve changes in the nuclei of atoms.

- The energy released in such transformations is emitted as nuclear particles (alpha particles, electrons, and positrons) and/or photons

RADIOACTIVITY QUANTITIES
ACTIVITY

- The activity of a radioactive material is a measure of its spontaneous transformation

- It is defined as the number of nuclear transformations (or disintegrations) per second.
  - The SI unit for activity is the Becquerel (Bq).
    - 1 Bq = 1 disintegration per second

RADIOACTIVITY QUANTITIES
ACTIVITY (A)

Quotient of **dN** by **dt**

dN- the mean change in the no. of nuclei in that energy state due to spontaneous nuclear transformations in the time interval **dt**

$$\mathbf{A = -\frac{dN}{dt}}$$

Unit: Sec^{-1}

Special unit: Becquerel (Bq) and Curie (Ci)

1Ci= 3.7 x 10^{10}Bq

RADIOACTIVITY QUANTITIES
ACTIVITY

– The old unit of activity is Curie (Ci).

- 1 Curie (Ci) $= 3.7\times10^{10}$ disintegrations/sec

  $= 3.7\times10^{10}$ dps

  $= 3.7\text{x}10^{10}$ Bq or 37 GBq

  – 1 millicurie = 37 MBq

  – 1 microcurie = 37 kBq

RADIOACTIVITY QUANTITIES

The activity A is equal to the product of the decay constant, λ, and the number N of nuclei in that state.

$$A=\lambda N$$

DECAY CONSTANT (Λ)

quotient of –dN/N by dt

-**dN/N** – Mean fractional disintegration taking place in the time interval **dt**

$$\lambda = -\frac{dN/N}{dt}$$

Unit: Sec^{-1}

CLASSIFICATION

- Dosimetric Quantities
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PROTECTION QUANTITIES

- Effect of radiation depends upon amount of energy and also on absorbed spatial distribution of ion pairs
- Damage due to same dose of radiation
  1. Varies with radiation type
  2. vary with radio-sensitivity of tissue
- Two factors were introduced to consider these variations such as:
  - Radiation weighting factor (W_R)
    - accounts effectiveness of radiation
  - Tissue weighting factor (W_T)
    - accounts radio-sensitivity of organs

PROTECTION QUANTITIES
EQUIVALENT DOSE

- Effect of radiation depends
  - Not only on the amount of energy absorbed
  - But also on the spatial distribution of ion pairs.
- Hence the biological damage caused by the same dose of different radiation are different.
  - Alpha radiation – higher charge and mass
    - Greater ionization per unit path length

PROTECTION QUANTITIES
EQUIVALENT DOSE

- In radiation protection, the *Radiation Weighting Factor*, **(W_R)** accounts for the variation in the effectiveness of different types of radiations.

- The product of the *absorbed dose, **D*** and *radiation weighting factor*, **(W_R)** of a particular radiation gives the measure of its biological damage.

- The weighted absorbed dose is called the Equivalent Dose **(H_T).**

PROTECTION QUANTITIES
EQUIVALENT DOSE

- $\mathbf{H_T = \Sigma_R W_R . D_{TR}}$
  - $\mathbf{D_{TR}}$ is the absorbed dose in tissue '**T**' for radiation '**R**' of radiation weighting factor W_R.
  - $\mathbf{W_R}$ is a dimensionless quantity
    - Formerly called as Quality factor **(QF).**

- The special unit of Equivalent Dose is Sievert **(Sv)**.
  - **1 Sv = 1 $\mathbf{Jkg^{-1}}$**

PROTECTION QUANTITIES
EQUIVALENT DOSE

- In radiation protection
  - 20 mGy of gamma dose, 1 mGy of alpha dose and 10 mGy of proton dose are equivalent.
- Equivalent dose in **Sv = Dose in Gy x W_R**
- The old unit of equivalent dose is rem.
  - <u>**R**</u>oentgen <u>**E**</u>quivalent <u>**M**</u>an
  - Equivalent dose in **rem = Dose in rad x QF**
- **1 Sv = 100 rem**

PROTECTION QUANTITIES
EFFECTIVE DOSE

- Exposure to radiation may occur to the whole body (uniform irradiation) or to individual organs of the body (non-uniform irradiation).
  - Non uniform radiation will have to be restricted in order to protect against not only deterministic effects but also to reduce stochastic effects.
  - ICRP recommends dose limits for both stochastic and deterministic effects.

PROTECTION QUANTITIES

RADIATION WEIGHTING FACTORS (W_R)

Radiation Type	Radiation Weighting Factor (W_R) based on ICRP 103	Radiation Weighting Factor (W_R) based on ICRP 60
Photons, Electrons & Muons	1	1
Protons & Charged Pions	2	5
Alpha particles, fission fragments, heavy ions	20	20
Neutrons	Continuous function of neutron energy	<1 MeV $2.5+18.2\ e^{-[\ln(E)2]/6}$ 1 to 50 MeV $5.0+17.0\ e^{-[\ln(2E)]2/6}$ >50 MeV $2.5+3.25\ e^{-[\ln(0.04\ E)2]/6}$

PROTECTION QUANTITIES
EFFECTIVE DOSE

- The Effective dose assesses risk by modifying the equivalent dose using a tissue weighting factor W_T.

- It is defined as the sum of the equivalent dose in all tissue and organs of the body multiplied by the corresponding tissue weighting factor.

  - $E = \Sigma W_T \,.\, H_T$
  - $E = \Sigma_R W_R \,.\, D_{TR} \,.\, W_T$

PROTECTION QUANTITIES
EFFECTIVE DOSE

- The unit of equivalent dose is Jkg^{-1}.
- The special unit of equivalent dose is Sievert (Sv).
- The old unit of equivalent dose is rem.
- 1 Sv = 1 Jkg^{-1}
- 1 Sv = 100 rem

PROTECTION QUANTITIES
EFFECTIVE DOSE

- W_T values are useful in converting equivalent dose received by one or more tissues (partial body exposure) to effective dose (whole body exposure equivalent).

- This equivalent to be used only for estimation of stochastic effects for radiation protection purpose only.

PROTECTION QUANTITIES

TISSUE WEIGHTING FACTORS (W_T)

ORGANS	ICRP 30 (136) 1979	ICRP 60 (13) 1991	ICRP 103 (16) 2008
Gonads	0.25	0.20	0.08
Red Bone Marrow	0.12	0.12	0.12
colon	-	0.12	0.12
Lung	0.12	0.12	0.12
Stomach	-	0.12	0.12
Breast	0.15	0.05	0.12
Bladder	-	0.05	0.04
Liver	-	0.05	0.04
Oesophagus	-	0.05	0.04
Thyroid	0.03	0.05	0.04
Skin	-	0.01	0.01
Bone Surface	0.03	0.01	0.01
Salivary gland	-	-	0.01
Brain	-	-	0.01
Remaining body	0.30	0.05	0.12

CLASSIFICATION

- Dosimetric Quantities
- Radioactivity
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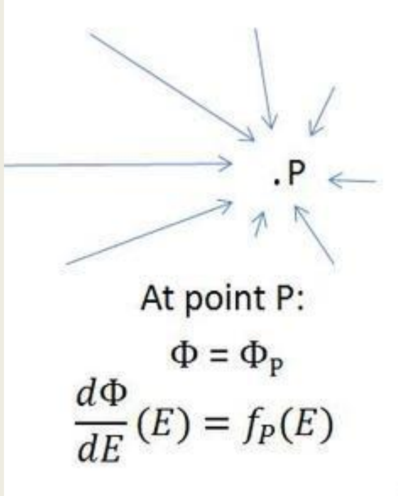
OPERATIONAL QUANTITIES

- Protection quantities in human body can not practically be measured
- Operational quantities are introduced to estimate Protectional quantities reasonably
- These quantities are determined at defined locations in defined phantoms
- While doses are estimated from area monitoring,
  1. Ambient dose equivalent $H^*(d)$
  2. Directional Dose equivalent $H^*(d,\Omega)$
- While doses are estimated from individuals,
  1. Personal Dose equivalent $H_P(d)$

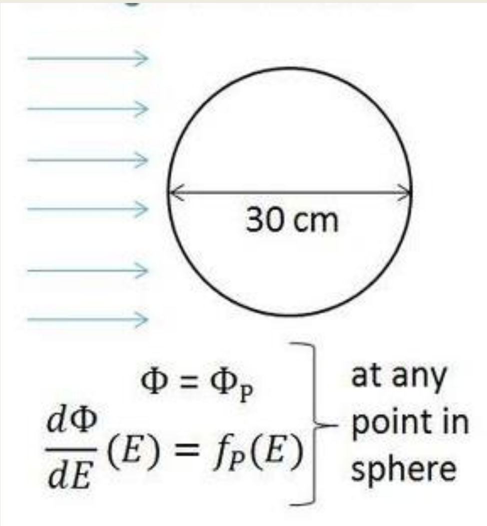
OPERATIONAL QUANTITIES
AMBIENT DOSE EQUIVALENT H*(D)

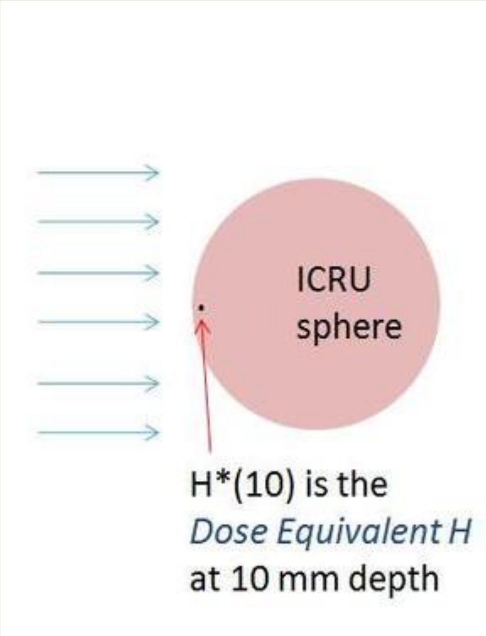
The dose equivalent that would be produced by the corresponding expanded and aligned field, in the ICRU sphere at a depth d in mm on radius opposing the direction of the aligned field

Actual Field



Corresponding expanded and aligned field





DOSIMETRIC QUANTITIES
KERMA

Special unit: Gray **(Gy)**

Gray – The transfer of one joule of radiation energy per kg of medium

$$\boxed{K = \psi\left(\frac{\mu_{tr}}{\rho}\right)}$$

$\boldsymbol{\mu_{tr}/\rho}$ - Mass energy transfer coefficient for the medium averaged over the energy fluence spectrum of photons $\boldsymbol{\psi}$

Energy transfer to ionizing particles may be :

- Collisional interaction results ionization & excitation
- Radiative interaction results bremsstrahlung

$$\mathbf{K = K_{col} + K_{rad}}$$

OPERATIONAL QUANTITIES

DIRECTIONAL DOSE EQUIVALENT H*(D, Ω)

- The dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth d in mm in a specified direction Ω

- This is of particular use in the assessment of dose to the skin and eye lens

Unit: J/kg and Sievert (Sv)

OPERATIONAL QUANTITIES
PERSONAL DOSE EQUIVALENT $H_P(D)$

- The dose equivalent in soft tissue at an appropriate depth d below a specified point on the body.

- HP(d) measured with a detector which is worn at the surface of the body and covered with an appropriate thickness of tissue equivalent material

Operational quantities, the depth of measurement is:

- For strongly penetrating radiation, d is 10mm
- For weakly penetrating radiation, d is 0.07mm
- For eye lens d becomes 3mm

CLASSIFICATION

- Dosimetric Quantities
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RADIOMETRY

- Radiation fields are characterized by radiometric quantities that apply in free space and in matter.

- The Radiometric quantities are :

  1. Particle Number, Radiant Energy
  2. Flux, Energy Flux
  3. Fluence, Energy Fluence

RADIOMETRY

Particle Number (N):

The number of particles that are emitted, transferred, or received

Radiant Energy (R):

The energy of the particles that are emitted, transferred or received

- For particles of energy E, the radiant energy, R, is equal to the product of NE.

$$R = N.E$$

RADIOMETRY

Flux (N):

Quotient of **dN** by **dt**

dN - the particle number in the time interval **dt**

$$\boxed{N = \frac{dN}{dt}}$$

Units: Sec^{-1}

Energy Flux (R):

Quotient of **dR** by **dt**

dR - the increment of radiant energy in the time interval **dt**

$$\boxed{R = \frac{dR}{dt}}$$

Units: W

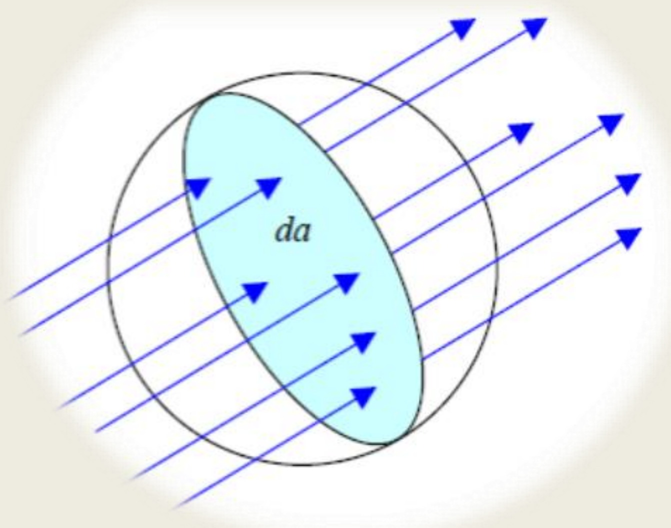
RADIOMETRY

Fluence (ϕ):

Quotient of dN by da

dN - the no. of particles incident on a sphere of cross-sectional area da

$$\boxed{\phi = \frac{dN}{da}}$$



Unit: m^{-2}

Fluence rate (ϕ'):

Quotient of dϕ by dt

dϕ - the increment of the fluence in the time interval dt

$$\boxed{\dot{\phi} = \frac{d\phi}{dt}}$$

Unit: $m^{-2}Sec^{-1}$

RADIOMETRY

Energy fluence (φ):

Quotient of **dR** by **da**

dR - the radiant energy incident on a sphere of cross-sectional area da

$$\boxed{\varphi = \frac{dR}{da}}$$

Unit: J/m^2

Energy fluence rate (φ'):

Quotient of dφ by dt

dφ - the increment of the energy fluence in the time interval dt

$$\boxed{\dot{\varphi} = \frac{d\varphi}{dt}}$$

Unit: J/m^2

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INTERACTION COEFFICIENTS

- Interaction process occur between radiation and matter.
- Either energy or direction of the incident particle is altered or particle is absorbed
- Interactions is characterized by various coefficients which specifies interaction process, type and energy of radiation and material
- Various interaction coefficients are defined such as :

  - Linear Attenuation Coefficient
  - Mass Attenuation Coefficient
  - Mass Energy Transfer Coefficient
  - Mass Energy Absorption Coefficient

  Uncharged Particle

  - Stopping power
  - Mass Stopping Power
  - Linear Energy Transfer
  - Radiation Chemical Yield

  Charged Particle

INTERACTION COEFFICIENTS (UNCHARGED PARTICLE)
LINEAR ATTENUATION COEFFICIENT (M)

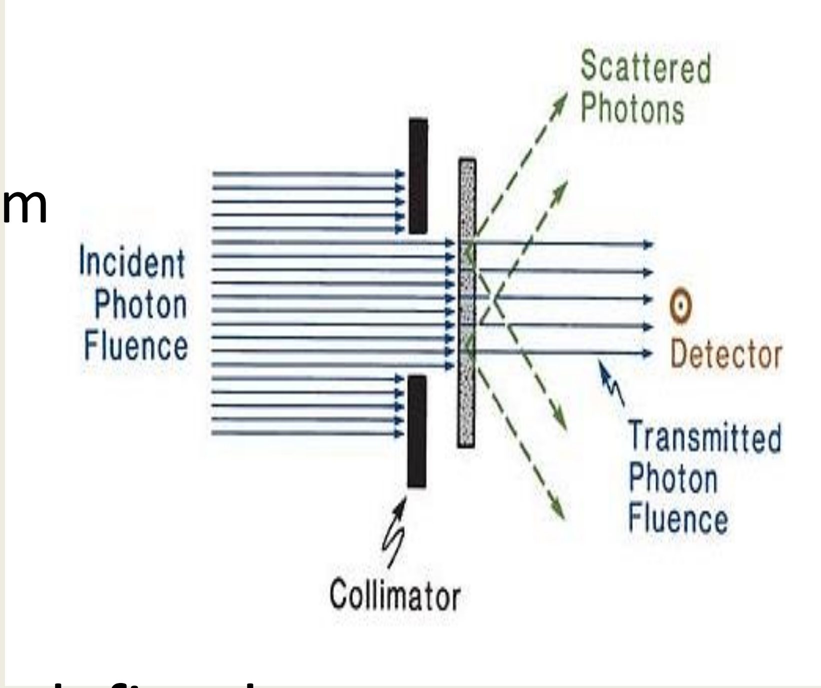
- The fraction photons (uncharged particles) attenuating per unit path length in medium

Let

N = No. of photons incident on medium

dN = Reduction of photons

L= Length of the medium



The linear attenuation coefficient is defined as:

Unit: cm^{-1}

$$\boxed{\mu = (\frac{dN}{N})(\frac{1}{dL})}$$

- μ depends on density of the medium

INTERACTION COEFFICIENTS (UNCHARGED PARTICLE)

MASS ATTENUATION COEFFICIENT (M/P)

Quotient of **μ** by **ρ**

μ – Linear Attenuation Coefficient
(fraction of photons attenuated per unit path length in medium)

ρ – Density of medium

Unit: cm^2g^{-1}

$$\boxed{\mu/\rho = \left(\frac{dN}{N}\right)\left(\frac{1}{\rho . dL}\right)}$$

INTERACTION COEFFICIENTS (UNCHARGED PARTICLE)

MASS ENERGY TRANSFER COEFFICIENT (M_{TR}/P)

Quotient of **dR_{tr}/R** by **ρdL**

dR_{tr}/R – The fraction of incident energy that is transferred as the kinetic energy of charged particles, in traversing a distance of **dL** in the medium of density **ρ**

$$\boxed{\mu_{tr}/\rho = \left(\frac{dR_{tr}}{R}\right)\left(\frac{1}{\rho . dL}\right)}$$

Unit: m^2kg^{-1}

- The binding energy of the liberated charged particles are not included in dR_{tr}

INTERACTION COEFFICIENTS (UNCHARGED PARTICLE)

MASS ENERGY ABSORPTION COEFFICIENT (μ_{en}/ρ)

- Product of mass energy transfer co-efficient (μ_{tr}/ρ) and (1-g)
- μ_{tr}/ρ – Mass energy-transfer Coefficient
- g – Fraction of the energy lost in Radiative process in the medium (bremsstrahlung)

$$\boxed{\mu_{en}/\rho = \left(\frac{d\mu_{tr}}{\rho}\right)(1-g)}$$

Unit: m^2kg^{-1}

INTERACTION COEFFICIENTS (CHARGED PARTICLE)
STOPPING POWER (S.P)

Quotient of **dE** by **ρdL**

dE- Mean energy lost by the charged particles in traversing a distance **dL** in the medium

$$\boxed{S.P = \left(\frac{dE}{dL}\right)}$$

Unit: $J.m^{-1}$ or $MeV.m^{-1}$

Mass Stopping Power (S.P/ρ):

Quotient of S.P by ρ

$$\boxed{S.P/\rho = \left(\frac{dE}{dL}\right).\left(\frac{1}{\rho}\right)}$$

Unit: Jm^2kg^{-2} or $MeV.m^2.kg^{-1}$

INTERACTION COEFFICIENTS (CHARGED PARTICLE)
LINEAR ENERGY TRANSFER (LET)

Energy lose per unit path length in medium

Energy lost is due to electronic collisions of charged particle in traversing medium

$$\boxed{\mathbf{LET = (\frac{dE}{dL})}}$$

Unit: keV/μm^{-1}

INTERACTION COEFFICIENTS (CHARGED PARTICLE)

RADIATION CHEMICAL YIELD

Quotient of **n(x)** by **ε**

(nx)- Mean amount of substance of the entity produced, destroyed, or changed in a system by the mean energy imparted ε, to the matter of that system

$$\boxed{G(x) = \left(\frac{n(x)}{\varepsilon}\right)}$$

Unit: **mol.J $^{-1}$**

- **G** value is the mean number of entities produced, destroyed or changed with an imparted energy of **100 eV**

SUMMARY

QUANTITY	OLD UNIT	NEW UNIT	RELATIONSHIP
Radioactivity	Ci	Bq	1 Bq = 0.27×10^{-10} Ci 1 Ci = 3.7×10^{10} Bq
Exposure	R	Ckg^{-1}	1 Ckg^{-1} = 3876 R 1 R = 2.58×10^{-4} Ckg^{-1} 1 Air Kerma = 114 R
Absorbed Dose	rad	Gy	1 Gy = 100 rad 1 Gy = 1 Jkg^{-1}
Equivalent dose / Effective dose	rem	Sv	1 Sv = 100 rem 1 Sv = 1 Jkg^{-1}


Thank You