

Fundamental Quantities and Units for Ionizing Radiation (ICRU Report 60)

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CONTENT

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 - i) Scaler Radiometric Quantities
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What is a quantity?

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- Quantity means to characterize a physical phenomenon in terms of something that is suitable for numerical expression.

What is a unit?

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- A unit is a selected reference sample of the quantity.
- A quantity is always expressed as the product of a number and a unit.

NEED OF MEASURING SYSTEM

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- To quantify biological effects in Radiotherapy and Radio diagnosis.
- To quantify dose sufficient to produce response.
- To quantify damage.
- To improve clinical practice based on the observations.

Radiation Units

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- Two systems are in common use:
 - Special Units
 - System Internationale (SI) Units
- Special units are used by most regulatory **agencies in the U.S.**
- SI units and are used in the rest of the **world, and are based on “MKS”**

Special & New Units

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Quantity	Unit		Relationship
	Special	SI	
Radioactivity	Ci	Bq	$1 \text{ Bq} = 0.27 \times 10^{-10} \text{ Ci}$
Exposure	R	C / Kg	$1 \text{ C Kg}^{-1} = 3876 \text{ R}$
Air Kerma	-	Gy	$1 \text{ Air Kerma} = 114 \text{ R}$
Dose	Rad	Gy	$1 \text{ Gy} = 100 \text{ Rad}$
Equivalent Dose	Rem	Sv	$1 \text{ Sv} = 100 \text{ rems}$

Radiation Units – Governing Bodies

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- ICRP- International Commission On Radiological Protection
- ICRU- International Commission On Radiation Units and Measurements

- The International Commission on Radiation Units and Measurements (ICRU, US, 1925) has objective to develop quantities, units of radiation and radioactivity, procedures for measurement & application of these quantities in radiology, radiation therapy, radiation biology, and industrial operations.

- The International Commission on Radiological Protection (ICRP, UK, 1928), a private organization having 100 members from different countries, is an advisory body providing recommendations and guidance on radiation protection against ionizing radiation.

ICRU Report 60

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- Issued on December 30, 1998.
- Supersedes Part A of ICRU Report 33 (ICRU, 1980), dealing with quantities and units for general use.
- Deals with fundamental Quantities & Units for ionizing radiation.
- Recommends the use of SI units.

Classification of Radiation Quantities (ICRU 60)

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- Radiometric Quantities
- Interaction Coefficients
- Dosimetric Quantities
- Radioactivity

Radiometric Quantities

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- Radiation fields consisting of various types of particles such as photons, electrons, neutrons are characterized by **Radiometric quantities**.
- **Radiometric quantities** specify radiation field at a point in free space as well as in matter and define the particle or energy fluence, energy distribution and also their variation in space and time.

Particle Number 'N'

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- Particle Number 'N' is the no. of particles that are emitted, transferred or received.

Unit: 1

Radiant Energy 'R'

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- Radiant Energy 'R' is the energy (excluding the rest energy) of the particles that are emitted, transferred or received.
- For particles of energy 'E', the Radiant energy is given by the expression:

$$R = NE$$

Unit: J

Flux (N)

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- Flux, N' , is the quotient of dN by dt , where dN is the increment of particle number in time interval dt .

$$N = dN/dt$$

Unit: s^{-1}

Energy Flux (R)

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- Energy Flux (R') is the quotient of dR by dt , where dR is the increment of Radiant Energy in time interval dt .

$$R = dR/dt$$

Unit: W or J/s⁻¹

Fluence (ϕ)

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- The Fluence (ϕ) is the quotient of dN by da , where dN is the no. of particles incident on a sphere of cross-sectional area da .

$$\phi = dN/da$$

Unit: m^{-2}

Energy Fluence (ψ)

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- The Energy Fluence (ψ) is the quotient of dR by da , where dR is the radiant energy incident on a sphere of cross-sectional area da .

$$\psi = dR/da$$

Unit: Jm^{-2}

The quantities Fluence and Energy Fluence are applicable in the common situation in which radiation interactions are independent of the direction of the incoming particles.

Fluence Rate(ϕ)

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- Fluence Rate (ϕ) is the quotient of $d\phi$ by dt , where $d\phi$ is the increment of fluence in the time interval dt .

$$\phi = d\phi/dt$$

Unit: $\text{m}^{-2} \text{s}^{-1}$

Energy Fluence Rate($\dot{\psi}$)

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- Energy Fluence Rate ($\dot{\psi}$) is the quotient of $d\psi$ by dt , where $d\psi$ is the increment of energy fluence in time interval dt .

$$\dot{\psi} = d\psi/dt$$

Unit: Wm^{-2}

Fluence Rate and Energy Fluence Rate are also known as Particle Flux Density and Energy Flux Density Respectively.

Particle Radiance (ϕ_Ω)

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- The Particle Radiance (ϕ_Ω) is the quotient of $d\phi$ by $d\Omega$, where $d\phi$ is the fluence rate of particles propagating within a solid angle $d\Omega$ around a specified direction.

$$\phi_\Omega = d\phi / d\Omega$$

Unit: $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$

Energy Radiance $\dot{\psi}_{\Omega}$

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- The Energy Radiance, $\dot{\psi}_{\Omega}$, is the quotient of $d\dot{\psi}$ by $d\Omega$, where $d\dot{\psi}$ is the energy fluence rate of particles propagating within a solid angle $d\Omega$ around a specified direction.

$$\dot{\psi}_{\Omega} = d\dot{\psi} / d\Omega$$

Unit: $\text{Wm}^{-2}\text{sr}^{-1}$

- All the quantities discussed so far were Scalar Radiometric Quantities.
- Since Radiometric Quantities are primarily concerned with the flow of radiation, it is appropriate to consider some of them as Vectorial Quantities.
- Vectorial quantities are used in radiation transport theory.

Examples of Vectorial Radiometric Quantities

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- Vectorial Particle Radiance

$$\Phi_{\Omega} = \Omega \phi_{\Omega}$$

where Ω is the unit vector in the direction specified for particle radiance ϕ_{Ω} .

Unit: $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$

- Vectorial Energy Radiance

$$\Psi_{\Omega} = \Omega \psi_{\Omega}$$

where Ω is the unit vector in the direction specified for energy radiance ψ_{Ω}

Unit: $\text{Wm}^{-2}\text{sr}^{-1}$

- Vectorial Fluence (Φ) = $\int \phi' dt$

Where , ϕ' , is the vectorial fluence rate.

Unit: m^{-2}

- Vectorial Energy Fluence (Ψ) = $\int \psi' dt$

Where , ψ' , is the Vectorial Energy fluence rate.

Unit: Jm^{-2}

- Vectorial Fluence Rate (Φ')

$$\Phi' = \int \Phi'_{\Omega} d\Omega$$

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

- Vectorial Energy Fluence Rate

$$\Psi' = \int \Psi'_{\Omega} d\Omega$$

Unit: Wm^{-2}

Interaction Coefficients

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- In an interaction of radiation with matter, energy or direction or both of the incident particle is altered or the particle is absorbed.
- The interaction may be followed by the emission of one or more secondary particles.
- The likelihood of such interactions is characterized by interaction Coefficients.

Cross Section

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- The cross section, σ , of a target entity, for a particular interaction produced by incident particles, is the quotient of P by Φ , where P is the probability of that interaction for a single target entity when subjected to the particle fluence, Φ , thus

$$\sigma = P/\Phi$$

Unit: m^2

Mass attenuation Coefficient

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- The mass attenuation coefficient, μ/ρ , of a material, for uncharged particles, is the quotient of dN/N by ρdl , where dN/N is the fraction of particles that experience interactions in traversing a distance dl in the material of density ρ , thus

$$\mu/\rho = \frac{1}{\rho dl} \frac{dN}{N}$$

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

Mass Energy Transfer Co-efficient

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- The mass energy transfer coefficient, μ_{tr}/ρ , of a material, for uncharged particles, is the quotient of dR_{tr}/R by ρdl , where dR_{tr}/R is the fraction of incident radiant energy that is transferred to kinetic energy of charged particles by interactions, in traversing a distance dl in the material of density ρ , thus
- $$\mu_{tr}/\rho = \frac{1}{\rho dl} dR_{tr}/R$$

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

- The product of μ_{tr}/ρ for a material and $(1-g)$, where g is the fraction of the energy of liberated charged particles that is lost in radiative processes in the material, is called the mass energy absorption coefficient, μ_{en}/ρ , of the material for uncharged particles.

Mass Stopping Power

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- The mass stopping power, S/ρ , of a material, for charged particles, is the quotient of dE by ρdl , where dE is the energy lost by a charged particle in traversing a distance dl in the material of density ρ , thus
- $$S/\rho = \frac{1}{\rho} \frac{dE}{dl}$$

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

$S = dE/dl$ denotes the linear stopping power.

Linear Energy Transfer (LET)

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- The linear energy transfer or restricted linear electronic stopping power, L_{Δ} , of a material, for charged particles, is the quotient of dE_{Δ} by dl , where dE_{Δ} is the energy lost by a charged particle due to electronic collisions in traversing a distance dl , minus the sum of the kinetic energies of all the electrons released with kinetic energies in excess of Δ , thus

$$L_{\Delta} = dE_{\Delta}/dl$$

Unit: Jm^{-1}

- This definition differs from ICRU,1980 in two respects:
 - i) L_{Δ} now includes the binding energy for all collisions.
 - ii) The threshold of the kinetic energy of the released electrons is now Δ as opposed to Δ minus the binding energy.

Linear Energy Transfer

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- A measure of how, as a function of distance, energy is transferred from radiation to the exposed matter
- A high value of LET indicates that energy is deposited within a small distance
- The concept involves lateral damage along the path, in contrast to path length or penetration capability.

- Imagine a colony of 1,000 living cells exposed to 1 cGy X-ray. There would be 2 or 3 cell deaths, 2 or 3 irreparable changes in DNA and about 100,000 ionizations in the whole colony of cells -- ranging from 11 to 460 ionizations per cell.
- A comparable 1 cGy exposure to neutrons would be expected to cause more cell deaths and more mutations. The ionizations caused would range from 145 to 1,100 per cell.

- Alpha particles would cause roughly 10 times as many cell deaths and mutations, and 3,700 to 4,500 ionizations per cell.

- Therefore x-rays are low LET radiation whereas Alpha particles are high LET radiation.

Radiation Chemical Yield

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- The Radiation Chemical Yield, $G(x)$, of an entity, x , is the quotient of $n(x)$ by ϵ , where $n(x)$ is the mean amount of substance of that entity produced, destroyed, or changed in a system by the energy imparted, ϵ , to the matter of that system, thus

$$G(x) = n(x)/\epsilon$$

Unit: mol J⁻¹

- Mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012Kg of carbon-12.
- When the energy imparted = 100eV, the corresponding quantity is known as the “G-Value”.

Mean Energy Expended in a Gas Per Ion Pair Formed

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- The Mean Energy Expended in a Gas Per Ion Pair Formed, W , is the quotient of E by N , where N is the mean number of ion pairs formed when the initial kinetic energy E of a charged particle is completely dissipated in the gas, thus

$$W = E/N$$

Unit: J

- Ions produced by bremsstrahlung and other secondary radiation emitted by the charged particles are included in N .

Dosimetric Quantities

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- Radiation interacts with matter in a series of processes in which particle energy is converted and finally deposited in matter. Dosimetric quantities describe THESE processes.
- Dosimetric quantities provide a physical measure, at a point or in a region of interest, which is correlated with the actual or potential effects of ionizing radiation field.

KERMA (K)

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KERMA - Kinetic Energy Released in the Medium.

$$K = dE_{\text{trans}}/dm$$

where dE_{trans} is the sum of the initial kinetic energies of all charged ionizing particles liberated by uncharged ionizing particles in a material of mass dm .

It is a measure of amount of total energy transferred by photons (x-rays or gamma rays) interacting in the medium.

Unit : Joule per kg (J/kg)

SI Unit : Gray (Gy)

- The quantity dE_{tr} includes the kinetic energy of auger electrons.
- For a fluence, Φ , of uncharged particles of energy, E , the Kerma, K , in a specified material is given by
-

$$K = \Phi E \mu_{tr} / \rho$$

Where μ_{tr} / ρ is the mass energy transfer coefficient of the material for these particles.

Kerma Rate

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The kerma rate, \dot{K} , is the quotient of dK by dt , where dK is the increment of kerma in the time interval dt , thus:

$$\dot{K} = \frac{dK}{dt}$$

The unit is $\text{J kg}^{-1} \text{s}^{-1}$ and the special name for the unit of kerma rate is gray per second
(Gy s^{-1})

Exposure

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- The Exposure, X , is the quotient of dQ by dm , where dQ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons and positrons liberated by photons in air of mass dm are completely stopped in air, thus

$$X = dQ/dm$$

Unit: Ckg^{-1}

The exposure, X , in units of C kg^{-1} , is related to the air kerma as follows:

$$X = \frac{K_a (1 - g) e}{W}$$

where “ W ” is the average energy spent by an electron to produce an ion pair and “ e ” is the electronic charge

where g is the fraction of initial secondary electron energy that is radiated as bremsstrahlung

- Exposure is measured under conditions of electronic equilibrium.
- Exposure is the ionization analogue of air kerma.
- Ionization due to photons emitted by radiative processes is not to be included in dQ .
- Ionization produced by Auger electrons is included in dQ .

Exposure - energy absorption relationship

$$1 \text{ R} = \frac{1 \text{ electrostatic unit of charge (esu)}}{1 \text{ cc of air at STP}}$$

$$= 3.33 \times 10^{-10} \text{ Coulomb} / 1.293 \times 10^{-3} \text{ gm of air}$$

$$\text{Charge} = 1.602 \times 10^{-19} \text{ Coulomb}$$

$$1 \text{ R} = 2.082 \times 10^9 \text{ ion-pairs} / 1.293 \times 10^{-3} \text{ gm of air}$$

$$1 \text{ R} = 1.61 \times 10^{12} \text{ ion-pairs/gm of air}$$

Average energy needed for creating one ion-pair in air is 34 eV.

$$1 \text{ eV} = 1.602 \times 10^{-12} \text{ ergs}$$

1 R corresponds to an energy absorption of
87.7 ergs/gm of air or 0.877 Rads.

$$1.14 \text{ R} = 1 \text{ Rad} \quad \text{OR} \quad 114 \text{ R} = 1 \text{ Gy}$$

Exposure Rate

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The exposure rate, X , is the quotient of dX by dt , where dX is the increment of exposure in the time interval dt , thus:

$$X = \frac{dX}{dt}$$

The unit is $C\ kg^{-1}\ s^{-1}$

- Therefore Exposure rate is production of ionization in air per unit time.

Cema- Converted Energy Per Unit Mass

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- The Cema, C , is the quotient of dE_c by dm , where dE_c is the energy lost by charged particles, except secondary electrons, in electronic collisions in a mass dm of a material, thus

$$C = dE_c / dm$$

Unit: J

Special Unit: Gray (Gy)

- **Cema** for charged particles is a parallel definition to **Kerma** for uncharged particles.
- **Cema** differs from **Kerma** in that **Cema** involves the energy lost in electronic collisions by the incoming charged particles while **Kerma** involves the energy imparted to outgoing charged particles.

- Energy lost by charged particles in electronic collisions includes the energy expended against binding energy and any kinetic energy of the liberated electrons.
- Energy subsequently lost by secondary electrons is excluded from dE_c

Cema Rate

55

- The Cema Rate, \dot{C} , is the quotient of dC by dt , where dC is the increment of cema in the time interval dt , thus

$$\dot{C} = dC/dt$$

- Unit: $Jkg^{-1}s^{-1}$
Special Unit: Gy

Energy deposit

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

$$\epsilon_i = \epsilon_{in} - \epsilon_{out} + Q$$

Where ϵ_{in} is the energy of the incident ionizing particle (excluding rest energy), ϵ_{out} is the sum of the energies of all ionizing particles leaving the interaction (excluding rest energies), Q is the change in the rest energies of the nucleus and of all particles involved in the interaction.

Unit: J

Energy Imparted

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

$$\epsilon = \sum_i \epsilon_i$$

Where the summation is performed over all energy deposits, ϵ_i , in that volume.

Unit: J

- Energy imparted is the energy incident **minus** the energy leaving the mass (excluding the energy released in nuclear transformations to keep the dose from becoming negative when the mass contains a radioactive source).
- Energy Imparted determines the dose.

Lineal Energy Transfer

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- Lineal energy transfer is the energy transferred from a particle to the medium traversed per unit length
- The magnitude is expressed in kilo-electron volts per micrometer (keV/ μm)
- Expresses the level of energy transferred at a microscopic scale

Lineal Energy Transfer

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- For alpha particles, as the dose decreases the number of hit cells decreases, but not the degree of impact on those cells, whereas for gamma rays the quantity of energy deposited per cell goes down, but not the number of cells hit.
- This difference makes alpha particles more damaging relative to gamma rays and thus they have a higher radiation weighting factor relative to gamma rays.
- The lineal energy transfer is the **microdosimetric analogue** of the linear energy transfer (LET).

Specific Energy

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- The **specific energy** (imparted), **z**, is the quotient of **ε** by **m**, where **ε** is the energy imparted to matter of mass **m**, thus

$$z = \epsilon / m$$

Unit: J kg⁻¹

Special Unit: Gray (Gy)

- Energy Imparted, Lineal Energy and Specific Energy are **STOCHASTIC** quantities.
- Specific energy leads to the **NON-STOCHASTIC** quantity **ABSORBED DOSE.**

Absorbed Dose

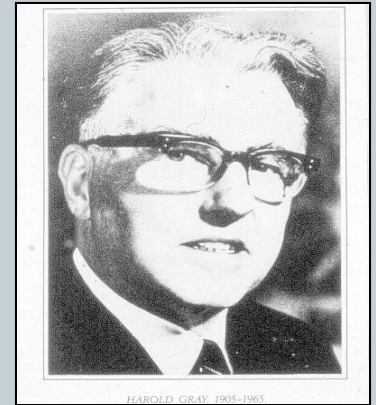
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The absorbed dose, D , is given by:

$$D = de/dm$$

Where de is the mean energy imparted to matter of mass dm .

- A fraction of Kerma will be radiated out from the medium in the form of bremsstrahlung.



Harold Gray
UK, 1905-1965

- The absorbed dose 'D' is defined for all ionizing radiation (not only for electromagnetic radiation, as in the case of the “exposure”), and for any material.

- In the region of electronic equilibrium, the kerma and absorbed dose are equal

Absorbed dose = Kerma – Bremsstrahlung loss

Unit : Joule per kg (J/kg) or Gray (Gy)

Old Unit : Rad (Rad. Abs. Dose)

1 Gy = 100 rad, 1 Rad = 100 ergs/gm

Absorbed Dose Rate

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The absorbed dose rate, \dot{D} , is the quotient of dD by dt , where dD is the increment of absorbed dose in the time interval dt , thus:

$$\dot{D} = \frac{dD}{dt}$$

The unit is $\text{J kg}^{-1} \text{s}^{-1}$ and the special name for the unit of absorbed dose rate is gray per second (Gy s^{-1}).

- The absorbed dose rate is simply the absorbed dose delivered per unit time period

Radioactivity

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- The term **Radioactivity** refers to those **spontaneous transformations** that involve changes of the nuclei of atoms.
- **Radioactivity** is a **stochastic** process.

- A **nuclide** is a species of atoms having a specified no. of protons and neutrons in its nucleus.
- Unstable nuclides, that transform to stable or unstable progeny, are called **radio-nuclides**.

Decay Constant & Half Life

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- **decay constant** is the probability of decay of a radionuclide in a time interval.
- It is denoted by λ

$$\lambda = dp/dt$$

dp = probability that a nucleus decays in time interval dt .

Quantity related to decay constant is **“Half life”**.

Activity (A)

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Quantity of radioactive material is expressed as **Activity**. It is defined as the number of nuclear transformation (or disintegration) per second.

$$A = N \lambda$$

Where

‘N’ is the no. of radioactive nuclei and

‘ λ ’ is the decay constant

Unit : Becquerel (Bq)

1 Bq = 1 transformation per second

Old unit : Curie (Ci)

1 Ci = 3.7×10^{10} transformation per second
= 3.7×10^{10} Bq

Activity

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For practical purposes, following sub-multiples of units are used

$$1 \mu\text{Ci} = 10^{-6} \text{ Ci}$$

$$1 \text{ mCi} = 10^{-3} \text{ Ci}$$

$$1 \text{ kCi} = 10^{+3} \text{ Ci}$$

$$1 \text{ kBq} = 10^{+3} \text{ Bq}$$

$$1 \text{ MBq} = 10^{+6} \text{ Bq}$$

$$1 \text{ GBq} = 10^{+9} \text{ Bq}$$

Air Kerma Rate Constant

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- The Air Kerma Rate Constant, Γ_δ , of a radionuclide emitting photons is the quotient of $r^2\dot{K}_\delta$ by A , where \dot{K}_δ is the air kerma rate due to photons of energy greater than δ , at a distance r in vacuum from a point source of the nuclide having an activity A , thus

$$\Gamma_\delta = r^2\dot{K}_\delta / A$$

- Unit: $\text{m}^2\text{Jkg}^{-1}$
- Special Unit: $\text{m}^2\text{GyBq}^{-1}\text{S}^{-1}$

- The photons referred to in the definition include gamma rays and characteristic x-rays.
- The Air kerma Rate Constant, a characteristic of a radionuclide, is defined in terms of an ideal point source.

- In a source of finite size, attenuation and scattering occur, and annihilation radiation may be produced. These processes may require significant correction.

- Any medium intervening between the source and the point of measurement will give rise to absorption and scattering for which corrections are needed.

References

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- International Commission on Radiation Units and Measurements, Quantities and Units in Radiation Protection Dosimetry, Report No. 51, ICRU, Bethesda (1993)
- ICRU Report 33 (ICRU, 1980).
- International Commission on Radiation Units and Measurements, Fundamental Quantities and Units for Ionizing Radiation, Report No. 60, ICRU, Bethesda (1998)
- Knoll, G.T., *Radiation Detection and Measurement*, 3rd Edition, Wiley, New York (2000)

Conclusion



“When you can measure what you are speaking about and express it in numbers, you know something about it; when you cannot... your knowledge is of a meager and unsatisfactory kind.”

Lord Kelvin (1889)

