Chapter II:
Radiometric and dosimetric quantities

Radiometric quantities

Stochastic and nonstochastic quantities

Stochastic quantity:

- occurs randomly → its probability is determined by a probability distribution
- is define for finite (noninfinitesimal) domain only et varies discontinuously in space and time → gradient is meaningless
- in principle can be measured with an arbitrarily small error
- its expectation value N_e is such as $\overline{N} \rightarrow N_e$ for $n \rightarrow \infty$

Nonstochastic quantity:

- for given conditions → can be determined by calculations
- can be defined in a point (point function) and varies continuously in space and time → gradient has a meaning
- in the context of ionizing radiation → its value is equal to the expectation value of a related stochastic quantity (or based upon)

Dosimetry and microdosimetry

- In dosimetry → nonstochastic quantities → infinitesimal quantities as d*V, dm, dt*, … have a meaning
- Nonstochastic quantities used in dosimetry are obtained by considering the expectation value of the related stochastic quantity
- Stochastic processes follow a Poisson distribution only characterized by its expectation value (for instance: radioactive decay)
- In microdosimetry (determination of the energy spent in small but finite volume – i.e.: at the cell level) → stochastic quantities have to be considered

Radiometric quantities

- Nonstochastic quantities defined in all points of space and characterizing the radiation field (which can formed by various types of particles)
- Each radiometric quantity is relative to **one** type of particles
- Two classes of radiometric quantities:
  - Referring to the particles number
  - Referring to the energy transported by them
- Both scalar and vector quantities can be used
- Practically → scalar quantities are required

Number of particles N – Radiant energy R

- N: **Particles number** → number of particles that are emitted, transferred, or received
- R: **Radiant energy** (unit: J, eV) → energy (excluding rest energy) of the particles that are emitted, transferred or received → if all particles have the same energy E → $R = EN$ (→ the mass energy-transfer coefficient becomes $(\mu_{tr}/\rho) = (dR_{tr}/R)/(\rho dl)$ with $R_{tr} = E_{tr}N$)
- These quantities are *global*
- Practically: type of particles, counting time, … have to be precised

Flux and energy flux

- $\dot{N}$: **Flux of particles** (unit: s^{-1}):→ quotient of *dN* by *dt*, where *dN* is the increment of the particle number in the time interval *dt*, thus →

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

- $\dot{R}$: **Energy flux** (unit: Js^{-1}or W): → quotient of *dR* by *dt*, where *dR* is the increment of radiant energy in the time interval *dt* →

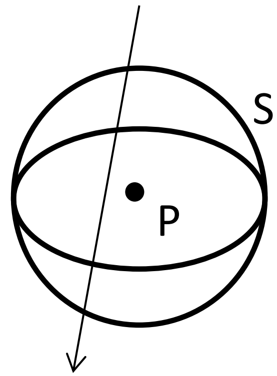
$$\dot{R} = \frac{dR}{dt}$$

- Quantities often associated to a surface → the flux is thus the number of particles that cross those surface by time unit. If the surface surrounds the radioactive source → the flux is the emission rate of the source

Distributions N_E and R_E

- For $E \in [E,E+dE]$:
  - Distribution with respect of *E* of the number of particles: $N_E = \frac{dN}{dE}$
  - Distribution with respect of *E* of the radiant energy: $R_E = \frac{dR}{dE}$
- $R_E = EN_E$
- By deduction: $N = \int_E N_{E'} dE'$ and $R = \int_E E' N_{E'} dE'$
- Complete description of the radiation field → space, direction and time distributions → definition of radiometric quantities based on the derivation of *N* and *R* with respect to the time, the area, the volume, the direction, the energy → local quantities: depend on the considered space point (not explicitly written)

Fluence



Let N be the mean number of particles striking a finite sphere S surrounding point P during a time interval Δt extending from an arbitrary starting time t_0 to a later time t → If the sphere is reduced to an infinitesimal at P (with a great-circle area of da) → definition of the **(particles) fluence** Φ: quotient of dN by da (unit: m^{-2}) →

$$\Phi = \frac{dN}{da}$$

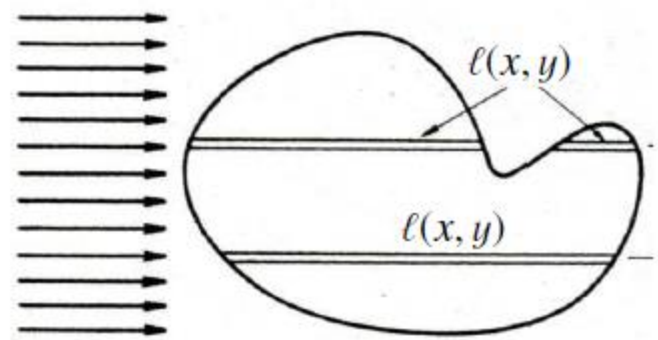
Other definition of the fluence

The fluence at point *P* is numerically equal to the mean value of the sum *ds* of the lengths of the particle trajectories (supposed rectilinear) inside the infinitesimal volume dV (non obligatory spherical) at *P*, divided by *dV* (with l_i the length of the trajectory of the i^e particle)

$$\Phi = \lim_{\Delta V \to 0} \frac{\sum_i l_i}{\Delta V} = \frac{ds}{dV}$$

→ definition particularly useful for Monte Carlo simulations

Demonstration



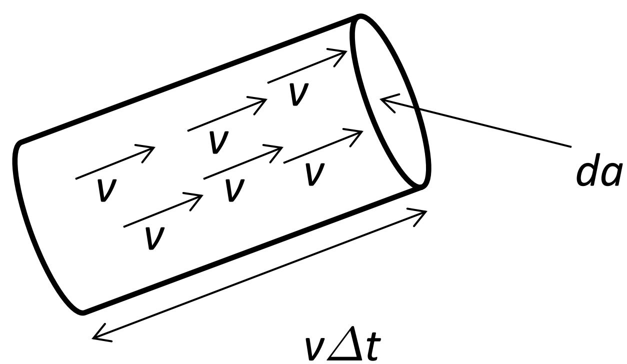
We divide the volume V crossing by N particles into tubes with section da and with length $l(x,y)$ (the plane OXY being $\perp$ to the direction of the particles) → at point (x,y): the section of the tube is crossing by dN particles. By definition of the fluence → $dN = \Phi da$ → observing that the sum of the lengths of the trajectories inside a tube $ds = \sum_i l_i = l(x,y)dN$ → $ds = l(x,y)\Phi da = \Phi dV$ because $dV = l(x,y)da$ → $\Phi = ds/dV$

Particular case for the fluence

For a particles field with a constant velocity *v* (in a time interval Δt) and with *n* the number of particles by unit of volume) →

$$\Phi = nv\Delta t$$

Demonstration: $\Phi = dN/da = ndV/da = ndav\Delta t/da = nv\Delta t$



Fluence rate

- $\varphi = \dot{\Phi}$: **Fluence rate** (unit: $m^{-2}s^{-1}$)→ quotient of *dΦ* by *dt,* where *dΦ* is the increment of the fluence in the time interval *dt*:

$$\varphi = \dot{\Phi} = \frac{d\Phi}{dt} = \frac{d^2 N}{da dt}$$

- The fluence in the time interval $[t_1, t_2]$ is the sum of the fluences φ(t)dt:

$$\Phi(t_1, t_2) = \int_{t_1}^{t_2} \varphi(t) dt$$

Energy fluence

- Ψ : **Energy fluence** at point P (unit: Jm^{-2}) → quotient of *dR* by *da*, where *dR* is the radiant energy incident on a sphere of cross-sectional area *da* →

$$\Psi = \frac{dR}{da}$$

- In the particular case for which only particles with a constant energy *E* are present →

$$R = EN \Rightarrow \Psi = E\Phi$$

Energy fluence rate

- $\dot{\Psi}$: **Energy fluence rate** (unit: $Jm^{-2}s^{-1}$) → quotient of dΨ by *dt*, where dΨ is the increment of the energy fluence in the time interval *dt*:

$$\dot{\Psi} = \frac{d\Psi}{dt} = \frac{d^2 R}{da dt}$$

- The energy fluence in the interval of time *[t_1,t_2]* is the sum of the energy fluences $\dot{\Psi}$(t)dt:

$$\Psi(t_1, t_2) = \int_{t_1}^{t_2} \dot{\Psi}(t) dt$$

- In the particular case for which only particles with a constant energy *E* are present →

$$\dot{\Psi} = E\varphi$$

Differential quantities with respect to angle and energy

Previous quantities are widely useful in practical applications in particular if all particles have the same energy et move in the same direction

→ if not: it is necessary to consider angular and energy distributions

Spectric fluence and spectric energy fluence

- Φ_E: **Spectric fluence** (unit: $J^{-1}m^{-2}$) → energy distribution of the fluence with $d\Phi$ the fluence of the particles with energy inside the interval [$E,E+dE$] :

$$\Phi_E = \frac{d\Phi}{dE}$$

- Ψ_E : **Spectric energy fluence** (unit: m^{-2}) → energy distribution of the energy fluence with $d\Psi$ the energy fluence of the particles with energy inside the interval [$E,E+dE$] :

$$\Psi_E = \frac{d\Psi}{dE}$$

Particle radiance and energy radiance

- $\dot{\Phi}_\Omega = \varphi_\Omega$: **Particle radiance** (unit: $m^{-2}s^{-1}sr^{-1}$) → quotient of $d\dot{\Phi}$ by $d\Omega$, where $d\dot{\Phi}$ is the fluence rate of particles propagating within a solid angle $d\Omega$ around a specified direction $\overrightarrow{1_\Omega}$:

$$\varphi_\Omega = \dot{\Phi}_\Omega = \frac{d\dot{\Phi}}{d\Omega}$$

- $\dot{\Psi}_\Omega$: **Energy radiance** (unit: $Wm^{-2}sr^{-1}$) → 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 $\overrightarrow{1_\Omega}$:

$$\dot{\Psi}_\Omega = \frac{d\dot{\Psi}}{d\Omega}$$

Remind: In spherical coordinates: $d\Omega = \sin\theta d\theta d\phi$ θ: polar angle ϕ: azimuthal angle

Energy Distribution of the radiance and of the energy radiance

$$\dot{\Phi}_{\Omega,E} = \frac{d\dot{\Phi}_{\Omega}}{dE}$$

$$\dot{\Psi}_{\Omega,E} = \frac{d\dot{\Psi}_{\Omega}}{dE}$$

Planar fluence

Planar fluence: number of particles crossing a fixed plane in either direction (i.e. summed by scalar addition) by unit of surface of the plane

Vector quantities

To describe the propagation of particles in a given direction $\overrightarrow{1_\Omega}$
→ definition of vector quantities related to previous quantities

Example:

Net flow (vector quantity related to the planar fluence): number of particles by time unit crossing one unit of surface of a given plane in one direction **minus** the number of particles by time unit crossing the plane in the opposite direction

→ **Attention**: Radiation dosimetry require scalar addition of the particles effects

Dosimetric quantities

Dosimetric quantities

- Dosimetric quantities → characterization of the «physical» effect of radiation on matter as a function of the transferred energy or of the deposit energy
- Dosimetric quantities → « combination » between radiometric quantities and interaction coefficients of ionizing radiations → calculation: everything must be known → measurement: direct access to some dosimetric quantities
- Definition of some stochastic quantities → the mean value will give the corresponding nonstochastic value
- In the following→ volume V and mass m
- Remark: neutrinos and their carrying energy are neglected in radiological physics and in radiation dosimetry because they have « no » interaction with matter and are « undetectable »

Energy deposit

ϵ_i **: Deposit energy** (unit: J or eV) → energy deposited in a single interaction, *i*, at a point (→ stochastic) →

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

with ϵ_{in} : energy of the incident particle (excluding rest energy)

ϵ_{out} : sum of the energies of the particles after the interaction (excluding rest energy)

Q: variation of the rest energy of the particles involved in the interaction (*Q > 0*: ↘ of the rest *E*; *Q < 0*: ↗ of the rest *E*)

Energy imparted

- ϵ**: Energy imparted** to the matter in a given volume *V* (unit: J or eV) → sum of all energies deposits in *V* (→ stochastic) →

$$\epsilon = \sum_i \epsilon_i$$

- The sum is performed on all *events* occurring in *V* (one or more)
- An *event* is defined as the total of the interactions inside the volume which are due to particles statistically correlated (interactions of a given primary particle and of created secondaries)

Mean energy imparted

$\bar{\epsilon}$ **: Mean energy imparted** (unit: J or eV) → stochastic quantity related to the energy imparted →

$$\bar{\epsilon} = R_{in} - R_{out} + \sum \bar{Q}$$

with R_{in} : radiant energy of all particles (charged or not) that enter the volume *V*

R_{out} : radiant energy of all particles (charged or not) that leave the volume *V*

$\sum \bar{Q}$: sum of all variations of the rest *E* of particles involved in the interactions (Q > 0: ↘ of the rest *E*; Q < 0: ↗ of the rest *E*)

Specific energy

z: **Specific energy** (unit: Jkg^{-1}) → quotient of the energy imparted ϵ in V by the mass m of this volume →

$$z = \frac{\epsilon}{m}$$

Absorbed dose

- D: **Absorbed dose** at point P (unit: Jkg^{-1} or gray, Gy) → quotient of $\overline{d\epsilon}$ by *dm* with $\overline{d\epsilon}$ the mean energy imparted in the volume *dV*, with mass *dm*, around P →

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

- We have also:

$$D = \lim_{V \to 0} \overline{\left(\frac{\epsilon}{m}\right)} = \lim_{V \to 0} \overline{z}$$

- The absorbed dose is thus the mean value of the energy imparted to the matter by mass unit at a given point

Integral dose

- For a non-uniform medium → $\rho(\overline{r})$ →

$$\overline{d\epsilon} = \int_V D(\overline{r})\rho(\overline{r})d\overline{r}$$

- Equivalently, for a non-uniform medium *V* with a mean mass *m* →

$$\overline{D} = \frac{(\overline{d\epsilon})_e}{dm}$$

with $(\overline{d\epsilon})_e = \overline{D}dm$: the **integral dose** (unit: J or eV)

Absorbed-dose rate

- $\dot{D}$: **Absorbed-dose rate** (unit: $Jkg^{-1}s^{-1}$ or Gys^{-1}) : quotient of *dD* by *dt*, with *dD* the increment of the absorbed dose in the time interval *dt* →

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

- The absorbed dose between times t_1 and t_2 →

$$D(t_0, t_1) = \int_{t_0}^{t_1} \dot{D}(t) dt$$

Energy transferred

$\bar{\epsilon}_{tr}$ **: Energy transferred** (unit: J or eV) → mean sum of the **initial** kinetic energies of all charged particles liberated inside *V* by the uncharged particles entering *V* – including Auger e^- →

$$\bar{\epsilon}_{tr} = (R_{in})_u - (R_{out})_u^{nonr} + \sum \bar{Q}$$

with $(R_{\mathrm{in}})_{\mathrm{u}}$: radiant energy of uncharged particles entering *V*

$(R_{out})_u^{nonr}$: radiant energy of uncharged particles leaving *V* (except that which originated from radiative losses of kinetic energy by charges particles while in *V* → Bremsstrahlung or in-flight annihilation of an e^+)

Net energy transferred

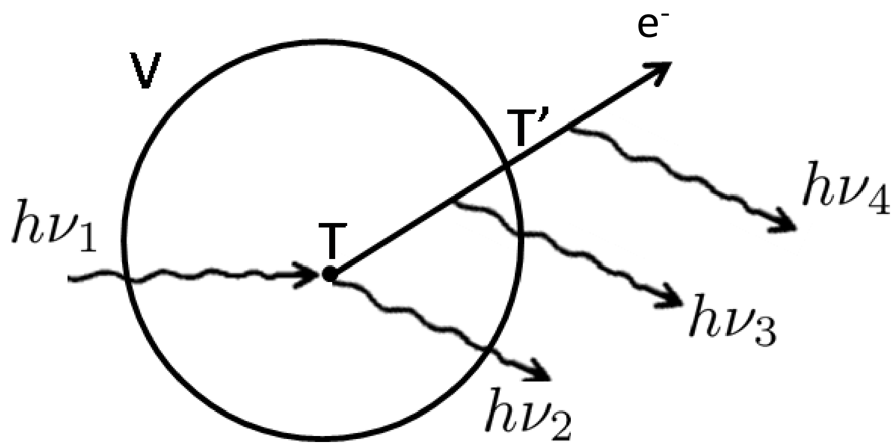
$\bar{\epsilon}_{tr}^{n}$ **: Net energy transferred** (unit: J or eV) → mean sum of the kinetic energies transferred by uncharged particles entering *V* to charged particles liberated in *V* minus the energy loses by these ones during radiative collisions (regardless the place where the loss occurs) →

$$\bar{\epsilon}_{tr}^{n} = (R_{in})_u - (R_{out})_u^{nonr} - (R_{out})_u^{rad} + \sum \bar{Q}$$

$$\bar{\epsilon}_{tr}^{n} = \bar{\epsilon}_{tr} - (R_{out})_u^{rad}$$

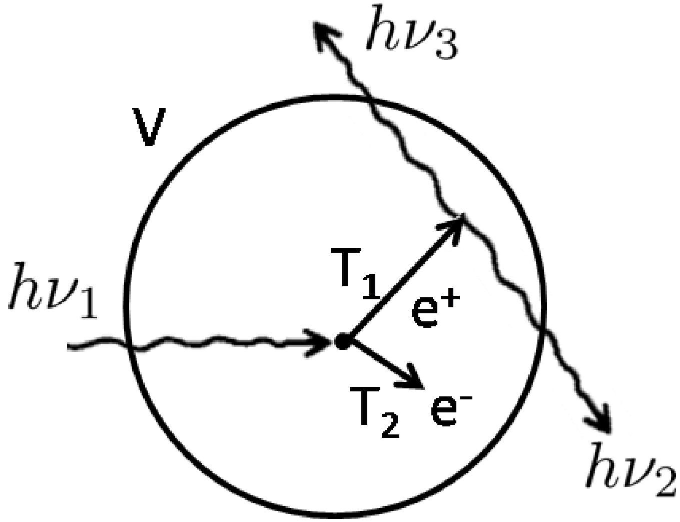
with $(R_{out})_u^{rad}$: the part of the radiance $(R_{out})_u^{nonr}$ corresponding to the radiative energy losses (regardless the place where the loss occurs)

Example 1



$$
\begin{aligned}
\overline{\epsilon} &= h\nu_1 - (h\nu_2 + h\nu_3 + T') \\
\overline{\epsilon}_{tr} &= h\nu_1 - h\nu_2 = T \\
\overline{\epsilon}_{tr}^{n} &= h\nu_1 - h\nu_2 - (h\nu_3 + h\nu_4) = T - (h\nu_3 + h\nu_4)
\end{aligned}
$$

Example 2



$$
\begin{aligned}
h\nu_2 &= 0.511\ \mathrm{MeV} + T_3 \\
h\nu_3 &= 0.511\ \mathrm{MeV} + T_4 \\
\rightarrow T_5 &= T_3 + T_4
\end{aligned}
$$

$$\sum \bar{Q} = -1.022\ \mathrm{MeV} + 1.022\ \mathrm{MeV} = 0$$

$$h\nu_1 - 1.022\ \mathrm{MeV} = T_1 + T_2$$

$$
\begin{aligned}
\bar{\epsilon} &= h\nu_1 - (h\nu_2 + h\nu_3) = h\nu_1 - 1.022\ \mathrm{MeV} - T_5 = T_1 + T_2 - T_5 \\
\bar{\epsilon}_{tr} &= h\nu_1 - 1.022\ \mathrm{MeV} = T_1 + T_2 \\
\bar{\epsilon}_{tr}^{n} &= h\nu_1 - 1.022\ \mathrm{MeV} - T_5 = T_1 + T_2 - T_5
\end{aligned}
$$

Kerma

- Quantity **only** applicable to uncharged particles

- *K*: **Kerma** (Kinetic energy released per unit mass) at point P (unit: Jkg^{-1} or Gy) → quotient of $\overline{d\epsilon_{tr}}$ by *dm* with $\overline{d\epsilon_{tr}}$ the energy transferred in the volume *dV*, with masse *dm*, around P →

$$K = \frac{\overline{d\epsilon_{tr}}}{dm}$$

- Kerma: mean value of the kinetic *E* transferred by uncharged particles to charged particles by mass unit at point P

Collision Kerma

- K_c: **collision Kerma** at point P (unit: Jkg^{-1} or Gy) → quotient of $\overline{d\epsilon}_{tr}^{n}$ by *dm* with $\overline{d\epsilon}_{tr}^{n}$ the net energy transferred in the volume *dV*, with mass *dm*, around P →

$$K_c = \frac{\overline{d\epsilon}_{tr}^{n}}{dm}$$

- Collision Kerma: mean value of the net *E* transferred by uncharged particles to charged particles by mass unit at point P → corresponds to the *E* destined to be lost by ionizations or excitations
- $K = K_c + K_r$ with K_r (*r* for radiative) corresponding to the *E* destined to be carried by photons
- Neutrons → *E* transferred to heavy particles → weak Bremsstrahlung → $K = K_c$

K and $K_c \leftrightarrow$ energy fluence (photons)

- For photons with energy E and energy fluence Ψ crossing a medium with density ρ and composed of atoms with atomic number Z → at point P

$$K = \Psi \left(\frac{\mu_{tr}}{\rho} \right)_{E,Z}$$

$$K_c = \Psi \left(\frac{\mu_{en}}{\rho} \right)_{E,Z}$$

- If non-constant E → spectrum in E between $E = 0$ and $E = E_{max}$ →

$$K = \int_0^{E_{max}} \Psi_E \left(\frac{\mu_{tr}}{\rho} \right)_{E,Z} dE$$

$$K_c = \int_0^{E_{max}} \Psi_E \left(\frac{\mu_{en}}{\rho} \right)_{E,Z} dE$$

K↔ Fluence (neutrons)

- For neutrons → description with fluence and no more energy fluence as for photons
- Definition of the Kerma factor F_n (often tabulated instead of μ_{tr} in literature for neutrons) →

$$(F_n)_{E,Z} = \left(\frac{\mu_{tr}}{\rho}\right)_{E,Z} E$$

- K becomes →

$$\begin{aligned} K &= \Phi(F_n)_{E,Z} \\ K &= \int_0^{E_{max}} \Phi_E (F_n)_{E,Z} dE \end{aligned}$$

Mean coefficients

$$\overline{\left(\frac{\mu_{tr}}{\rho}\right)}_{\Psi_E(E),Z} = \frac{K}{\Psi} = \frac{\int_0^{E_{max}} \Psi_E \left(\frac{\mu_{tr}}{\rho}\right)_{E,Z} dE}{\int_0^{E_{max}} \Psi_E dE}$$

$$\overline{\left(\frac{\mu_{en}}{\rho}\right)}_{\Psi_E(E),Z} = \frac{K_c}{\Psi} = \frac{\int_0^{E_{max}} \Psi_E \left(\frac{\mu_{en}}{\rho}\right)_{E,Z} dE}{\int_0^{E_{max}} \Psi_E dE}$$

$$\overline{(F_n)}_{\Phi_E(E),Z} = \frac{K}{\Phi} = \frac{\int_0^{E_{max}} \Phi_E (F_n)_{E,Z} dE}{\int_0^{E_{max}} \Phi_E dE}$$

Kerma rate

- $\dot{K}$: **Kerma rate** (unit: $Jkg^{-1}s^{-1}$ or Gys^{-1}): quotient of *dK* by *dt*, with *dK*, the increment of Kerma in the time interval *dt* →

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

- The Kerma between times t_1 and t_2 →

$$K(t_0, t_1) = \int_{t_0}^{t_1} \dot{K}(t)dt$$

Exposure

- X: **Exposure** (unit: Ckg^{-1}) → quotient of dQ by dm, where dQ is the absolute value of the mean total charge of the ions of one sign produced when all the electrons and positrons liberated or created by photons incident on a mass dm of dry air are completely stopped in dry air→

$$X = \frac{dQ}{dm}$$

- Exposure → measurement of the ionization produced in <u>air</u> by <u>X-rays</u> or by <u>γ rays</u>
- Ionizations produce by Auger e^- are included in dQ but not the ones due to photons coming from radiative processes
- Equivalent in « charge » to collision Kerma in air for X-ray or γ

Energy transferred to one unit of air mass (by unit of exposure)

- For dry air → the mean energy transferred to the medium per ion pair: W_{air} = 33.97 eV (for X-rays and γ with E > a few keV) → constant

- Energy transferred to one unit of air mass (by unit of exposure) →

$$\frac{W_{air}}{e} = \frac{33.97 \times 1.602 \times 10^{-19}}{1.602 \times 10^{-19}} = 33.97\ \mathrm{J/C}$$

$X \leftrightarrow K_c \leftrightarrow \mathit{\Psi}$ or $\mathit{\Phi}$

- Exposure at point *P* due to photons with energy *E* and energy fluence $\mathit{\Psi}$ →

$$X = (K_c)_{air} \left(\frac{e}{W}\right)_{air} = (K_c)_{air} / 33.97$$

$$X = \Psi \left(\frac{\mu_{en}}{\rho}\right)_{E,air} \left(\frac{e}{W}\right)_{air}$$

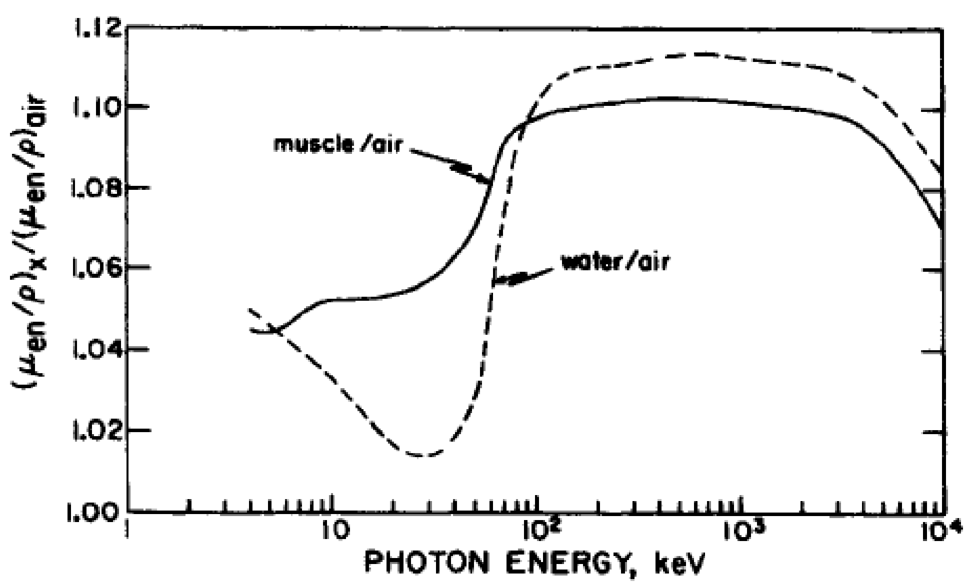
- If *E* is not a constant → spectrum in *E* between *E = 0* and $E = E_{max}$ →

$$X = \int_0^{E_{max}} \Psi_E \left(\frac{\mu_{en}}{\rho}\right)_{E,air} (e/W)_{air} dE$$

$$X = (e/W)_{air} \int_0^{E_{max}} E\Phi_E \left(\frac{\mu_{tr}}{\rho}\right)_{E,air} (1-g) dE$$

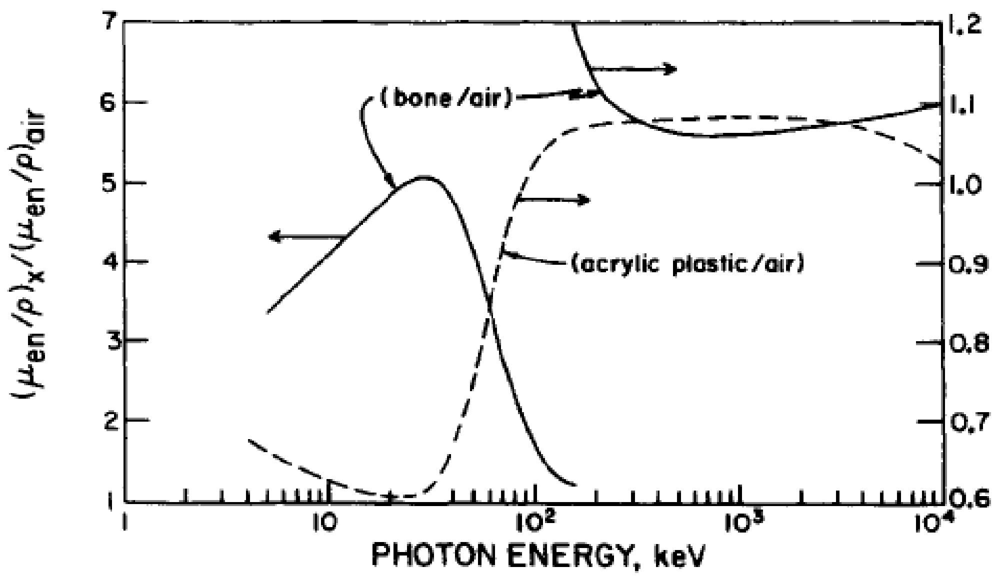
Exposure meaning (1)

- For constant $E \rightarrow X \propto \Psi$
- Air is approximatively « tissue-equivalent » (muscles) for X-rays or γ → air is a good reference medium



Exposure meaning (2)

- We remark the large difference between the absorption in air and in bones → due to the ↗ of the photoelectric effect in bones because Z ↗ (bones: calcium (Z = 20) et phosphorus (Z = 15))



Exposure meaning (3)

- For given Ψ and E → X $\propto (\mu_{en}/\rho)_{E,air}$
- $(\mu_{en}/\rho)_{E,muscle} / (\mu_{en}/\rho)_{E,air} \approx 1.07 \pm 3\%$
- K_c in muscle $\propto (\mu_{en}/\rho)_{E,muscle}$
- K_c in muscle, per exposure unit, is approximatively independent on the photon energy

Exposure rate

- $\dot{X}$: **Exposure rate** (unit: $Ckg^{-1} s^{-1}$) → quotient of *dX* by *dt*, with *dX*, the increment of the exposure during time interval *dt* →

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

- The Exposure between times t_1 and t_2 →

$$X(t_0, t_1) = \int_{t_0}^{t_1} \dot{X}(t)dt$$

Cema

- Quantity **only** applicable to charged particles
- C: **Cema** (converted energy per unit mass) at point P (unit: Jkg^{-1}) → quotient of $\overline{d\epsilon_{elec}}$ by dm with $\overline{d\epsilon_{elec}}$ the energy lost by charges particles during electronic interactions, except for the secondary electrons, in the dV, with mass dm, around P →

$$C = \frac{\overline{d\epsilon_{elec}}}{dm}$$

- Cema can be expressed as a function of Φ →

$$C = \int_0^{E_{max}} \Phi_E \left(\frac{dE}{\rho dx} \right) dE$$

- The spectric fluence Φ_E does not include the secondary e^- → they deposit their energy locally

Restricted Cema

- OK for ions but problem for e^- → fluence of incident e^- cannot be separated from the fluence of secondary e^-

- Solution → definition of the restricted Cema:

$$C = \int_0^{E_{max}} \Phi'_E \frac{L_\Delta}{\rho} dE$$

with Φ' including secondary e^- with $E > \Delta$

- Secondary e^- are no more locally absorbed but well e^- with $E < \Delta$

Cema rate

- $\dot{C}$: **Cema rate** (unit: $Jkg^{-1}\,s^{-1}$) → quotient of *dC* by *dt*, with *dC* the increment of Cema during time interval *dt* →

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

- Cema during times t_1 and t_2 →

$$C(t_0, t_1) = \int_{t_0}^{t_1} \dot{C}(t)dt$$

Dose equivalent

- w_R: **Radiation weighting factor** (for radiation R) → dimensionless quantity which characterizes the relative biological effectiveness for human of various types and energies of ionizing radiations → they have to be applied as a weighting factor to the absorbed dose for radiation R
- H_T: **Dose equivalent** in an organ or a tissue (unit: Jkg^{-1} or sievert (Sv)) →

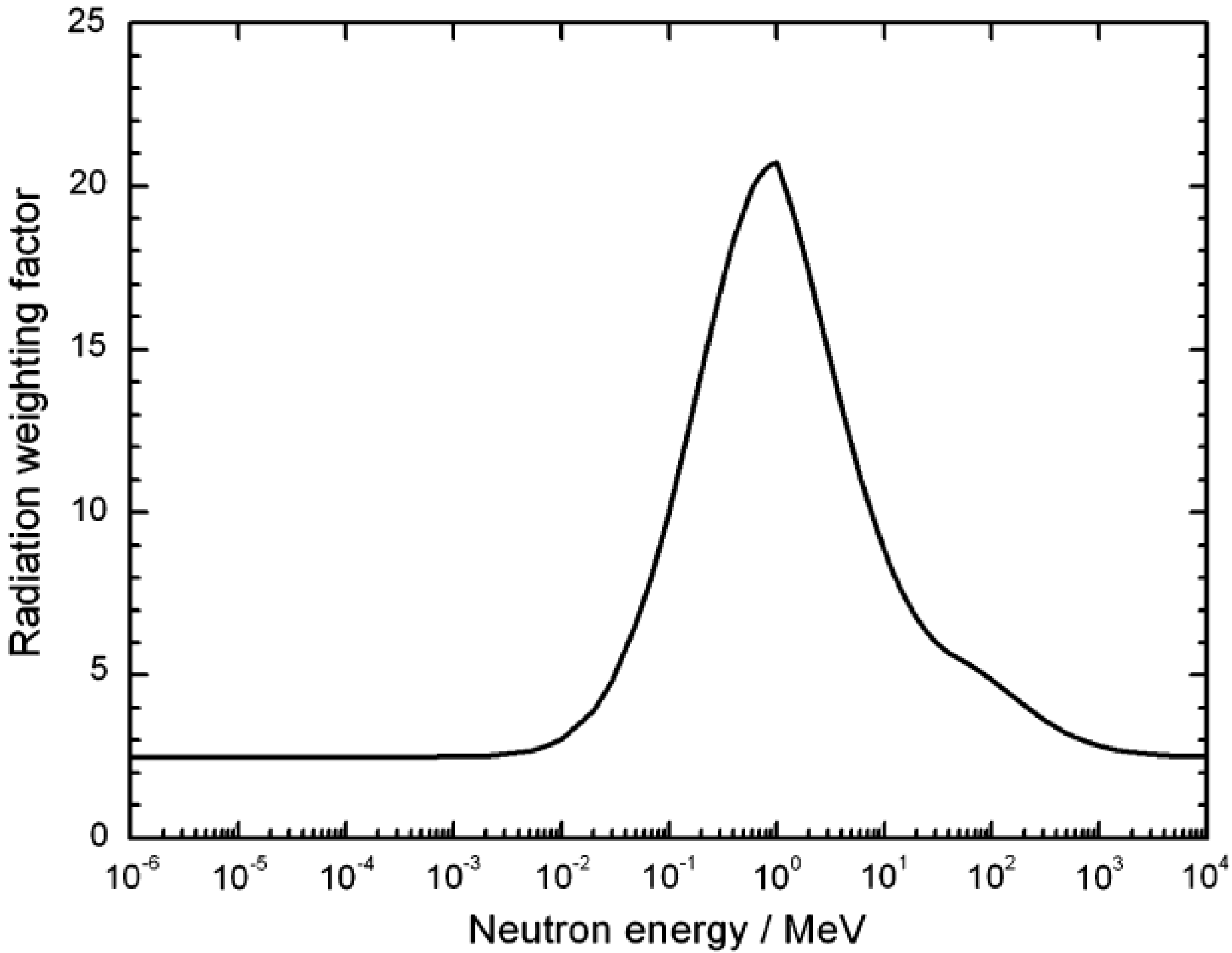
$$H_T = \sum_R w_R D_{T,R}$$

  with $D_{T,R}$ is the mean absorbed dose in the volume of a specified organ or tissue T
- Attention → to be rigorous → unit of w_R: Sv/Gy

Radiation weighting factor (ICRP 103)

Radiation type	**Radiation weighting factor, w_R**
Photons	1
Electrons[a] and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy

Weighting factor for neutrons (ICRP 103)



Effective dose

- w_T: **Tissue weighting factor** (for tissue T) → « These values are chosen to represent the contributions of individual organs and tissues to overall radiation detriment from stochastic effects. » (ICRP103) → $\sum_T w_T = 1$

- E: **effective dose** (unit: Sv) → weighted sum of tissue equivalent doses

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}$$

Tissue weighting factor

Tissue	w_T	$\sum w_T$
Bone-marrow (red), Colon, Lung, Stomach, Breast, Remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, Oesophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04
	Total	1.00

* Remainder tissues: Adrenals, Extrathoracic (ET) region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate (♂), Small intestine, Spleen, Thymus, Uterus/cervix (♀).

Remark about units

Historically, other units have been used for some quantities → now, SI units must be used, but sometimes these other units are considered (USA):

- Erg (erg): CGS unit for energy → 1 erg = 10^{-7} J
- Rad (rad): dose equivalent to 100 ergs energy absorbed in one gram of matter → 1 rad = 10^{-2} Gy
- Rem (rem): Roentgen Equivalent Man → 1 rem = 10^{-2} Sv
- Electrostatic charge unit (esu): CGS unit of electric charge → 1 esu = 3.3356×10^{-10} C
- Roentgen (R): exposure which produces, in 1 cm^3 of dry air at normal pressure and temperature, 1 esu → 1 R = $2.58\ 10^{-4}$ C/kg
- Curie (Ci): activity of 1 g of ^{226}Ra → 1 Ci = $3.7\ 10^{10}$ Bq