Elements of dosimetry

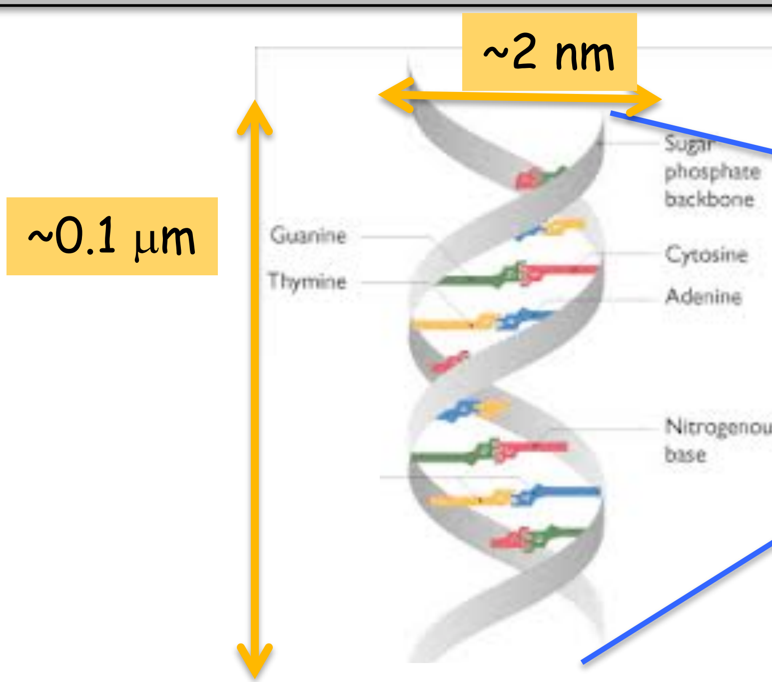
Dosimetry

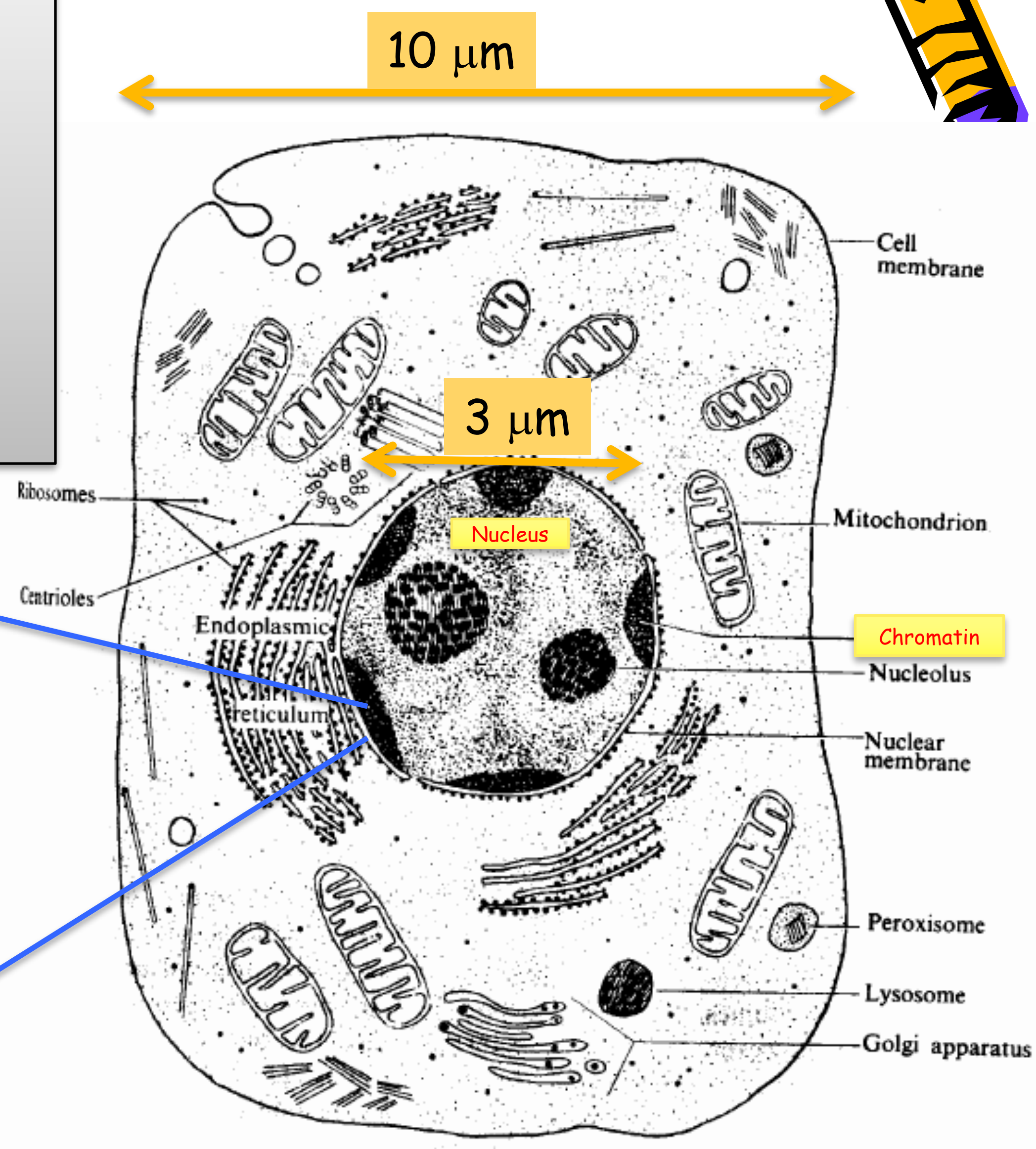
- Estimate of damage caused by radiation on objects and in particular human beings:
  - Evaluation of probability of damage due to accidentals
  - Evaluation of intensity of intentional irradiation

Cellular biology

Key points:

- ~ 10^{13} cells/body
- Nucleus is the "control center"
- Chromatin contains DNA
- Destroying DNA can prevent reproduction of cell or cause a mutation --> Cell Death or Cancer

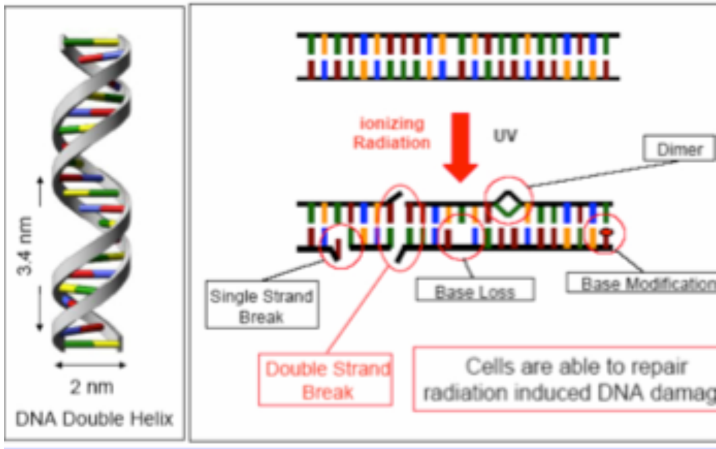




Radiobiological effect

- Direct:

  Deliver energy on tumor cells in order to break them in an irreparable way

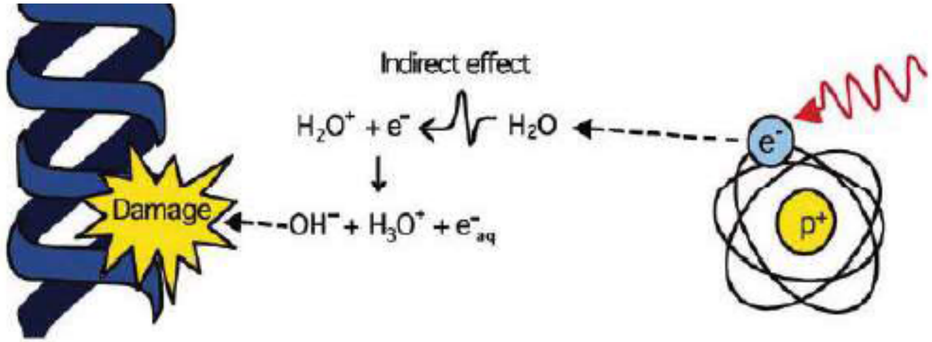


- Indirect:
  - Ionization
  - electrolysis
  - Reaction with water

H_2O + radiation → $H_2O^+ + e^-$

→ $OH^- + H^+$

$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH^0$$

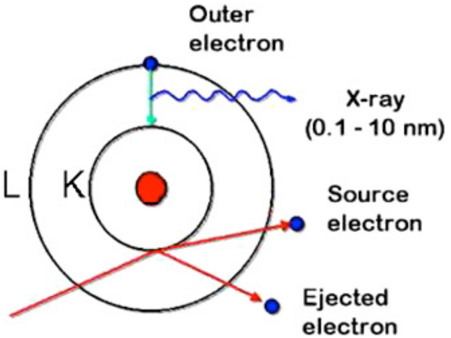


Perossido di idrogeno

$O_2 + H_30 \rightarrow H_2O_2 + HO$

Biological effect of radiation

- Neutral radiation converts into charged radiation before having an effect
- Charged radiation has an effect by ionization
  - A ion and a free electron (ionizing itself) are produced
  - The original molecule loses its chemical properties



<u>Twofold effect:</u>

- if both DNA helixes are broken→ direct damage (rare)
- The ion (free radical) initiates a chemical reaction that attacks DNA (most common)

Possible effects

- If somatic cells are affected:
  - Cancer (or cure of)

- If genetic cells are affected
  - Genetic mutations

- Stochastic effects: depends on the organs affected and have a probability to occur or not

- Non stochastic effects: due to dose to total body. Effects are proportional to irradiation

Key features of radiation

- To have a biological effect, radiation must:
  - release sufficient energy per unit of path
  - ionize with sufficient frequency
  - impact molecules sensitive to the DNA killing

Dosimetry defines measurable quantities that allow to quantify these effects

Dosimetric quantities

- Exposure (rate)
- KERMA
- Dose (rate)
- Effective Dose

Exposure (X)

The exposure is defined as the ratio of the charge (of one sign) ΔQ produced in a medium **when** all the electrons liberated by photons in the volume element of the medium with mass Δm, are completely stopped in the volume. Thus

$$X = \frac{\Delta Q}{\Delta m}$$

The (old) unit of exposure is the ***Roentgen (R)***.

The natural SI unit for exposure would be C/Kg but is never used. 1 Roentgen = 2.58×10^{-4} C/Kg

Exposure Rate: dX/dt

Exposure ***only applies*** to ***X- and γ-rays***, not p, α, n, e^- etc.

Defined if electrons stop within the volume of interest (typically Eγ<2-3MeV)

Calculation of exposure

Sample exposed to a fluence $\Phi = \frac{dN}{da}$

of photons of energy E=hv

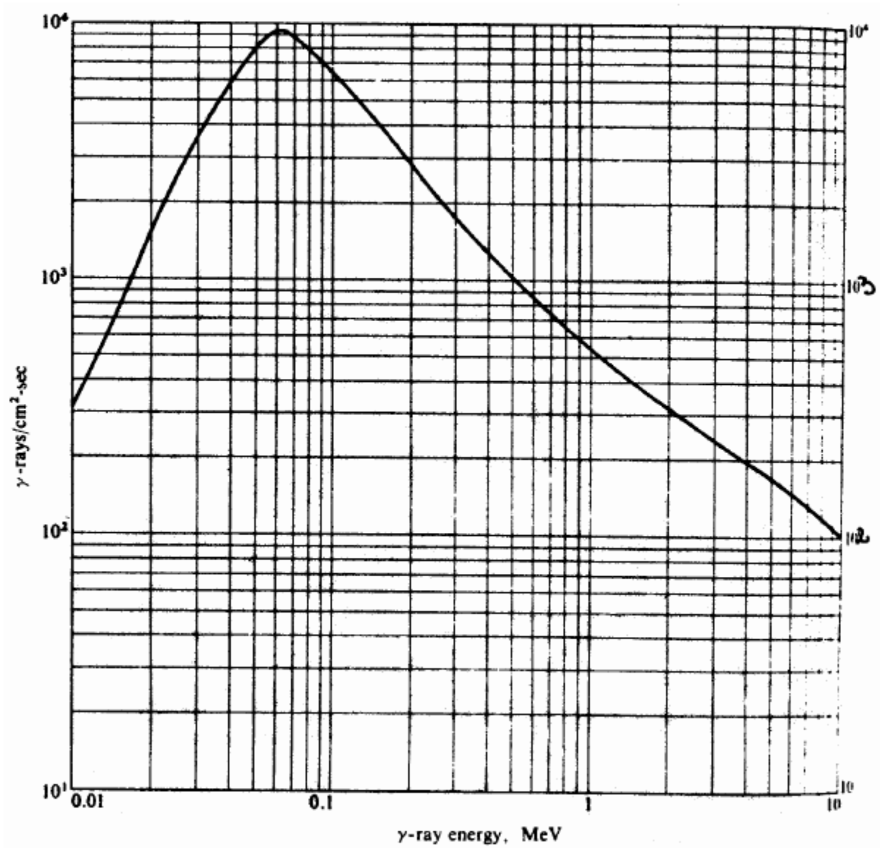
$$\left.\begin{aligned} dQ &= e \cdot dN \cdot dE/w \\ dm &= \rho \cdot dV = \rho \cdot da \cdot dx \end{aligned}\right\} \Rightarrow X = \frac{dQ}{dm} = \frac{1}{\rho}\frac{e}{w}\frac{dN\,dE}{da\,dx}$$

w= mean ionization energy = 34 eV in air

Given the definition of mass coefficient μ

$$X = \frac{dQ}{dm} = \frac{e}{w}\left(\frac{\mu_{en}}{\rho}\right) E\,\Phi$$

Exposure in air



The measurement of exposure is necessarily in air

Required flux for 1mR/h

Exposure with γ sources

$$\dot{X}_{aria} = \Gamma \cdot \frac{A}{d^2}$$

A: Activity

d: distance from source

Tabella 2.II — *Costante gamma specifica Γ per alcuni radionuclidi*

Radio-nuclide	Tempo di dimezzamento	Energia dei fotoni (MeV)	Probabilità di emissione	$\Gamma\left(10^{-18}\frac{Cm^2}{kg\ s\ Bq}\right)$	$\Gamma\left(\frac{Rm^2}{hCi}\right)$
22-Na	2,6 anni	0,511	1,800	2,30	1,192
		1,275	1,000		
41-A	1,83 ore	1,293	0,990	1,27	0,660
54-Mn	297 giorni	0,835	1,000	0,90	0,468
60-Co	5,23 anni	1,173	1,000	2,50	1,298
		1,332	1,000		
85-Kr	10,15 anni	0,514	0,0041	0,0023	0,0012
137-Cs	29,9 anni	0,662	0,858	0,62	0,323
113-Xe	5,36 giorni	0,081	0,370	0,027	0,0142
198-Au	2,70 giorni	0,412	0,950	0,44	0,231
		0,676	0,010		
		1,088	0,002		
226-Ra	1608 anni	0,186	0,040	0,0073	0,0038
		0,260	0,00007		

Full listing in
http://www.iem-inc.com/information/tools/gamma-ray-dose-constants

Dose

- Most important dosimetric quantity
- Absorbed energy due to radiation per unit mass

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

$$\varepsilon = R_{in} - R_{out} + \Sigma Q$$

- Dose rate: $\dot{D} = \frac{dD}{dt}$
- Units of measurement:

  1 Gy=1J/kg

  1 rad=10^{-2} Gy

Dose calculation

- Charged particles

$$D = \frac{d\varepsilon}{dm} = \frac{dE\,dN}{\rho\,dx\,da} = \left(\frac{1}{\rho}\frac{dE}{dx}\right)\cdot\Phi$$

- Photons

$$D = \frac{d\varepsilon}{dm} = \frac{dE\,dN}{\rho\,dx\,da} = \frac{\mu_{en}E_\gamma\,dN}{\rho\,da} = \left(\frac{\mu_{en}}{\rho}\right)E_\gamma\,\Phi$$

  - Relationship with exposure

If not monochromatic integrate over $d\Phi/dE$

Relationship with exposure

$$D_{aria} = \frac{W_{aria}}{e} \cdot X \quad \rightarrow \quad D_{aria}[Gy] = 8.74 \cdot 10^{-3} \cdot X[R]$$

Translation from measurements in air and in a generic material:

$$D_M = D_{aria} \frac{(\mu_{en}/\rho)_M}{(\mu_{en}/\rho)_{aria}} = X \frac{W_{aria}}{e} \frac{(\mu_{en}/\rho)_M}{(\mu_{en}/\rho)_{aria}}$$

Exercises

1) Compute dD/dt for a gamma beam with E=3MeV and $\Phi=10^7$ cm^{-2} s^{-1} in air and water
2) Compute dD/dt in water for a 100mCi source of Co60 at a distance of 1cm
3) Find the rate of 4100 MeV Carbon ions needed to yield 2Gy in 1min, 1 mm before end of range.

<u>KERMA</u> (Alpen p8, p90)

Typically, when radiation (x-rays, γ rays and charged particles) interact with their environment, they <u>transfer kinetic energy</u> to the medium in which they are interacting.

It is possible however, that <u>not all of the transferred kinetic energy remains in the volume of interest</u>. This can be due to radiative losses (bremsstrahlung) and kinetic energy losses associated with secondary particles produced.

KERMA is the **K**inetic **E**nergy **R**elease in the **M**edium (**A** is added!)

Kerma, (K) accounts for the energy transferred to the volume (without correcting for energy losses after interaction). It is defined by the expression,

$$K = \frac{\Delta E_K}{\Delta m}$$

where ΔE_K is the sum of initial kinetic energies of all the charged particles liberated by ionising particles or photons in a volume element of a specific material. <u>Kerma is thus reflects the energy RELEASED in a medium</u>. Kerma has the SI unit of the gray (Gy)

Kerma is critical for neutrons, where the dose is difficult to compute

Charged Particle Equilibrium (CPE) : Charged particle equilibrium is said to exist at a point ***p***, centred in a volume ***V***, if each charged particle carrying out a certain energy from this volume is replaced by another identical particle carrying the same energy into the volume.

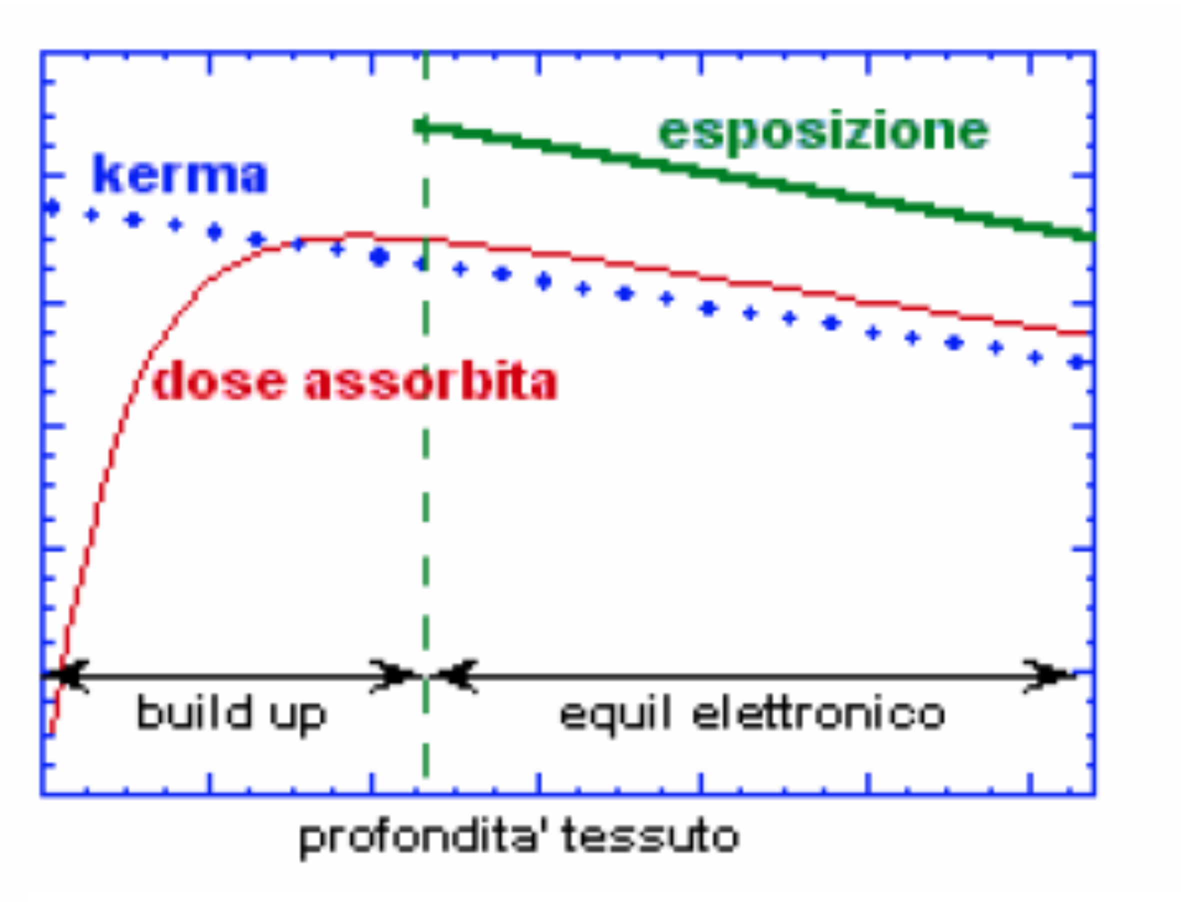
If CPE exists at a point, the dose = kerma (D = K) at that point (provided that the secondary radiation losses by the charged particles such as bremsstrahlung are negligible).

Dose is the energy absorbed in the unit volume,

while

kerma is the energy transferred from the original particle in the same unit volume.

Example: photon beam



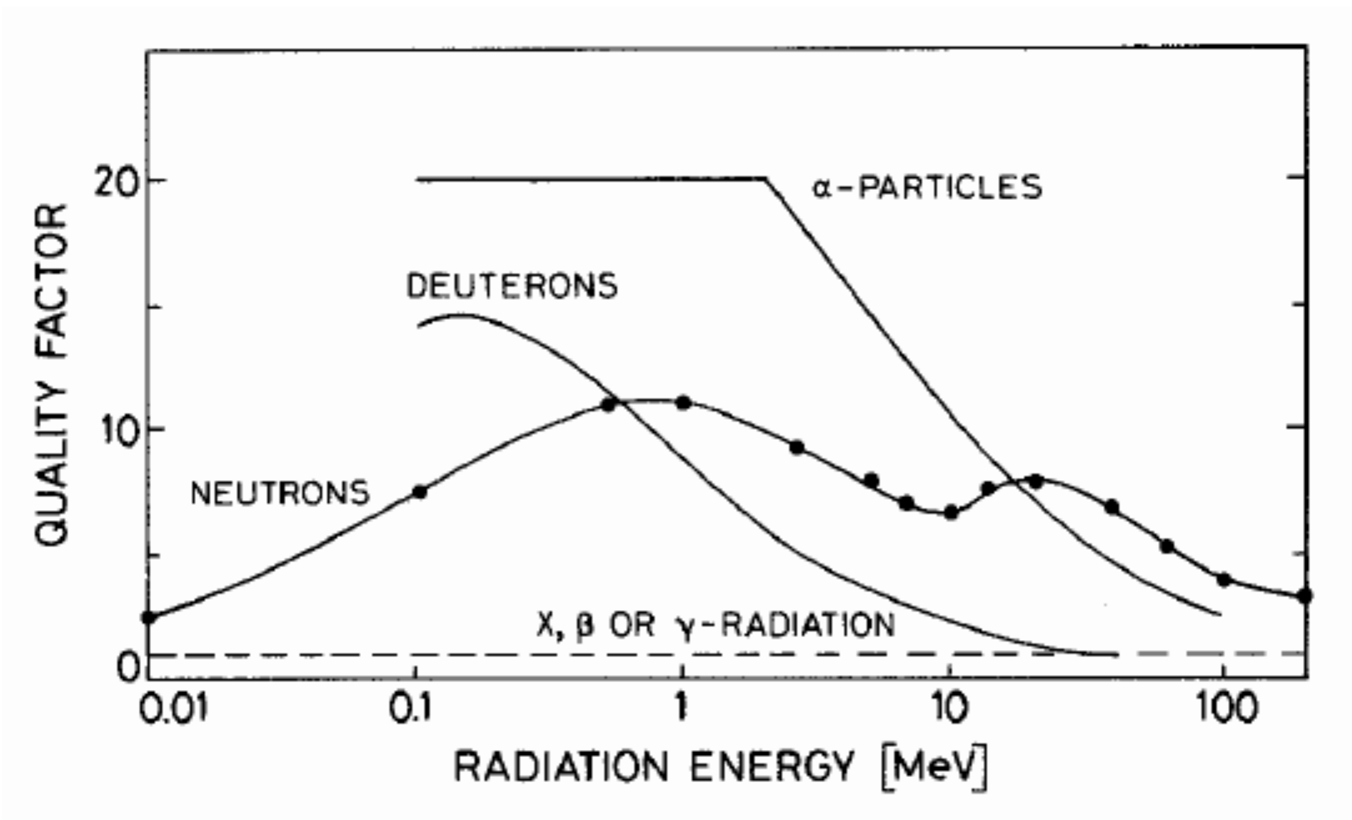
Equivalent Dose

- Needed to account for different biological effects
- H=D*Q
  - Q depends on
    - Radiation
    - Microscopic details of energy release ➔ LET for charged particles

Units of measurement:
1 Sv=1J/kg
100 rem=1Sv (old)

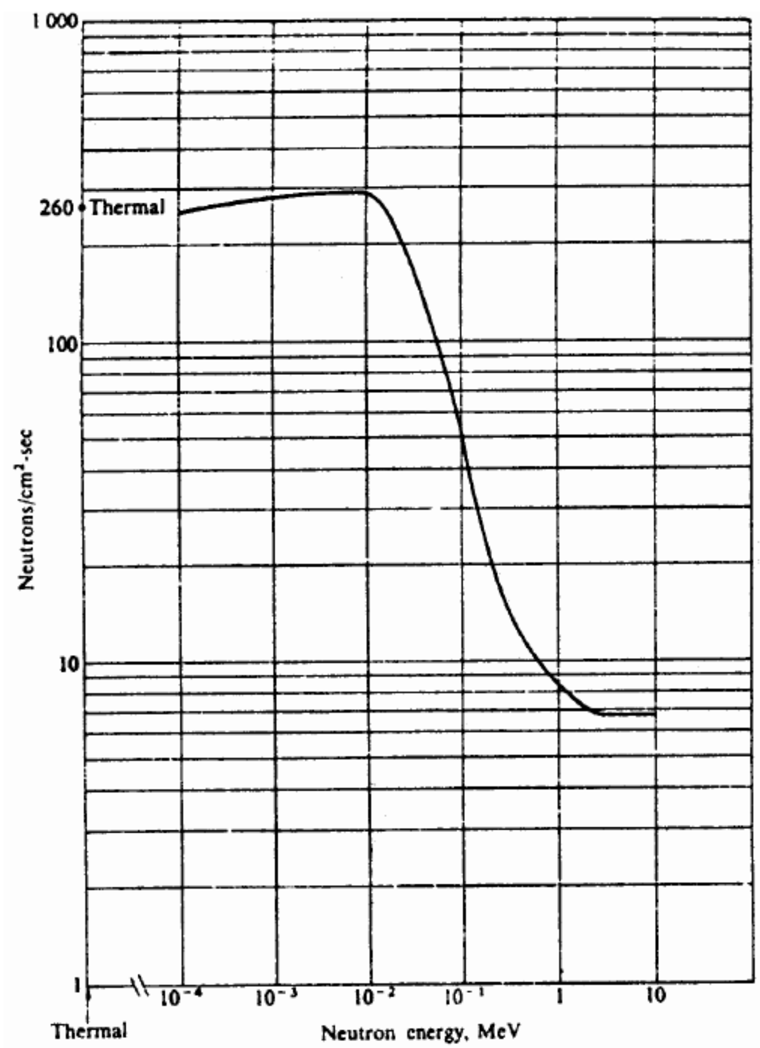
Quality factor (Q)

- Q depends on LET and particle type



Equivalent dose for neutrons

Neutron flux that yields
H=10^{-5} Sv/h on healthy tissue



Exercises

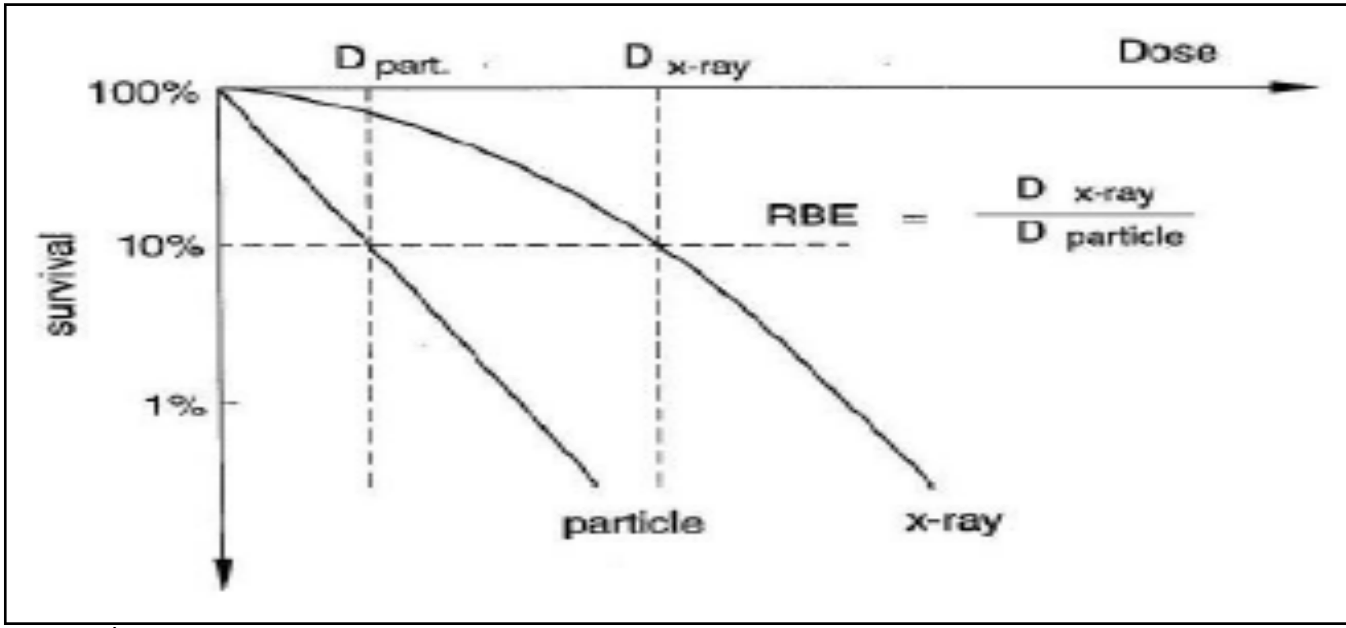
1) Compare the equivalent dose to healthy tissues in the case of

BNCT: 30' of thermal neutron flux $\Phi \sim 10^9/m^2/s$

HT with carbons (4100 MeV) before the BRAGG peek. Beam sufficient to deliver 10 Gy 1mm before the bragg peak

2) A 226Ra-Be source produces 10^8 n/s with E>1MeV. For each neutron also 350 gamma of E~1MeV are produced. If an operator moves the source with a poke that allows him to be 2.5m away from the source, how long can he hold the source in a year to be within the limits of law (20mSv/y)?

RELATIVE BIOLOGICAL EFECTIVENESS (RBE)



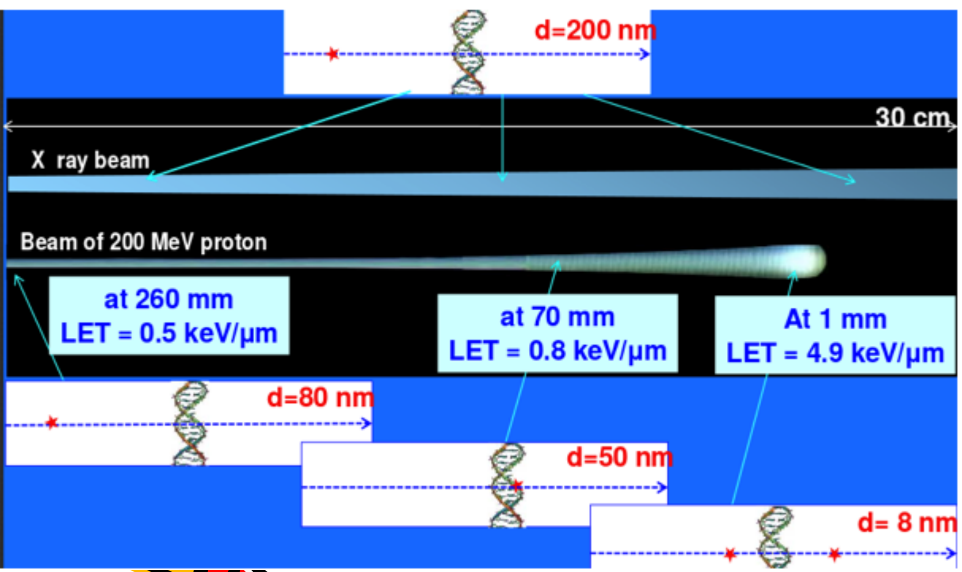
RBE = Dose X / Dose T

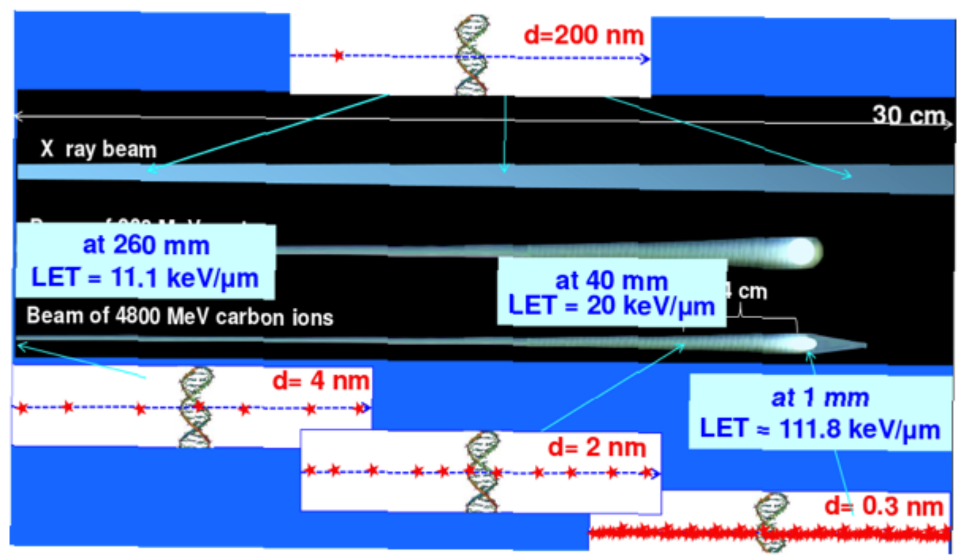
- Dose X = dose of 200 keV X rays needed to achieve a given biological effect
- Dose T = dose of the kind under consideration needed to achieve the same effect

LET and RBE

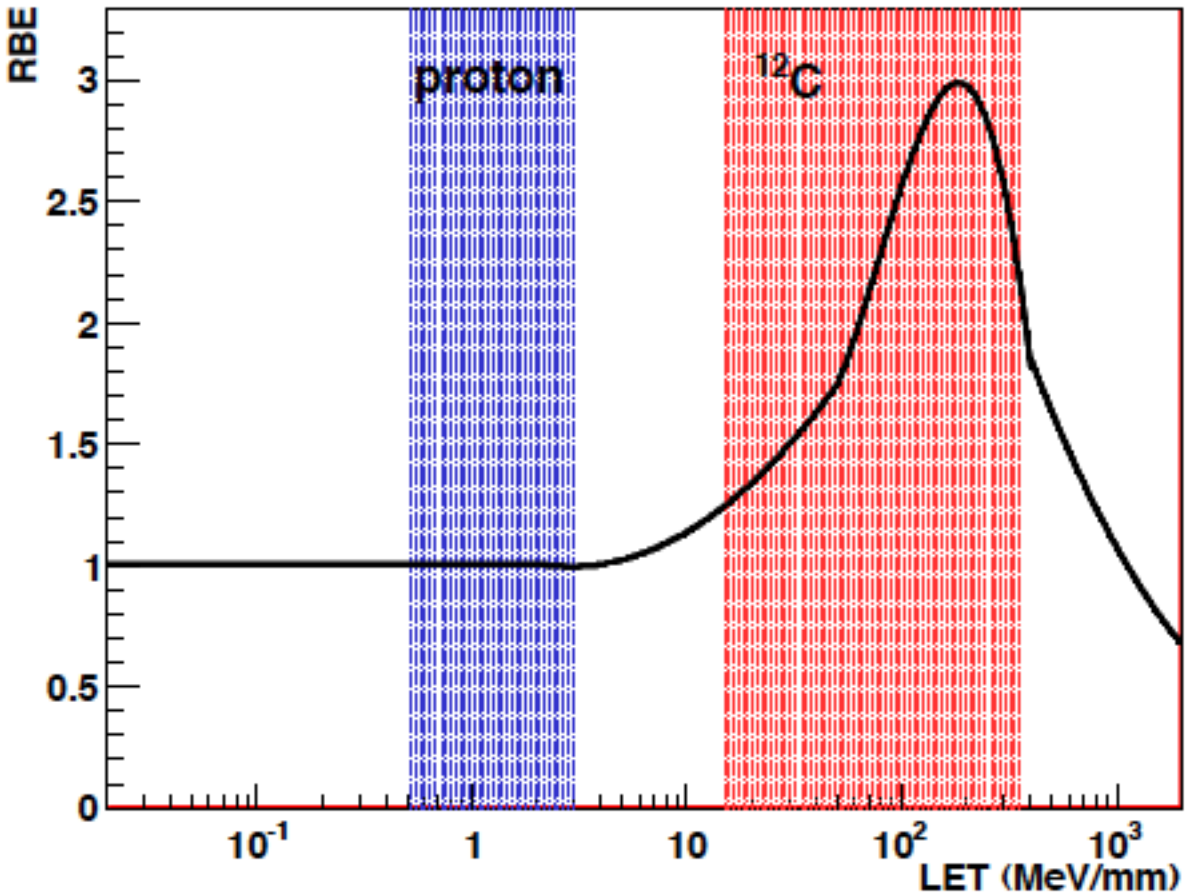
The biological effectiveness depends on the distance between deposits energetic enough to break a molecule

$$d \sim \frac{40\left[eV\right]}{LET\left[eV/nm\right]}$$



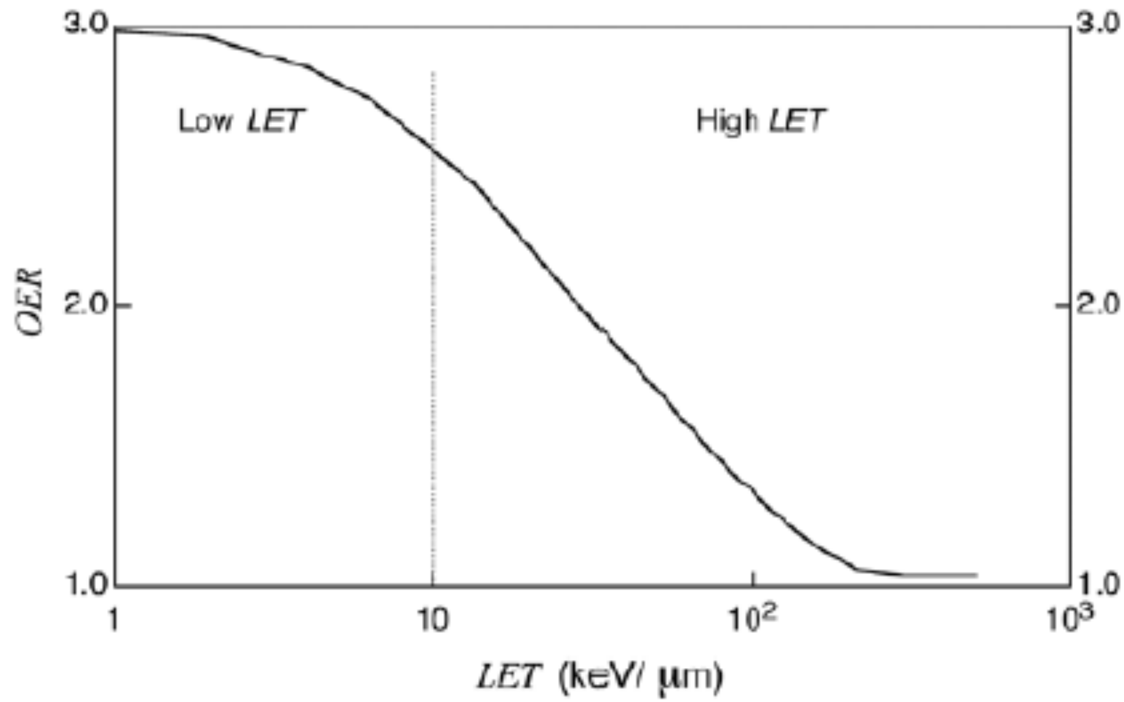


RBE vs LET



Oxygenation Enhancement Ratio

$$OER = \frac{Radiation\ dose\ in\ hypoxia}{Radiation\ dose\ in\ air}$$



Effective Dose

The measurement of biological effects needs to include

- which organs are affected
- by which radiation

$$E = \sum_T W_T \sum_R W_R \cdot \frac{\int_T D_R(x,y,z)\rho(x,y,z)dV}{\int_T \rho(x,y,z)dV}$$

Where

E is the effective dose to the entire organism
H_T is the equivalent dose absorbed by tissue T
W_T is the tissue weighting factor defined by regulation
W_R is the radiation weighting factor defined by regulation
$\bar{D}_{T,R}$ is the mass-averaged absorbed dose in tissue T by radiation type R
$D_R(x,y,z)$ is the absorbed dose from radiation type R as a function of location
$\rho(x,y,z)$ is the density as a function of location
V is volume
T is the tissue or organ of interest

Esempi: fondo naturale

Sorgente	*Irradiazione esterna*	*Irradiazione interna*	*Totale*
	Equivalente di dose efficace (mSv/anno)		
Raggi cosmici			
Componente dirett. ionizz.	0.30		0.30
Neutroni	0.055		0.055
Radionuclidi cosmogenici		0.015	0.015
Radionuclidi primordiali			
K-40	0.15	0.18	0.33
Rb-87		0.006	0.006
U-238 (serie)	0.10	1.24	1.34
Th-232 (serie)	0.16	0.18	0.34
TOTALE (arrotondato)	0.8	1.6	2.4

Tab. 18.5 Equivalente di dose annuale dovuto al fondo naturale

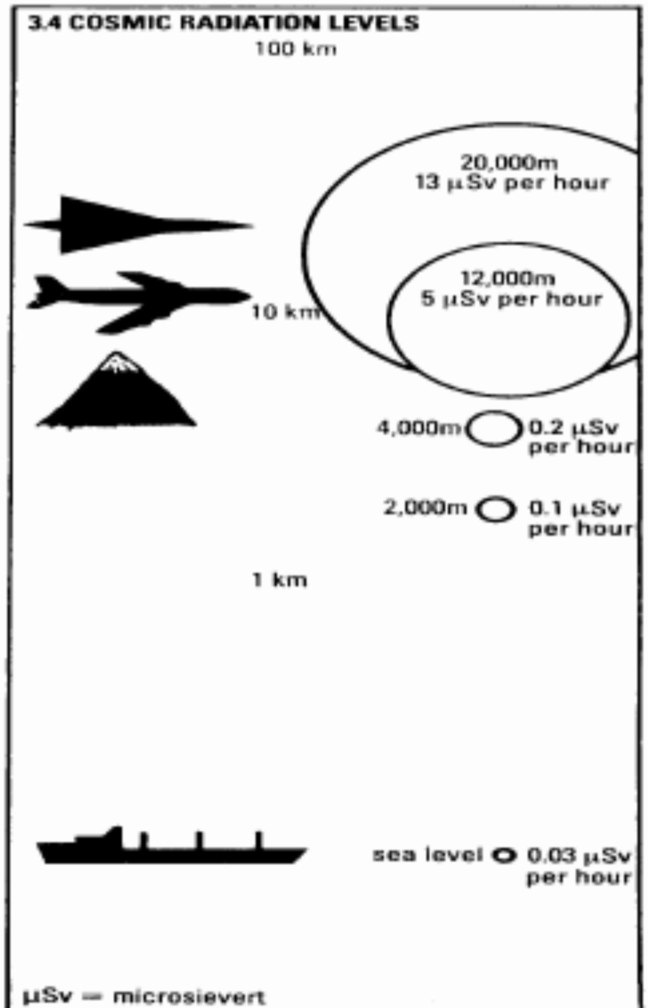
Esempi: radiazione medica

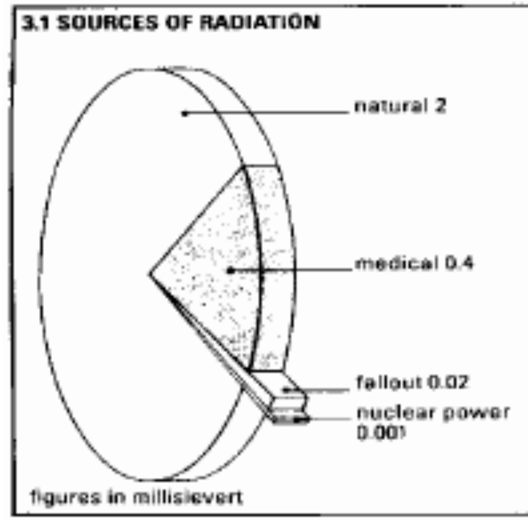
Tab. 8.II. Dosi ricevute nei più comuni esami radiografici in vari organi protezionisticamente significativi, secondo calcoli per un fantoccio antropomorfo da 70 kg (dati tratti da ICPR82b).

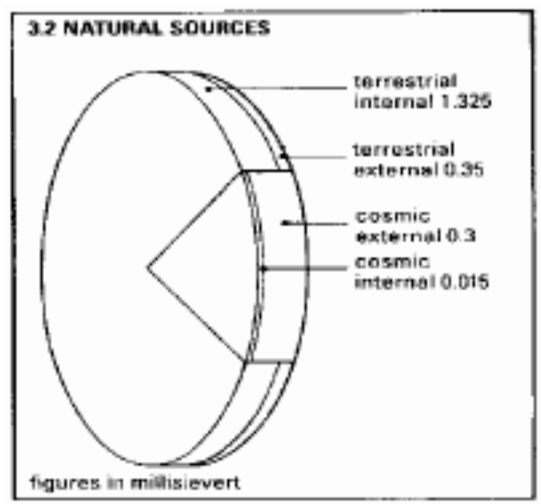
Esame	*Tiroide*	*Midollo osseo attivo*		*Polmone*		*Gonadi* ♂	*Gonadi* ♀	*Mammella*
	Dose nell' organo (mGy)							
Torace	0.065	0.04	(0.03)	0.19	(0.20)	–	–	0.14
Cranio	2.22	0.31		0.02		–	–	–
Rachide cervicale	4.04	0.11		0.14		–	–	–
Costole	1.54	0.49	(0.42)	3.24	(2.96)	–	0.004	4.11
Spalla (una proiezione)	0.58	0.06		0.39	(0.27)	–	–	0.77
Rachide dorsale	0.75	0.43	(0.32)	2.63	(2.65)	–	0.006	2.76
Colecistogramma	0.01	0.66		1.76		–	0.06	–
Rachide lombare	0.003	1.26		1.33		0.07	4.05	–
Porzione sup. tratto G-I	0.07	1.17	(1.14)	5.32	(4.76)	0.004	0.45	0.53
Rene, uretere, vescica	–	0.48		0.12		0.16	2.12	–
Clisma	0.002	2.98		0.48		0.58	7.87	–
Rachide lombosacrale	–	2.24		0.35		0.43	6.40	–
Pielografia intravenosa	–	1.16		0.35		0.49	6.36	–
Bacino	–	0.27		0.011		0.57	1.48	–
Anca (una proiezione)	–	0.17		–		3.68	0.78	–
Rachide in toto (chiroprassi)	2.71	0.35		1.49	(1.17)	0.10	1.00	2.34
Mammografia								
(1) Xeroradiografia	–		(–)		(–)		–	7.66
(2) Pellicola-schermo	–		(–)		(–)		–	2.12

(–) Trascurabile rispetto agli altri organi.
I dati tra parentesi si riferiscono alla donna se diversi da quelli per l'uomo.

Other sources







ICRP Recommended Annual Dose Limits

Body Part	Occupational	General Public
Whole body (HE)	20mSv	1mSv
Eye lens (HT)	150mSv	15mSv
Skin (HT)	500mSv	50mSv
Hands & Feet (HT)	500mSv	---------

Note these recommended limits EXCLUDE any medical or natural background radiation doses.

ICRP= International Commission in Radiation Protection
www.icrp.org/

RADIATION DOSIMETERS

Ionization chamber dosimetry systems

Film dosimetry

Luminescence dosimetry

Semiconductor dosimetry

Neutron dosimeters

Dosimeter

- Dosimeter is a device that measures directly or indirectly
  - Exposure
  - Kerma
  - Absorbed dose
  - Equivalent dose
  - Or other related quantities.
- The dosimeter along with its reader is referred to as a Dosimetry System.

Properties of dosimeters

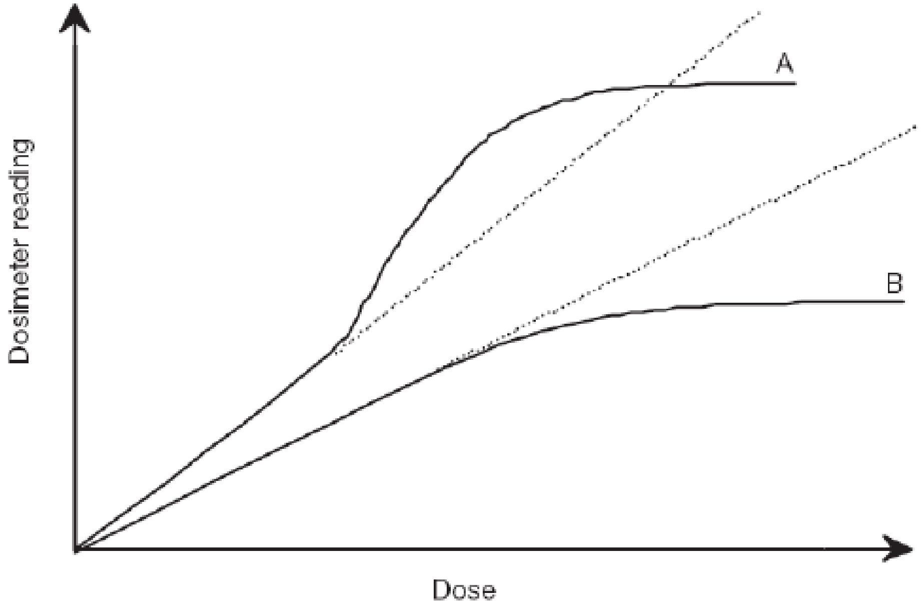
- A useful dosimeter exhibits the following properties:
  - High accuracy and precision
  - Linearity of signal with dose over a wide range
  - Small dose and dose rate dependence
  - Flat Energy response
  - Small directional dependence
  - High spatial resolution
  - Large dynamic range

Characteristics of Dosimeters

- **Linearity**
  - The dosimeter reading should be linearly proportional to the dosimetric quantity.
  - Beyond a certain range, usually there is non linearity.
  - This effect depends on the type of dosimeter.

Characteristics of Dosimeters

Linearity



CaseA:

- Linearity
- Supralinearity
- Saturation

Case B:

- Linearity
- saturation

Characteristics of Dosimeters

Dose Rate

- The response of a dosimeter should be **constant for different dose rates**.
- In reality, this is not completely possible, requiring corrections such as for ion recombination effect for ionization chambers in pulsed beam.

Characteristics of Dosimeters

Energy

- The response of a dosimetric system is generally a function of the radiation energy.
- Since calibration is done at a specified beam quality, a reading should generally be corrected if the user's beam quality is not identical to the calibration beam quality.
- Important characteristic of a dosimetric system.

Characteristics of Dosimeters

Directional

- Directional dependence is due to construction details and physical size.

Spatial resolution

- The quantity absorbed dose is a point quantity
- Ideal measurement requires a point-like detector.
- Measurement result can be attributed to a point within the volume referred to as the effective point of measurement.

Ionization Chamber

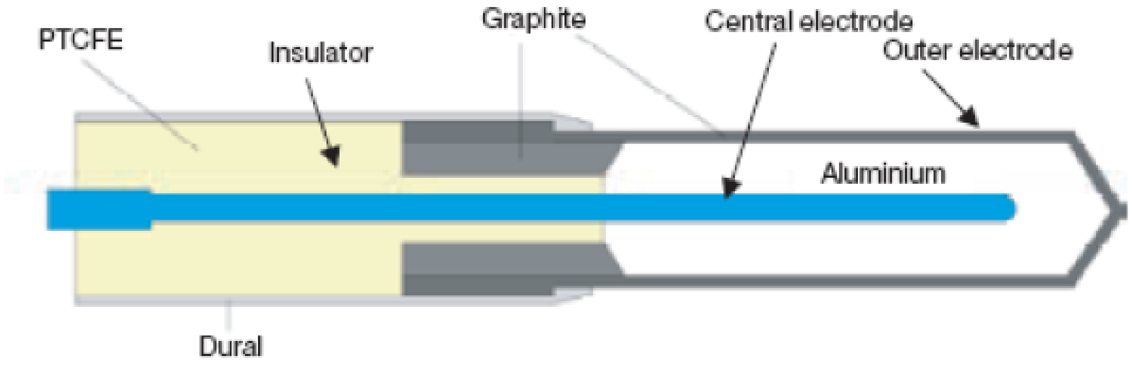
Principle

- X-ray pass through medium: attenuated
- Attenuation processes cause ionizations
- Ions can be collected at oppositely charged plates
- Total charge is proportional to exposure.
- Which is proportional to Absorbed Dose.
- Mass irradiated depends on temperature and pressure.

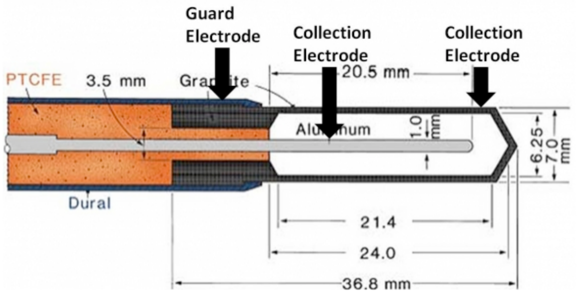
Ionization Chamber

*Basic design of **cylindrical Farmer-type ionization chamber***

- A **gas filled cavity**
- surrounded by a conductive **outer wall**
- **central collecting electrode**.



Ionization Chamber



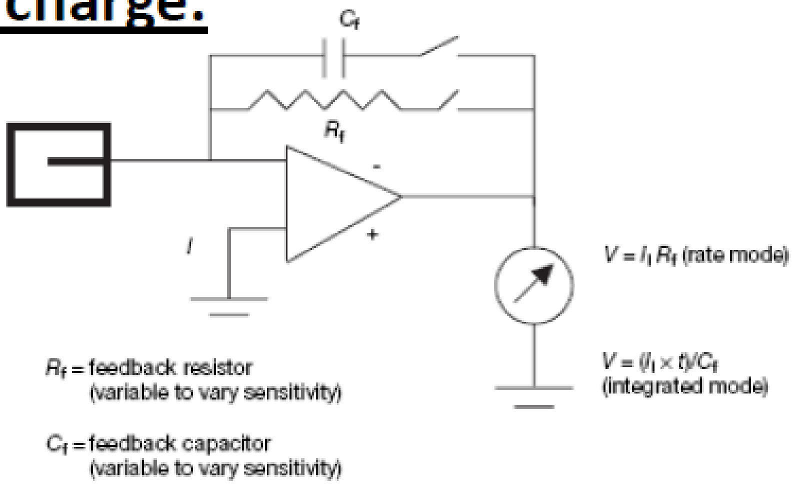
- The wall and the collecting electrode are separated with a high quality insulator to reduce the leakage current when a polarizing voltage is applied to the chamber.
- A guard electrode is usually provided in the chamber to further reduce chamber leakage.
- The guard electrode intercepts the leakage current and allows it to flow to ground directly, bypassing the collecting electrode.
- The guard electrode ensures improved field uniformity in the active or sensitive volume of the chamber (for better charge collection).

Ionization Chamber

An electrometer:

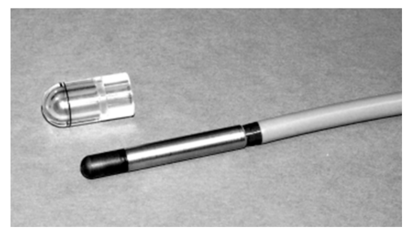
- A high gain, negative feedback, operational amplifier with a standard resistor or a standard capacitor in the feedback path to **measure the chamber current and charge.**

I.C.



Ionization Chamber

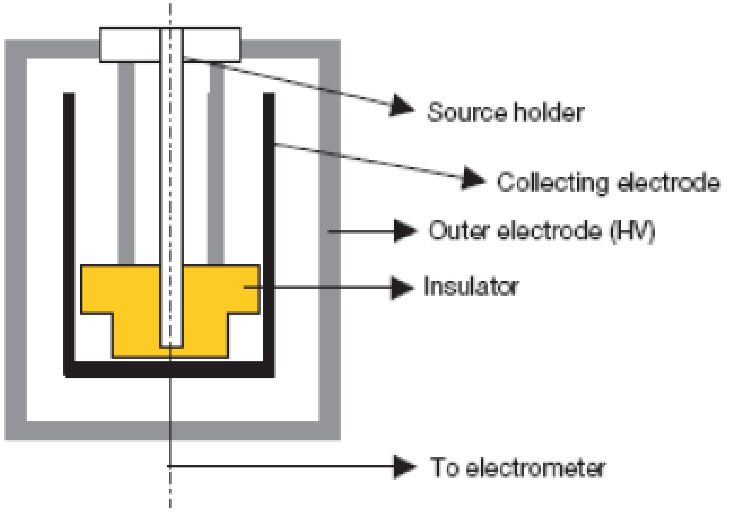
- Cylindrical (thimble) ionization chamber
  - Most popular design
  - Independent of radial beam direction
  - Typical volume between 0.05 -1.00 cm3
  - Typical radius ~2-7 mm
  - Length~ 4-25 mm
  - Thin walls: ~0.1 g/cm2
  - Used for: electron, photon, proton, or ion beams.



Ionization Chamber

Well type chamber

- High sensitivity (useful for low rate sources as used in brachytherapy)
- Large volumes (about 250 cm^3)
- Can be designed to accommodate various sources sizes
- Usually calibrated in terms of the reference air kerma rate

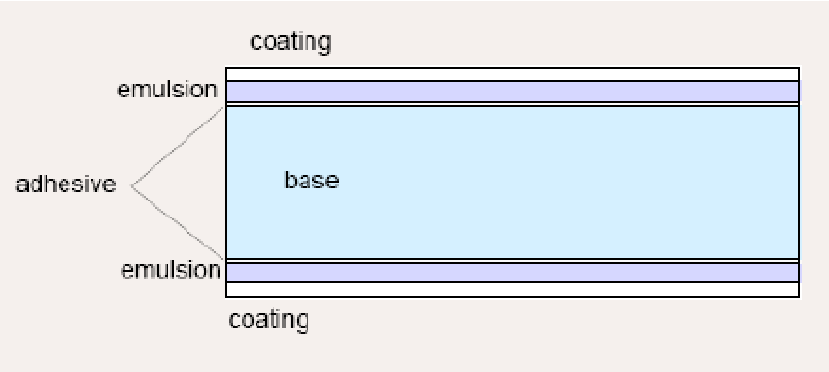


Film Dosimetry

Radiographic X-ray film

Principle

- A thin plastic base layer (200 µm) is covered with a sensitive emulsion of AgBr crystals in gelatine (10-20 µm).

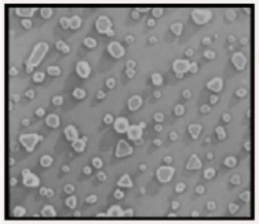


Film Dosimetry

Radiographic film

Principle :

- During irradiation, the following reaction occur (simplified):
  - ❑ Ag Br is ionized
  - ❑ Ag+ ions are reduced to Ag: $Ag^+ + e^- = Ag$
  - ❑ The elemental silver is black and produces a so-called latent image.
- During the **developmen**t, other silver ions (not yet reduced) are also reduced in the presence of silver atoms.
- The rest of the silver bromide (in undeveloped grains) is washed away from the film during the fixation process.
- The film opacity is proportional to the dose.



Electron micrograph of AgBr grains in gelatine with size of 0.1-3 µm

Film Dosimetry

Radiographic film

- Light transmission is a function of the film opacity and can be measured in terms of optical density (OD) with devices called densitometers.
- The OD is defined as $OD = \log_{10}(I_0/I)$ and is a function of dose, where

  I_0 is the initial light intensity, and

  I is the intensity transmitted through the film.
- Film gives excellent 2-D spatial resolution and, in a single exposure, provides information about the spatial distribution of radiation in the area of interest or the attenuation of radiation by intervening objects.

Film Dosimetry

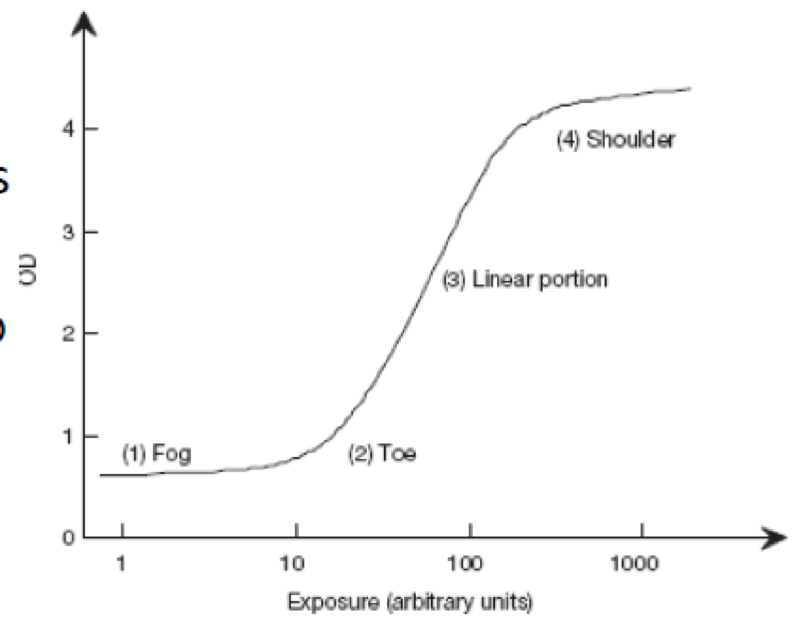
Radiographic film

- Response of film depends on several parameters, which are difficult to control:
  - Consistent processing of the film is a particular challenge.
  - Useful dose range of film is limited and the energy dependence is pronounced for lower energy photons.
- Typically, film is used for qualitative dosimetry, but with proper calibration, careful use and analysis film can also be used for dose evaluation.
- Various types of film are available for radiotherapy work
  - for field size verification: direct exposure non-screen films
  - with simulators: phosphor screen films
  - in portal imaging: metallic screen films

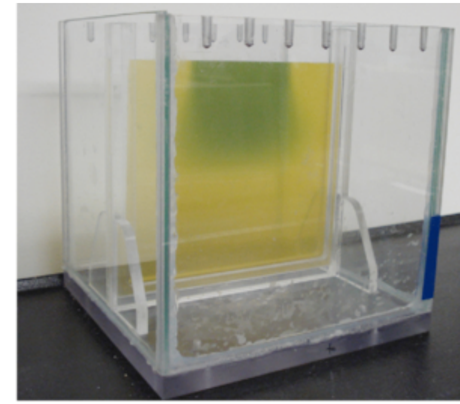
Film Dosimetry

Radiographic film

- **Gamma**: slope of the linear part
- **Latitude**: range of exposures that fall in the linear part
- **Speed**: exposure required to produce an OD >1 over the fog
- **Fog:** OD of unexposed film



Film Dosimetry



- **Radiochromic film**
  - A new type of film well suited for radio-therapy dosimetry.
    - This film type is **self-developing**, requiring neither a developer nor a fixer.
  - **Principle**: Contains a special dye that is polymerized and develops a blue color upon exposure to radiation.
  - Similarly to radiographic film, the radiochromic film dose response is determined with a suitable densitometer.
  - The most commonly used radiochromic film type is the GafChromic film.

Luminescence Dosimetry

- Some materials retain part of the absorbed energy in metastable state.
- This energy is susequently released in the form of light (ultraviolet, visible or infrared).
- This phenomenon is called **Luminescence**.

Luminescence Dosimetry

Two types:

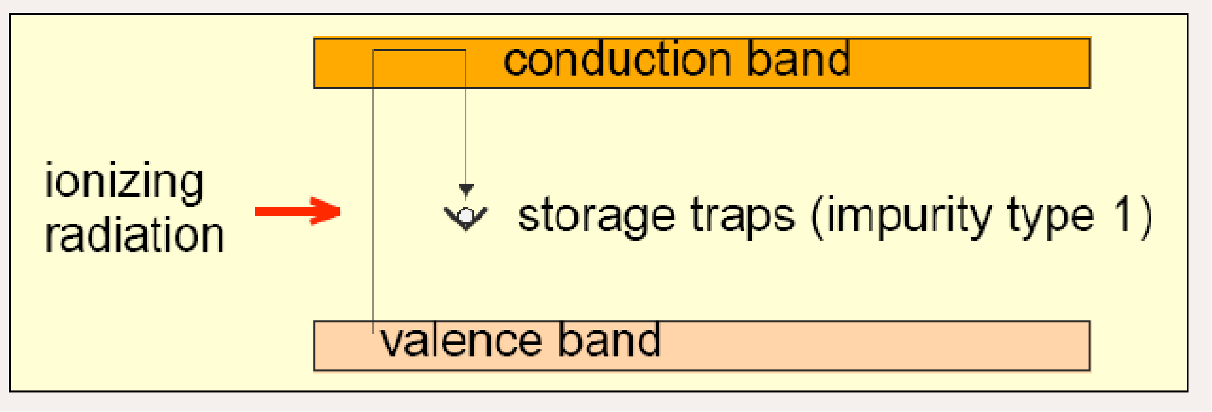
- ❑Fluorescence
- ❑Phosphorescence

Depends on the time delay between the stimulation and the emission of light:

- ❑Fluorescence has a time delay between 10^{-10} to 10^{-8} s.
- ❑Phosphorescence has a time delay exceeding 10^{-8} s.

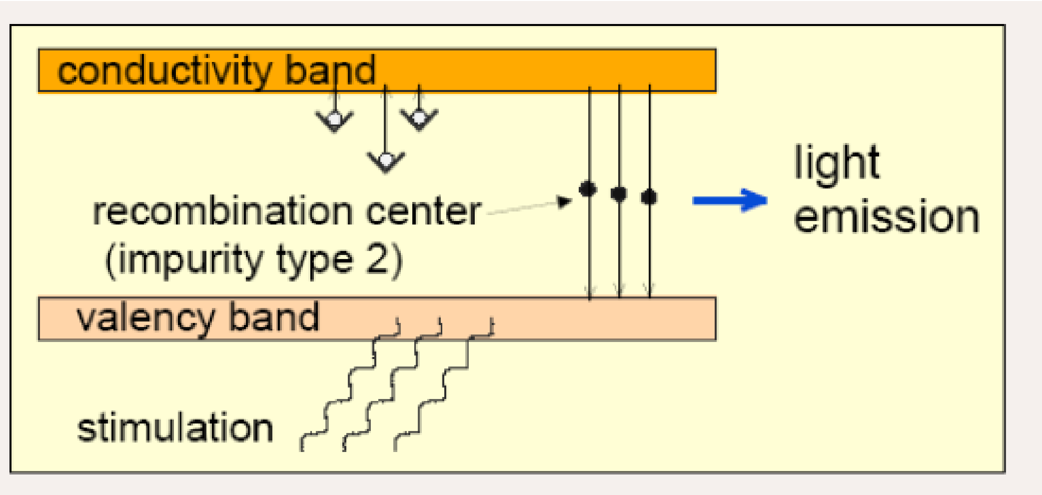
Luminescence Dosimetry

- Upon radiation, free electrons and holes are produced
- In a luminescence material, there are so-called storage traps
- Free electrons and holes will either recombine immediately or become trapped (at any energy between valence and conduction band)



Luminescence Dosimetry

- Upon stimulation, the probability increases for the electrons to be raised to the conduction band ....
- and to release energy (light) when they combine with a positive hole (needs an impurity of type 2)



Luminescence Dosimetry

- The process of luminescence can be accelerated with a suitable excitation in the form of heat or light.
- If the exciting agent is **heat**, the phenomenon is known as **thermoluminescence**
- When used for purposes of dosimetry, the material is called
  - Thermoluminescent (**TL**) material
  - Or
  - Thermoluminescent dosimeter (**TLD**).

Luminescence Dosimetry

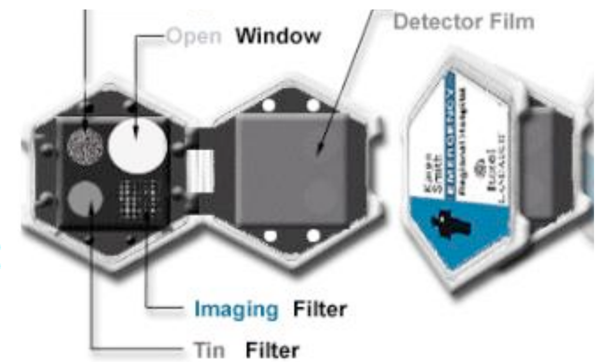
Thermoluminiscence

- TL dosimeters most commonly used in medical applications are (because of their tissue equivalence):
  - LiF:Mg,Ti
  - LiF:Mg,Cu,P
  - Li2B4O7:Mn

neutrons

- Other TLDs are (because of their high sensitivity):
  - CaSO4:Dy
  - Al2O3:C
  - CaF2:Mn

gammas



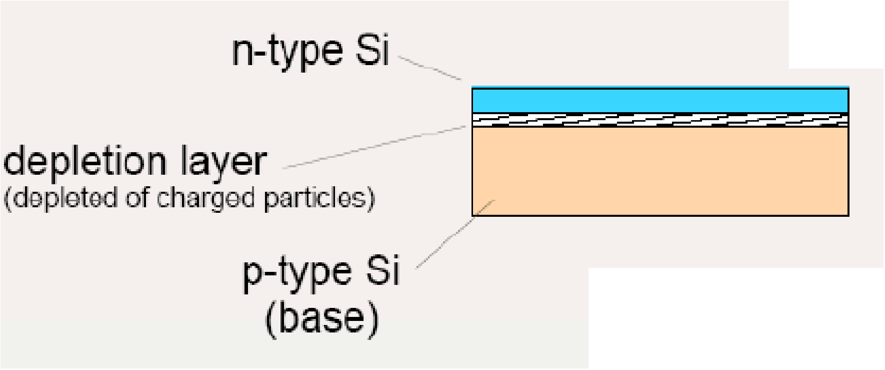
www.uos.harvard.edu/ehs/radsafety/d

- TLDs are available in various forms (e.g., powder, chip, rod, ribbon, etc.)
- TLDs have to be annealed to erase any residual signal.

Semiconductor Dosimetry

Silicon diode

- A silicon diode dosimeter is a positive-negative junction diode.
- The diodes are produced by taking n-type or p-type silicon and counter-doping the surface to produce the opposite type material.

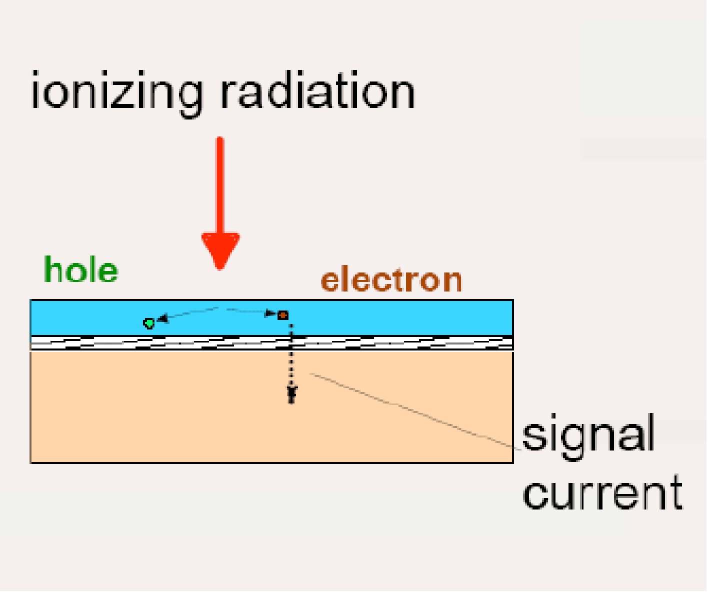


Semiconductor Dosimetry

Silicon diode

Principle:

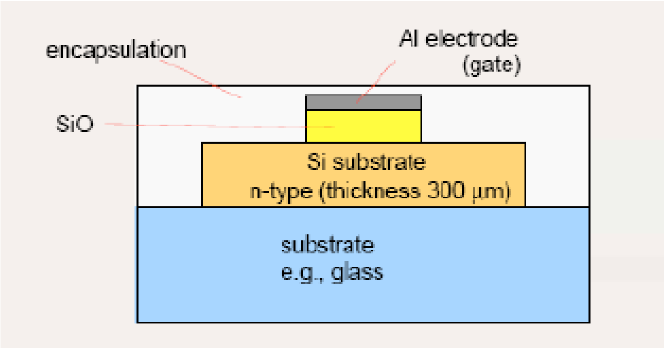
- The depletion layer is typically several μm thick.
- When the dosimeter is irradiated, charged particles are set free which allows a signal current to flow.
- Diodes can be operated with and without bias.
- In the photovoltaic mode (without bias), the generated voltage is proportional to the dose rate.



Semiconductor Dosimetry

MOSFET

- A MOSFET dosimeter is a **M**etal-**O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor.



- **Physical principle**:
- Ionizing radiation generates charge carriers in the Si oxide.
- The charge carries moves towards the silicon substrate where they are trapped.
- This leads to a charge build up causing a change in threshold voltage between the gate and the silicon substrate.

Semiconductor Dosimetry

MOSFET

Measuring Principle:

- MOSFET dosimeters are based on the measurement of the threshold voltage, which is a linear function of absorbed dose.
- The integrated dose may be measured during or after irradiation.

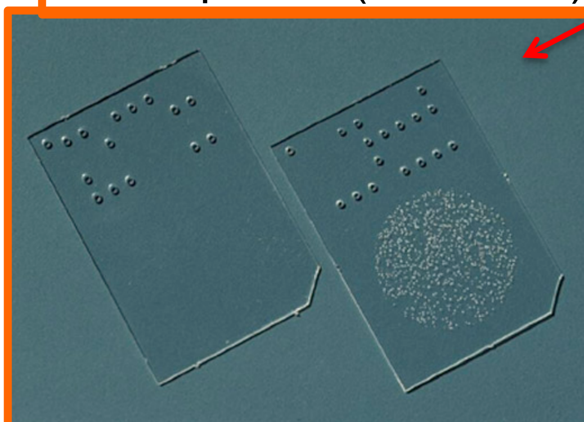
Characteristics:

- MOSFETs require a connection to a bias voltage during irradiation.
- They have a limited lifespan.
- The measured signal depends on the history of the MOSFET dosimeter.

CR-39 detectors

Slabs of poly-allyl-diglicol-carbonate (PADC) produced by intercast

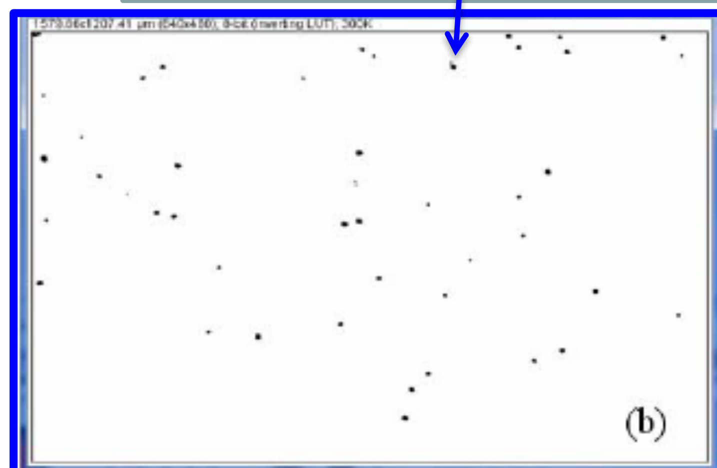
Cut in pieces (2.224cm^2)



R. Bedogni, et al, Radiat. Meas. **43**, S491 (2008)

Sensitive to **fast neutrons**:

- After n,p scattering protons leave a track
- Etching with potassium hydroxide at 70^{o}C
- Read with a custom reader



Number of tracks proportional to integrated impinging neutrons

CR-39 detectors for thermal neutrons

<1.8 MeV α particles produced via

B(n,α)Li

The α release tracks in CR-39 detectors

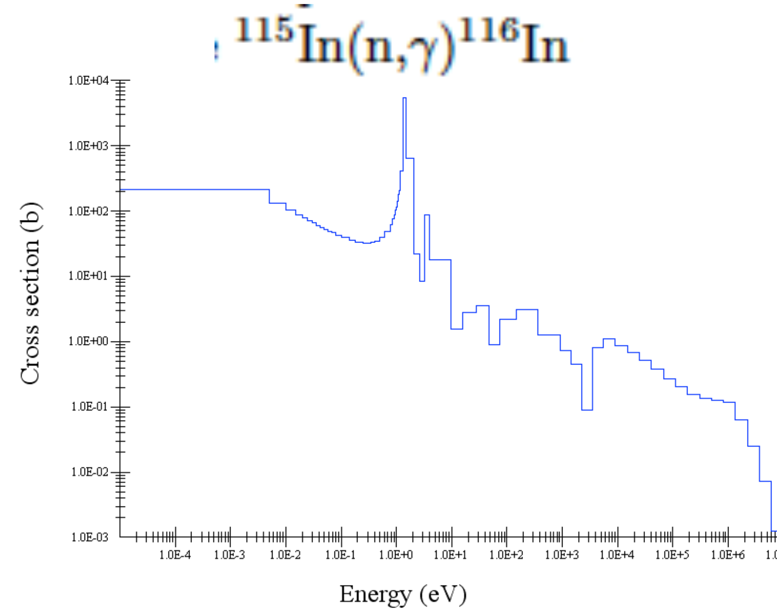
Wrap detectors in Boron films

Activation detectors: Indium disks

5cm Indium disks (30g total)

Two steps:

- Neutrons activate Indium
  - More sensitive to thermal neutrons
- Gamma lines @1293, 1047 and 416 keV with $T_{1/2}=\log(2)/\lambda=54$ min
- The activity (α) from an irradiation lasted t_r is measured with a HPGe detector (after a time t_a)



From activity to flux (ϕ)

$$\phi = \frac{\alpha}{N\sigma\left(1-\exp\left(-\lambda t_r\right)\right)\exp\left(-\lambda t_a\right)}$$

Also Cd and Au