Dosimetry of ionizing radiations

02-24, 2022

Károly Liliom

Radiation = spreading of energy

energy > ionization energy:

ionizing radiation

Ionizing radiation

Classification according to the primary effect

↙ ↘

Direct ionization

Incoming particles are charged and ionize until loosing their energy.
(α- and β-particles, protons, ions)

Indirect ionization

Primary electrons ejected by the incoming radiation and secondary electrons ionize further.
(γ and X ray photons, neutrons)

Tasks for dosimetry

Estimation of health risk for prevention.

Estimation of biological damages.

Design of therapeutic procedures.

Definition of quantities

↓

Design of measuring techniques

↓

Estimation of consequences

1. Dose values sholud be

- proportional to the damagas and expected risk
- additive
- independent of other factors

Dose concepts

Physical dose concepts:
Absorbed dose,
Exposure

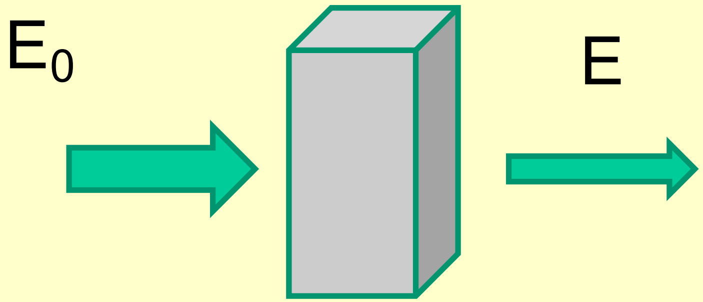
Biological dose concepts:
Equivalent dose,
Effective dose

Derived dose concepts:
Collective dose,
Dose rate

1. Absorbed dose

measures the absorbed energy in a unit mass

$\Delta E = E_0 - E$



$$D = \frac{\Delta E}{\Delta m} [J/kg]$$

Validity: for any kind of material and any type of radiation without restriction

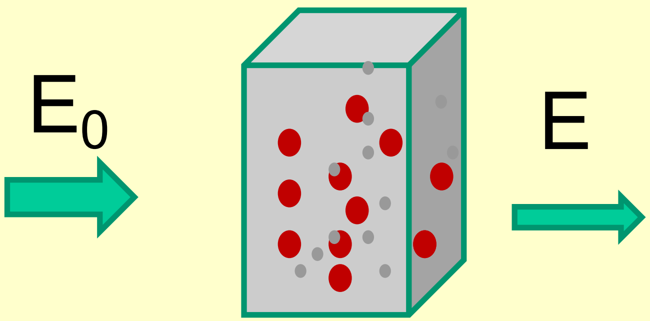
Louis Harold Gray
(1905-1965).

Unit: $[J/kg] \equiv Gy$

How to be measured?!

2. Exposure

measures the amount of positive or negative charges generated by the radiation in a unit mass.



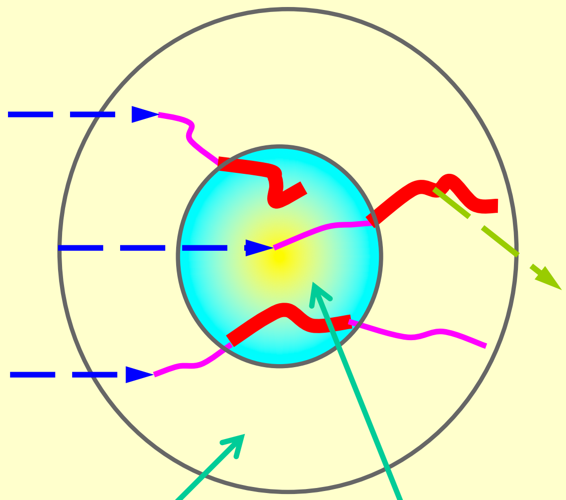
$$X = \frac{\Delta Q}{\Delta m} [C / kg]$$

Validity: in the air, only γ and X –rays, measured in electron equilibrium*

$$X = \frac{\Delta Q}{\Delta m} [C / kg]$$

ΔQ – secondary electrons!!

Electron-equilibrium: net number of the secondary electrons living and entering volume of the cavity are equal.



To be considered:

- composition of surrounding material (chamber wall) – **air-equivalent wall!**
- thickness of the wall
- Photon energy: E< 0.6 MeV

Calculation of the absorbed dose from the exposure

$$X = \frac{\Delta Q}{\Delta m}[C / kg]$$

$$D_{air} = f_0 X$$

$$D = \frac{\Delta E}{\Delta m}[J / kg]$$

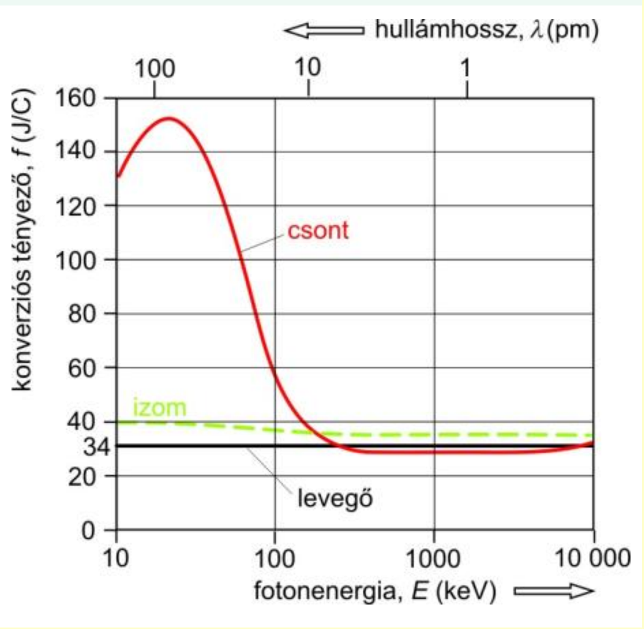
~ 34 J/C

Average ionization energy in air

~ 34 eV.

Absorbed dose in tissue

$$D = f\,X$$



$$\frac{\Delta E}{\Delta m} \approx \mu_m \cdot J$$

$$D_{air} = \frac{\Delta E}{\Delta m}[J/kg]$$

$$\frac{D_{air}}{D_{tissue}} = \frac{\mu_{m.air}}{\mu_{m,tissue}}$$

Photon energy (MeV)	$\mu_{m,air.}/\mu_{m,tissue}$ (soft tissues)	$\mu_{m,air.}/\mu_{m,tissue}$ (bones)
0,1	1,07	3,54
0,2	1,08	2,04
0,4	1,10	1,24

Biological dose concepts

Equivalent dose

Effective dose

The absorbed energy (absorbed dose) is not sufficient to measure the possible biological consequences.

The biological consequences are influenced by :

the type of radiation.

↓

radiation weighting factor

the sensitivity and biological function of target

↓

tissue weighting factor

Equivalent dose (H)

Rolf Sievert
1896-1966

„Efficiency" of various forms of radiation is not uniform.

$$H_T = w_R D_T$$

Radiation weighting factor – estimation of the relative risk of the given radiation

Absorbed dose in tissue

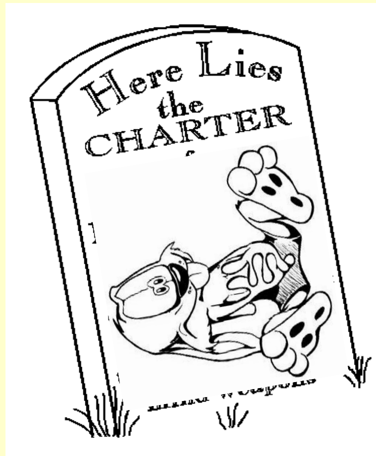
Unit of ***H*** : ***Sievert (Sv)***

radiation	w_R
photon	1
electron	1
neutron	5-20
proton	5
α-particle	20

Why are the fates of the rabbits different?

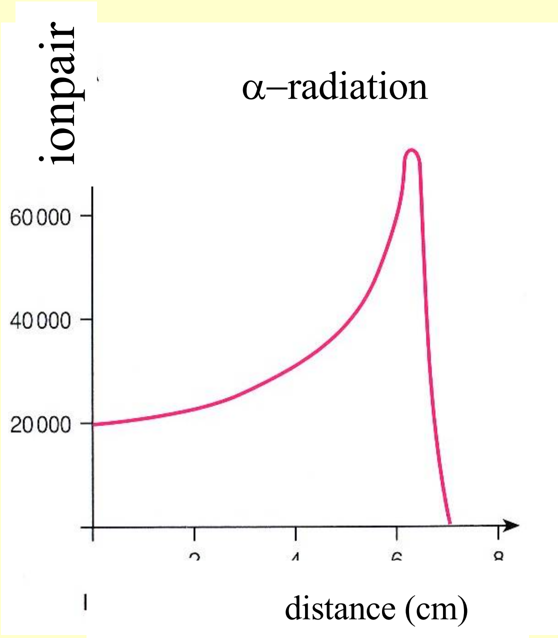
2 Gy absorbed dose – ***X-ray***

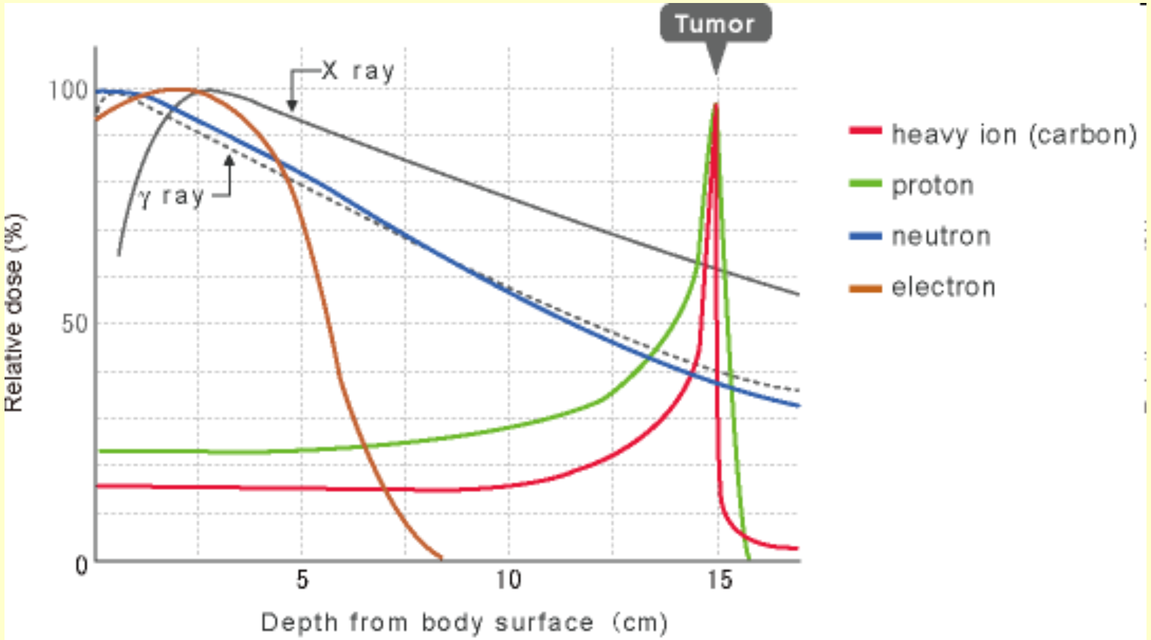
2 Gy absorbed dose – ***α-particles***



Equivalent dose (H)

„Efficiency” of various forms of radiation is not uniform.





LET (Linear Energy Transfer: the energy transferred to the material surrounding the particle track, by means of secondary electrons. *($nE_{ionpair}/l$)*

Equivalent dose (H)

„Efficiency” of various forms of radiation is not uniform.

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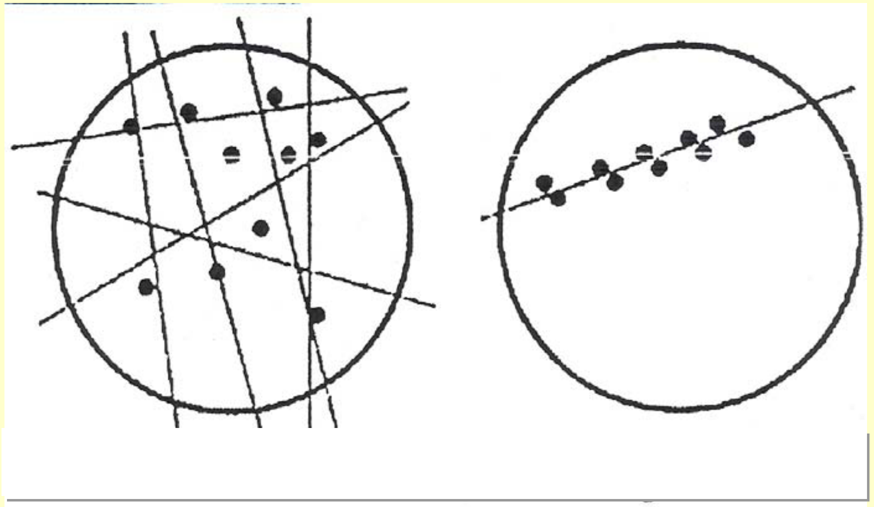
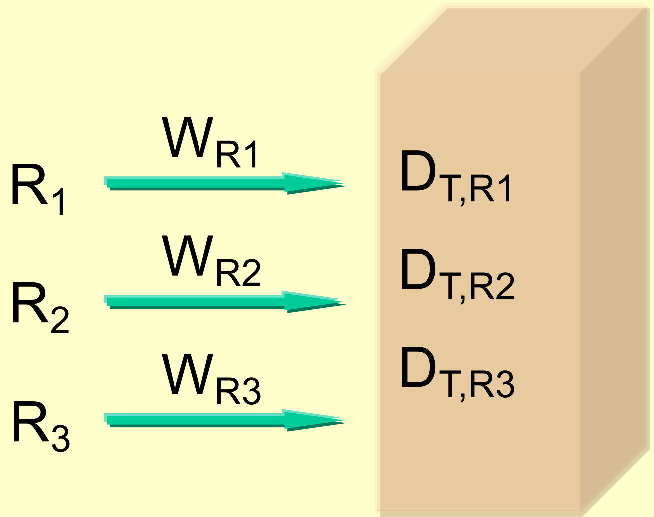


Small LET
e.g. γ, X-ray

High LET
e.g. α, proton

radiatiom	W_R
photon	1
electron	1
neutron	5-20
proton	5
α-particle	20

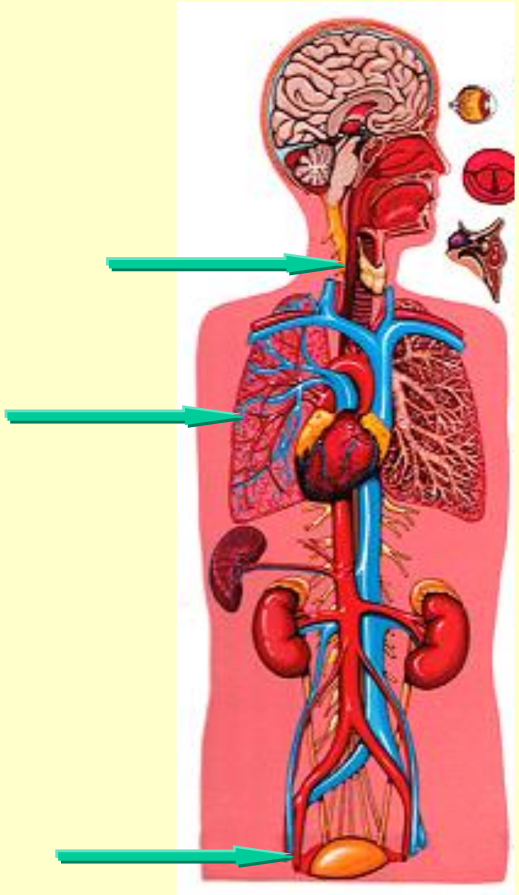
If someone is exposed to more than one type of radiation:



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

Effective dose (E)

Various sensitivity of tissues has to be considered



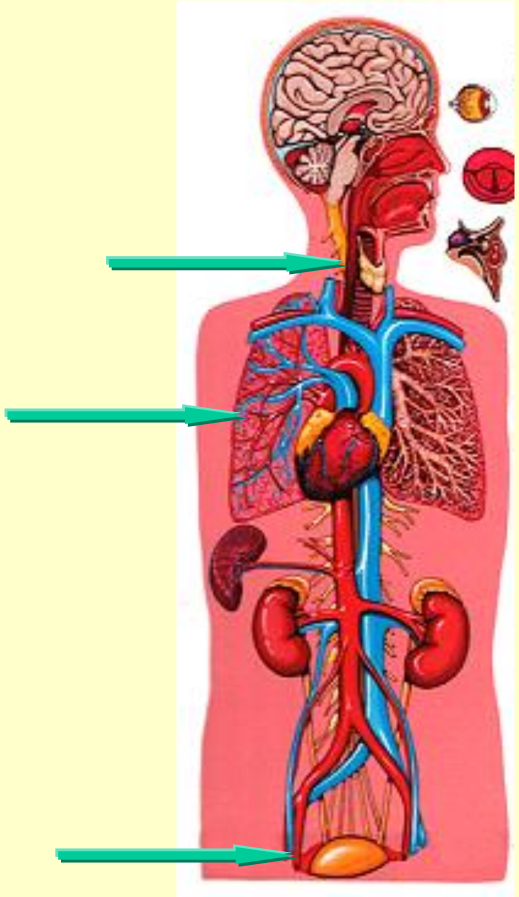
$$E = \sum_T w_T H_T$$

Tissue weighting factor – estimation of the relative sensitivity of tissue

Equivalent dose in the given tissue

Unit of ***E*** : ***Sievert (Sv)***

$$E = \sum_T w_T H_T$$

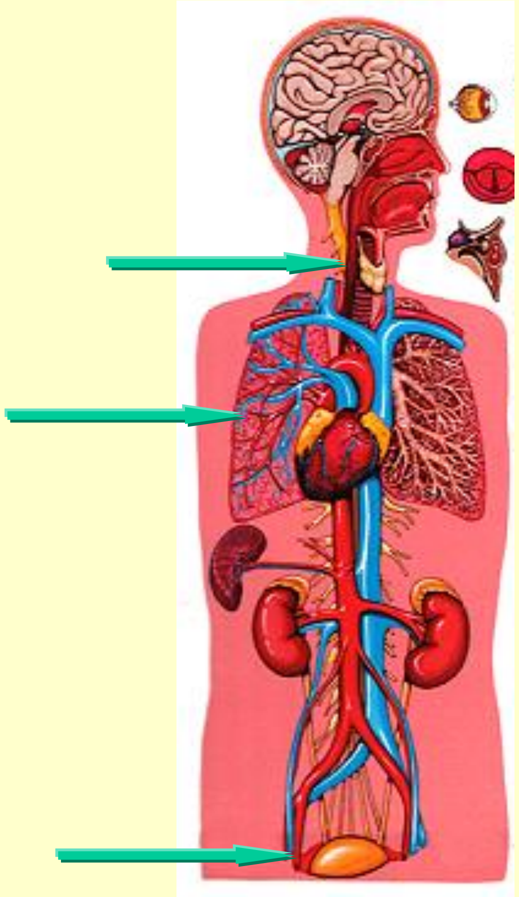


tissue	W_T	tissue	W_T
gonads	0,2	breast	0,05
bone marrow	0,12	liver	0,05
colon	0,12	oesophagus	0,05
lung	0,12	thyroid gland	0,05
stomach	0,12	skin	0,01
bladder	0,05	bone surface	0,01

$$\sum_T w_T = 1$$

$$E = \sum_T w_T H_T$$

$$\sum_T w_T = 1$$



Organ or tissue	W_T ICRP 30 (1979)[a]	W_T ICRP 60 (1991)	W_T ICRP 103 (2007)
Gonads	0.25	0.20	0.08
Red bone marrow	0.12	0.12	0.12
Large intestine		0.12	0.12
Lung	0.12	0.12	0.12
Stomach		0.12	0.12
Bladder		0.05	0.04
Breast	0.15	0.05	0.12
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
Rest[b]	0.30	0.05	0.12
Brain			0.01
Total	1.00	1.00	1.00

[a] ICRP 30 W_T are used to calculate EDE, whereas ICPR 60 W_T and ICRP 103 W_T give *E* values.

[b] 'Rest' includes adrenals, small intestine, kidney, muscle, brain (except ICRP 103 W_T), pancreas, spleen, thymus and uterus.

Dose rate

Received dose over time.

Unit: varies with the type of radiation and the time period (pl. Gy/month, mSv/year etc.)

Collective dose

Sum of the doses received by a given number of people (N_i) in the course of a given time interval.

Collective dose

Sum of the doses received by a given number of people (N_i) in the course of a given time interval.

$$S = \sum_i N_i E_i$$

E_i effective dose in each person

Consider an α-emitting isotope of 5 MBq activity. The energy of the emitted α particles is 6.2 MeV. The total emitted energy is absorbed in 0.1 kg water. Calculate the the absorbed dose in the water after half an hour irradiation. (There is no significant change in the activity of the radioactive sample during the time of the experiment.)

Λ=5 MBq, azaz $5*10^6$ decay/s

N=$5*10^6 * 1800 = 9*10^9$ decay in half an hour

$E_{abs}=E_\alpha*N$

$E_{abs}=6.2*10^6 eV* 9*10^9$

$E_{abs}=5,58*10^{16}$ eV=$8,92*10^{-3}$ J

$$D=\frac{E_{abs}}{m}=\frac{8.92*10^{-3}}{0.1}=8.92*10^{-2}[Gy]$$

Consider an α-emitting isotope of 5 MBq activity. The energy of the emitted α particles is 6.2 MeV. The total emitted energy is absorbed in 0.1 kg water. Calculate the temperature change of the water after half an hour irradiation. (There is no significant change in the activity of the radioactive sample during the time of the experiment.)

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$E_{abs}=5,58*10^{16}$ eV$=8,92*10^{-3}$ J

$E_{abs}=c*m*\Delta T$

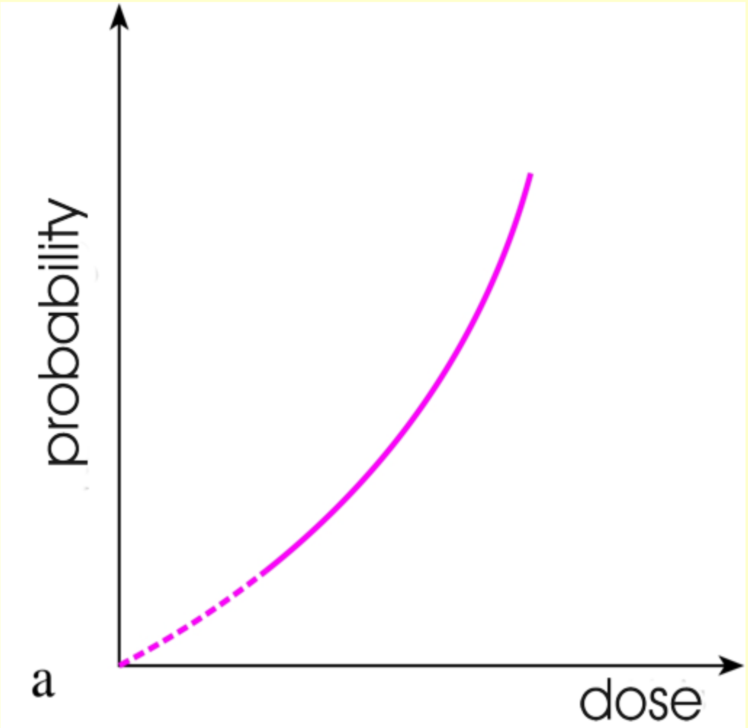
$$\Delta T = \frac{8.92*10^{-3}}{4.18*10^{3*0.1}} = 2.1*10^{-5}$$

Types of damages

Stochastic damages

Deterministic damages

Stochastic damages



NO threshold!

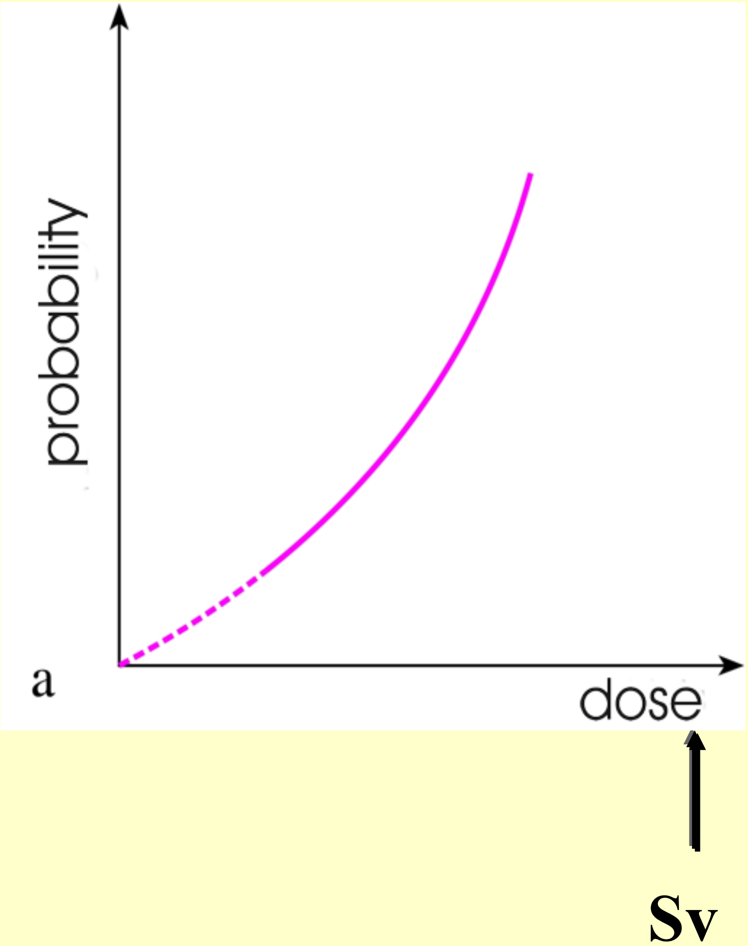
The probability of stochastic damage depends on the dose.

Severity (e.g. cancer) independent of the dose.

Delayed biological effects.

e.g.tumours, heriditary diseases

Stochastic damages



H_T (equivalent dose) and
E (effective dose) provide a basis for ***estimating the probability of stochastic effects*** for doses below the threshold of deterministic effects.

Dose range is under the threshold of deterministic damages.

Stochastic damages

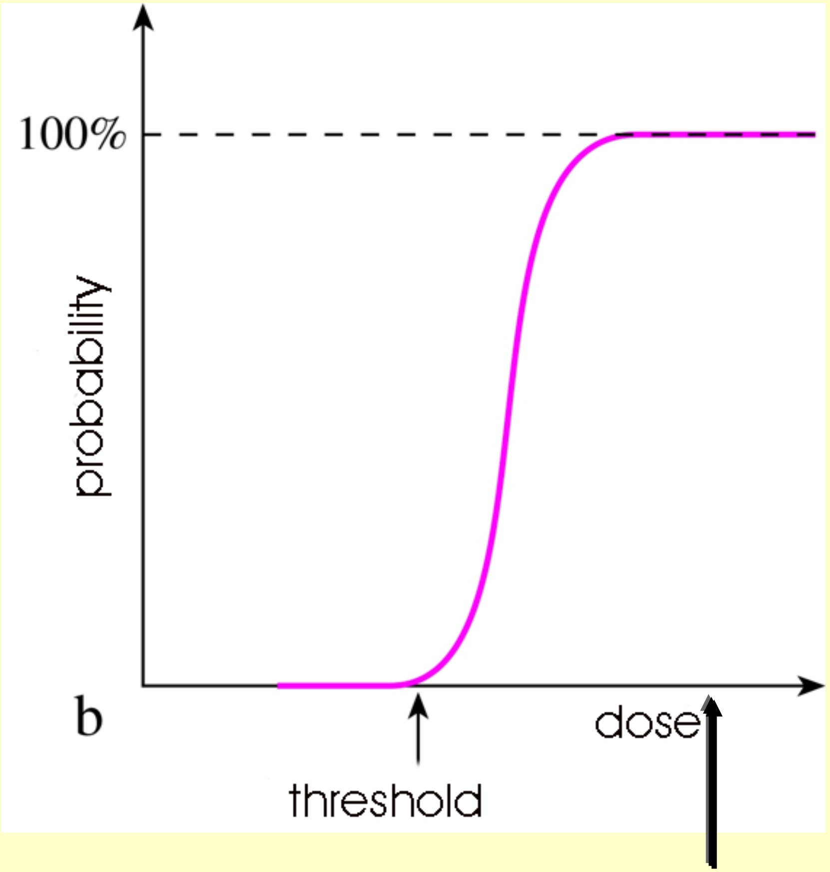
Irradiated cell is modified rather than killed

Severity is not affected by the dose

With increasing dose only the probability* increases

*1 gamma photon: the probability to cause cancer is 3×10^{-16} (1: 3,000 billion, but this is a Russian roulette!)

Deterministic damages



Gy

Deterministic damages

A threshold dose exists.

Above threshold severity depends on the dose.

Appear soon after exposition.

Must not be induced during diagnostic procedures.

e.g. erythema, epilation, cataract

*1% lethal 60 days after exposition

Dose (Gy) (whole body)	Biological effect
< 0,15-0,2	No observable effect
0,5	Slight blood changes – limit of detection by hematological methods.
0,8	Critical dose – threshold of acute radiation syndrome
2,0	Minimal lethal dose (LD1/60)*
4,0	Half lethal dose (LD50/60)
7,0	Minimal absolute lethal dose (LD99/60)

Chest X-ray: cc 160 μGy in the skin

Radiotherapy

Which radiation is the best?

What is the optimal dose of radiation?

What is the best technique for generating radiation?

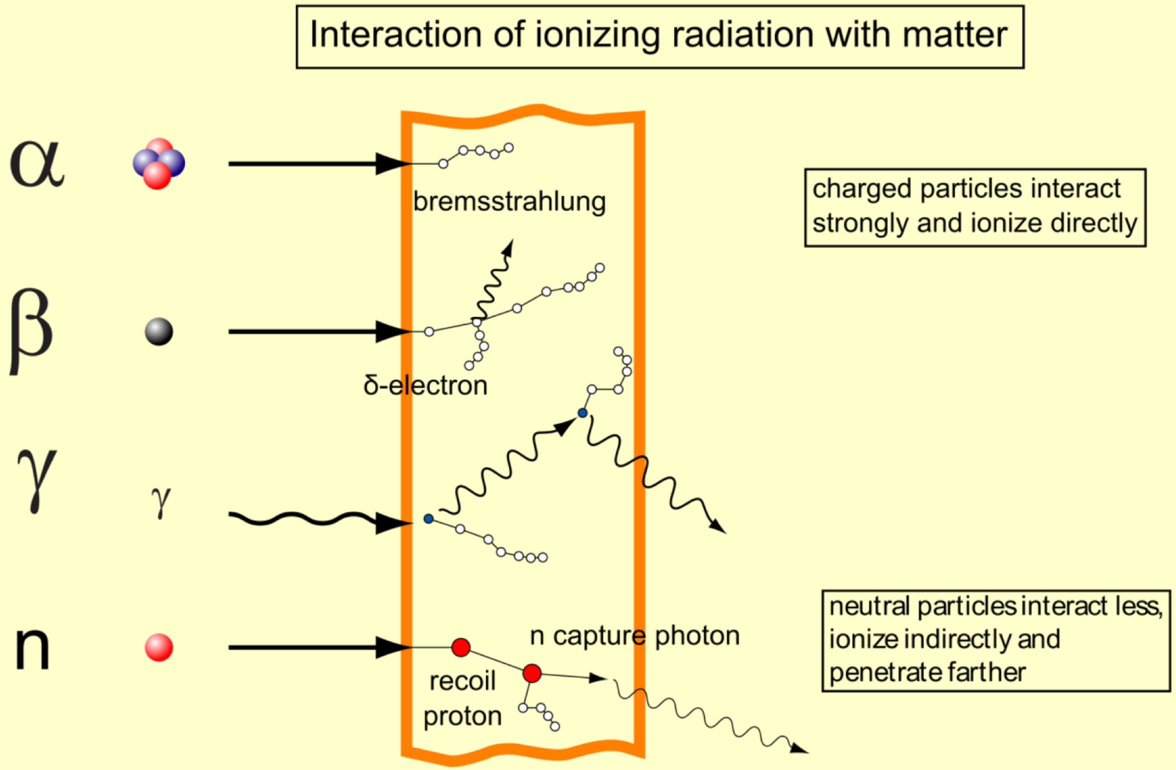
Irradiation selectivity – protection of healthy structures?

Radiation therapy is a clinical modality dealing with the use of ionizing radiations in the treatment of patients with malignant neoplasias (and occasionally benign diseases).

The **aim of radiation therapy** is to deliver a **curative** dose of irradiation to a defined tumor volume with as minimal damage as possible to surrounding healthy tissue.

Consequences of the absorption of ionizing radiation.

1. Physical events — Direct or indirect ionization



The amount of secondary ionization depends on the material; it can be up to 10 times the amount of primary ionization.

The gamma photon emitted by the nucleus of the cesium isotope with 137 mass number is absorbed with photoeffect. The absorbing medium is air, assume the work function to be 34 eV. What will be the kinetic energy of the photoelectron in eV?

$$E_{^{137}Cs} = 0{,}661 \text{MeV}$$

$$hf = A + 1/2mv^2$$

$$1/2mv^2 \approx 661\ 000 \text{ eV}$$

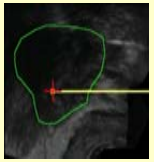
What is the maximum number of ion pairs that the ejected photoelectron is able to produce during the secondary ionization process?

$$n_{max} = 661\ 000 \text{ eV}/34\text{eV}$$

$$n_{max} = 19440$$

Radiotherapy

α



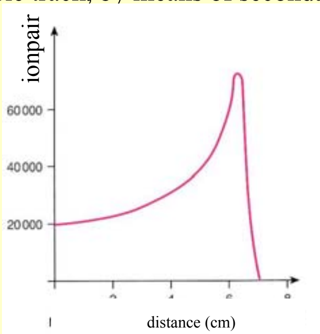
Internally deposited radioactivity

β-, e-, γ, Rtg, p, n

Linear ion density:
the amount of ion pairs in a line generated in a unit distance *(n/l)*

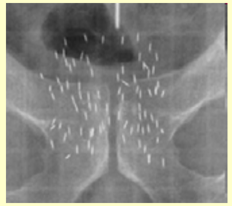
LET (Linear Energy Transfer : the energy transferred to the material surrounding the particle track, by means of secondary electrons. $(nE_{ionpair}/l)$

In the air: $E_{ionpair}=34\ eV$



α

β⁻: Particle energy is not optimal
continuous energy spectrum
typical energy: few MeV



Internally seeded radioactivity

e⁻: accelerated electron - 10-20 MeV

γ, Rtg, p, n

production: linear accelerator

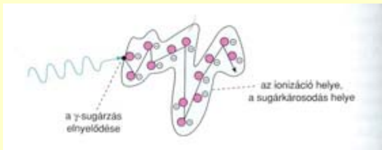
Efficient distance! ≈1cm/3MeV

In the practice 6-21 Mev => 2-7 cm
treatment of superficial tumours

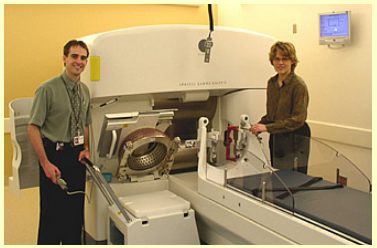
γ : external radiation source

Site of absorption≠ sites of ionization = site of radiation damages

Penetration distance
is energy dependent



γ-knife: focused dose of radiation

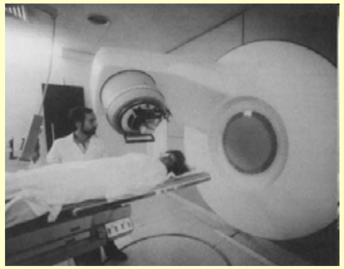


about 200 portals in a specifically designed helmet

e.g., ^{60}Co Eγ≈MeV ,
about TBq activity

Treat tumours and lesions in the brain

X/ray:



The X-rays are generated by a linear accelerator .

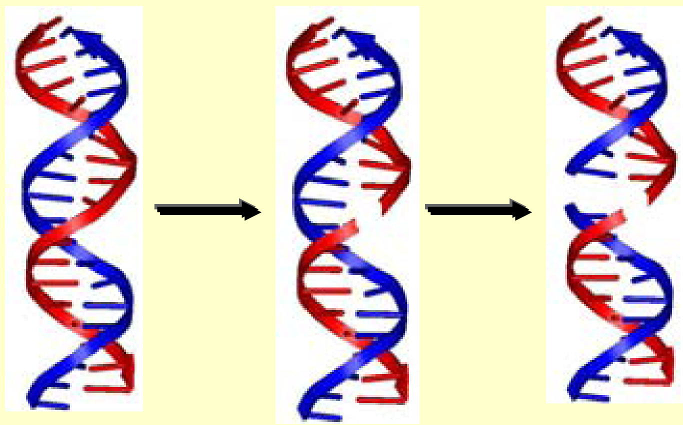
Few MeV photon energy.

2. Chemical reactions

Direct effect

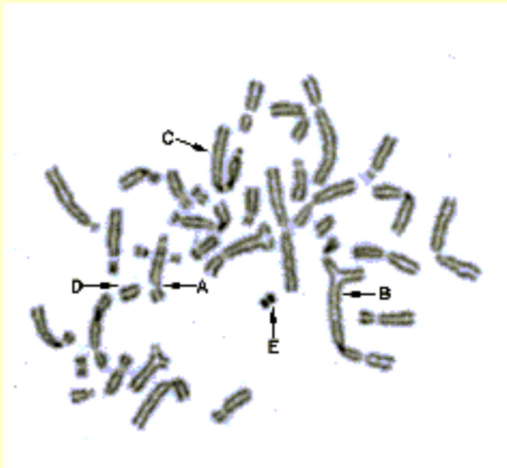
Direct ionization of the macromolecules.

DNA damage is the most important!



single double

strand breaks



chromosome aberrations

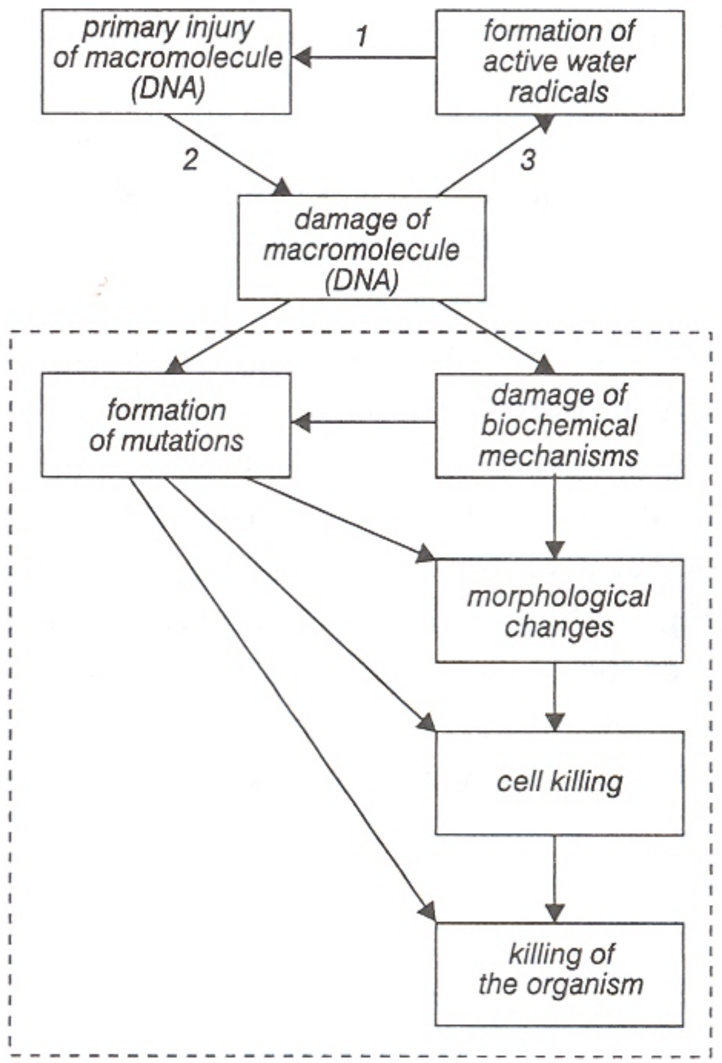
Indirect effect

Reactive ions (e.g. OH^-) and/or radicals (e.g. *OH) are generated manly from water molecules.
(65-70% of the human body is water)

↓

Reactive species induce damages in macromolecules and membrane structures.

3. Biological consequences



Timescale of events

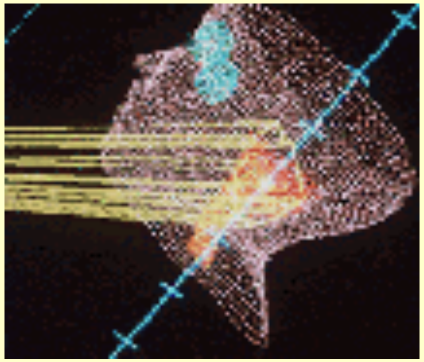
Physical	$10^{-20} – 10^{-8}$ s	Ionization, excitation
Chemical	$10^{-18} – 10^{-9}$ s	Direct/indirect chemical reactions
	10^{-3} – few hours	Repair of damages
Early biological	hours – weeks	Cell death, death of living system
Delayed biological	years	Carcinogenesis, genetic transformation

Approaches

- **Palliative radiotherapy** to reduce pain and address acute symptoms – e.g. bone metastasis, spinal cord compression etc.,

- **Radical radiotherapy** as primary modality for cure – e.g. head and neck tumours

- **Adjuvant treatment** in conjunction with surgery – e.g. breast cancer




Ionizing radiation in radiotherapy

Electromagnetic

- X-ray – Bremsstrahlung and characteristic
- gamma
  - ^{60}Co (1,25MeV) – tele-therapy
  - ^{192}Ir, ^{125}I (35 keV), ^{137}Cs, ^{60}Co - brachytherapy

Electron/β^{-} – energy range 6 – 21 MeV

Alpha - ^{225}Ac 6 MeV, ^{226}Ra 4,78 MeV

Proton – increasing use

Heavy ions – limited use

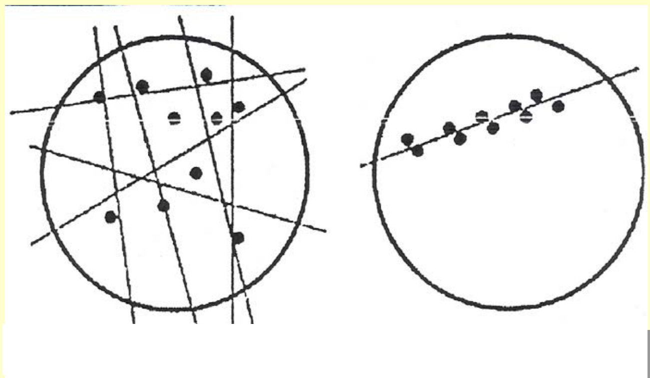
Neutron – limited use

„Efficacy" of various modalities are different

Linear ion density:

the amount of ion pairs in a line generated in a unit istance *(n/l)*

LET (Linear Energy Transfer : the energy transferred to the material surrounding the particle track, by means of secondary electrons. *($nE_{ionpair}/l$)*



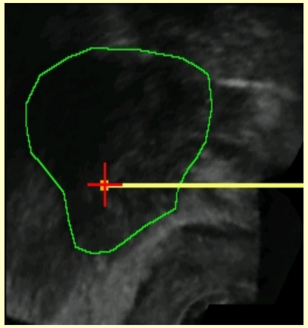
Low LET
e.g.,. γ, rtg

High LET
e.g., α, proton

Typical LET values

LET	Radiation	Energy(MeV):	LET(keV/µm):
high	α – particles	5.0	90
	fast neutron s	6.2	21
	protons	2.0	17
low	X-rays	0.2	2.5
	60-Co γ–radiation	1.25	0.3
	β – particles	2.0	0.3
	accelerated electrons	10.0	

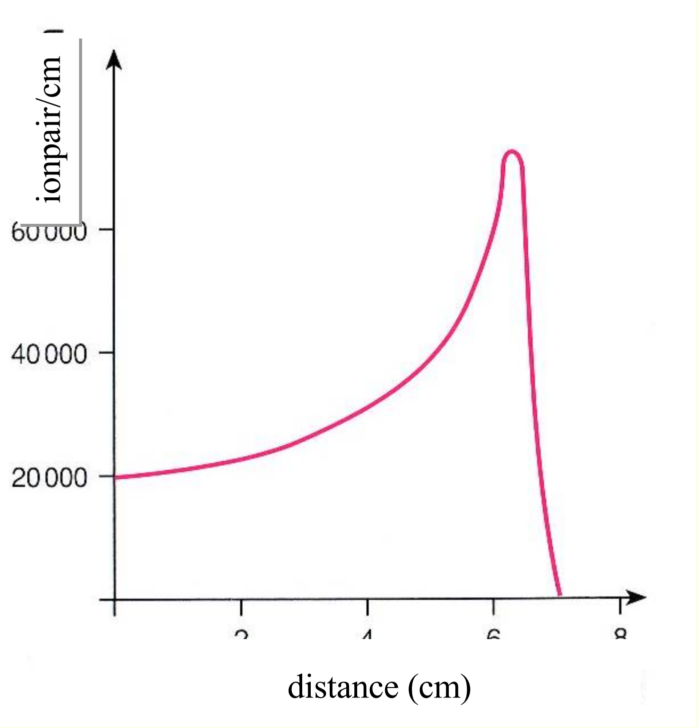
α



Internally deposited radioactivity

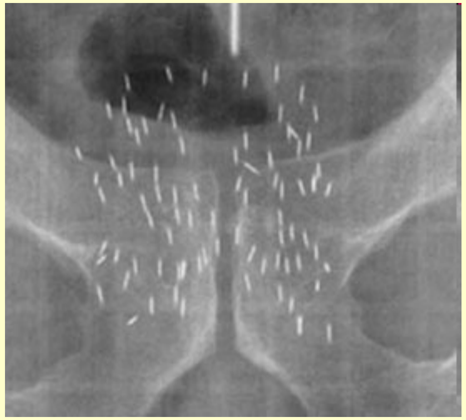
Brachytherapy

In the air: $E_{ionpair} = 34\ eV$



β^-:

Internally seeded radioactivity



Particle energy is not optimal

continuous energy spectrum

typical energy: few MeV

e^-:

accelerated electron - 10-20 MeV

production: linear accelerator

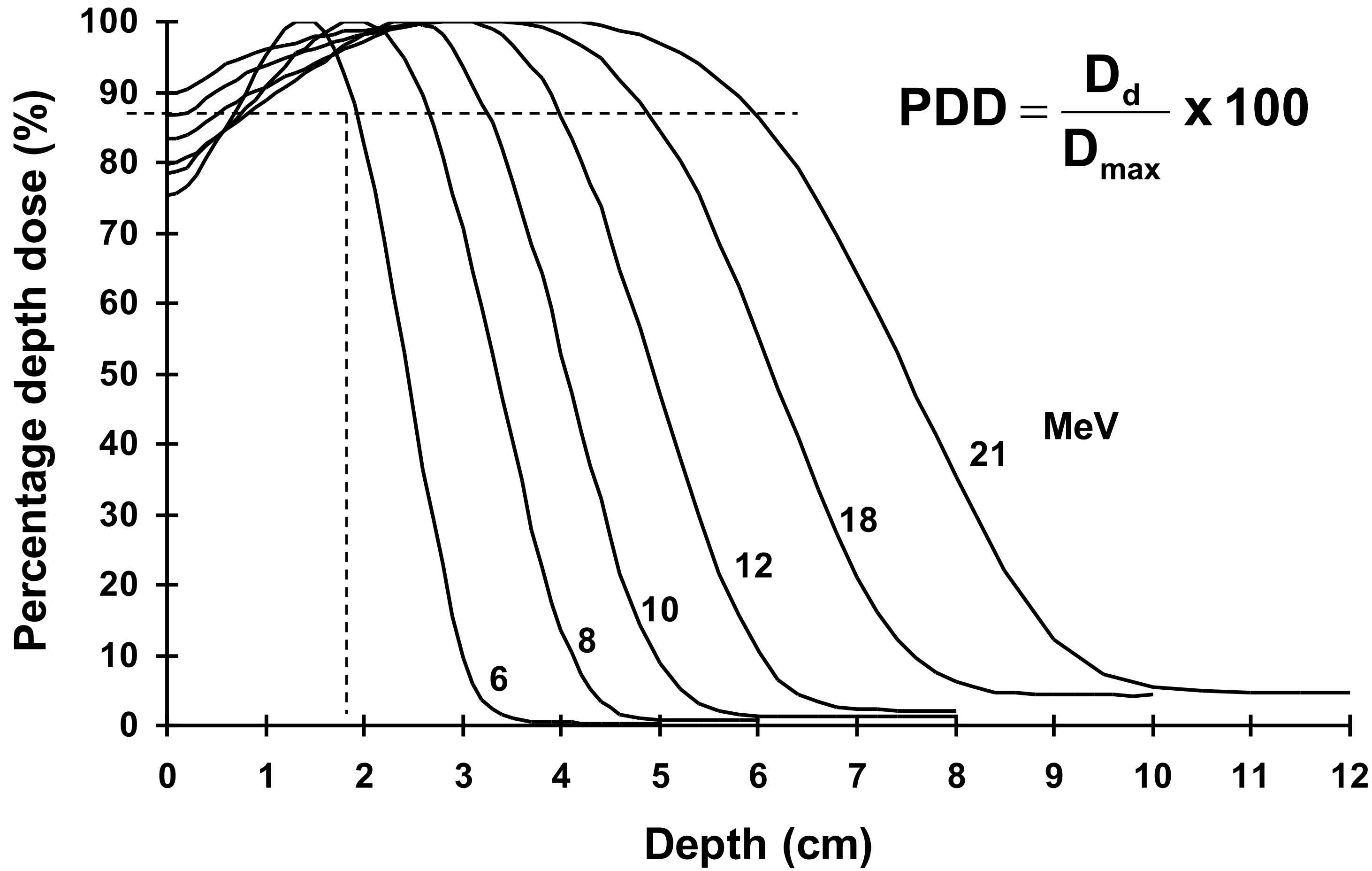
Efficient distance! ≈1cm/3MeV

In the practice 6-21 MeV => 2-7 cm

treatment of superficial tumours

Electron PDD (percentage depth dose) **curves with different energies**

Reduced skin-sparing effect



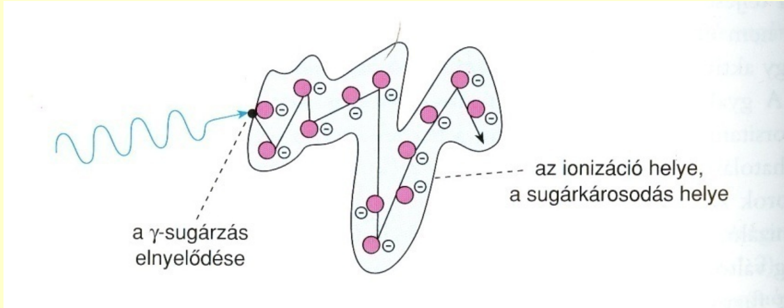
$$PDD = \frac{D_d}{D_{max}} \times 100$$

<u>Conclusion:</u> only superficial tumors can be treated with electron beams

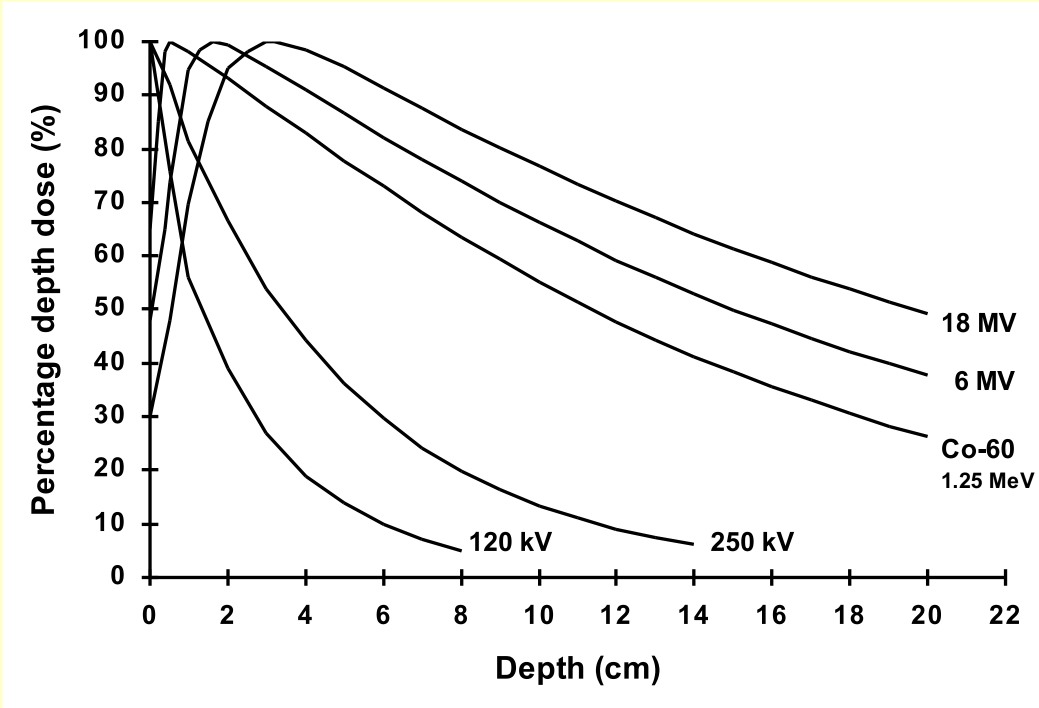
γ :

Site of absorption≠ sites of ionization = site of radiation damages

Penetration distance
is energy dependent



PDD curves at voltages (see X-ray) and various photon energies



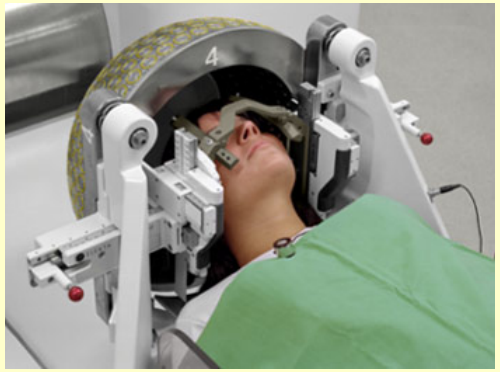
γ :

γ-knife: focused dose of radiation

about 200 portals in a specifically designed helmet

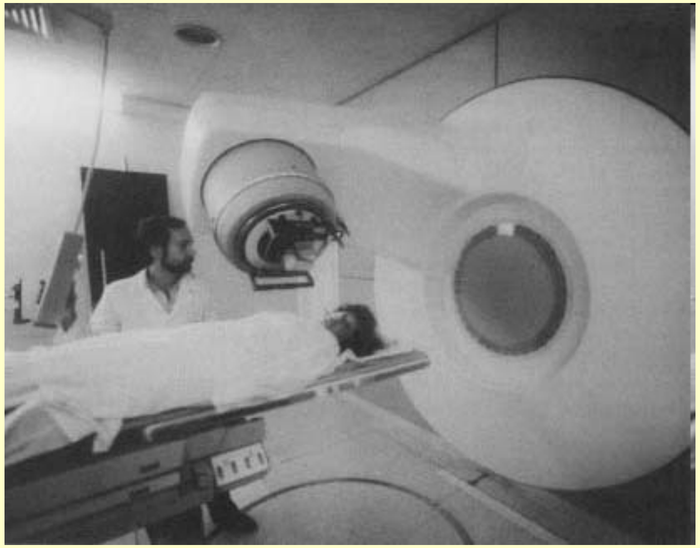
e.g., ^{60}Co Eγ≈MeV , about TBq activity

The radiation isocenter is the point in space where radiation beams intersect



Treat tumours and lesions in the brain

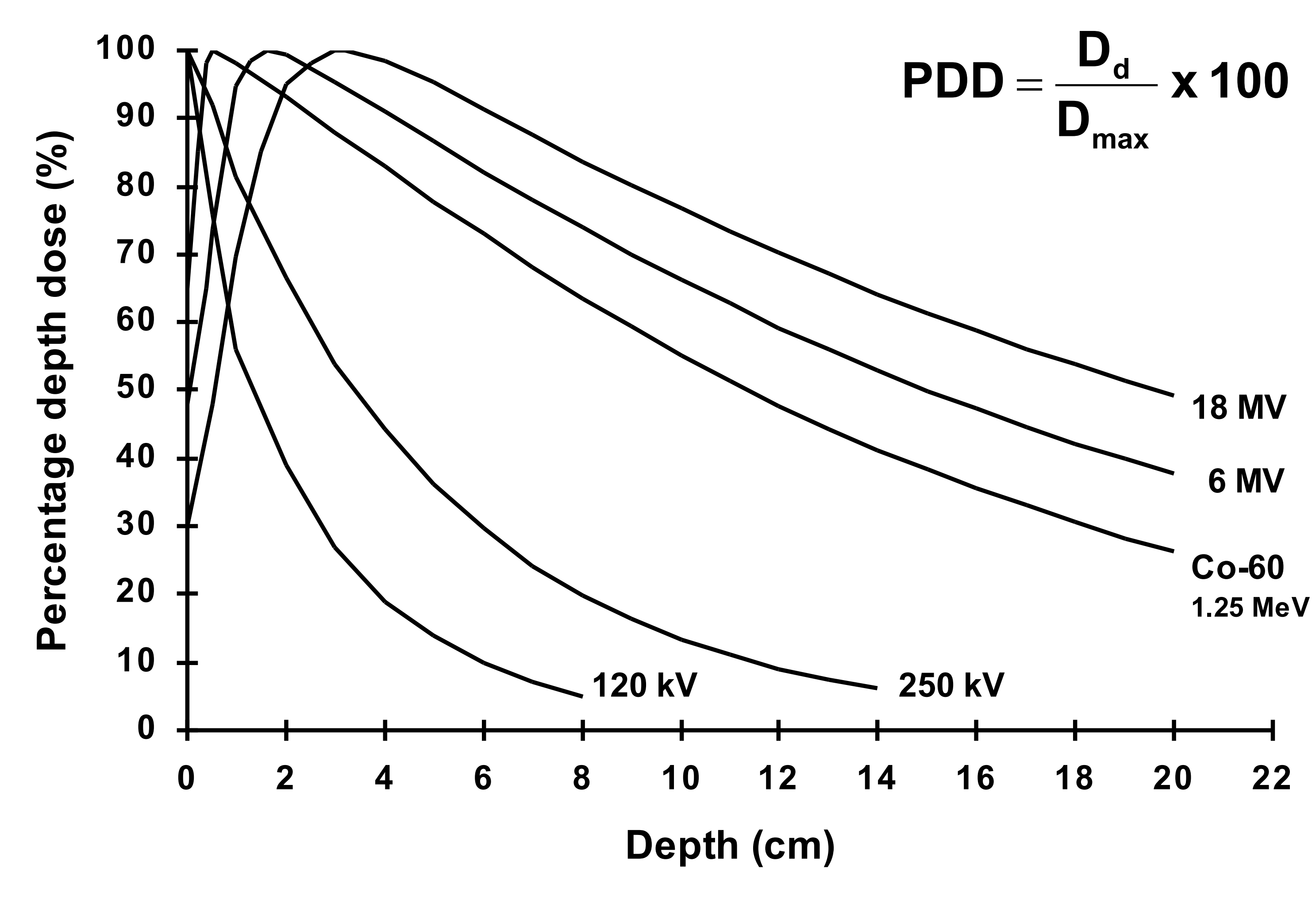
X-ray:



The X-rays are generated by a linear accelerator .

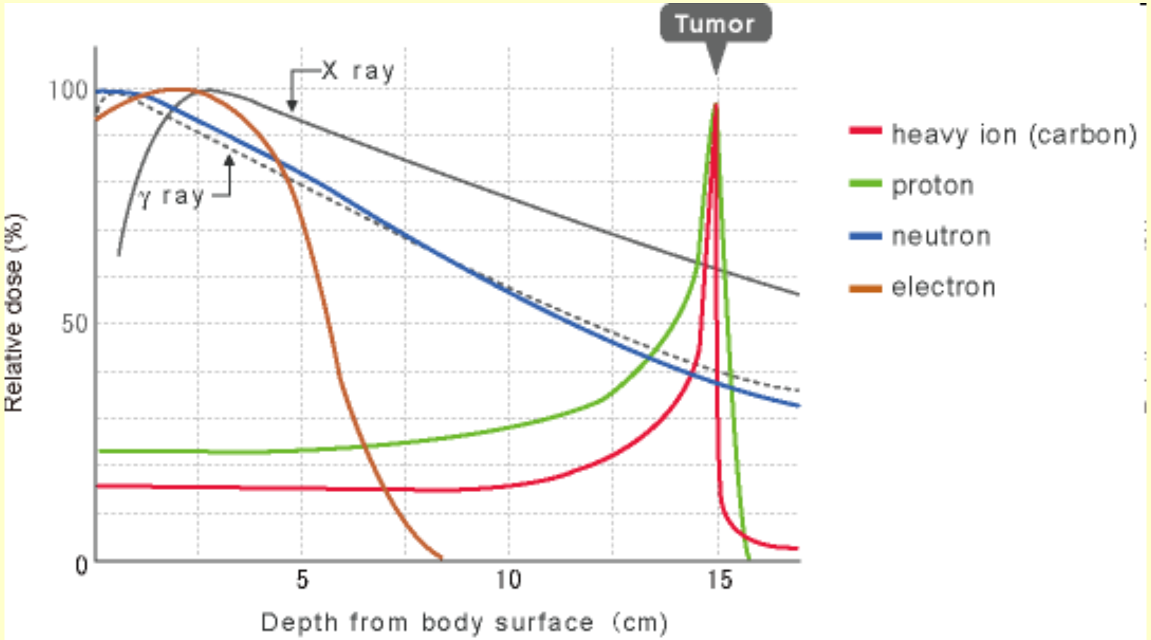
Few MeV photon energy.

Photon PDD (percentage depth dose) curves with different energies

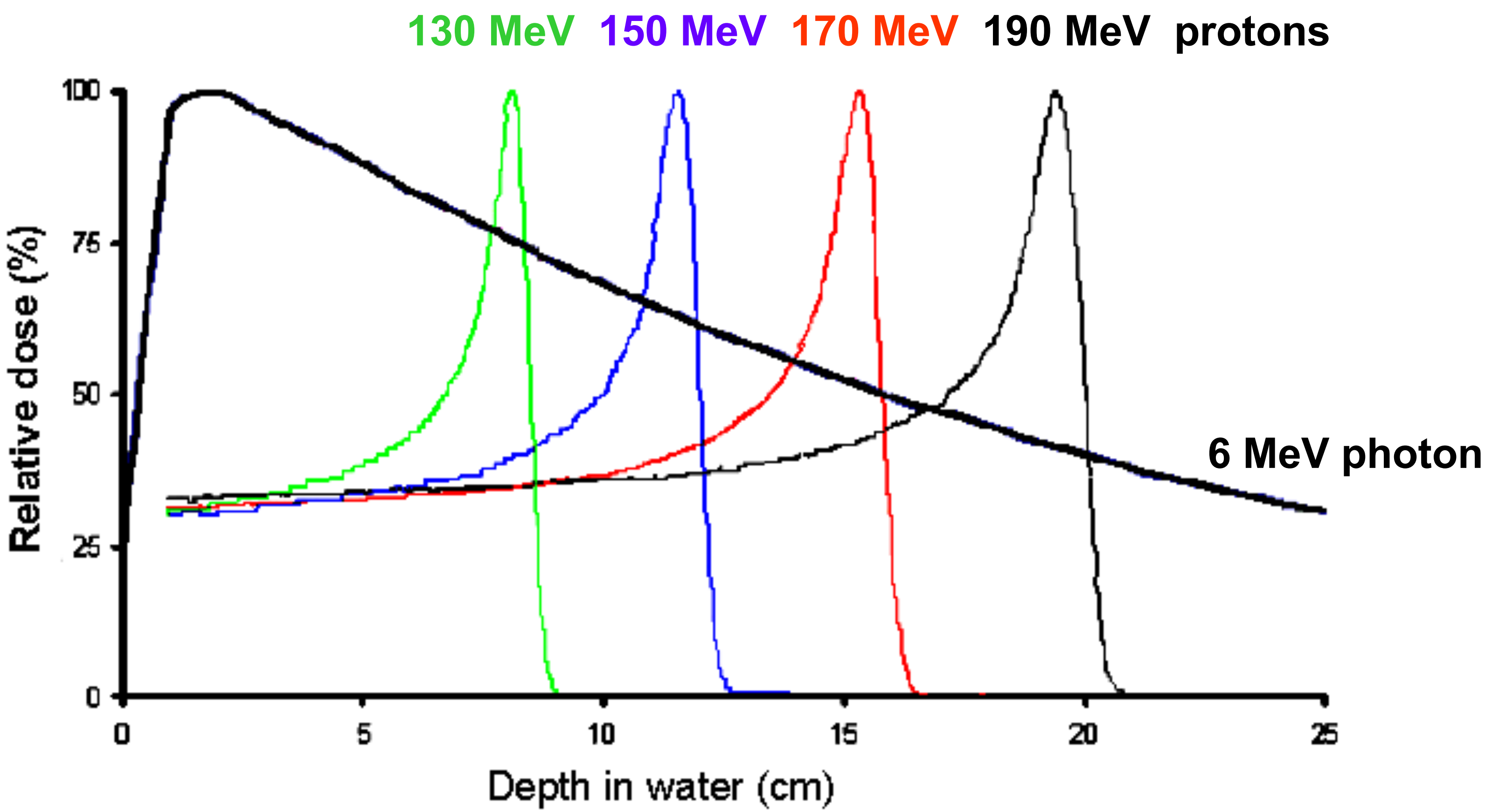


Would be ideal, but very expensive!

proton:

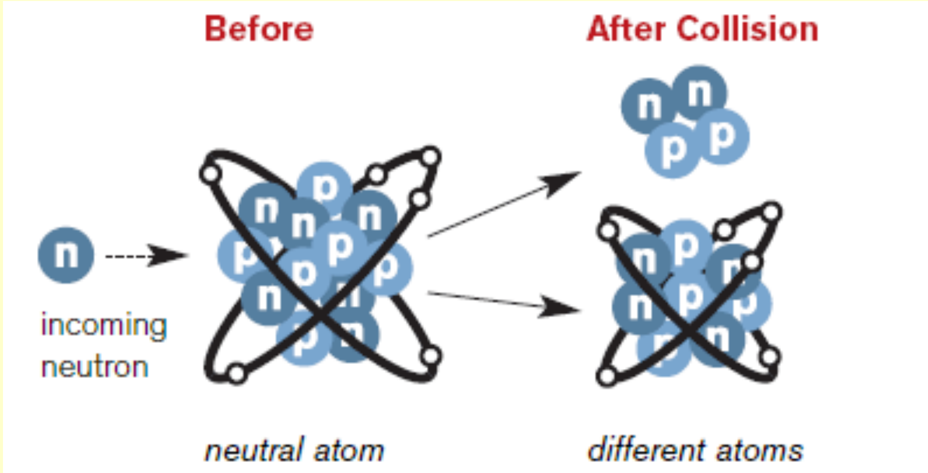


Comparison of photon and proton depth doses



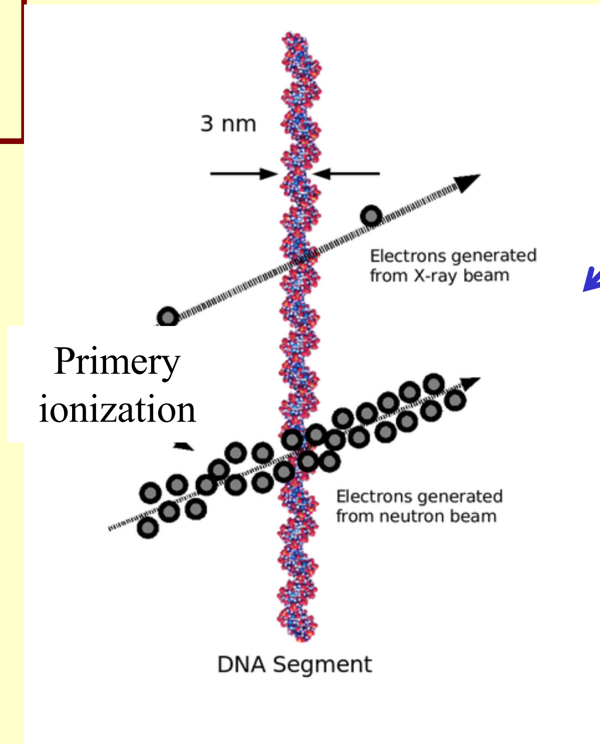
Neutron radiation: collision of high energy protons (66 MeV) into berillium target (p(66) +Be)

Neutrons induce nuclear reactions.



neutron:

High LET



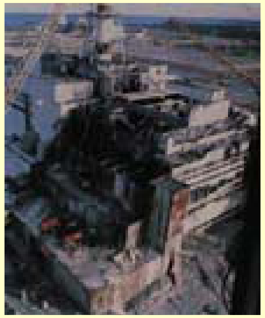
Estimated average of annual dose from natural background and man-made sources is 3.6 mSv.

environmental

occupation

military

nuclear industry



medical use

Distribution of annual dose among sources

^{238}U

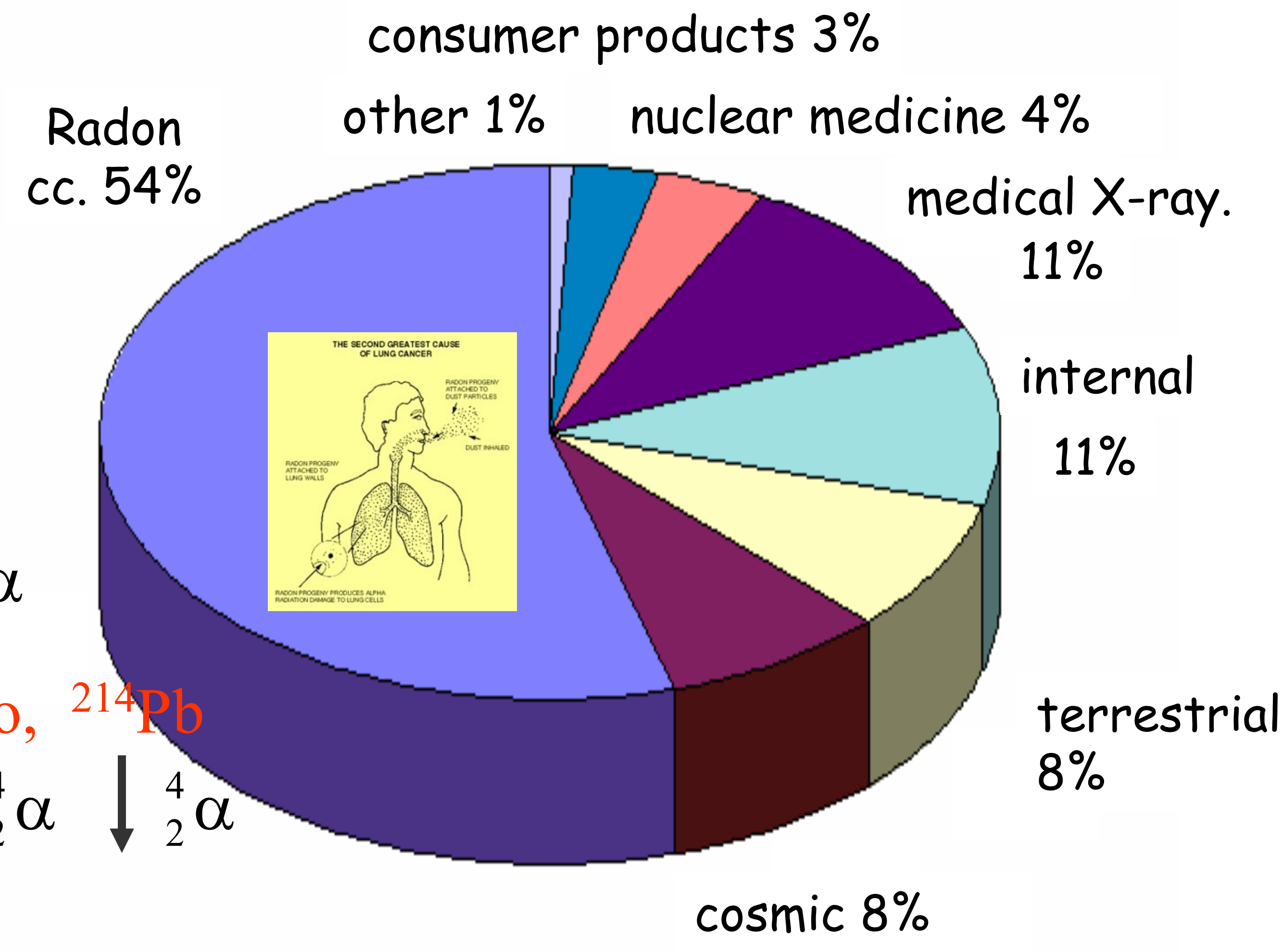
↓

^{222}Rn

↓ $^{4}_{2}\alpha$

^{232}Th, ^{218}Po, ^{214}Pb

↓ $^{4}_{2}\alpha$ ↓ $^{4}_{2}\alpha$



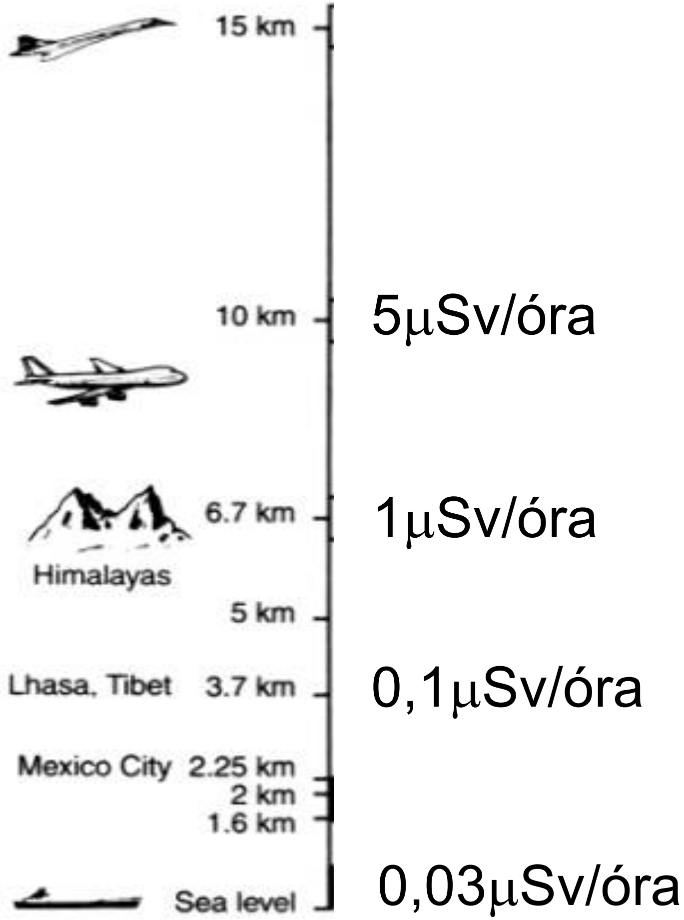
Sources of natural background

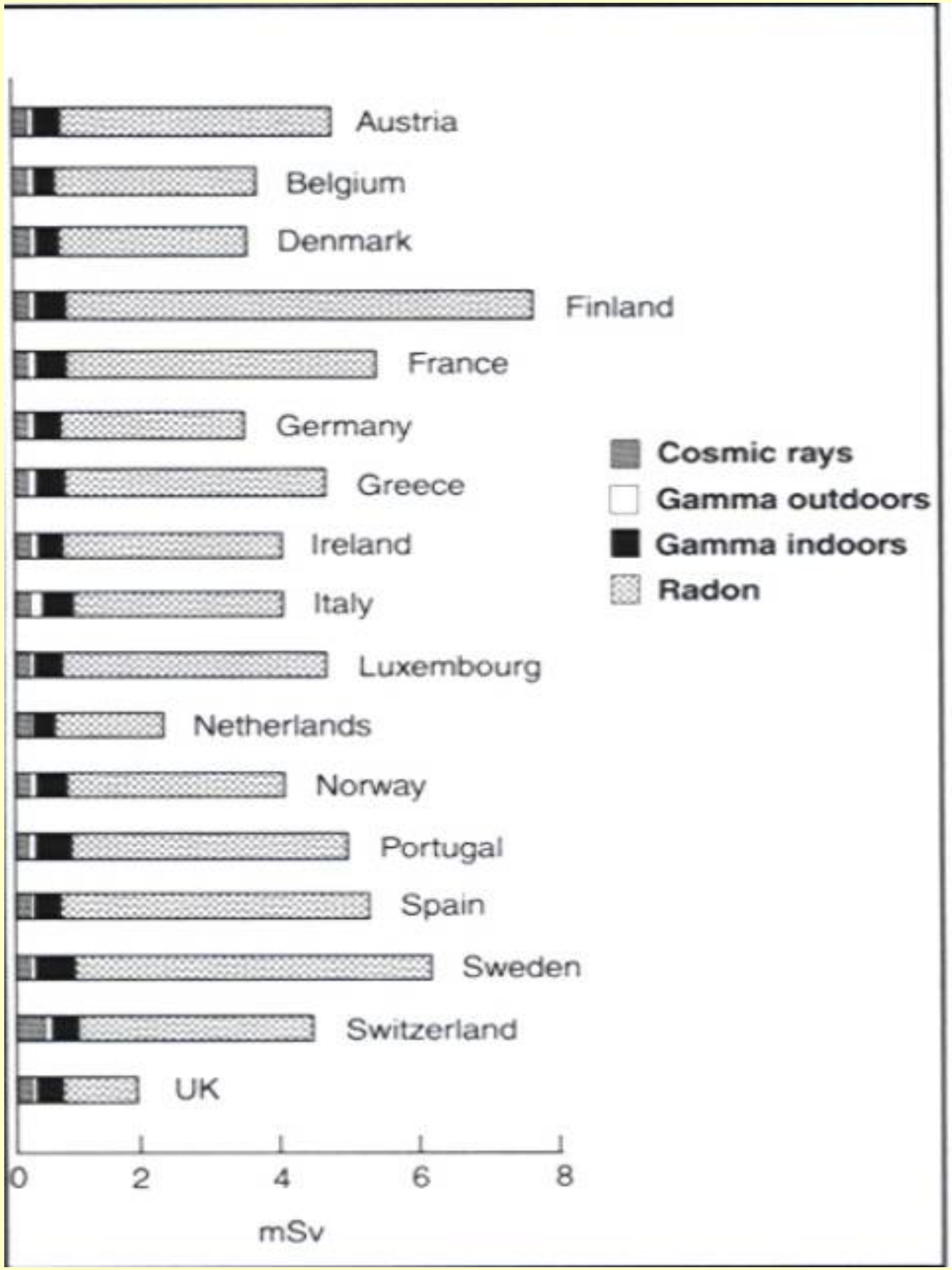
cosmic radiatiom
~ 0,4 mSv/year

radon: cc. 1,8 mSv/year

potassium: cc 0,1 mSv/year

Cosmic ray contributions to dose rate as the function of the altitude





Distribution of naturally occuring background levels of radiation in Europe

The highest known level of background radiation is in Kerala and Madras States in India where a population of over 100,000 people receive an annual dose rate which averages 13 millisieverts.

Risk – loss of life expectancy

Days of average life expectancy lost

Being unmarried male	3500
Smoking (pack/day)	2250
Being unmarried female	1600
Being a coal miner	1100
25% overweight	777
Alcohol abuse	365
Being a construction worker	227
Driving motorcycle	207
1 mSv/year effective dose for 70 years	10
Coffee	6

Radiation protection

Aims of radiation protection:

Prevention from deterministic effects (except in radiotherapy those that are intentionally produced)

Keeping the occupational risk of the users of the sources at the level of occupational risk of other professionals.

Keeping the public risk from ionising radiation sources at the level of public risk of other civilization related harms.

Radiation protection lies on the following ***principles:***

Optimization: All exposures should be kept As Low As Reasonable Achievable (ALARA)

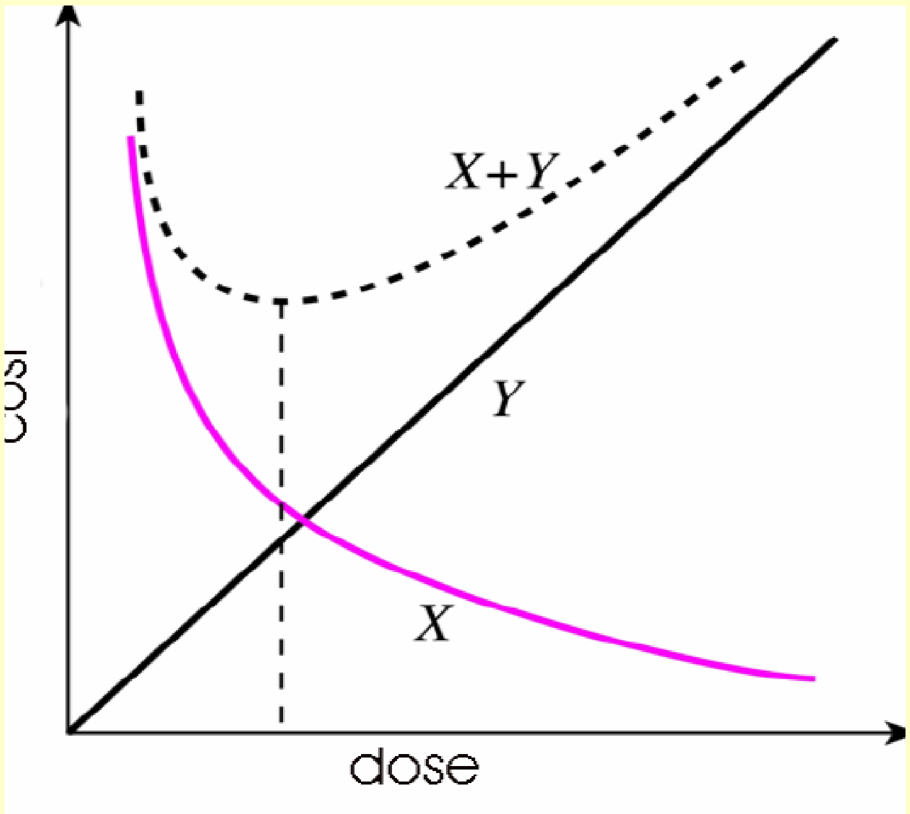
Justification: no practice shall be adapted unless it produces a positive net benefit

Limitation: the effective dose (E) to individuals shall not exceed the limits recommended by the ICRP (maximum permitted doses)

Optimization of radiation protection

ALARA-principle

As **L**ow **A**s **R**easonably **A**chievable



X : cost of radiation protection

Y : cost of treatment

X+Y: total cost

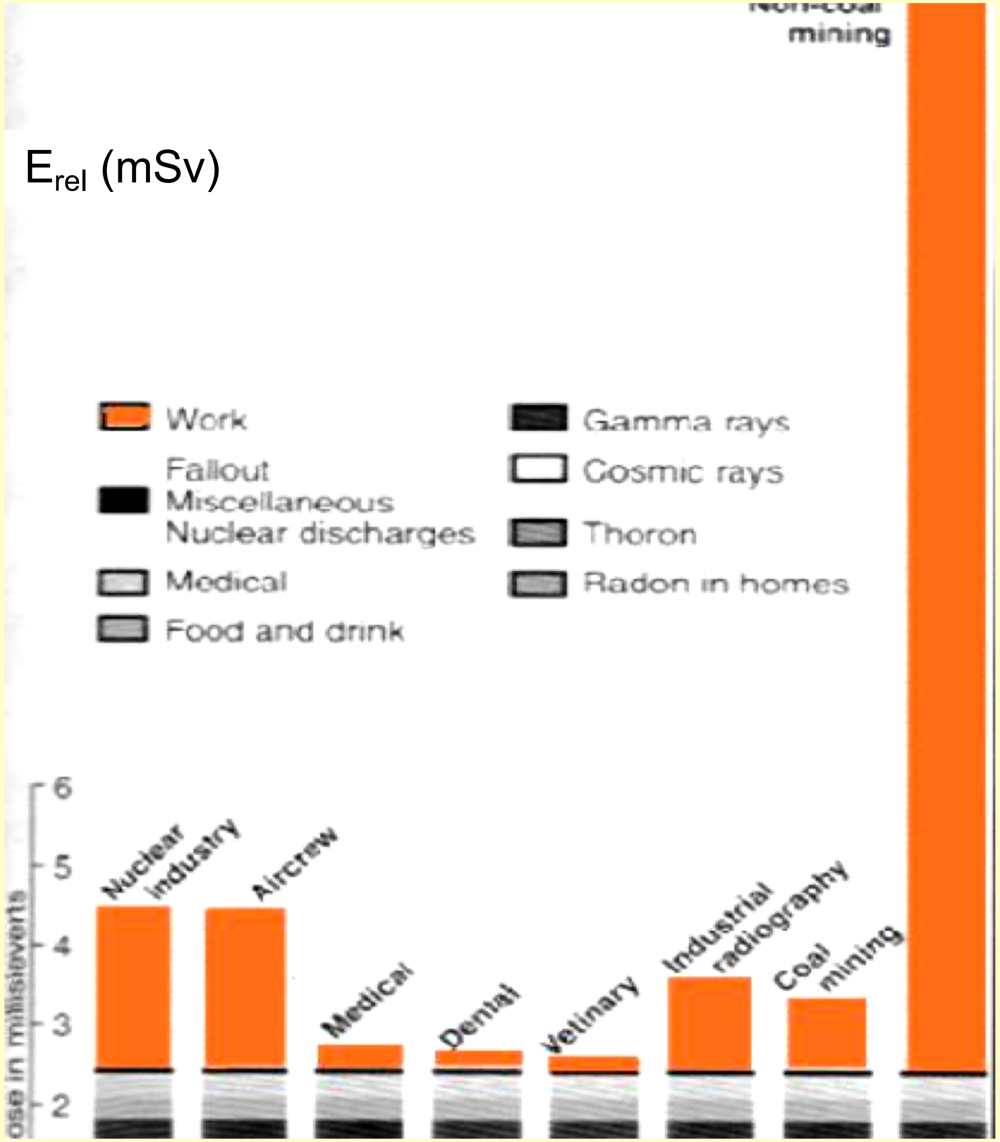
Optimum is the minimum

Dose limits in radiation protection

	Occupational (mSv/year)	Population (mSv/year)
Effective dose	20*	1
Dose equivalent (eye lens)	150	15
Dose equivalent (limb/skin)	500	50

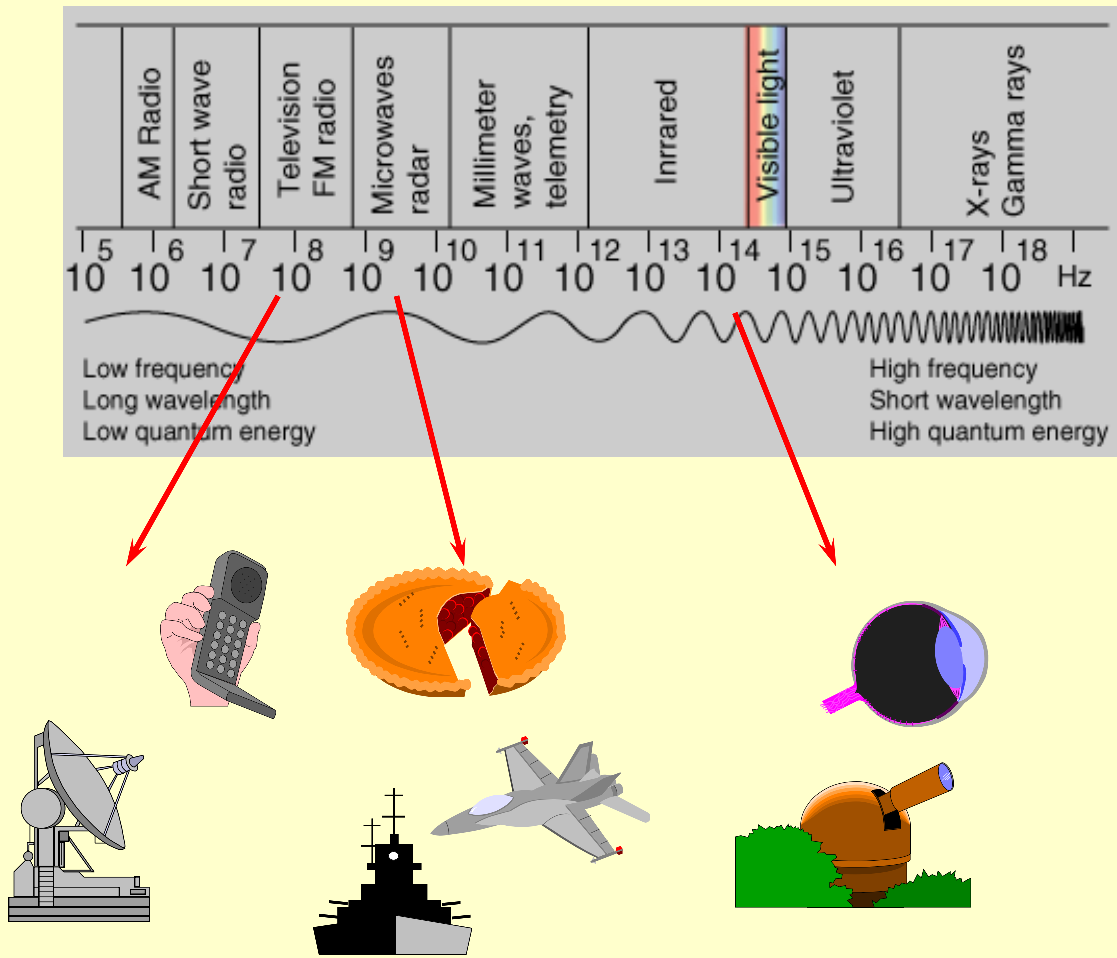
* Over the average of 5 years but maximum 50 mSv/year

Relative risk of various professions

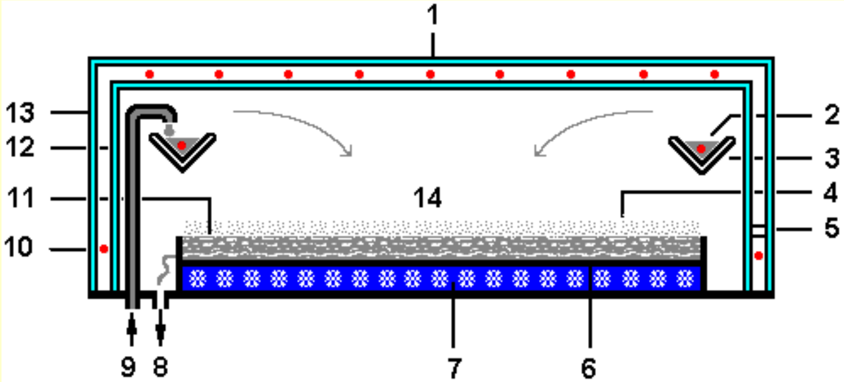


Detection of radiation – dose measurement

- What? α^{++} p^{+} (n) β γ ν
- How much energy?
- How much intensity?
- How good accuracy?



Detection of particles

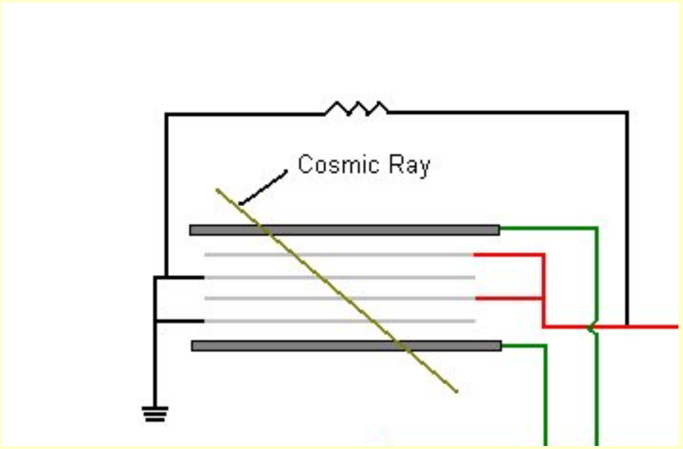


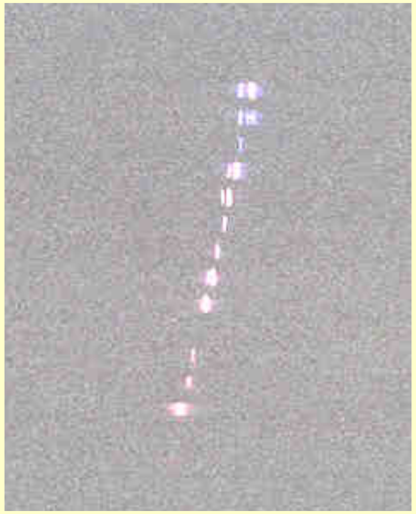
- **Cloud chamber**

  supersaturated vapor of water or alcohol

- **Spark chamber**

  high voltage wiers





- **Bubble chamber**
  - **superheated transparent liquid (H_2, Ar, Xe)**
  - **entire chamber is subject to a constant magnetic field**

Dose and dose rate measuring devices

*electronic detectors – absorbed energy generats free charges

gas-ionization detectors – prompt and/or delayed evaluation

scintillation detectors

semi-conductor detectors –

* Chemical detectors – based on radiochemical alterations

film – follow-up evaluation

* Solid materials – based on physical parameters of solid materials

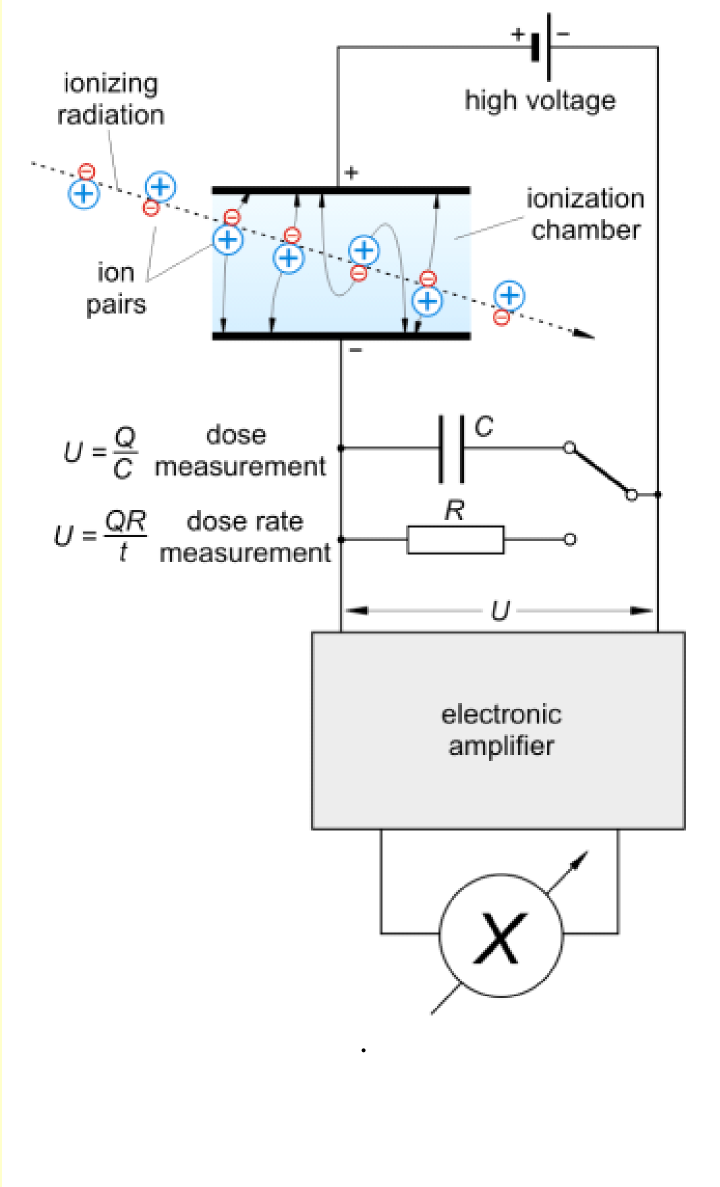
thermoluminescent detector – TLD (LiF, CaF_2, BeO, Al_2O_3)

Electronic Dosimeters

Ionization chambers

Dose measurement: the voltage U that is produced by collected charge Q on the capacitor C is proportional to the total amount of the separated charges.

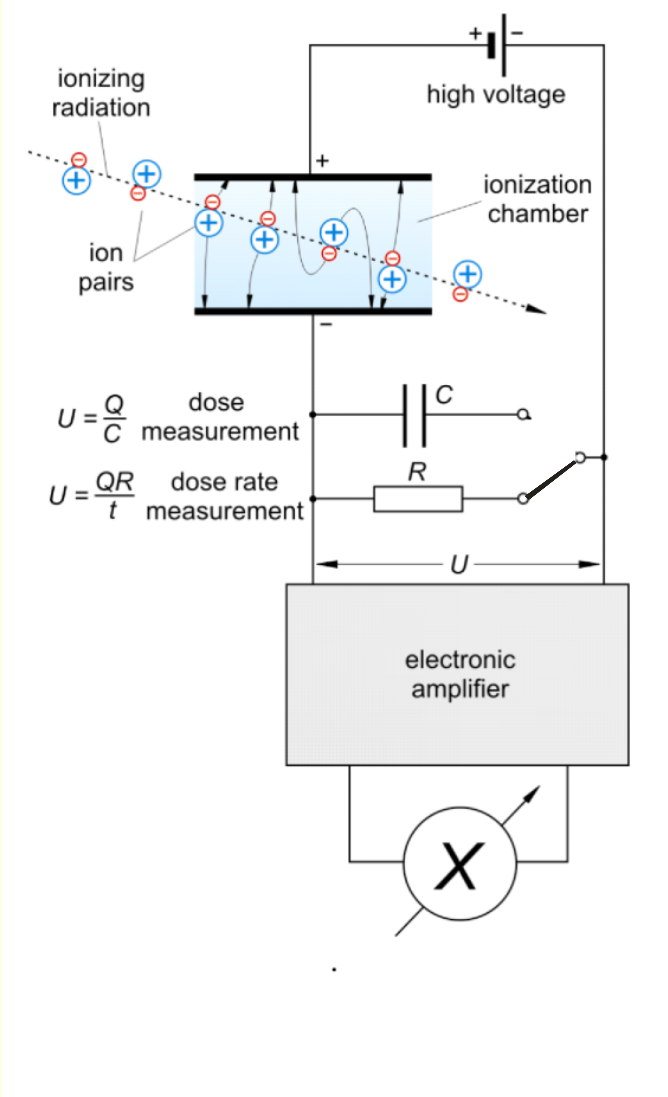
$$U = \frac{Q}{C} \sim X$$

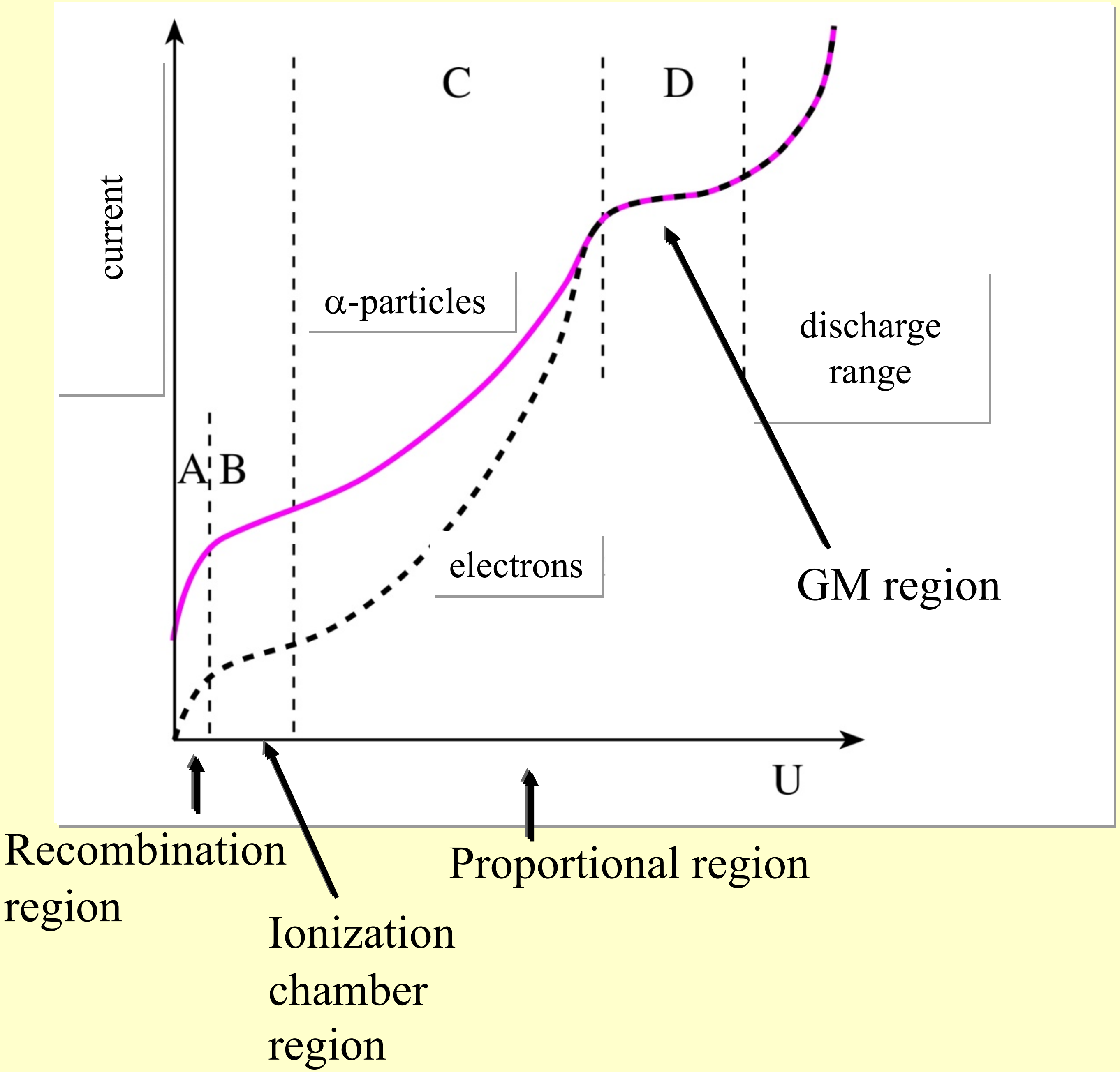


Ionization chambers

***Dose rate measurement**:* the potential drop is measured on a large resistance R , that is proportional to the charge Q that flows through at unit time.

$$U = \frac{QR}{t} \sim \frac{X}{t}$$





The dependence
of
ionization
on voltage

Ionization chambers– Geiger-Müller counter

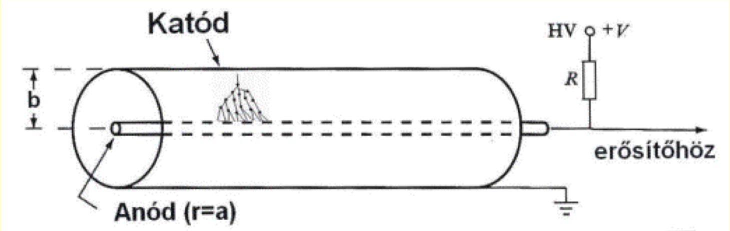
- Inert gas filling
- High accelerating voltage

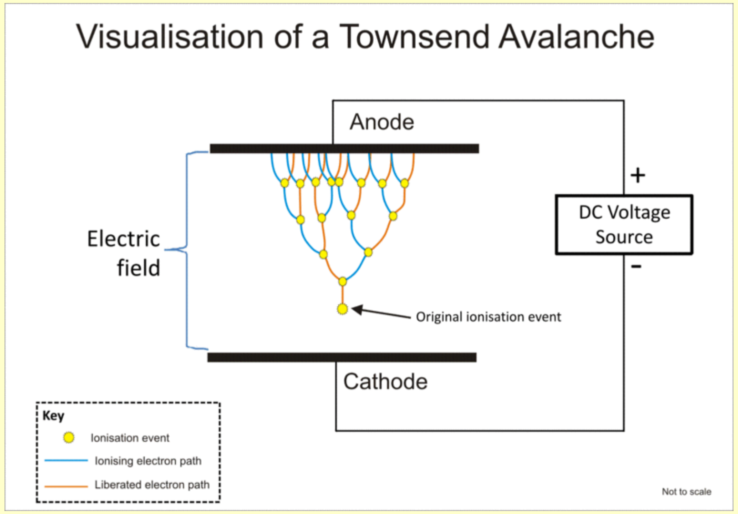
↓

Avalanche effect between electrods

↓

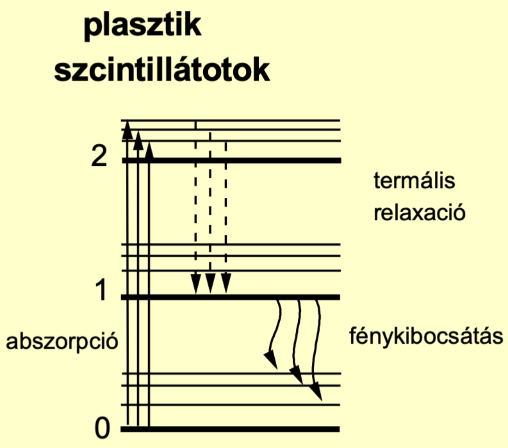
Current pulse

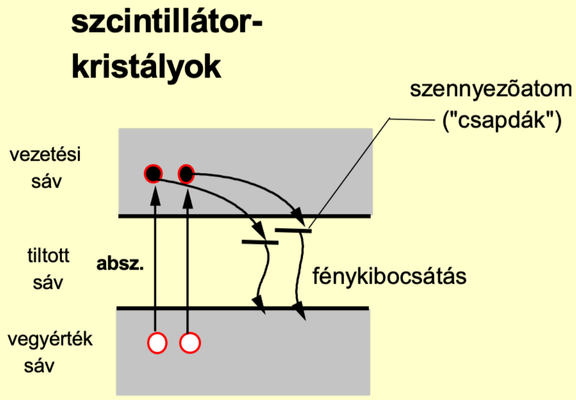




Number of current pulses ~ number of ionising particles

Scintillation detectors



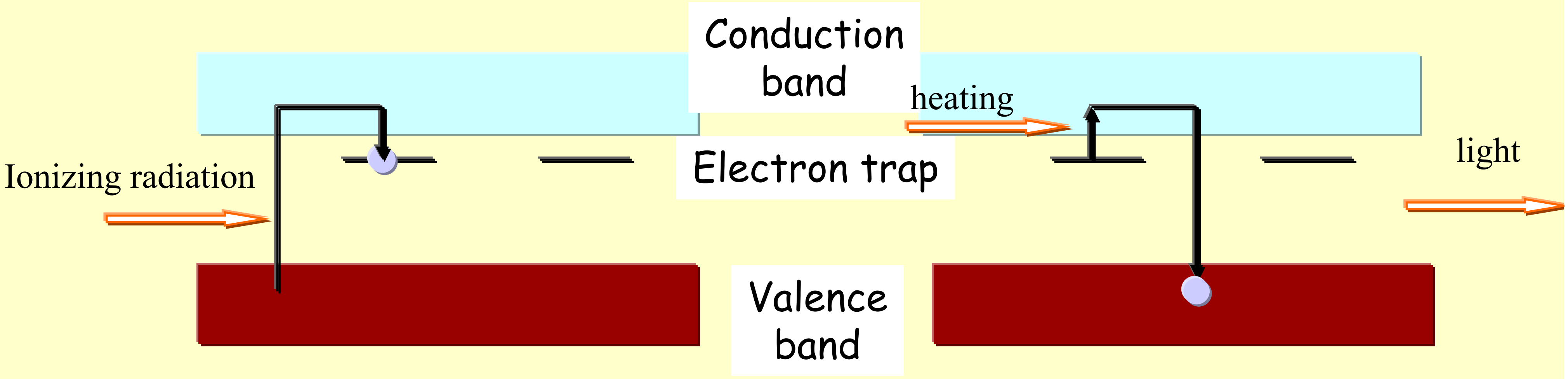


- Liquid scintillator
  - Solution of fluorescent compounds
  - Primary excitation of solvent and follow-up excitation of diluted compound
  - Light emission
- Plastic scintillator
  - Solid materials
- Inorganic crystals
  - Primary excitation of crystal, follow-up excitation of luminescent atoms

Solid phase detectors

Thermoluminescent dosimeter

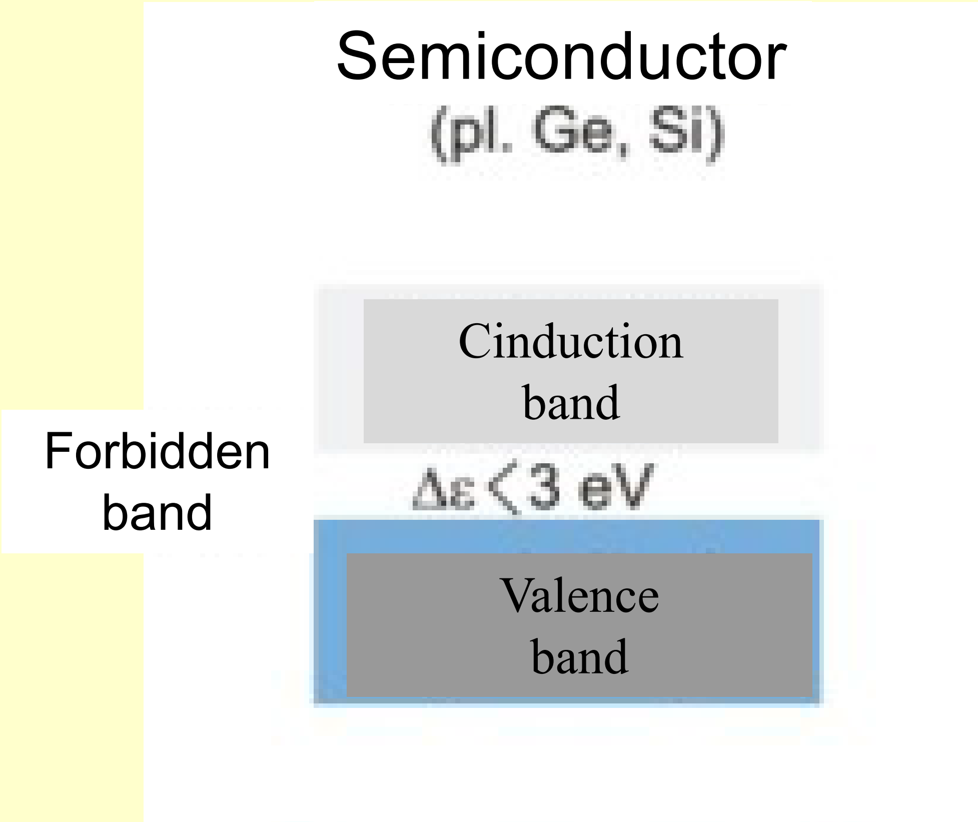
Band structure on electronic transitions



exposition

evaluation

Semiconductor detectors



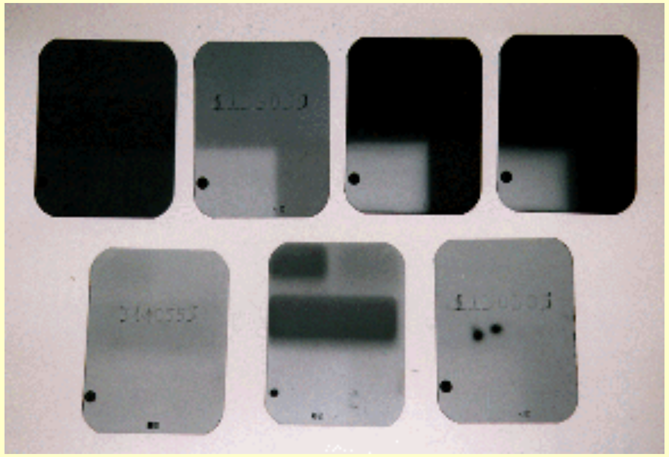
$$\frac{n}{n_0} = e^{-\frac{\Delta\varepsilon}{kT}}$$

$$\sigma \approx e^{-\frac{\Delta\varepsilon}{2kT}}$$

Conductivity ~ number of excitations

Film badges

It measures darkening of the developed photographic film that was exposed to ionizing radiation.



Darkening of the developed photographic film is proportional to the dose rate of the ionizing radiation and to the irradiation time.

Damjanovich, Fidy, Szöllősi „Medical Biophysics”:

II. 4.

- 4.1
- 4.2
- 4.3
- 4.4
- 4.5

IX.3.

Kellermayer „Medical Biophysics Practices”: Dosimetry