Biophysics II

Dosimetry of ionizing radiations

Liliom, Károly
07-03-2025

liliom.karoly@semmelweis.hu
karoly.liliom.mta@gmail.com

Radiation = spreading of energy

energy > ionization energy:

ionizing radiation

Ionizing radiations

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 which generate secondary electrons (ionize further).
(γ and X-ray photons, neutrons)

Tasks for dosimetry

Definition of quantities

↓

Design of measuring techniques

↓

Estimation of consequences

Estimation of health risk for prevention.

Estimation of biological damages.

Design of therapeutic procedures.

Dose values should be

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

Dose concepts

Physical dose concepts:
Absorbed dose,
Exposure

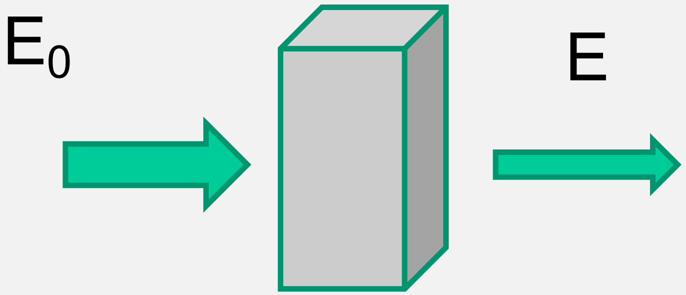
Biological dose concepts:
Equivalent dose,
Effective dose

Derived dose concepts:
Collective dose,
Dose rate

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

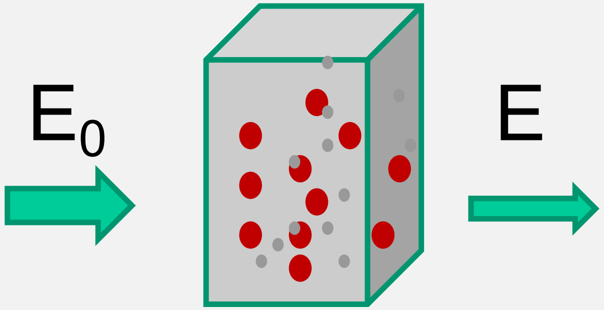
$$\textit{Unit:} \quad [J / kg] \equiv Gy$$

Louis Harold Gray
(1905-1965)

But how to measure it!

Exposure

measures the amount of positive charges generated by the radiation in a unit mass in air



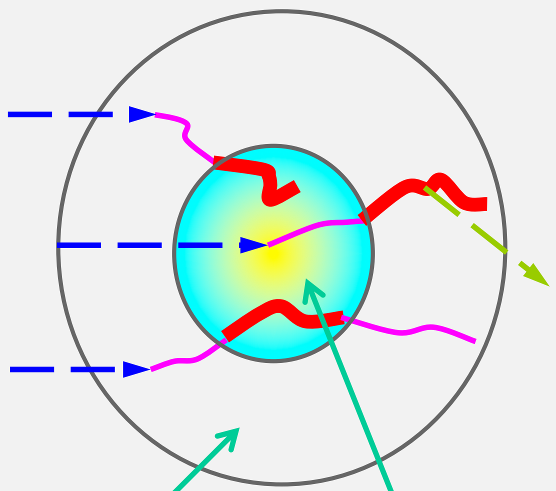
$$X = \frac{\Delta Q}{\Delta m} [C / kg]$$

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

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

ΔQ are the 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

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

$$\mathrm{D_{air}} = \mathrm{f_0 X}$$

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

↑

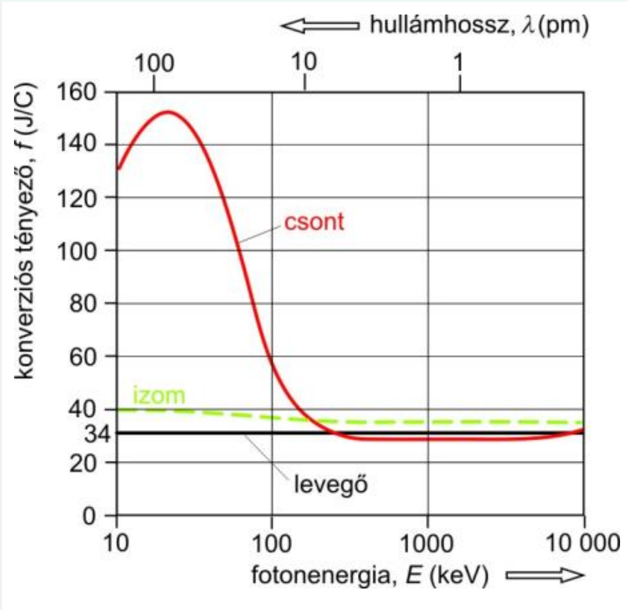
~ 34 J/C

↑

Average ionization energy in air ~ 34 eV

Absorbed dose in tissues

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 types of radiation is different.

$$H_T = w_R * D_T$$

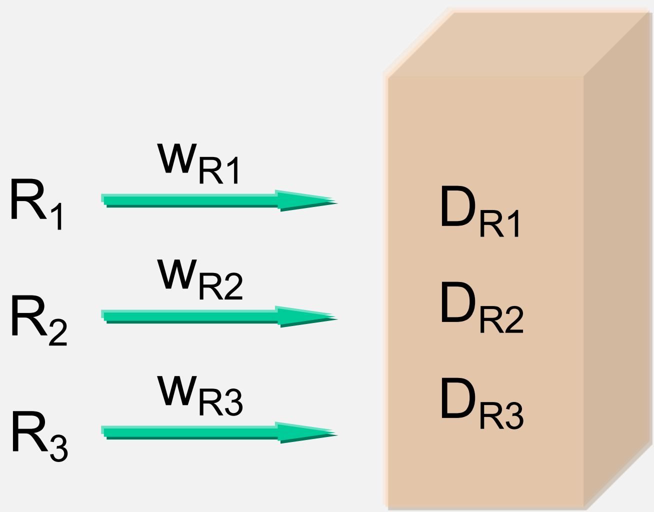
Radiation weighting factor – estimation of the relative efficiency of the given ionizing radiation compared to photons

Absorbed dose in tissue

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

Unit of H: [J/kg] = Sievert (Sv)

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)***

$$E = \sum_T w_T H_T \qquad \sum_T w_T = 1$$

tissue	W_T	tissue	W_T
gonads	0,12	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

$$E = \sum_T w_T H_T$$

$$\sum_T w_T = 1$$

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.

Tissue weighting factor values are re-estimated by ICRP (International Commission on Radiological Protection) as more experimental results are accumulating.

Dose rate

Received dose over time.

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

Collective dose

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

$$S = \sum_i N_i E_i$$

Types of damages

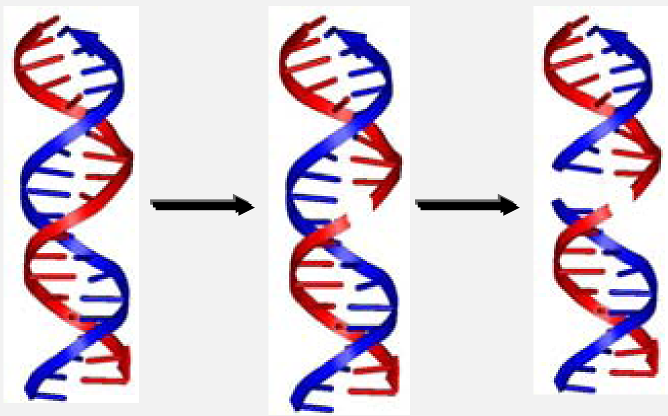
Stochastic damages

Deterministic damages

Chemical reactions – Direct effect

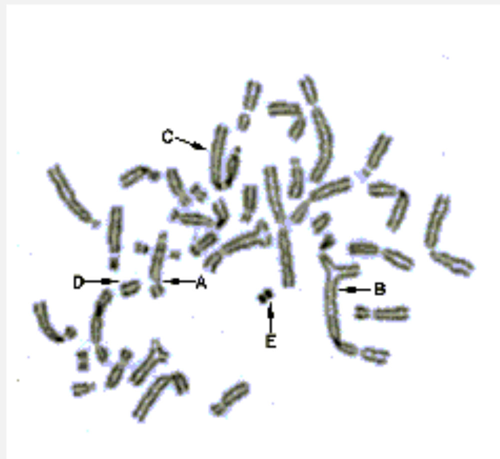
Direct ionization damage of the macromolecules

DNA damage is the most important!



single double

strand breaks



chromosome aberrations

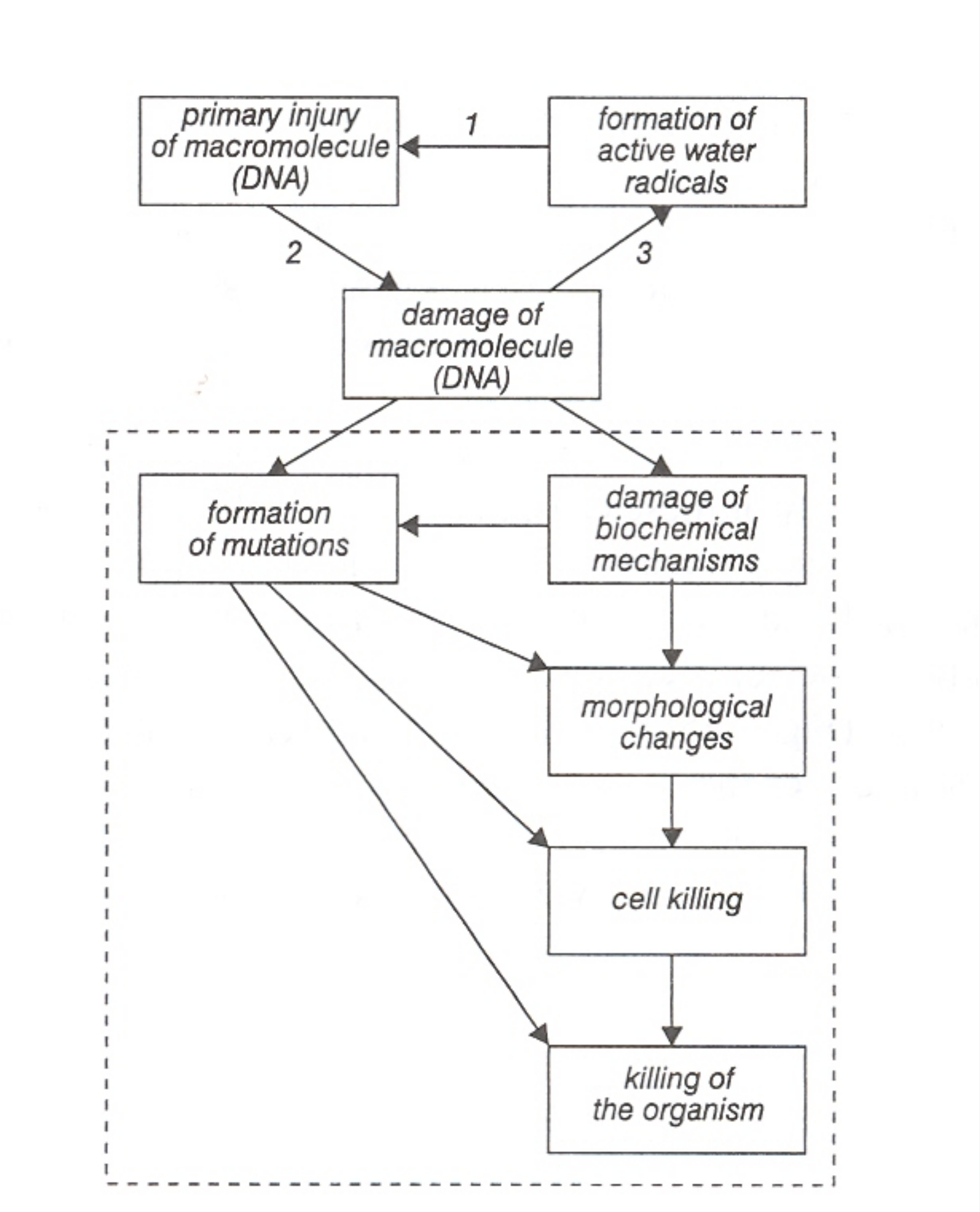
Chemical reactions – Indirect effect

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.

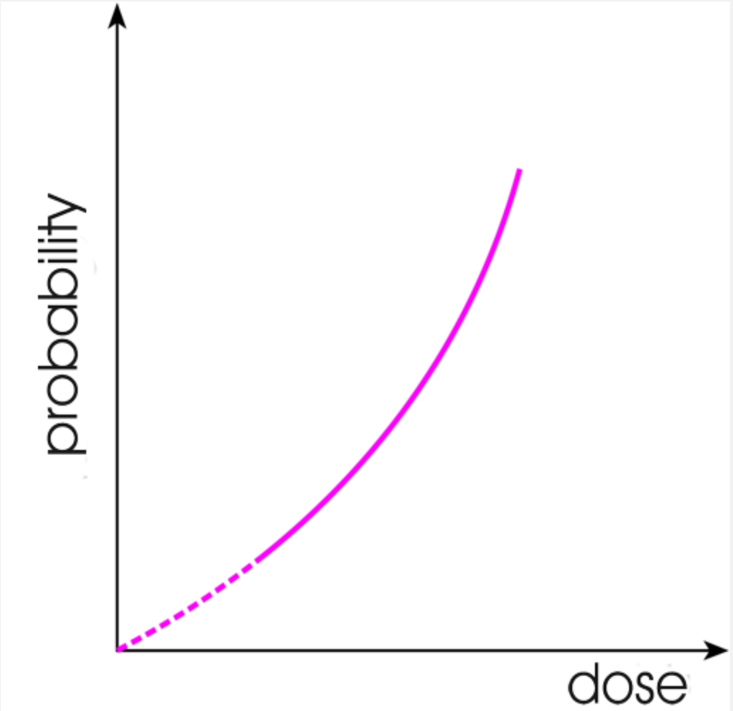
Biological consequences



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 transformations

Stochastic damages



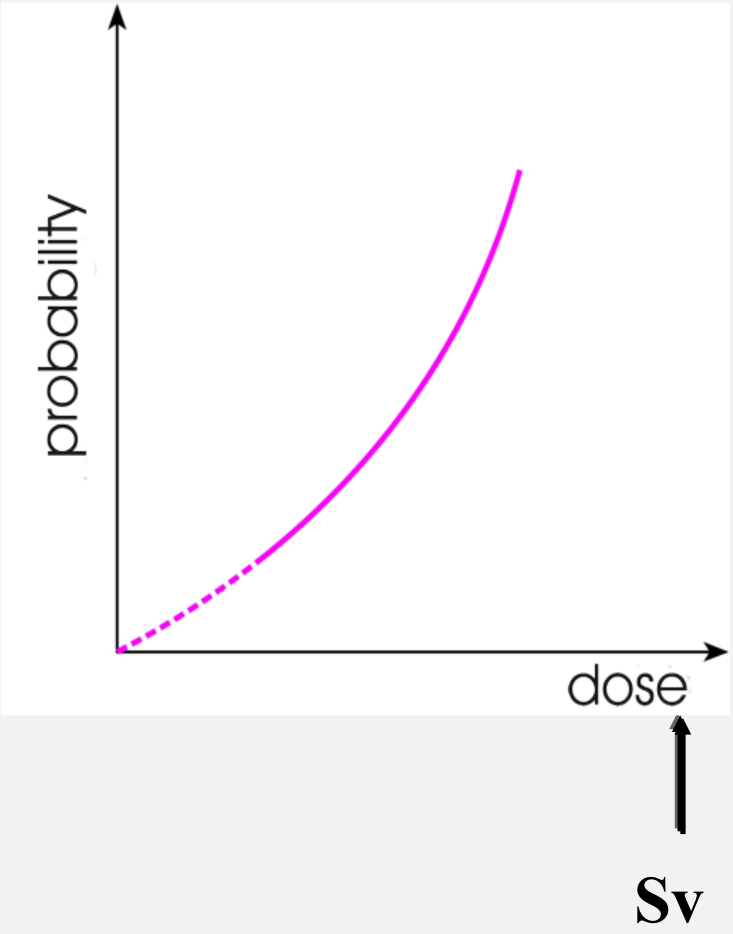
The probability of stochastic damage depends on the dose.

Severity (e.g. cancer) is independent of the dose.
(e.g. not known)

Delayed biological effects.
(tumors, heriditary diseases)

NO threshold!

Stochastic damages



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

Stochastic damages

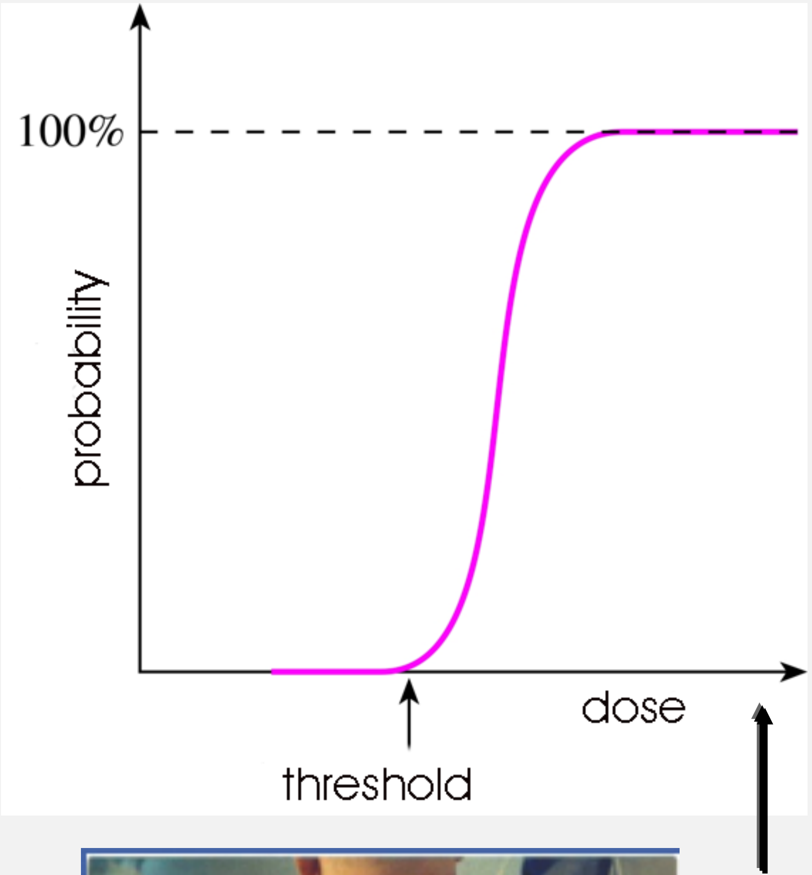
Irradiated cell is modified rather than killed.

Severity is not directly affected by the dose.

With increasing dose the probability of a damage increases.

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

Deterministic damages



Gy

A threshold dose exists.

Above threshold severity depends on the dose.

Appear soon after exposition.
(erythema, epilation, cataract)

Typical for high dose of one type.

Must not be induced during diagnostic procedures.

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)

**1% lethality at 60 days after exposition*

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?

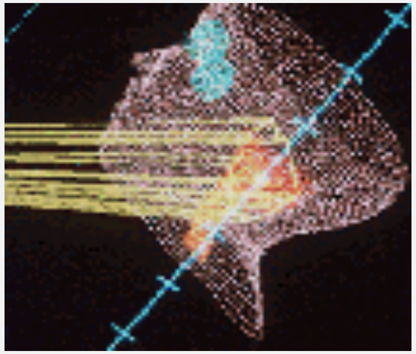
Radiotherapy

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.

Approaches

- **Palliative radiotherapy** to reduce pain and address acute symptoms – e.g. bone metastasis, spinal cord compression
- **Radical radiotherapy** as primary modality for cure – e.g. head and neck tumors
- **Adjuvant treatment** in conjunction with surgery – e.g. breast cancer




Ionizing radiations 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

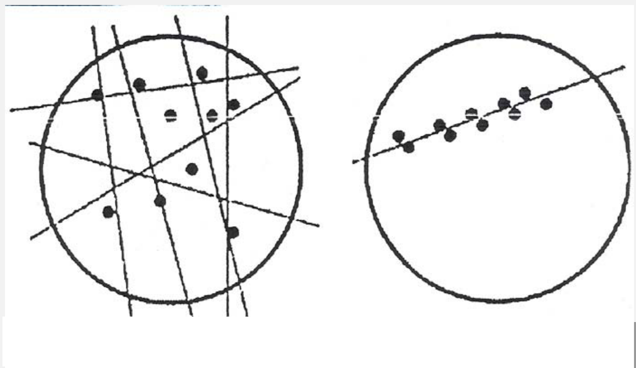
Heavy ions – limited use

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
γ, rtg

High LET
α, proton

Typical LET values

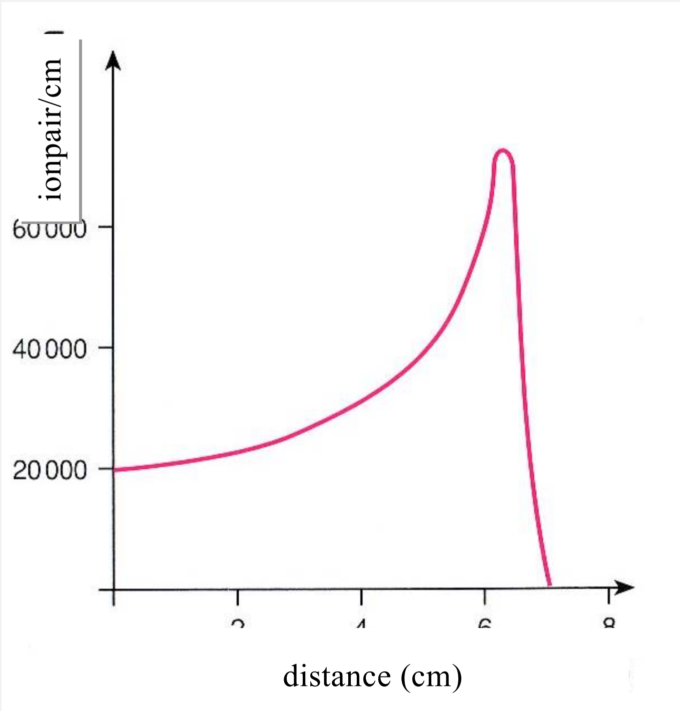
LET	Radiation	Energy(MeV):	LET(keV/µm):
high	α – particles	5.0	90
	fast neutrons	6.2	21
	protons	2.0	17
low	X-rays	0.2	2.5
	^{60}Co γ–radiation	1.25	0.3
	β – particles	2.0	0.3
	accelerated electrons	10.0	

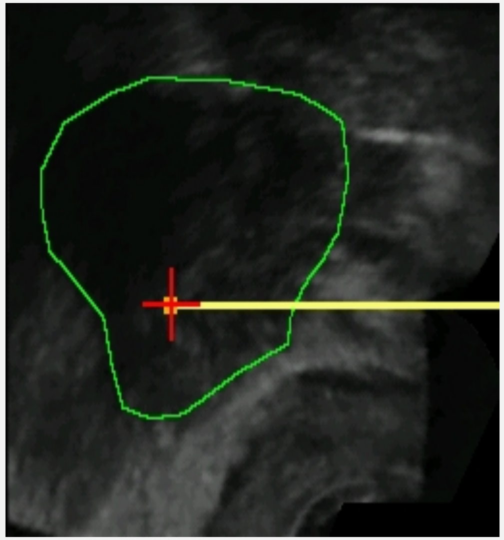
α particles

Internally deposited radioactivity

=

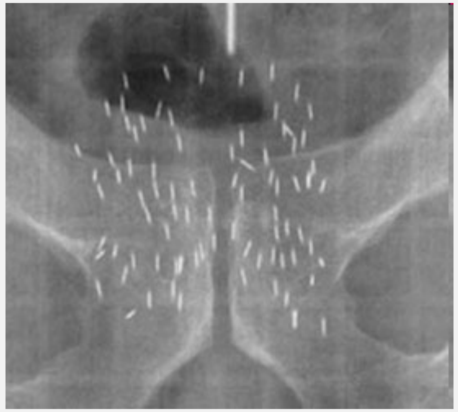
Brachytherapy





β^-

Internally seeded radioactivity



Particle energy is not optimal

continuous energy spectrum

typical energy: few MeV

e^-

accelerated electrons - 10-20 MeV

production: linear accelerator

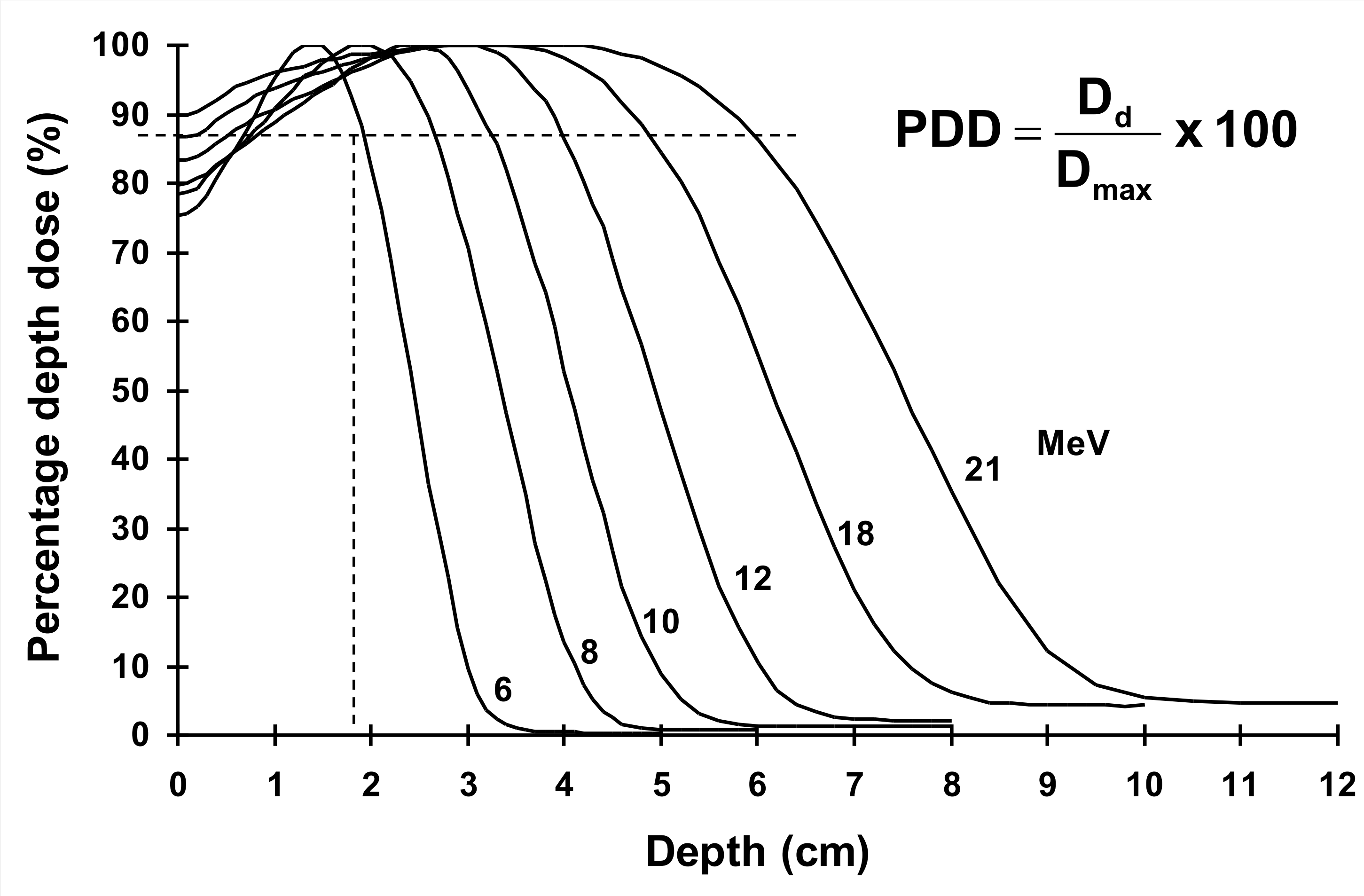
Efficient distance! ≈1cm/3MeV

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

treatment of superficial tumors

Electron PDD (percentage depth dose) curves with different energies

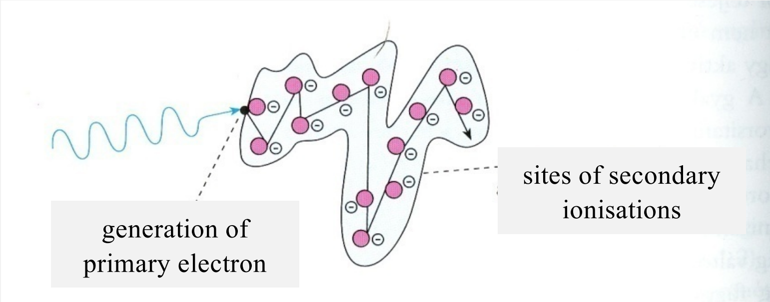
Reduced skin-sparing effect



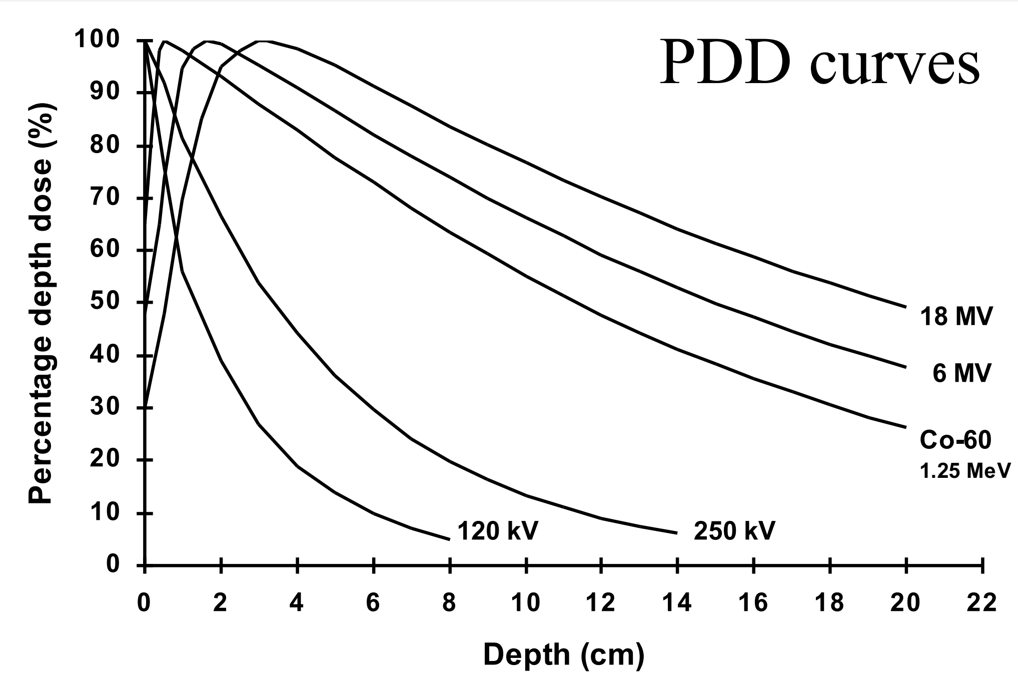
<u>Conclusion:</u> only superficial tumors can be treated with electron beams

γ

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



Penetration distance is energy dependent

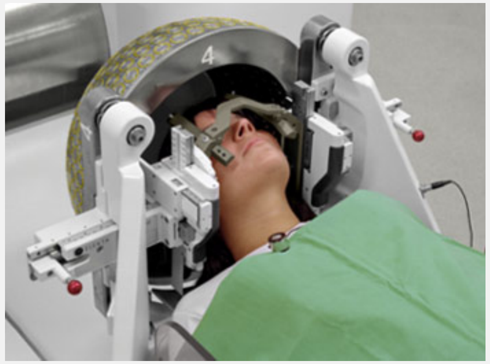


γ

γ-knife: focused dose of radiation –
about 200 portals in a specifically designed helmet

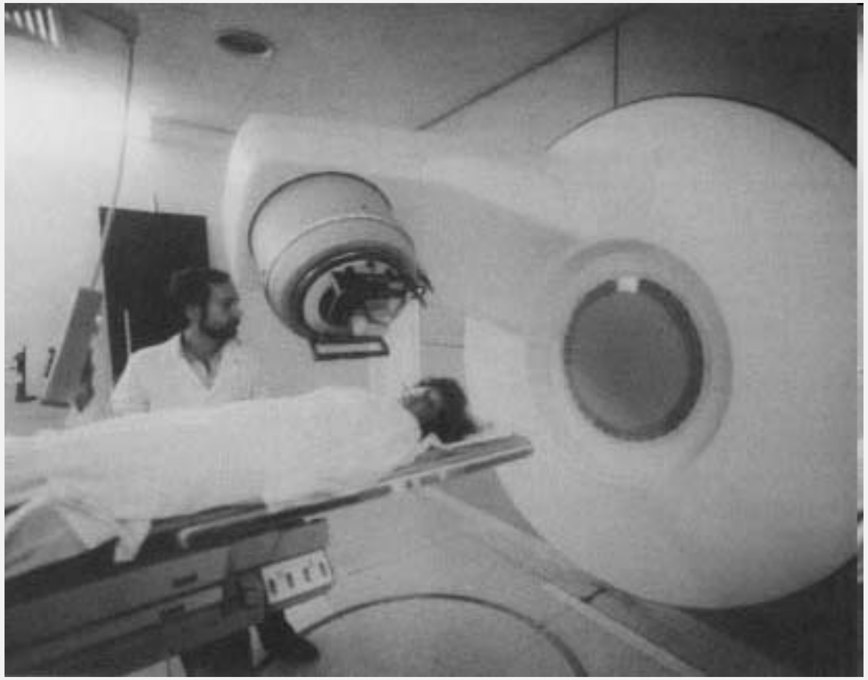
^{60}Co Eγ =1.25 MeV, about TBq activity

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



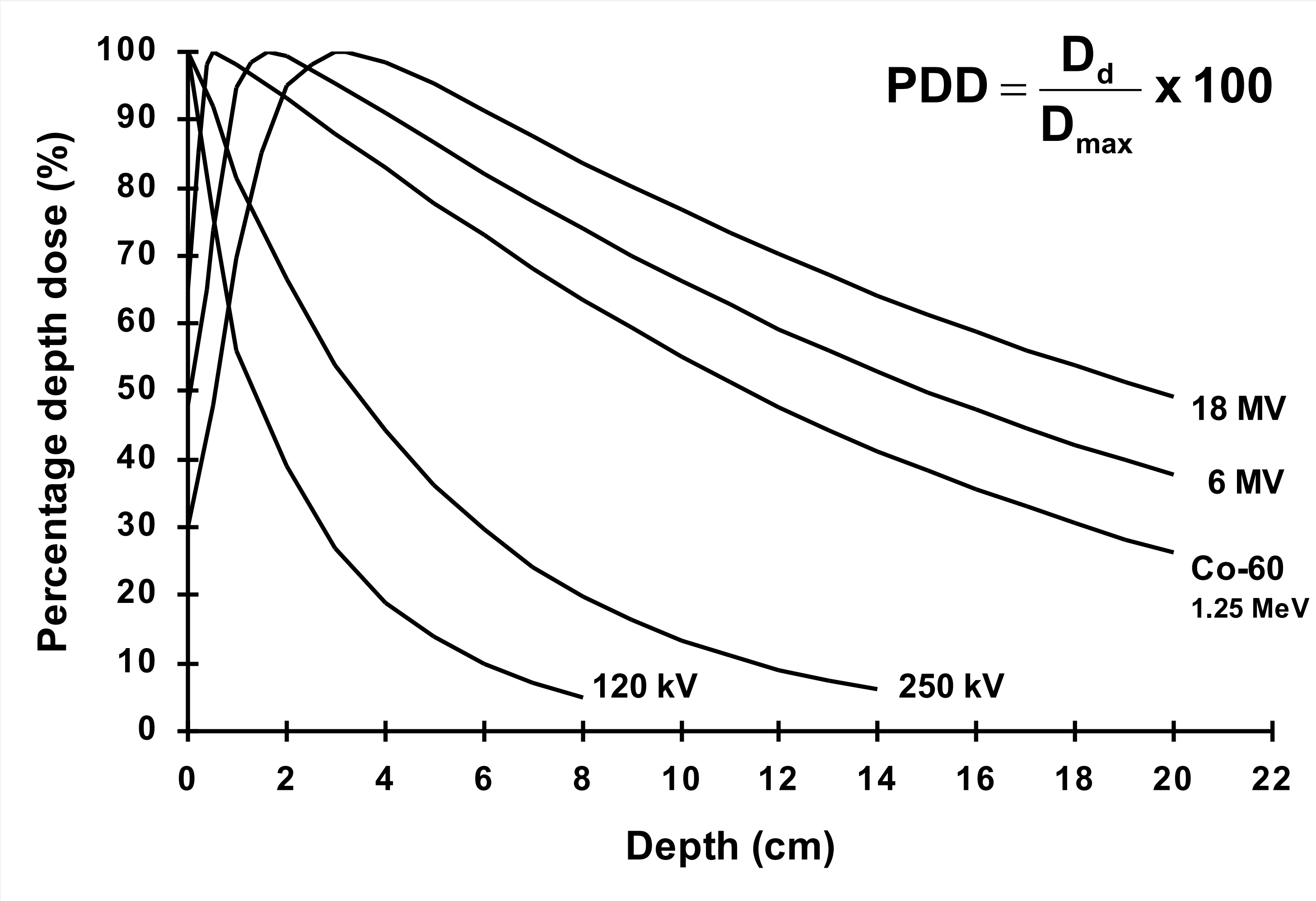
Treat tumors and lesions in the brain

X-ray



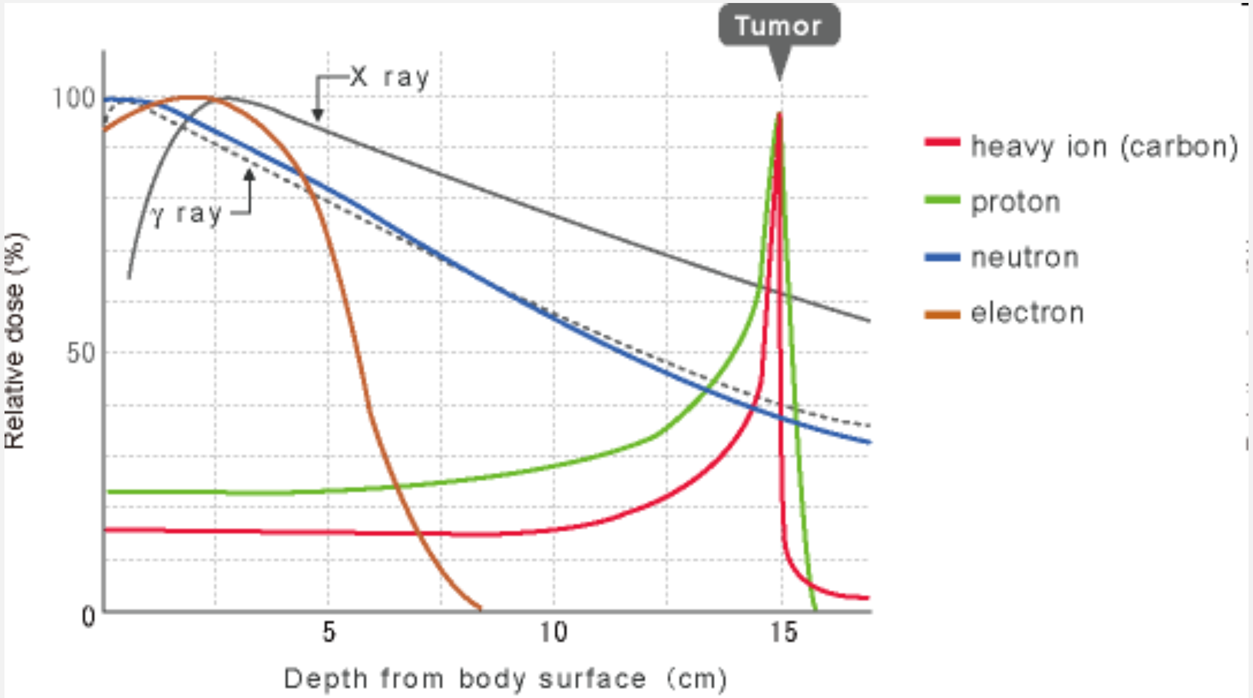
The X-rays are generated by a linear accelerator with a few MeV photon energy.

Photon PDD (percentage depth dose) curves with different energies

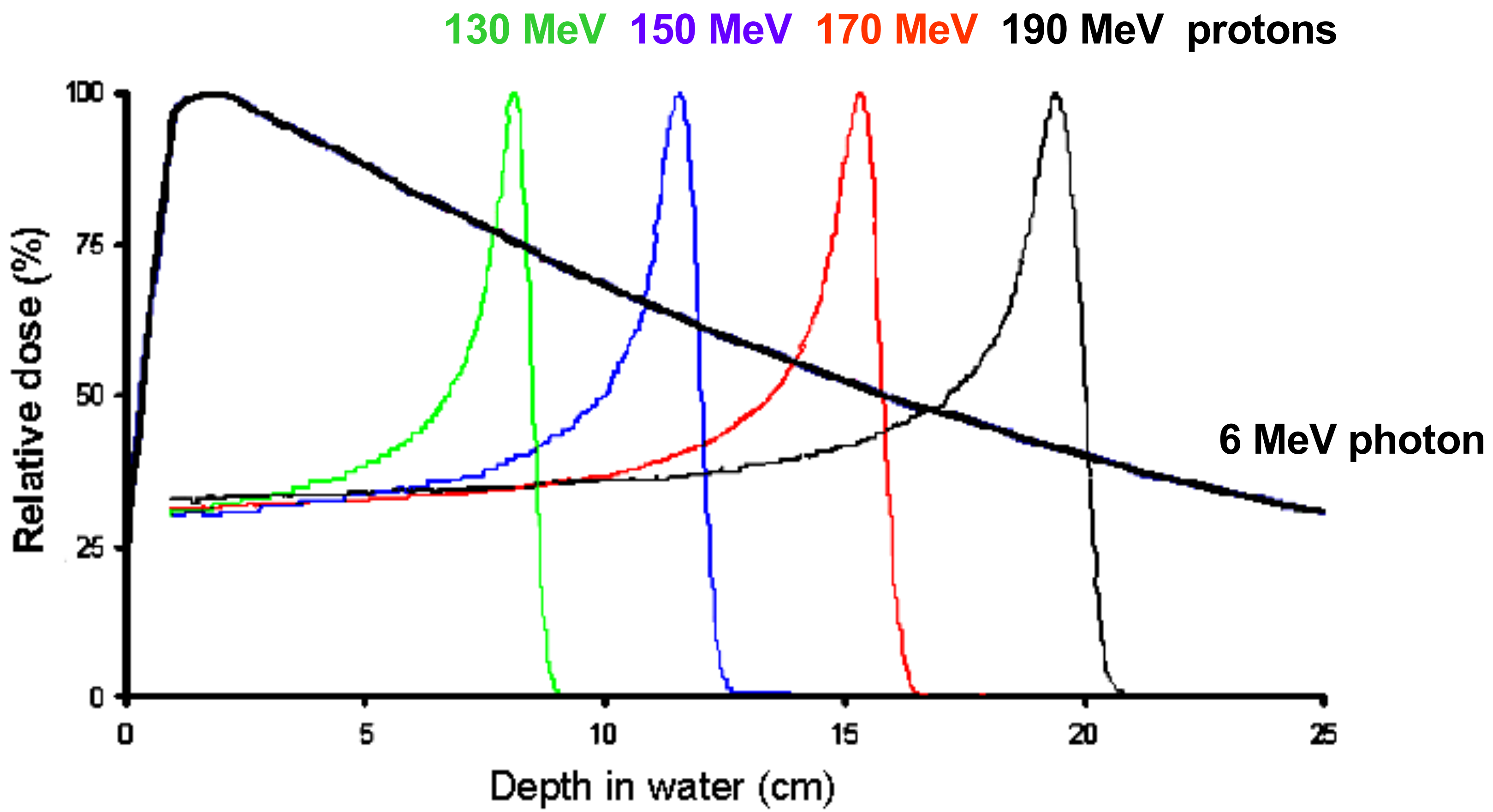


proton

Would be ideal,
but expensive!

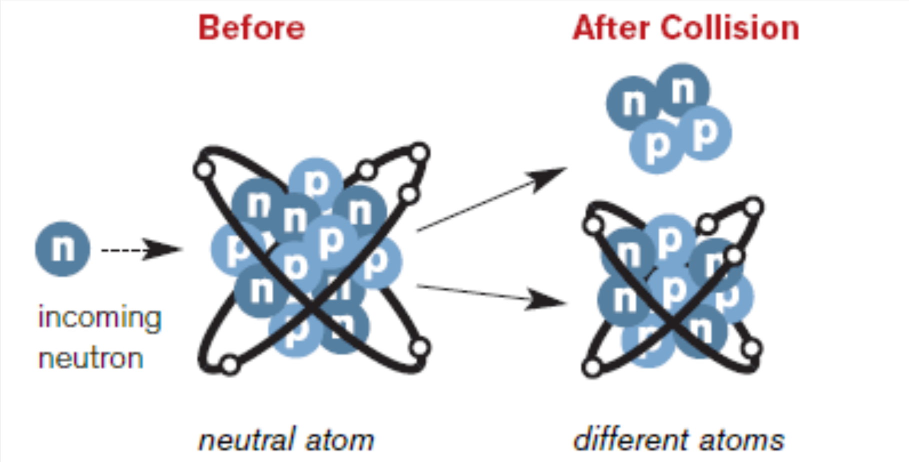


Comparison of photon and proton depth doses

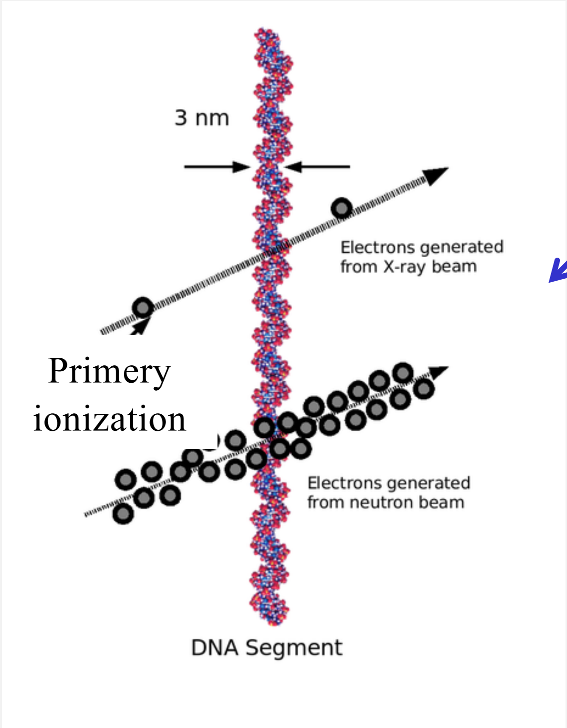


Neutron radiation: collision of high energy protons (66 MeV) into berillium target (p(66) +Be)

Neutrons induce nuclear reactions.



neutrons



High LET

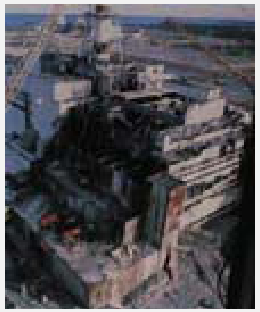
Background dose-load: an estimated average of annual dose from natural background and man-made sources is 3.6 mSv.

environmental

occupation

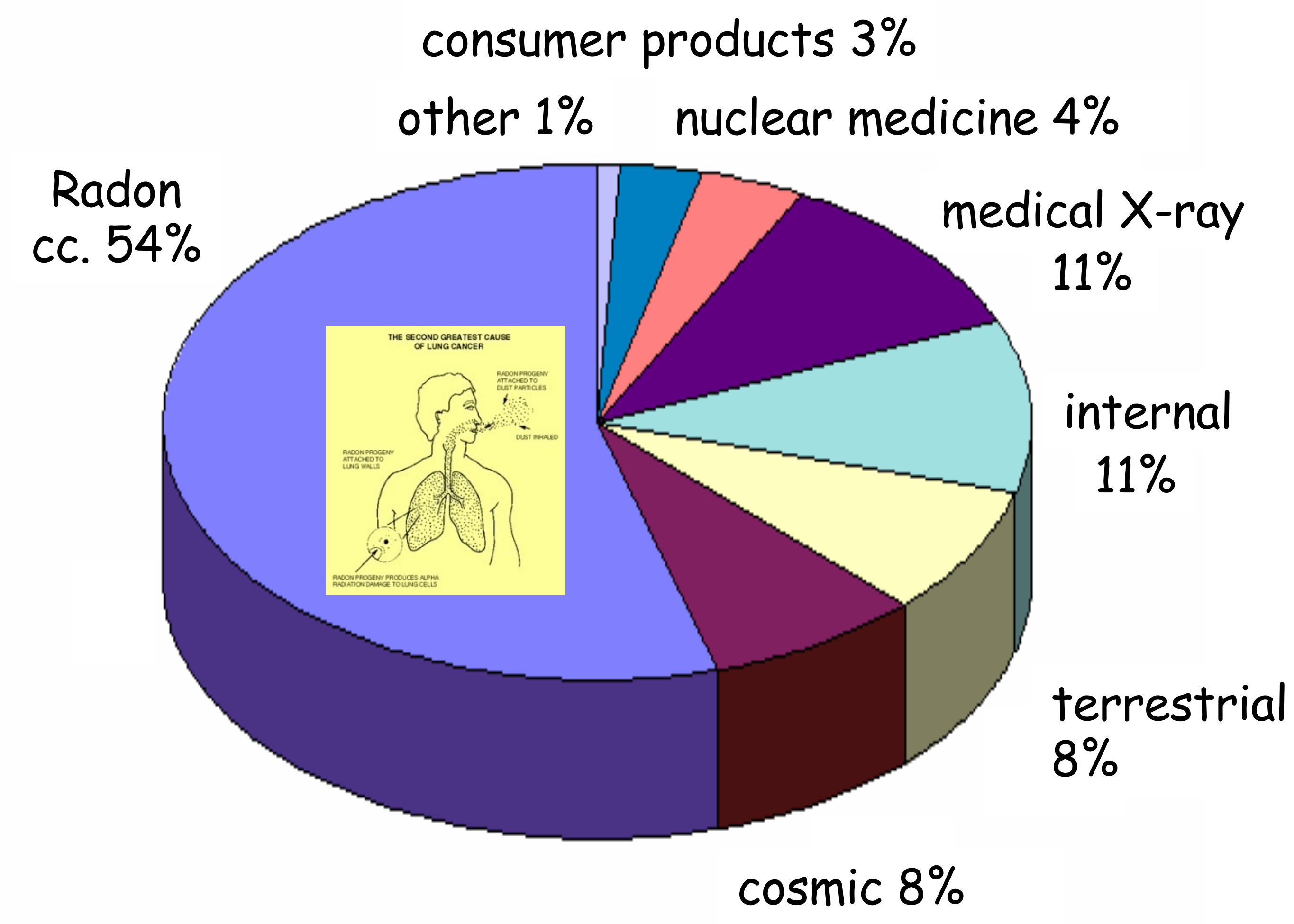
military

nuclear industry



medical use

Distribution of annual dose among sources



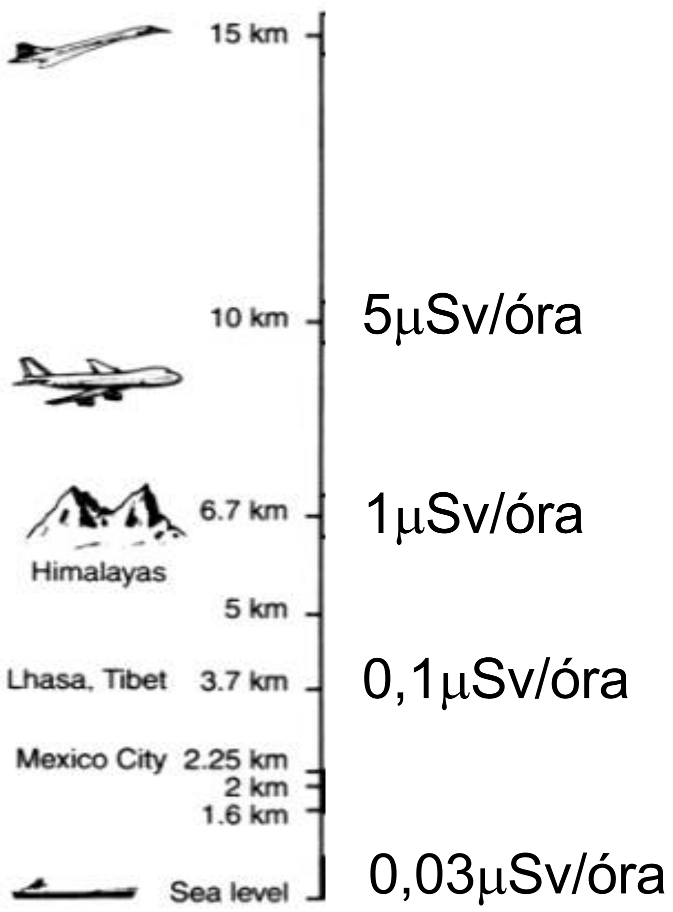
Sources of natural background

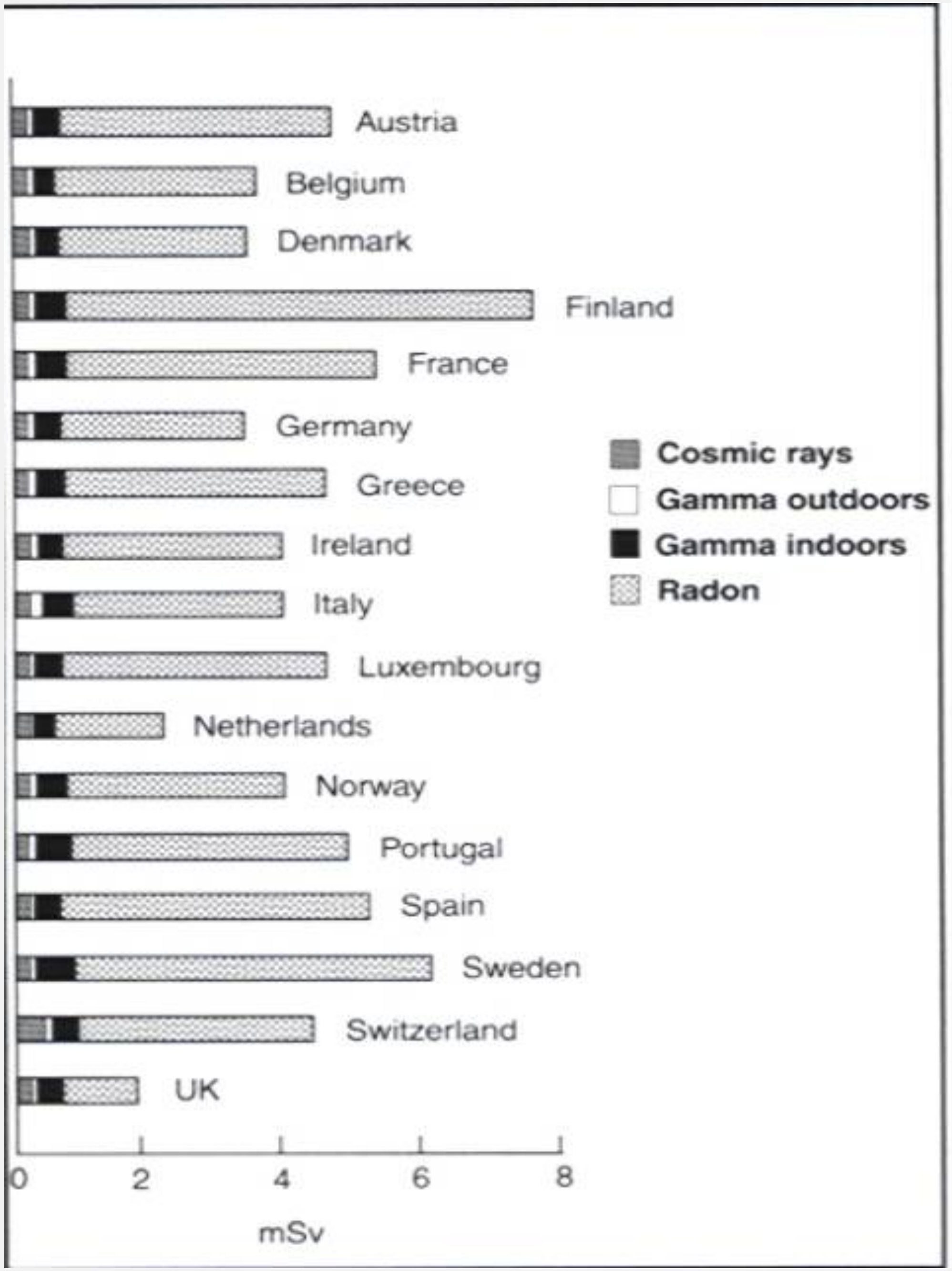
cosmic radiatiom
~ 0,4 mSv/year

radon: cc. 1,8 mSv/year

potassium: cc 0,1 mSv/year

Cosmic ray contributions to dose rate as the function of altitude





Distribution of naturally occuring background levels of radiation in Europe

The highest known level of background radiation on Earth 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.

Risks – 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 which they 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 relies on the following principles:

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

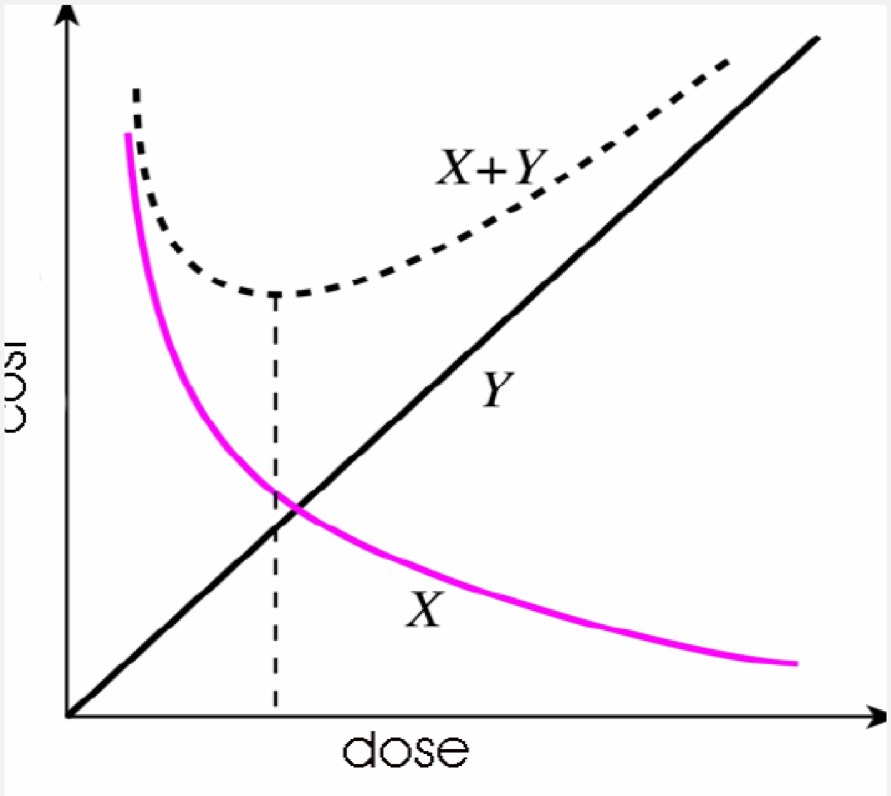
Justification: no practice shall be adapted unless it produces a positive net benefit

Limitation: the effective dose to individuals shall not exceed the limits recommended by the ICRP

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

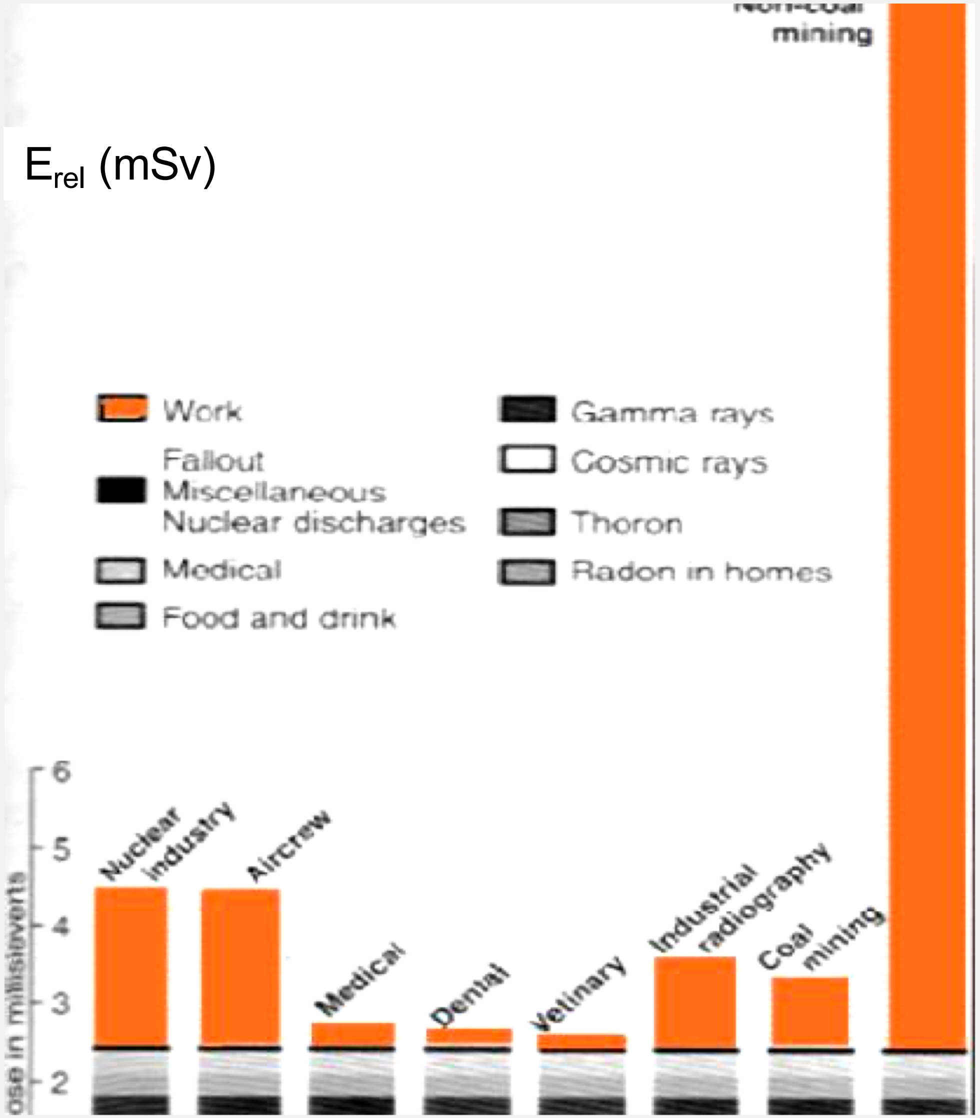
Optimum is the minimum of the combined costs.

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

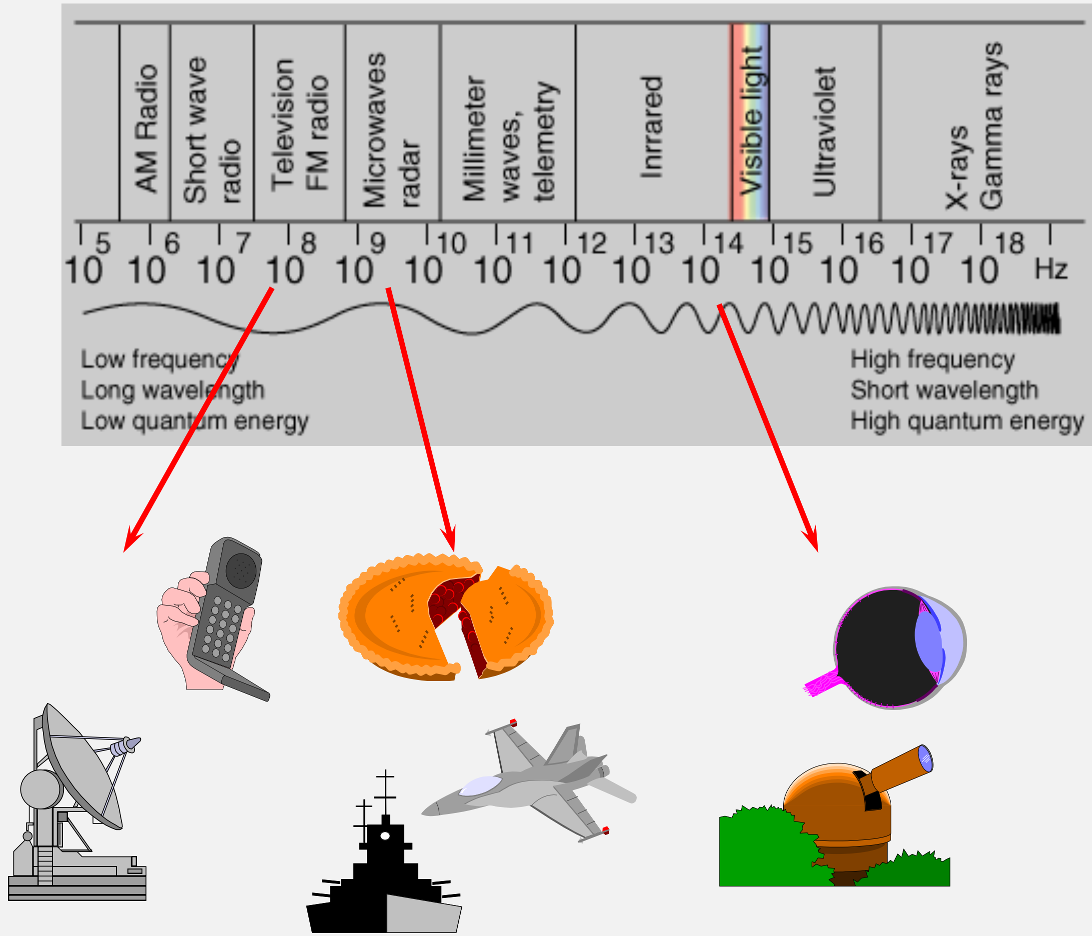
*** Over the average of 5 years but maximum 50 mSv/year**

Relative risk of various professions



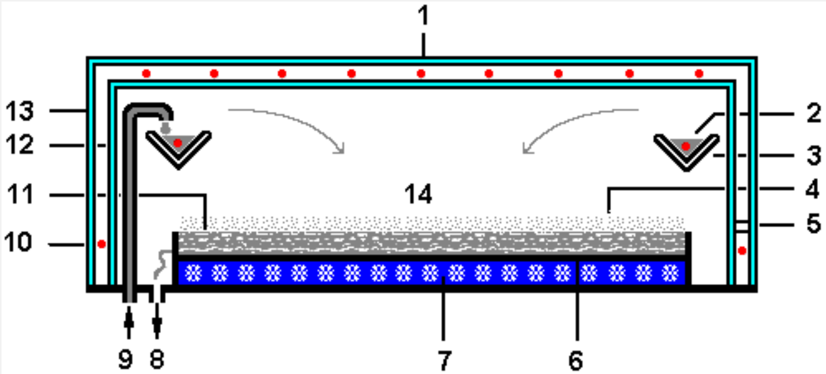
Detection of radiation – dose measurement

- What? α^{++} p^{+} (n) β γ ν



- How much energy?
- How much intensity?
- How good accuracy?

Detection of particles - history

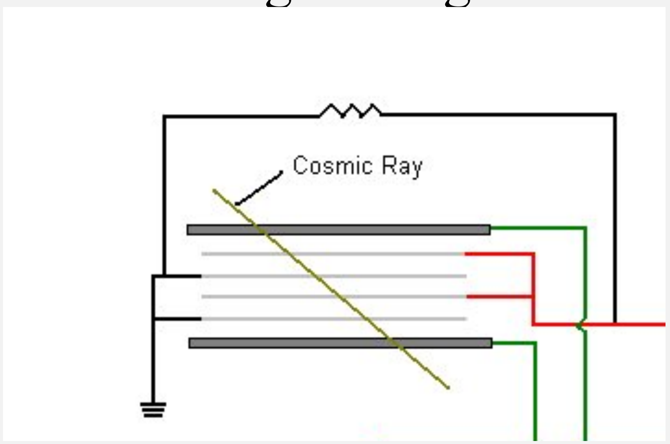


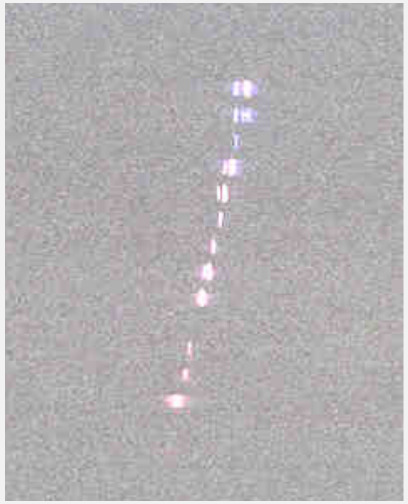
- **Cloud chamber**

  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 produces 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

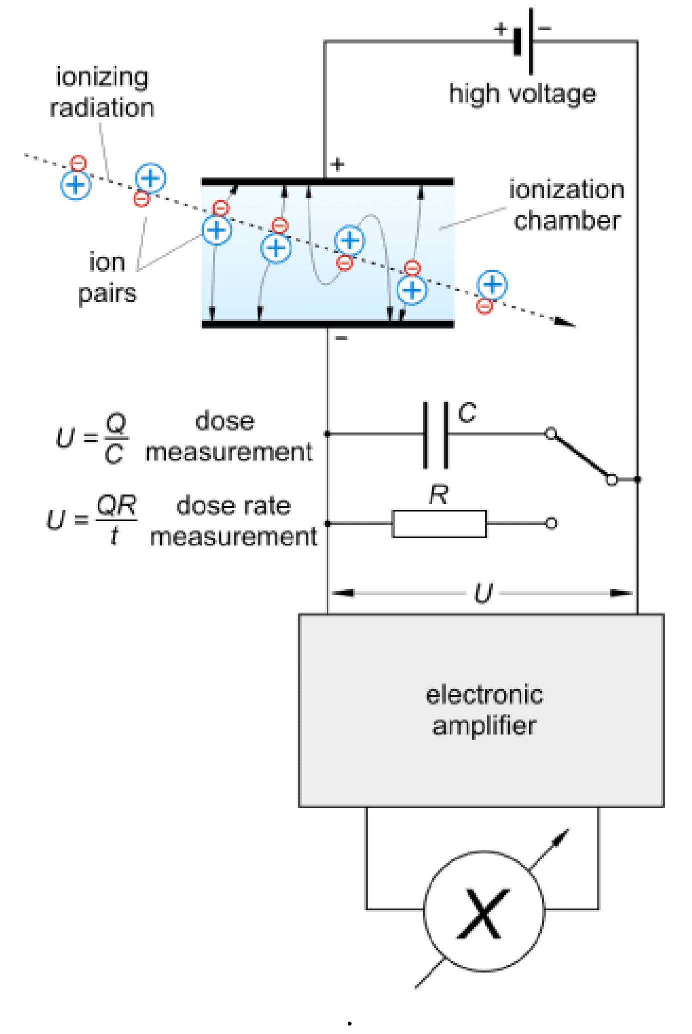
* Solid states – based on physical parameters of solid materials

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.

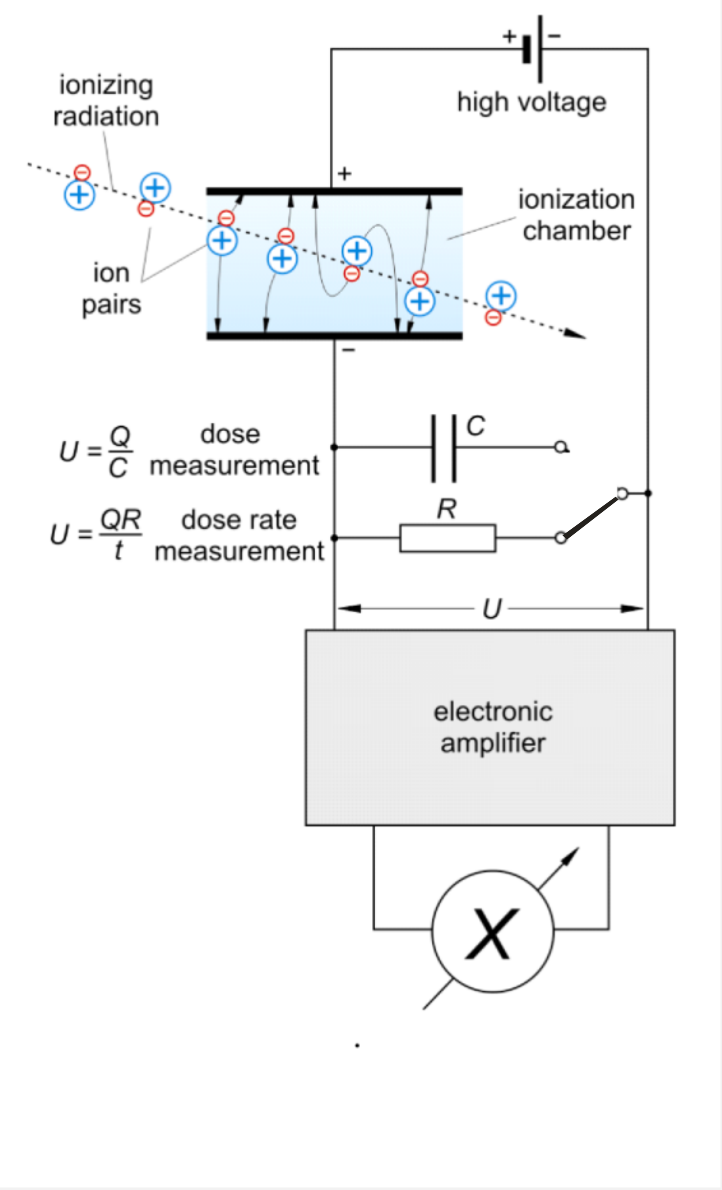
$$U = \frac{Q}{C} \sim X$$



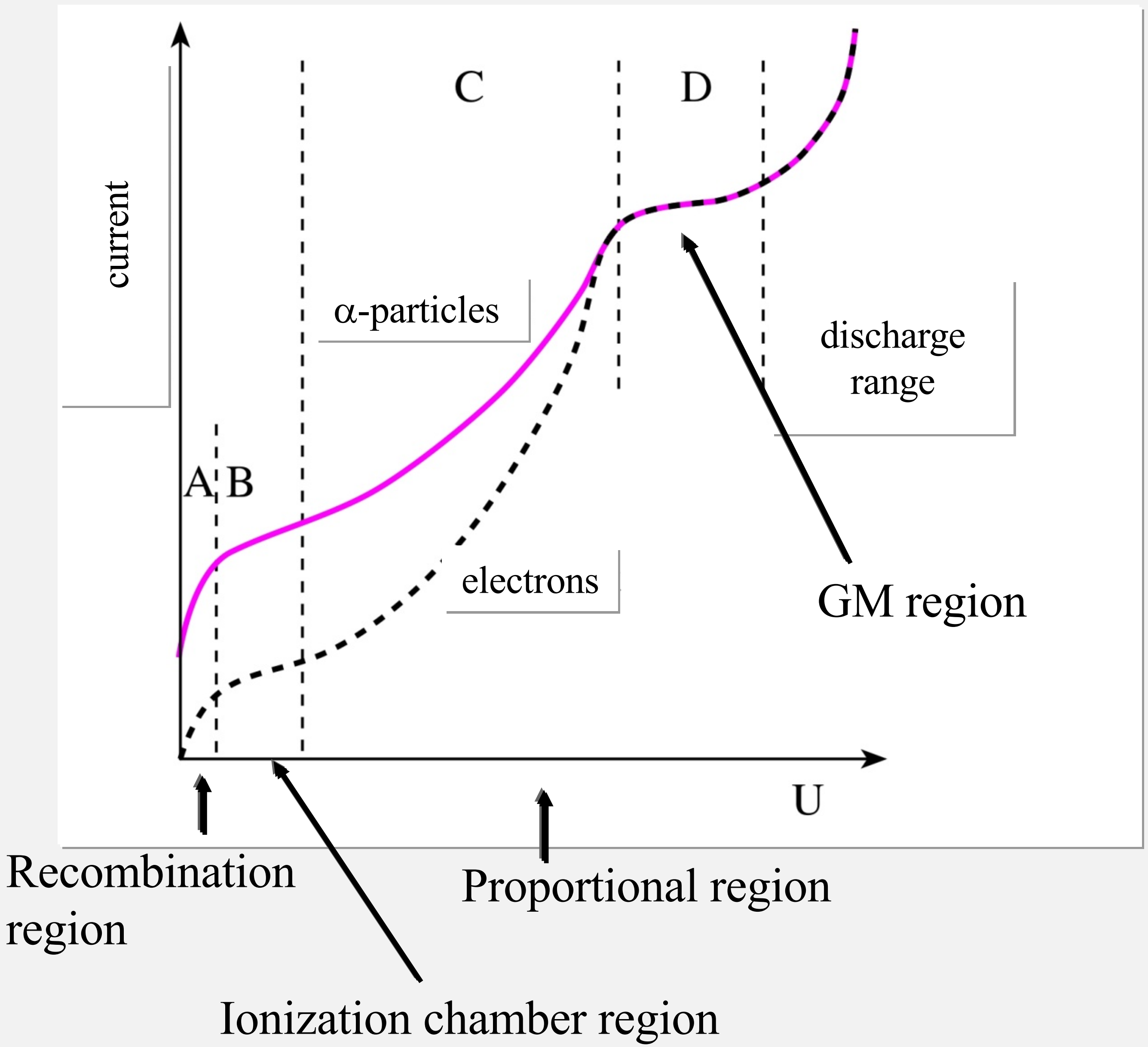
Ionization chambers

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.

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



Ionization chambers



Ionization chambers – Geiger-Müller counter

Inert gas filling

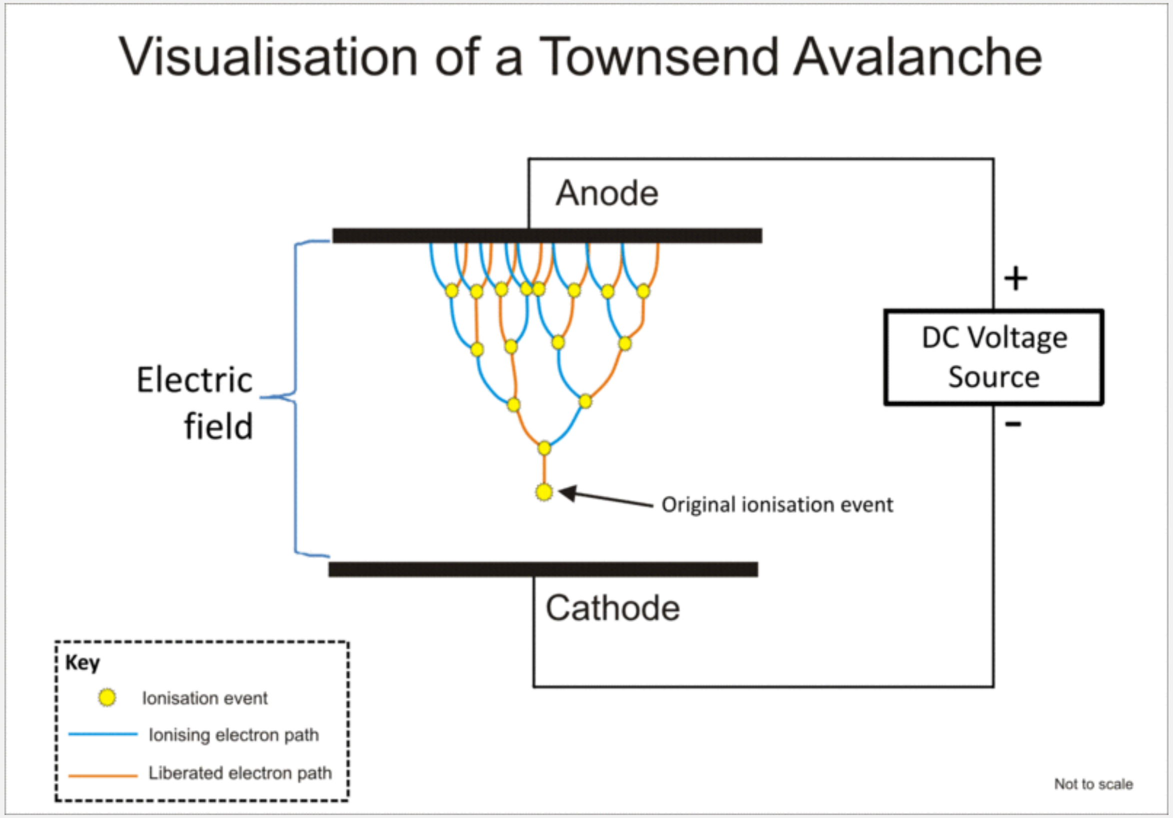
High accelerating voltage

↓

Avalanche effect between electrodes

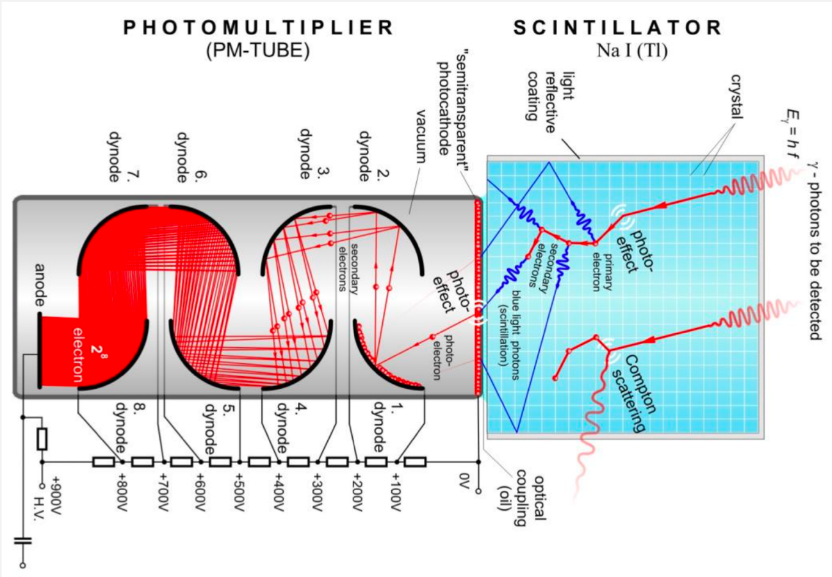
↓

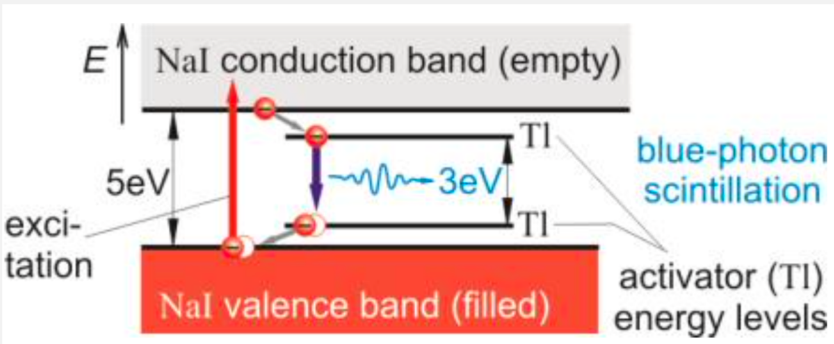
Current pulse



Number of current pulses ~ number of ionising particles

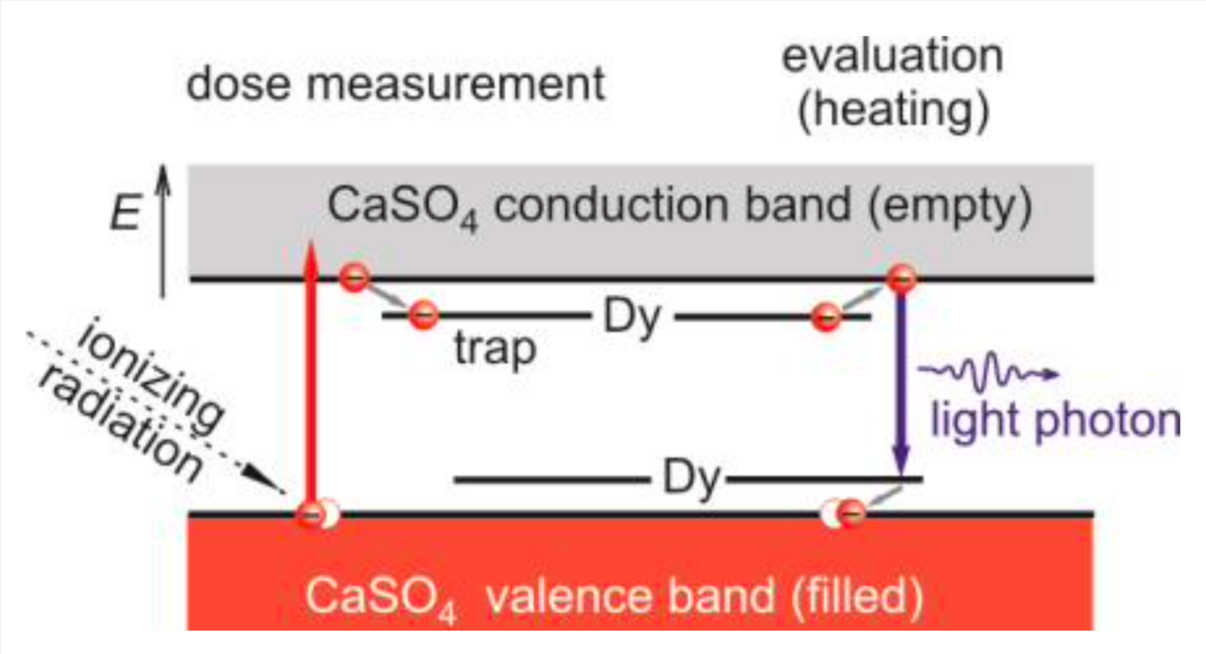
Scintillation detectors





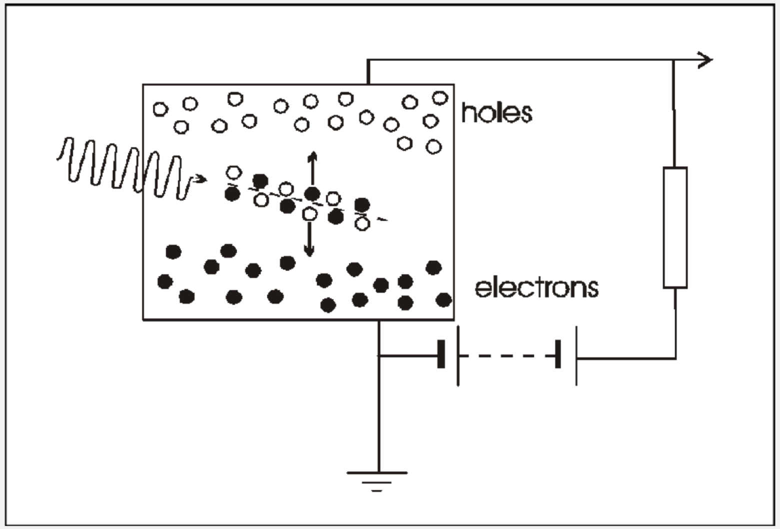
- Liquid scintillator
  - Solution of fluorescent compounds
  - Primary excitation of solvent and follow-up excitation of diluted compound
  - Light emission
- Plastic scintillator
  - Solid materials
- Inorganic crystals
  - Primary excitation of crystal, follow-up excitation of luminescent atoms

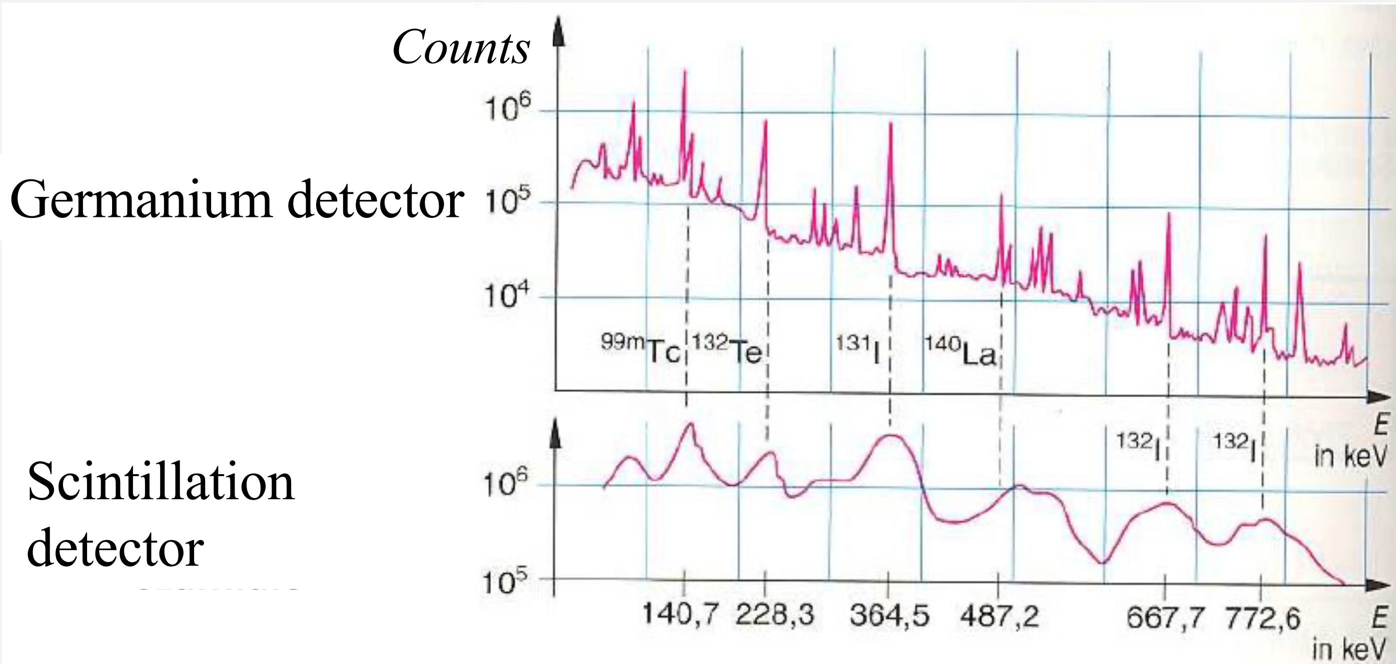
Solid phase detectors - Thermoluminescent dosimeter



The cumulative dose is measured off-line
by heating and scintillation counting

Semiconductor detectors





Chemical processes – 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 and Nuclear medicine

Typical dosimetry calculation...

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 absorbed dose after half an hour irradiation and the temperature change of the water. *(There is no significant change in the activity of the radioactive sample during the time of the experiment.)*

Λ=5 MBq, that is $5*10^6$ decay/s

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

$E_{abs}= N*E_\alpha=9*10^9*6.2*10^6 eV = 5,58*10^{16} eV=8,92*10^{-3}$ J

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

$E_{abs}=c*m*\Delta T \Rightarrow 8.92*10^{-2} / (4.18*10^3*0.1)=2.1*10^{-4}$C