African School of Fundamental Physics and Applications

Radiation dosimetry, radiation protection and measurements

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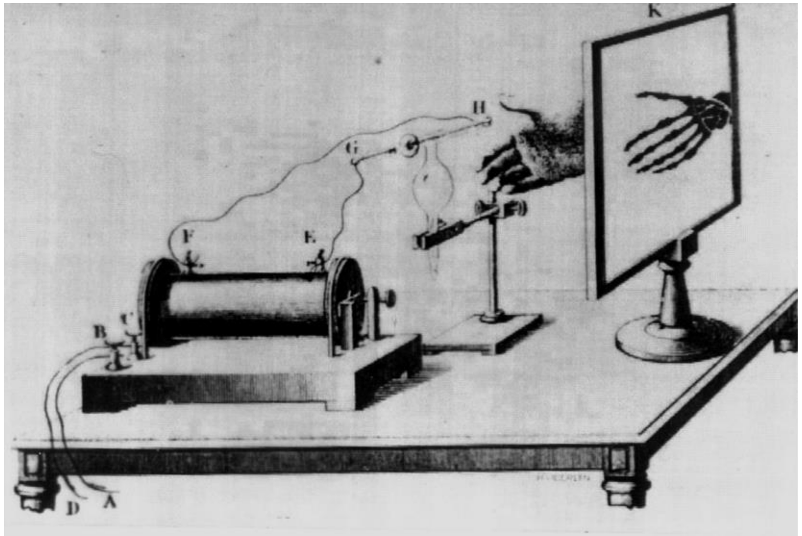
- A very brief historical introduction
- Directly and indirectly ionizing radiation
  - Radioactivity
  - Natural exposures
- The effects of ionizing radiation
  - Deterministic and stochastic effects
- Radiological quantities and units
  - physical, protection and operational quantities
- Principles of radiation protection
  - Justification, optimization and dose limitation
  - The ALARA principle
- Protection means
- Instrumentation for measuring ionizing radiation

The discovery of radiation



1895

Discovery of X rays

Wilhelm C. Röntgen

1897

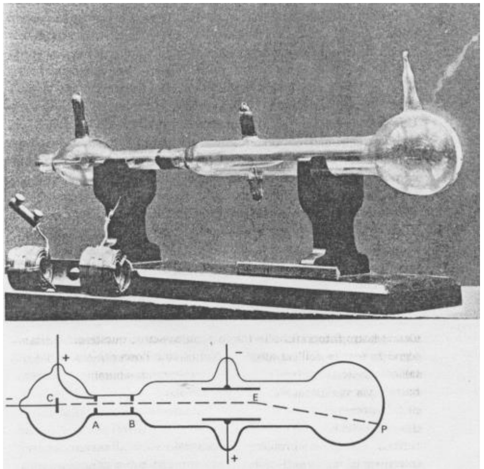
First treatment of tissue with X rays

Leopold Freund

J.J. Thompson

1897

“Discovery” of the electron



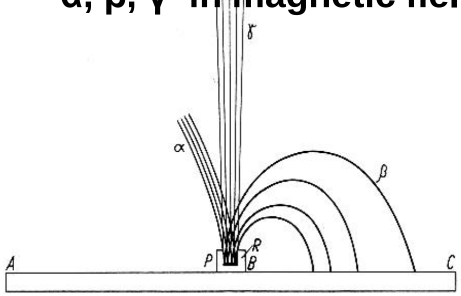
Henri Becquerel (1852-1908)

1896

Discovery of natural radioactivity

Thesis of Mme. Curie – 1904

α, β, γ in magnetic field



Hundred years ago

1898

Discovery of polonium and radium

Marie Curie (1867 – 1934) **Pierre Curie (1859 – 1906)**

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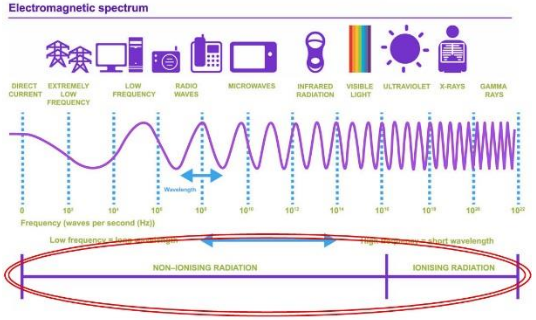

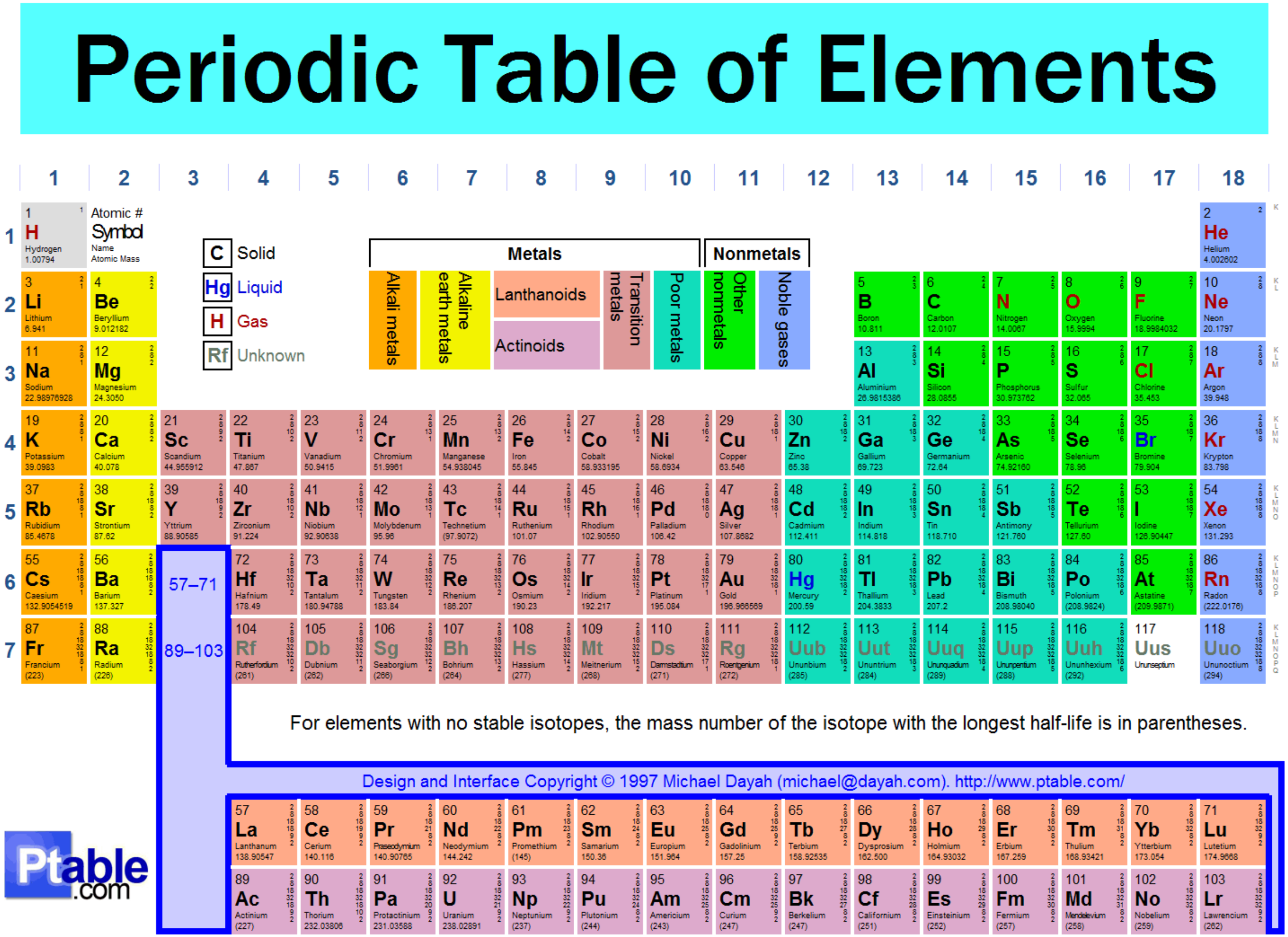
Periodic Table of Elements
Atomic #
Symbol
Name
Atomic Mass
C Solid
Hg Liquid
H Gas
Rf Unknown
Metals
Nonmetals
Alkali metals
Alkaline earth metals
Lanthanoids
Actinoids
Transition metals
Poor metals
Other nonmetals
Noble gases
57–71
89–103
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.
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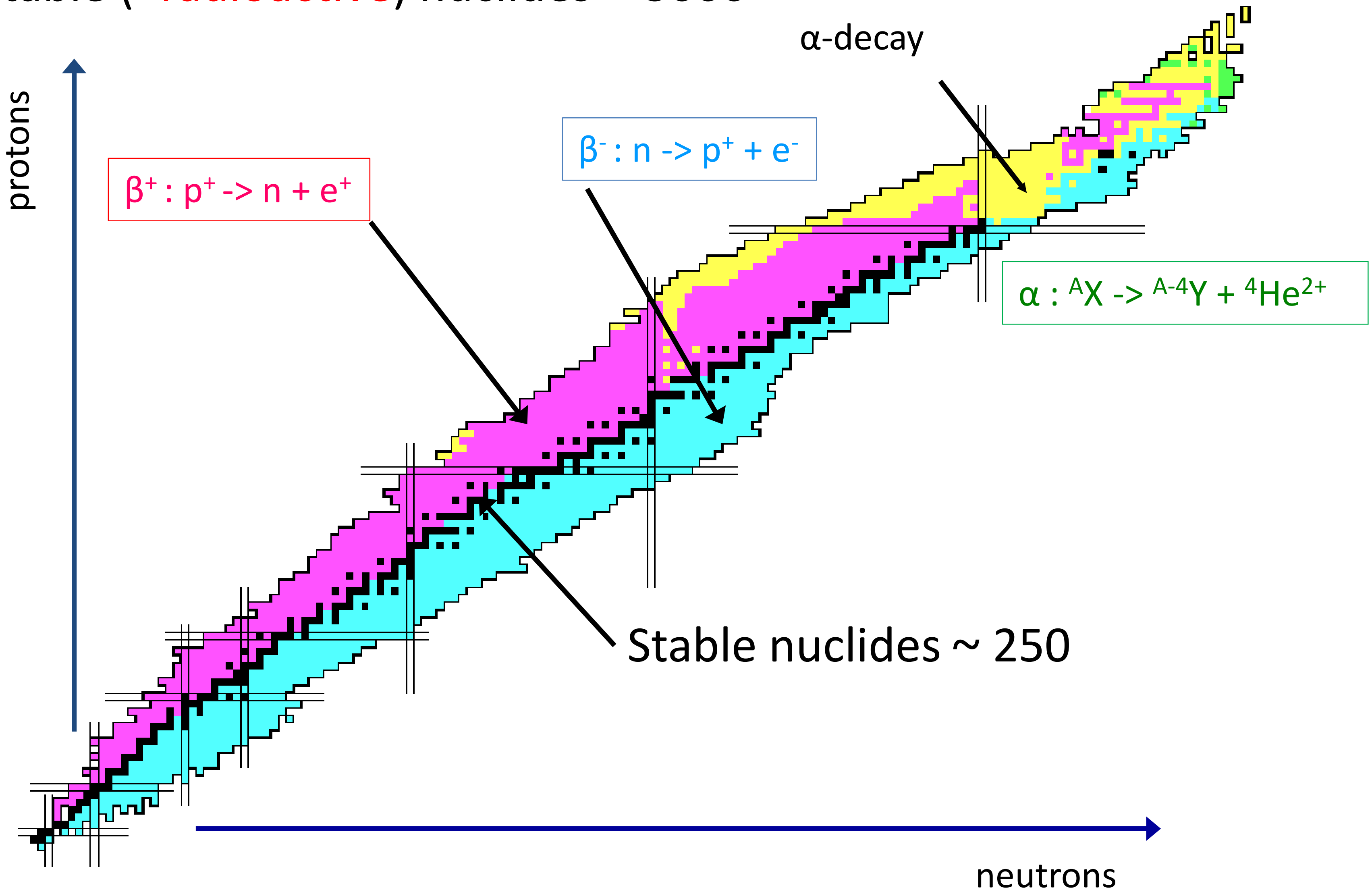
Ptable.com

Chart of nuclides

Unstable (=radioactive) nuclides ~ 3000



Directly ionizing radiation:

- **fast charged particles** (e.g., electrons, protons, alpha particles), which deliver their energy to matter directly, through many small ***Coulomb-force interactions*** along the particle's track

Indirectly ionizing radiation:

- X- or γ-ray photons or neutrons (i.e., **uncharged particles**), which first transfer their energy to charged particles in the matter through which they pass in a relatively few large interactions, or cause nuclear reactions
- The ***resulting fast charged particles*** then in turn deliver the energy in matter

The deposition of energy in matter by indirectly ionising radiation is a **two-step process**

photon → electron
neutron → proton or recoiling nuclei

Radioactivity: the phenomenon whereby atoms undergo spontaneous random disintegration, usually accompanied by the emission of ionising radiation.

The rate at which this nuclear transformations occurs in matter containing radionuclides is called **activity** and it is expressed in **Bequerels**:

$$A(t) = -dN/dt\ [Bq] \qquad 1\ Bq = s^{-1}$$

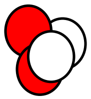
(the old unit is the Curie: 1 Ci = 3.7×10^{10} Bq)

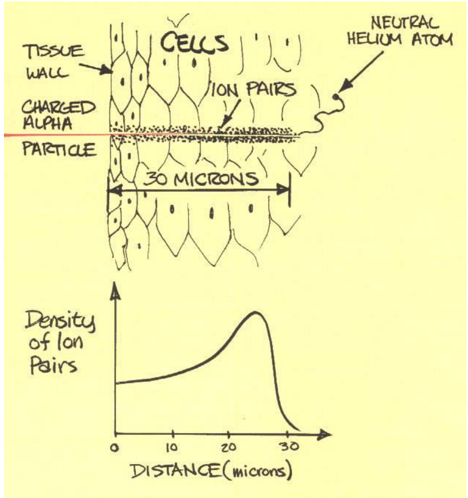
where N is the number of nuclei of the radionuclide, and hence the rate of change of N with time is negative

The radioactive **half-life** ($T_{1/2}$) of a radionuclide is the time necessary for half of the nuclei present in the sample to decay

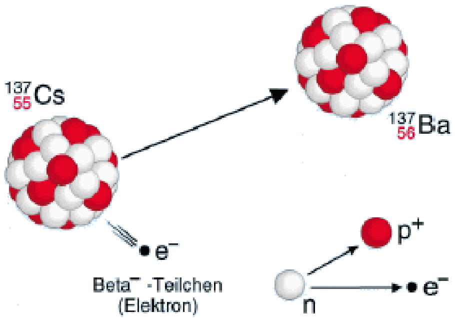
Radionuclides are either of ***natural origin*** or produced by ***nuclear reactions*** (**artificial** radionuclides)

(Emitted in the de-excitation of unstable nuclei)

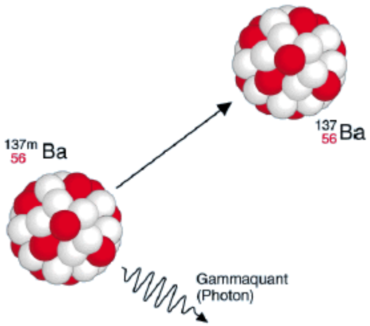
- **ALPHA** 
  - Helium nuclei (2 protons + 2 neutrons)
  - Energy: a few MeV
  - Non-penetrating
  - Radiological hazard only if inhaled, ingested or absorbed through a wound (internal irradiation)



- **BETA** 
  - Electrons or positrons
  - Energy: a few keV to a few MeV
  - Limited penetration
  - Dangerous for skin and eyes in case of external irradiation
  - Increased radiological hazard if inhaled, ingested or absorbed through a wound (internal irradiation)

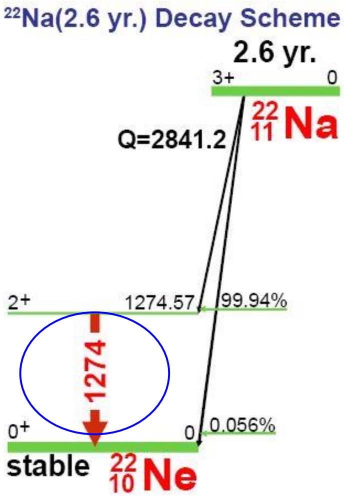


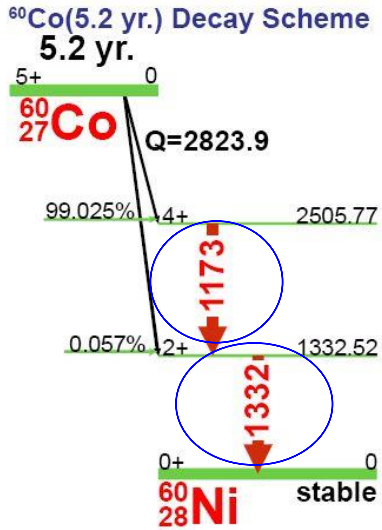
- **PHOTONS**
  - Electromagnetic radiation
  - Energy: a few keV to a few MeV
  - Very penetrating
  - Radiological hazard only by external irradiation

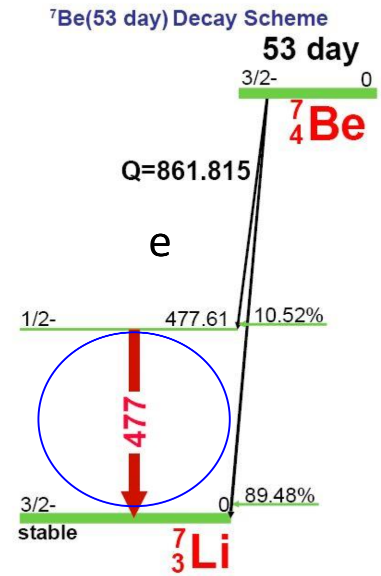


- **NEUTRONS**
  - Neutral particles (constituents of the atomic nucleus together with protons)
  - Very penetrating
  - External irradiation
  - Enhanced biological effect (high LET radiation), which depends on their energy
- **HEAVY CHARGED PARTICLES (protons, ions)**
  - External irradiation
  - Enhanced biological effect (high LET radiation)

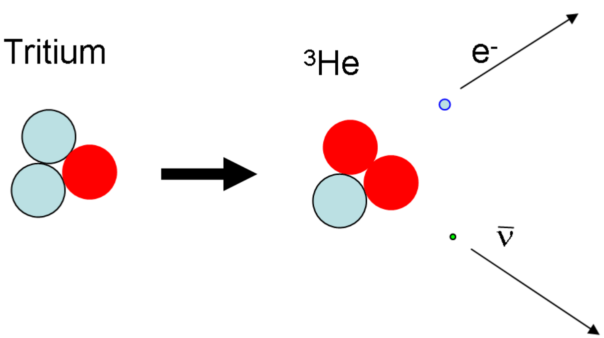
β-, γ-emitter





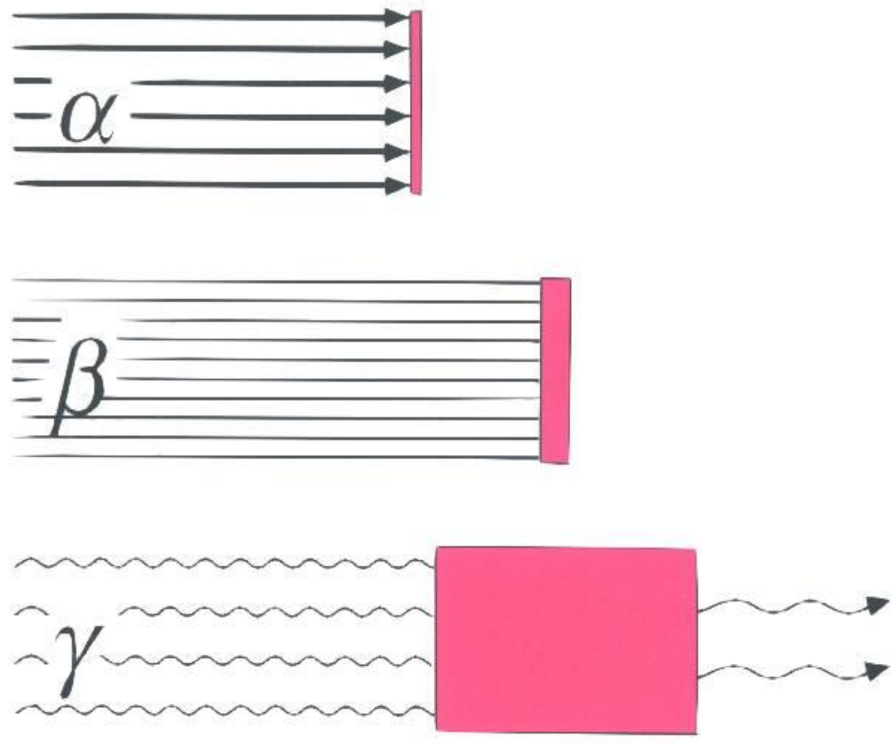


Pure β-emitter

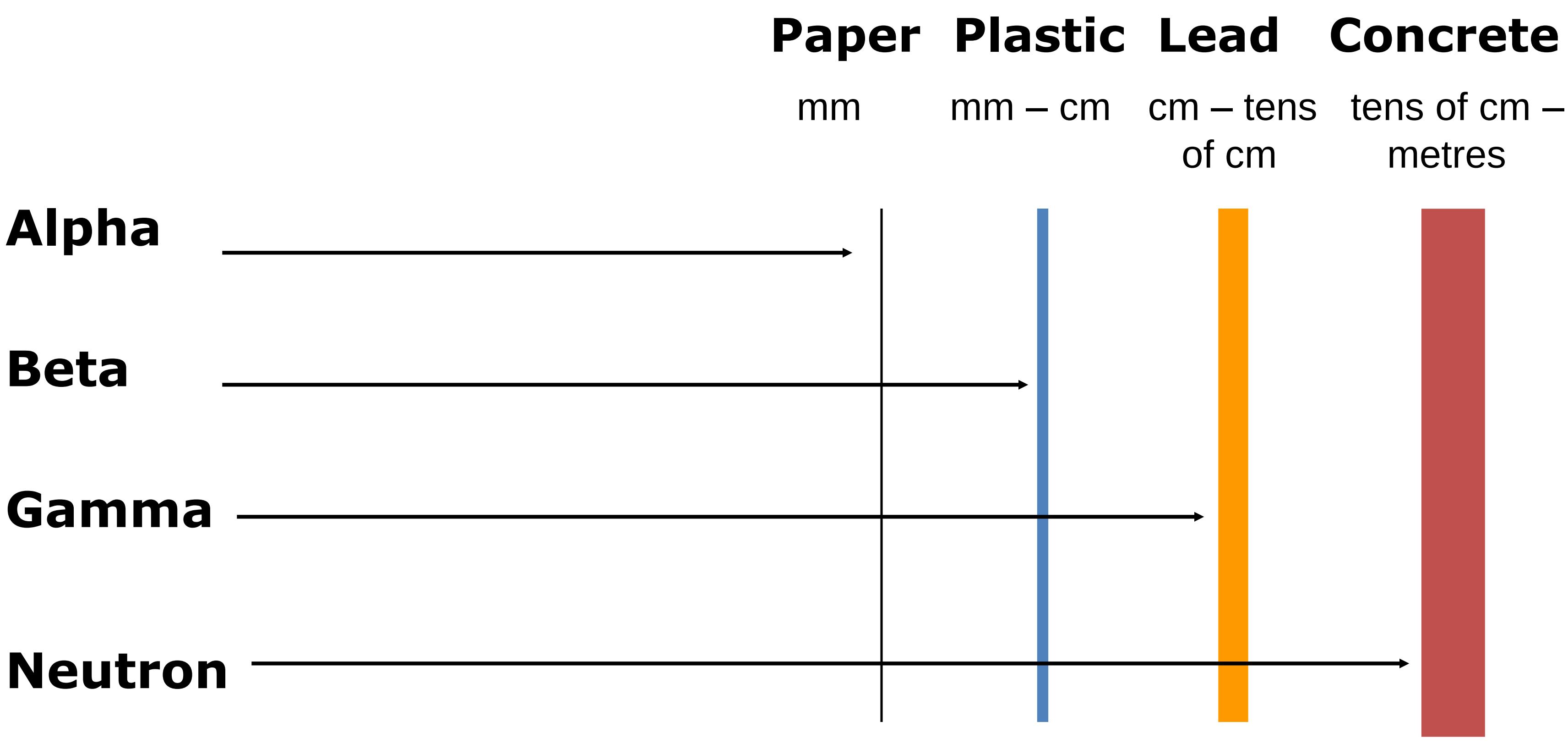


α-, β- and γ are emitted with end energies up to few MeV α- and β-particles are degraded in energy while traversing a material, until they are completely brought to rest

γ-rays are attenuated in intensity by the material



Qualitative!



Beta sources are usually shielded with Plexiglas, gamma sources with lead

For a given particle, target element and nuclide

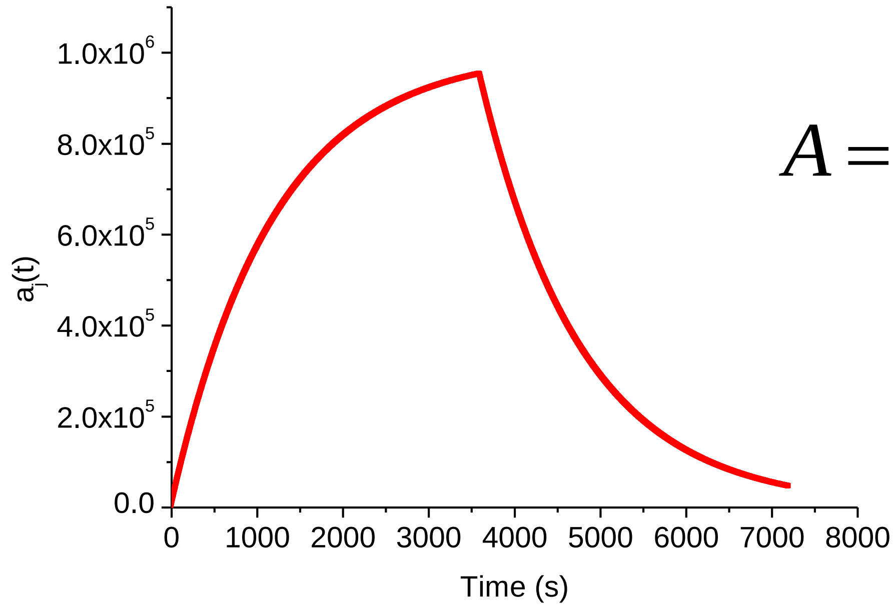
- Interaction probability, σ (*cross section*)
- Flux (spectrum), Φ
- Beam intensity, I_p

$$n = I_p \frac{\rho N_{Av}}{A} \sum_{i=p,n,\pi,pho} \int \Phi_i(E)\sigma_i(E)\,dE$$

Nuclide production rate

Rule-of-thumb (probably very obvious):

The shorter the half-life, the fastest the build-up, the fastest the decay



$$A = A_s(1 - e^{-t_{irr}/\tau})e^{-t_{dec}/\tau}$$

It takes about 5 half-lives to reach saturation of activity

The absorbed dose is the energy deposited by a given radiation in a unit mass of matter

The unit of absorbed dose is the Gray (mGy, μGy):

1 Gy = 1 J/Kg

(the old unit is the rad: 1 rad = 10^{-2} Gy)

Radiation protection uses the operational quantity "dose equivalent H" in Sievert (mSv, μSv)

$$H = Q \cdot D$$

1 Sv = 1 J/Kg

Q = quality factor of the radiation

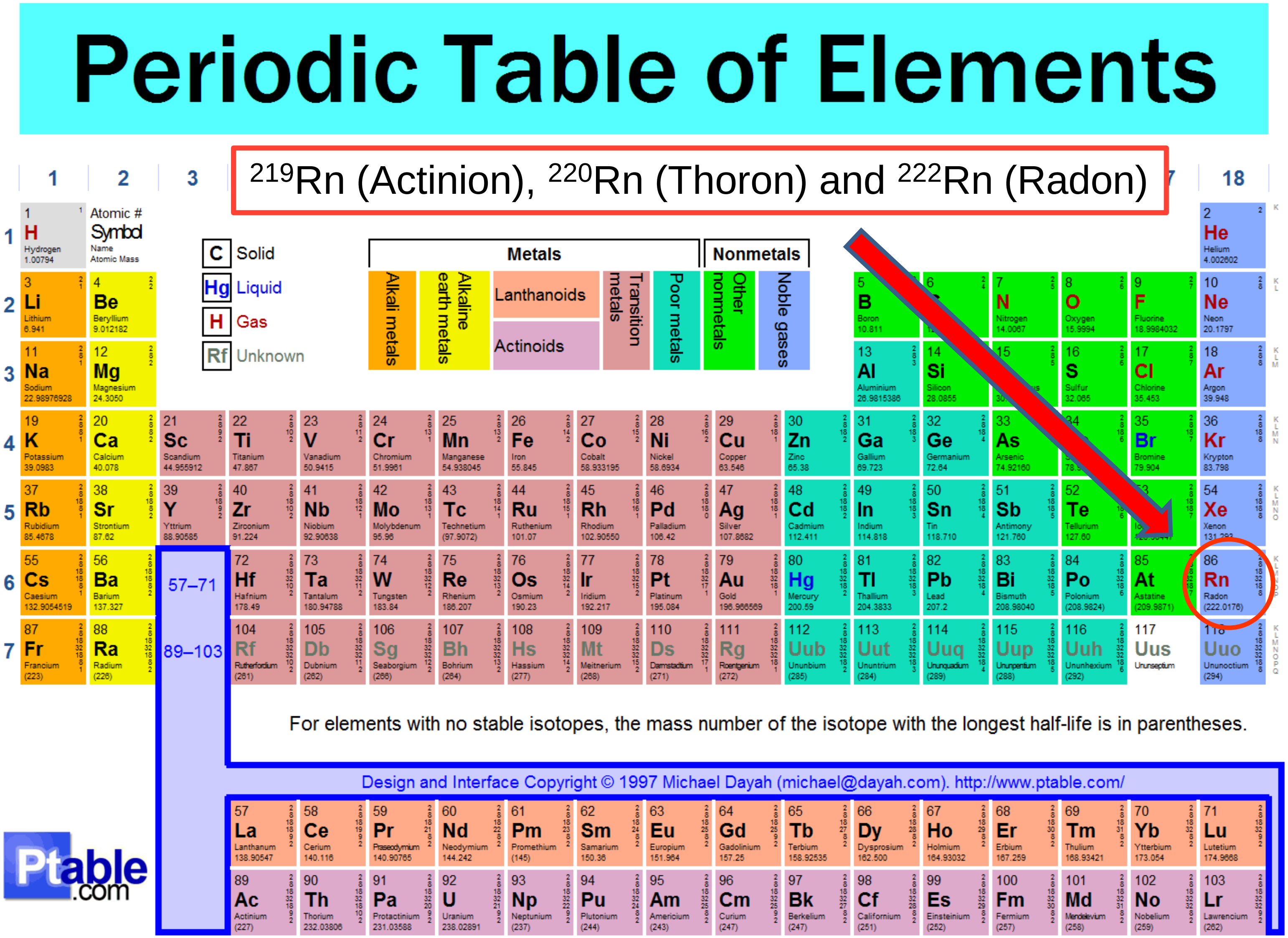
Are we all exposed (voluntarily or not) to some radiation sources?

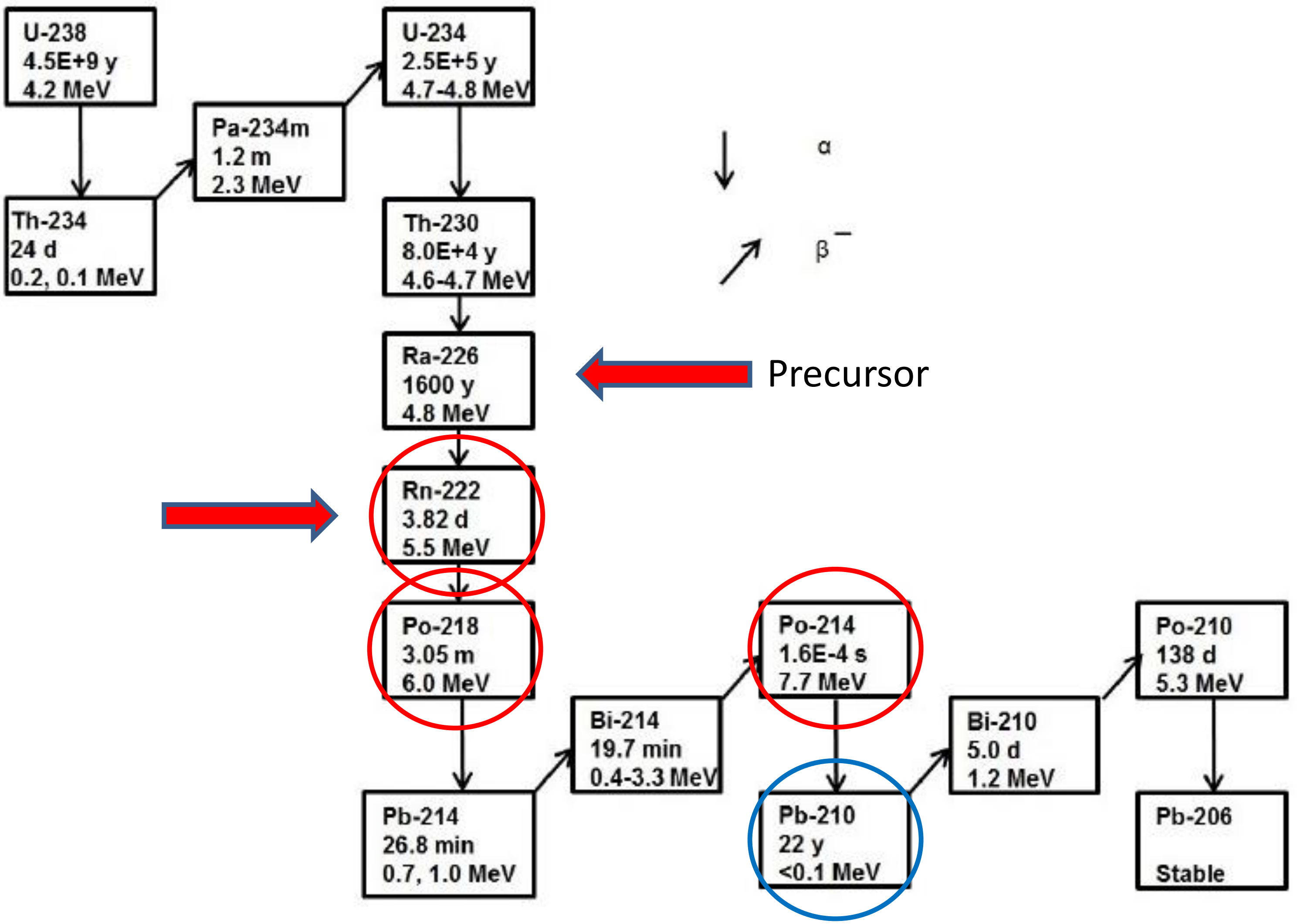
Yes/No?

If the answer is yes,
what are the natural radiation levels?

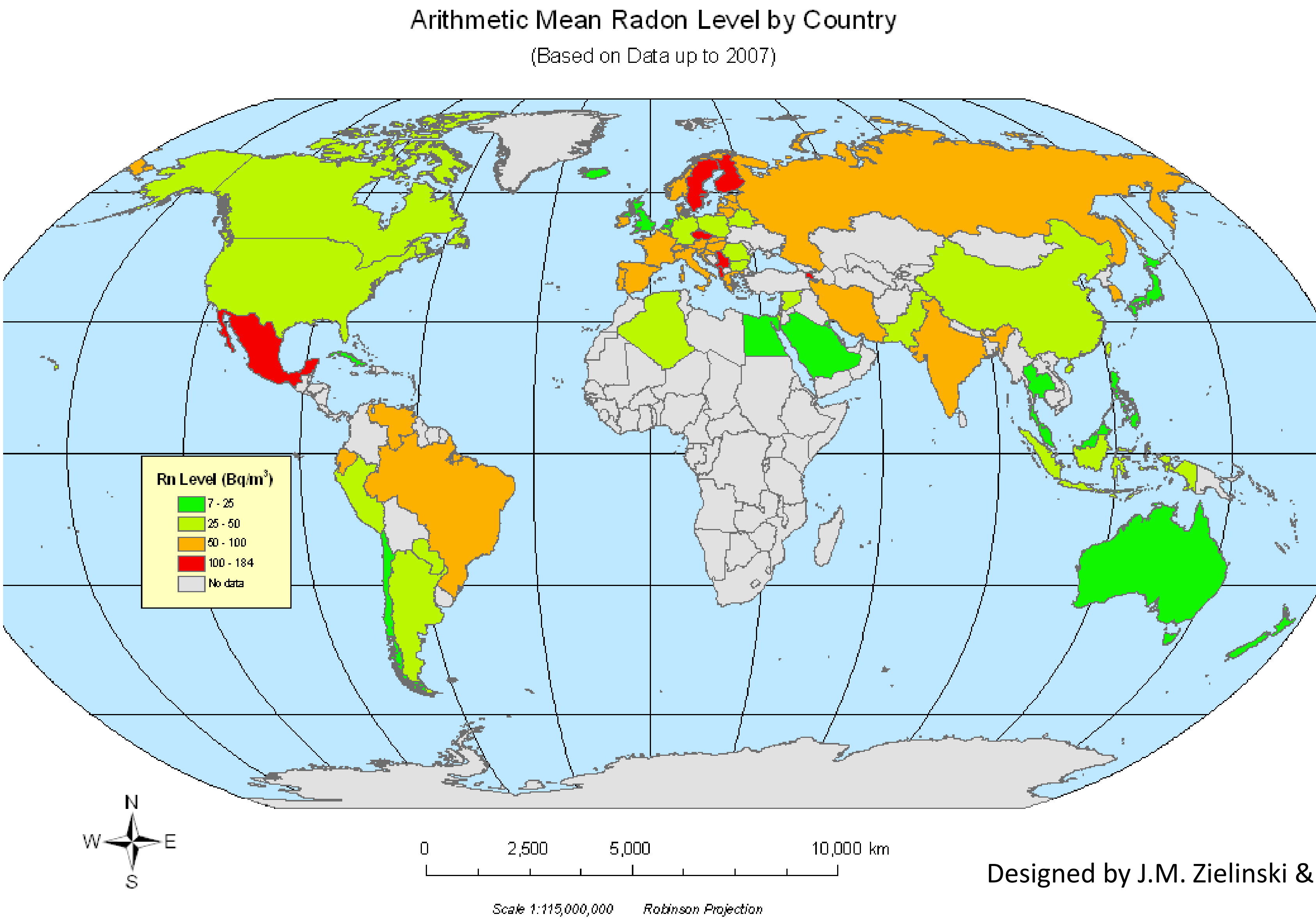
Annual exposure to natural radioactivity in **France** = 2.5 mSv (3.3 mSv including medical exposures)

^{219}Rn (Actinion), ^{220}Rn (Thoron) and ^{222}Rn (Radon)




U-238
4.5E+9 y
4.2 MeV
Th-234
24 d
0.2, 0.1 MeV
Pa-234m
1.2 m
2.3 MeV
U-234
2.5E+5 y
4.7-4.8 MeV
Th-230
8.0E+4 y
4.6-4.7 MeV
Ra-226
1600 y
4.8 MeV
Precursor
Rn-222
3.82 d
5.5 MeV
Po-218
3.05 m
6.0 MeV
Pb-214
26.8 min
0.7, 1.0 MeV
Bi-214
19.7 min
0.4-3.3 MeV
Po-214
1.6E-4 s
7.7 MeV
Pb-210
22 y
<0.1 MeV
Bi-210
5.0 d
1.2 MeV
Po-210
138 d
5.3 MeV
Pb-206
Stable
α
β−

Worldwide radon risk



Designed by J.M. Zielinski & H. Jiang

http://www.mclaughlincentre.ca/research/map_radon/Index.htm

During the creation of the Earth, terrestrial nuclides had been incorporated into the earth crust ($T_{1/2}$ some millions to billions of years)

Nuclide	Symbol	Half-life	
Uranium-235	^{235}U	7.04×10^{8} y	0.72% of natural Uranium
Uranium-238	^{238}U	4.47×10^{9} y	99.3% of natural Uranium
Thorium-232	^{232}Th	1.41×10^{10} y	
Potassium-40	^{40}K	1.28×10^{9} y	Earth: 0.037-1.1 Bq/g

...and some more:

^{50}V, ^{87}Rb, ^{113}Cd, ^{115}In, … ^{190}Pt, ^{192}Pt, ^{209}Bi, …

Cosmogenic nuclides are produced by nuclear reactions of cosmic particles with stable nuclei of the atmosphere

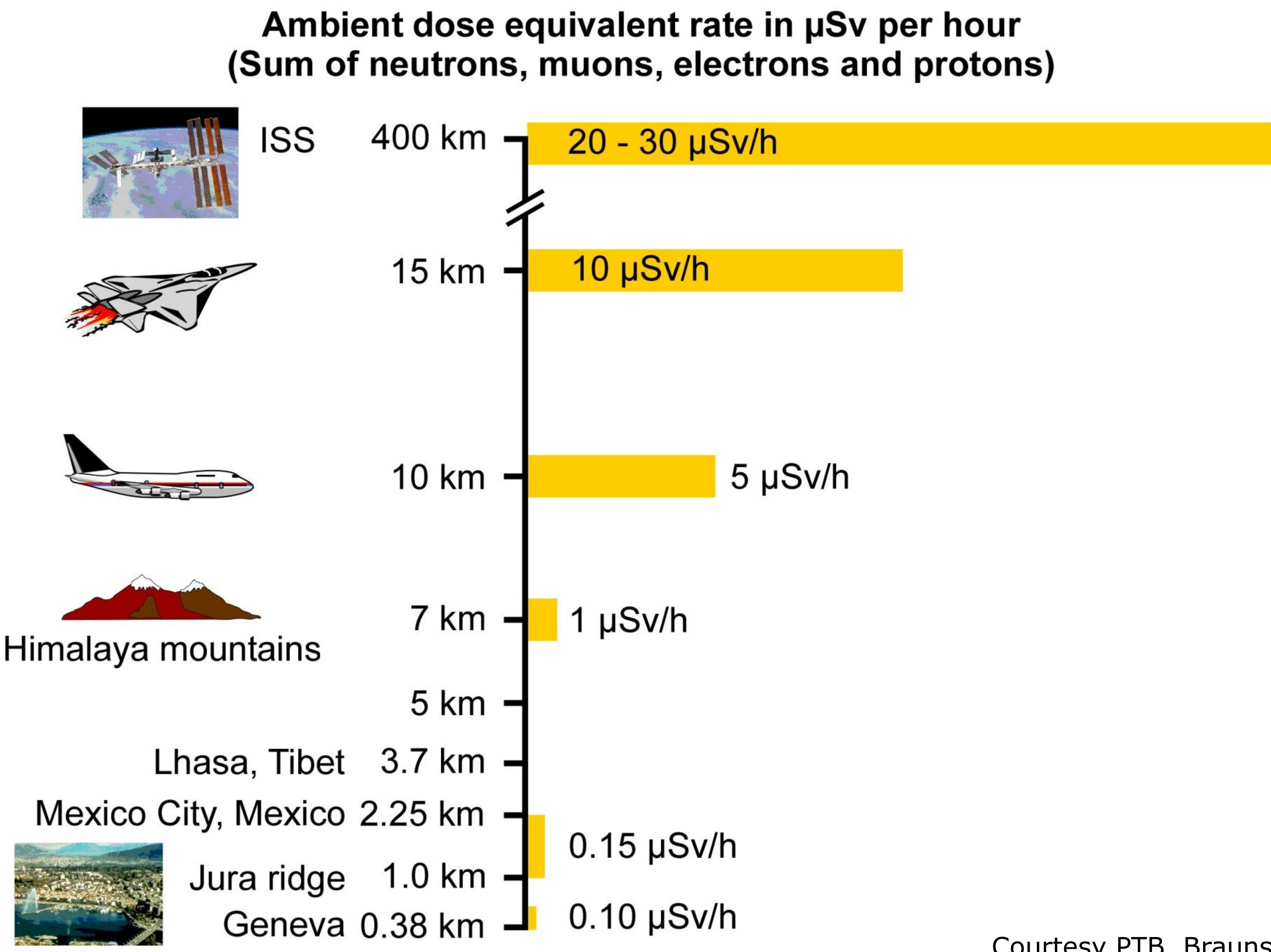
Nuclide	Symbol	Half-life	Nuclear Reaction
Carbon-14	^{14}C	5730 y	e.g. $^{14}N(n,p)^{14}C$
Tritium-3	^{3}H	12.3 y	Interaction of cosmic radiation with N or O $^{6}Li(n,\alpha)^{3}H$
Beryllium-7	^{7}Be	53.28 d	Interaction of cosmic radiation with N or O

More cosmogenic radionuclides:

^{10}Be, ^{26}Al, ^{36}Cl, ^{80}Kr, …

Nuclide	Total activity in human body (~ 70 kg)
Potassium-40	~ 5 kBq
Carbon-14	~ 3 kBq
Tritium	~ 20 Bq
Polonium-210	~ 18 Bq
Uranium	~ 1 Bq
Radium	~1 Bq
Thorium	~ 0.1 Bq

TOTAL	~ 8 kBq



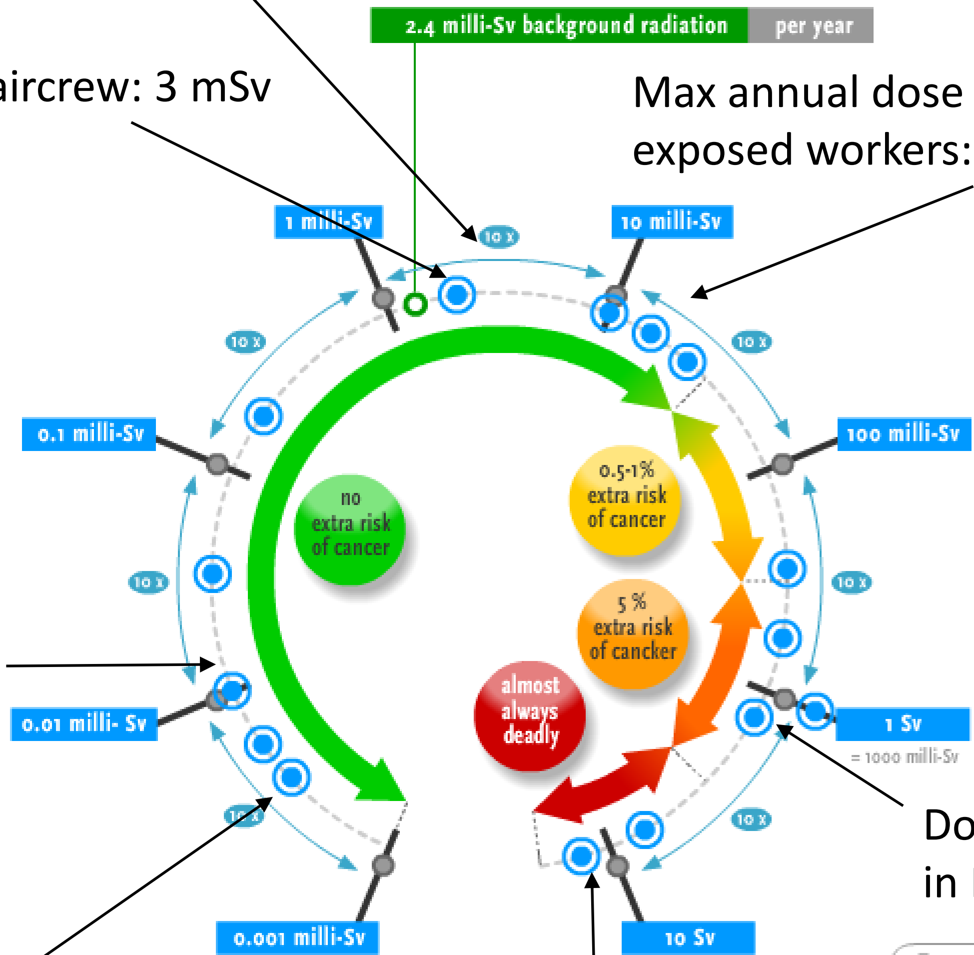
Courtesy PTB, Braunschweig

Dose comparison

CT scan: up to 10 mSv

Average annual dose for aircrew: 3 mSv

Max annual dose for occupationally exposed workers: 20 mSv



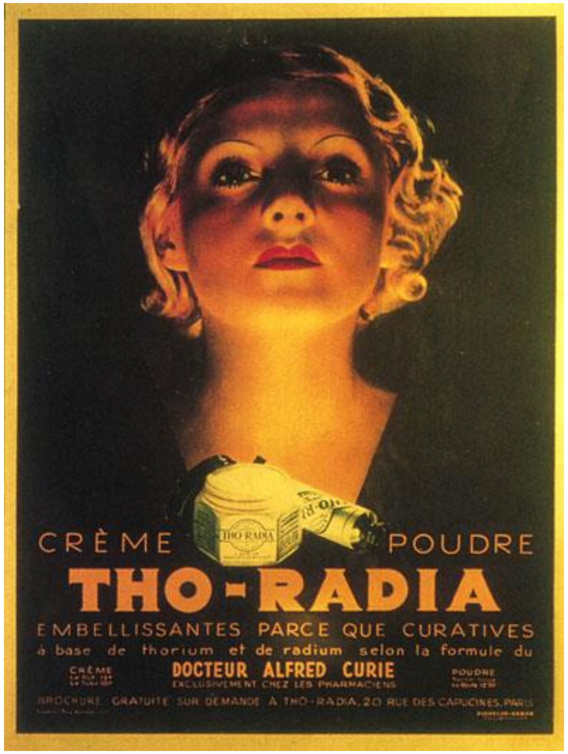
Chest x-ray: 10 μSv

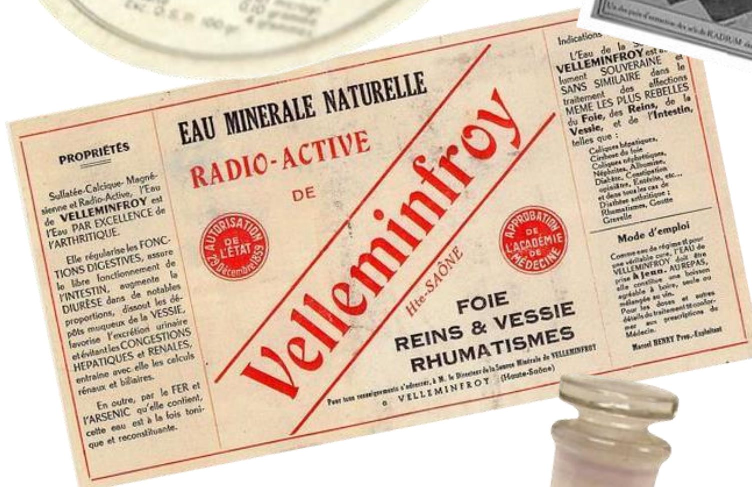
Dose per fraction in RT: 2 Sv

Daily natural background radiation: 2-3 μSv

Estimated dose absorbed by the Russian spy Litvinenko : 18 Sv

Times change… This is what we had in the past!





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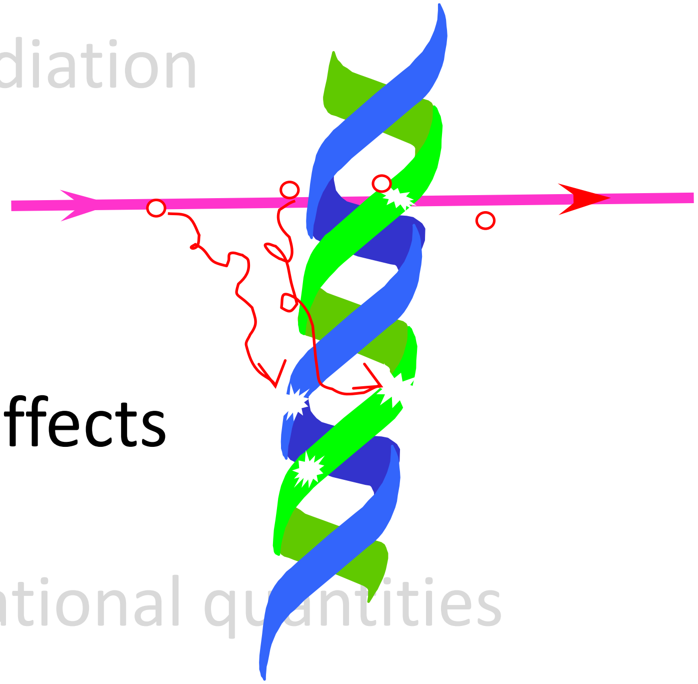
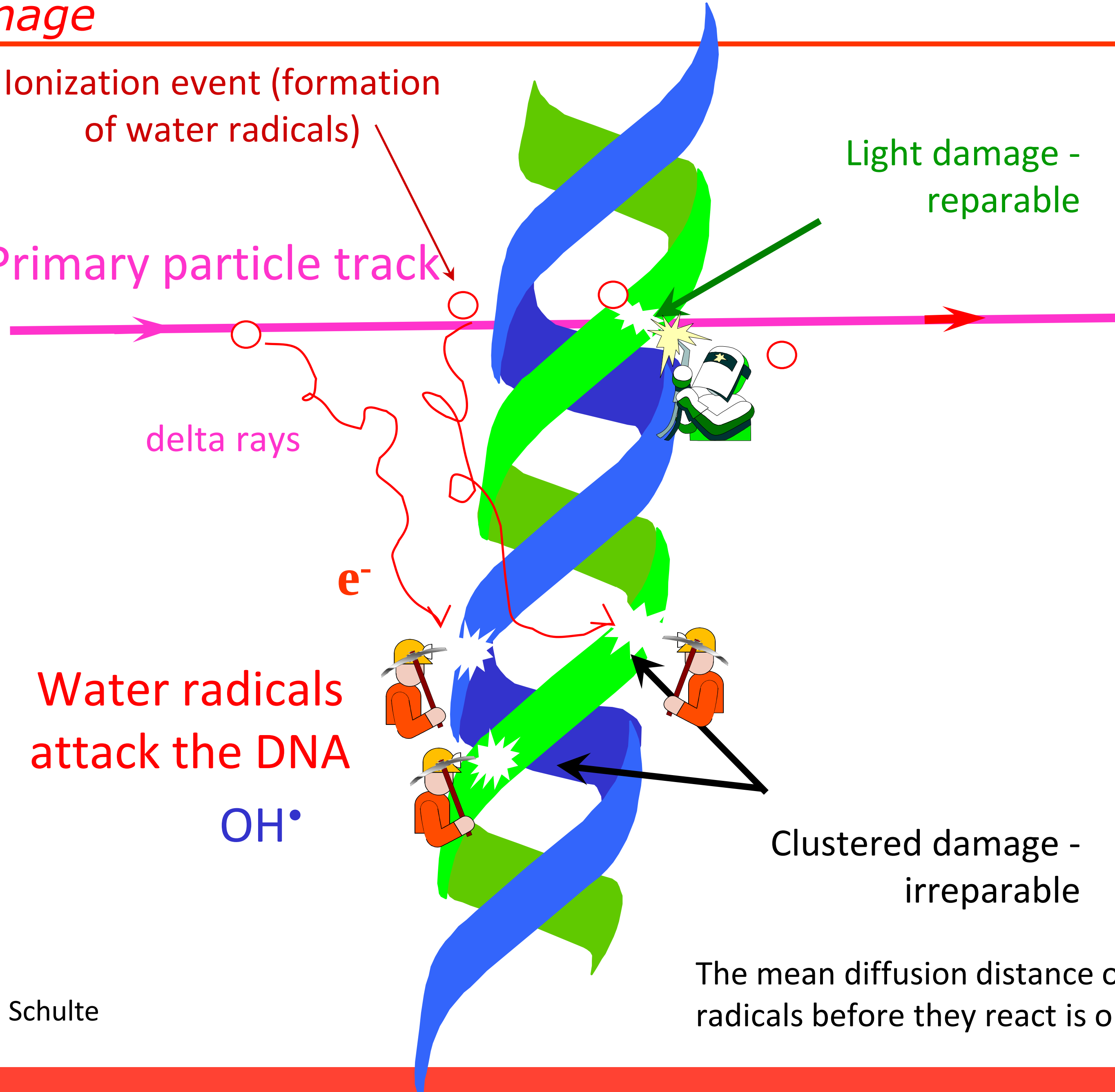


Unique effects of interaction of ionizing radiation with matter

- Biological systems (humans in particular) are particularly susceptible to damage by ionizing radiation
- The expenditure of a trivial amount of energy (~ 4 J/kg = 4 Gy) to the whole body is likely to cause death…
- …even if this amount of energy can only raise the gross temperature by about 0.001 °C
- This is because of the ability of ionizing radiation to impart their energy to individual atoms and molecules
- The resulting high local concentration of absorbed energy can kill a cell either ***directly*** or through the formation of highly reactive chemical species such as ***free radicals*** (atom or compound in which there is an unpaired electron, such as H or CH_3) in the water medium that constitutes the bulk of the biological material

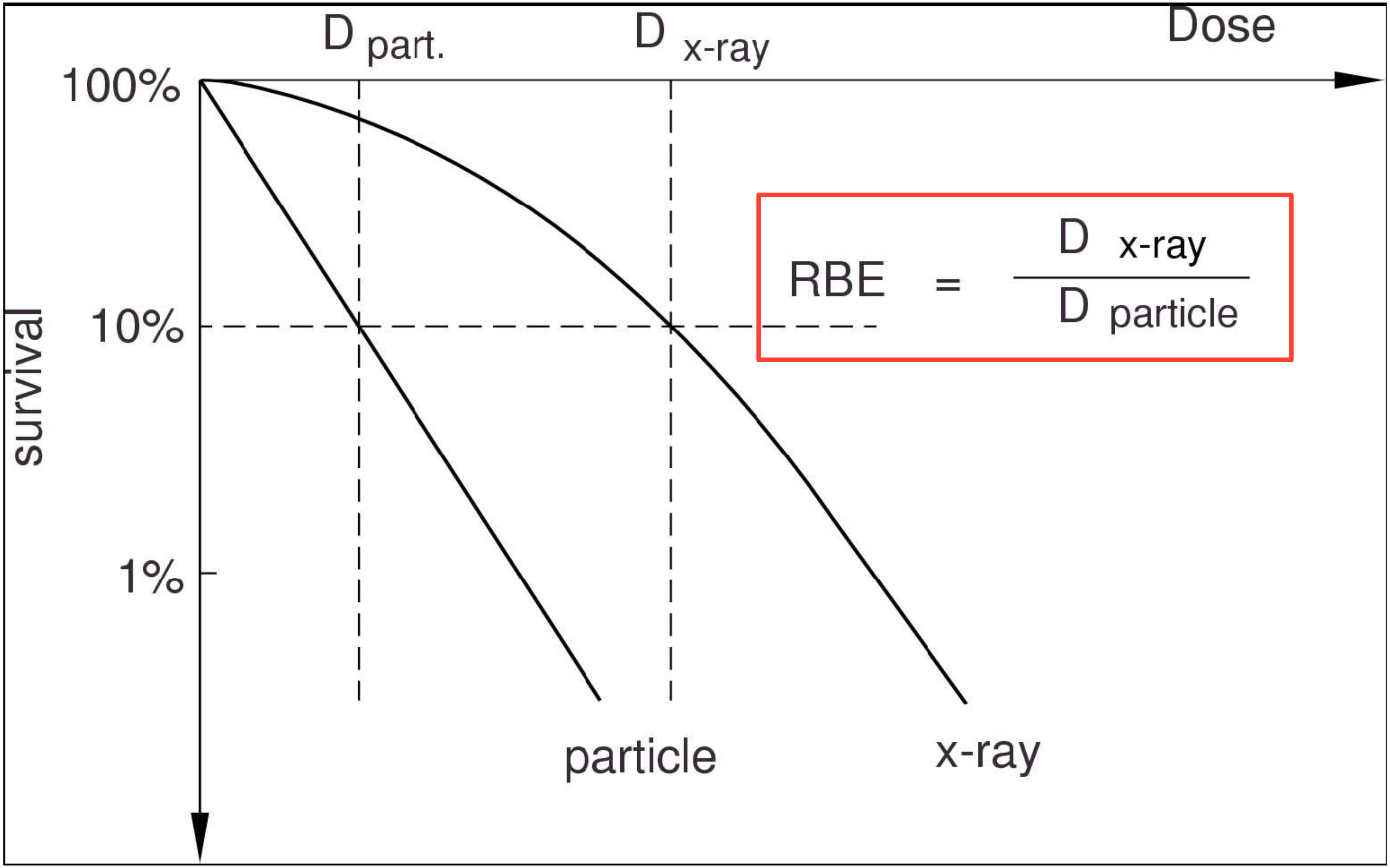
Main aim of **dosimetry** = measurement of the absorbed dose (energy/mass)



The mean diffusion distance of OH radicals before they react is only 2-3 nm

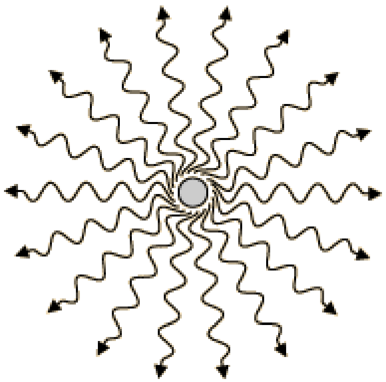
Courtesy R. Schulte

DIFFERENT TYPES OF RADIATION MAKE DIFFERENT DAMAGE



$$RBE = \frac{D_{x\text{-}ray}}{D_{particle}}$$

What are the biological effects of radiation?



Stochastic effects

no dose threshold (linear function of dose)

increase of probability by 5% per Sv for:

- genetic defects
- cancer

result does not dependent on the amount of absorbed dose

delayed health detriments

Deterministic effects

dose received in short time interval
dose threshold: > 500 mSv

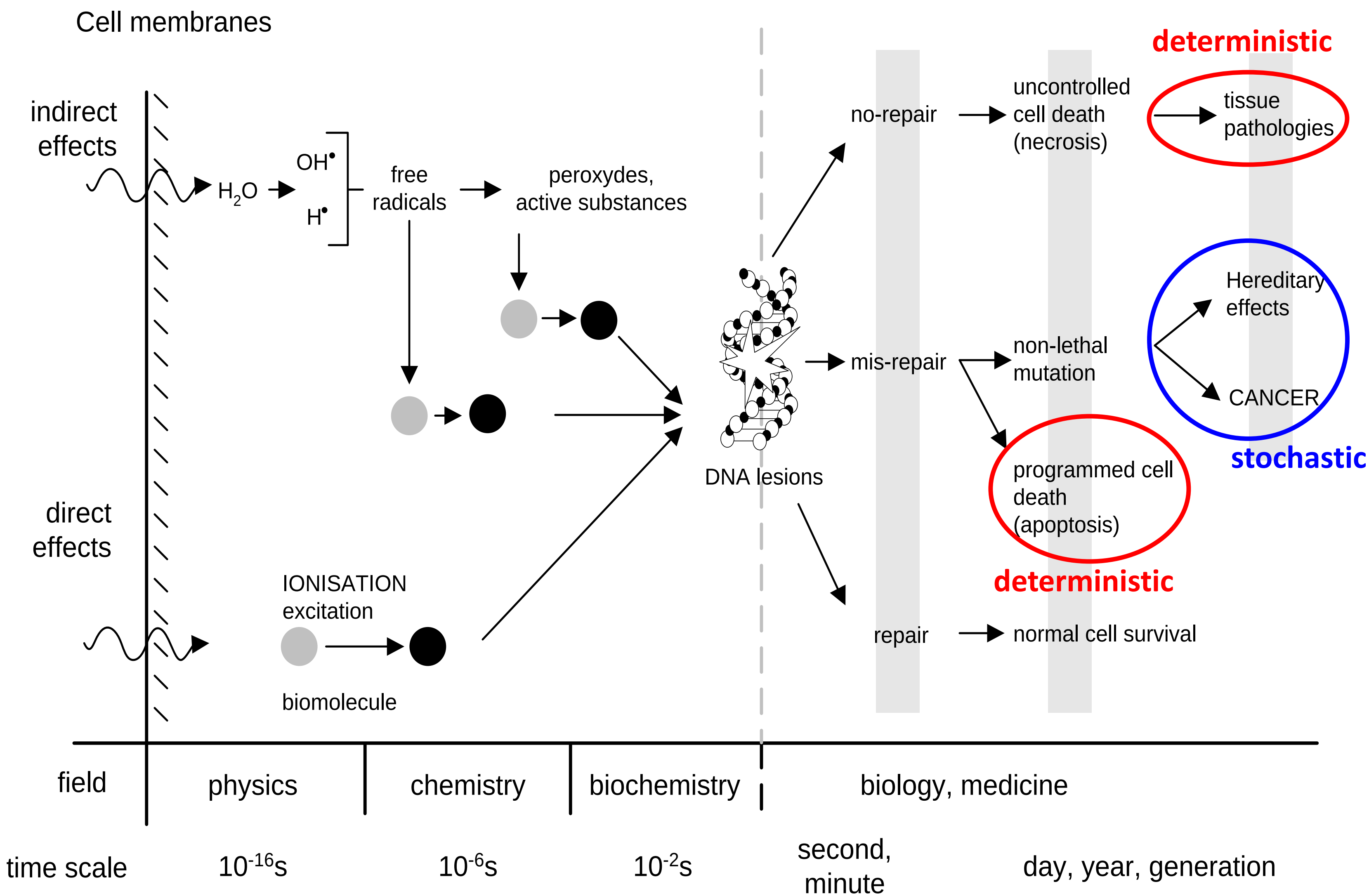
immediate consequences:

- vomiting
- immun deficiency
- erythema and necrose

health detriments are function of the dose

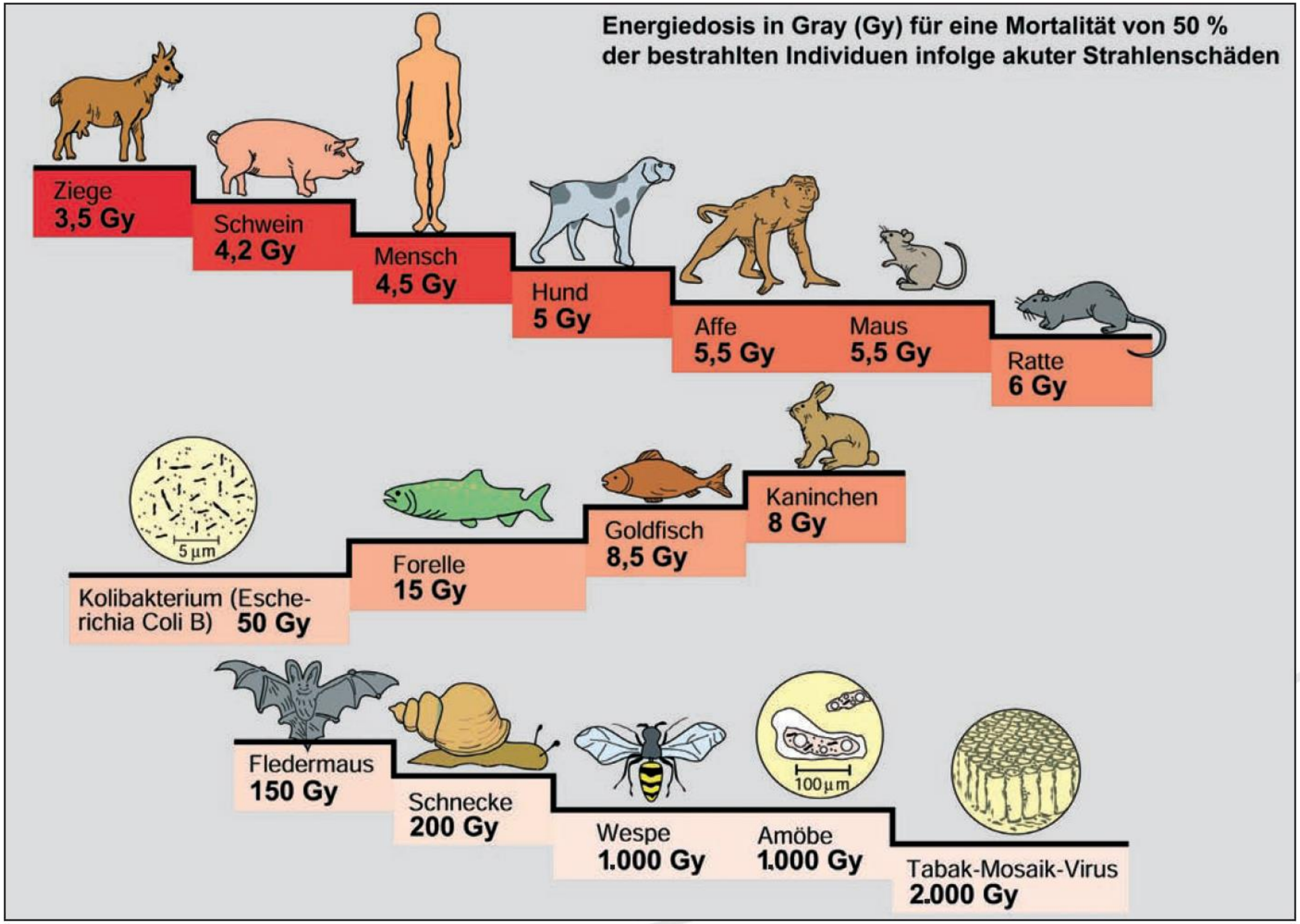
lethal dose: 5 – 7 Sv

The biological actions of radiation



Step	Time of appearance	Mechanisms
Physical	~ 10^{-16} s	Energy deposition by ionisation and excitation of the atoms
Physico-chemical	~ 10^{-10} s	Production of chemical compounds (ions radicals) which diffuse in the cell
Chemical	~ 10^{-6} s	Production of molecular lesions in the DNA
Cellular	~ hours	Lesions at cellular level and cell repair involvement
Deterministic effects	~ weeks	Expression of dysfunctions at the tissues and organs level
Stochastic effects	~ tens of years	Cancer induction and induction of heritable disorders

Lethal dose ($LD_{50/30}$) for various organisms



Source: Martin Volkmer, Radioaktivität und Strahlenschutz, Informationskreis Kernenergie

LD50 and effect of acute irradiation to humans

Whole body dose (Gy)	Organ or tissue failure responsible for death	Time at which death occurs after exposure (days)
3-5	Bone marrow	30-60
5-15	Intestine and lungs	10-20
>15	Nervous system	1-5

Lethal effects: LD50 for humans 3-5 Gy due to damage to bone marrow, in absence of bone marrow transplantation

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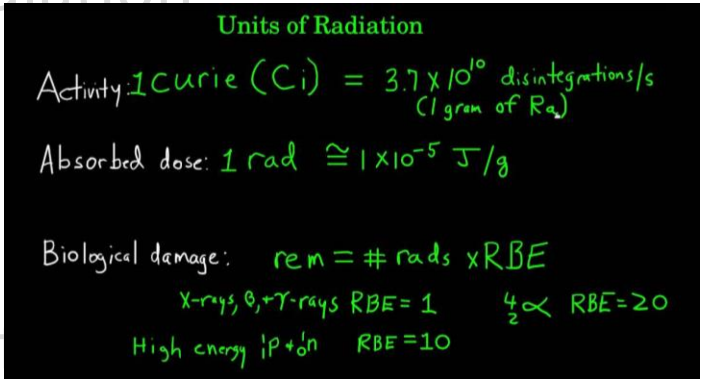

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1) **Justification**

   any exposure of persons to ionizing radiation has to be justified

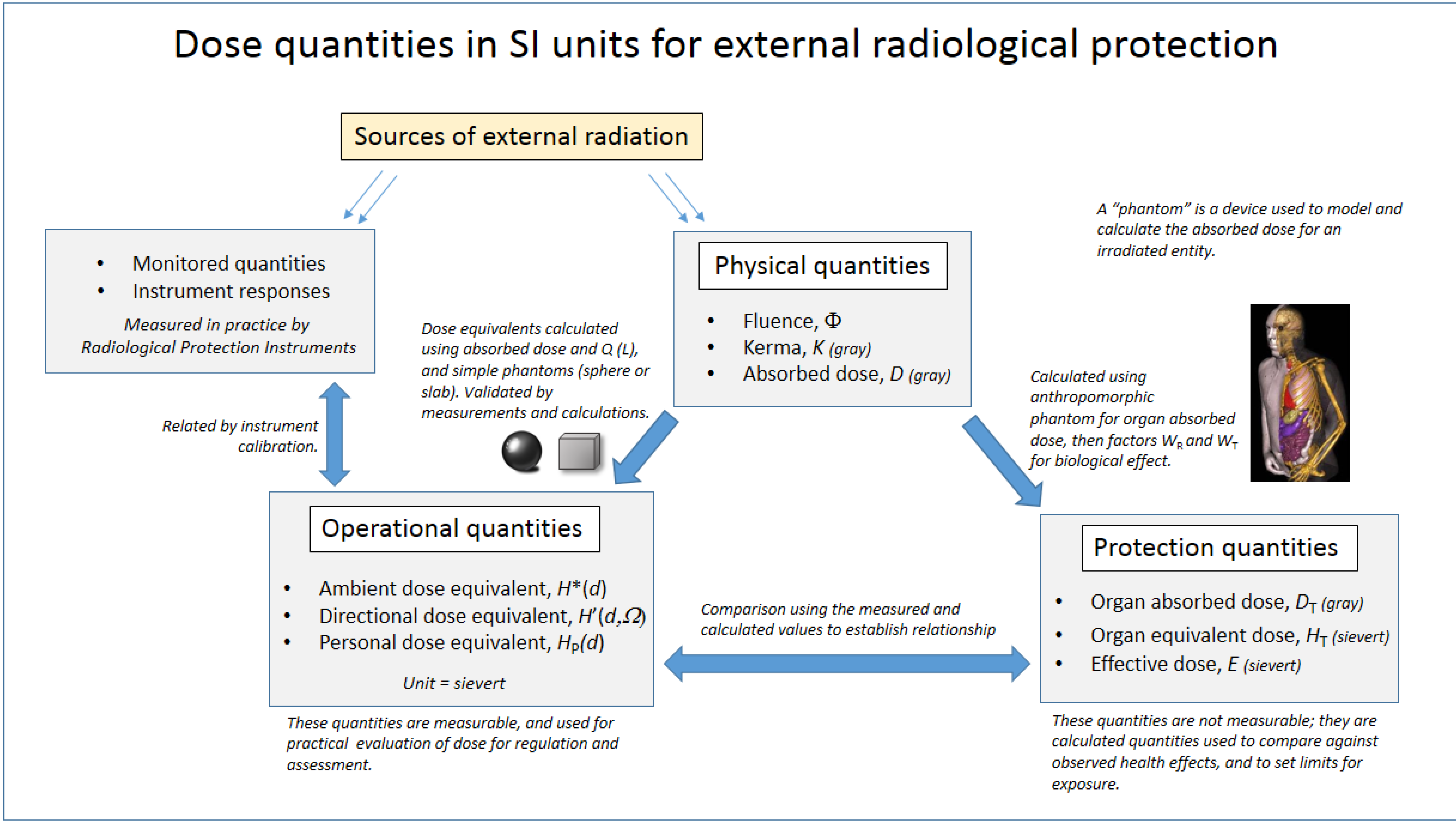
2) **Limitation**

   the personal doses have to be kept below the legal limits

3) **Optimization**

   the personal doses and collective doses have to be kept As Low As Reasonable Achievable (**ALARA**) – including social and economical factors into account

International Commission on Radiological Protection



Source: Wikipedia

Absorbed Dose D: energy absorbed per mass

Unit: Gy 1 Gy = 1 J/kg

(1 Gy = 100 rad)

$$D = \frac{1}{m}\int E\,dV$$

Equivalent Dose H: absorbed dose of organs weighted by the radiation weighting factor w_R of radiation R:

Unit: Sv (1 Sv = 100 rem)

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

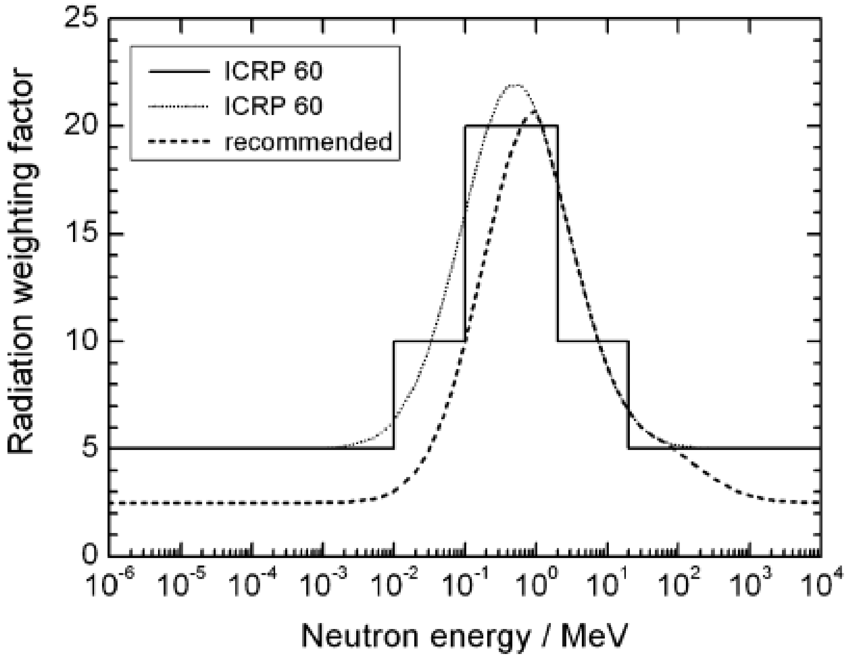
Effective dose E: Sum of all equivalent doses weighted with the weighting factor w_T for tissue T

Unit: Sv (1 Sv = 100 rem)

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

Type and energy of radiation R	w_R
Photons, all energies	1
Electrons and muons, all energies	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	

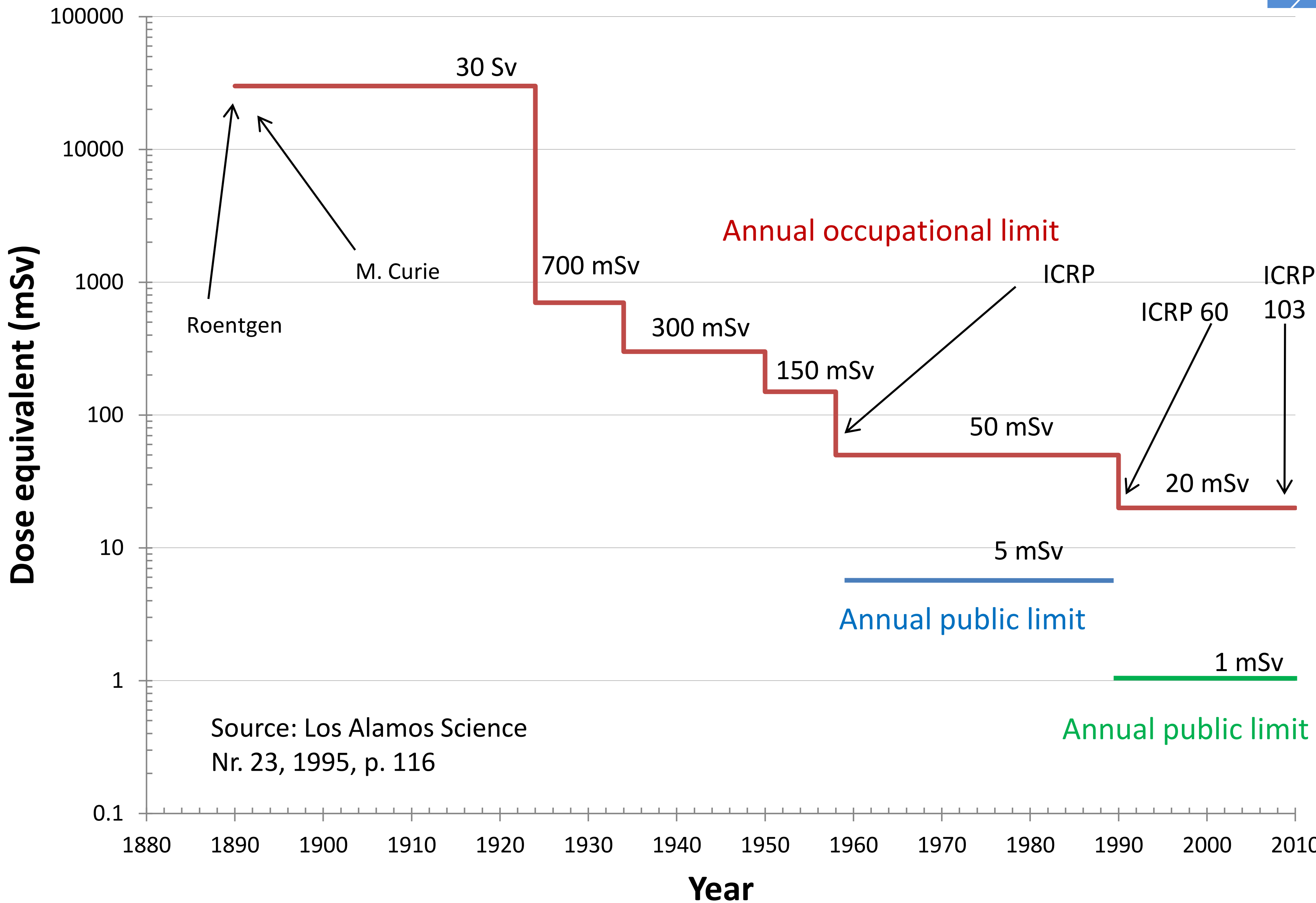
$$w_R = \begin{cases} 2.5 + 18.2\, e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0\, e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leqslant E_n \leqslant 50 \text{ MeV} \\ 2.5 + 3.25\, e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases}$$



Organ / tissue	No of tissues	W_T	Total contribution
Bone-marrow, colon, lung, breast, stomach, remainder tissues	6	0.12	0.72
Gonads	1	0.08	0.08
Bladder, esophagus, liver, thyroid	4	0.04	0.16
Bone surface, brain, salivary glands, skin	4	0.01	0.04

The tissue weighting factors are sex- and age-averaged values for all organs and tissues

- **Quantities on which limits are based** (effective dose, organ equivalent dose) are not measurable
- So **operational quantities** are defined
  - measurable quantities
  - quantities which are representative of the quantities on which limits are based (where possible overestimating these)
- **For external exposure:**
  - ambient dose: **H*(10)**
  - personal dose: **$H_p(10)$** and **$H_p(0,07)$**
- **For internal exposure** (after an intake):
  - committed effective dose (over 50 years): **E(50)**



Source: Los Alamos Science
Nr. 23, 1995, p. 116

External radiation source → external exposure

Contamination → Surface

Contamination → Volumetric (air)

Internal radiation source → internal exposure

- Person **occupationally exposed** to radiation (> 1 mSv/y)
  - Category **A** workers: > 6 mSv/y
  - Category **B** workers: < 6 mSv/y
- **Supervised area**: area with dose > 1 mSv/y

  (accessible to categories A and B workers)
- **Controlled area**: area with dose > 6 mSv/y

  (accessible to categories A workers, and with limited stay to category B workers)
- Exposure situations:
  - **risk of external exposure only** (sealed radioactive sources, radiation generators, for example X-ray tube)
  - **risk of internal and external exposure** (use of unsealed radioactive sources)

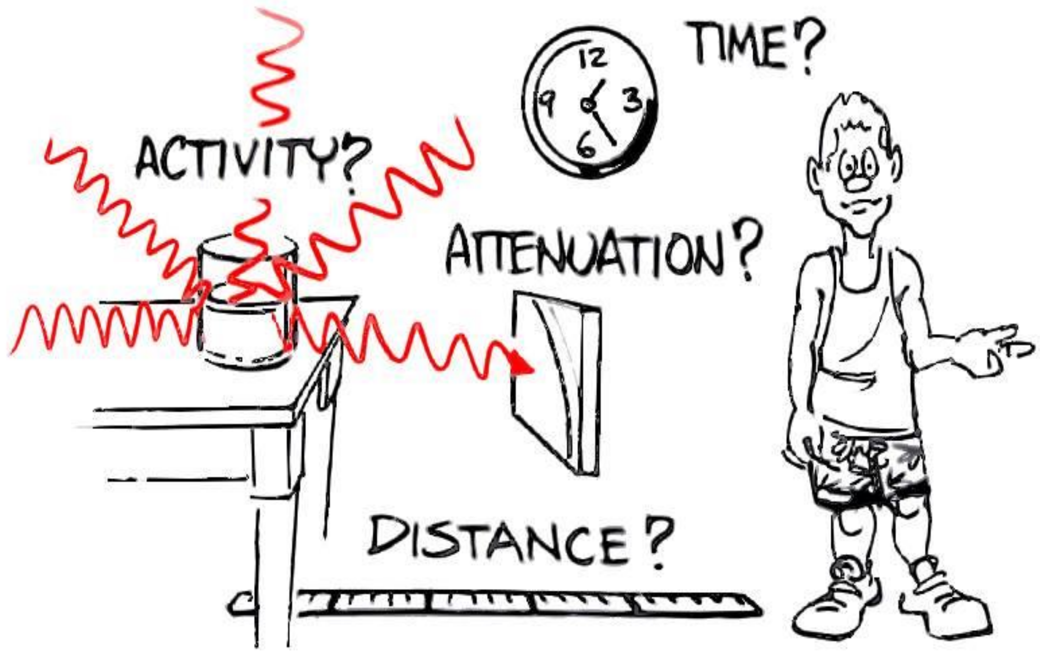
Area	Dose limit [year]	Ambient dose equivalent rate		Sign
		Work place	Low occupancy	RADIATION ZONE SURVEILLÉE SUPERVISED AREA
Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h	Dosimeter obligatory Dosimètre obligatoire Radiation Protection Radioprotection
Supervised	6 mSv	3 µSv/h	15 µSv/h	Dosimeter obligatory Dosimètre obligatoire Radiation Protection Radioprotection
Simple	20 mSv	10 µSv/h	50 µSv/h	
Limited Stay	20 mSv		2 mSv/h	LIMITED STAY SÉJOUR LIMITÉ Dosimeters obligatory Dosimètres obligatoires Radiation Protection Radioprotection
High Radiation	20 mSv		100 mSv/h	HIGH RADIATION HAUTE RADIATION Dosimeters obligatory Dosimètres obligatoires Radiation Protection Radioprotection
Prohibited	20 mSv		> 100 mSv/h	PROHIBITED AREA ZONE INTERDITE No Entry Défense d'entrer Radiation Protection Radioprotection

Radiation Area

Controlled Area

How you can protect yourself from radiation?

Three means: distance, time, shielding



- **Distance**: the dose rate decreases with the inverse squared of the distance (from a point-like source)
- **Time**: the dose is proportional to the time spent close to the source **D = dD/dt x t**
- **Shielding**: the dose rate approximately reduces as exp(-d/λ)
  λ = shielding properties of the material

For β radiation: plexiglass
For γ radiation: iron or lead
For n: concrete

- **Time:** limit the duration of the stay in the radiation field
  - Job preparation
  - Dry run
  - Monitoring of the duration of exposure
- **Distance:** stay as far as possible from the source
  - Dispersion law: $1/r^2$ for a point source, more like $1/r$ for an extended source
  - Very important at short distances
  - Factor of 100 between 1 cm and 10 cm (use of tongs/tweezers)
- **Shielding:** use of protective shields
  - Material and thickness of the shield depend of the type and energy of the radiation and of the reduction factor required

- Use of work processes and special tooling to reduce time in work area
- Staging and preparation of necessary materials and special tools
- Maximization of prefabrication in workshop
- Use of mock-ups for complex tasks
- “Dry-run” of the activities using applicable procedures
- Engineering, design and use of temporary shielding
- Use of remote handling procedures

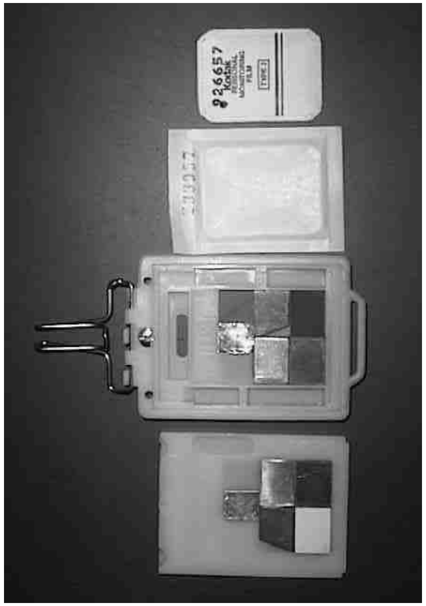
- **Isolating the radioactive substance**
  – use of containment
  – use of glove boxes
  – use of fume cupboards

- **Isolating the person**
  – do not eat, drink, or smoke in a supervised or controlled area
  – wear protection gloves and laboratory coats
  – use respiratory protective equipment

- **Wearing of a personal dosimeter** on the chest or at the waist
  - monthly measurement (at least)
  - delayed information (depends on dosimeter)
  - measurement threshold ~0.1 mSv/month
- **Wearing of an electronic dosimeter**
  - instantaneous information
  - possibility to setting a dose or dose rate alarm
- **Wearing an extremity dosimeter**
  - In the case of specific hand exposure risk (handling of radioactive substances)

- **The dosimeter is calibrated to measure:**
  - **$H_p(10)$:** personal equivalent dose at a depth of 10 mm in the chest
  - **$H_p(0.07)$:** personal equivalent dose at a depth of 0.07 mm in the chest
- **At low measured doses** (less than the limits) it is assumed that:
  - the effective dose and the equivalent dose to each organ is equal to $H_p(10)$;
  - the equivalent dose to the skin is equal to $H_p(0.07)$;
- **At high measured doses** (exceeding the limits),
  - an investigation is undertaken (**dosimetric reconstruction**) in order to determine the effective dose and the equivalent doses to the organs which were actually received.

Personal dosimetry for monitoring external exposure

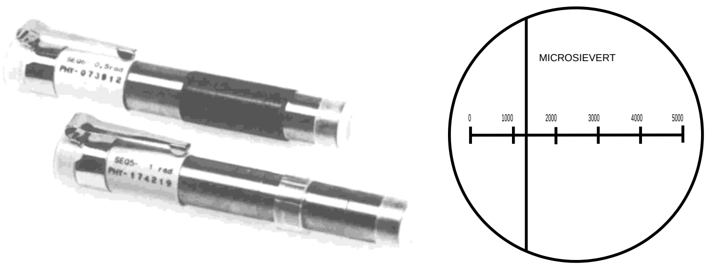


Kodak film badge

Personal dosimeter: "Legal dose"

RADOS DIS

Finger dosimeter

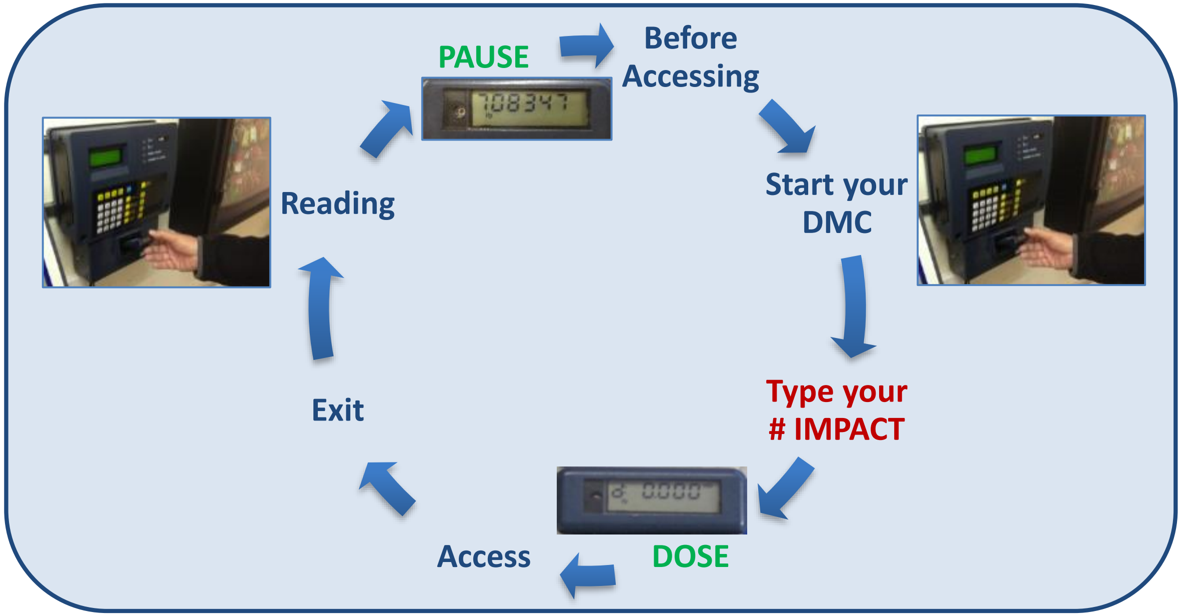


Quartz-fiber dosimeter (ionisation chamber and electroscope)

Operational dosimeter DMC: “Operational dose”

- Continuous measurement of $\beta\gamma$-dose (DIS-system) and integration of the neutron dose (track dosimeter)
- Obligation to wear the dosimeter in supervised and controlled areas
- Wearing of the dosimeter on the chest
- Reading at least once a month at a reader (about 50 readers available on the site)
- Possibility of checking the dose associated with a given operation (read the dosimeter before and after)
- Dosimeter to be returned to the dosimetry service at the end of stay or at the end of a 12 month period

- Obligation to wear an operational dosimeter in a controlled area
- Continuous βγ-dose measurement
- Instrument: DMC
- Display of Hp(10) (resolution of 1 mSv)
- Dose alarm at 2 mSv
- Dose rate alarm at 2 mSv/h
- Audible detection signal (« bip »)
- Record the dose before and after the operation


PAUSE
Before Accessing
Start your DMC
Type your # IMPACT
DOSE
Access
Exit
Reading


MGP
DMC 2000 S
07982

Radioactive contamination at particle accelerators can arise from:

- the use of unsealed radioactive sources
- activation of air and dust around the accelerators
- activation of oils or cooling fluids
- the machining or treatment of radioactive components
- normal or accidental emissions from targets whilst they are irradiated or after irradiation

Two factors should be considered in defining precautions for the control of unsealed radioactivity:

- the prevention of the contamination of
  - personnel
  - equipment

- Material that has been brought into and removed from an accelerator tunnel or bunker during shutdown (maintenance) will no be activated BUT …
- … it might be contaminated
- If there is a suspicion of contamination, it has to be checked before leaving the area

- **Internal** (+ **external**) exposure: the incorporated radionuclides irradiate the organs and tissues to which they attach
- Exposure lasts until the complete elimination of the radionuclides by radioactive decay and biological metabolism

Internal exposure can occur by:

- ingestion

- inhalation

- skin

- Determination of the activity taken into the body and calculation of the **committed effective dose** with a standard model
- **Measurements to determine the activity taken into the body:**
  - direct measurement of the radiation emitted by the person using a thyroid monitor, a lung monitor or a whole body monitor (WBC, whole body counter)
  - measurement of the activity in the excreta (urine, faeces)
- **Two stages strategy:**
  - screening measurement (with a simple laboratory instrument)
  - If a threshold is exceeded, actual measurement of the intake

- **Operational quantity**: committed effective dose E_{50}
- For radionuclides with **short half-live**, the dose is received in the days following the intake;
- For radionuclides with a **long half-live** (strontium-90, actinides), the dose is received over many years following the intake;
- **The committed dose** is attributed to the period of intake;
- Dose is calculated using standard metabolic models;
- If dose limits are exceeded an **investigation is undertaken** (dosimetric reconstruction) to determine the committed dose; an adaptation of the model may be necessary.

For low level contamination / low risk

« Tyvek » overall
(synthetic paper)

Rubber gloves

… generally completed
by overshoes

For higher levels of contamination = higher risk

- Tyvek overall
- Tape-sealed gloves
- Overshoes
- Respiratory Protective Equipment

Personal protection equipment against contamination

Whole body protection from contamination



Ventilated, filter and over-pressurized

Tyvek

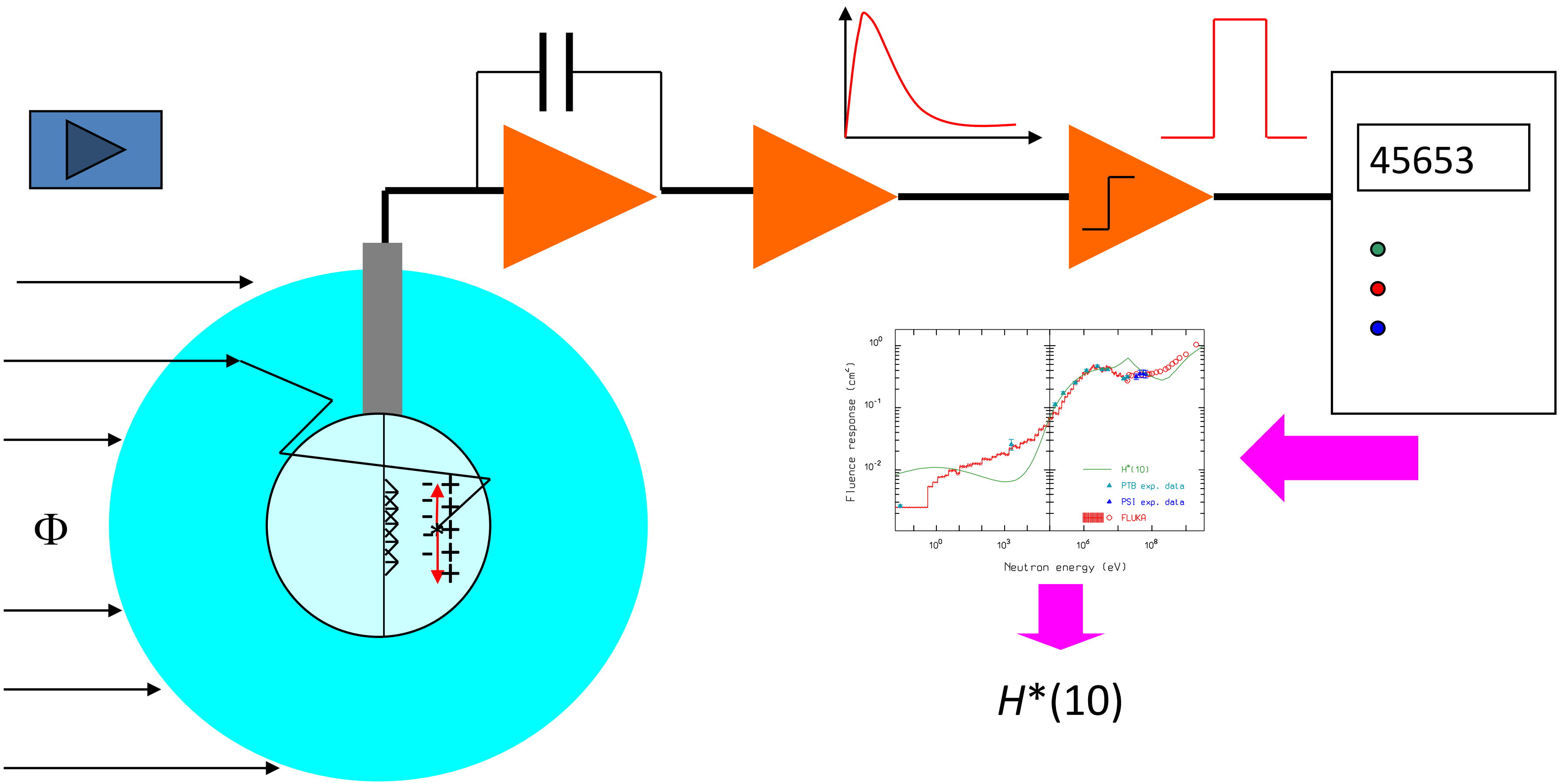



Personal protection equipment against contamination

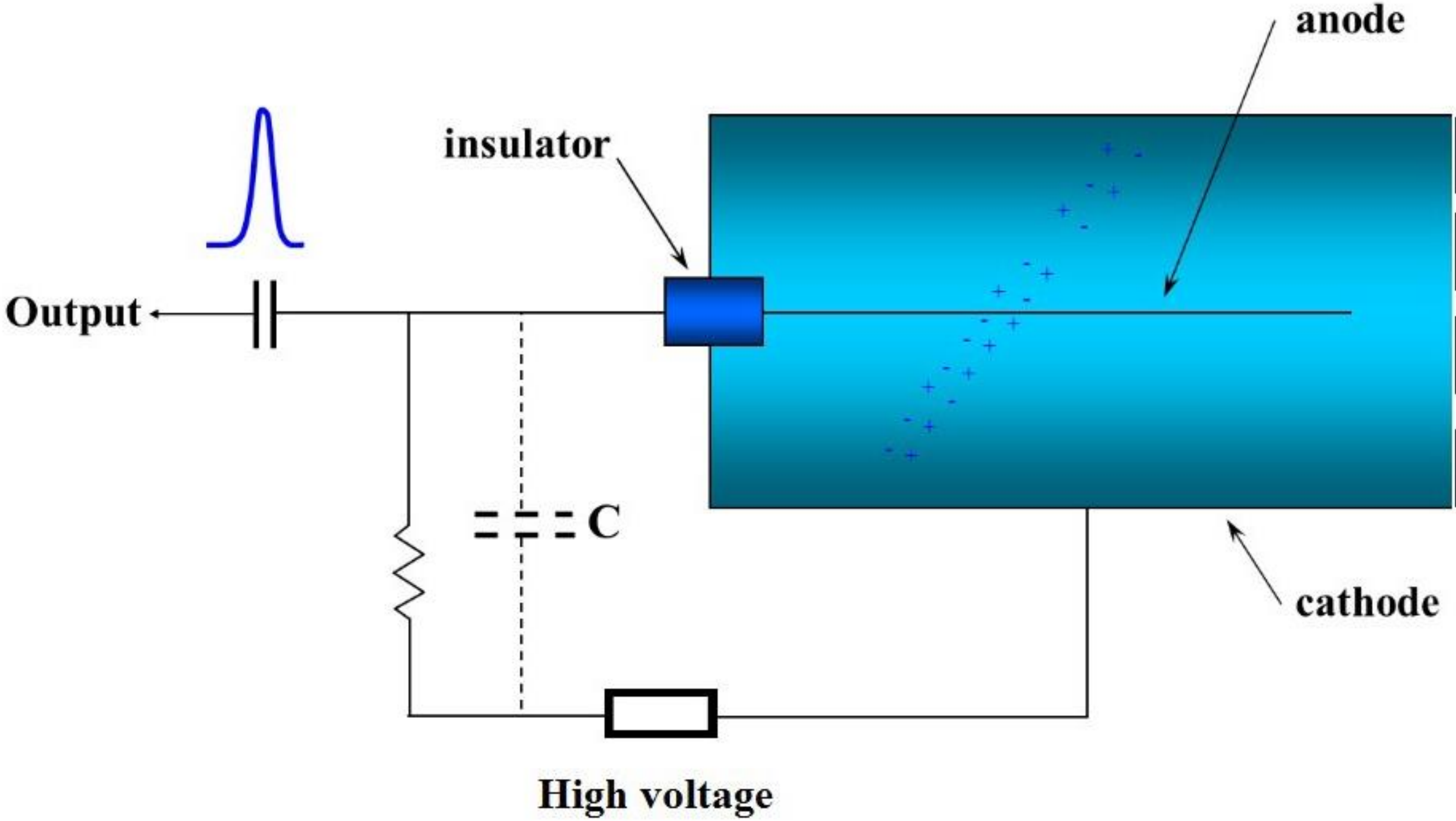
Individual protection equipment is mandatory for work in areas with contamination risk (cleaning operations, machining of radioactive material or equipment, …)

- A very brief historical introduction
- Directly and indirectly ionizing radiation
  - Radioactivity
  - Natural exposures
- The effects of ionizing radiation
  - Deterministic and stochastic effects
- Radiological quantities and units
  - physical, protection and operational quantiti
- Principles of radiation protection
  - Justification, optimization and do
  - The ALARA principle
- Protection means
- **Instrumentation for measuring ionizing radiation**

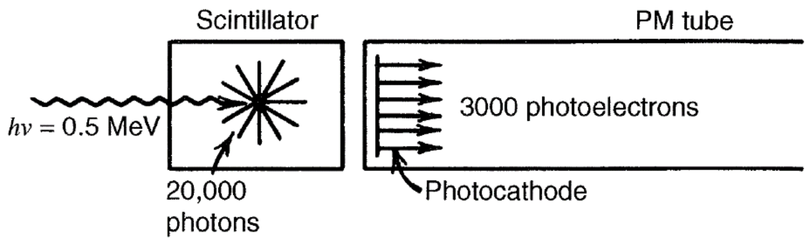
Since the Radiation Protection quantities are not directly measurable, their estimate involves the measurement of a physical quantity.

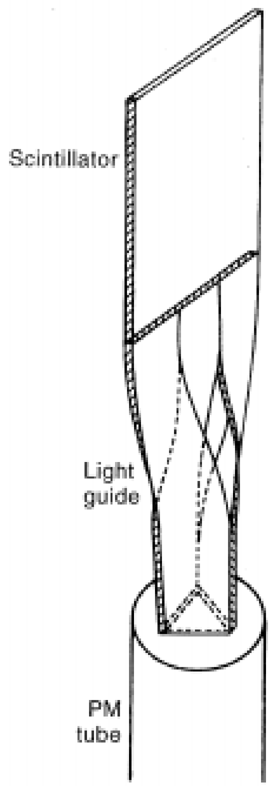


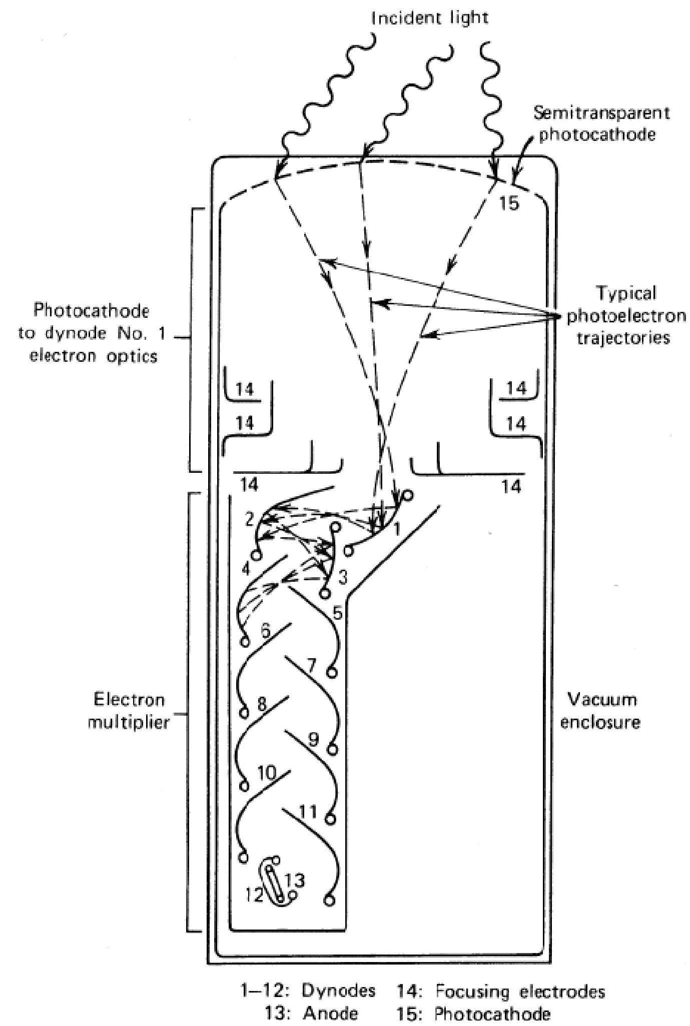
Courtesy S. Agosteo, Politecnico di Milano


anode
insulator
Output
C
cathode
High voltage

Scintillating crystal coupled to a PMT



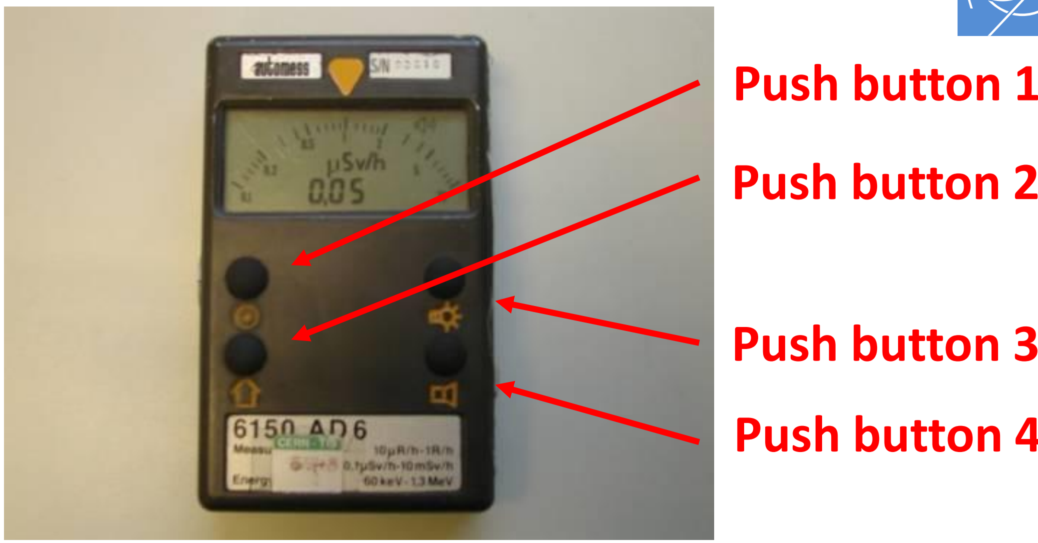




From Glenn F. Knoll, Radiation Detection and Measurement

AUTOMESS dose rate meter 6150 AD6

AD17 external probe



Detector: Geiger Müller counter
Range: 0.5 µSv/h – 10 mSv/h
Energy range: 60 keV – 1.3 MeV
Dimensions: 130 mm x 80 mm x 29 mm
Alimentation: 9 V standard battery

ADK surface contamination meter for α, β and γ radiation
Detector: sealed proportional counter
Active surface 100 cm²

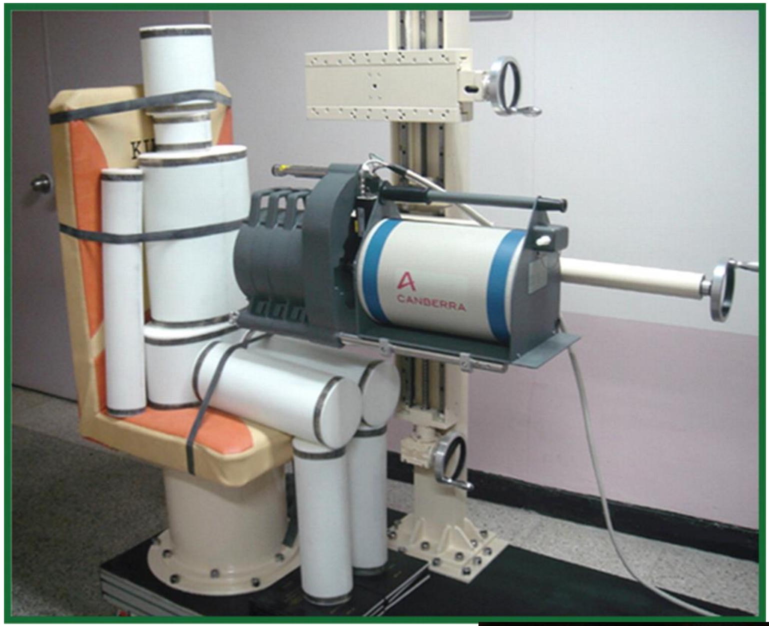
APA

CMS2000

Air contamination monitors

Hand and foot monitor

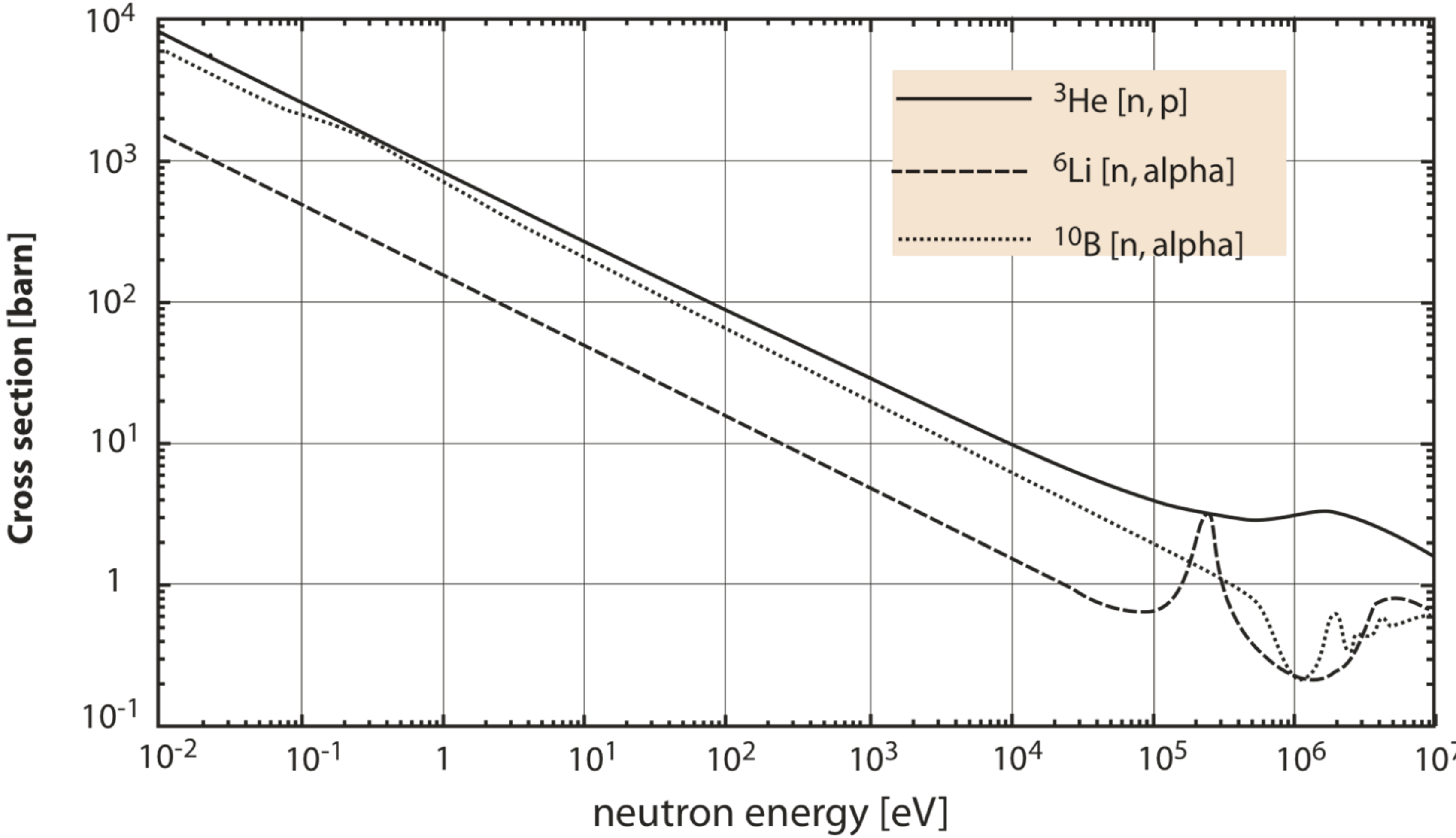
ABPM203M


CANBERRA

Some elements have a very large cross section for slow neutrons and can be exploited for neutron detection

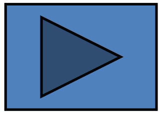
1)	Boron	$^{10}B + n \rightarrow {}^{7}Li + \alpha$	Q = 2.793 MeV
		$^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha$	Q = 2.310 MeV
2)	Lithium	$^{6}Li + n \rightarrow {}^{3}H + \alpha$	Q = 4.78 MeV
3)	^{3}He	$^{3}He + n \rightarrow {}^{3}H + p$	Q = 764 keV

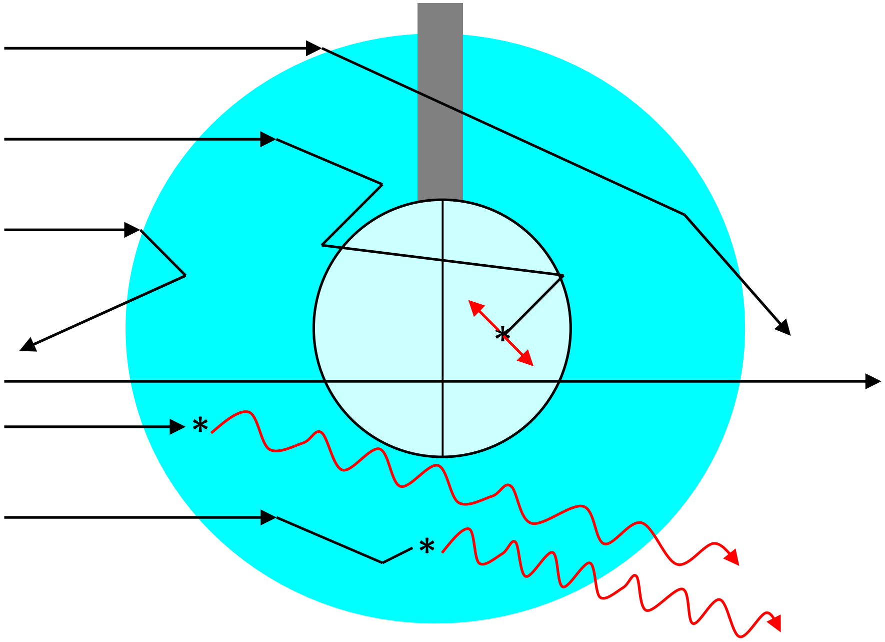
Neutron cross sections



Mean free path of thermal neutrons
- in ^{3}He gas ≈ 7 cm
- in solid ^{10}B ≈ 70 µm

Moderator-type neutron detector



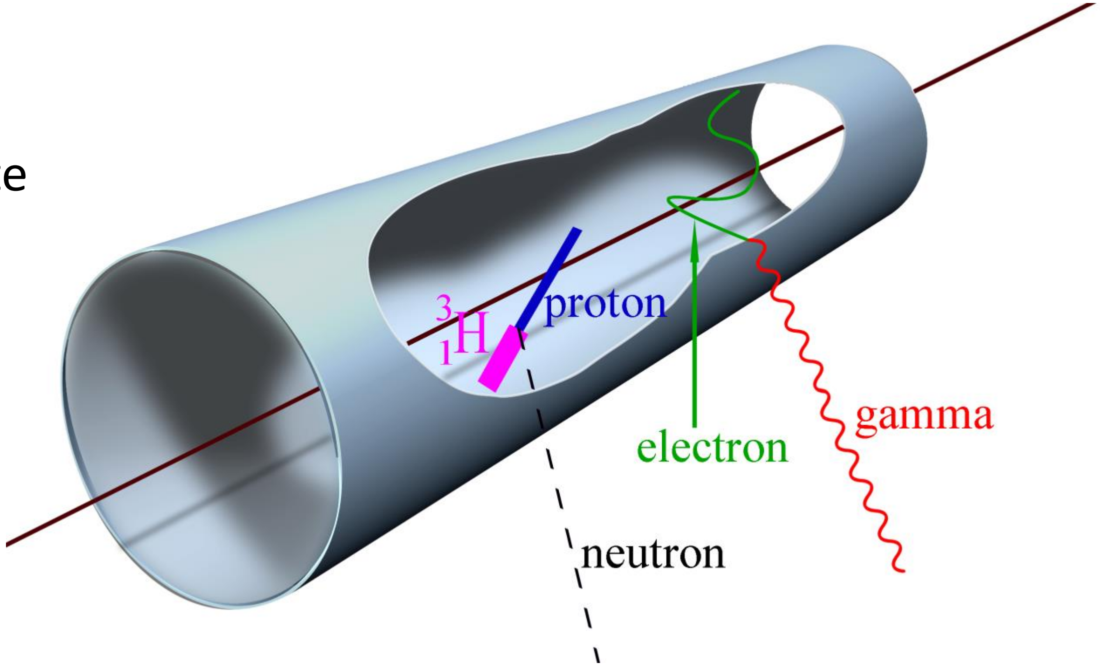


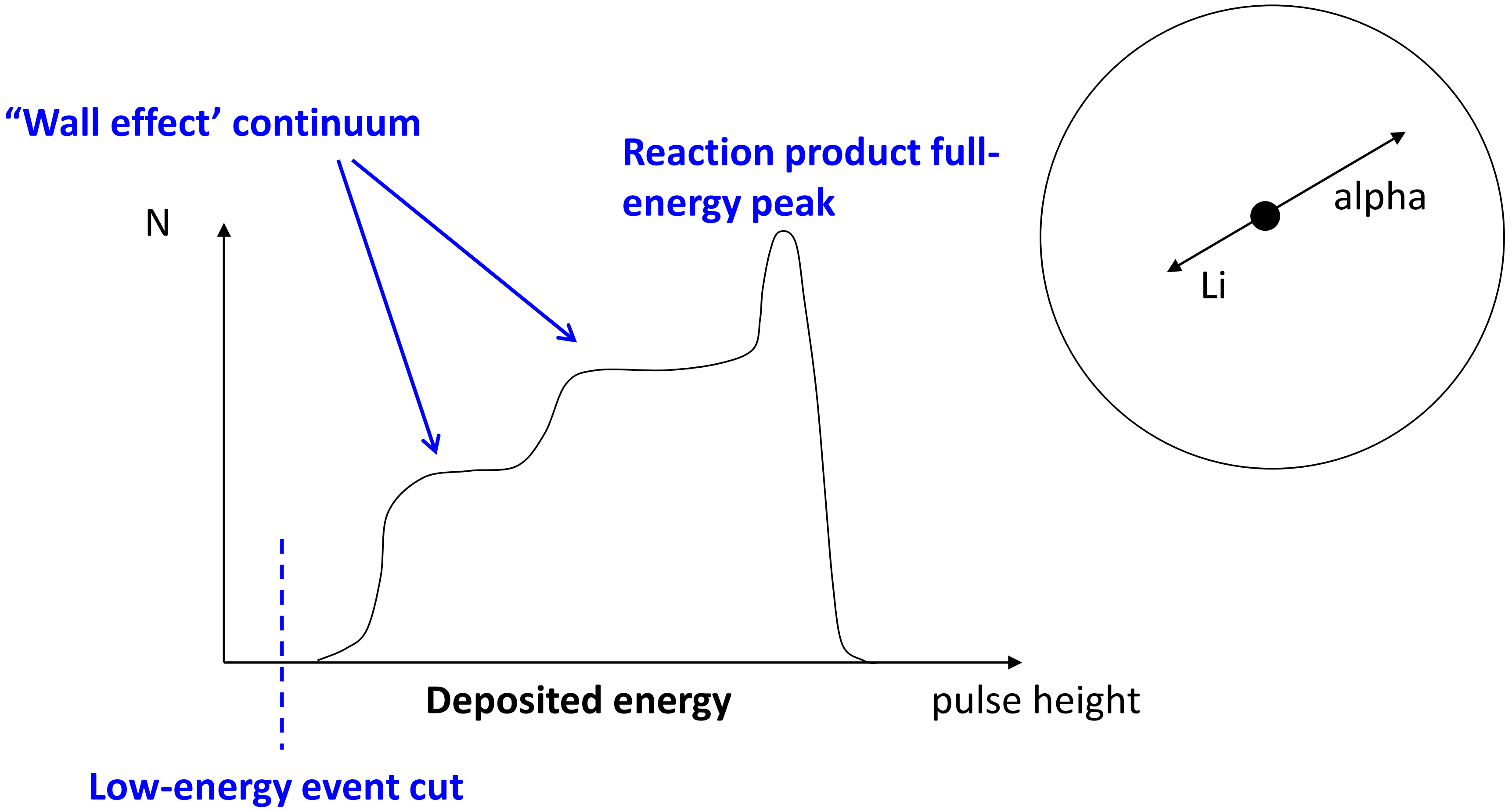
Courtesy S. Agosteo, Politecnico di Milano

BF_3 gas and ^3He gas make detectors for slow neutrons with excellent gamma discrimination

Gamma rays can interact in the walls and produce electrons in the gas, but the energy loss of electrons is small (≈ 2 keV/cm), so that these pulses are much smaller than those due to neutrons

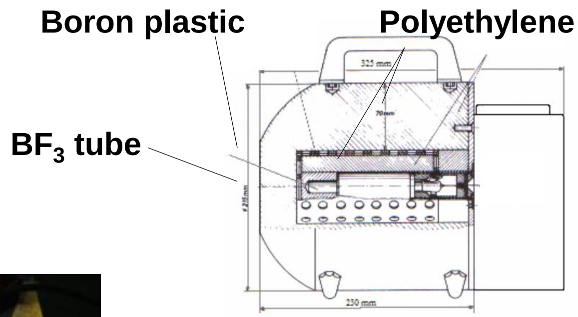
A suitable pulse amplitude threshold can thus eliminate most gamma interactions.



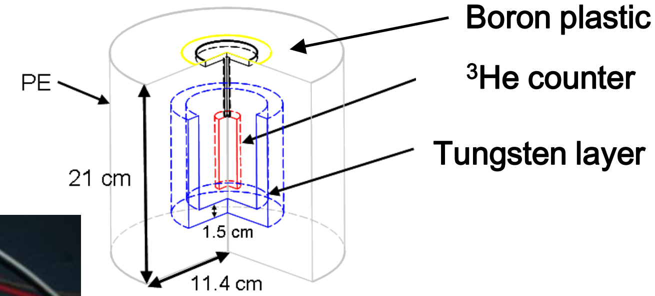


The shape of the pulse height spectrum is due to the energy loss of the recoils in the gas

Rem counters

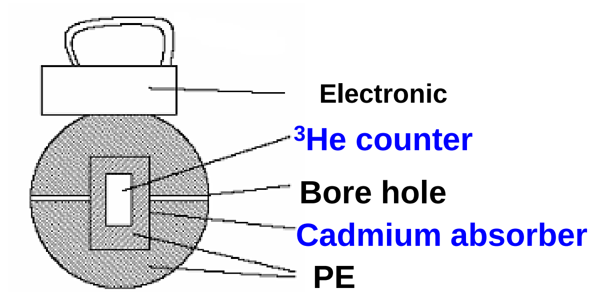


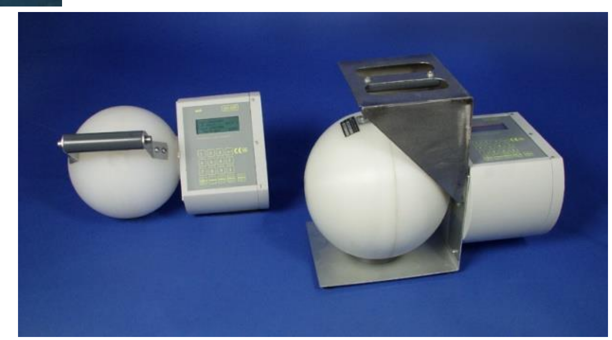
Studsvik 2202D



Eberline WENDI-2

Berthold LB6411 (also LB6411Pb)

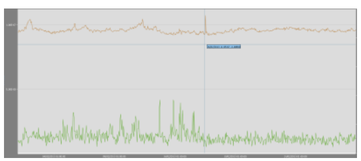




MAB SNM500(X)

- **Active monitoring**
  - Ambient dose rate
  - Water contamination
  - Airborne contamination
  - Weather parameters
  - Gate monitors
- **Passive monitoring**
  - Thermoluminescent dosimeters placed in the environment

Stray radiation



Air

Water

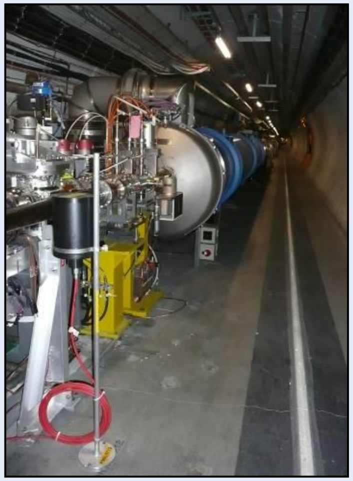
Other environ-mental samples

REM counter

Gas filled, high pressure ionization chamber

Beam-on: to protect workers in areas adjacent to accelerator tunnels and experiments against prompt radiation (mainly neutrons, E < some GeV)

Alarm function



Air filled ionization chamber

Beam-off: to protect workers during maintenance and repair against radiation fields caused by decay of radionuclides (mainly gammas, E < 2.7 MeV)

No alarm function

Site Gate Monitor

Reading of radiation levels directly available

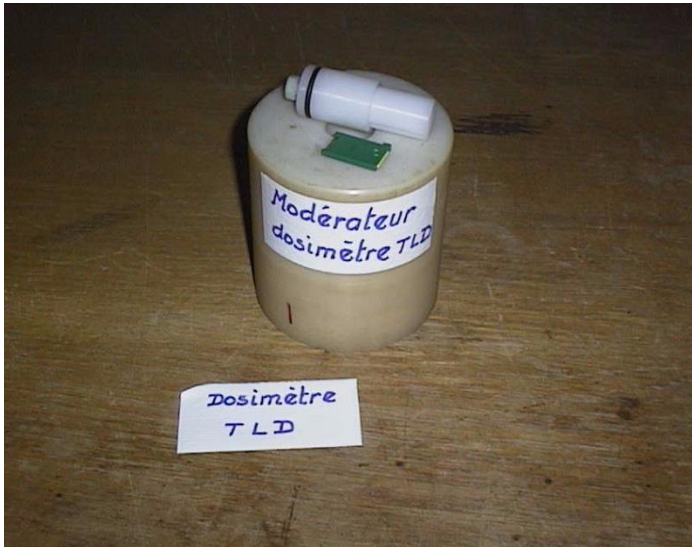
Radiation Alarm Unit (RAMSES)

RED flashing light + SOUND
ALARM → Evacuation of the area

ORANGE flashing light + SOUND
WARNING → Limited stay

Green fixed light = NORMAL situation
(radiation levels low, monitoring system ON)

Thermoluminescence dosimeters (TLD) inside a polyethylene moderators are used to monitor neutron and gamma doses in the experimental areas and in the environment.



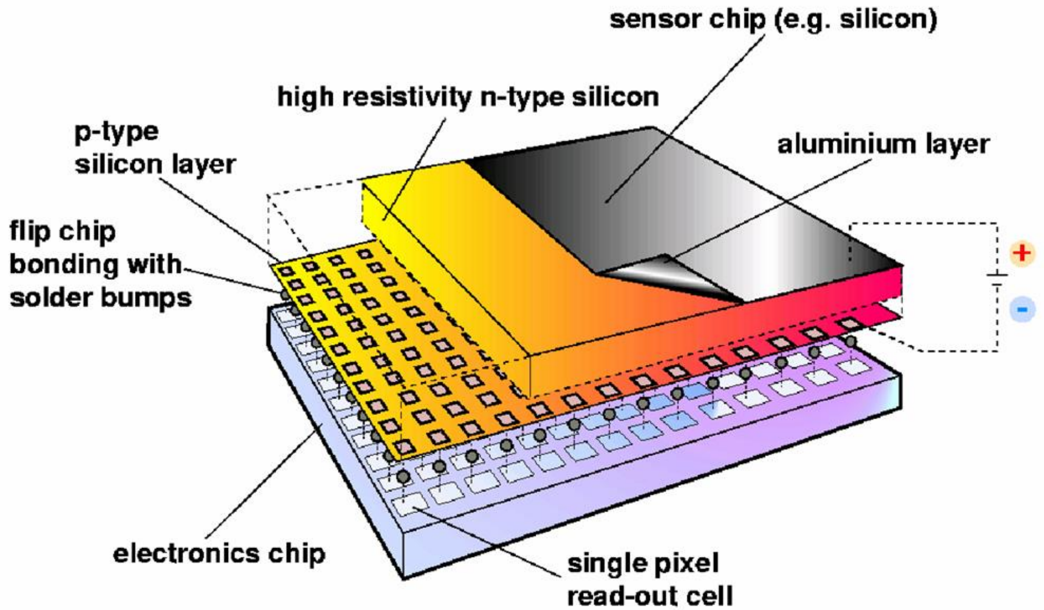
TLDs are passive devices used CERN-wide to integrate radiation doses over a period of several months.

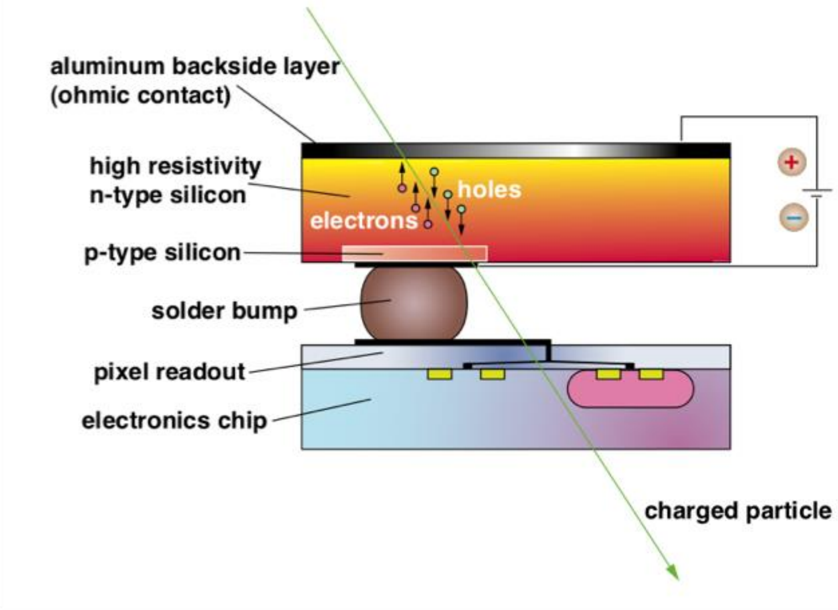
Glenn F. Knoll, Radiation Detection and Measurement, 4th edition

Frank H. Attix, Introduction to Radiological Physics and Radiation Dosimetry

Annals of the ICRP (International Commission on Radiological Protection)
http://www.icrp.org/publications.asp

ICRU publications, International Commission on Radiation Units and Measurements
http://www.icru.org/


sensor chip (e.g. silicon)
high resistivity n-type silicon
p-type
silicon layer
aluminium layer
flip chip
bonding with
solder bumps
+
-
electronics chip
single pixel
read-out cell


aluminum backside layer
(ohmic contact)
high resistivity
n-type silicon
holes
electrons
p-type silicon
solder bump
pixel readout
electronics chip
charged particle

Uranium glass

- Usually about 2% weight of ^{238}U in form of oxide diuranate
- Negligibly radioactive
- Decays according to the Radium (Uranium) series decay chain
  - α – 4.270 MeV (4.47E9 years)
  - β – 0.273 MeV (24.1 hour)
  - β – 2.197 MeV (6.7 hour)
  - α – 4.859 MeV (245500 years)
  - α – 4.770 MeV (75380 years)
  - α – 4.871 MeV (1602 years)
  - α – 5.590 MeV (3.82 days)
  - …