THE THIRD BIENNIAL AFRICAN SCHOOL OF FUNDAMENTAL PHYSICS AND ITS APPLICATIONS

Cheikh Anta Diop University
Dakar, Senegal
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Radiation measurements and dosimetry

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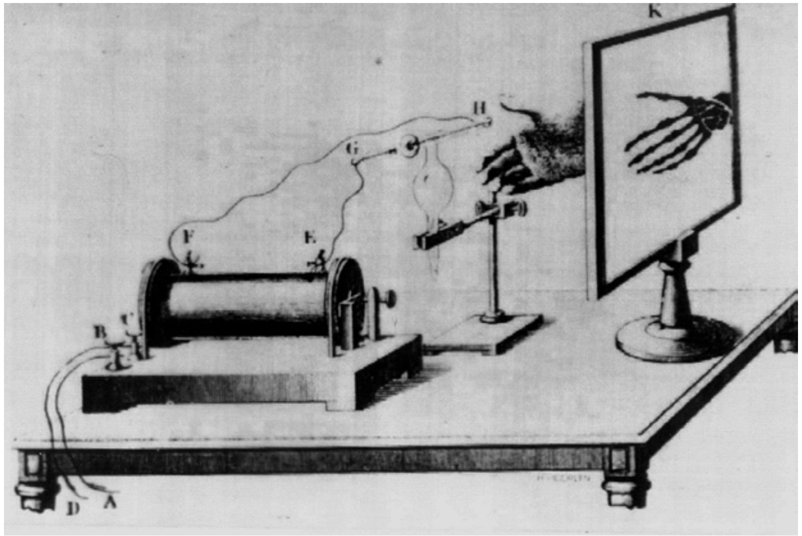
- Directly and indirectly ionizing radiation, radioactivity
- The effects of ionizing radiation
  - deterministic and stochastic effects
  - natural exposures
- Radiological quantities and units
  - physical, protection and operational quantities
- Principles of radiation protection
  - justification, optimization and dose limitation
  - the ALARA principle
- Protection means
- Instrumentation for measuring ionizing radiation



1895

Discovery of X rays

Wilhelm C. Röntgen

1897

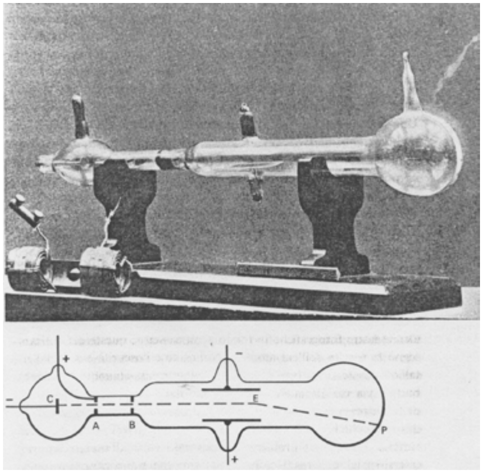
First treatment of tissue with X rays

Leopold Freund

J.J. Thompson

1897

"Discovery" of the electron



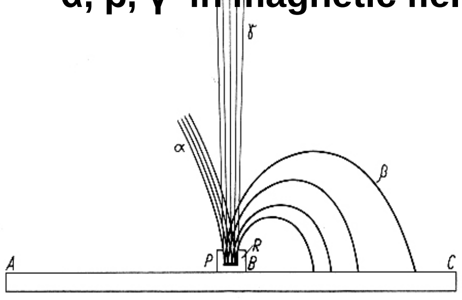
Henri Becquerel (1852-1908)

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)**

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

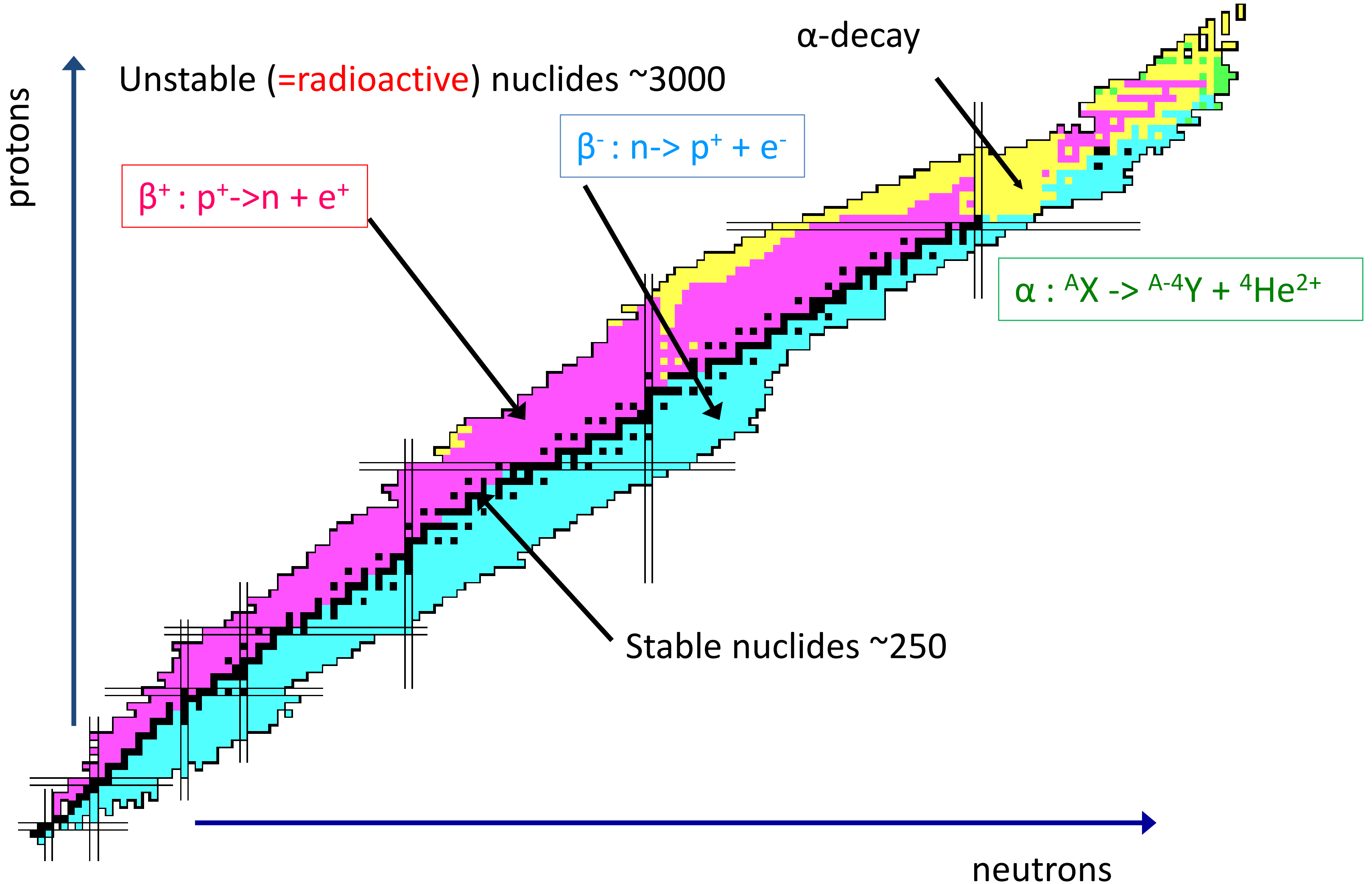
Radioactivity: the phenomenon whereby atoms undergo spontaneous random disintegration, usually accompanied by the emission of ionising radiation. The rate at which this nuclear transformations occurs in matter containing radionuclides is called **activity**:

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

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** 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)


protons
Unstable (=radioactive) nuclides ~3000
α-decay
β⁻ : n-> p⁺ + e⁻
β⁺ : p⁺->n + e⁺
α : ᴬX -> ᴬ⁻⁴Y + ⁴He²⁺
Stable nuclides ~250
neutrons

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

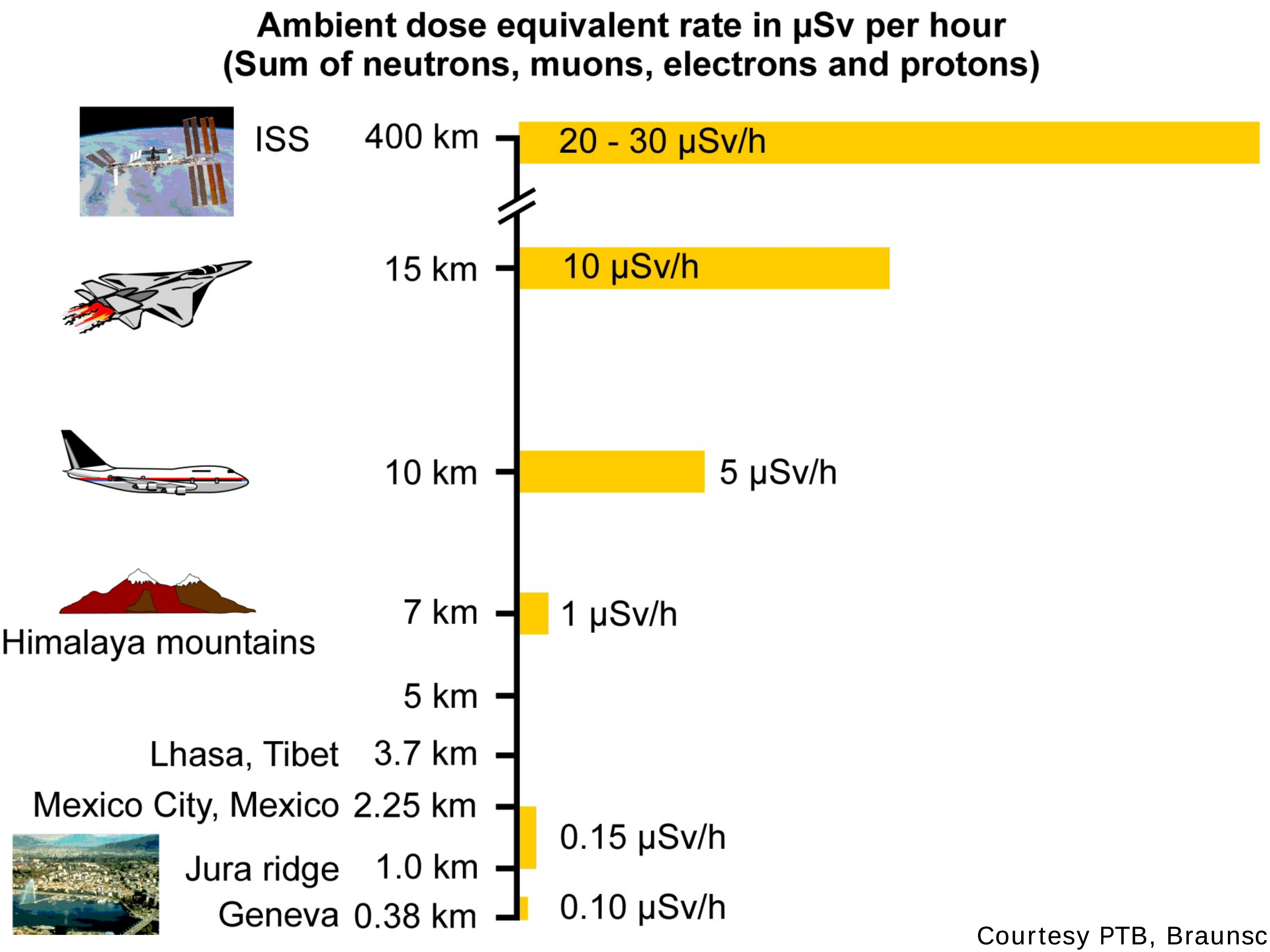
Nuclide	Symbol	Half-life	Nuclear Reaction
Carbon-14	^{14}C	5730 y	e.g. $^{14}N(n,p)^{14}C$
Tritium-3	^{3}H	12.3 y	Interaction of cosmic radiation with N or O $^{6}Li(n,\alpha)^{3}H$
Beryllium-7	^{7}Be	53.28 d	Interaction of cosmic radiation with N or O

More cosmogenic radionuclides:

^{10}Be, ^{26}Al, ^{36}Cl, ^{80}Kr, …

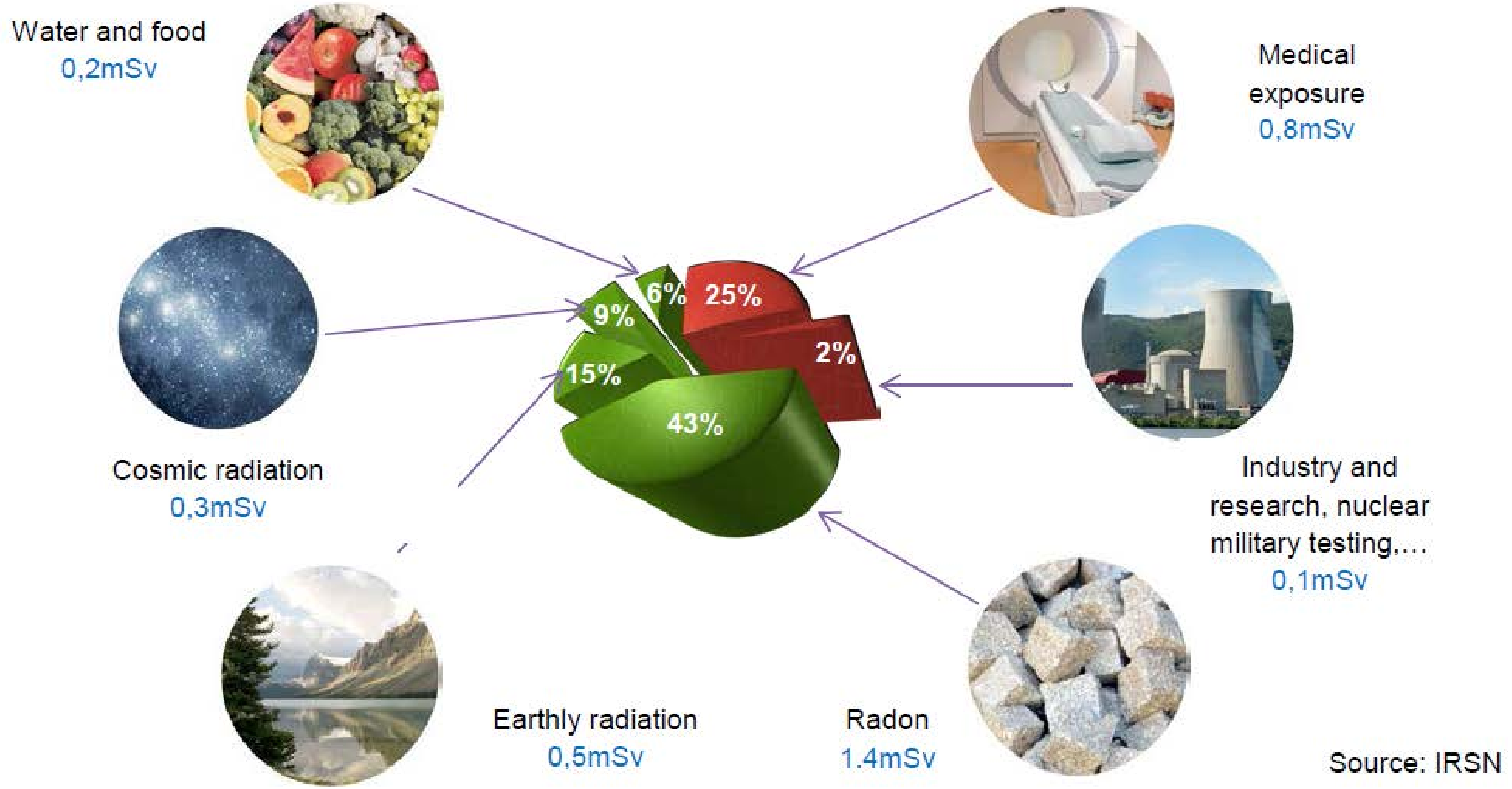
Nuclide	Total activity in human body (~ 70 kg)
Potassium-40	~ 5 kBq
Carbon-14	~ 3 kBq
Tritium	~ 20 Bq
Polonium-210	~ 18 Bq
Uranium	~ 1 Bq
Radium	~ 1 Bq
Thorium	~ 0.1 Bq

TOTAL	~ 8 kBq



Courtesy PTB, Braunschweig

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



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 or 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)

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

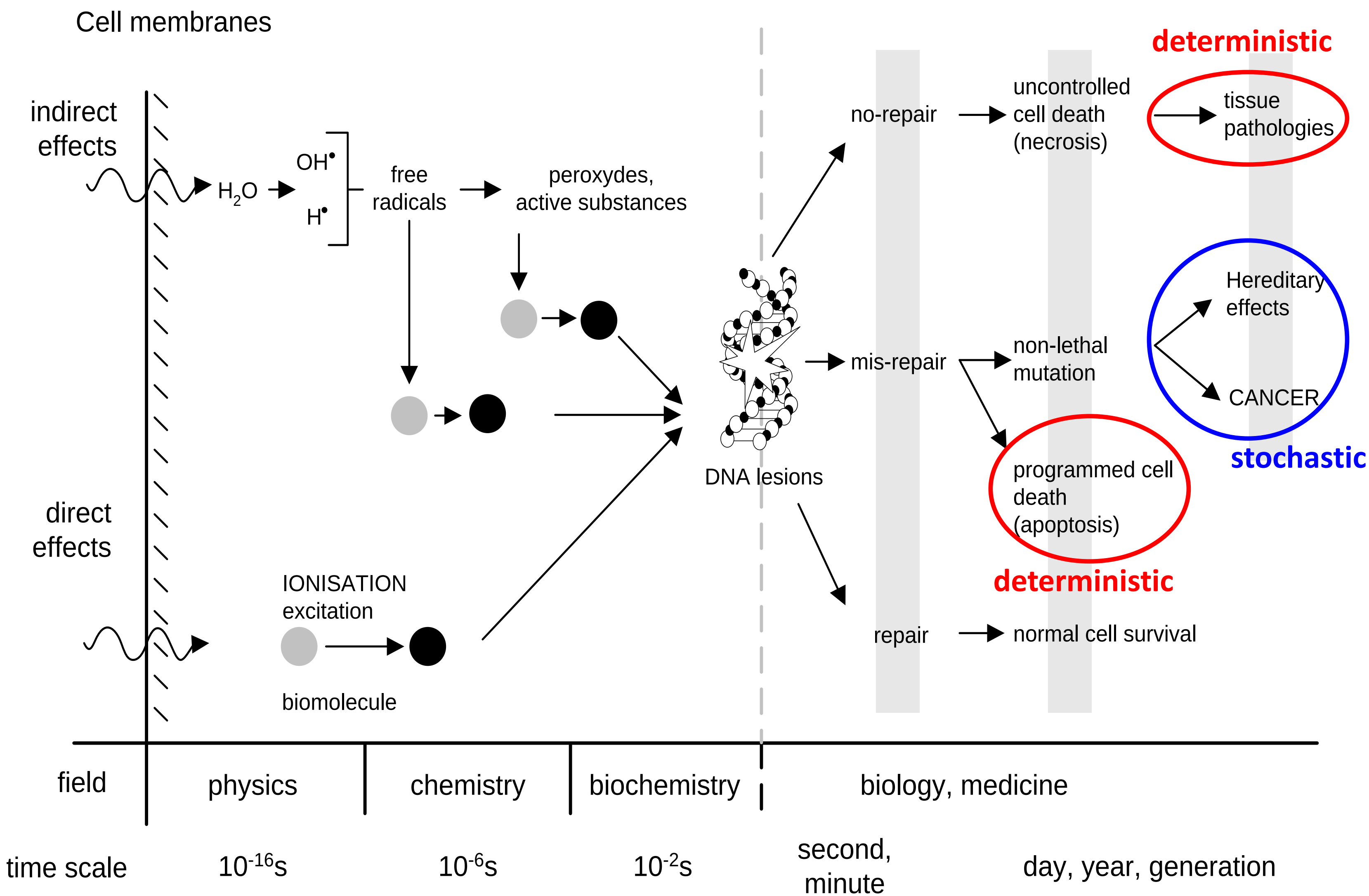
dose received in short time interval
dose threshold: > 500 mSv

immediate consequences:
- vomiting
- immun deficiency
- erythema and necrose

health detriments are function of the dose

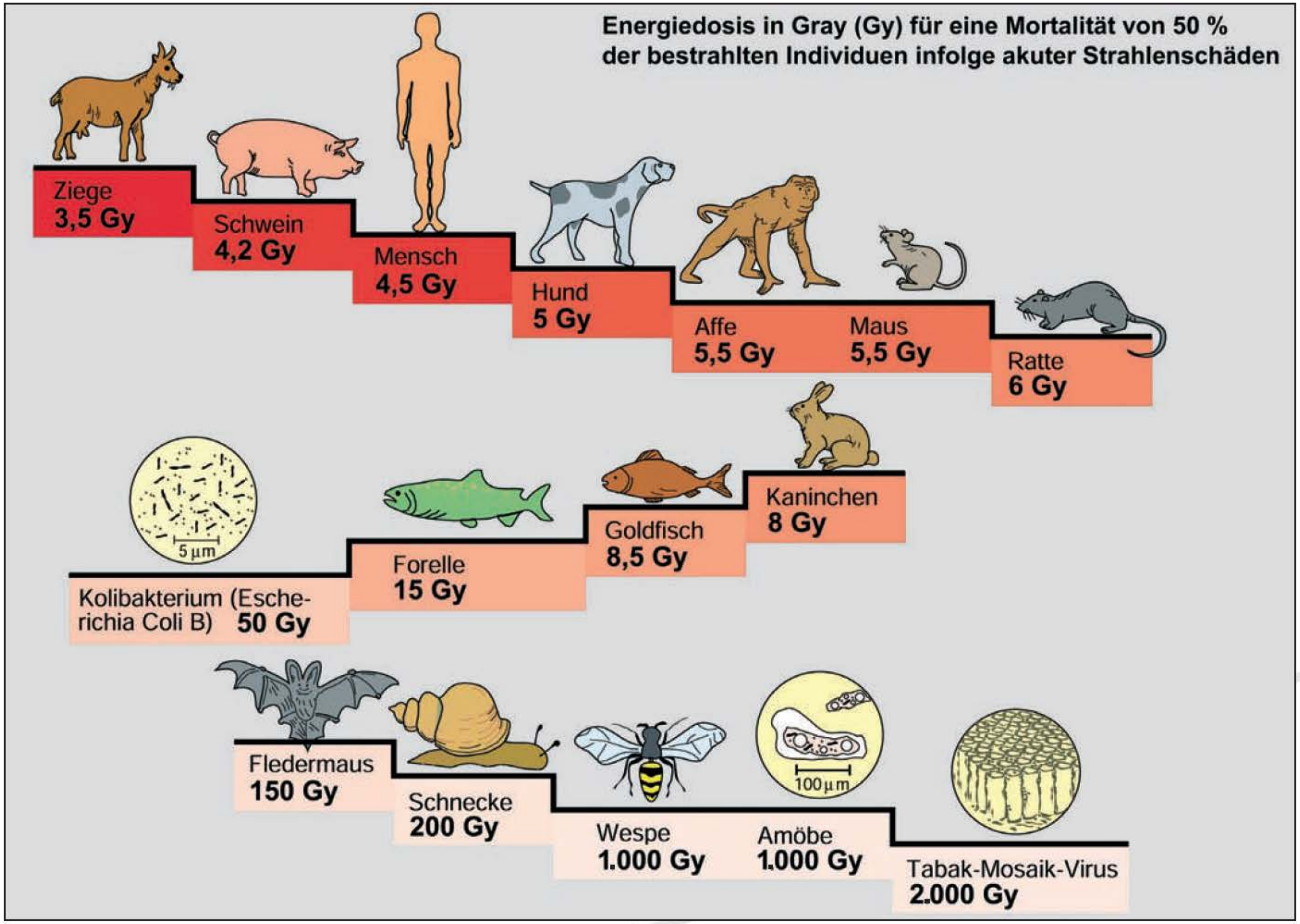
lethal dose: 5 – 7 Sv

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

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

- Any justified job is considered as optimized when different appropriate solutions have been evaluated and judged against each other from the radiation protection viewpoint
- The decisional process leading to the chosen solution can be reconstructed at any time, and the risk of failure and the elimination of radioactive sources have been taken into account
- Optimisation can be considered as respected if the activity never gives rise to an annual dose of more than 100 μSv for persons professionally exposed or 10 μSv for members of the public

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 wR 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 wT for tissue T

Unit: Sv (1 Sv = 100 rem)

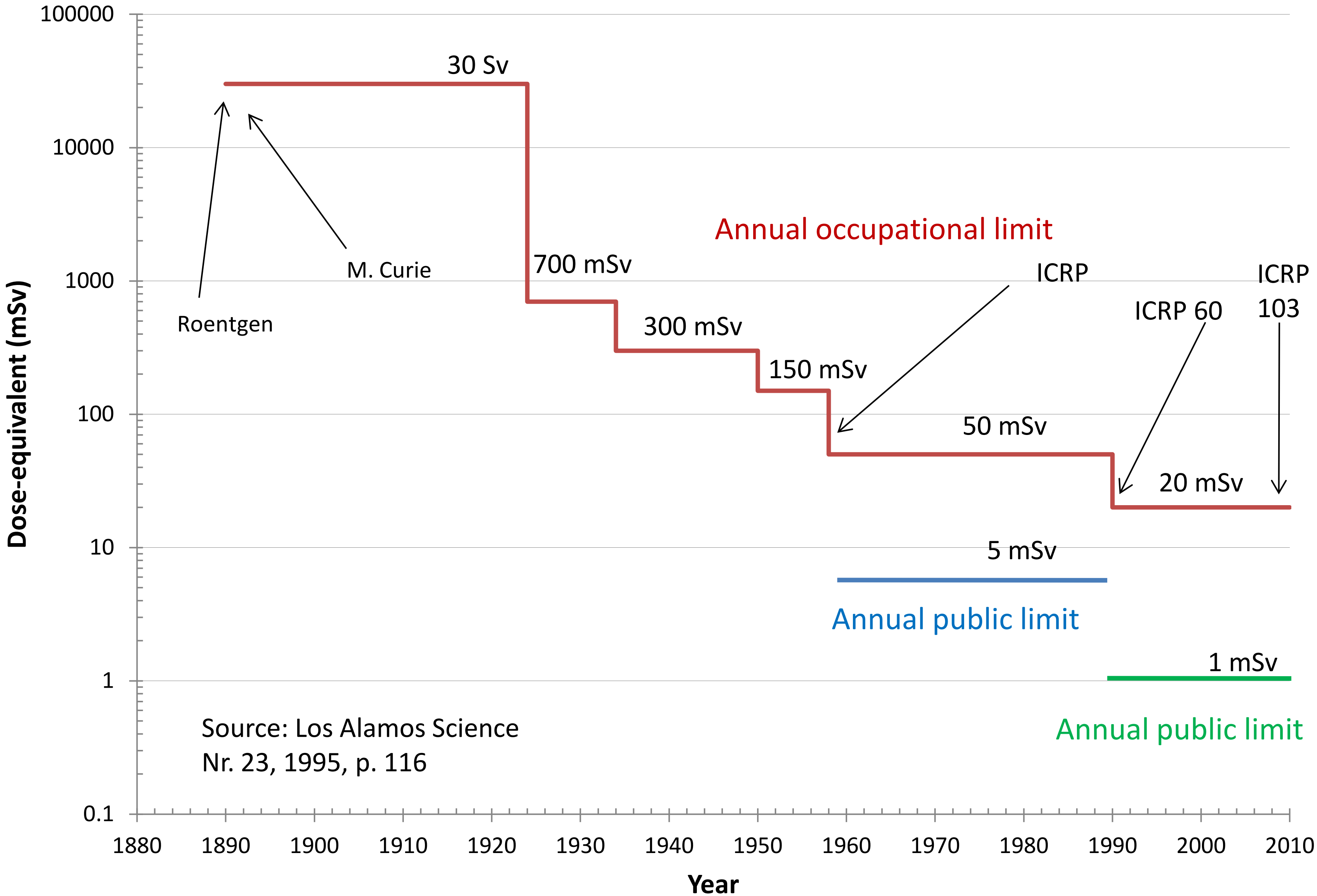
$$E = \sum_T w_T H_T$$

Type and energy of radiation R	Radiation weighting factor, w_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons:	
<10 keV	5
10 to 100 keV	10
> 0.1 to 2 MeV	20
> 2 to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, E > 2 MeV ICRP 103 (protons and charged pions)	5 (2)
Alpha particles, fission fragments, heavy nuclei	20

Tissue sensitivity and tissue weighting factors, W_T

Sensitivity	Organ or tissue
High	Haematopoietic and lymphatic systems (bone marrow, spleen, thymus, ganglions), intestinal mucosa, gonads, lens
Intermediate	Skin, eye (exception lens)
Low	Lung, liver, kidneys
Resistant	Heart, nervous system(adult), muscle, supporting tissue

Tissue or organ	w_T
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surfaces	0.01
Remainder	0.05



100000
10000
1000
100
10
1
0.1
Dose-equivalent (mSv)
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year
30 Sv
Roentgen
M. Curie
700 mSv
300 mSv
150 mSv
Annual occupational limit
ICRP
50 mSv
ICRP 60
ICRP
103
20 mSv
5 mSv
Annual public limit
1 mSv
Annual public limit
Source: Los Alamos Science
Nr. 23, 1995, p. 116

External exposure

Contamination → Surface

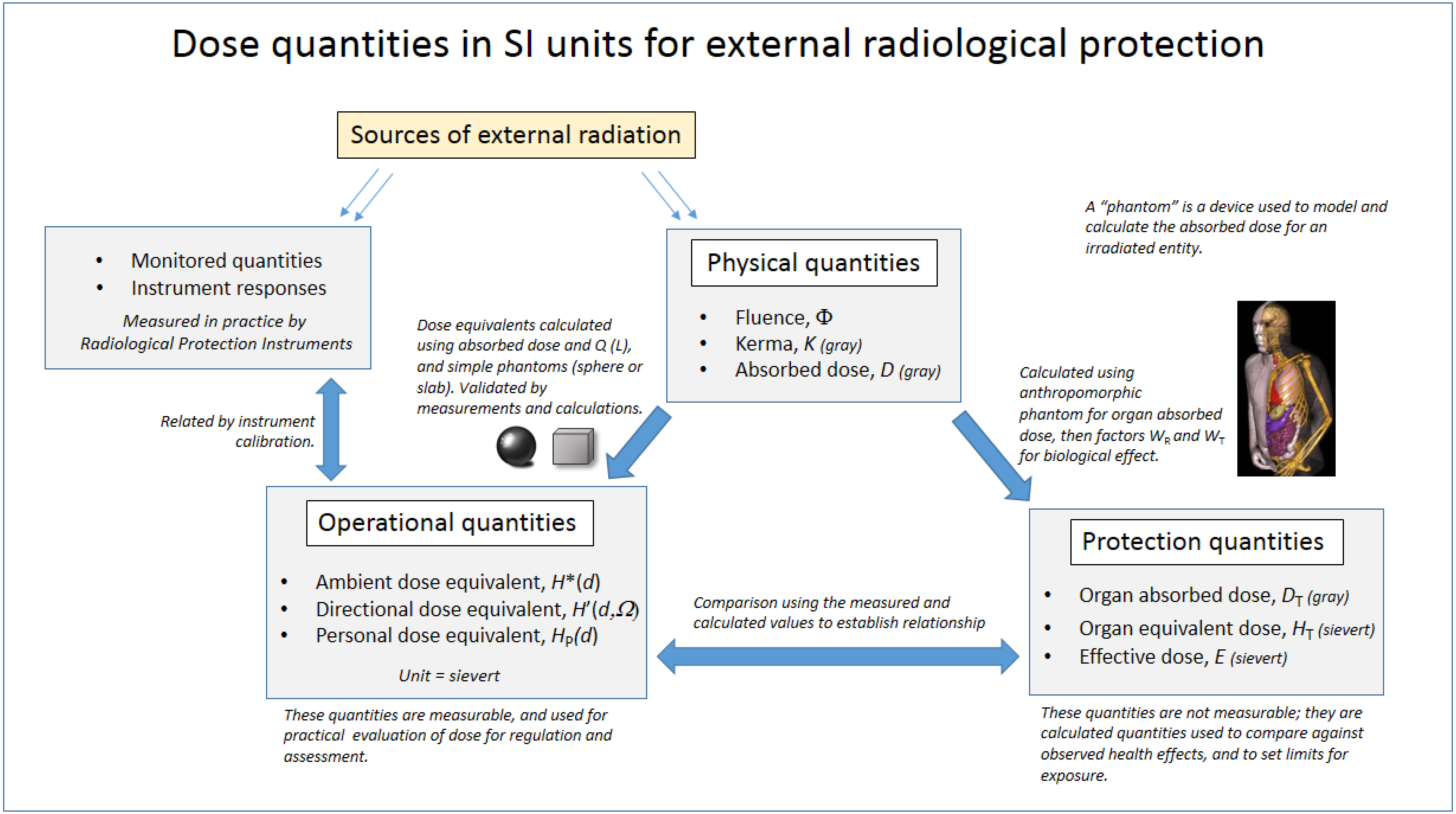
Contamination → Volumetric (air)

- 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)

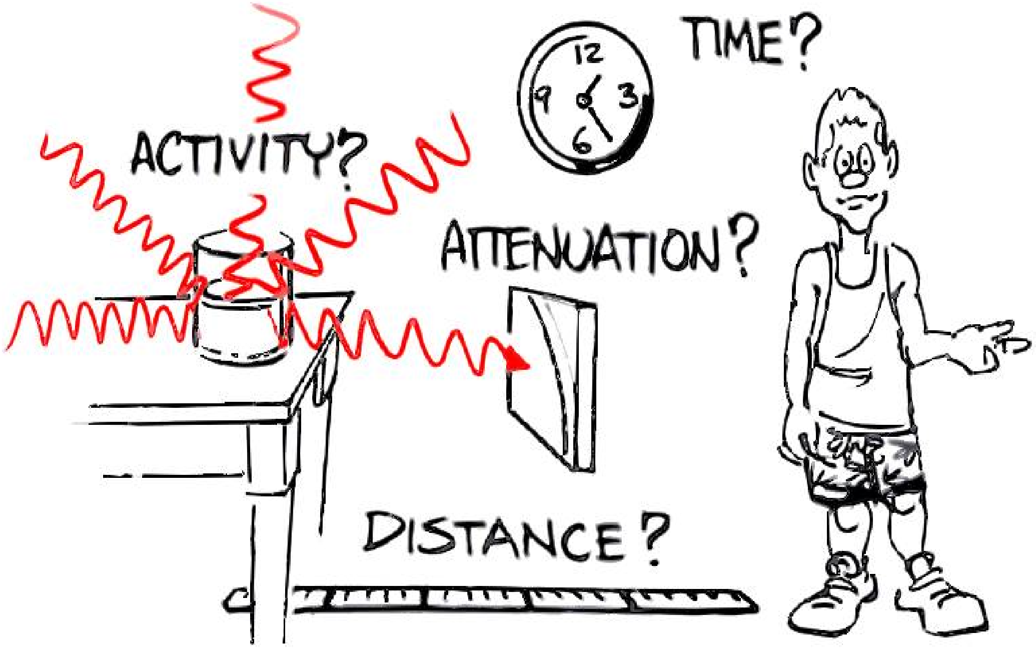
International Commission on Radiological Protection



Source: Wikipedia

- **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): **$E(50)$**

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

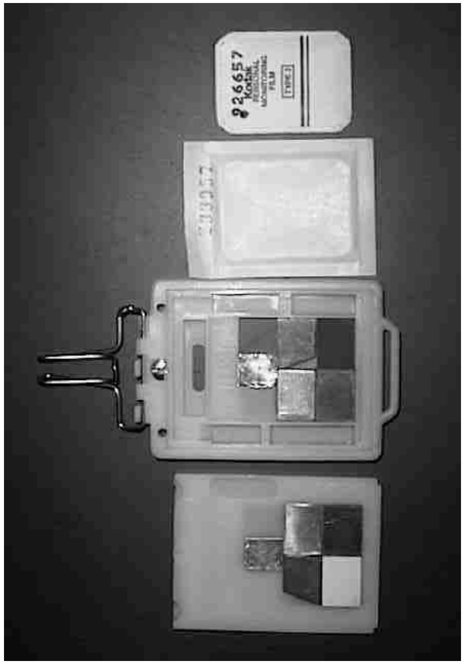
for β radiation: plexiglass
for γ radiation: iron or lead
for n: concrete

- **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)

Personal dosimeter: "Legal dose”



Kodak film badge

RADOS DIS

Finger dosimeter

Operational dosimeter DMC: “Operational dose”

- **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

For low level contamination / low risk

« Tyvek » overall
(synthetic paper)

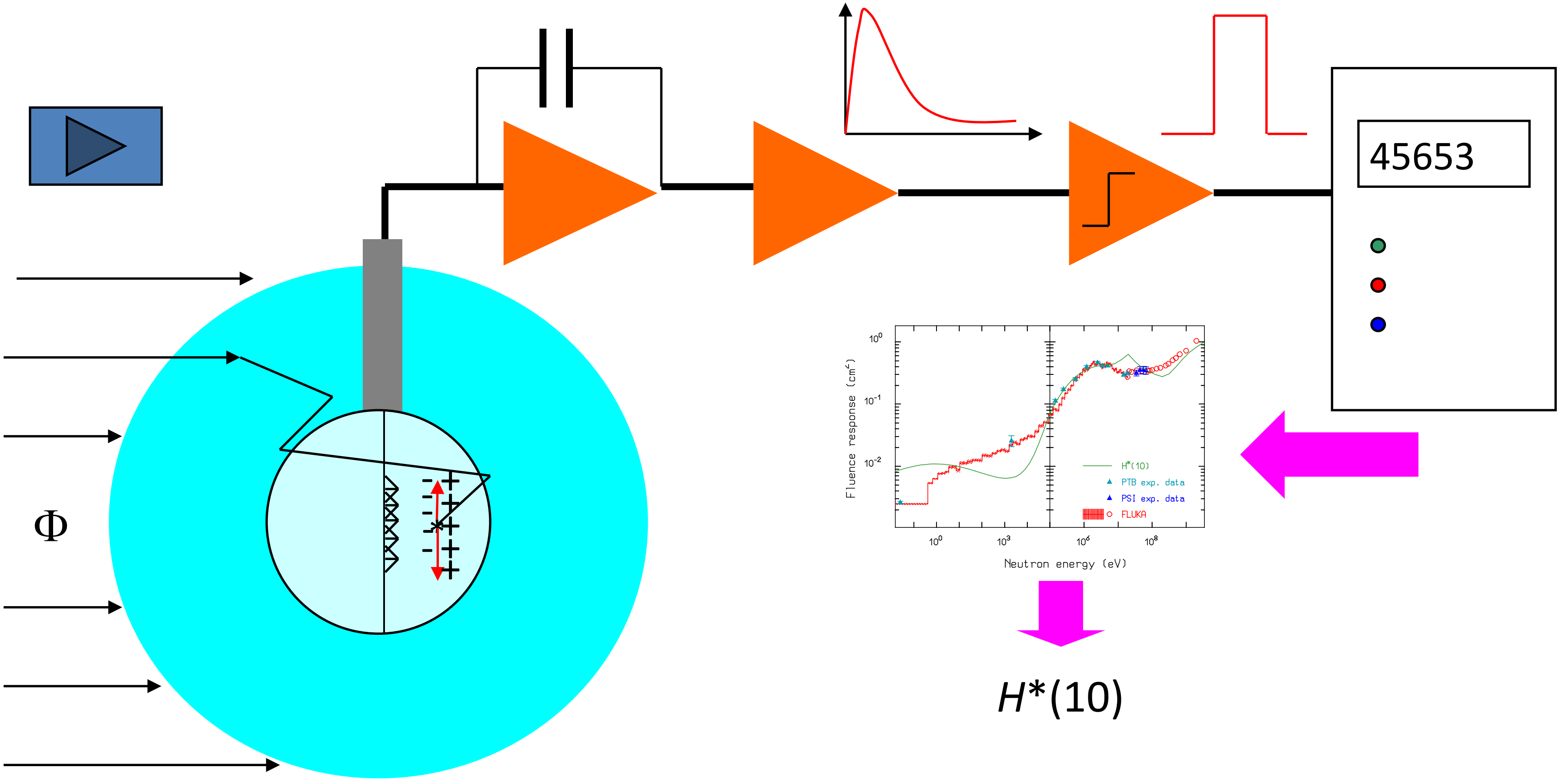
Rubber gloves

… generally completed
by overshoes

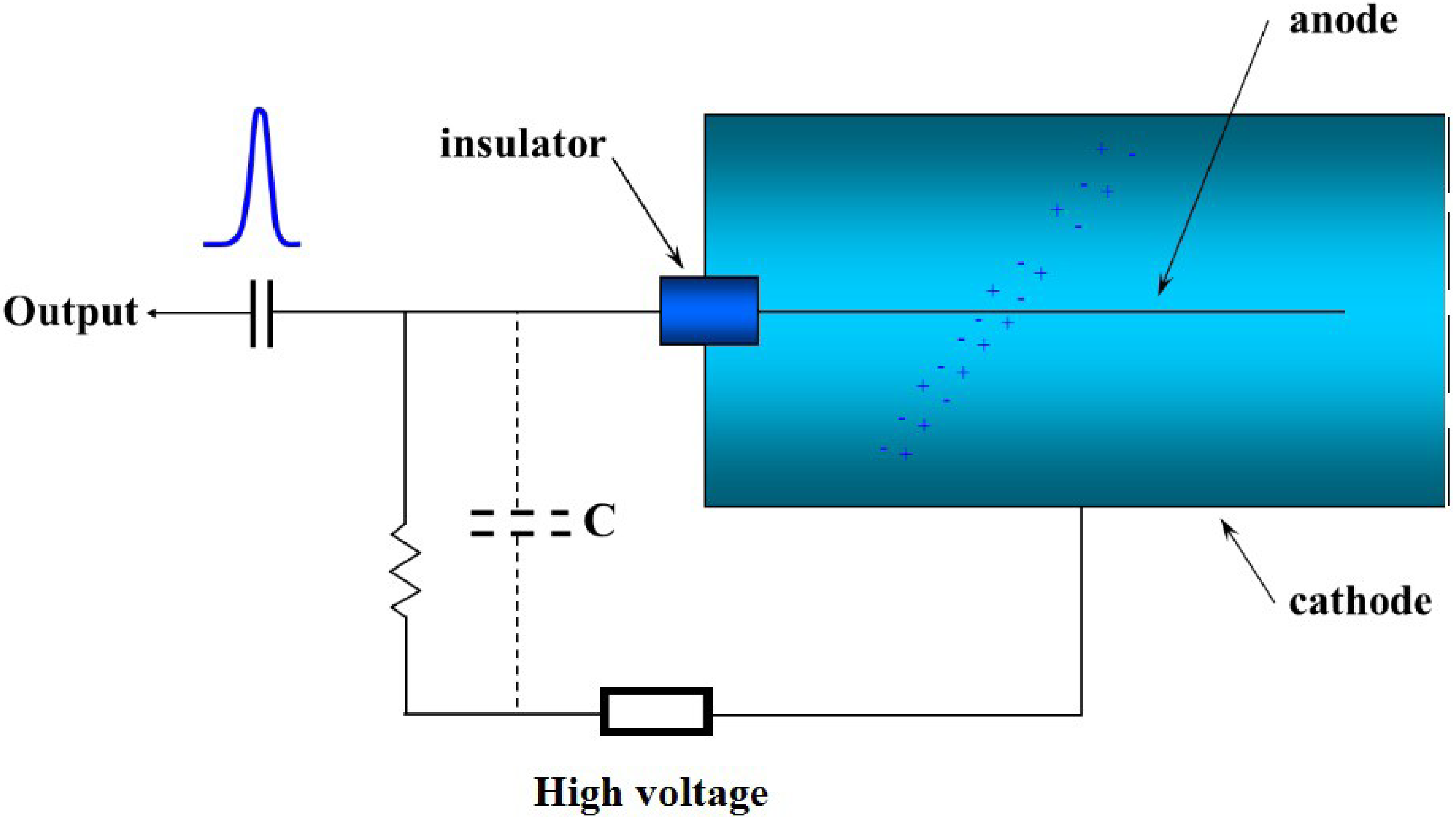
For higher levels of contamination = higher risk

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

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

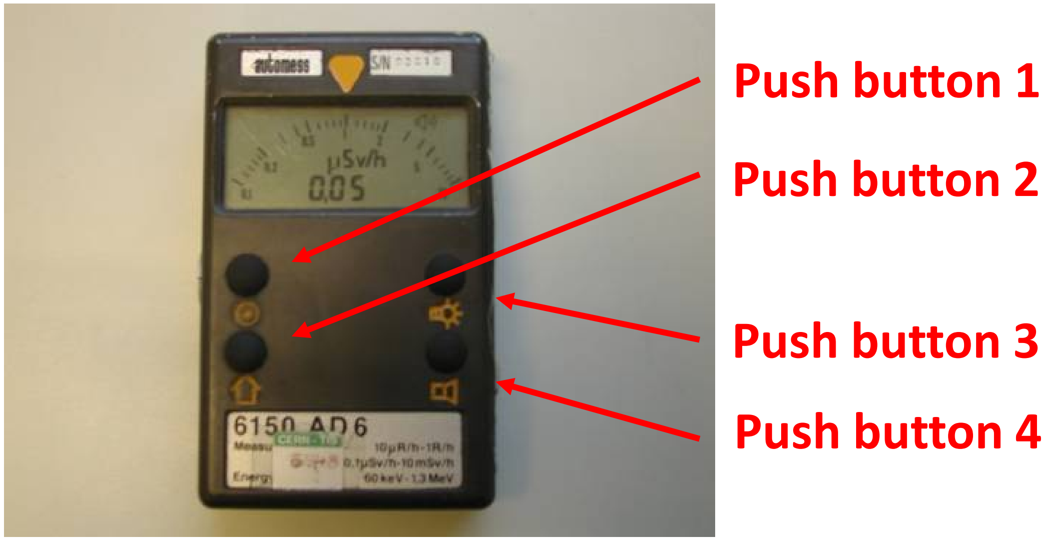


Courtesy S. Agosteo, Politecnico di Milano


anode
insulator
Output
C
cathode
High voltage

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 cm^2

APA

CMS2000

Air contamination monitors

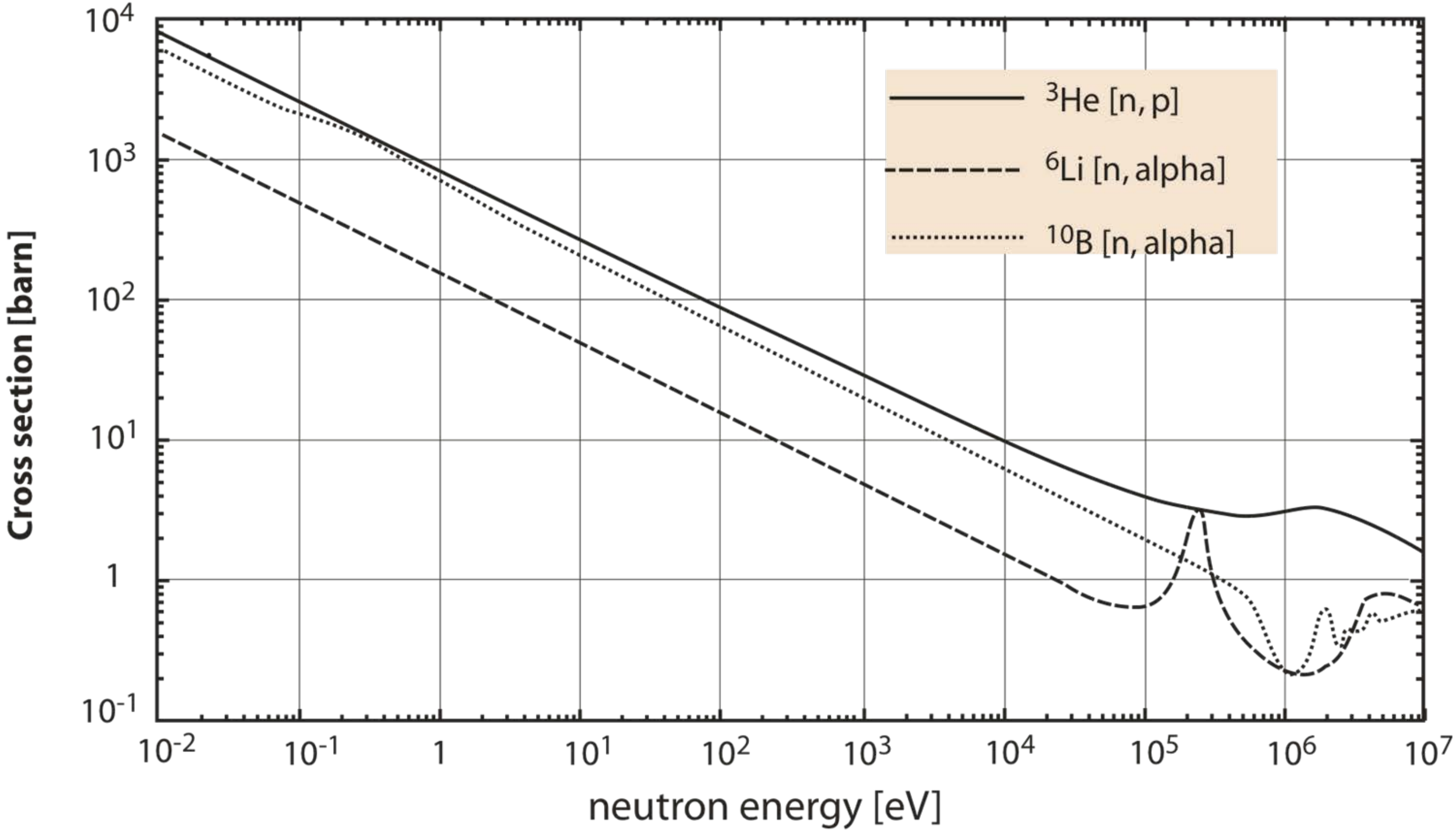
Hand and foot monitor

ABPM203M

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

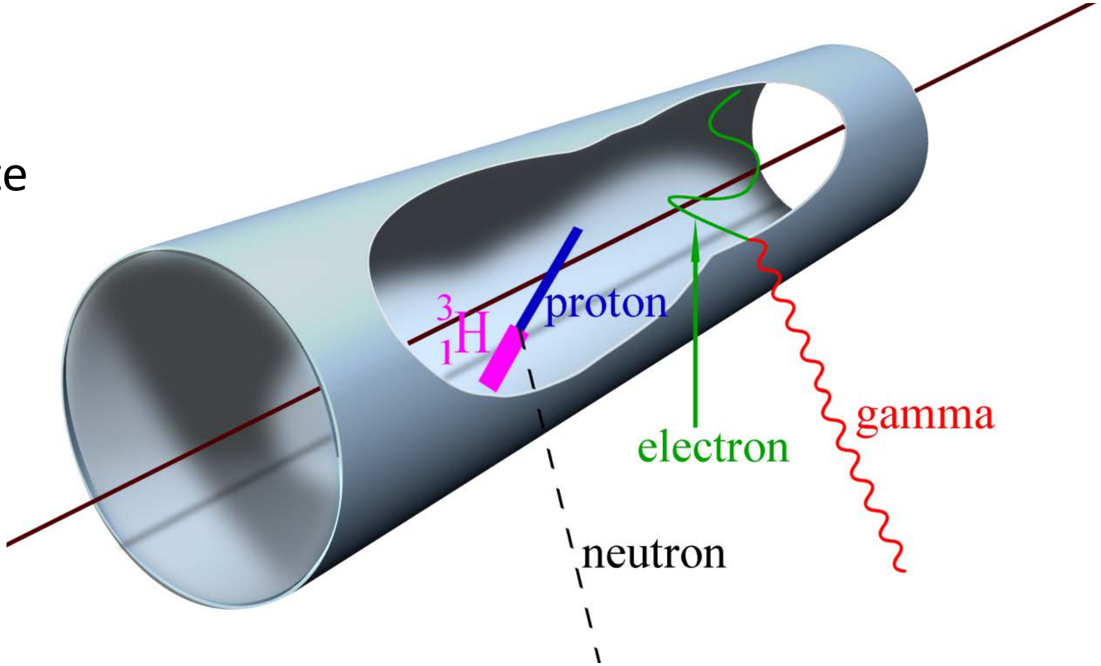


Mean free path of thermal neutrons
- in ^{3}He gas ≈ 7 cm
- in solid ^{10}B ≈ 70 µm

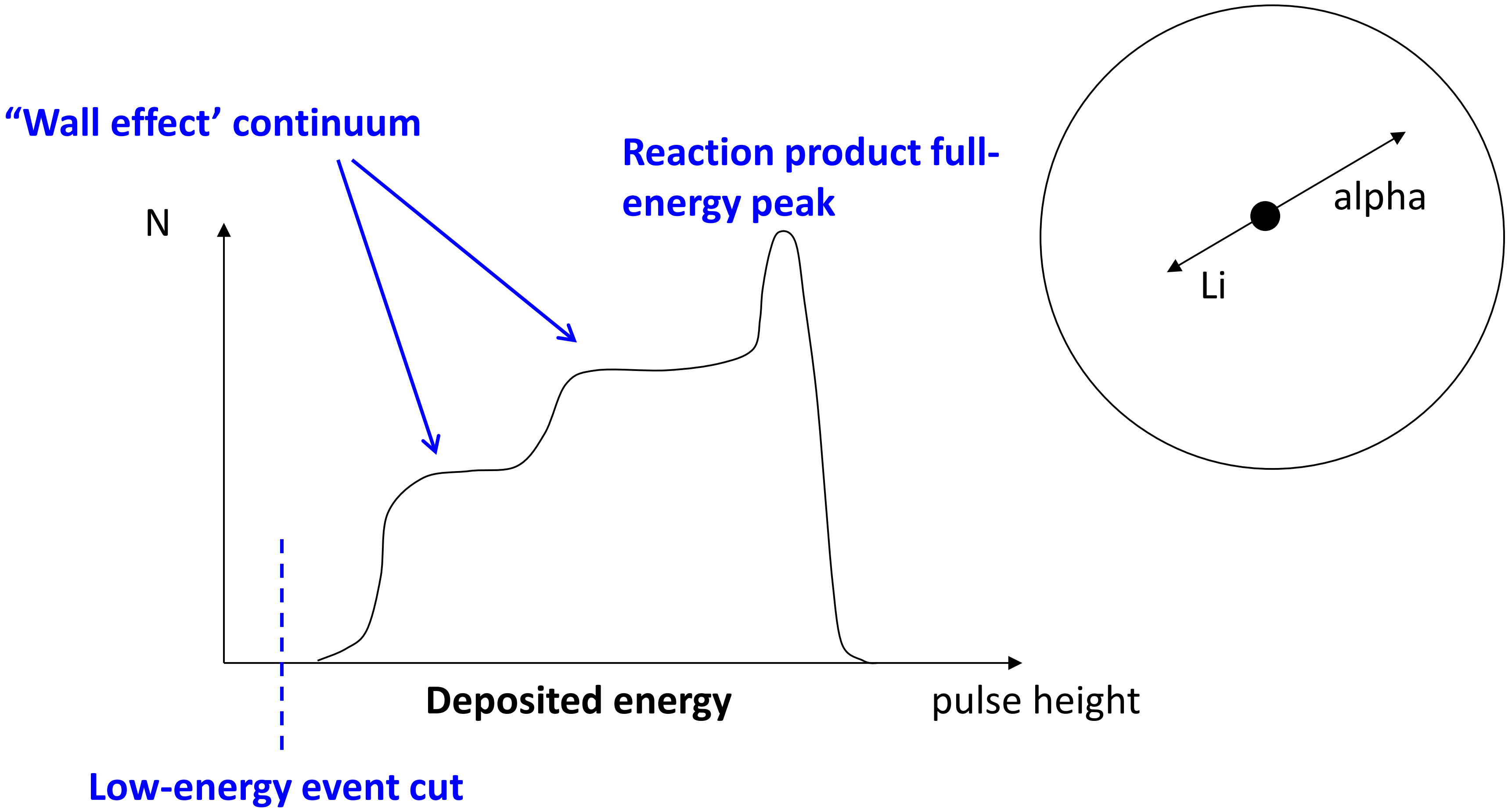
BF_3 gas and ^{3}He gas make detectors for slow neutrons with excellent gamma discrimination

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.



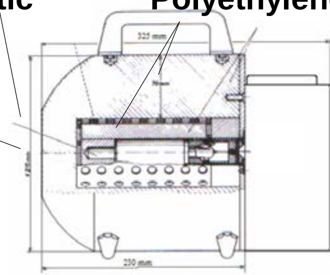
Pulse height spectrum from a BF_3 proportional counter

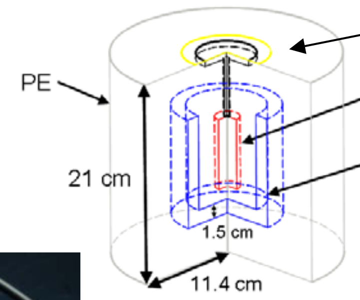


The shape of the pulse height spectrum is due to the energy loss of the recoils in the gas

Rem counters

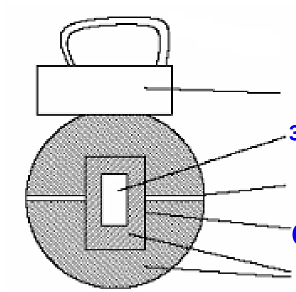
Studsvik 2202D

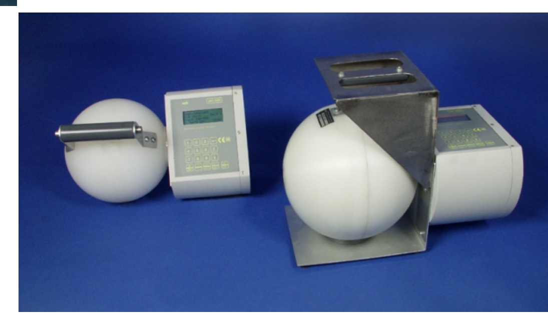




Eberline WENDI-2

Berthold LB6411 (also LB6411Pb)





MAB SNM500(X)

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/