African School of Fundamental
Physics and Applications

Radiation dosimetry, radiation protection and measurements

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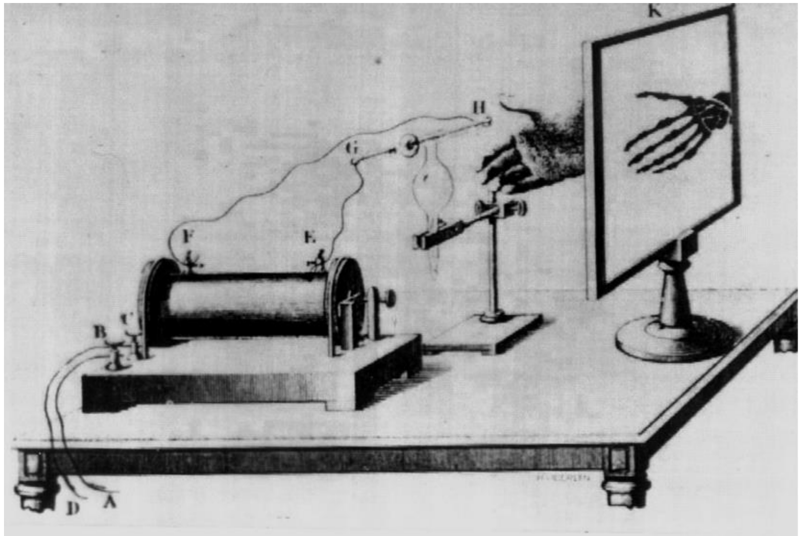
Outline of the lecture

- 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

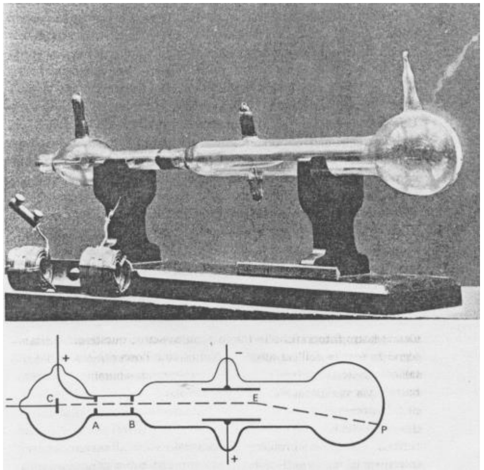
First treatment of tissue with X rays

Leopold Freund

J.J. Thompson

1897

“Discovery” of the electron



The discovery of radiation

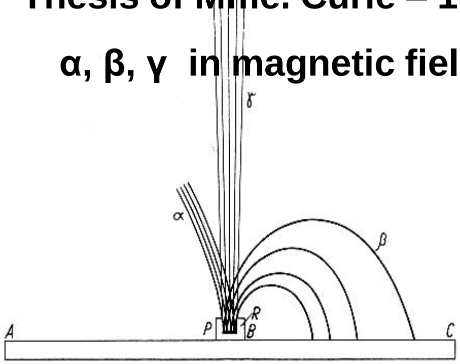
Henri Becquerel
(1852-1908)

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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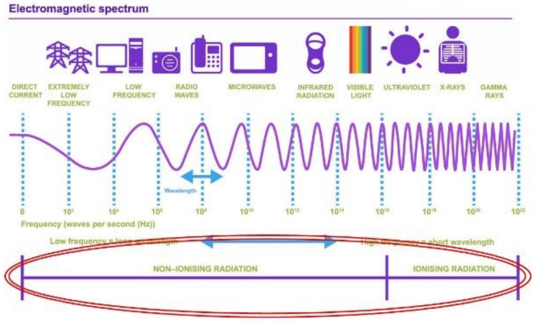
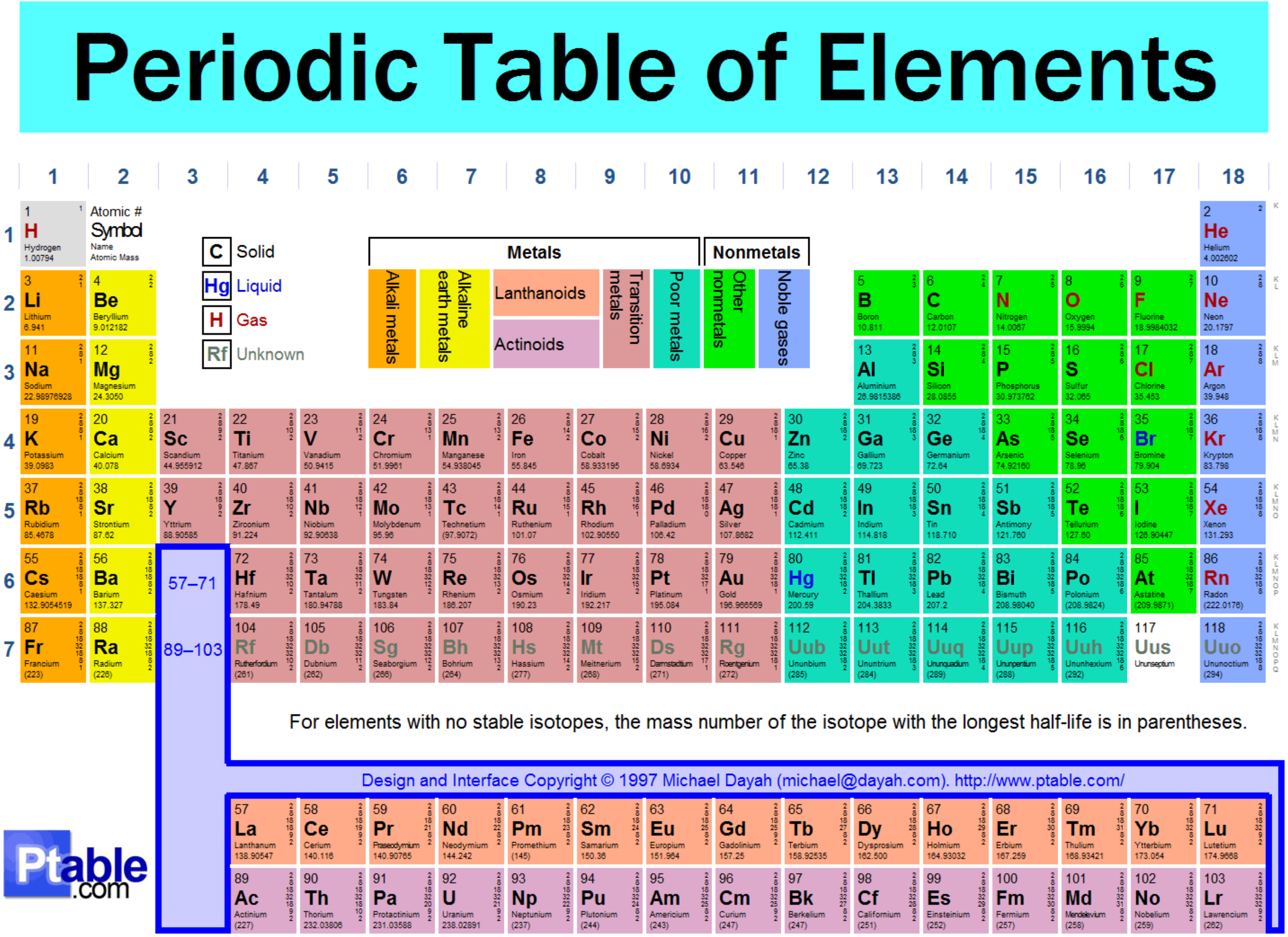


Periodic table of elements



Periodic Table of Elements

Atomic #
Symbol
Name
Atomic Mass

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals: Alkali metals, Alkaline earth metals, Lanthanoids, Actinoids, Transition metals, Poor metals
Nonmetals: Other nonmetals, Noble gases

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1	1 H Hydrogen 1.00794 1																	2 He Helium 4.002602 2	K
2	3 Li Lithium 6.941 2 1	4 Be Beryllium 9.012182 2 2											5 B Boron 10.811 2 3	6 C Carbon 12.0107 2 4	7 N Nitrogen 14.0067 2 5	8 O Oxygen 15.9994 2 6	9 F Fluorine 18.9984032 2 7	10 Ne Neon 20.1797 2 8	K L
3	11 Na Sodium 22.98976928 2 8 1	12 Mg Magnesium 24.3050 2 8 2											13 Al Aluminium 26.9815386 2 8 3	14 Si Silicon 28.0855 2 8 4	15 P Phosphorus 30.973762 2 8 5	16 S Sulfur 32.065 2 8 6	17 Cl Chlorine 35.453 2 8 7	18 Ar Argon 39.948 2 8 8	K L M
4	19 K Potassium 39.0983 2 8 8 1	20 Ca Calcium 40.078 2 8 8 2	21 Sc Scandium 44.955912 2 8 9 2	22 Ti Titanium 47.867 2 8 10 2	23 V Vanadium 50.9415 2 8 11 2	24 Cr Chromium 51.9961 2 8 13 1	25 Mn Manganese 54.938045 2 8 13 2	26 Fe Iron 55.845 2 8 14 2	27 Co Cobalt 58.933195 2 8 15 2	28 Ni Nickel 58.6934 2 8 16 2	29 Cu Copper 63.546 2 8 18 1	30 Zn Zinc 65.38 2 8 18 2	31 Ga Gallium 69.723 2 8 18 3	32 Ge Germanium 72.64 2 8 18 4	33 As Arsenic 74.92160 2 8 18 5	34 Se Selenium 78.96 2 8 18 6	35 Br Bromine 79.904 2 8 18 7	36 Kr Krypton 83.798 2 8 18 8	K L M N
5	37 Rb Rubidium 85.4678 2 8 18 8 1	38 Sr Strontium 87.62 2 8 18 8 2	39 Y Yttrium 88.90585 2 8 18 9 2	40 Zr Zirconium 91.224 2 8 18 10 2	41 Nb Niobium 92.90638 2 8 18 12 1	42 Mo Molybdenum 95.96 2 8 18 13 1	43 Tc Technetium (97.9072) 2 8 18 14 1	44 Ru Ruthenium 101.07 2 8 18 15 1	45 Rh Rhodium 102.90550 2 8 18 16 1	46 Pd Palladium 106.42 2 8 18 18 0	47 Ag Silver 107.8682 2 8 18 18 1	48 Cd Cadmium 112.411 2 8 18 18 2	49 In Indium 114.818 2 8 18 18 3	50 Sn Tin 118.710 2 8 18 18 4	51 Sb Antimony 121.760 2 8 18 18 5	52 Te Tellurium 127.60 2 8 18 18 6	53 I Iodine 126.90447 2 8 18 18 7	54 Xe Xenon 131.293 2 8 18 18 8	K L M N O
6	55 Cs Caesium 132.9054519 2 8 18 18 8 1	56 Ba Barium 137.327 2 8 18 18 8 2	57–71	72 Hf Hafnium 178.49 2 8 18 32 10 2	73 Ta Tantalum 180.94788 2 8 18 32 11 2	74 W Tungsten 183.84 2 8 18 32 12 2	75 Re Rhenium 186.207 2 8 18 32 13 2	76 Os Osmium 190.23 2 8 18 32 14 2	77 Ir Iridium 192.217 2 8 18 32 15 2	78 Pt Platinum 195.084 2 8 18 32 17 1	79 Au Gold 196.966569 2 8 18 32 18 1	80 Hg Mercury 200.59 2 8 18 32 18 2	81 Tl Thallium 204.3833 2 8 18 32 18 3	82 Pb Lead 207.2 2 8 18 32 18 4	83 Bi Bismuth 208.98040 2 8 18 32 18 5	84 Po Polonium (208.9824) 2 8 18 32 18 6	85 At Astatine (209.9871) 2 8 18 32 18 7	86 Rn Radon (222.0176) 2 8 18 32 18 8	K L M N O P
7	87 Fr Francium (223) 2 8 18 32 18 8 1	88 Ra Radium (226) 2 8 18 32 18 8 2	89–103	104 Rf Rutherfordium (261) 2 8 18 32 32 10 2	105 Db Dubnium (262) 2 8 18 32 32 11 2	106 Sg Seaborgium (266) 2 8 18 32 32 12 2	107 Bh Bohrium (264) 2 8 18 32 32 13 2	108 Hs Hassium (277) 2 8 18 32 32 14 2	109 Mt Meitnerium (268) 2 8 18 32 32 15 2	110 Ds Darmstadtium (271) 2 8 18 32 32 17 1	111 Rg Roentgenium (272) 2 8 18 32 32 18 1	112 Uub Ununbium (285) 2 8 18 32 32 18 2	113 Uut Ununtrium (284) 2 8 18 32 32 18 3	114 Uuq Ununquadium (289) 2 8 18 32 32 18 4	115 Uup Ununpentium (288) 2 8 18 32 32 18 5	116 Uuh Ununhexium (292) 2 8 18 32 32 18 6	117 Uus Ununseptium	118 Uuo Ununoctium (294) 2 8 18 32 32 18 8	K L M N O P Q

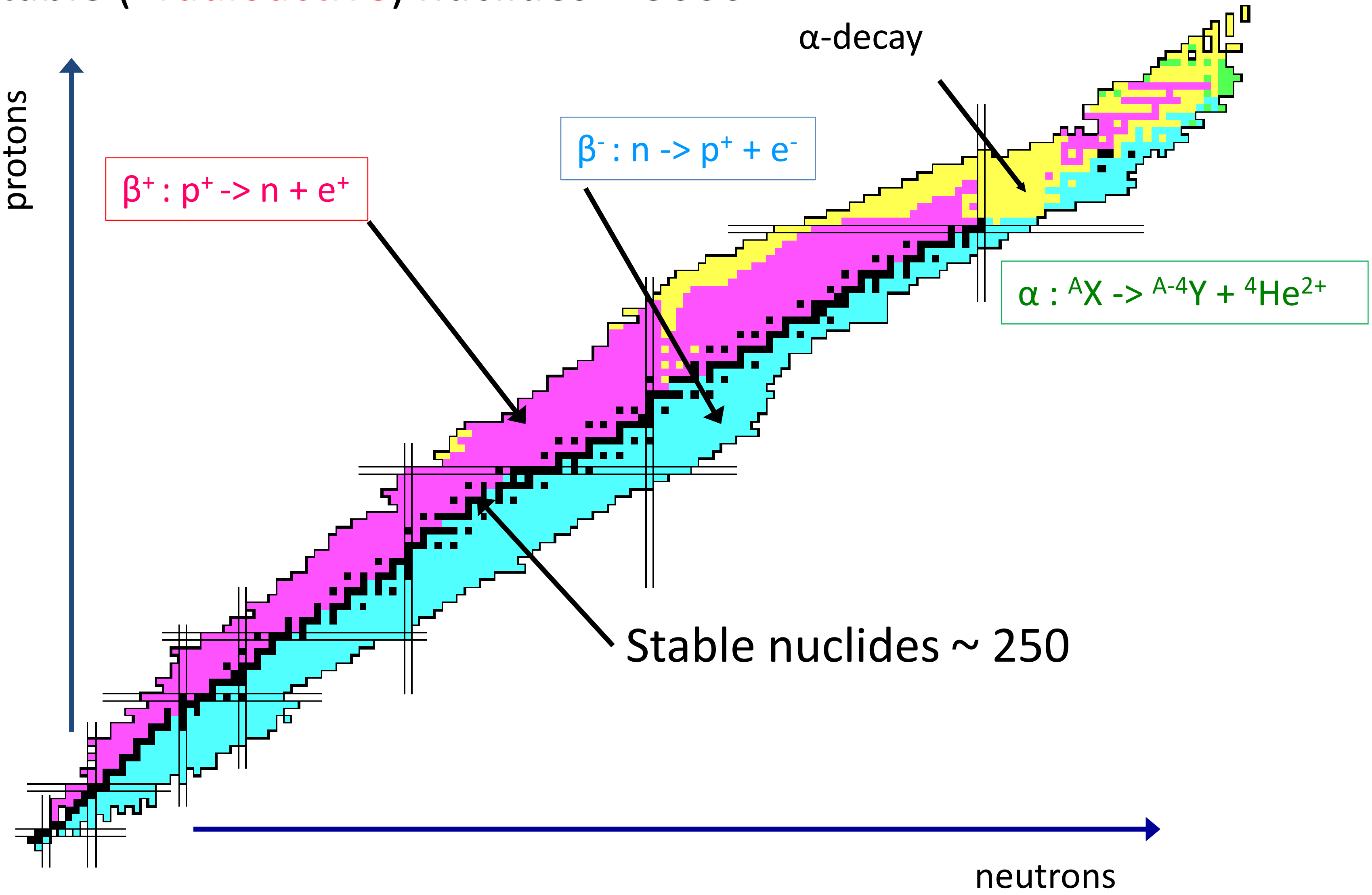
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

57 La Lanthanum 138.90547 2 8 18 18 9 2	58 Ce Cerium 140.116 2 8 18 19 9 2	59 Pr Praseodymium 140.90765 2 8 18 21 8 2	60 Nd Neodymium 144.242 2 8 18 22 8 2	61 Pm Promethium (145) 2 8 18 23 8 2	62 Sm Samarium 150.36 2 8 18 24 8 2	63 Eu Europium 151.964 2 8 18 25 8 2	64 Gd Gadolinium 157.25 2 8 18 25 9 2	65 Tb Terbium 158.92535 2 8 18 27 8 2	66 Dy Dysprosium 162.500 2 8 18 28 8 2	67 Ho Holmium 164.93032 2 8 18 29 8 2	68 Er Erbium 167.259 2 8 18 30 8 2	69 Tm Thulium 168.93421 2 8 18 31 8 2	70 Yb Ytterbium 173.054 2 8 18 32 8 2	71 Lu Lutetium 174.9668 2 8 18 32 9 2
89 Ac Actinium (227) 2 8 18 32 18 9 2	90 Th Thorium 232.03806 2 8 18 32 18 10 2	91 Pa Protactinium 231.03588 2 8 18 32 20 9 2	92 U Uranium 238.02891 2 8 18 32 21 9 2	93 Np Neptunium (237) 2 8 18 32 22 9 2	94 Pu Plutonium (244) 2 8 18 32 24 8 2	95 Am Americium (243) 2 8 18 32 25 8 2	96 Cm Curium (247) 2 8 18 32 25 9 2	97 Bk Berkelium (247) 2 8 18 32 27 8 2	98 Cf Californium (251) 2 8 18 32 28 8 2	99 Es Einsteinium (252) 2 8 18 32 29 8 2	100 Fm Fermium (257) 2 8 18 32 30 8 2	101 Md Mendelevium (258) 2 8 18 32 31 8 2	102 No Nobelium (259) 2 8 18 32 32 8 2	103 Lr Lawrencium (262) 2 8 18 32 32 9 2

Ptable.com

Chart of nuclides

Unstable (=radioactive) nuclides ~ 3000



α-decay

$\beta^{+} : p^{+} \to n + e^{+}$

$\beta^{-} : n \to p^{+} + e^{-}$

$\alpha : {}^{A}X \to {}^{A-4}Y + {}^{4}He^{2+}$

Stable nuclides ~ 250

Directly and indirectly ionising radiation

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 and ionising radiation

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**:

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

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

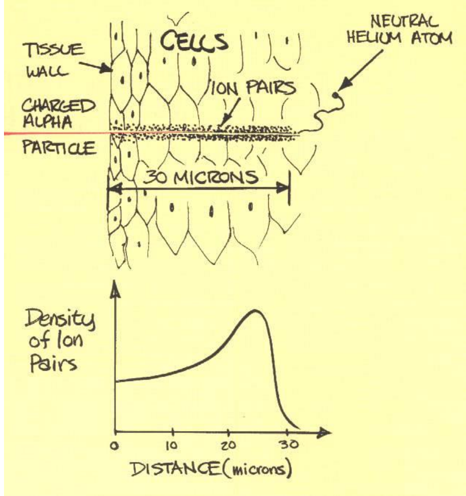
where N is the number of nuclei of the radionuclide, and hence the rate of change of N with time is negative

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

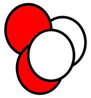
Radionuclides are either of ***natural origin*** or produced by ***nuclear reactions*** (**artificial** radionuclides)

Radioactivity and ionising radiation / hazard

(Emitted in the de-excitation of unstable nuclei)

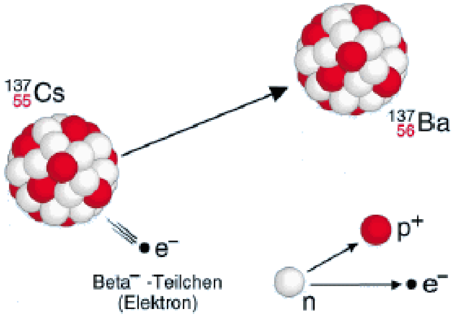


- **ALPHA**



  - 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)

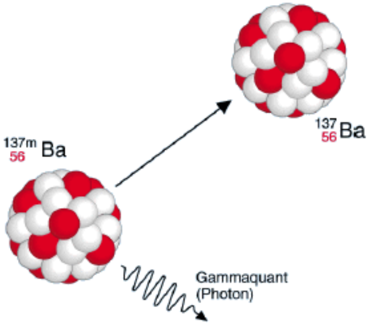
- **BETA** ●



  - 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)

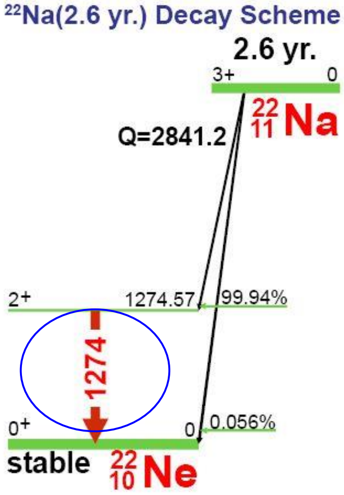
Radioactivity and ionising radiation / hazard

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

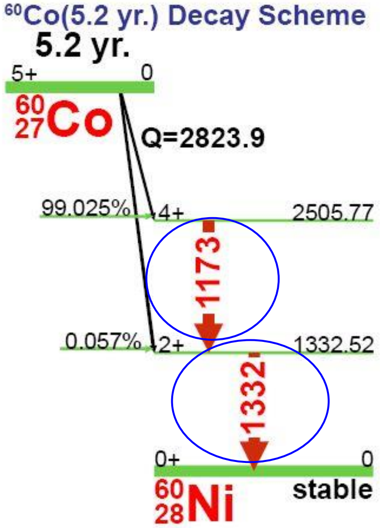


- **NEUTRONS**
  - Neutral particles (constituents of the atomic nucleus together with protons)
  - Very penetrating
  - External irradiation
  - Enhanced biological effect (high LET radiation), which depends on their energy
- **HEAVY CHARGED PARTICLES (protons, ions)**
  - External irradiation
  - Enhanced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

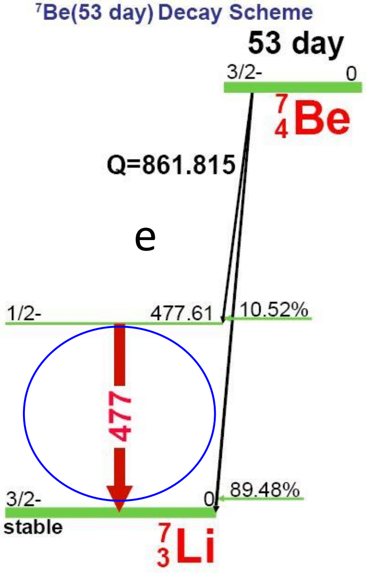
β-, γ-emitter



^{22}Na(2.6 yr.) Decay Scheme

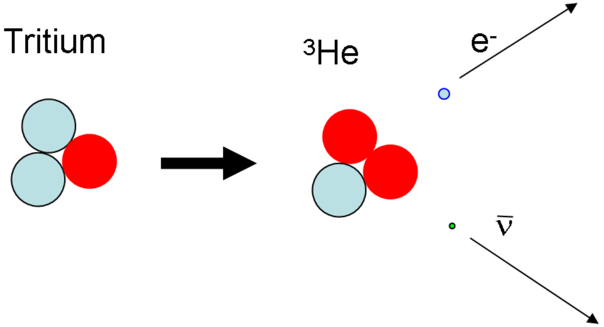


^{60}Co(5.2 yr.) Decay Scheme



^{7}Be(53 day) Decay Scheme

Pure β-emitter

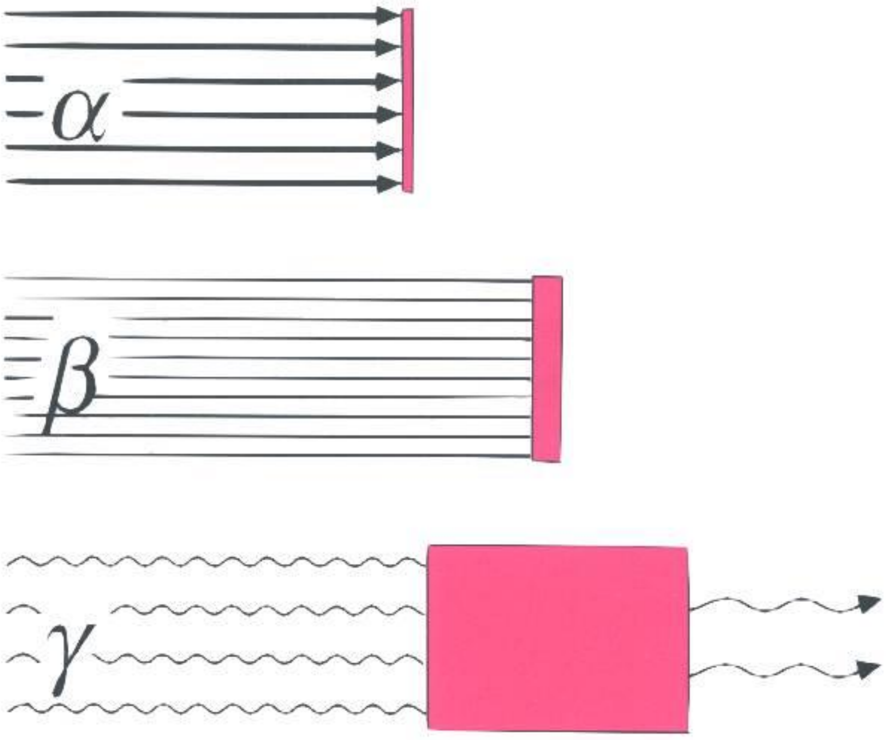


α-, β- and γ are emitted with end energies up to few MeV

Absorption / attenuation of radiation

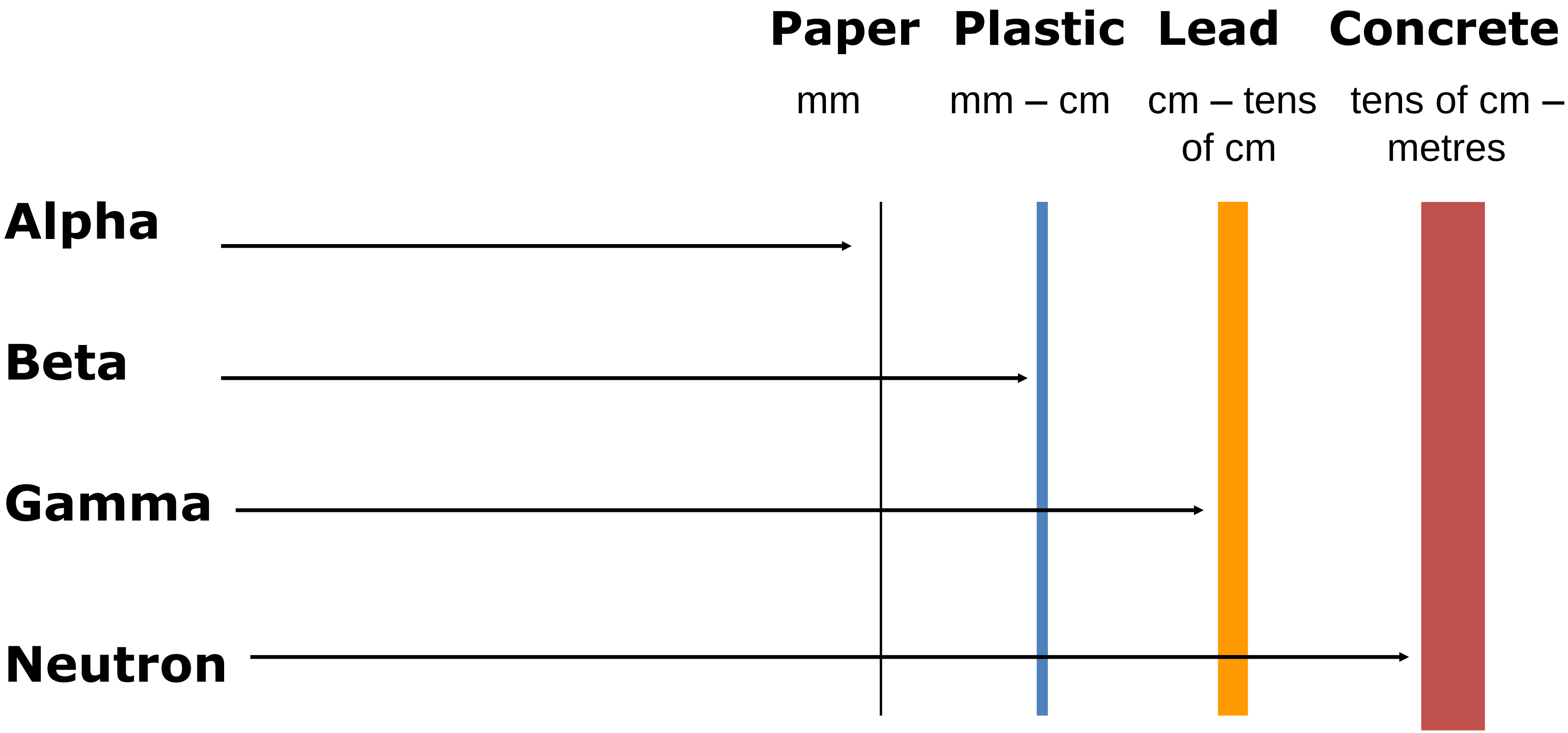
α- and β-particles are degraded in energy while traversing a material, until they are completely brought to rest

γ-rays are attenuated in intensity by the material



Absorption / attenuation of radiation

Qualitative!



Paper **Plastic** **Lead** **Concrete**

mm · mm – cm · cm – tens of cm · tens of cm – metres

Alpha

Beta

Gamma

Neutron

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

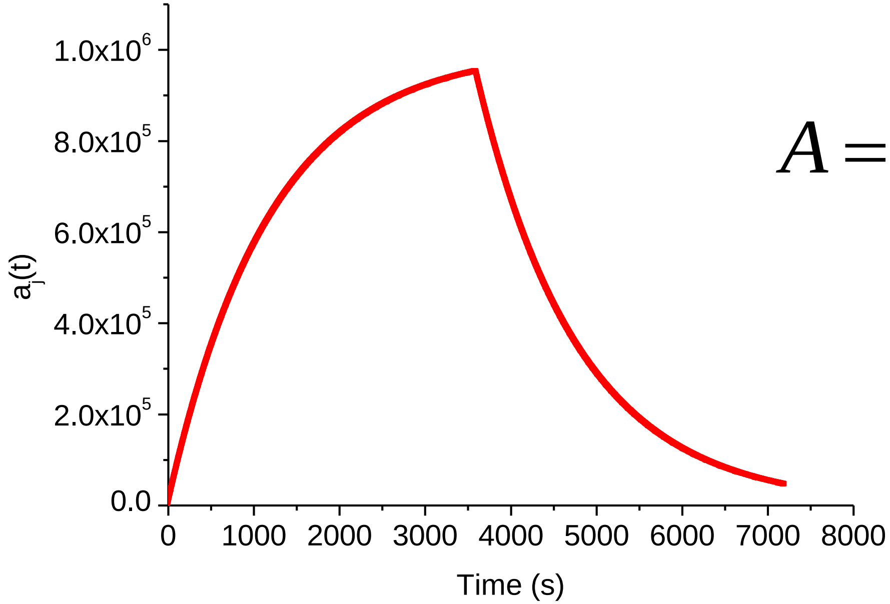
$$n = I_p \frac{\rho N_{Av}}{A} \sum_{i=p,n,\pi,pho} \int \Phi_i(E)\,\sigma_i(E)\,dE$$

Nuclide production rate

Production and decay of radionuclides

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

Unit

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

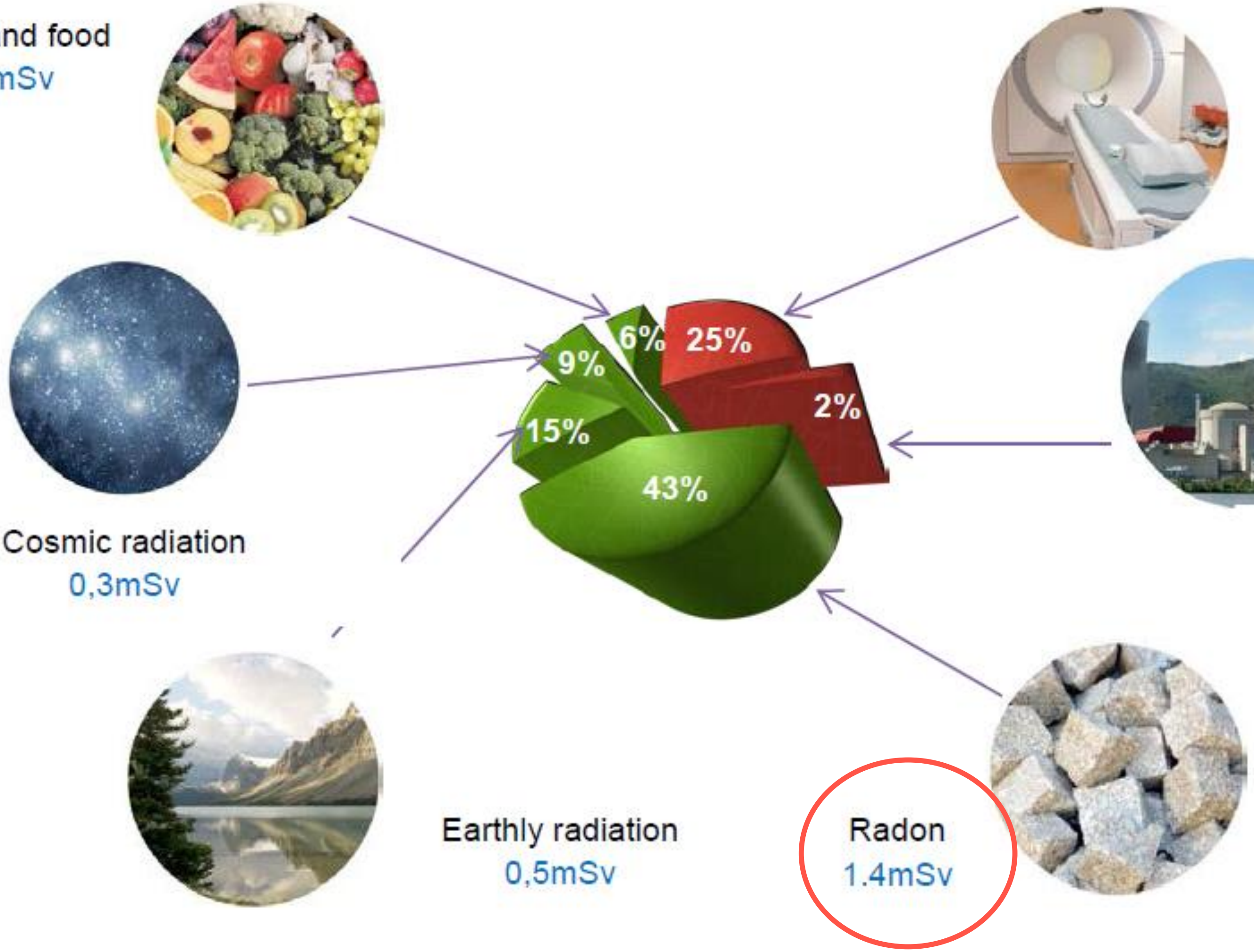
Are we all exposed (voluntarily or not) to some radiation sources?

Yes/No?

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

Natural radiation exposures

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



Water and food
0,2mSv

Medical
exposure
0,8mSv

Cosmic radiation
0,3mSv

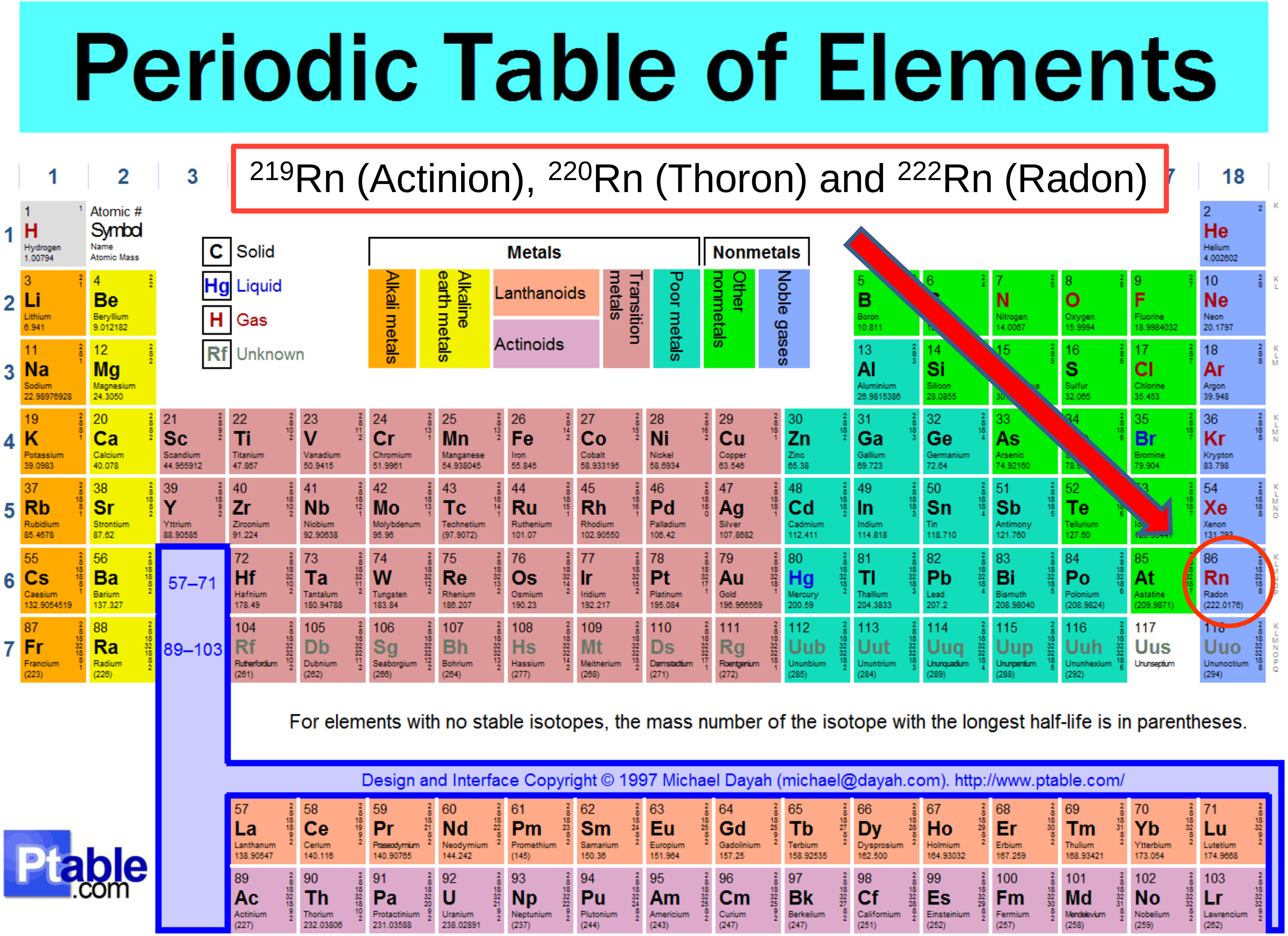
Industry and
research, nuclear
military testing,…
0,1mSv

Earthly radiation
0,5mSv

Radon
1.4mSv

Source: IRSN

Periodic table of elements



Periodic Table of Elements

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

Atomic # Symbol Name Atomic Mass

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals: Alkali metals, Alkaline earth metals, Lanthanoids, Actinoids, Transition metals, Poor metals
Nonmetals: Other nonmetals, Noble gases

	1	2	3															18
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7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)
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For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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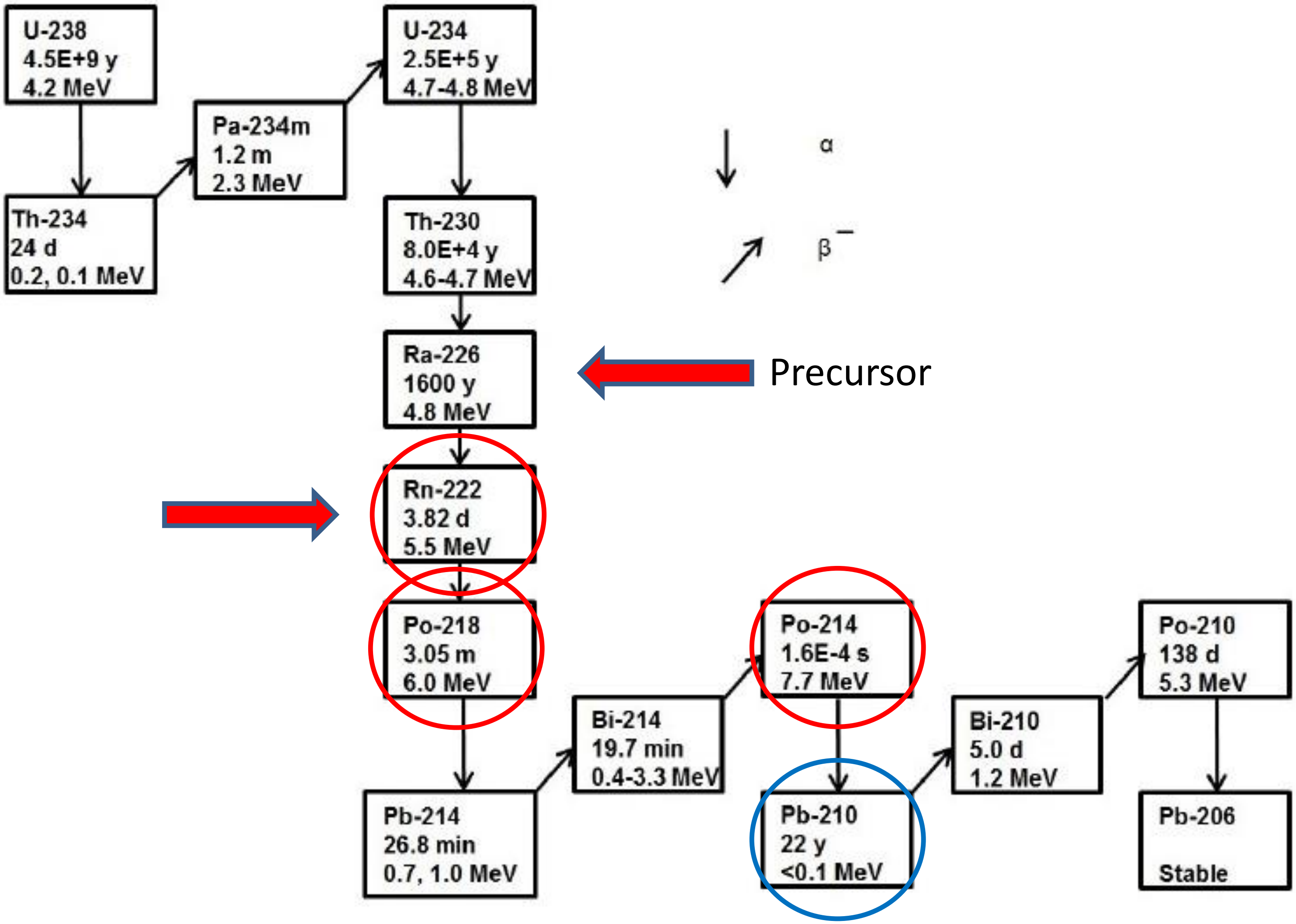
Decay chain of uranium



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

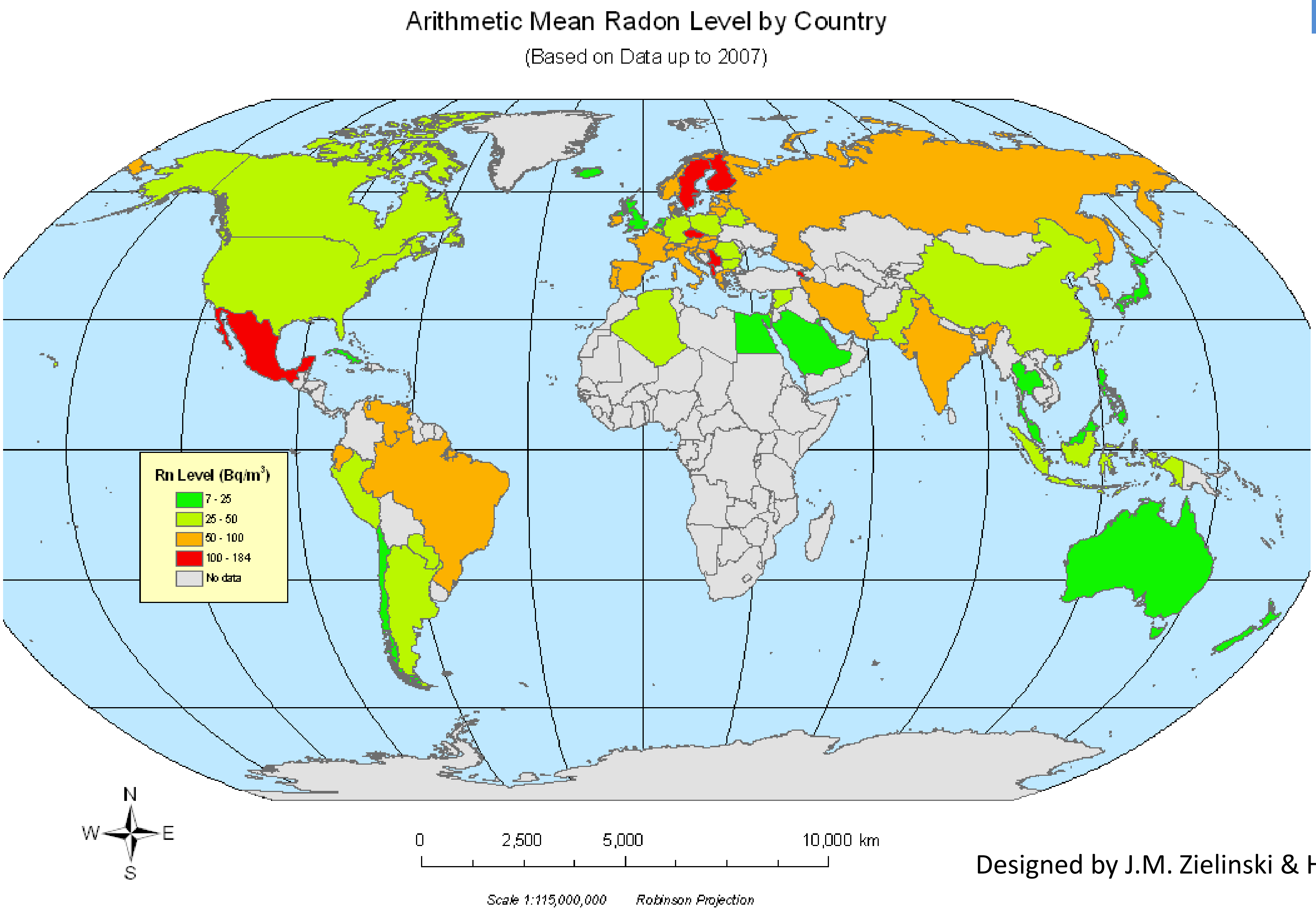
Pb-210
22 y
<0.1 MeV

Bi-210
5.0 d
1.2 MeV

Po-210
138 d
5.3 MeV

Pb-206
Stable

Worldwide radon risk



Arithmetic Mean Radon Level by Country

(Based on Data up to 2007)

Designed by J.M. Zielinski & H. Jiang

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

Terrestrial radionuclides

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 radionuclides

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:

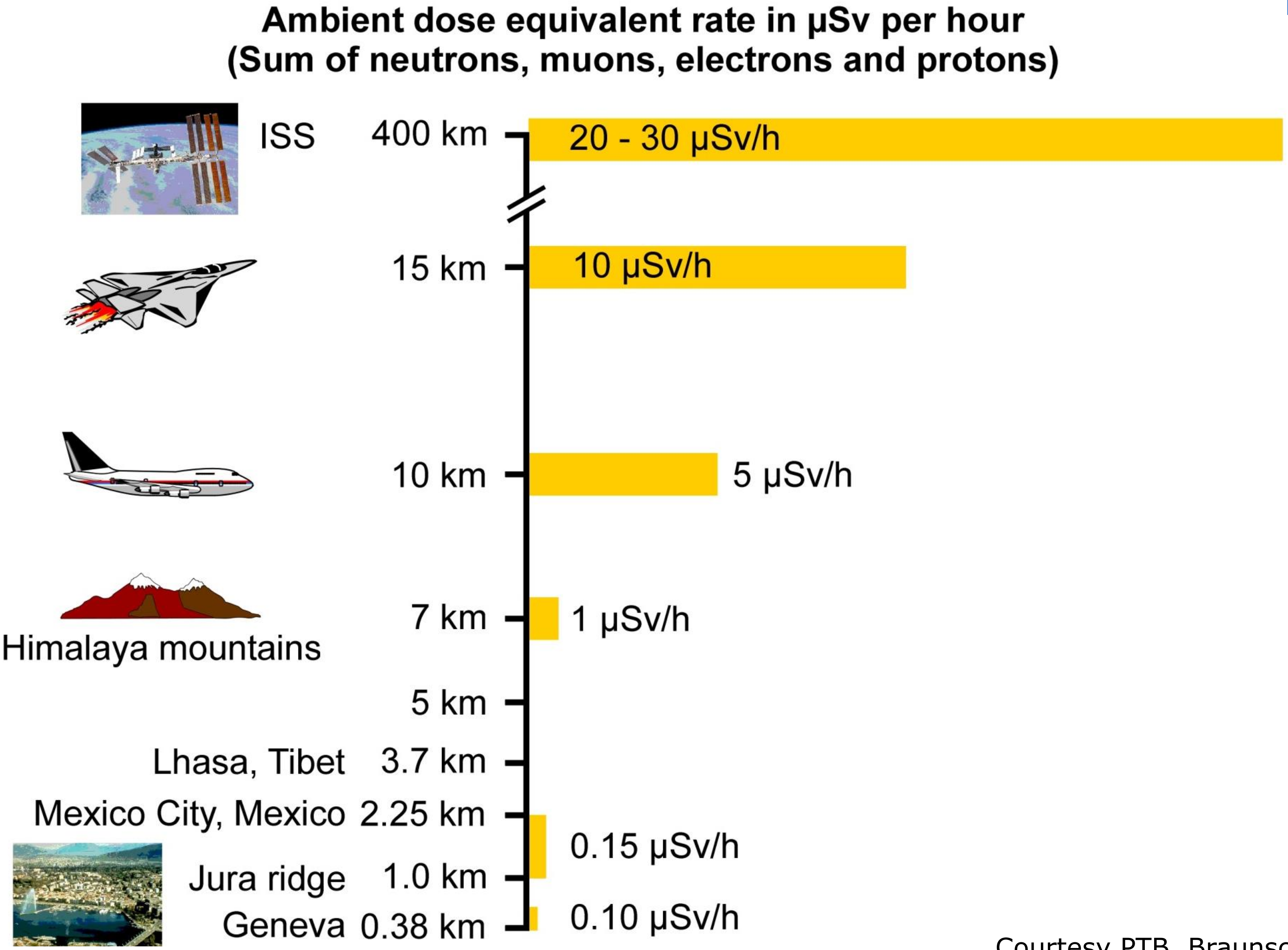
^{10}Be, ^{26}Al, ^{36}Cl, ^{80}Kr, …

The radioactivity inside our body

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

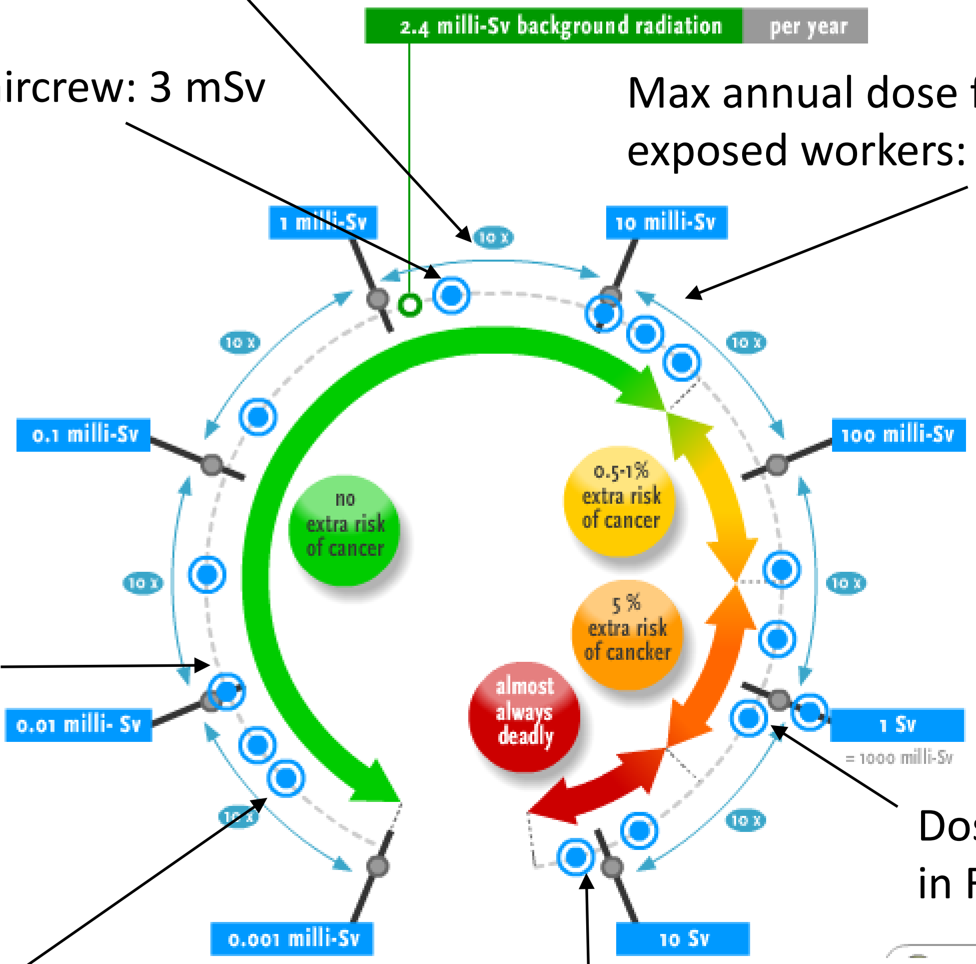
Cosmic radiation exposure versus altitude



Ambient dose equivalent rate in µSv per hour
(Sum of neutrons, muons, electrons and protons)

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

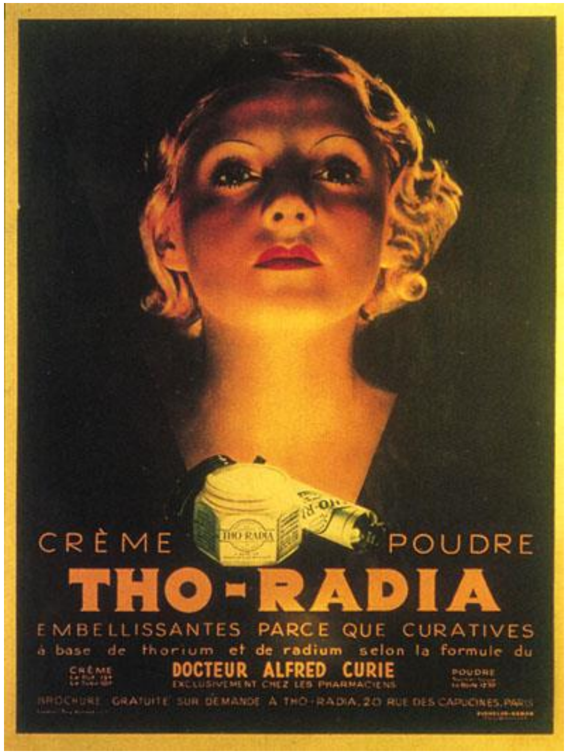
Chest x-ray: 10 µSv

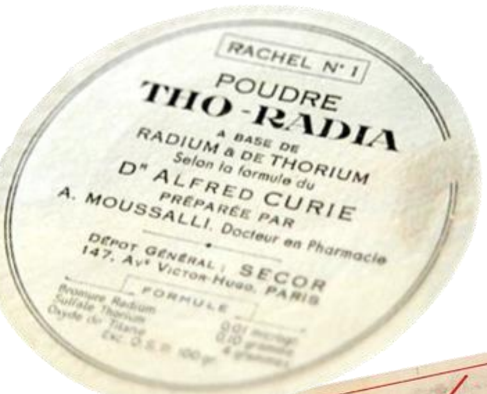
Dose per fraction in RT: 2 Sv

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!




RACHEL N° 1

POUDRE
THO-RADIA
A BASE DE
RADIUM & DE THORIUM
Selon la formule du
Dr ALFRED CURIE
PRÉPARÉE PAR
A. MOUSSALLI, Docteur en Pharmacie

DÉPOT GÉNÉRAL : SECOR
147, Ave Victor-Hugo, PARIS

FORMULE

Bromure Radium
Sulfate Thorium
Oxyde de Titane
Exc. Q.S.P. 100 gr


La SCIENCE au secours de la BEAUTÉ
par les
RADIUMELYS
Produits de Beauté
RADIOACTIFS
des Laboratoires de la
Cie Française Industrielle
et Commerciale du
RADIUM

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Velleminfroy
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FOIE
REINS & VESSIE
RHUMATISMES

AUTORISATION DE L'ÉTAT 23 Décembre 1859

APPROBATION DE L'ACADÉMIE DE MÉDECINE

PROPRIÉTÉS

Sulfatée-Calcique-Magnésienne et Radio-Active, l'Eau de **VELLEMINFROY** est l'Eau PAR EXCELLENCE de l'ARTHRITIQUE.

Elle régularise les FONCTIONS DIGESTIVES, assure le libre fonctionnement de l'INTESTIN, augmente la DIURÈSE dans de notables proportions, dissout les dépôts muqueux de la VESSIE, favorise l'excrétion urinaire et évitant les CONGESTIONS HEPATIQUES et RENALES, entraîne avec elle les calculs rénaux et biliaires.

En outre, par le FER et l'ARSENIC qu'elle contient, cette eau est à la fois tonique et reconstituante.

Indications

L'Eau de la Source de **VELLEMINFROY** est absolument SOUVERAINE et SANS SIMILAIRE dans le traitement des affections MEME LES PLUS REBELLES du **Foie**, des **Reins**, de la **Vessie**, et de l'**Intestin**, telles que :

Coliques hépatiques, Cirrhose du foie, Coliques néphrétiques, Néphrites, Albuminurie, Diabète, Constipation opiniâtre, Entérite, etc… et dans tous les cas de Diathèse arthritique ; Rhumatismes, Goutte, Gravelle

Mode d'emploi

Comme eau de régime et pour une véritable cure, l'EAU de VELLEMINFROY doit être prise **à jeun**, AU REPAS, elle constitue une boisson agréable à boire, seule ou mélangée au vin. Pour les doses et autres détails du traitement se conformer aux prescriptions du Médecin.

Marcel HENRY Prop.-Exploitant

Pour tous renseignements s'adresser, à M. le Directeur de la Source Minérale de VELLEMINFROY à VELLEMINFROY (Haute-Saône)


154

MÉTHODE
THO-RADIA
EMBELLISSANTE PARCE QUE CURATIVE
4°
DENTIFRICE
THO-RADIA
A BASE DE SELS DE THORIUM
FORMULE
du Docteur Alfred CURIE

Le grand tube :
6 francs

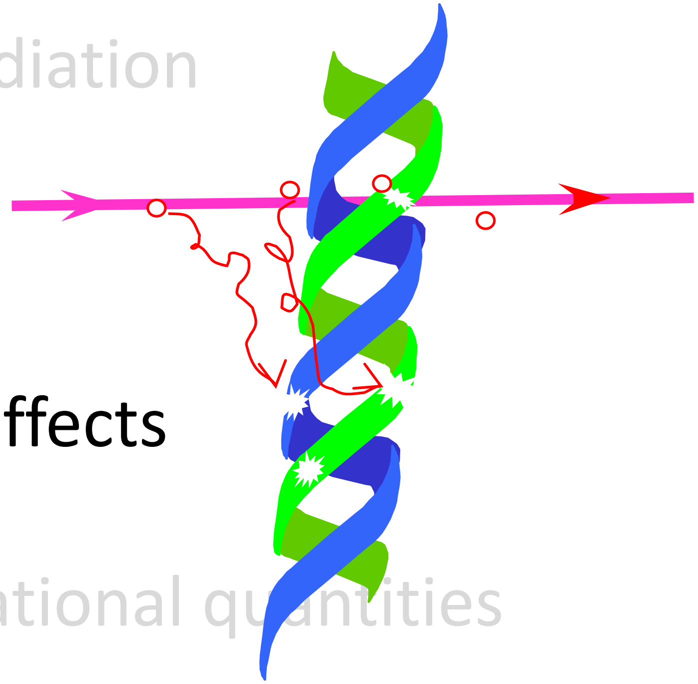
Astringent et bactéricide, il stérilise la cavité buccale, évite et combat les gingivites, prévient la carie et les pyorrhées alvéolaires. Il assainit les dents, laisse dans la bouche une délicieuse impression de fraîcheur, conserve l'éclat, la blancheur et l'intégrité de la dentition.

Pas de joli sourire sans de jolies dents

CHEZ LES PHARMACIENS EXCLUSIVEMENT

Outline of the lecture

- 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



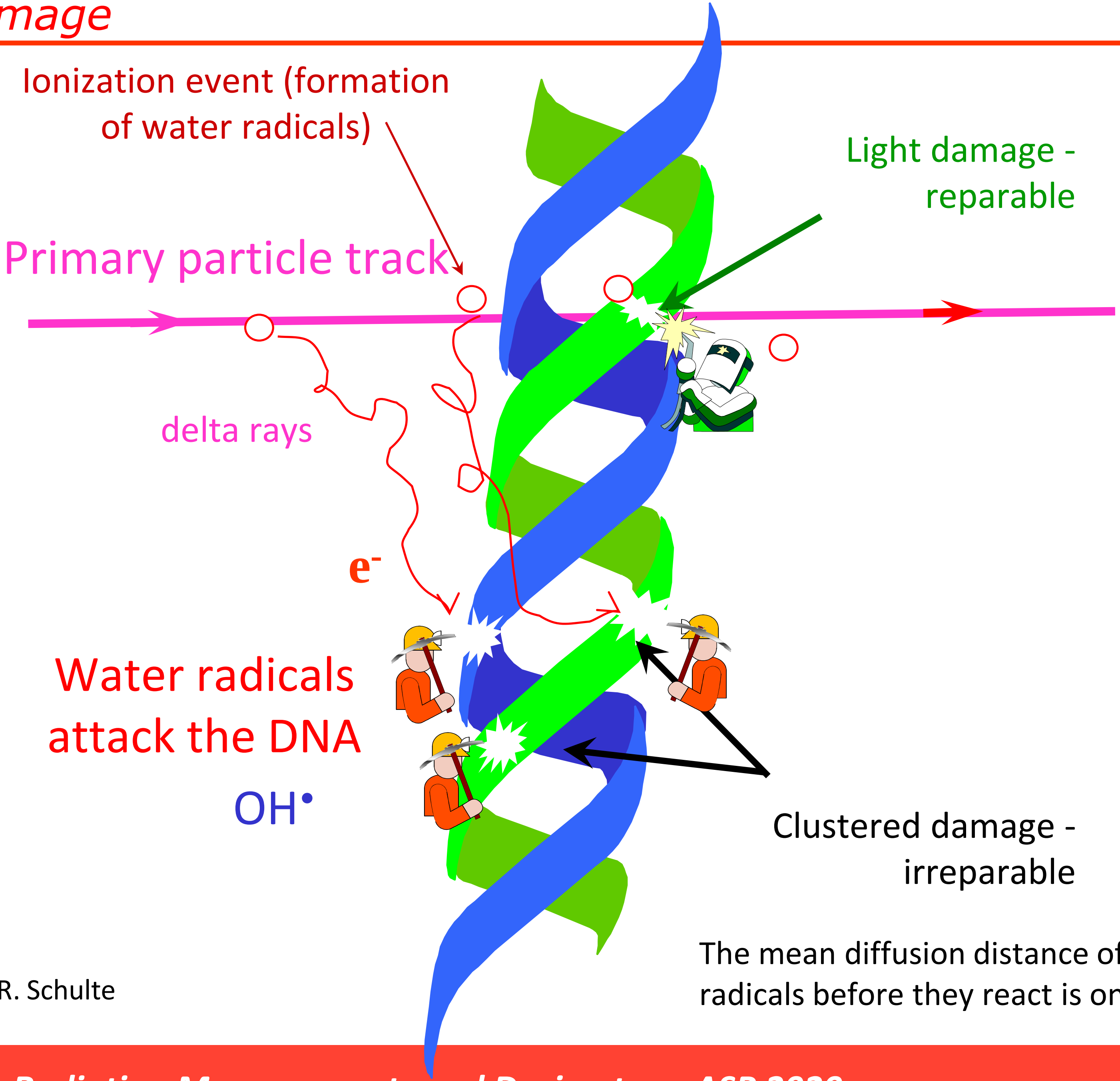
Why is radiation dosimetry important?

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)

DNA damage



Ionization event (formation of water radicals)

Light damage - reparable

Primary particle track

delta rays

e^-

Water radicals attack the DNA

$OH^\bullet$

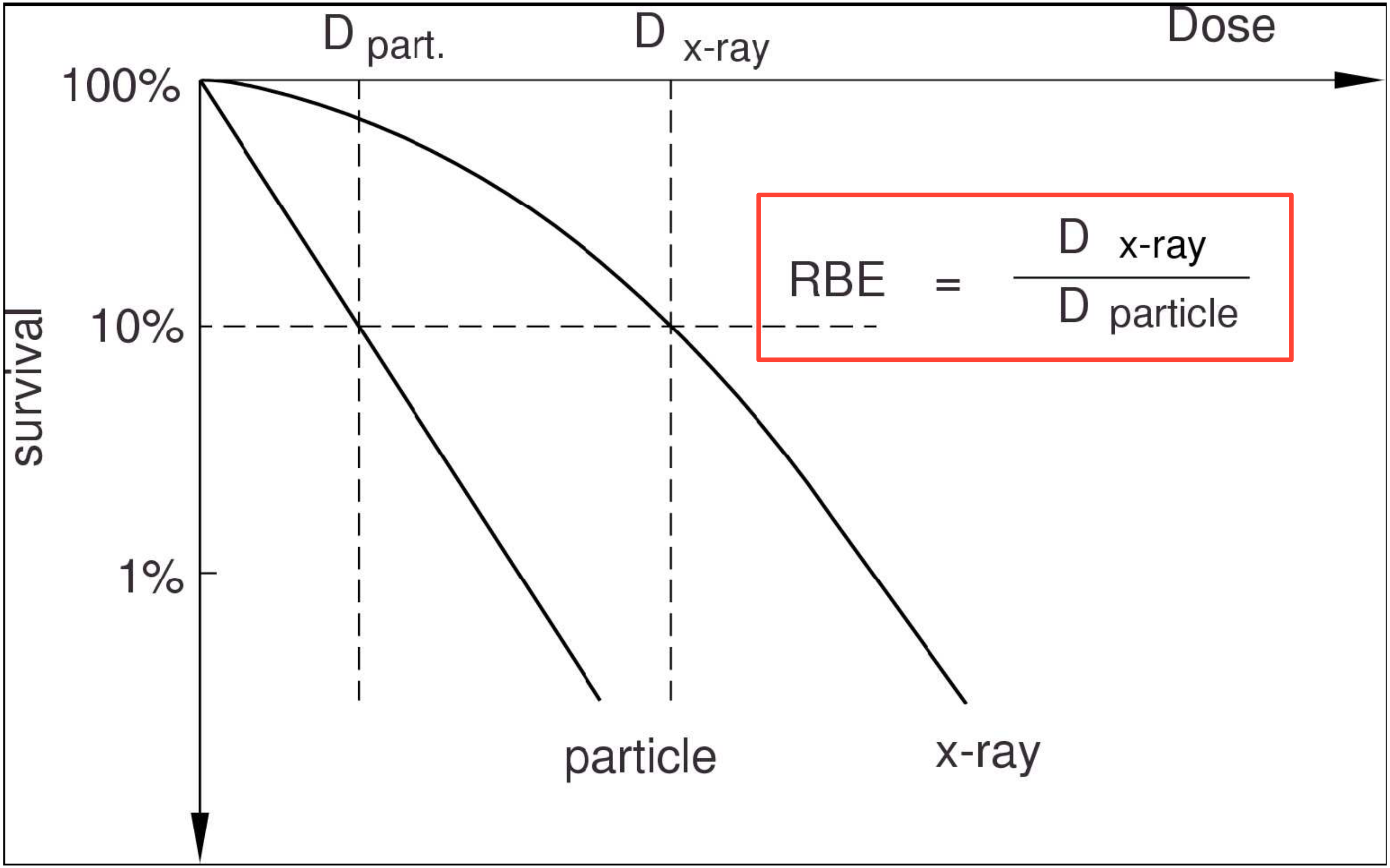
Clustered damage - irreparable

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

Courtesy R. Schulte

Radiobiological effectiveness (RBE)

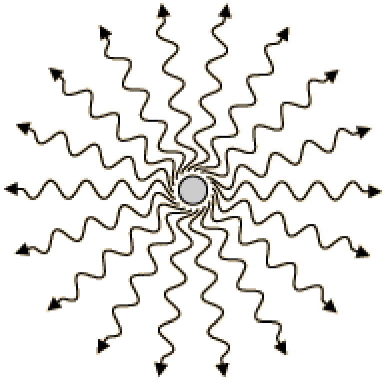
DIFFERENT TYPES OF RADIATION MAKE DIFFERENT DAMAGE



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

QUESTION 2

What are the biological effects of radiation?



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

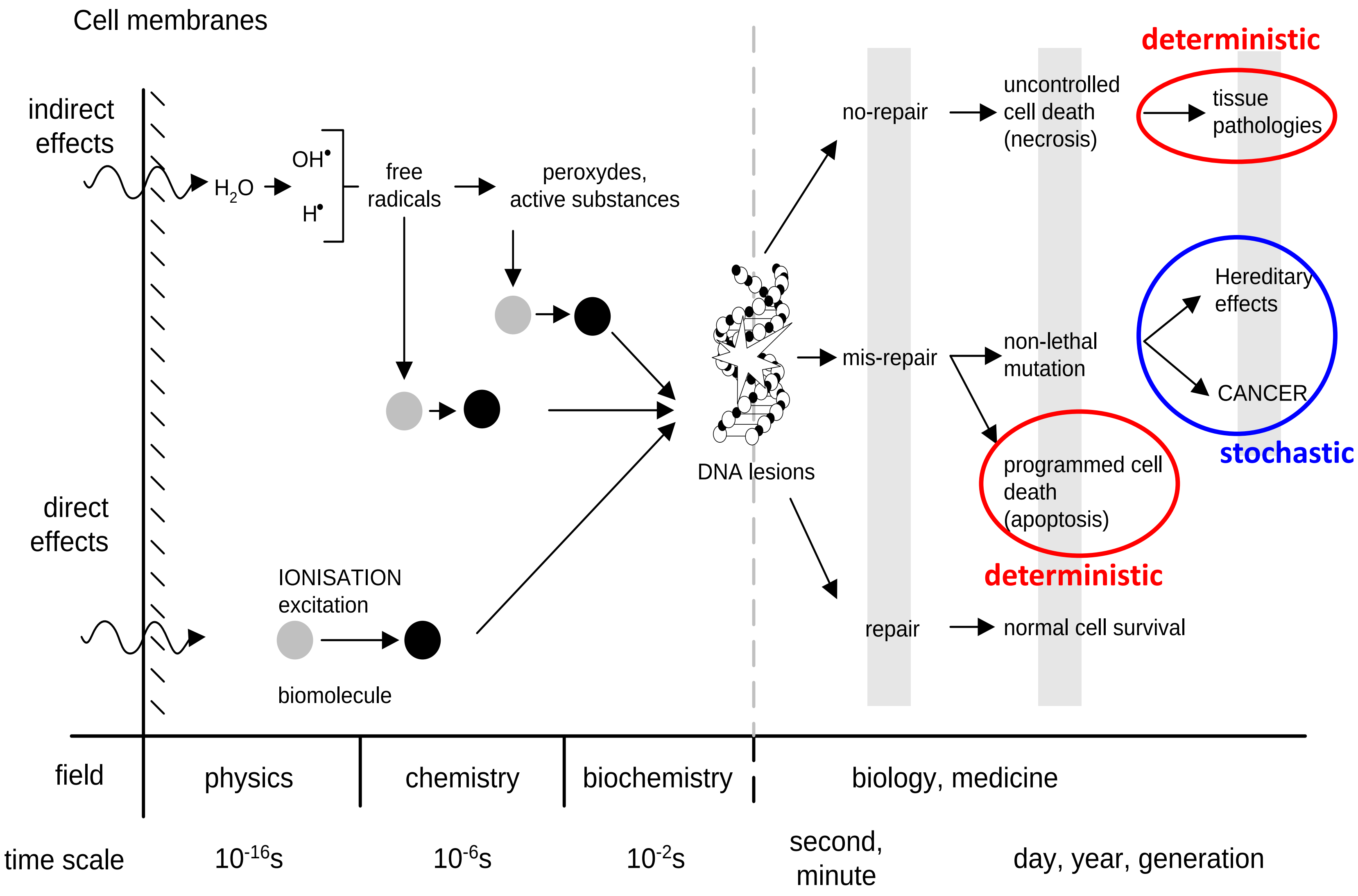
dose received in short time interval
dose threshold: > 500 mSv

immediate consequences:
    vomiting
    immun deficiency
    erythema and necrose

health detriments are function of the dose

lethal dose: 5 – 7 Sv

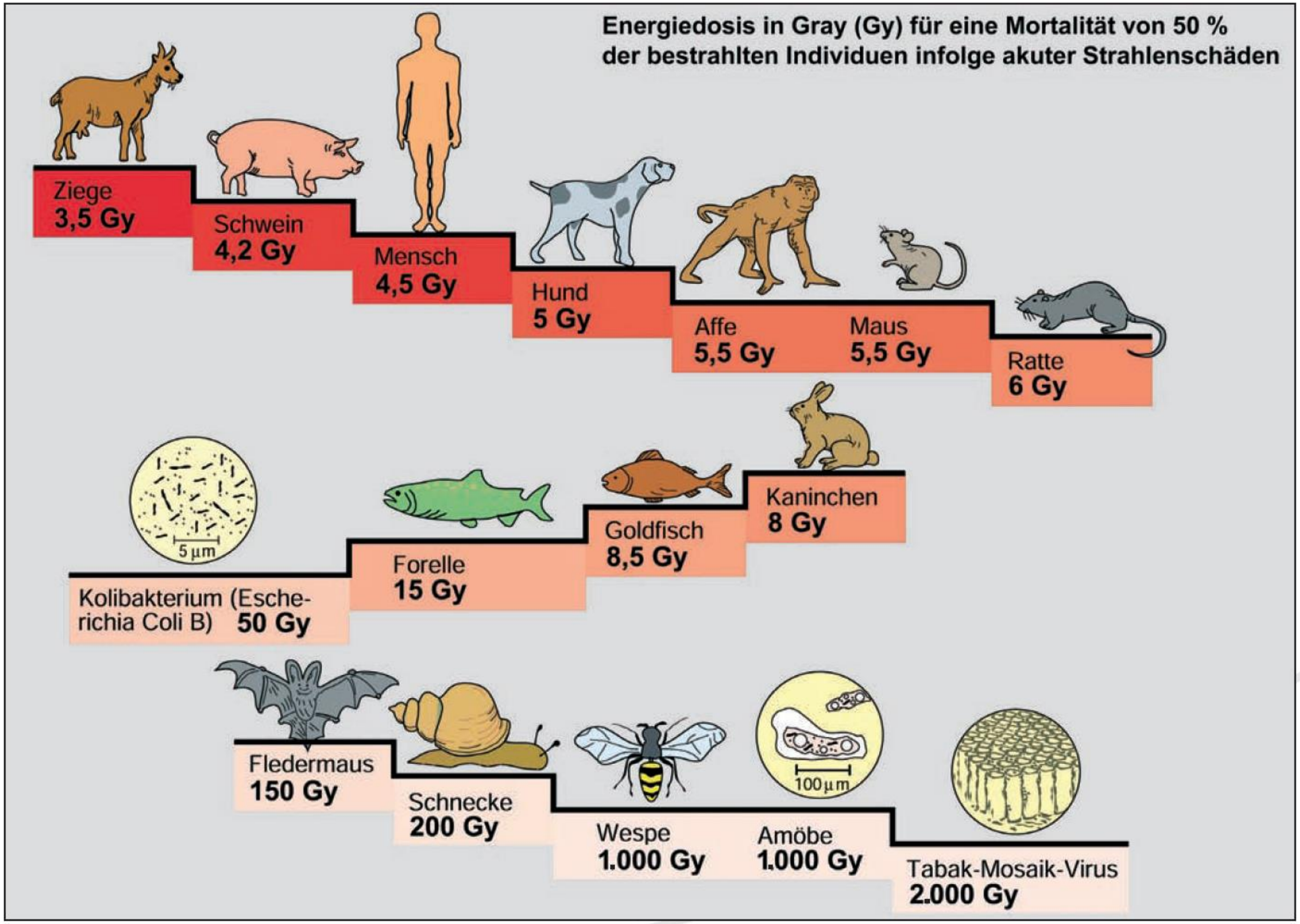
The biological actions of radiation



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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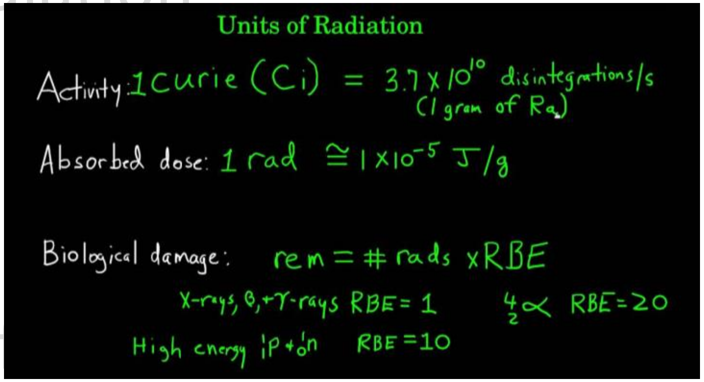


Units of Radiation

Activity: 1 curie (Ci) = 3.7×10^{10} disintegrations/s (1 gram of Ra)

Absorbed dose: 1 rad $\cong 1 \times 10^{-5}$ J/g

Biological damage: rem = # rads x RBE

X-rays, β, + γ-rays RBE = 1 $\quad {}^{4}_{2}\alpha$ RBE = 20

High energy ${}^{1}_{1}p + {}^{1}_{0}n$ RBE = 10

General principles of radiation protection

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

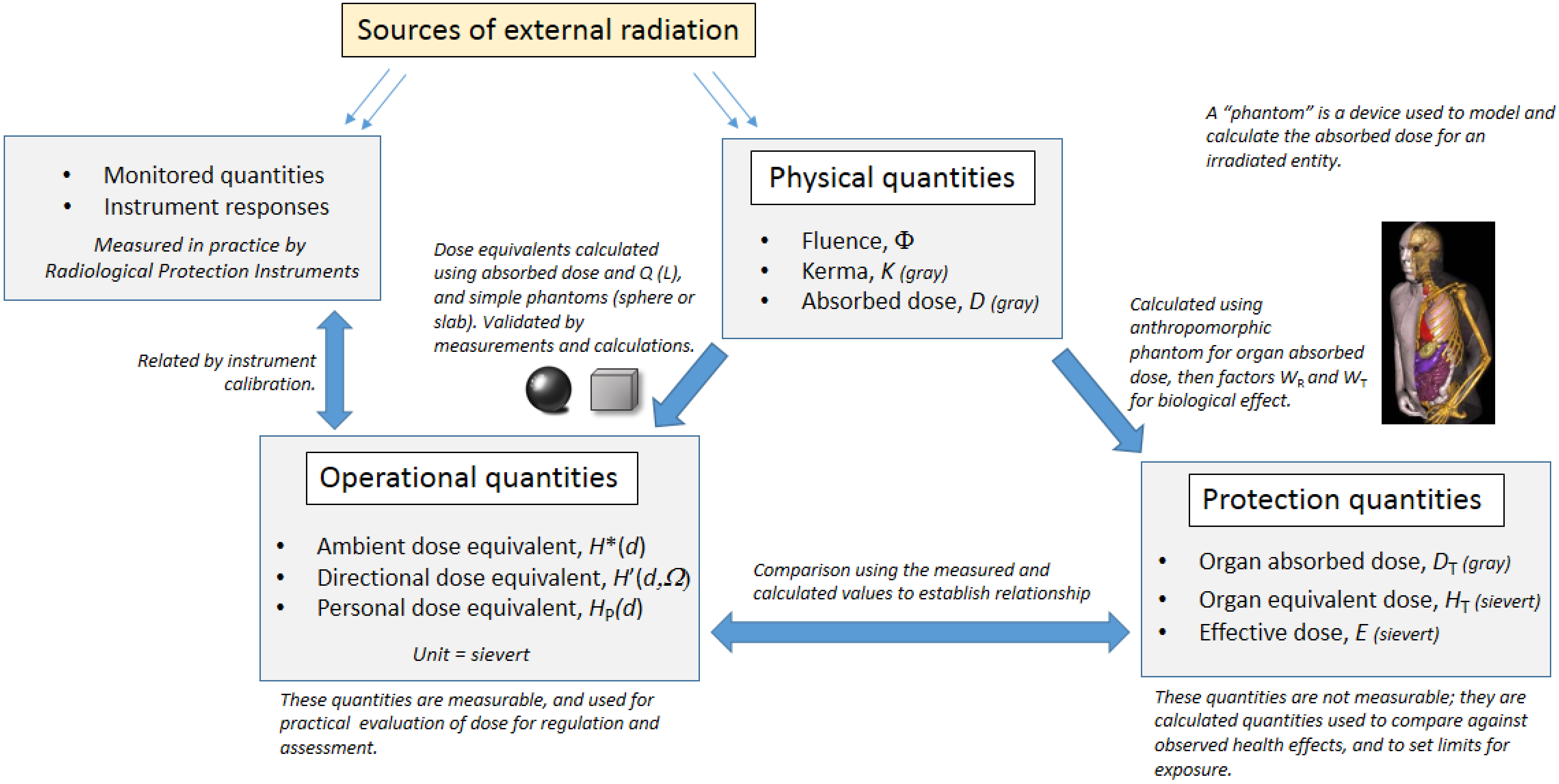
3) **Optimization**

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

Physical, protection and operational quantities

International Commission on Radiological Protection

Dose quantities in SI units for external radiological protection



Sources of external radiation

- Monitored quantities
- Instrument responses

Measured in practice by Radiological Protection Instruments

Related by instrument calibration.

Dose equivalents calculated using absorbed dose and Q (L), and simple phantoms (sphere or slab). Validated by measurements and calculations.

Physical quantities

- Fluence, Φ
- Kerma, K *(gray)*
- Absorbed dose, D *(gray)*

A "phantom" is a device used to model and calculate the absorbed dose for an irradiated entity.

Calculated using anthropomorphic phantom for organ absorbed dose, then factors W_R and W_T for biological effect.

Operational quantities

- Ambient dose equivalent, $H^*(d)$
- Directional dose equivalent, $H'(d,\Omega)$
- Personal dose equivalent, $H_P(d)$

Unit = sievert

These quantities are measurable, and used for practical evaluation of dose for regulation and assessment.

Comparison using the measured and calculated values to establish relationship

Protection quantities

- Organ absorbed dose, D_T *(gray)*
- Organ equivalent dose, H_T *(sievert)*
- Effective dose, E *(sievert)*

These quantities are not measurable; they are calculated quantities used to compare against observed health effects, and to set limits for exposure.

Source: Wikipedia

Radiological quantities and units

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)

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

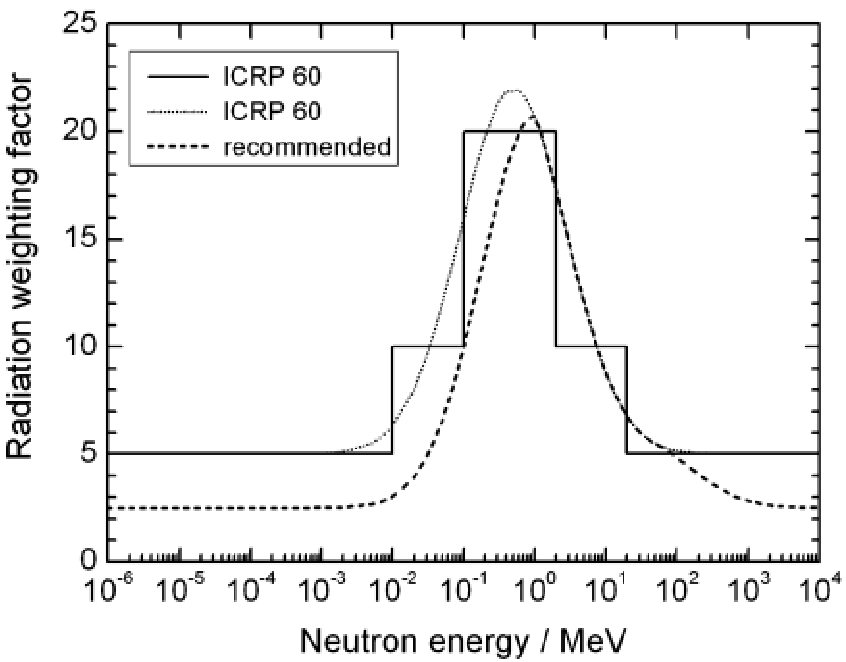
Effective dose E: Sum of all equivalent doses weighted with the weighting factor w_T for tissue T

Unit: Sv — (1 Sv = 100 rem)

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

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



Tissue sensitivity and tissue weighting factors, W_T

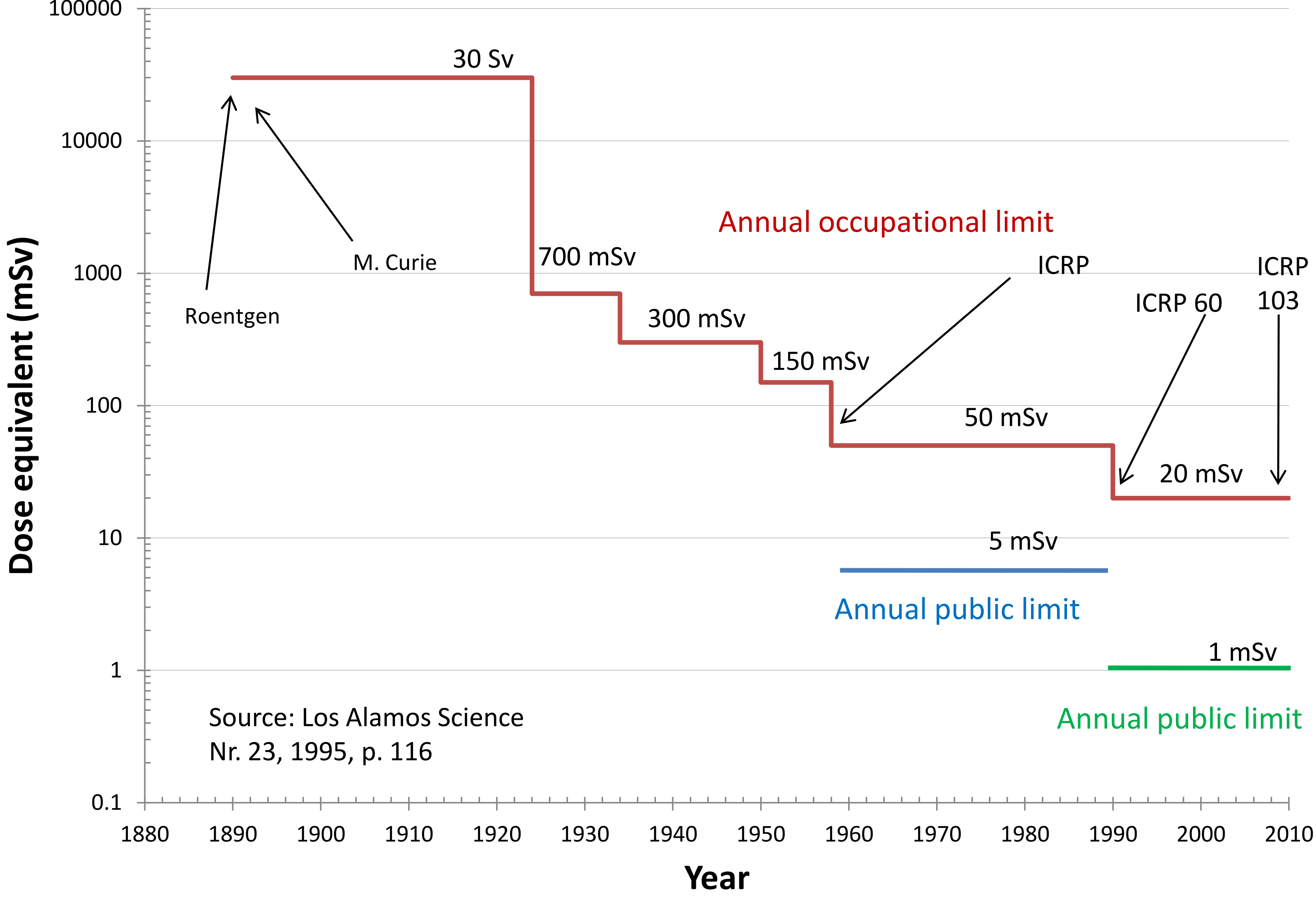
Organ / tissue	No of tissues	W_T	Total contribution
Bone-marrow, colon, lung, breast, stomach, remainder tissues	6	0.12	0.72
Gonads	1	0.08	0.08
Bladder, esophagus, liver, thyroid	4	0.04	0.16
Bone surface, brain, salivary glands, skin	4	0.01	0.04

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

Operational quantities

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

History of radiation protection



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

Radiological risks

External radiation source → external exposure

Contamination → Surface

Contamination → Volumetric (air)

Internal radiation source → internal exposure

Basic concepts in radiation protection

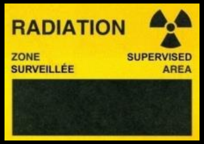
- Person **occupationally exposed** to radiation (> 1 mSv/y)
  - Category **A** workers: > 6 mSv/y
  - Category **B** workers: < 6 mSv/y
- **Supervised area**: area with dose > 1 mSv/y

  (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)

Classification of radiological areas at CERN

Radiation Area

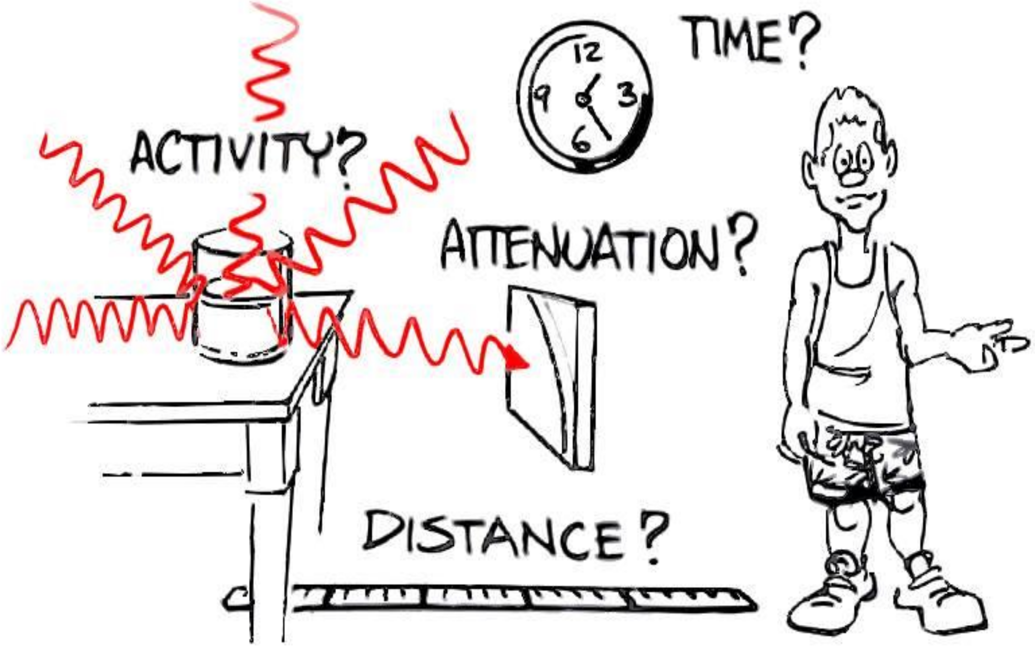
Area	Dose limit [year]	Ambient dose equivalent rate		Sign
		Work place	Low occupancy	Sign  RADIATION ZONE SURVEILLÉE SUPERVISED AREA
Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h	 Dosimeter obligatory Dosimètre obligatoire Radiation Protection Radioprotection
Supervised	6 mSv	3 µSv/h	15 µSv/h	 Dosimeter obligatory 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

Controlled Area

QUESTION 3

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

Protection against external exposure

- **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

Job and dose planning

- 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


Lead shielding

Protection methods against intakes of radioactivity

- **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

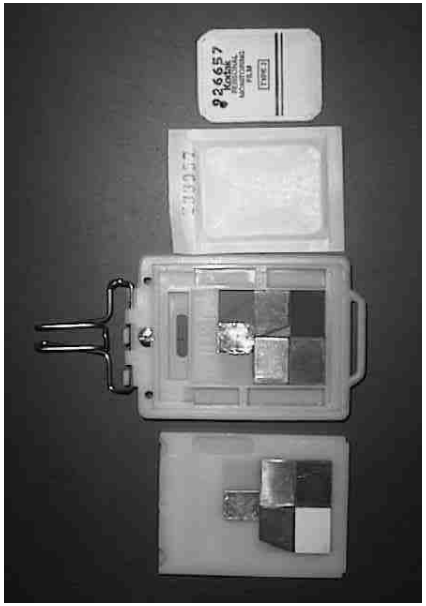
Monitoring of external exposure

- **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)

Operational quantities and dose limits

- **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

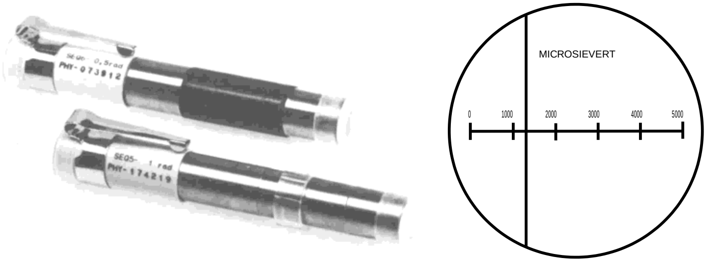


Kodak film badge

Personal dosimeter: "Legal dose”

RADOS DIS

Finger dosimeter



Quartz-fiber dosimeter (ionisation chamber and electroscope)

Operational dosimeter DMC: “Operational dose”

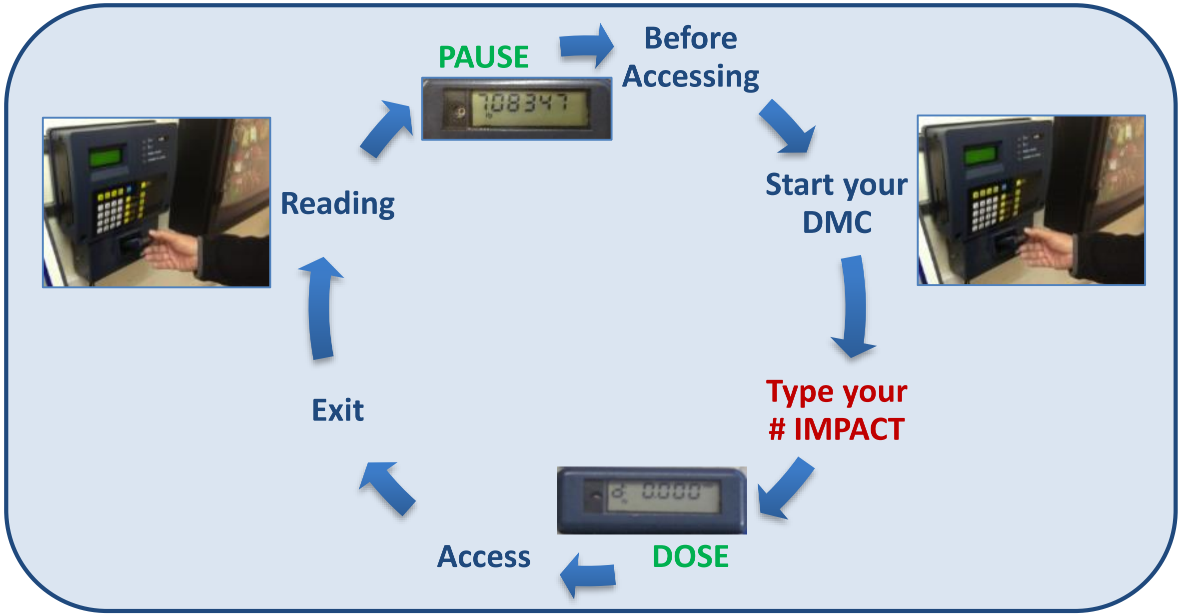
Personal dosimetry at CERN

- Continuous measurement of βγ-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

Operational dosimetry at CERN

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

Operational dosimetry



PAUSE

Before Accessing

Start your DMC

Type your # IMPACT

DOSE

Access

Exit

Reading

Radioactive contamination at particle accelerators

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

Radioactive contamination at particle accelerators

- 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

Contamination

- **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**

Monitoring of internal exposure

- 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

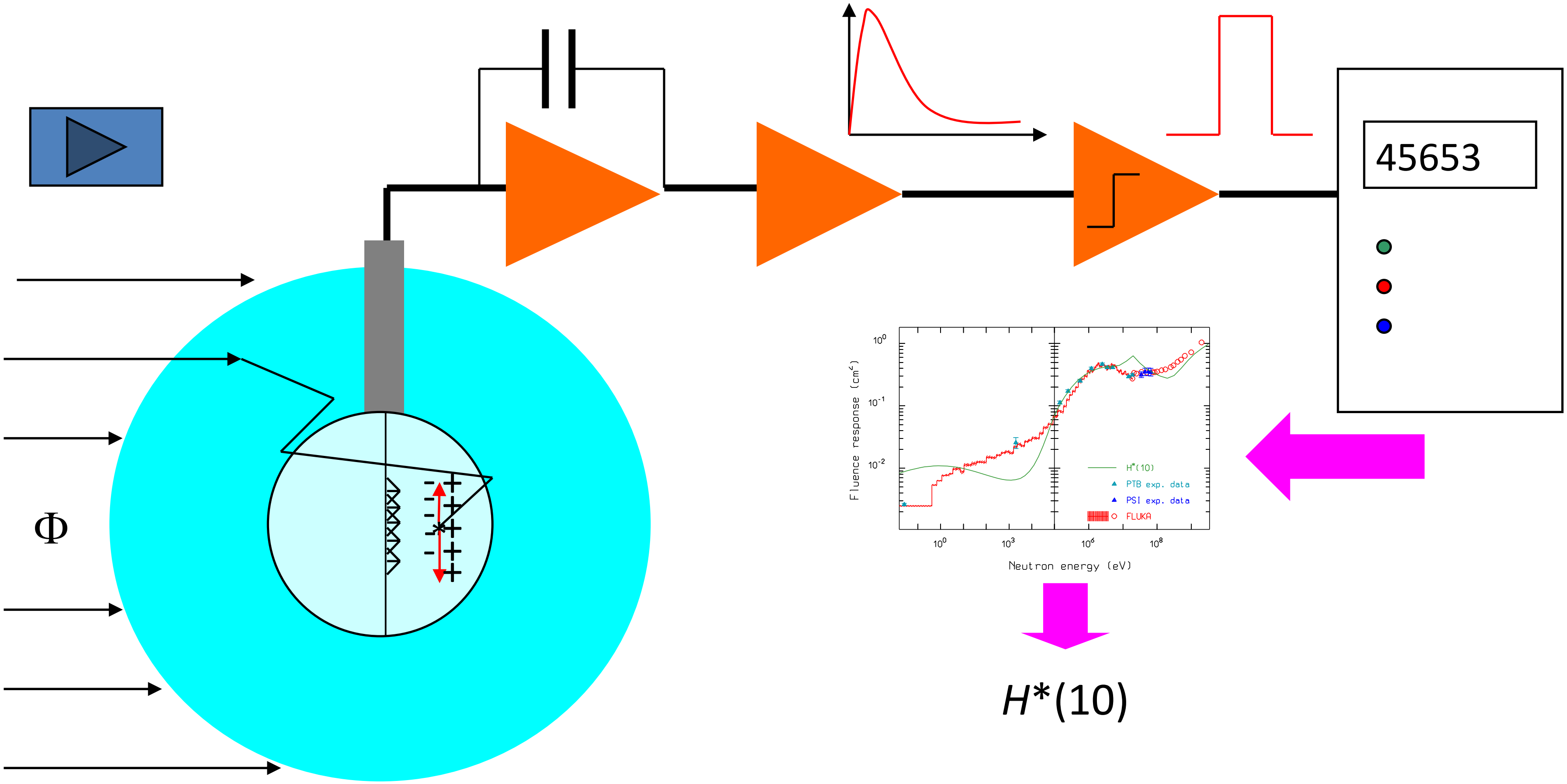
Individual protection equipment is mandatory for work in areas with contamination risk (cleaning operations, machining of radioactive material or equipment, …)

Outline of the lecture

- 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 qua
- Principles of radiation protection
  - Justification, optimization and do
  - The ALARA principle
- Protection means
- **Instrumentation for measuring ionizing radiation**

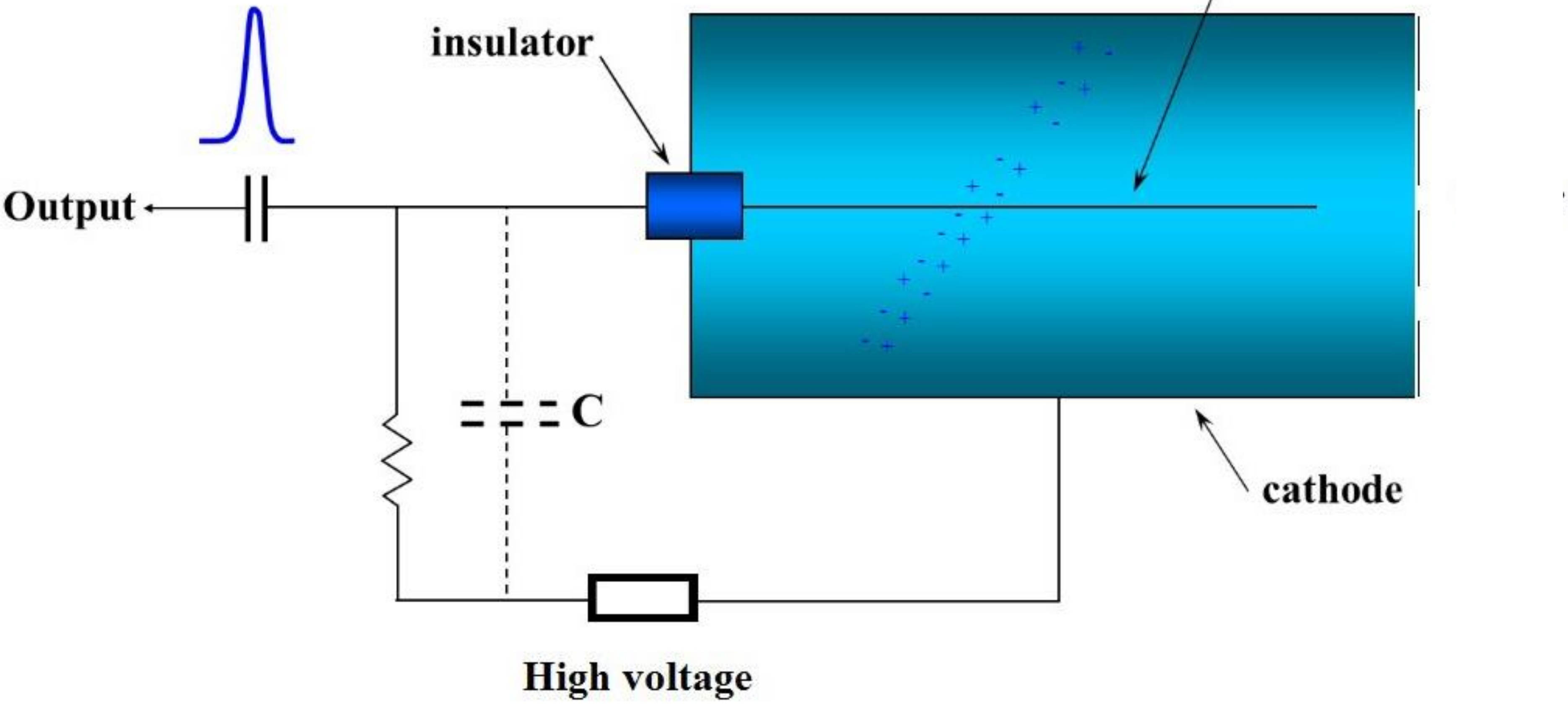
Radiation measurements

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

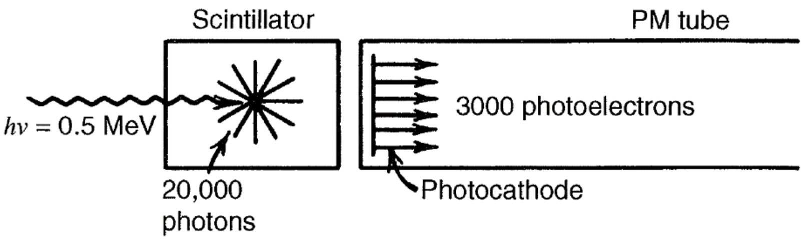


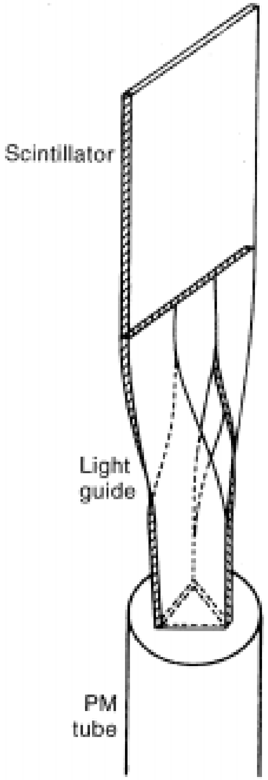
Courtesy S. Agosteo, Politecnico di Milano

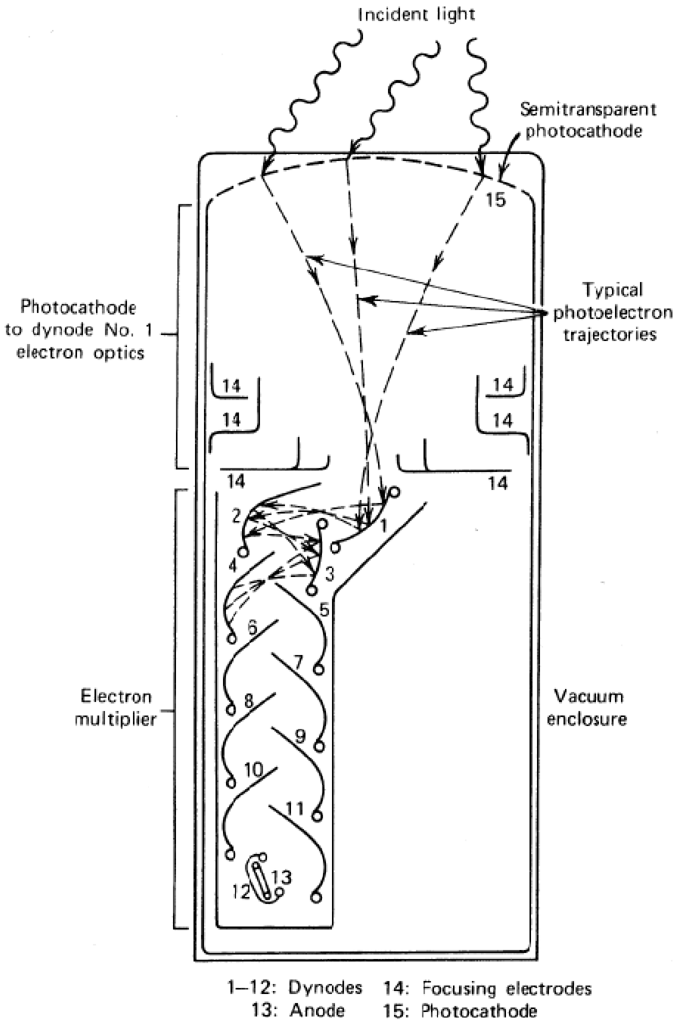
Ionization chamber



Scintillating crystal coupled to a PMT







From Glenn F. Knoll, Radiation Detection and Measurement

AUTOMESS dose rate meter 6150 AD6

AD17 external probe

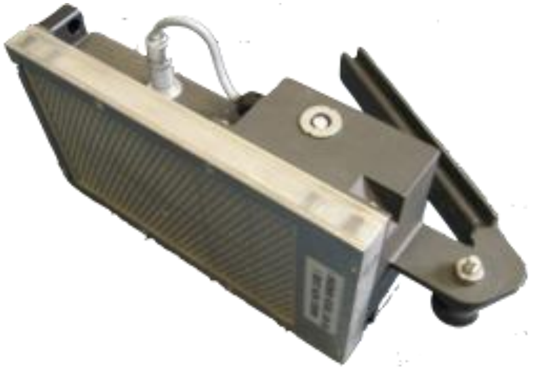
Push button 1

Push button 2

Push button 3

Push button 4

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



ADK surface contamination meter for α, β and γ radiation
<u>*Detector:*</u> sealed proportional counter
Active surface 100 cm^2

Contamination monitors

APA

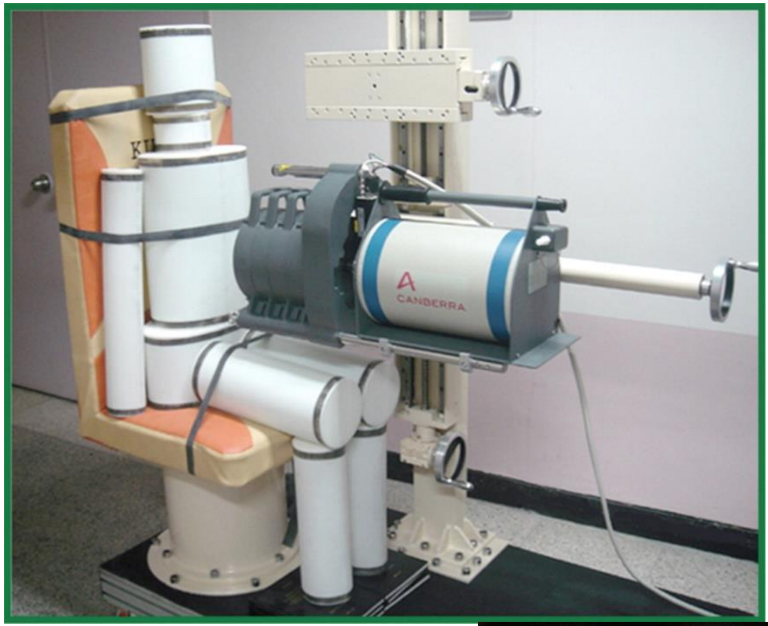
CMS2000

Air contamination monitors

Hand and foot monitor

ABPM203M

Whole body counting

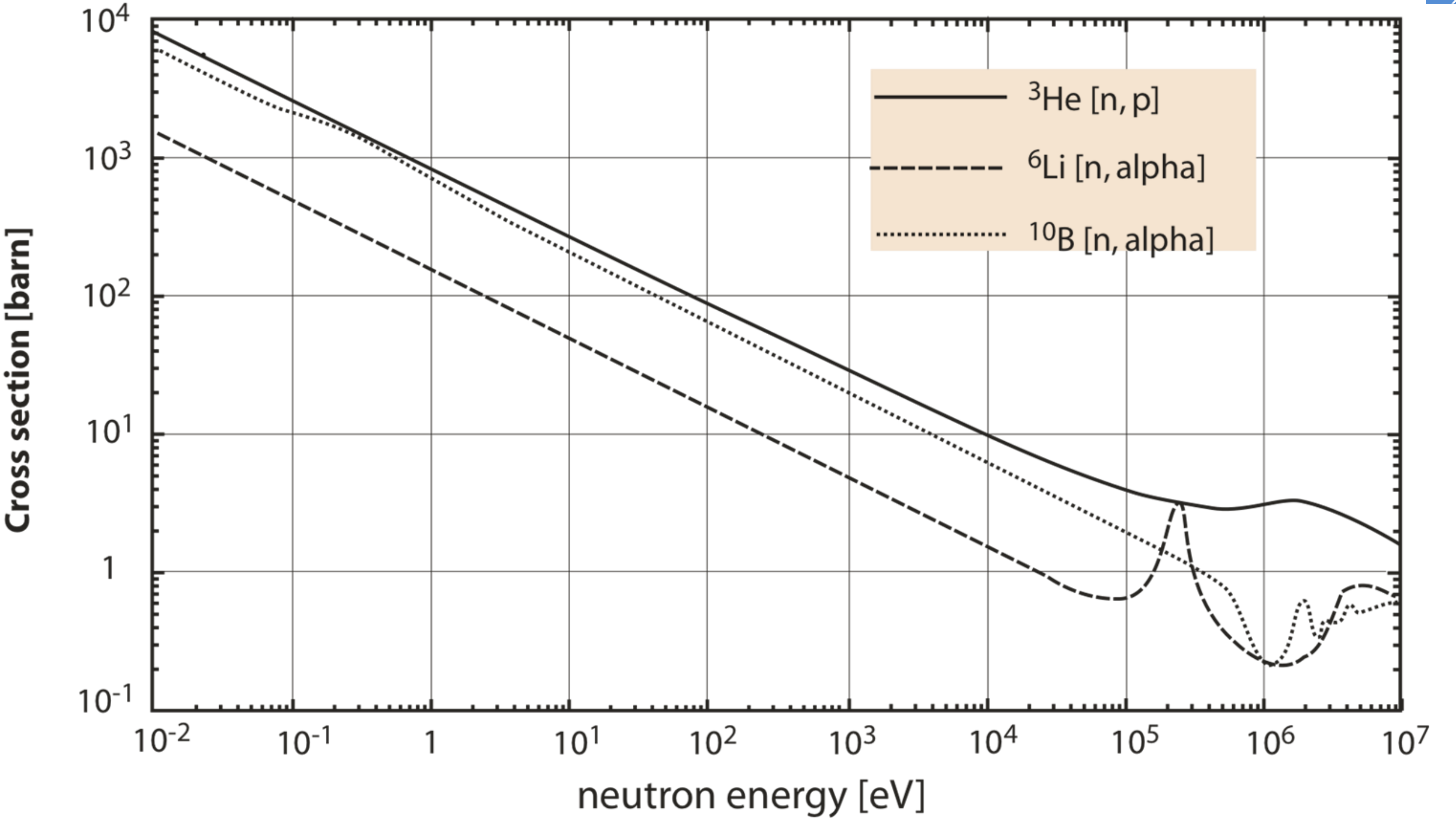


Slow neutron detection

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

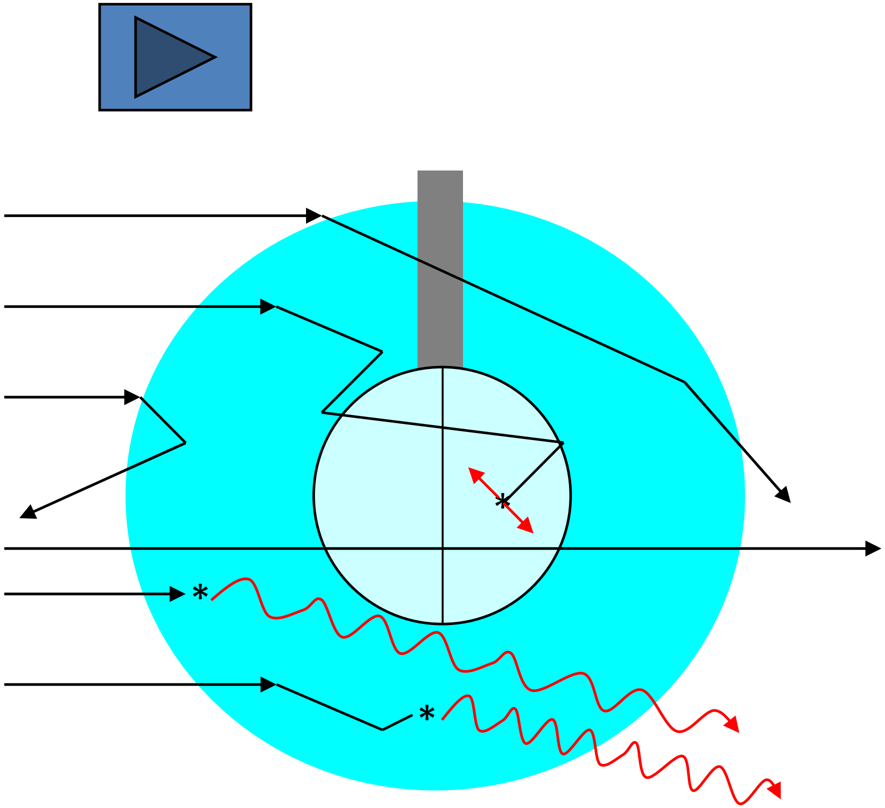
1) Boron	$^{10}B + n \rightarrow {}^{7}Li + \alpha$	Q = 2.793 MeV
	$^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha$	Q = 2.310 MeV
2) Lithium	$^{6}Li + n \rightarrow {}^{3}H + \alpha$	Q = 4.78 MeV
3) ^{3}He	$^{3}He + n \rightarrow {}^{3}H + p$	Q = 764 keV

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



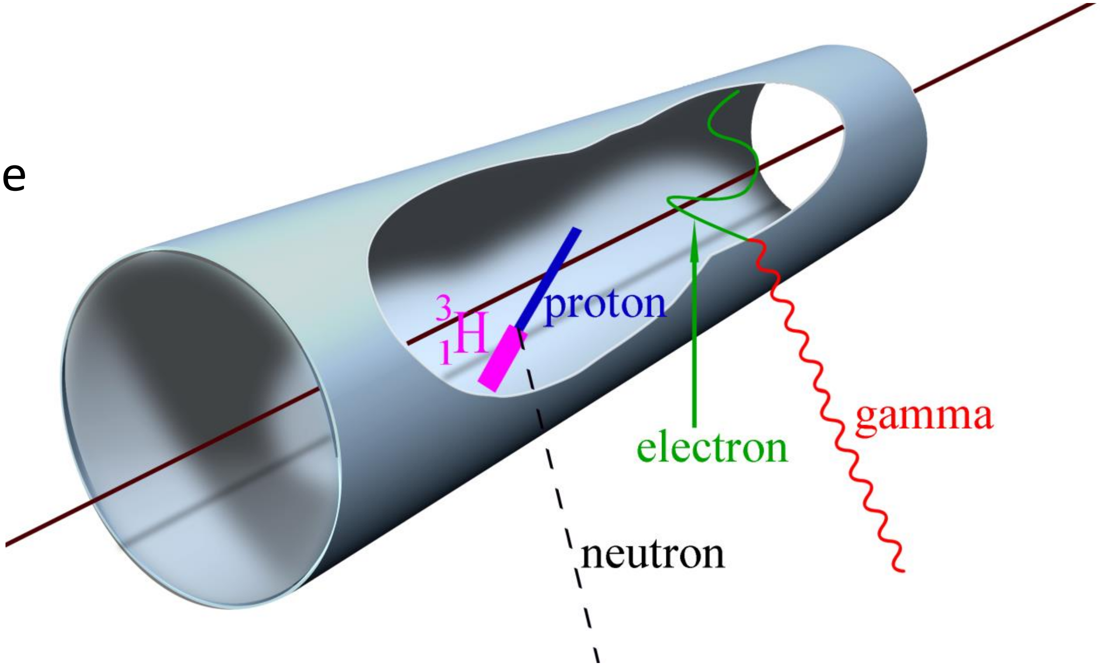
Courtesy S. Agosteo, Politecnico di Milano

Proportional counters for slow neutron detection

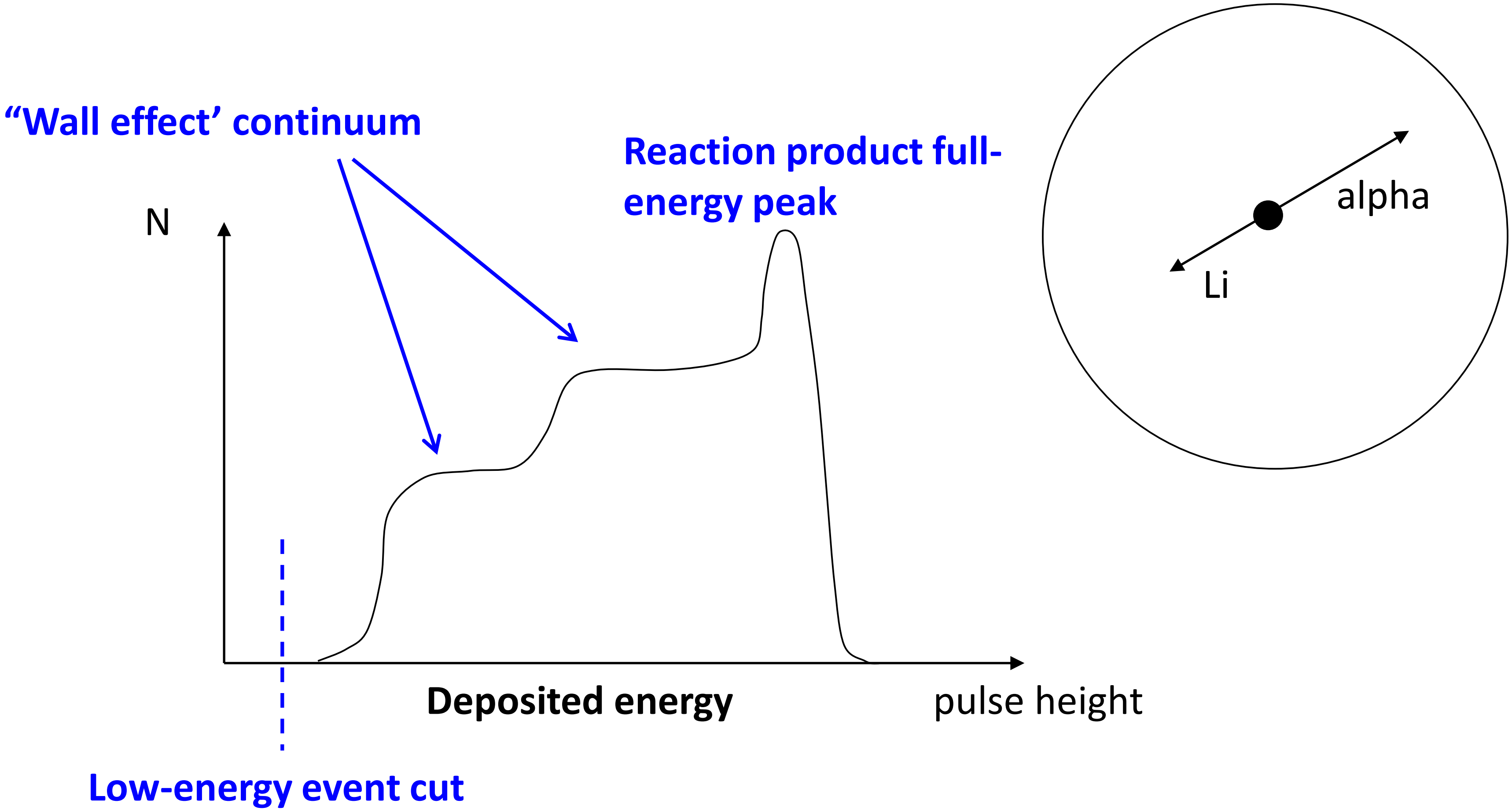
BF_3 gas and ^3He gas make detectors for slow neutrons with excellent gamma discrimination

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.



Pulse height spectrum from a BF_3 proportional counter



“Wall effect’ continuum

Reaction product full-energy peak

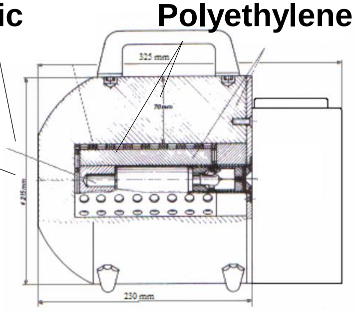
Deposited energy

Low-energy event cut

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

Rem counters

Studsvik 2202D

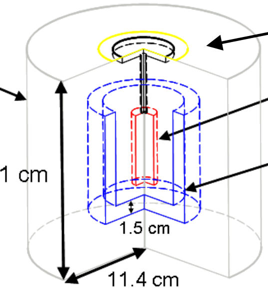


Boron plastic

Polyethylene

BF_3 tube

Eberline WENDI-2

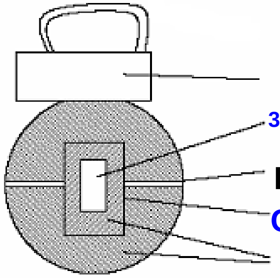


Boron plastic

^{3}He counter

Tungsten layer

Berthold LB6411 (also LB6411Pb)



Electronic

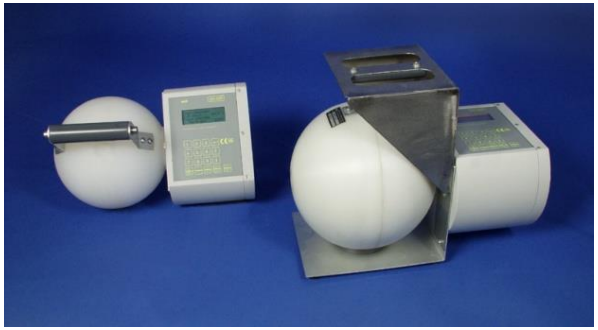
^{3}He counter

Bore hole

Cadmium absorber

PE

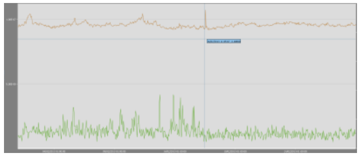
MAB SNM500(X)



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

Environmental monitoring

Stray radiation



Air

Water

Other environmental samples

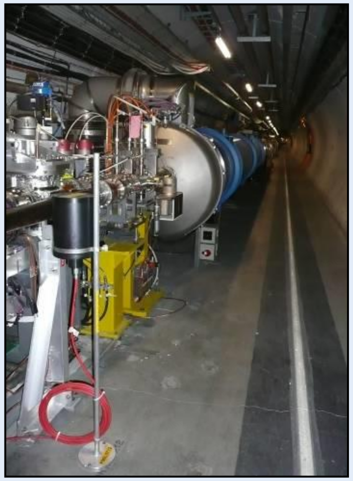
Operational radiation protection monitoring

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

Operational radiation protection monitoring

Site Gate Monitor

Reading of radiation levels directly available

Radiation Alarm Unit (RAMSES)

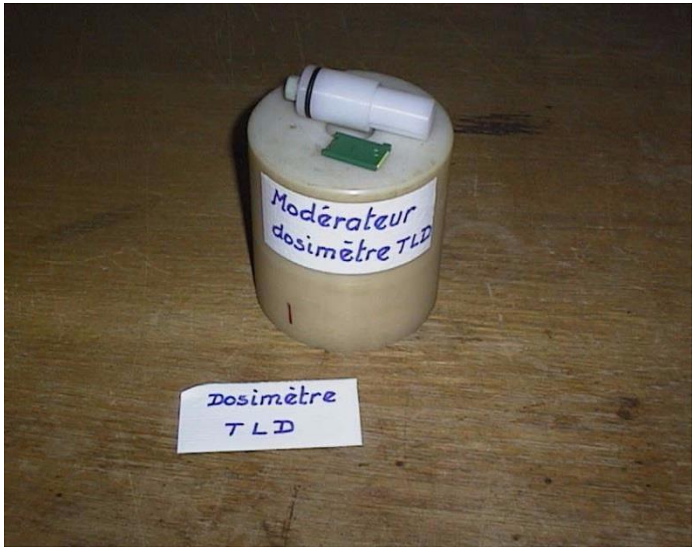
Radiation alarm display

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.

Some textbooks

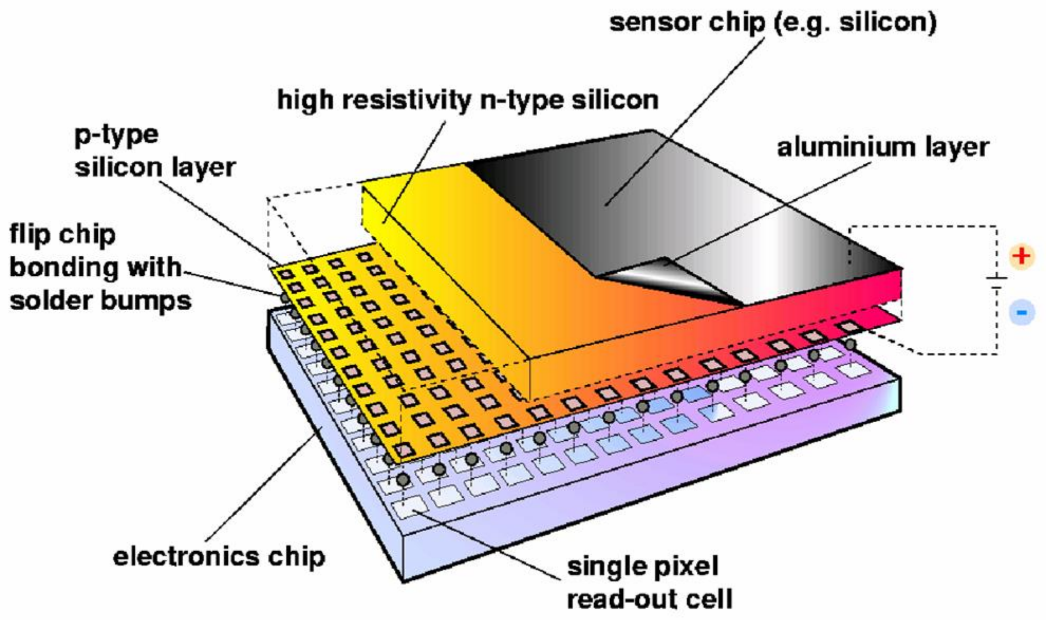
Glenn F. Knoll, Radiation Detection and Measurement, 4th edition

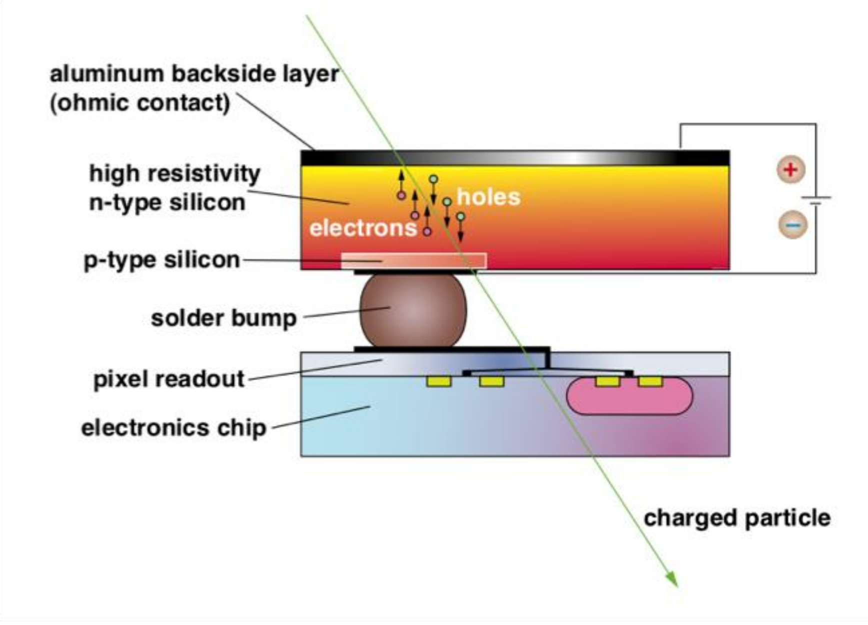
Frank H. Attix, Introduction to Radiological Physics and Radiation Dosimetry

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/

The Medipix pixel detector

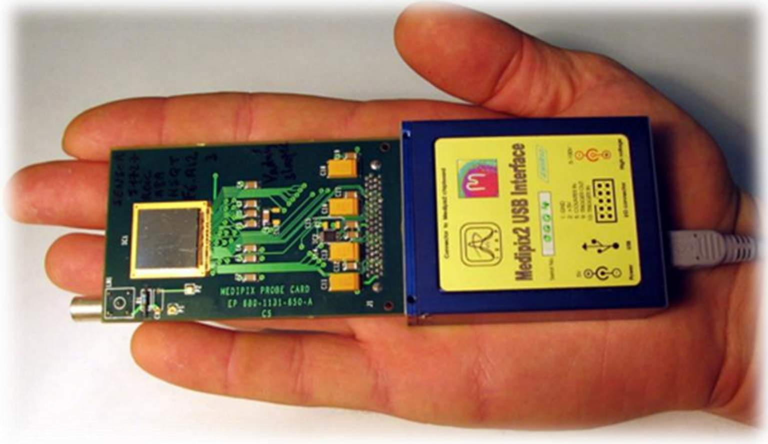


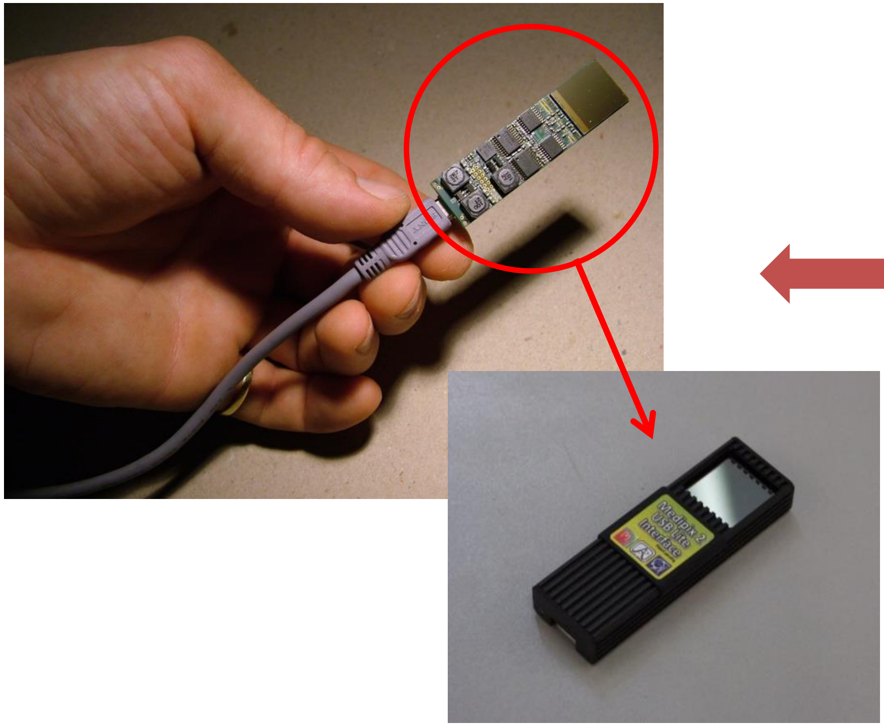


- In the hybrid pixel detector architecture the radiation sensor element and the readout are processed separately
- The sensor is segmented with the same geometry as the readout chip and detector and readout cells are connected using standard flip-chip technology
- The separation in processing allows for independent optimization of readout and sensor and different sensor materials can be used with the same readout.

The Medipix pixel detector

- **Use USB standard for detector read-out and data acquisition control**
- **Plug & Play**
- **Fully USB powered**
- **External triggering**
- **Compact size of interface**

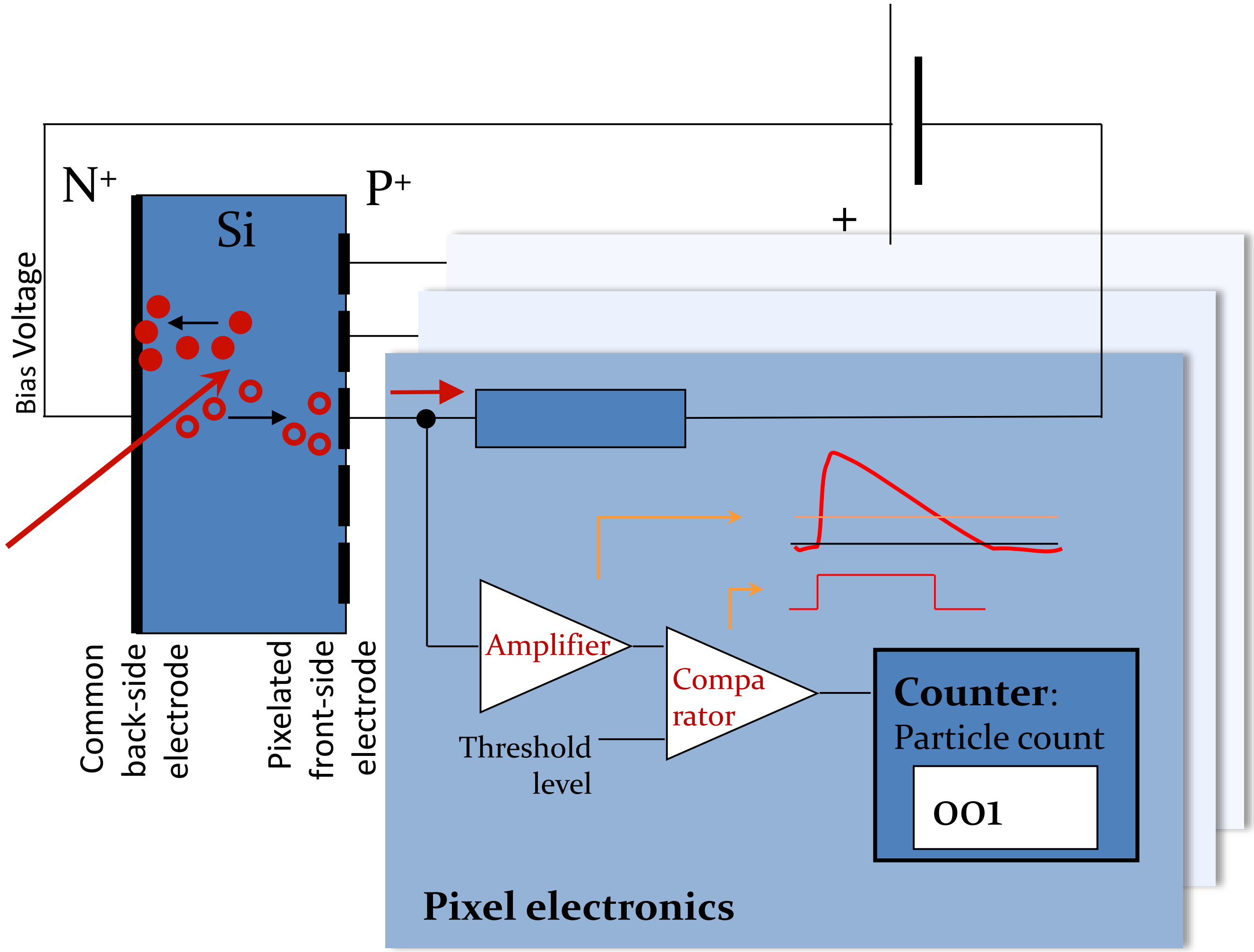




USB-Lite Interface

- USB Lite interface is miniaturized version
- Very compact size of 60 x 15 mm

Principle of single particle counting detector



Planar pixellated detector bump-bonded to read-out chip

Ionizing particle creates a charge in a sensitive volume

The charge in each pixel is amplified and compared with a threshold

Digital counter is incremented

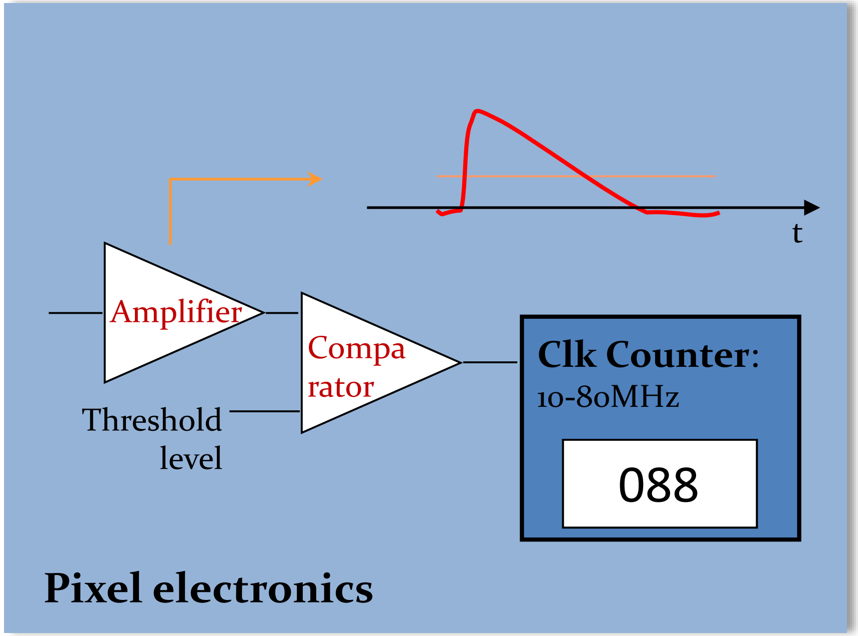
Courtesy Z. Vykydal, IEAP Prague

Timepix

Direct measurement of particle *energy* or its *arrival time* in each pixel

The *Ref_clock is* used to generate the clock

Time-over-Threshold: ToT



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Amplifier

Compa
rator

Threshold
level

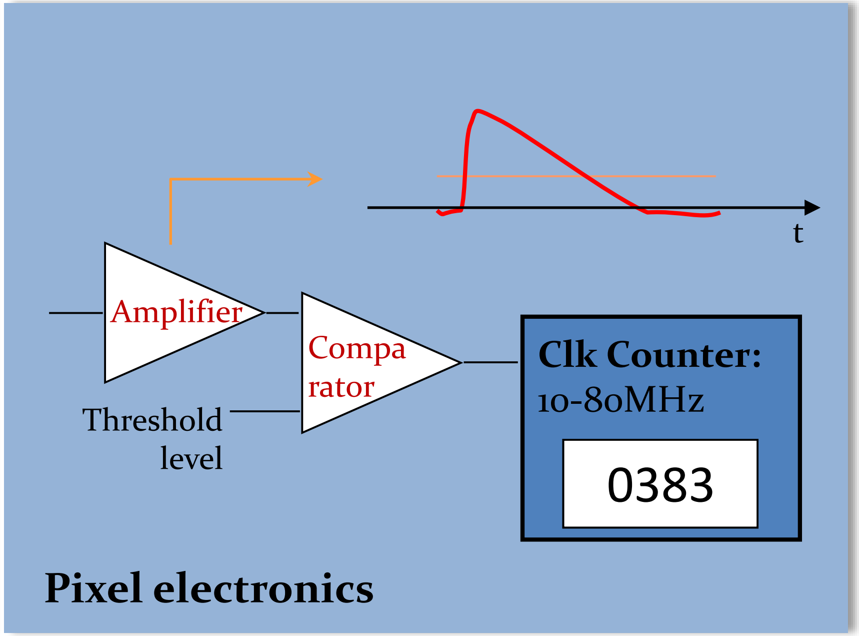
Clk Counter:
10-80MHz

088

Pixel electronics

Counter value ~ Energy

Time-of-Arrival: ToA



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Amplifier

Compa
rator

Threshold
level

Clk Counter:
10-80MHz

0383

Pixel electronics

Counter value ~ Arrival time

Courtesy Z. Vykydal, IEAP Prague

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)
  - …