



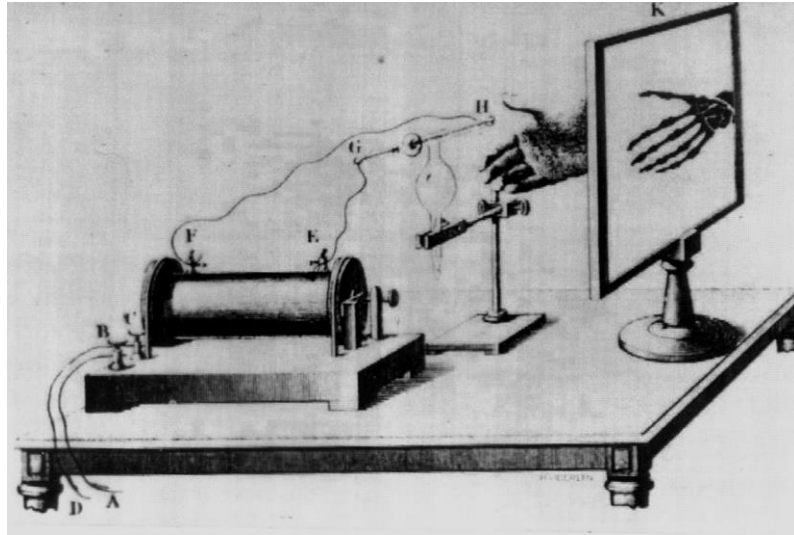
Radiation dosimetry, radiation protection and measurements

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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

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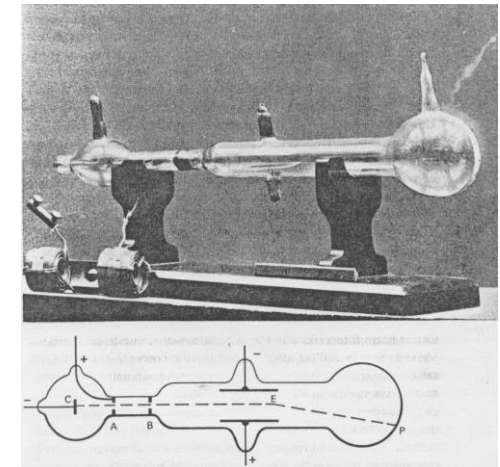
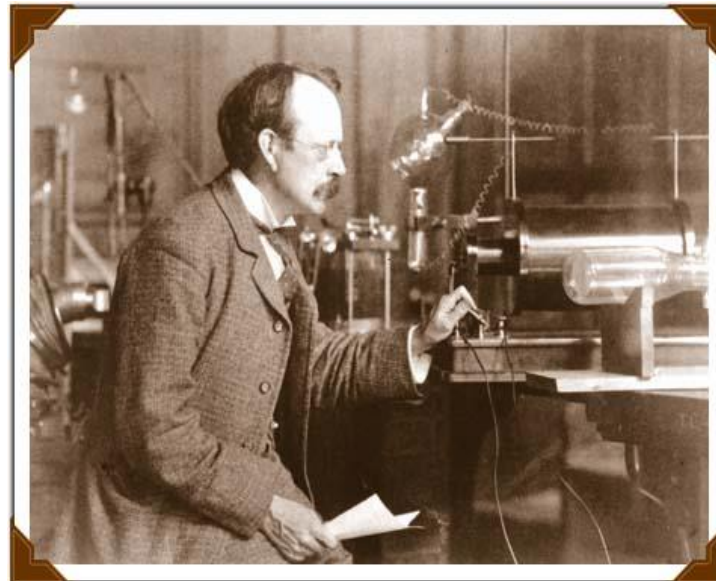
1895
Discovery of X rays
Wilhelm C. Röntgen



1897
First treatment of
tissue with X rays
Leopold Freund

J.J. Thompson

1897
"Discovery" of the
electron





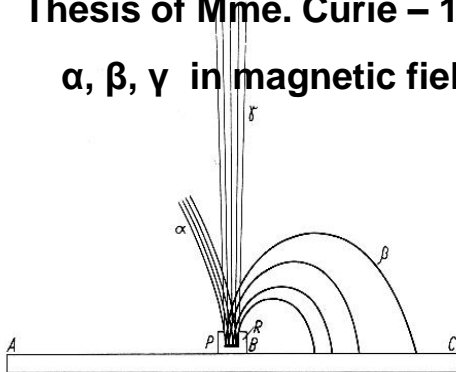
Henri Becquerel (1852-1908)

1896

Discovery of natural
radioactivity

Thesis of Mme. Curie – 1904

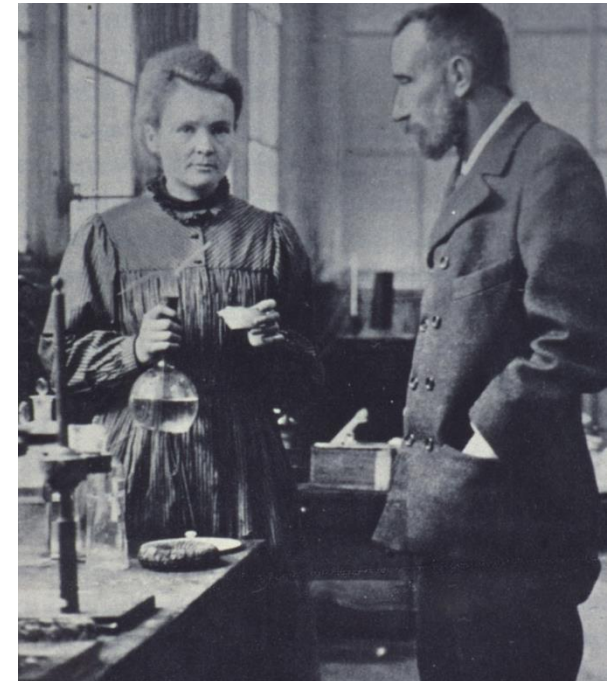
α , β , γ in magnetic field



Hundred years ago

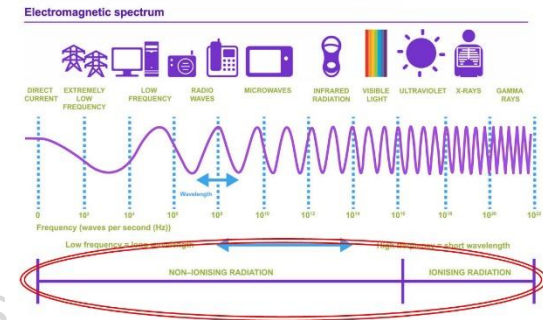
1898

Discovery of polonium
and radium



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

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Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18																																																										
1 H Hydrogen 1.00794	2 He Helium 4.002602	<table border="1"> <tr> <td>C Solid</td> <td colspan="10">Metals</td> <td colspan="4">Nonmetals</td> </tr> <tr> <td>Hg Liquid</td> <td>Alkali metals</td> <td>Alkaline earth metals</td> <td>Lanthanoids</td> <td>Transition metals</td> <td>Poor metals</td> <td>Other nonmetals</td> <td>Noble gases</td> <td colspan="7"></td> </tr> <tr> <td>H Gas</td> <td colspan="10"></td> <td colspan="4"></td> </tr> <tr> <td>Rf Unknown</td> <td colspan="10"></td> <td colspan="4"></td> </tr> </table>														C Solid	Metals										Nonmetals				Hg Liquid	Alkali metals	Alkaline earth metals	Lanthanoids	Transition metals	Poor metals	Other nonmetals	Noble gases								H Gas															Rf Unknown														
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Rf Unknown																																																																											
3 Li Lithium 6.941	4 Be Beryllium 9.012182	5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050	13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948																																																												
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.887	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798																																																										
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90586	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293																																																										
55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57-71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (209.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)																																																										
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinoids	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 (282)	117 Uus Ununseptium	118 Uuo Ununoctium (284)																																																										

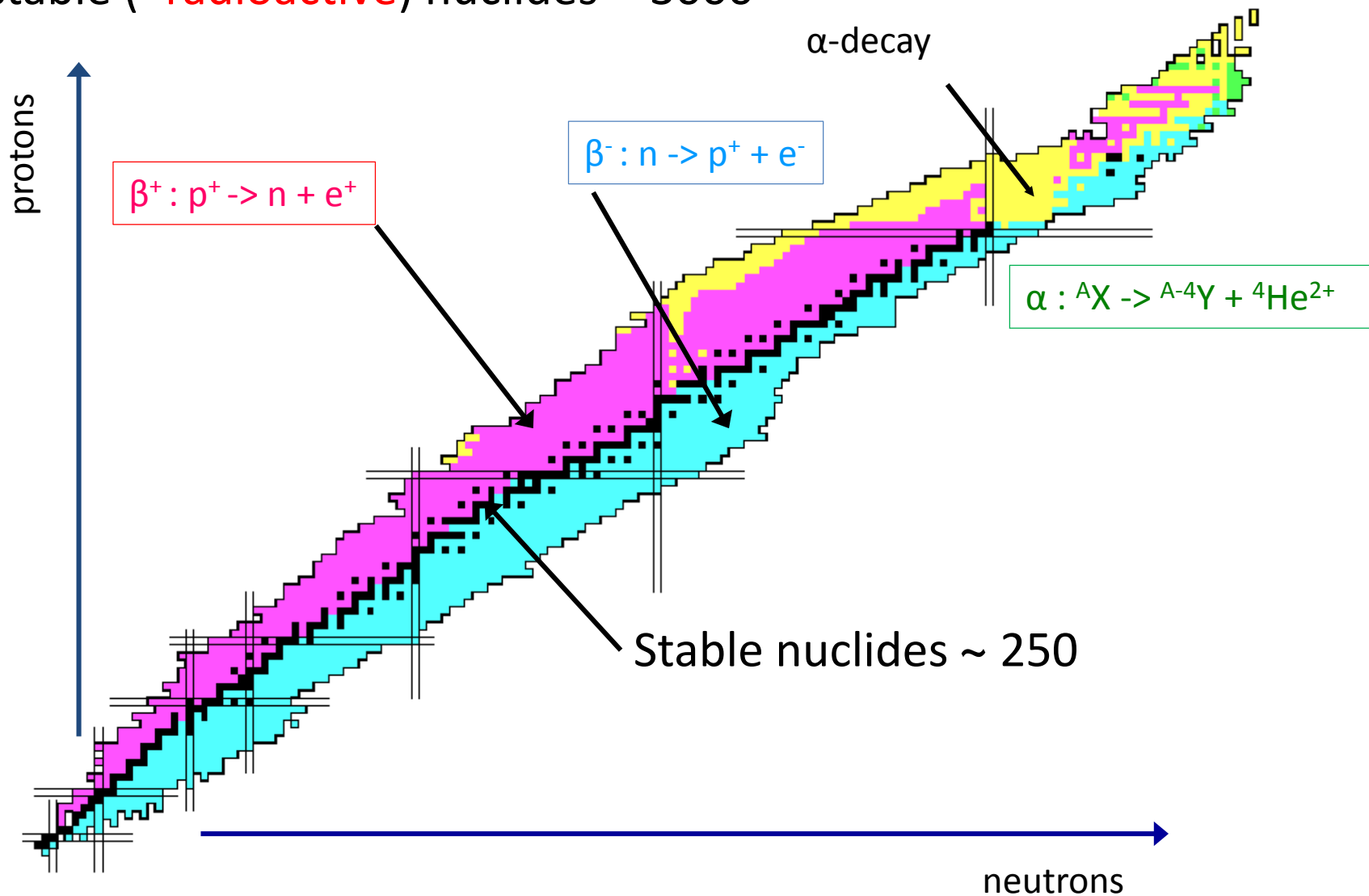
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

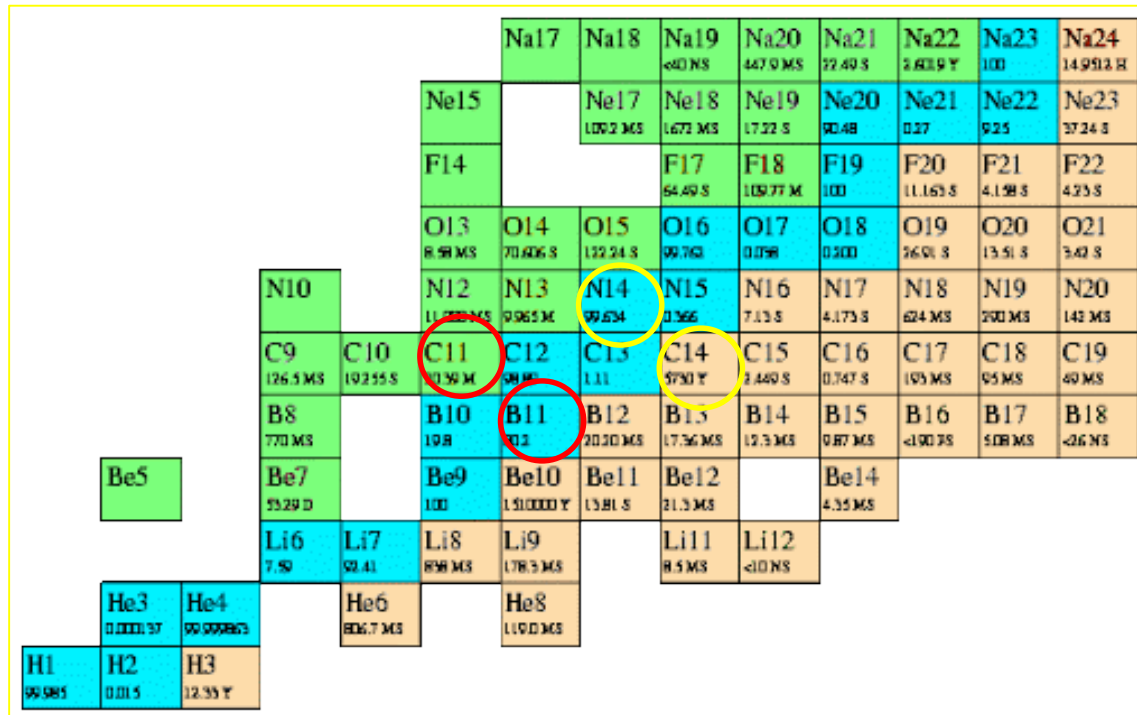
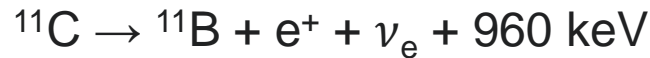
Design and Interface Copyright © 1997 Michael Dayah (michael@dayah.com) <http://www.ptable.com/>



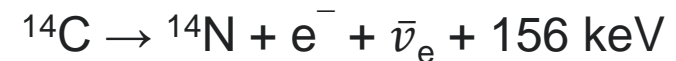
57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (268)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Unstable (=radioactive) nuclides ~ 3000





				Na17	Na18	Na19	Na20	Na21	Na22	Na23	Na24
						<10 NS	447.0 MS	27.40 S	2.6019 Y	10D	14.9512 H
			Ne15		Ne17	Ne18	Ne19	Ne20	Ne21	Ne22	Ne23
					100.2 MS	1.671 MS	17.22 S	90.48	0.27	9.25	37.24 S
			F14			F17	F18	F19	F20	F21	F22
						64.49 S	109.77 M	10D	11.163 S	4.158 S	4.23 S
			O13	O14	O15	O16	O17	O18	O19	O20	O21
			8.98 MS	70.606 S	122.24 S	99.76D	0.098	0.300	26.01 S	13.51 S	3.42 S
	N10		N12	N13	N14	N15	N16	N17	N18	N19	N20
			11.700 MS	0.965 M	99.634	0.366	7.13 S	4.173 S	624 MS	200 MS	142 MS
	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19
	126.5 MS	19.255 S	0.339 M	98.9D	1.11	5730 Y	2.449 S	0.747 S	193 MS	65 MS	49 MS
	B8		B10	B11	B12	B13	B14	B15	B16	B17	B18
	770 MS		19.8	20.2	20.20 MS	17.36 MS	12.3 MS	0.87 MS	<100 FS	5.08 MS	<26 NS
	Be5		Be7	Be9	Be10	Be11	Be12		Be14		
			53.29 D	10D	1.510000 Y	13.81 S	21.3 MS		4.35 MS		
		Li6	Li7	Li8	Li9		Li11	Li12			
		7.39	82.41	838 MS	178.3 MS		8.5 MS	<10 NS			
		He3	He4		He6		He8				
		0.000137	99.999863		826.7 MS		119.0 MS				
H1	H2	H3									
6.5985	0.015	12.35 Y									



<http://www.fmboschetto.it/tde4/carta.htm>

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 \rightarrow electron

neutron \rightarrow 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: $1 Ci = 3.7 \times 10^{10} Bq$)

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

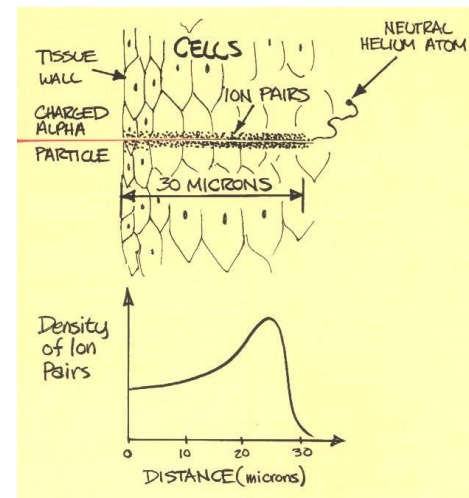
The radioactive **half-life** ($T_{1/2}$) of a radionuclide is the time necessary for half of the nuclei present in the sample to decay

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

(Emitted in the de-excitation of unstable nuclei)

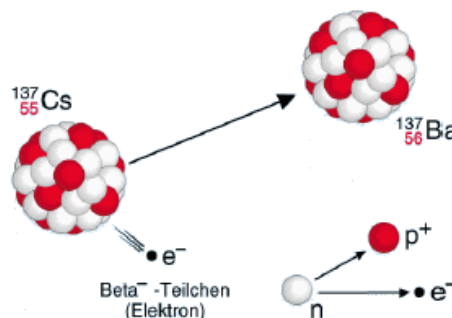
◆ ALPHA

- 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)



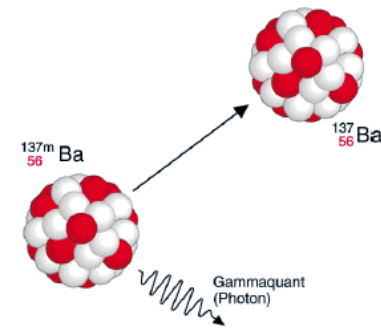
◆ BETA

- 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

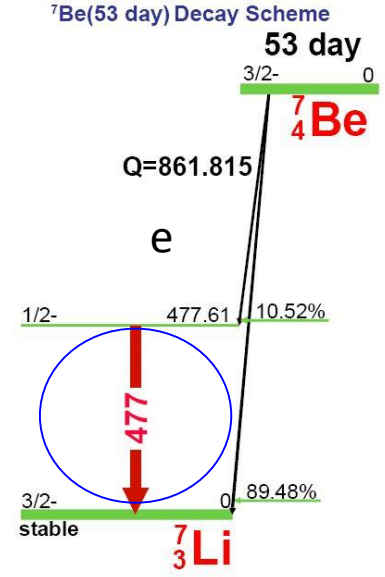
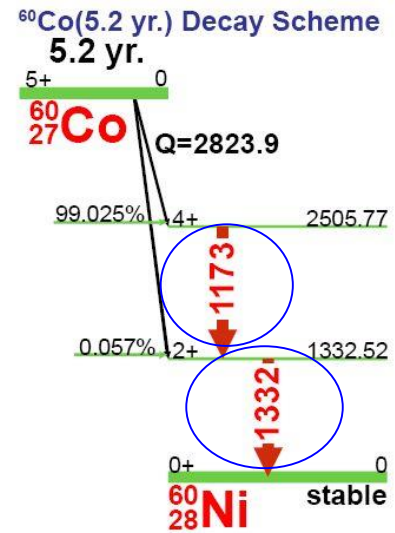
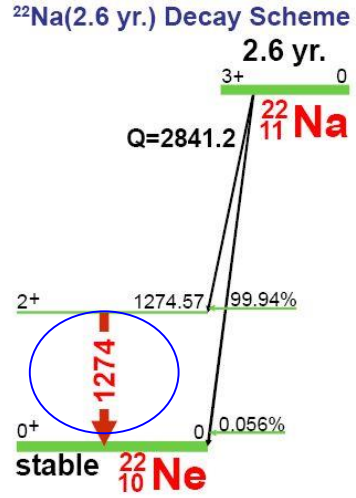
- Neutral particles (constituents of the atomic nucleus together with protons)
- Very penetrating
- External irradiation
- **Enhanced biological effect** (high LET – Linear Energy Transfer radiation), which depends on their energy

◆ HEAVY CHARGED PARTICLES (protons, ions)

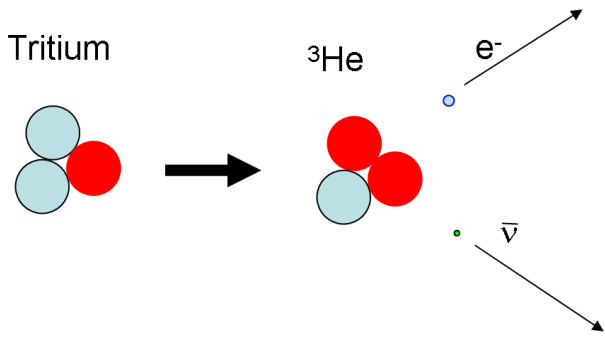
- External irradiation
- **Enhanced biological effect** (high LET – Linear Energy Transfer radiation)



β^- , γ -emitter

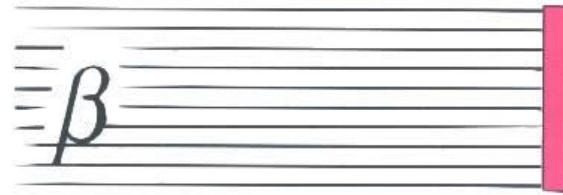
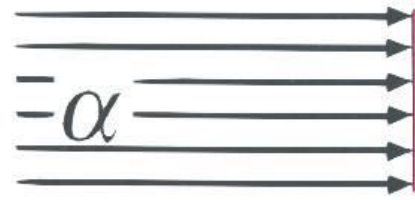


Pure β^- -emitter

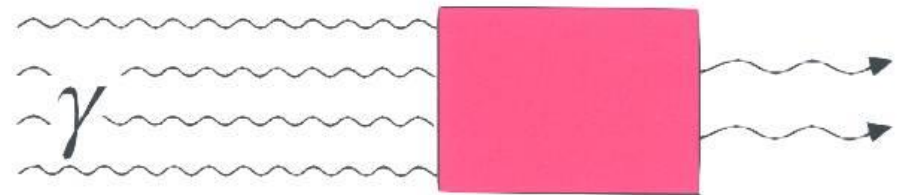


α^- , β^- and γ are emitted with end energies up to few MeV

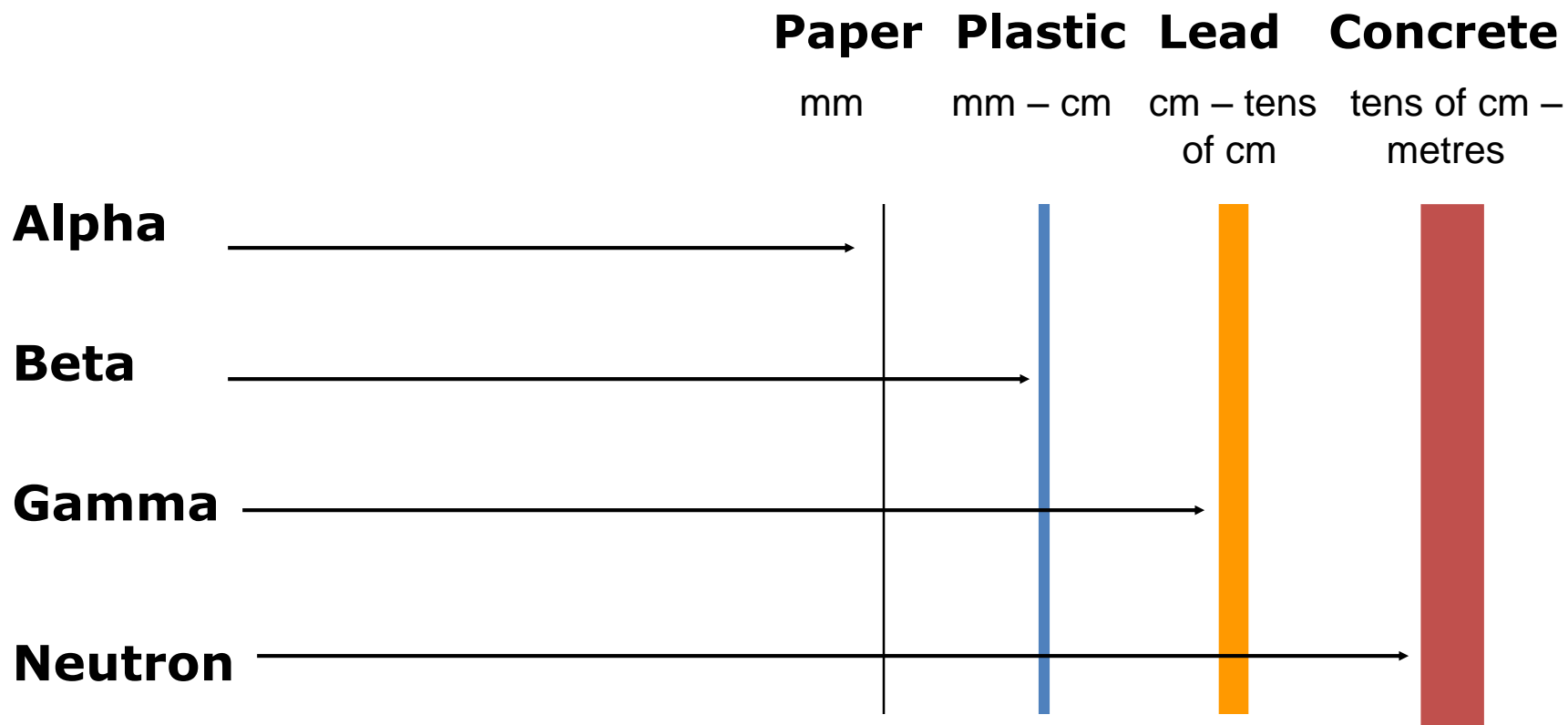
α - and β -particles are degraded in energy while traversing a material, until they are completely brought to rest



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

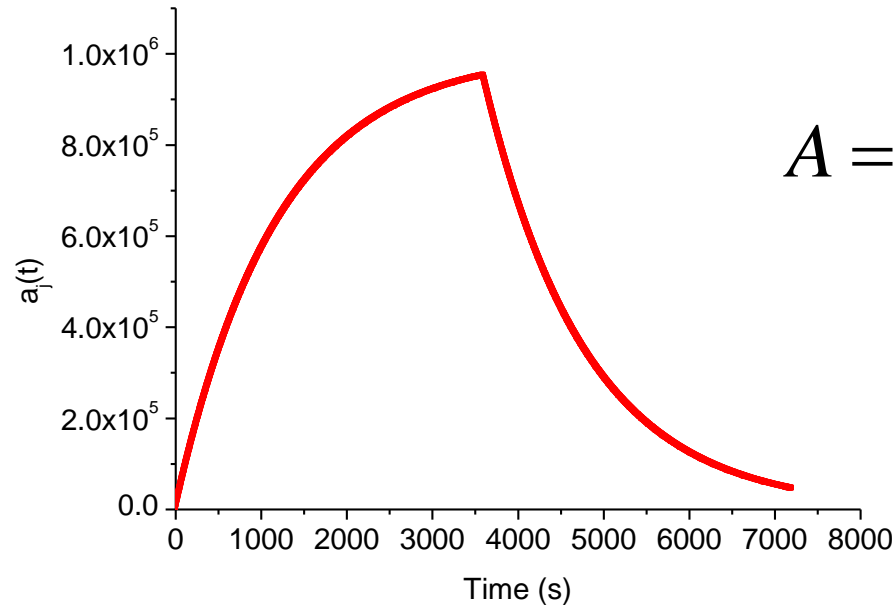
- Interaction probability, σ (*cross section*)
- Flux (spectrum), Φ
- Beam intensity, I_p

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

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, μ Gy):

$$1 \text{ Gy} = 1 \text{ J/kg}$$

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

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

$$H = Q \cdot D$$

$$1 \text{ Sv} = 1 \text{ J/kg}$$

Q = quality factor of the radiation

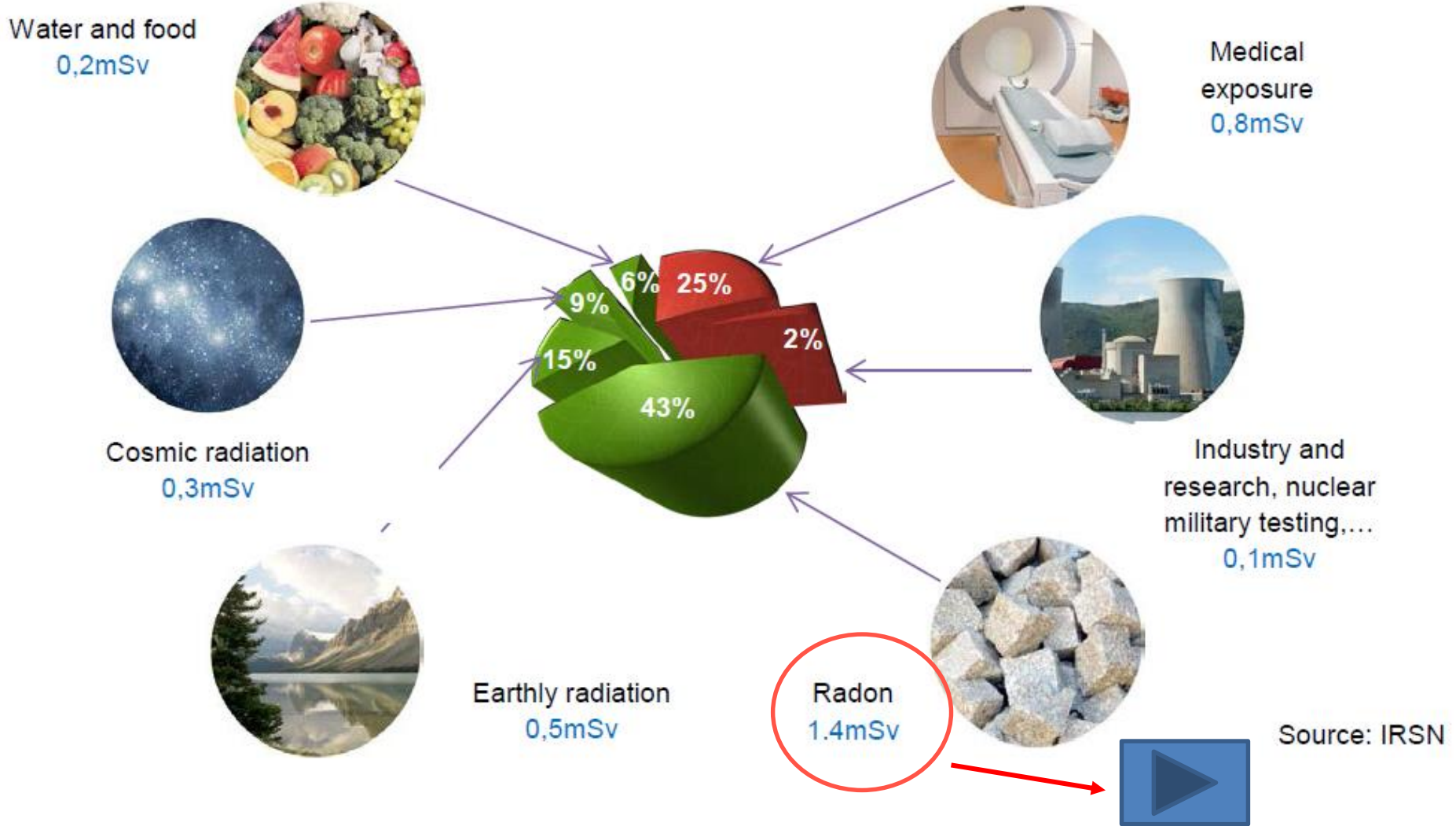
Are we all exposed (voluntarily or not) to some radiation sources?

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)



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	$7.04 \times 10^8 \text{ y}$	0.72% of natural Uranium
Uranium-238	^{238}U	$4.47 \times 10^9 \text{ y}$	99.3% of natural Uranium
Thorium-232	^{232}Th	$1.41 \times 10^{10} \text{ y}$	
Potassium-40	^{40}K	$1.28 \times 10^9 \text{ y}$	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

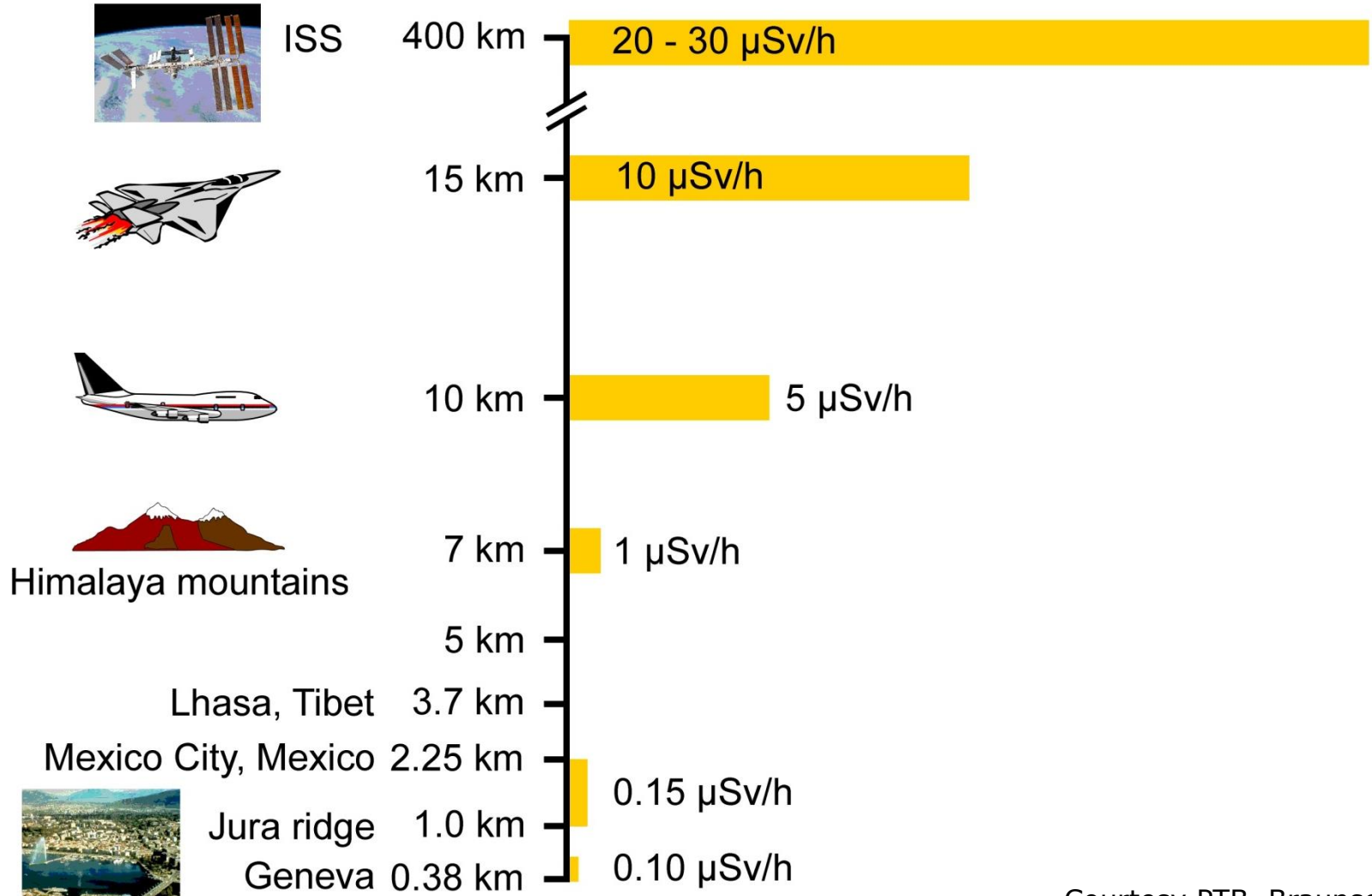
Nuclide	Symbol	Half-life	Nuclear Reaction
Carbon-14	^{14}C	5730 y	e.g. $^{14}\text{N}(n,p)^{14}\text{C}$
Tritium-3	^3H	12.3 y	Interaction of cosmic radiation with N or O $^6\text{Li}(n,\alpha)^3\text{H}$
Beryllium-7	^7Be	53.28 d	Interaction of cosmic radiation with N or O

More cosmogenic radionuclides:

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

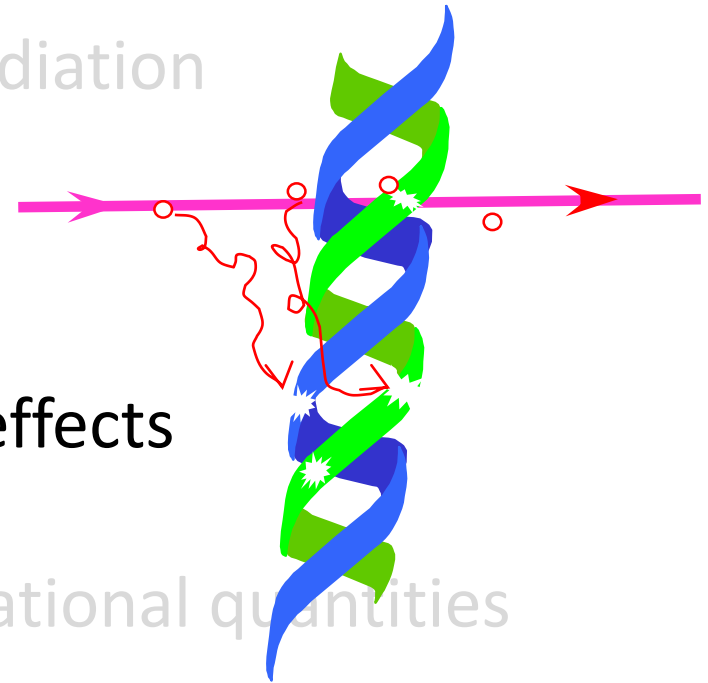
Nuclide	Total activity in human body (~ 70 kg)
Potassium-40	~ 5 kBq
Carbon-14	~ 3 kBq
Tritium	~ 20 Bq
Polonium-210	~ 18 Bq
Uranium	~ 1 Bq
Radium	~ 1 Bq
Thorium	~ 0.1 Bq
TOTAL	~ 8 kBq

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



Courtesy PTB, Braunschweig

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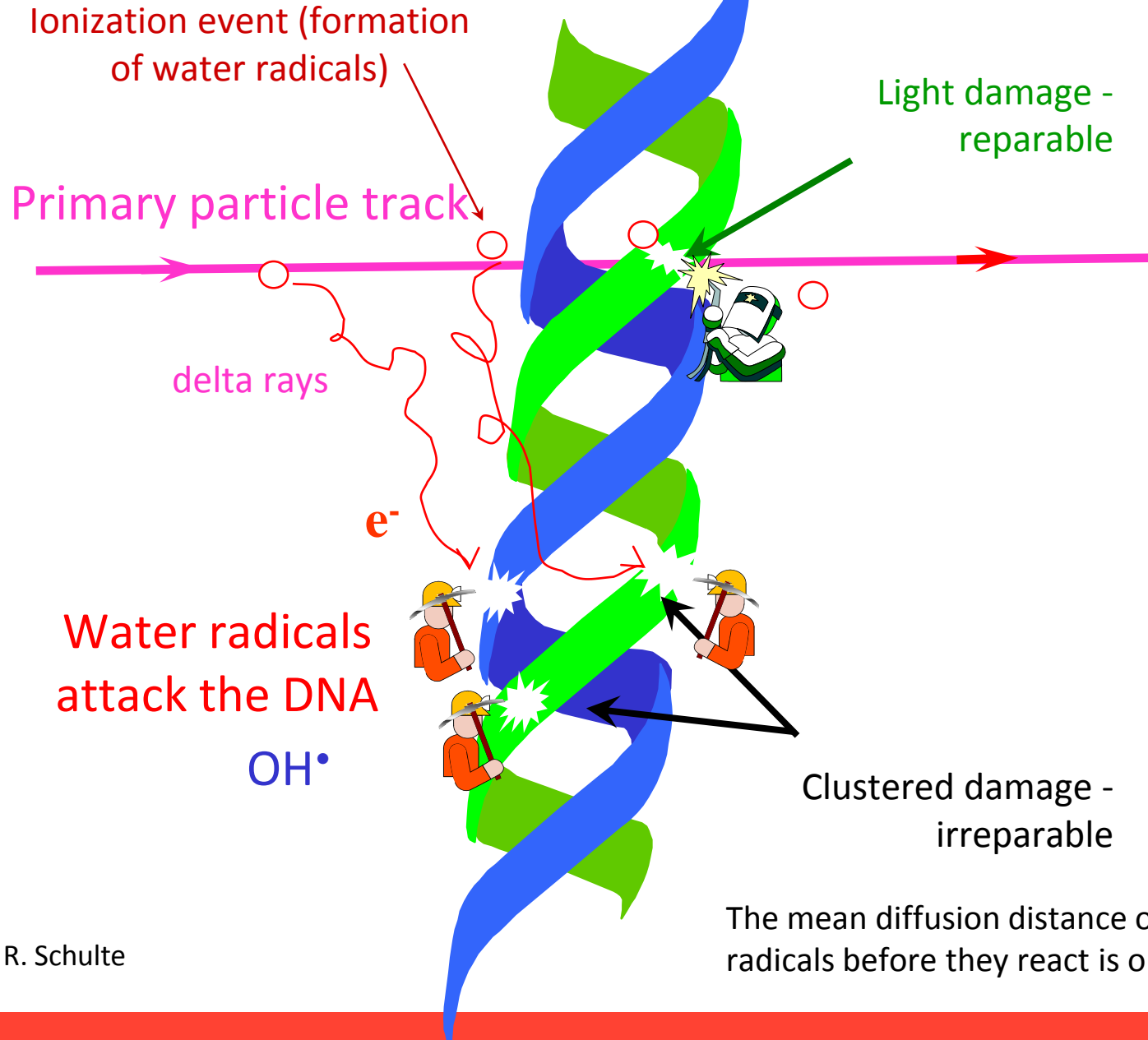


Unique effects of interaction of ionizing radiation with matter

- Biological systems (humans in particular) are particularly susceptible to damage by ionizing radiation
- The expenditure of a trivial amount of energy ($\sim 4 \text{ J/kg} = 4 \text{ Gy}$) to the whole body is likely to cause death...
- ...even if this amount of energy can only raise the gross temperature by about $0.001 \text{ }^\circ\text{C}$
- 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

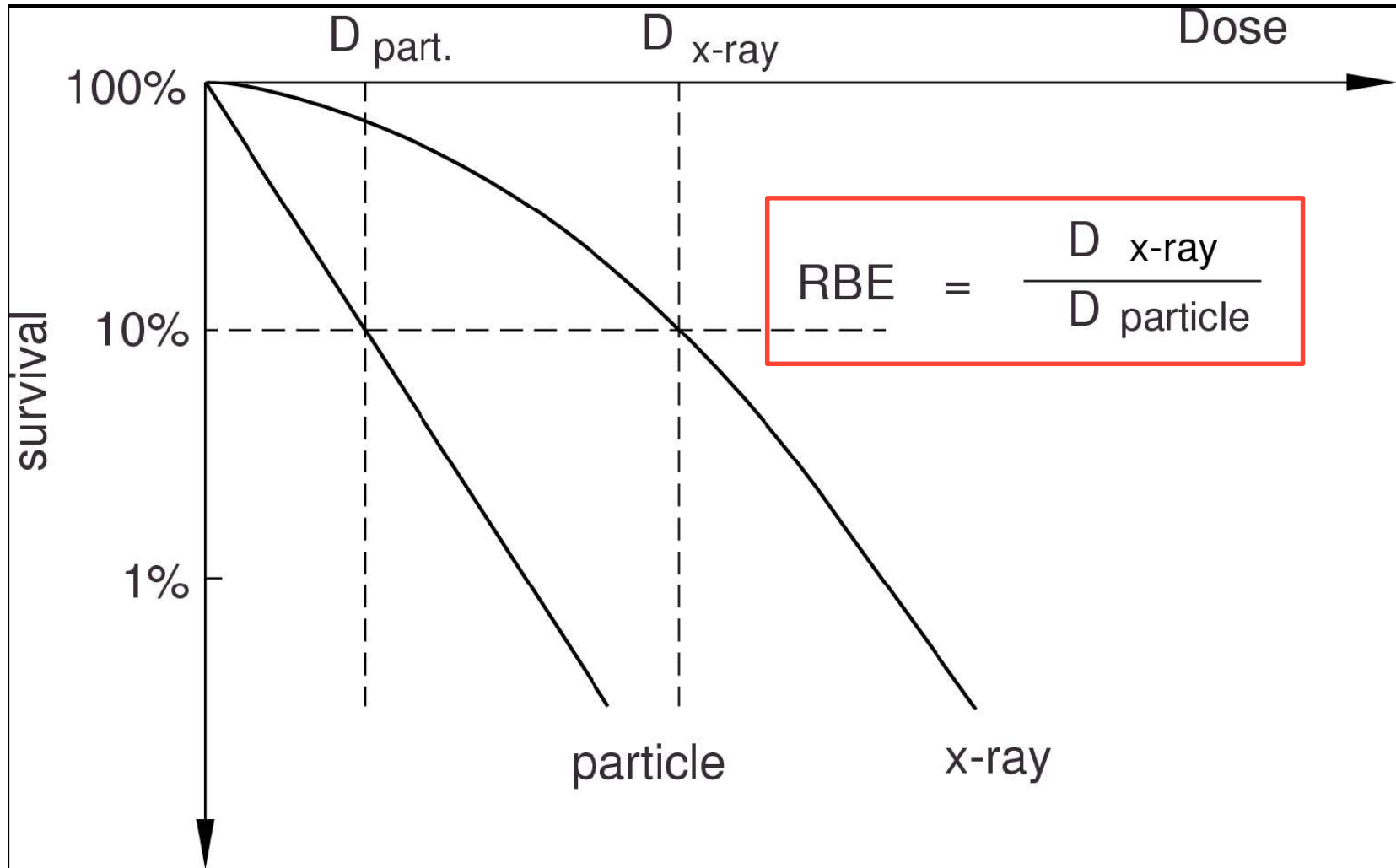
Main aim of **dosimetry** = measurement of the absorbed dose (energy/mass)

DNA damage

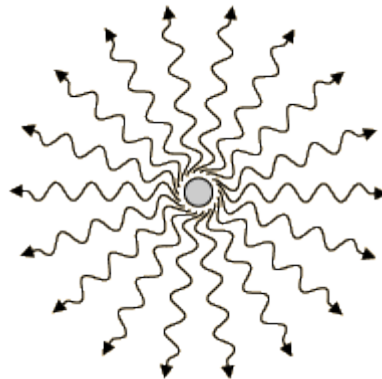


Courtesy R. Schulte

DIFFERENT TYPES OF RADIATION MAKE DIFFERENT DAMAGE



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

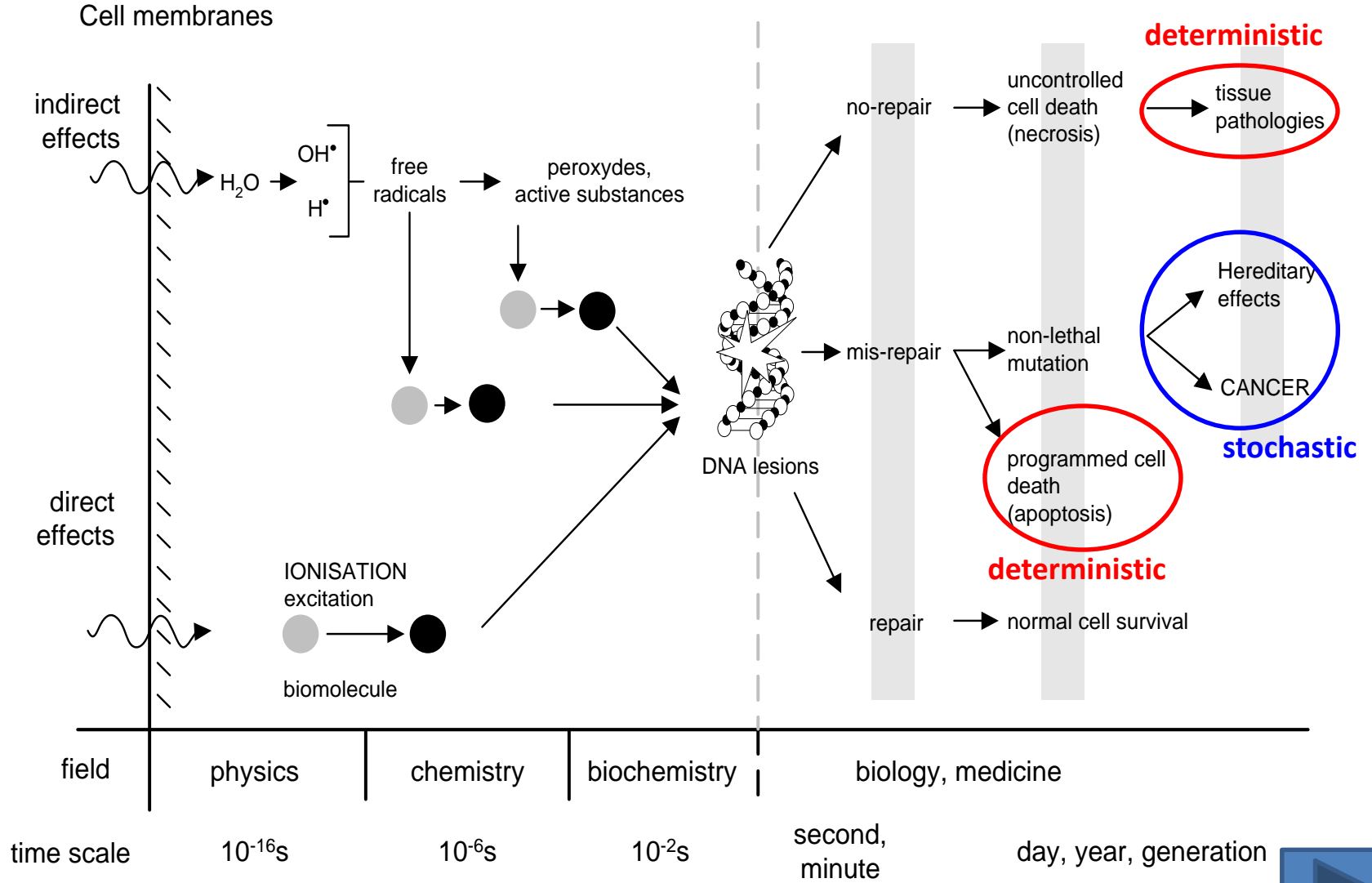
dose received in short time interval
dose threshold: > 500 mSv

immediate consequences:

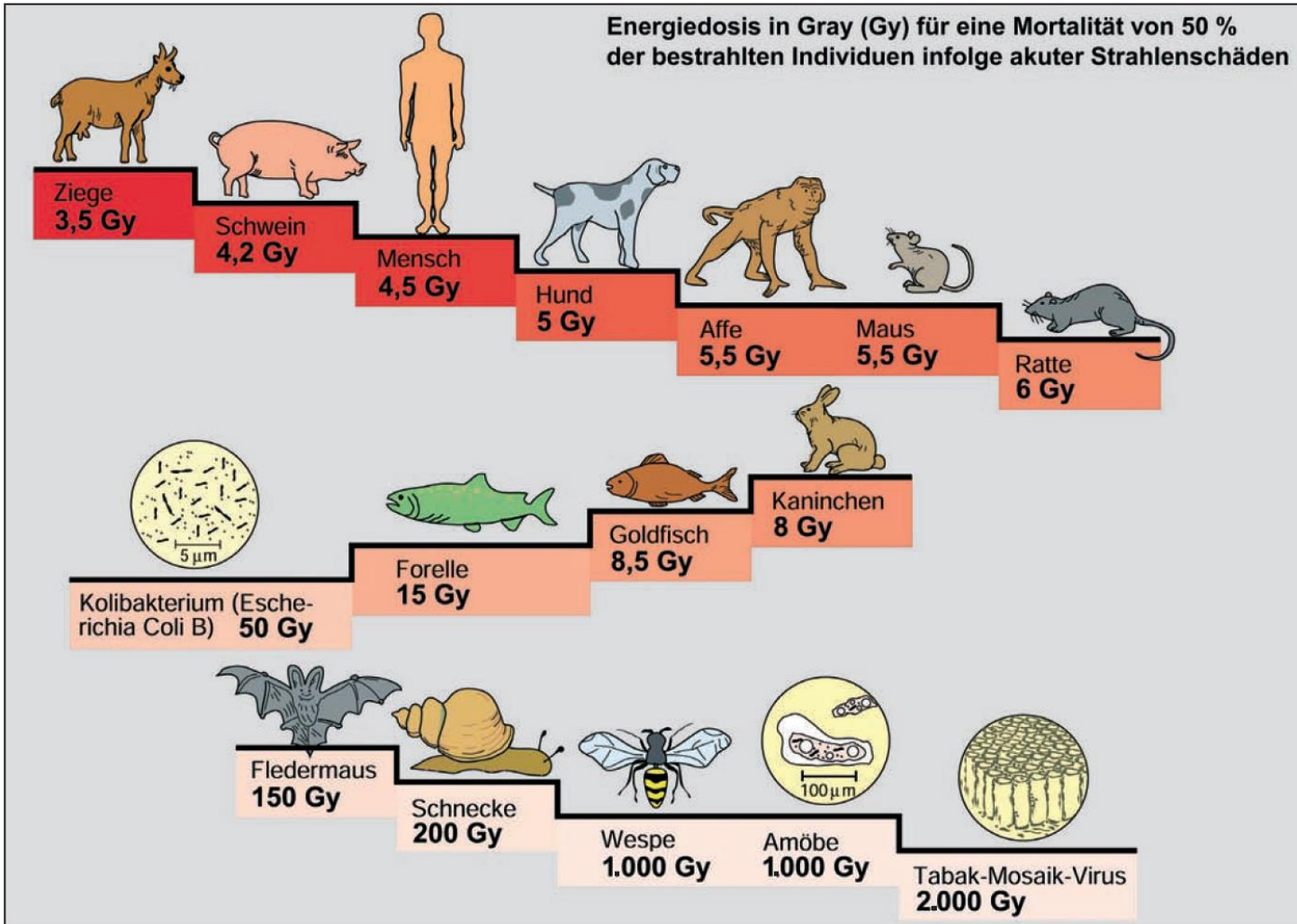
- vomiting
- immun deficiency
- erythema and necrose

health detriments are function of the dose

lethal dose: 5 – 7 Sv



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



Source: Martin Volkmer, Radioaktivität und Strahlenschutz, Informationskreis Kernenergie

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 \times RBE

X-rays, β , γ -rays RBE = 1 $\frac{1}{2}$ \times RBE = 20

High energy p & n RBE = 10

1) Justification

any exposure of persons to ionizing radiation has to be justified

2) Limitation

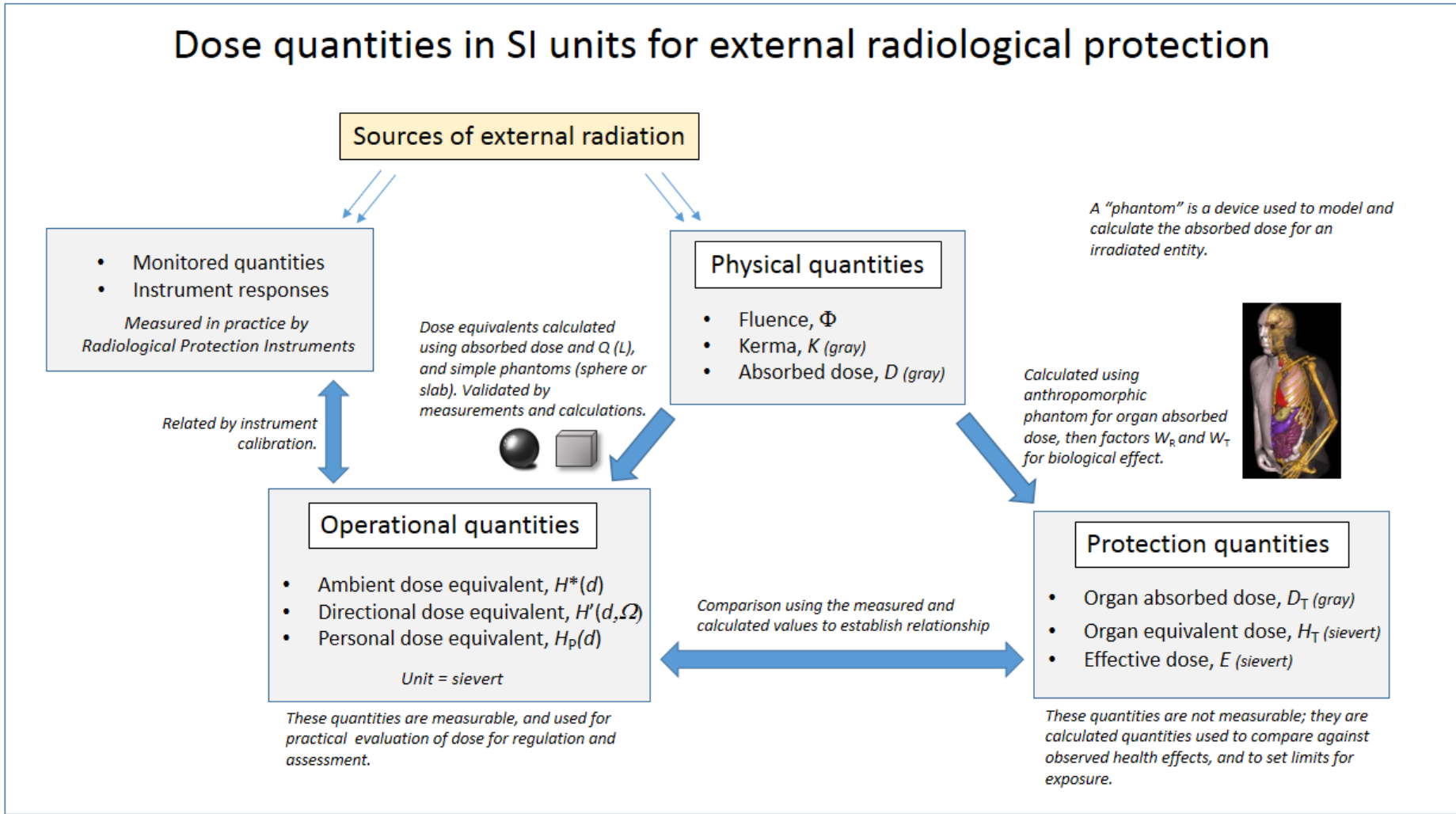
the personal doses have to be kept below the legal limits

3) Optimization

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

International Commission on Radiological Protection

Dose quantities in SI units for external radiological protection



Source: Wikipedia

Absorbed Dose D:

Unit: Gy

energy absorbed per mass
1 Gy = 1 J/kg
(1 Gy = 100 rad)

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

Equivalent Dose H:

Unit: Sv

absorbed dose of organs weighted by
the radiation weighting factor w_R of radiation R:
(1 Sv = 100 rem)

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

Effective dose E:

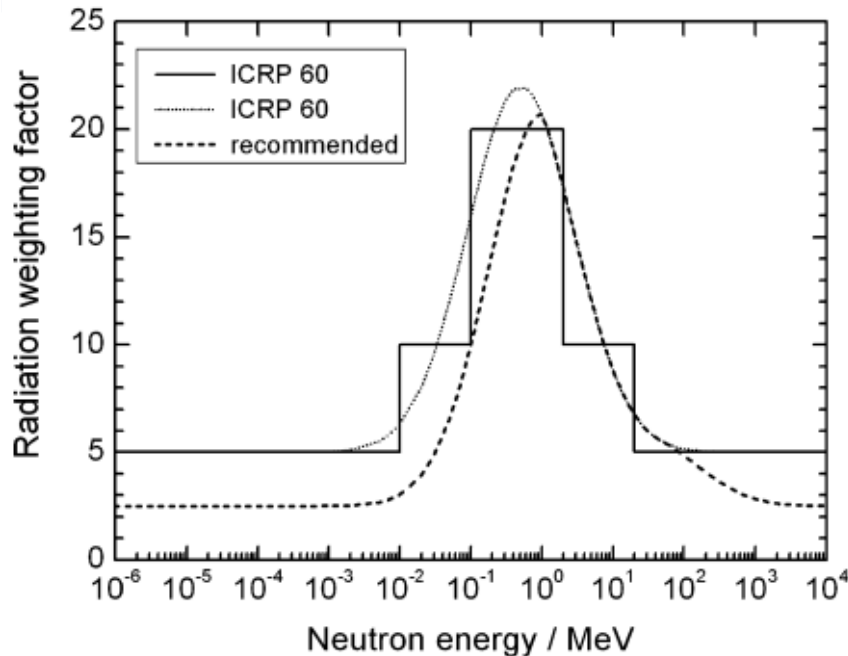
Unit: Sv

Sum of all equivalent doses weighted
with the weighting factor w_T for tissue T
(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	

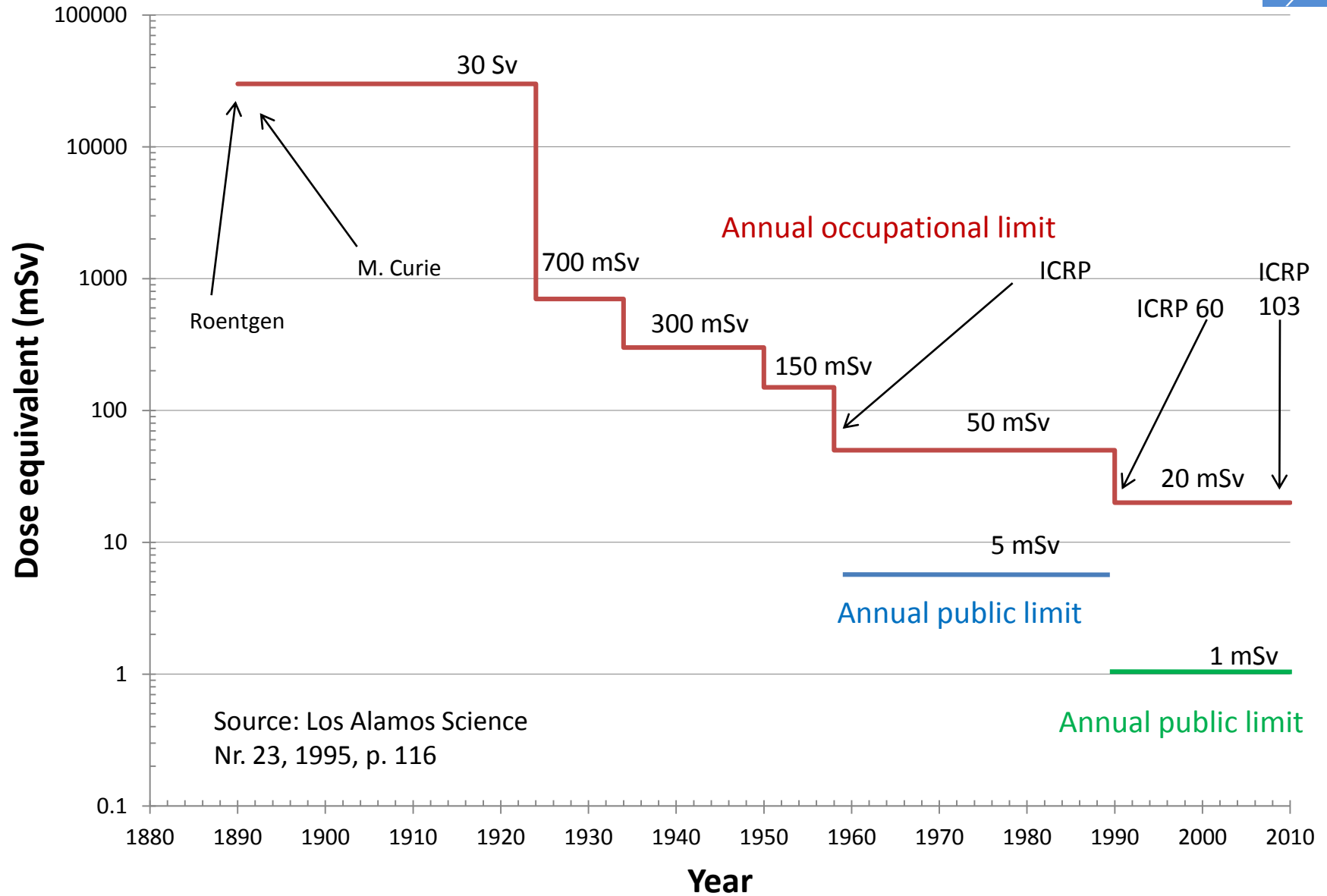
$$w_R = \begin{cases} 2.5 + 18.2 e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0 e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leq E_n \leq 50 \text{ MeV} \\ 2.5 + 3.25 e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases}$$



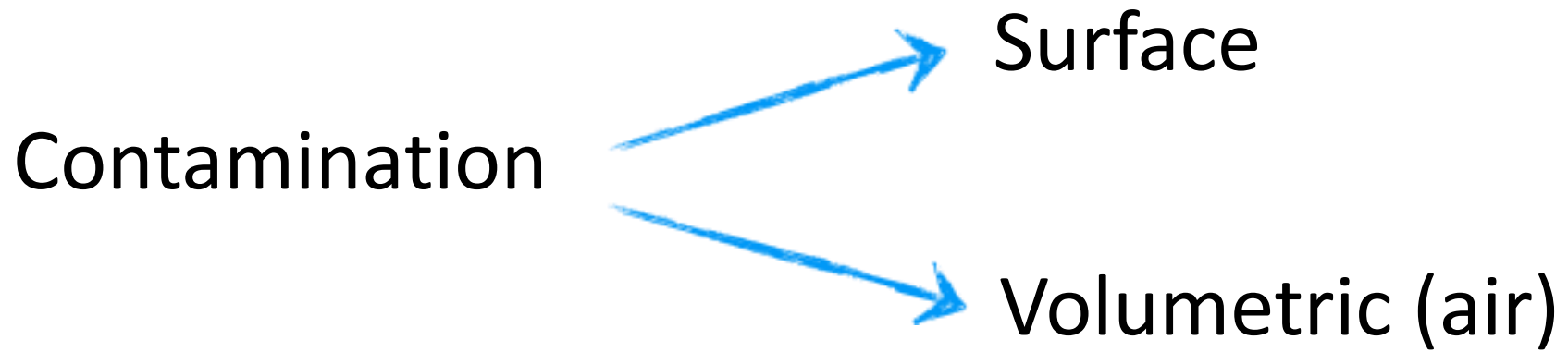
Organ / tissue	No of tissues	W_T	Total contribution
Bone-marrow, colon, lung, breast, stomach, remainder tissues	6	0.12	0.72
Gonads	1	0.08	0.08
Bladder, esophagus, liver, thyroid	4	0.04	0.16
Bone surface, brain, salivary glands, skin	4	0.01	0.04

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): $E(50)$



External radiation source → external exposure



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)



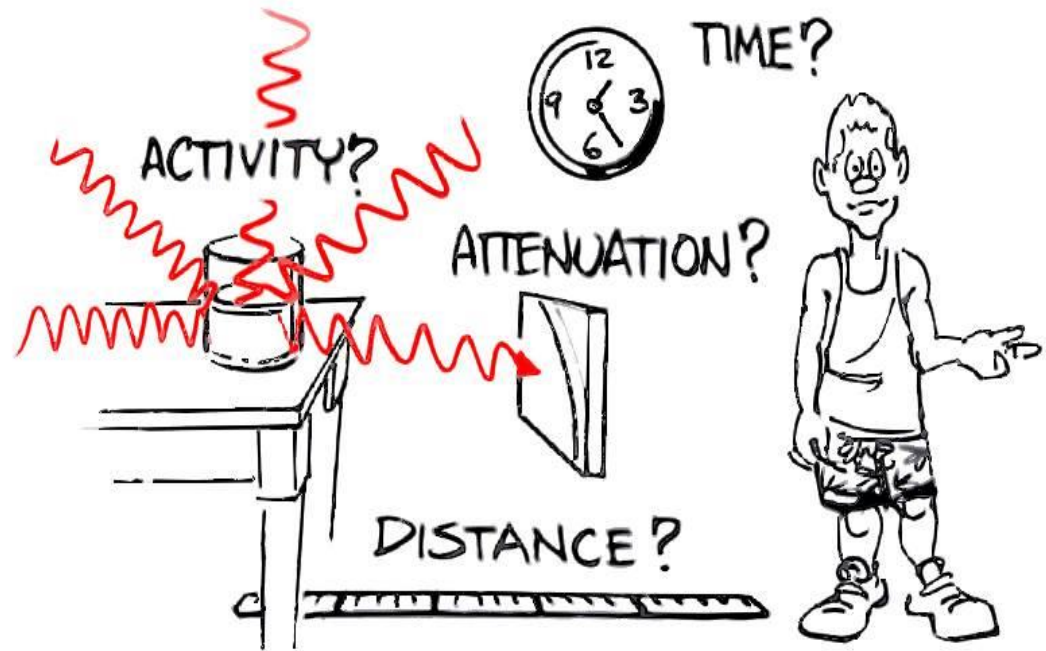
How you can protect yourself from radiation?



www.shutterstock.com · 384981319

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 $D = dD/dt \times t$
- ◆ **Shielding**: the dose rate approximately reduces as $\exp(-d/\lambda)$
 λ = shielding properties of the material



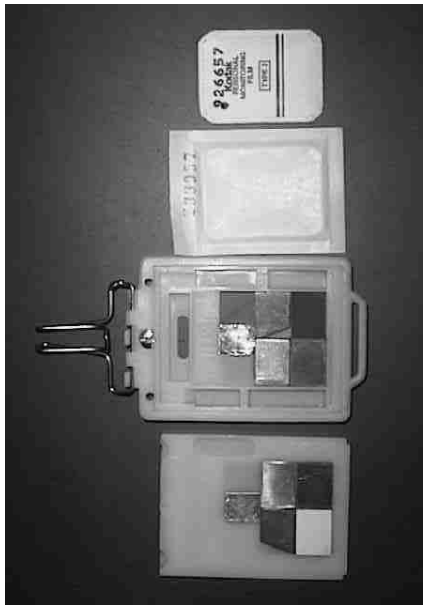
For β radiation: plexiglass
For γ radiation: iron or lead
For n: concrete

- **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



- **Wearing 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 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.



Kodak film badge

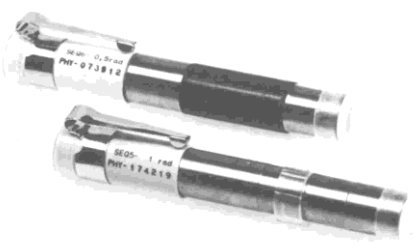
Personal dosimeter: "Legal dose"



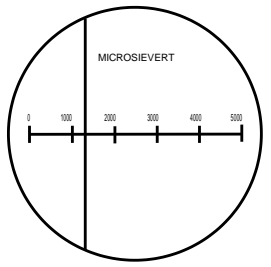
RADOS DIS



Finger dosimeter



Quartz-fiber dosimeter (ionisation chamber and electroscope)



Operational dosimeter DMC: "Operational dose"



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 not 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-life**, the dose is received in the days following the intake;
- For radionuclides with a **long half-life** (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

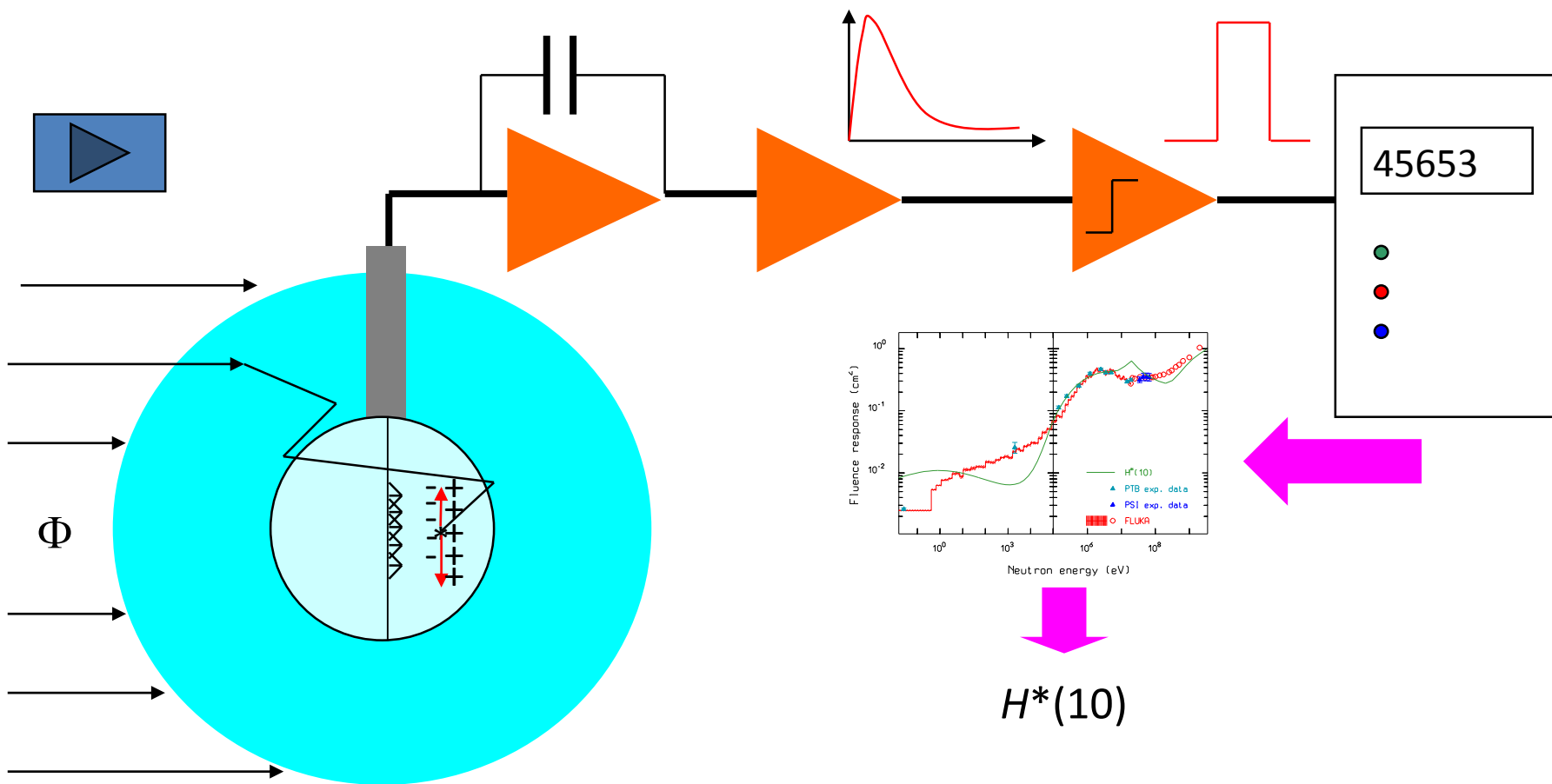
... generally completed
by overshoes



- 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 limits
 - The ALARA principle
- Protection means
- Instrumentation for measuring ionizing radiation

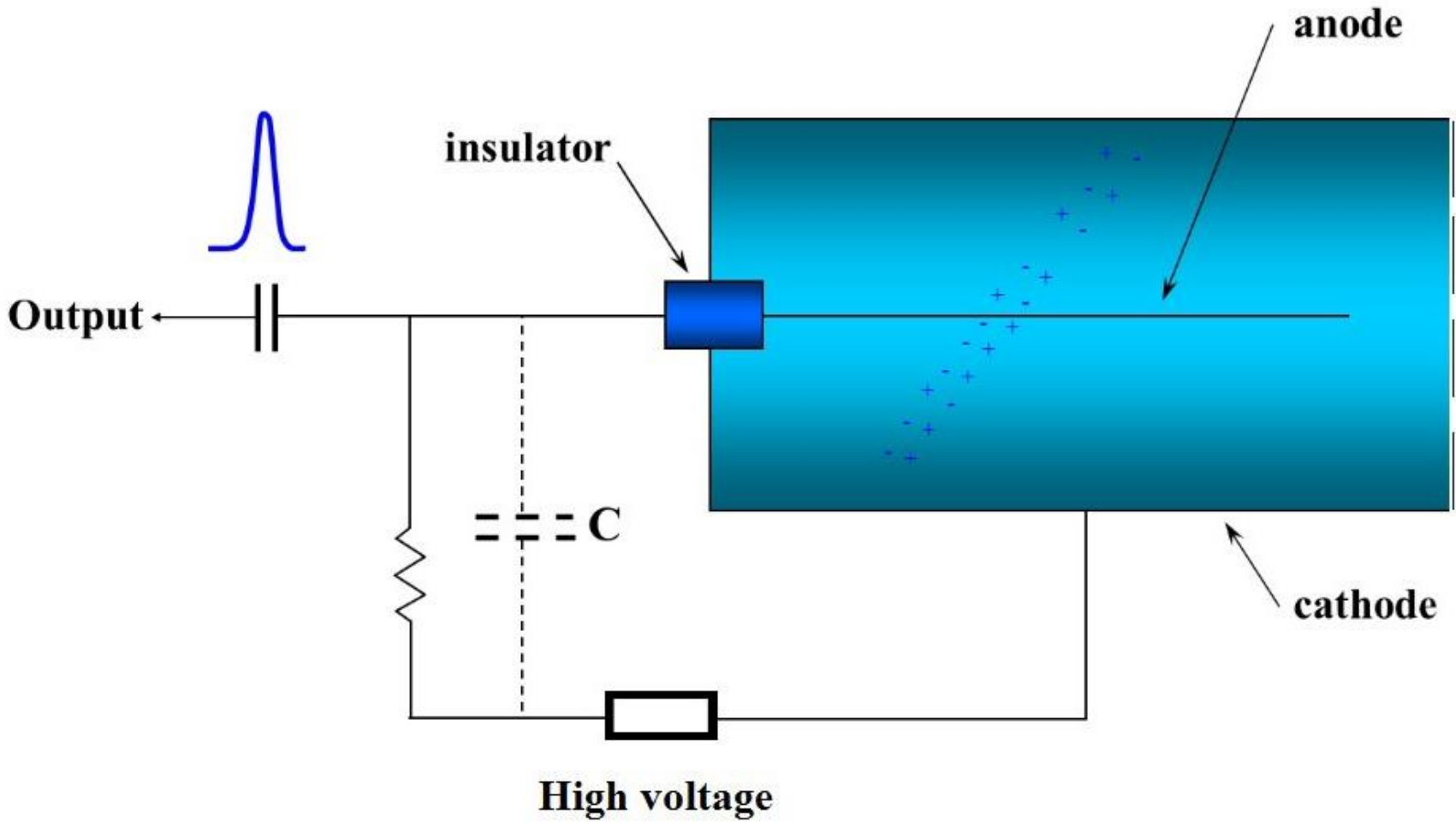


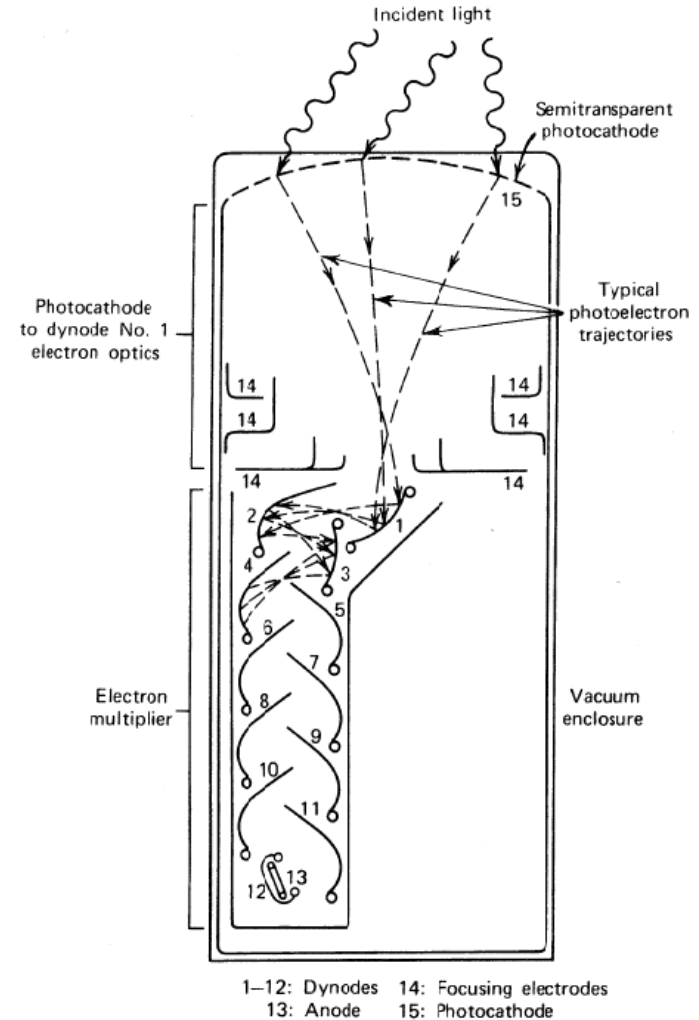
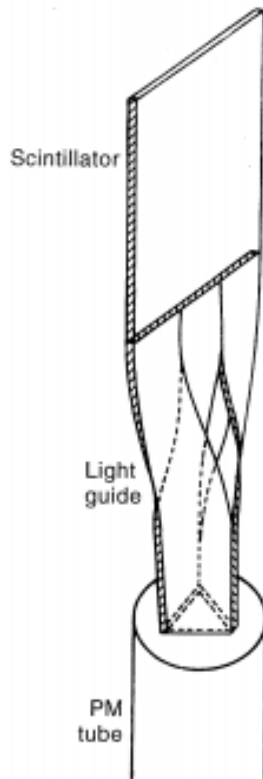
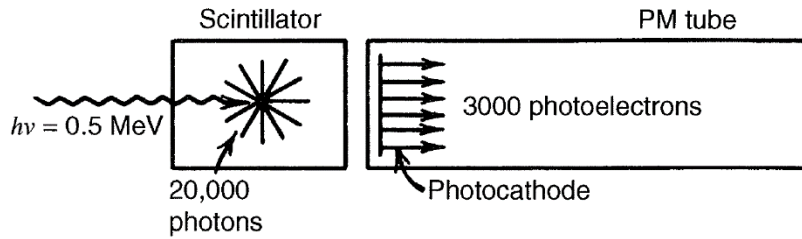
Since the Radiation Protection quantities are not directly measurable, their estimate involves the measurement of a physical quantity.



$H^*(10)$

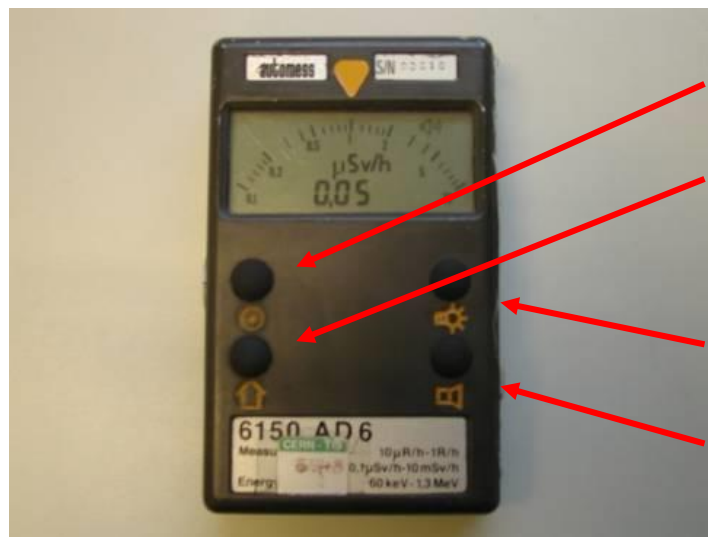
Courtesy S. Agosteo, Politecnico di Milano





From Glenn F. Knoll, Radiation Detection and Measurement

AD17 external probe

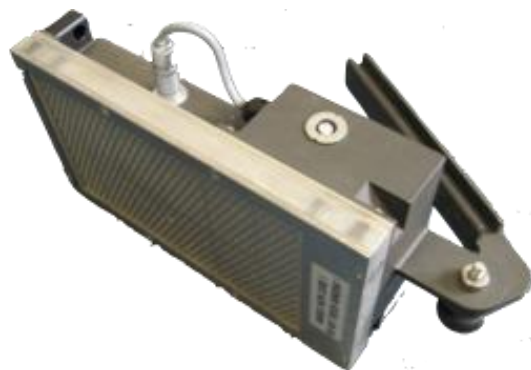


Push button 1

Push button 2

Push button 3

Push button 4



Detector: Geiger Müller counter
Range: 0.5 $\mu\text{Sv/h}$ – 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

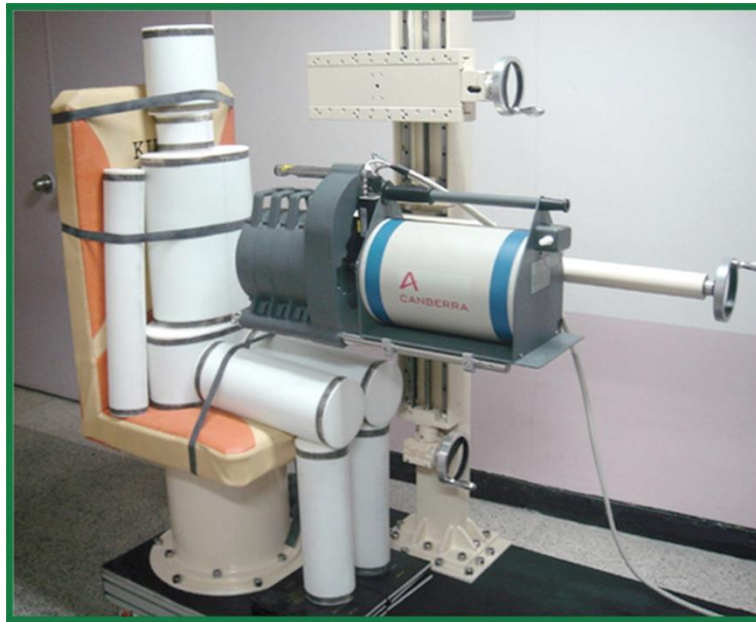
Air contamination monitors



Hand and foot monitor

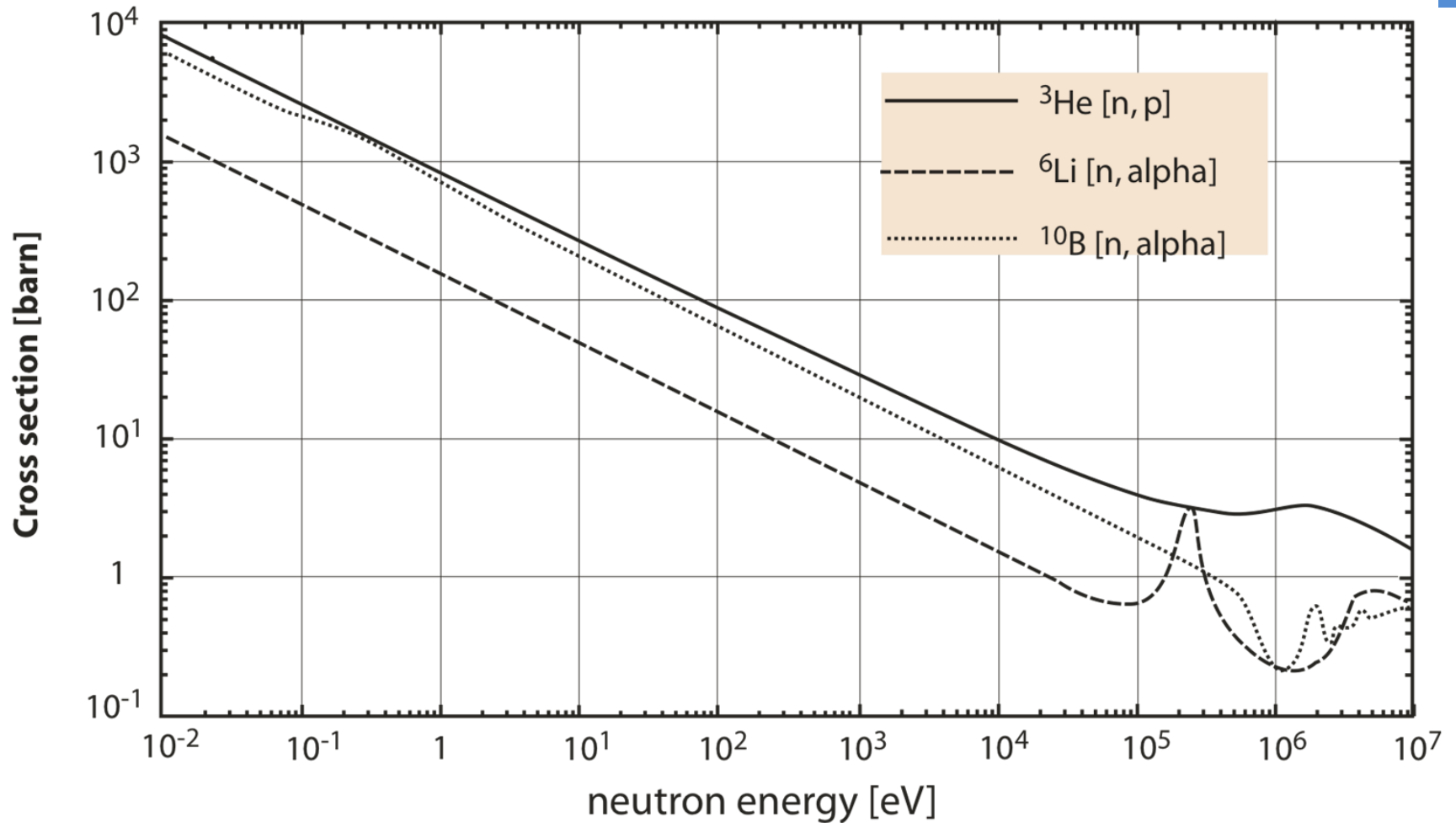


ABPM203M



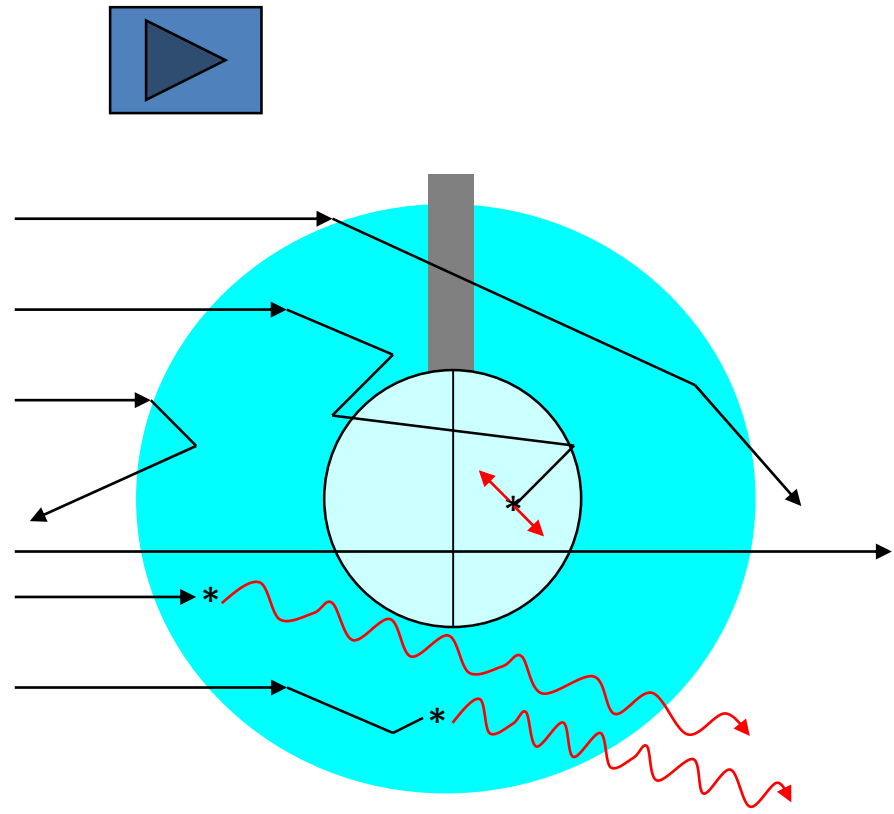
Some elements have a very large cross section for slow neutrons and can be exploited for neutron detection

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



Mean free path of thermal neutrons

- in ^3He gas ≈ 7 cm
- in solid ^{10}B ≈ 70 μm

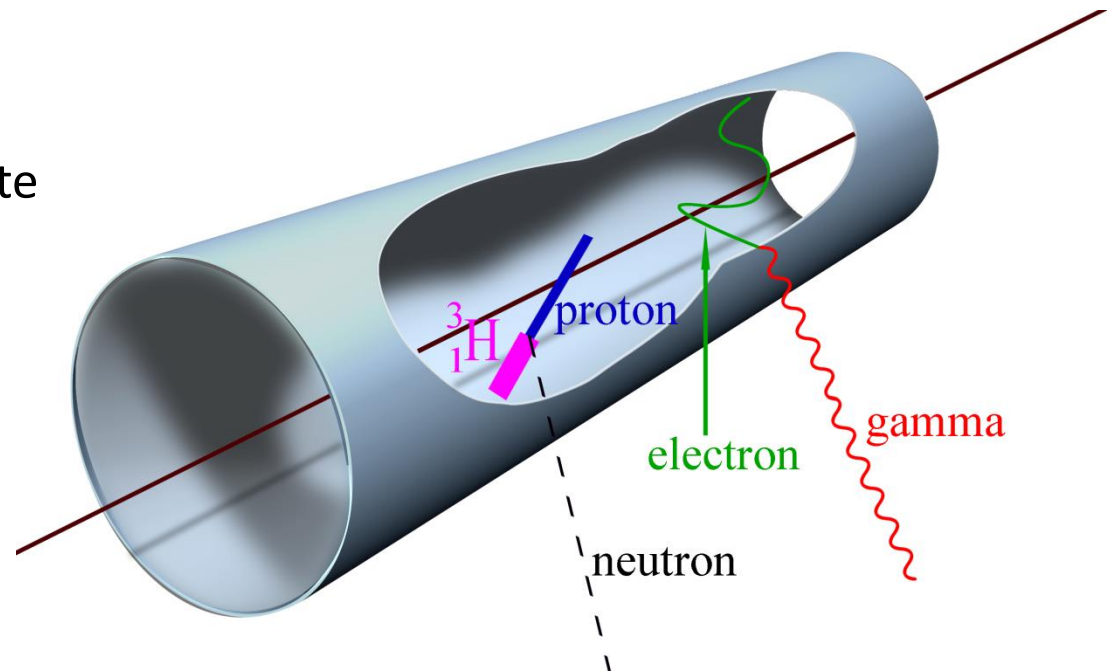


Courtesy S. Agosteo, Politecnico di Milano

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 ($\approx 2 \text{ keV/cm}$), so that these pulses are much smaller than those due to **neutrons**

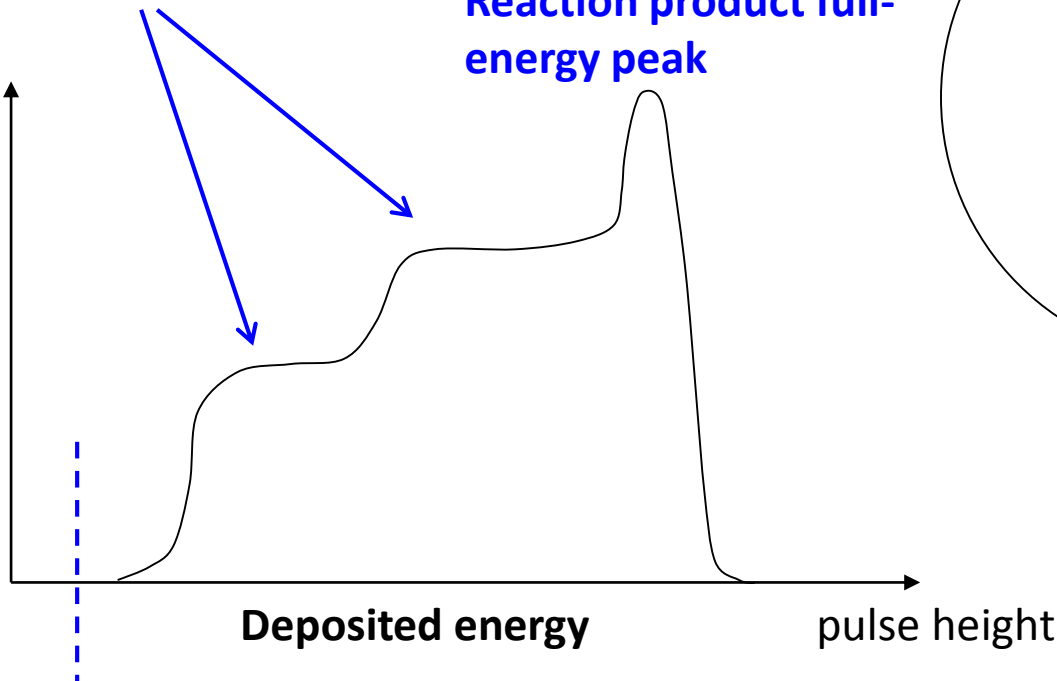
A suitable pulse amplitude threshold can thus eliminate most gamma interactions.



“Wall effect” continuum

N

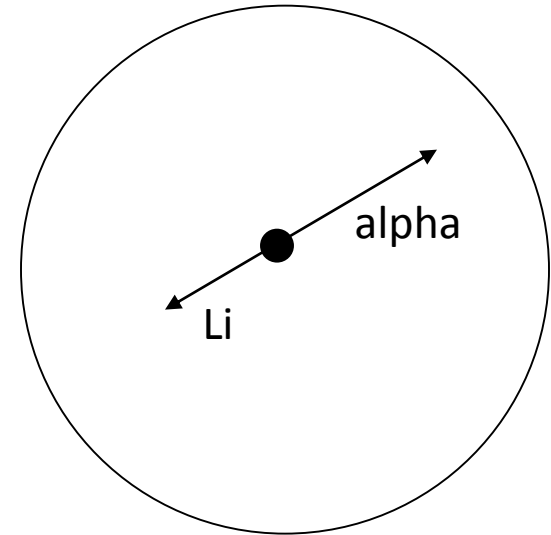
Reaction product full-energy peak



Deposited energy

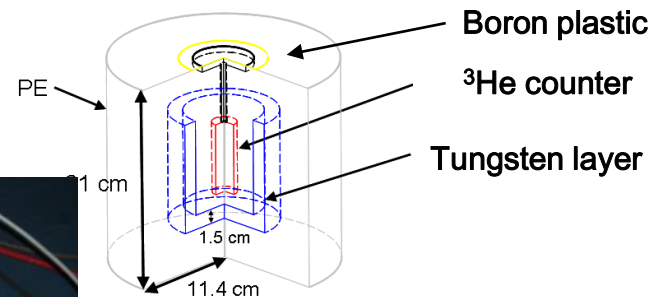
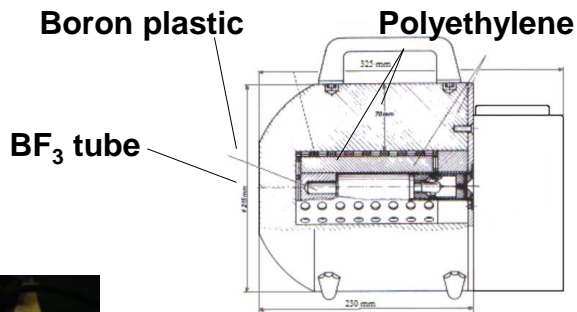
pulse height

Low-energy event cut



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

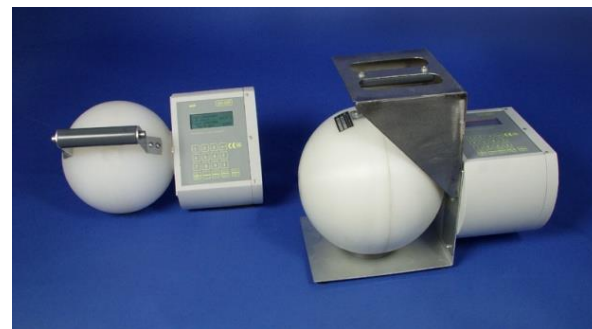
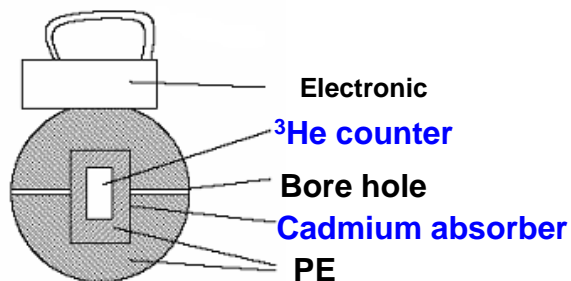
Studsvik 2202D



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 environmental samples





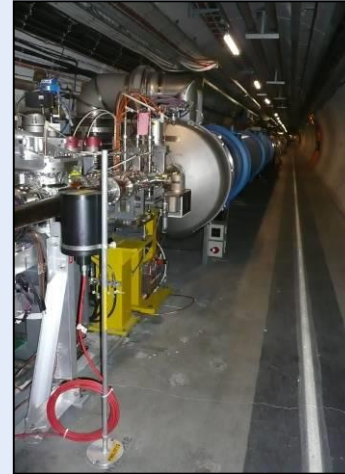
REM counter



Gas filled, high pressure ionization chamber

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

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, $E < 2.7 \text{ MeV}$)

No alarm function



Site Gate Monitor

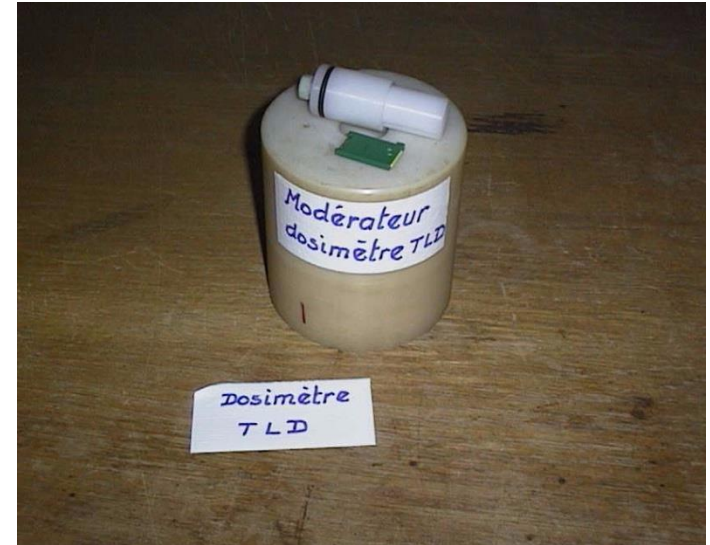


Reading of radiation levels directly available



Radiation Alarm Unit (RAMSES)

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/>

Supplementary material



Periodic Table of Elements

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

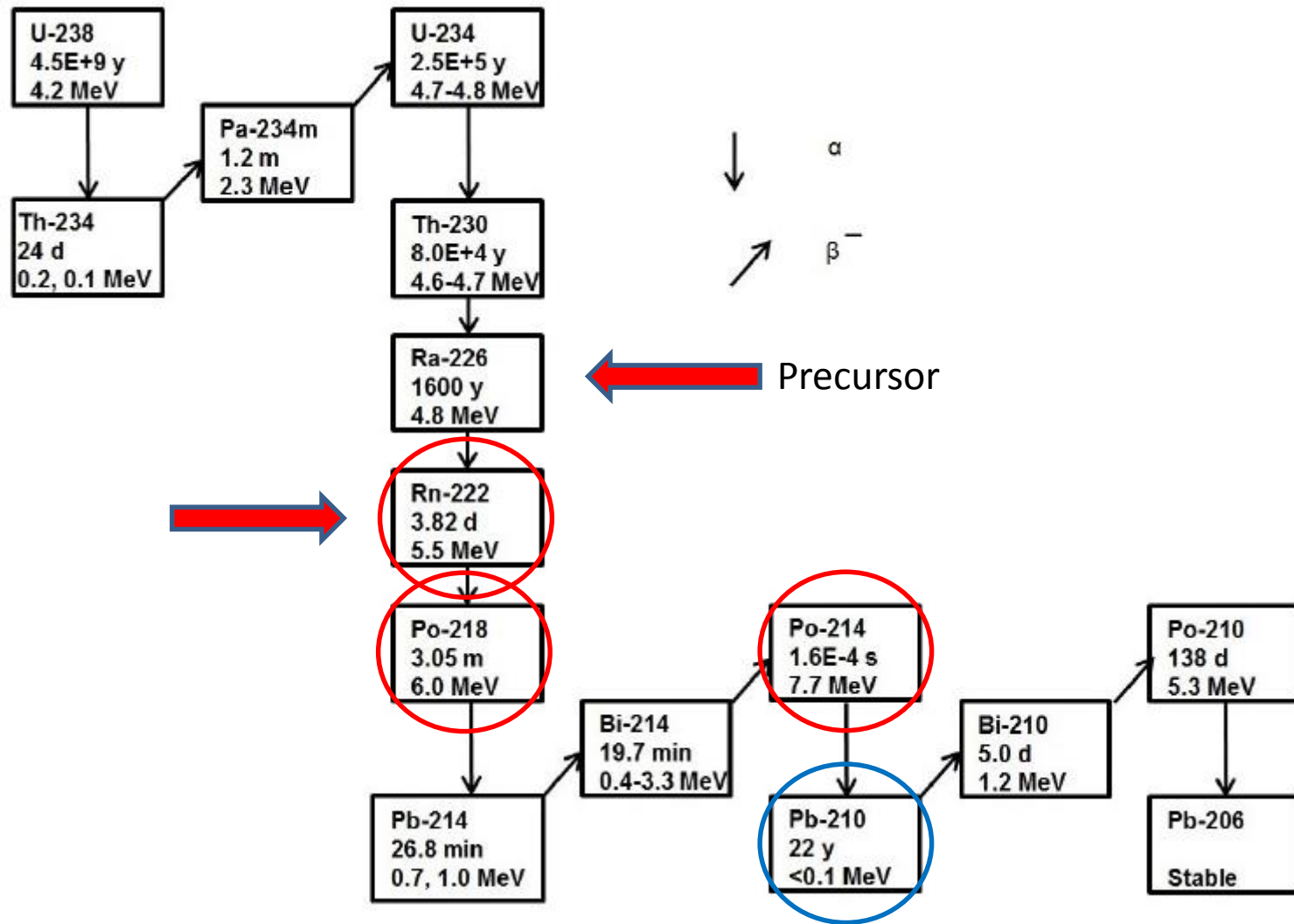
1	2	3											17	18			
1 H Hydrogen 1.00794	2 He Helium 4.002602											17 Cl Chlorine 35.453	18 Ar Argon 39.948				
3 Li Lithium 6.941	4 Be Beryllium 9.012182											15 S Sulfur 32.065	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948		
11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 S Sulfur 32.065	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.887	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.905	54 Xe Xenon 131.29
55 Cs Cesium 132.9054519	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
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 (282)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

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

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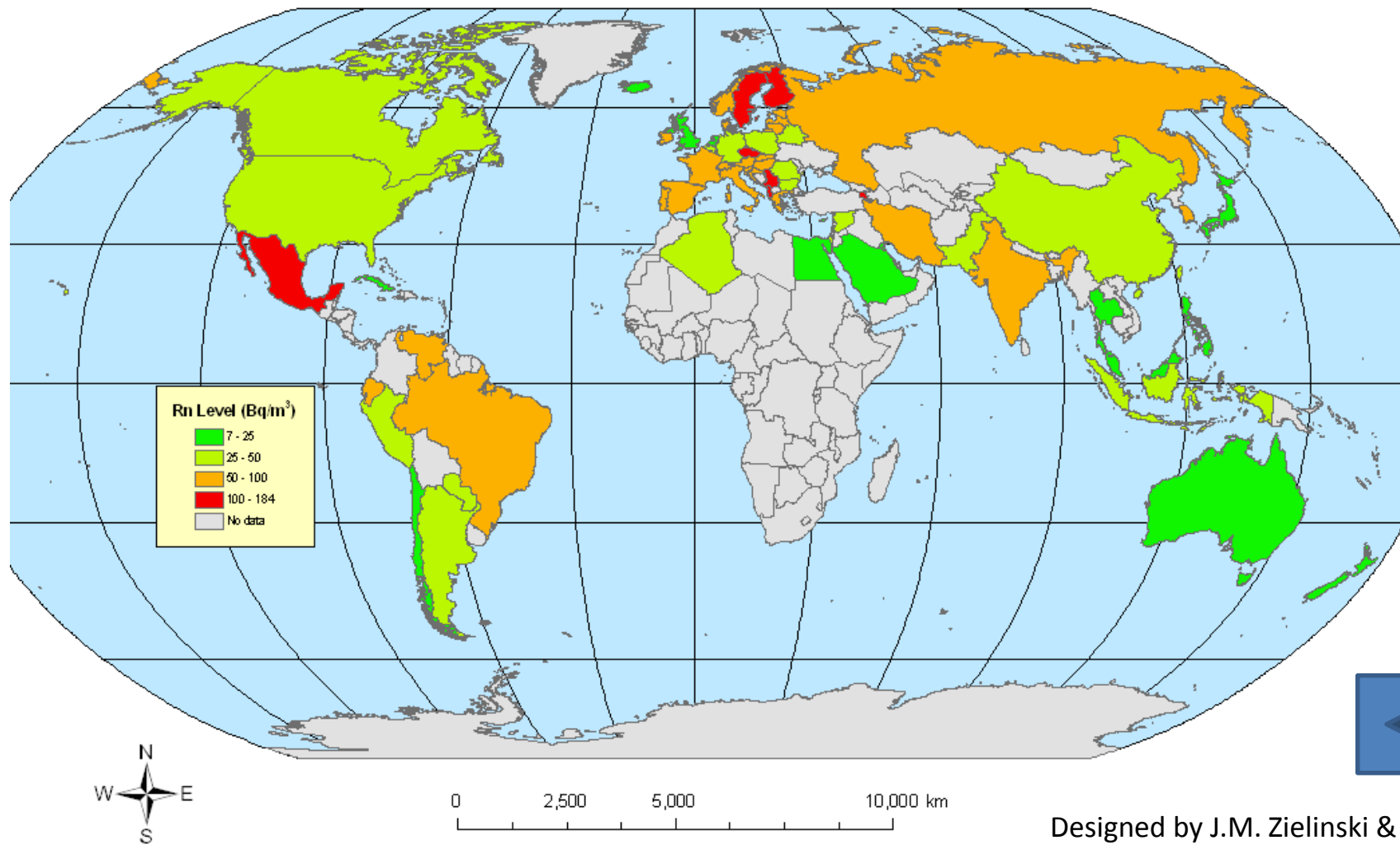


57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421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



Arithmetic Mean Radon Level by Country

(Based on Data up to 2007)



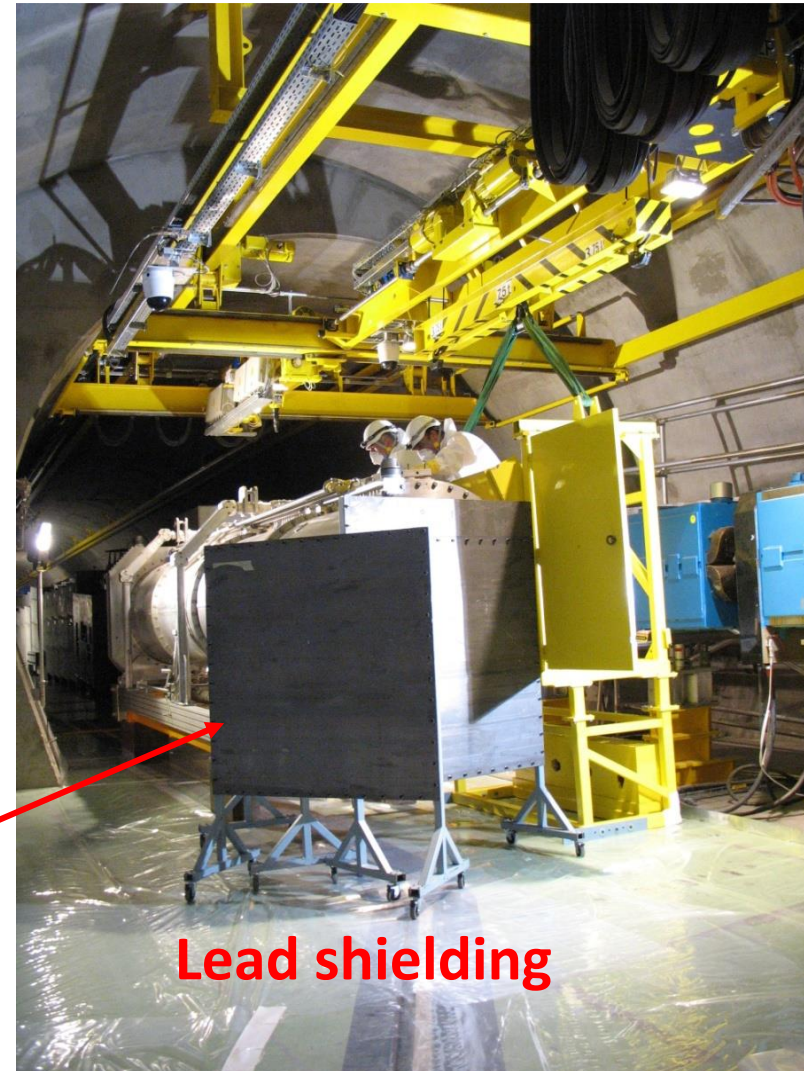
http://www.mclaughlincentre.ca/research/map_radon/Index.htm

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



	Area	Dose limit [year]	Ambient dose equivalent rate		Sign
			Work place	Low occupancy	
Radiation Area	Non-designated	1 mSv	0.5 μ Sv/h	2.5 μ Sv/h	
	Supervised	6 mSv	3 μ Sv/h	15 μ Sv/h	
	Simple	20 mSv	10 μ Sv/h	50 μ Sv/h	
	Limited Stay	20 mSv		2 mSv/h	
	High Radiation	20 mSv		100 mSv/h	
	Prohibited	20 mSv		> 100 mSv/h	
Controlled Area					

- 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

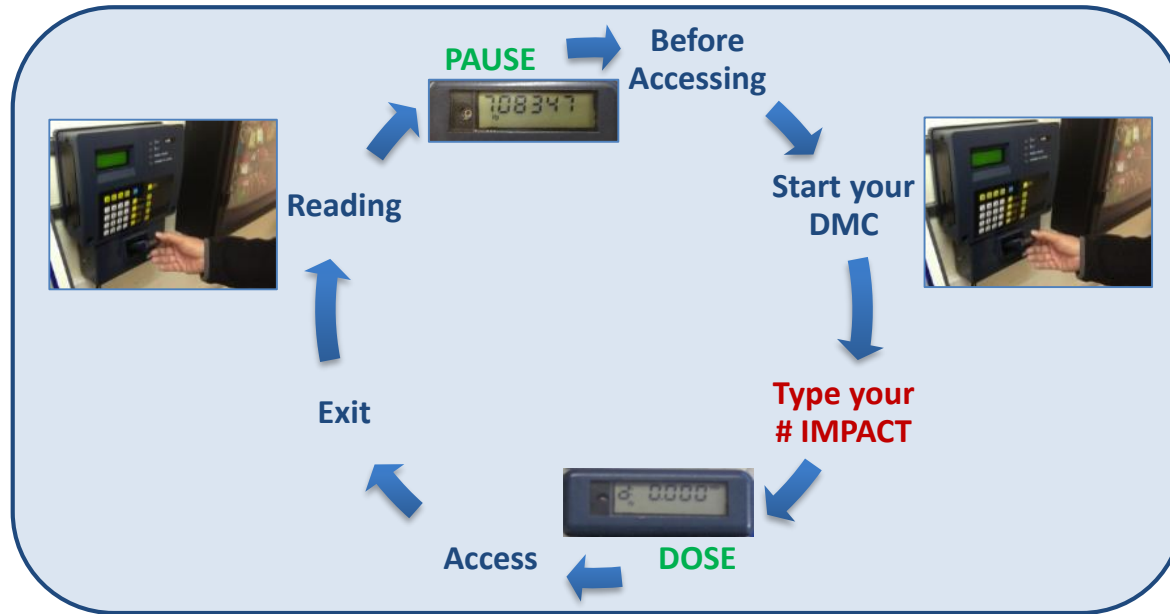


- Continuous measurement of $\beta\gamma$ -dose (DIS-system) and integration of the neutron dose (track dosimeter)
- Obligation to wear the dosimeter in supervised and controlled areas
- Wearing of the dosimeter on the chest
- Reading at least once a month at a reader (about 50 readers available on the 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 $\beta\gamma$ -dose measurement
- Instrument: DMC
- Display of $H_p(10)$ (resolution of $1 \mu\text{Sv}$)
- Dose alarm at 2 mSv
- Dose rate alarm at 2 mSv/h
- Audible detection signal (« bip »)
- Record the dose before and after the operation





For higher levels of contamination = higher risk



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



Whole body protection from contamination



Ventilated, filter and over-pressurized

Tyvek





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

