



Radiation dosimetry, radiation protection and measurements

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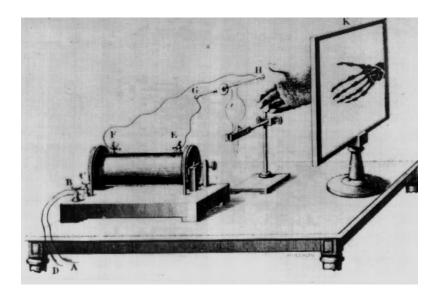
- A very brief historical introduction
- Directly and indirectly ionizing radiation
 - Radioactivity
 - Natural exposures
- The effects of ionizing radiation
 - Deterministic and stochastic effects
- Radiological quantities and units
 - physical, protection and operational quantities
- Principles of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



A very brief historical introduction

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The discovery of radiation



1895 Discovery of X rays Wilhelm C. Röntgen

1897 First treatment of tissue with X rays

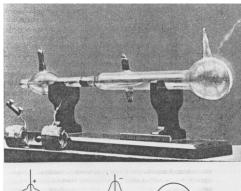
Leopold Freund

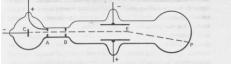


J.J. Thompson

1897 "Discovery" of the electron







The discovery of radiation





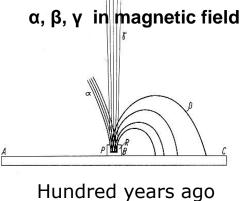
Henri Becquerel (1852-1908)

1896

Discovery of natural

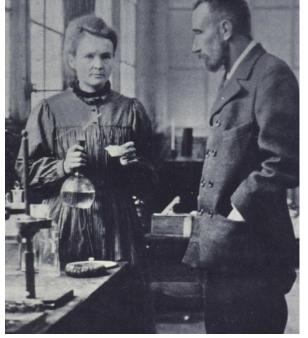
radioactivity





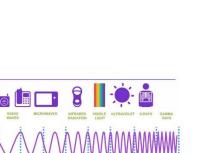
1898

Discovery of polonium and radium



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

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Periodic Table of Elements

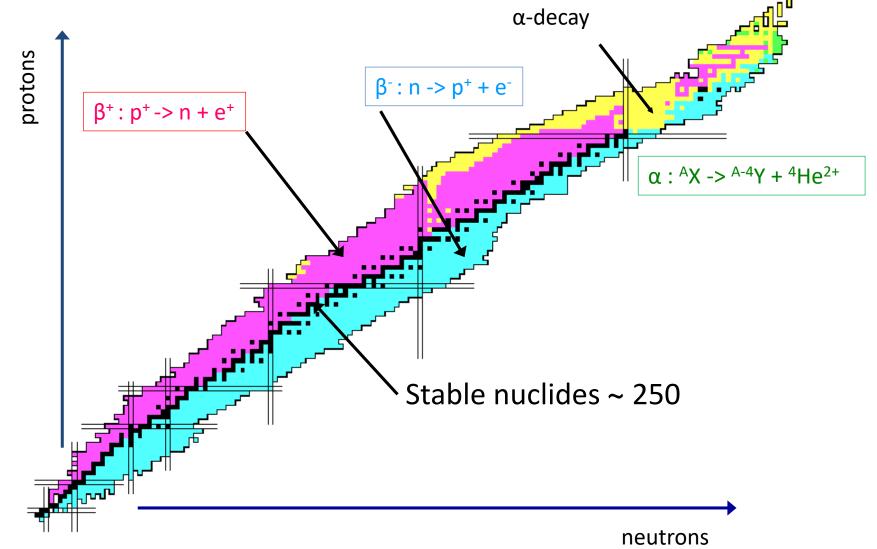
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1 ¹ H _{Hydrogen} 1.00794	Atomic # Symbol Name Atomic Mass	С	Solid				Metals			Nonme	tals						2 ² He Helium 4.002602	К
3 ² 1 2 Li Lithium 6.941	4 22 Be Beryllium 9.012182	H	=		Alkali metals	Alkaline earth metals	Lanthano	als	Poor metals	Other nonmetals	Noble ga	5 ² 3 B Boron 10.811	6 4 C Carbon 12.0107	7 g N Nitrogen 14.0067	8 2 e 0 0xygen 15.9994	9 F Fluorine 18.9984032	10 ² Ne Neon 20.1797	K L
11 2 3 Na Sodium 22,98976928	12 2 Mg Magnesium 24.3050	R	f Unkno	wn	tals	tals	Actinoids		tals	<u>8</u>	gases	13 ² Al Aluminium 26.9815386	14 2 Si Silicon 28.0855	15 2 P Phosphorus 30.973762	16 2 S Sulfur 32.065	17 Cl Chlorine 35.453	18 ² Ar ^{Argon} 39.948	K L M
4 K Potassium 39.0983	20 28 Ca Calcium 40.078	21 28 29 2 Scandium 44.955912	22 Ti ^{Titanium} 47.887	23 10 2 Vanadium 50.9415	² ¹¹ ² ¹¹ ² ¹ ¹ ¹ ¹ ¹ ¹ ¹ ¹ ¹ ¹	25 Mn Manganese 54.938045	26 13 2 Fe 100 55.845	² ¹⁴ ² ² ² ¹⁵ ¹⁵ ¹⁵ ² ² ² ² ² ² ² ² ² ²	28 Ni Nickel 58.6934	29 16 2 Copper 63.546	30 Zn 2inc 65.38	² 31 ² Ga ¹⁸ Gallium 69.723	32 28 Ge Germanium 72.84	33 ¹⁸ Ass ^{Arsenio} 74.92160	34 38 Se Selenium 78.90	35 Br Bromine 79.904	36 28 Kr 18 Krypton 83.798	K L M N
37 2 5 Rb 18 Rubidium 85.4678	38 28 Sr 28 Strontium 87.62	39 28 Y 18 Y(ttrium 88.90585	40 Zr ^{Zirconium} 91.224	41 Niobium 92.90638	42 10 11 12 10 12 10 10 10 10 10 10 10 10 10 10 10 10 10	43 TC (97.9072)	² ¹⁸ ¹⁴ 1 Ruthenium 101.07	² ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸	46 Pd Palladium 108.42	47 Ag Silver 107.8682	² ¹⁸ 10 Cadmium 112.411	49 28 In 18 Indium 114.818	50 28 Sn 18 Tin 118.710	51 28 Sb 18 Antimony 121.780	52 2 Te 18 Tellurium 127.60	53 18 100ine 126.90447	54 28 Xe 18 Xenon 131.293	K L M N O
55 28 6 Cs 18 Caesium 1 132.9054519	56 28 Ba 18 Barium 2 137.327	57–71	72 Hf Hafnium 178.49	² ¹⁸ ¹⁰ ¹⁰ ² ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰	² / ₈ 74 ¹⁸ / ₂₂ W ¹ / ₃₁ ¹ / ₂ Tungsten 183.84	75 Re Rhenium 186.207	² ¹⁸ ¹⁸ ¹³ ² ² ⁰ ⁰ ⁰ ⁰ ⁰ ¹⁸ ¹⁹ ²	² ⁸ ¹⁶ ¹⁶ ¹⁷ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	² ⁸ ⁸ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰	82 28 Pb 32 Lead 4 207.2	83 28 Bi 18 Bismuth 5 208.98040	84 28 Polonium (208.9824)	85 At Astatine (209.9871)	86 28 Rn 18 Radon 22 222.0178)	KLMNOP
87 87 8 Fr 18 Francium (223) 18	88 28 Ra 18 Radium 22 (226)	89–103	104 Rf Rutherfordium (281)	² ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰	² ⁸ ¹⁰ ¹² ¹² ¹² ¹¹ ² ¹² ¹² ¹²	107 Bh Bohrium (284)	2 8 108 182 22 13 2 13 2 13 2 13 2 13 2 108 HS Hassium (277)	² ⁸ ¹⁶ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸	110 DS Damstadium (271)	1111 18 12 12 17 1 Roentgenium (272)	² ¹⁰ 	² ² ² ² ² ² ² ² ¹¹³ ² ¹⁸ ¹⁸ ¹⁸ ²² ²² ²² ²² ²² ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰	114 Uuq Uhunquadum (289)	115 2 Uup 32 Ununpentum 18 (288)	116 Uuh Ununhexium ¹⁸ (292)	117 Uus ^{Uhurseptum}	118 Uuo Ununoctium (294)	KLMNOPQ
				For eler	ments wit	th no st	able isot	opes, the	mass	number o	of the iso	otope wit	h the lor	igest hal	f-life is i	n parent	heses.	
					Design a	nd Inter	face Copy	right © 19	97 Mich	ael Dayah	(michael	@dayah.c	om). http:	//www.pta	able.com/	1		
Dto	bla		57 La Lanthanum 138.90547	2 58 Ce 2 2 Cerium 140.116	² ¹⁸ ¹⁹ ² ² ² ¹ ² ² ² ² ² ² ² ² ² ²	60 Nd Neodymium 144.242	61 18 22 8 2 Promethium (145)	² ⁸ ¹⁸ ² ² ⁸ ¹⁸ Sm ¹⁸ ¹⁸ ²⁸ ¹⁸ ²⁸ ²⁰ ²⁰ ²⁰ ²⁰ ²¹ ²⁰ ²⁰ ²⁰ ²⁰ ²⁰ ²⁰ ²⁰ ²⁰	63 Eu ^{Europium} 151.984	64 63 Gd 32 32 32 33 32 33 34 34 34 34 34 34 34 34 34 34 34 34	² ⁸ ¹⁵ ⁹ ² ¹ Tb ¹ ² ¹ ² ¹ ² ¹ ¹ ²	66 28 Dy 28 Dysprosium 2 162.500	67 28 Ho 28 Holmium 2 184.93032	68 28 Er 30 Erbium 2 187.259	69 28 Tm 31 Thulium 168.93421	70 Yb Ytterbium 173.054	² ² ² ² ² ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰	
	com		89 Ac Actinium (227)	90 18 12 13 12 13 13 13 13 14 15 15 15 15 15 15 15 15 15 15	² ¹⁶ ¹² ¹⁸ ¹⁰ ² ¹⁰ ¹⁰ ² ¹⁰ ¹⁰ ¹⁰ ¹⁰ ² ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰	8 92 U Uranium 238.02891	2 3 3 2 2 9 2 Np Neptunium (237)	$\begin{array}{c} & & \\$	95 Am Americium (243)	96 18 22 25 2 2 2 2 2 2 2 2 2 2 2 2 2	² ¹⁶ ¹⁶ ¹⁶ ¹⁸ ¹⁸ ¹⁸ ¹⁹ ¹⁹ ¹⁹ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰	² ² ² ² ² ² ² ² ² ²	99 2 Es 29 Einsteinium 2 (252) 2 29 29 29 29 29 29 29 29 29 2	100 2 Fm 32 Fermium 2 (257) 2	101 2 Md 32 Mendelevium 2 (258)	102 No Nobelium (259)	² ² ² ² ² ² ² ¹⁰³ ¹⁶ ¹⁶ ¹⁸ ²² ²² ²² ²² ²² ²² ²²	

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Chart of nuclides



Unstable (=radioactive) nuclides ~ 3000



 β^+ and β^- decays



 ${}^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + \mathrm{e^{+}} + \nu_{\mathrm{e}} + 960 \ \mathrm{keV}$

						Na17	Na18	Na19 Mains	Na20 447.9 MS	Na21 22.49.8	Na22 2.619 Y	Na23 100	Na24 149912 H
					Ne15		Ne17 1002 MS	Ne18 1672 мз	Ne19 1722 s	Ne20 90.48	Ne21 027	Ne22 925	Ne23 3724 8
					F14			F17 64.49 8	F18 10977 м	F19 100	F20 ពេស	F21 4.158 S	F22 4238
					O13 8.50MS	014 70.606 s	O15 122.24.8	O16 99.761	017 0.098	O18 0300	019 2691 3	O20 13.51.8	O21 342.8
			N10		NI2 ILZENS	N13 9965 M	N14 99.694	N15 0366	N16 7.138	N17 4.1758	N18 624 MS	N19 200 MS	N20 142 MS
			C9 126.5 MS	C10 192558	С11 лжи	C12	C13 111	C14 5730 T	C15	C16 0.747 s	С17 195 мз	C18 95MS	С19 49 мз
			B8 770 мз		B10 198	BNI Pl	B12 2020368	B13 17.36 MS	B14 12.3368	B15 087 MS	B16	B17 Sorms	B18 -26 NS
	Be5		Be7 5129 D		Be9 100	Be10	Bell ISBLS	Be12 21.3 MS		Be14 4.35 MS			
		-	Li6 7.50	Li7 92.41	LiS 898 MS	Li9 178.3343		Li11 8.5 MS	Li12 anns		-		
	He3 ann sr	He4 90,999acs		Неб въсл жа		He8 LIVD XX				-			
H1 99.985	H2 DDIS	H3 1239 Y											

 $^{14}\text{C} \rightarrow ^{14}\text{N} + e^- + \bar{v}_e + 156 \text{ keV}$

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 **twostep 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**:

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

(the old unit is the Curie: $1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$)

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)





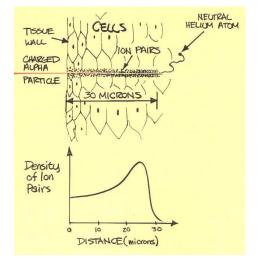
(Emitted in the de-excitation of unstable nuclei)

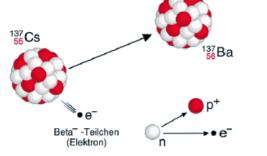


- Helium nuclei (2 protons + 2 neutrons)
- Energy: a few MeV
- Non-penetrating
- Radiological hazard only if inhaled, ingested or absorbed through a wound (internal irradiation)

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

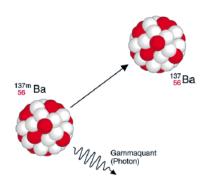
- Electromagnetic radiation
- Energy: a few keV to a few MeV
- Very penetrating
- Radiological hazard only by external irradiation

NEUTRONS

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

HEAVY CHARGED PARTICLES (protons, ions)

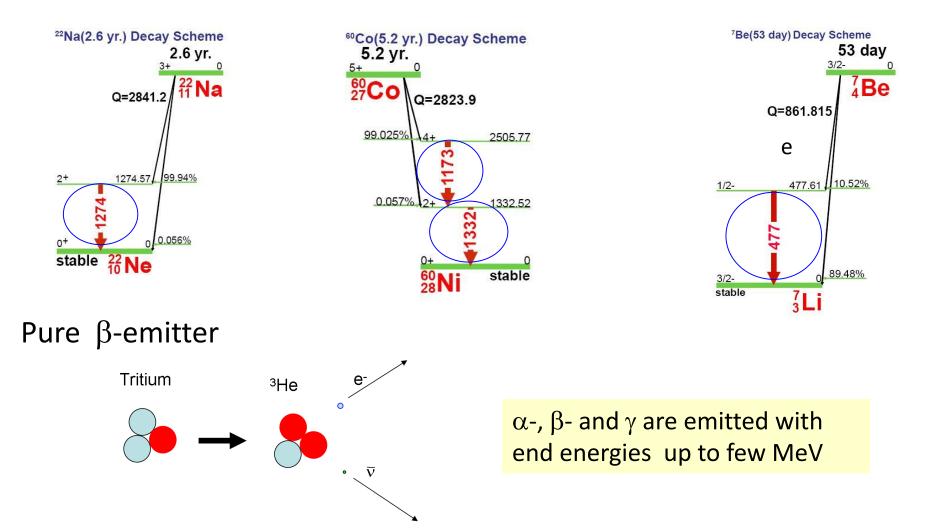
- External irradiation
- Enhanced biological effect (high LET Linear Energy Transfer radiation)





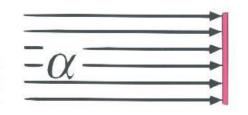


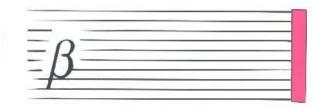
β -, γ -emitter



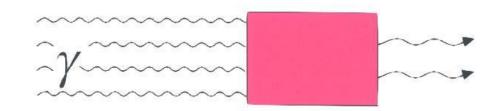


 α - and β -particles are degraded in energy while traversing a material, until they are completely brought to rest

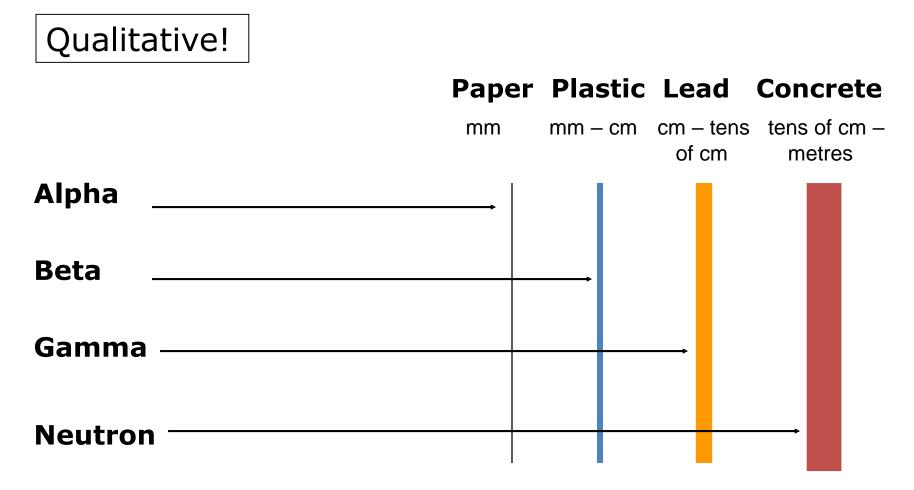




 γ -rays are attenuated in intensity by the material







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

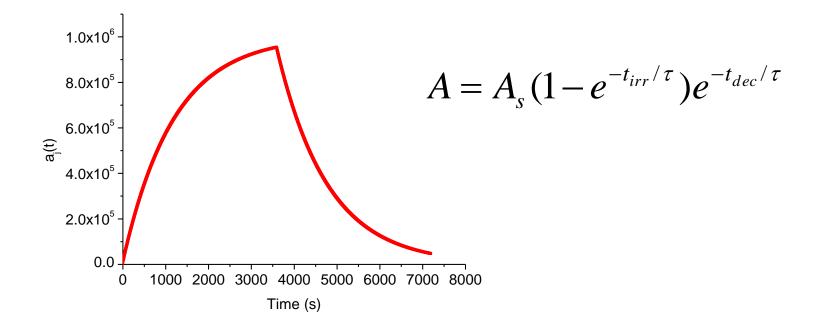
$$n = I_p \frac{\rho N_{Av}}{A} \sum_{i=p,n,\pi,pho} \int \Phi_i(E) \sigma_i(E) dE$$

Nuclide production rate



Rule-of-thumb (probably very obvious):

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



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 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, μ Sv)

 $H=Q\cdot D$ 1 Sv = 1 J/kg

Q = quality factor of the radiation

QUESTION 1



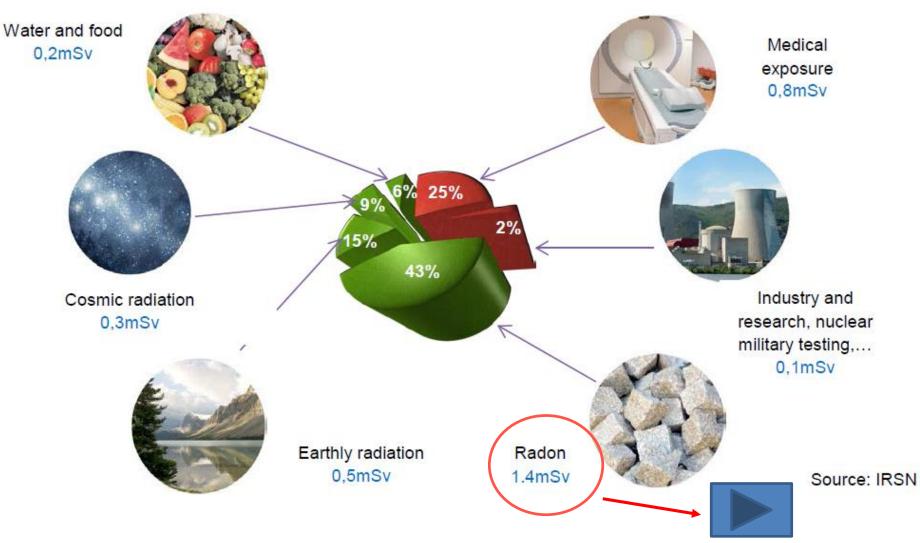
Are we all exposed (voluntarily or not) to some radiation sources?

Yes/No?

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



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





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 x 10 ⁸ y	0.72% of natural Uranium
Uranium-238	²³⁸ U	4.47 x 10 ⁹ y	99.3% of natural Uranium
Thorium-232	²³² Th	1.41 x 10 ¹⁰ y	
Potassium-40	⁴⁰ K	1.28 x 10 ⁹ y	Earth: 0.037-1.1 Bq/g

...and some more:

⁵⁰V, ⁸⁷Rb, ¹¹³Cd, ¹¹⁵In, ... ¹⁹⁰Pt, ¹⁹²Pt, ²⁰⁹Bi, ...



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 ${}^{\rm 6}$ Li(n, α) ³ H		
Beryllium-7	⁷ Be	53.28 d	Interaction of cosmic radiation with N or O		

More cosmogenic radionuclides:

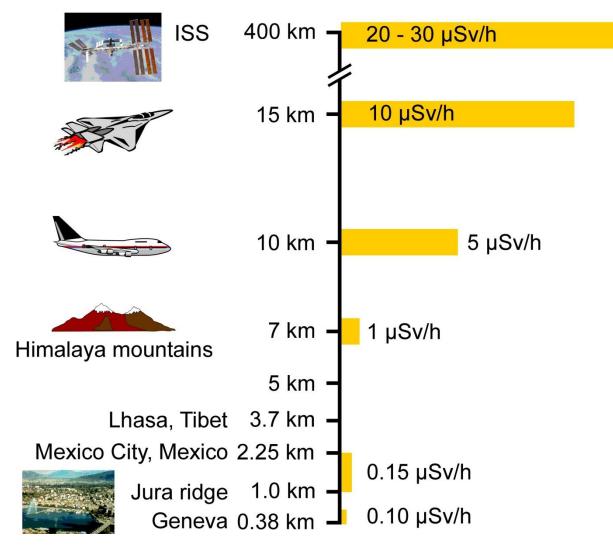
¹⁰Be, ²⁶Al, ³⁶Cl, ⁸⁰Kr, ...



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 μ Sv per hour (Sum of neutrons, muons, electrons and protons)



Courtesy PTB, Braunschweig



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The effects of ionizing radiation

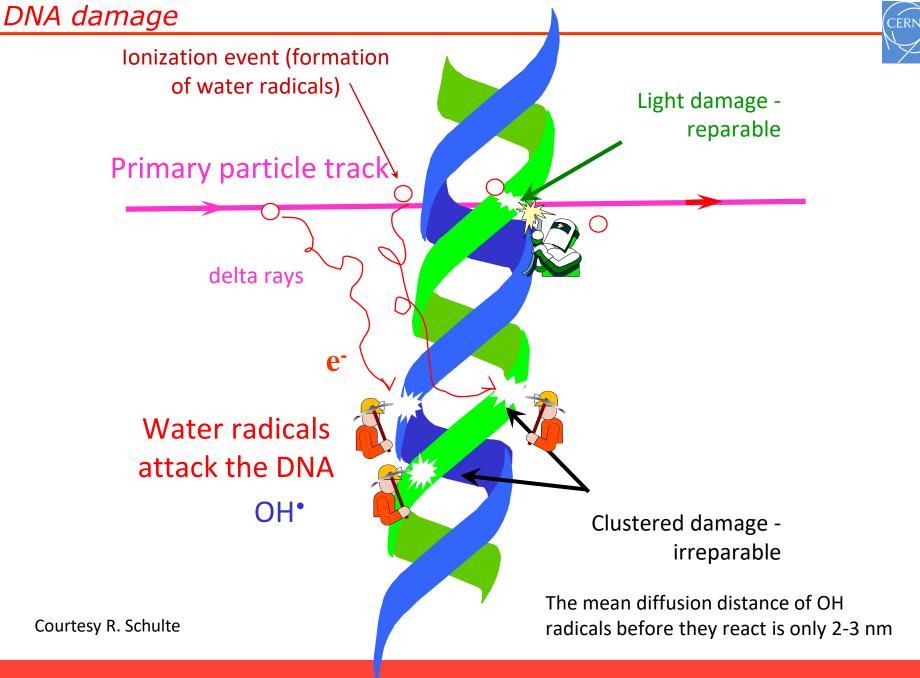
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Unique effects of interaction of ionizing radiation with matter

- Biological systems (humans in particular) are particularly susceptible to damage by ionizing radiation
- The expenditure of a trivial amount of energy (~ 4 J/kg = 4 Gy) to the whole body is likely to cause death...
- …even if this amount of energy can only raise the gross temperature by about 0.001 °C
- This is because of the ability of ionizing radiation to impart their energy to individual atoms and molecules
- The resulting high local concentration of absorbed energy can kill a cell either *directly* or through the formation of highly reactive chemical species such as *free radicals* (atom or compound in which there is an unpaired electron, such as H or CH₃) in the water medium that constitutes the bulk of the biological material

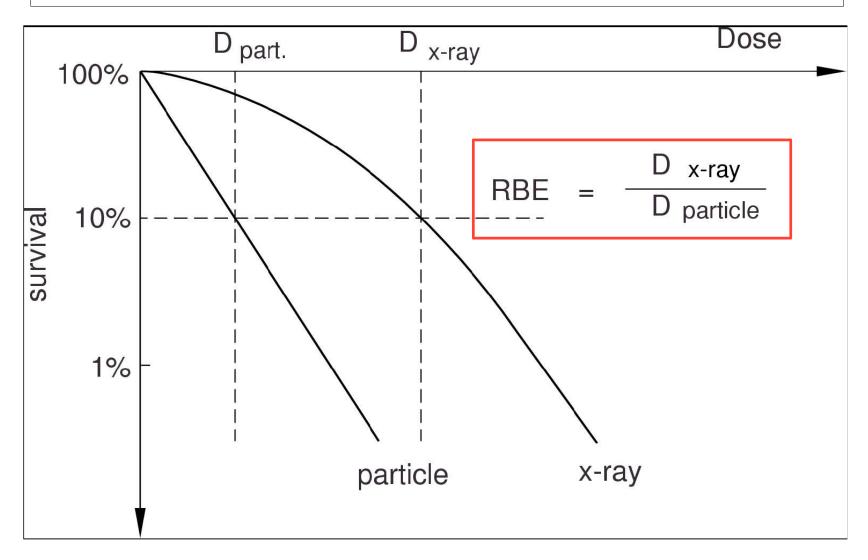
Main aim of **dosimetry** = measurement of the absorbed dose (energy/mass)





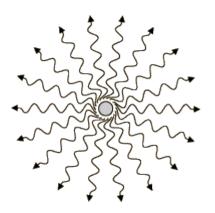
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DIFFERENT TYPES OF RADIATION MAKE DIFFERENT DAMAGE





What are the biological effects of radiation?





Stochastic effects

no dose threshold (linear function of dose)

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increase of probability by 5% per Sv for:
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genetic defects cancer

result does not dependent on the amount of absorbed dose

delayed health detriments

Deterministic effects

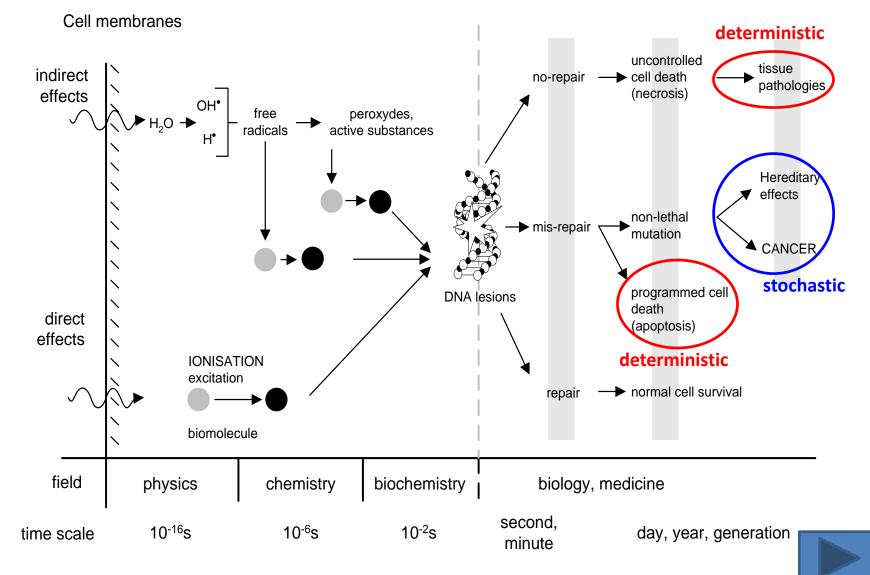
dose received in short time interval dose threshold: > 500 mSv

immediate consequences: vomiting immun deficiency erythema and necrose

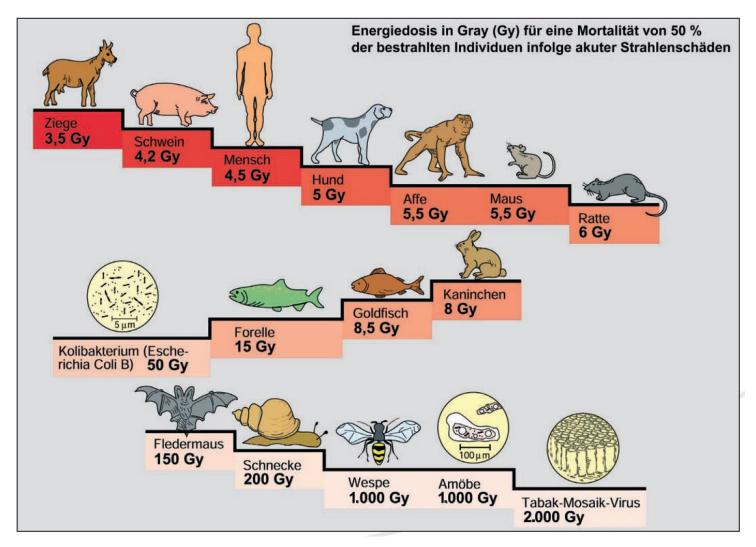
health detriments are function of the dose

lethal dose: 5 – 7 Sv









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

CERN

4~ RBE=20

Units of Radiation

Absorbed dose: 1 rad = 1×10-5 J/g

High energy ip +on

Biological damage: rem = # rads xRBE X-russ, 0,+7-rays RBE= 1 4~

Activity: Icurie (Ci) = 3.7 × 1010 disintegrations/s

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1) Justification

any exposure of persons to ionizing radiation has to be justified

2) Limitation

the personal doses have to be kept below the legal limits

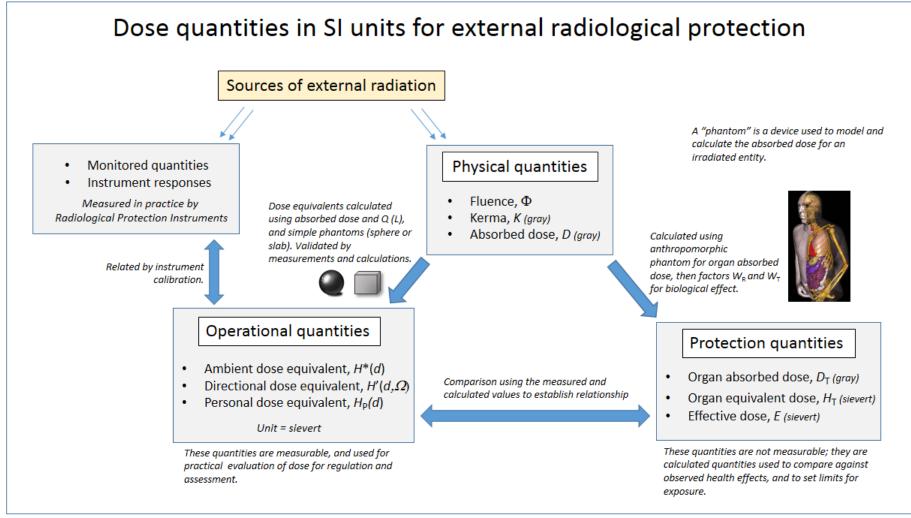
3) Optimization

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





International Commission on 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:

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

Unit: Sv

(1 Sv = 100 rem)

 H_{T}

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





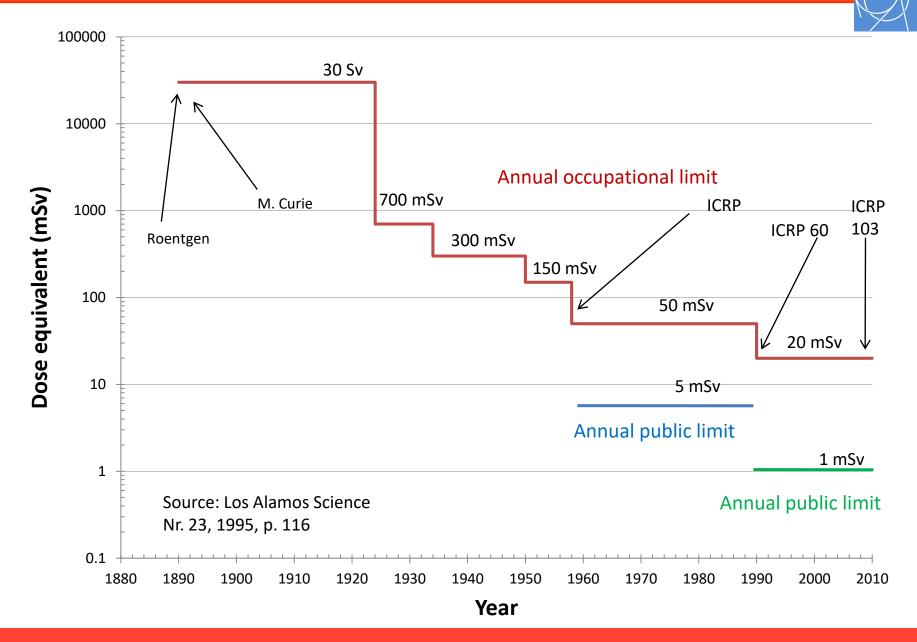
Organ / tissue	No of tissues	w _T	Total contribution
Bone-marrow, colon, lung, breast, stomach, remainder tissues	6	0.12	0.72
Gonads	1	0.08	0.08
Bladder, esophagus, liver, thyroid	4	0.04	0.16
Bone surface, brain, salivary glands, skin	4	0.01	0.04

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)

History of radiation protection



M. Silari – Radiation Measurements and Dosimetry – ASP 2022

Contamination



External radiation source a external exposure



Volumetric (air)

Internal radiation source internal exposure

- Person **occupationally exposed** to radiation (> 1 mSv/y)
 - Category A workers: > 6 mSv/y
 - Category B workers: < 6 mSv/y</p>
- 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?

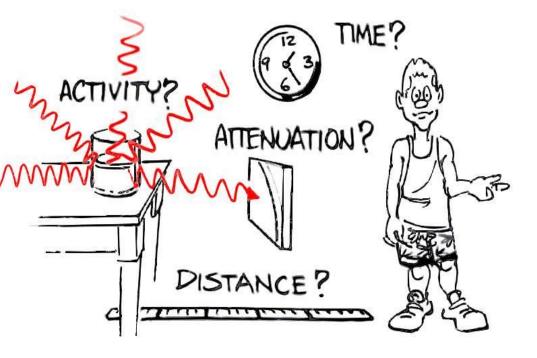


www.shutterstock.com · 384981319



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 x t
- Shielding: the dose rate approximately reduces as exp(-d/λ)
 - λ = shielding properties of the material



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

- **Time:** limit the duration of the stay in the radiation field
 - Job preparation
 - Dry run
 - Monitoring of the duration of exposure
- **Distance:** stay as far as possible from the source
 - Dispersion law: 1/r² 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

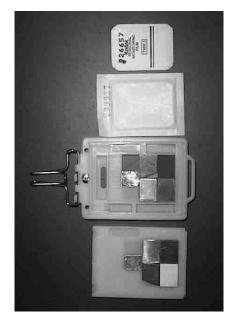


- Wearing a personal dosimeter on the chest or at the waist
 - monthly measurement (at least)
 - Information may be delayed (depends on dosimeter)
 - measurement threshold ~0.1 mSv/month
- Wearing an electronic dosimeter
 - instantaneous information
 - possibility to setting a dose or dose rate alarm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



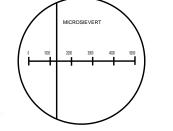
- The dosimeter is calibrated to measure:
 - H_p(10): personal equivalent dose at a depth of 10 mm in the chest
 - H_p(0.07): personal equivalent dose at a depth of 0.07 mm in the chest
- At low measured doses (less than the limits) it is assumed that:
 - the effective dose and the equivalent dose to 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.

Personal dosimetry for monitoring external exposure



Kodak film badge





Quartz-fiber dosimeter (ionisation chamber and electroscope)

Personal dosimeter: "Legal dose"





RADOS DIS

Finger dosimeter

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 no be activated BUT ...
- ... it might be contaminated
- If there is a suspicion of contamination, it has to be checked before leaving the area









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



Internal exposure can occur by:

- ingestion
- inhalation
- skin



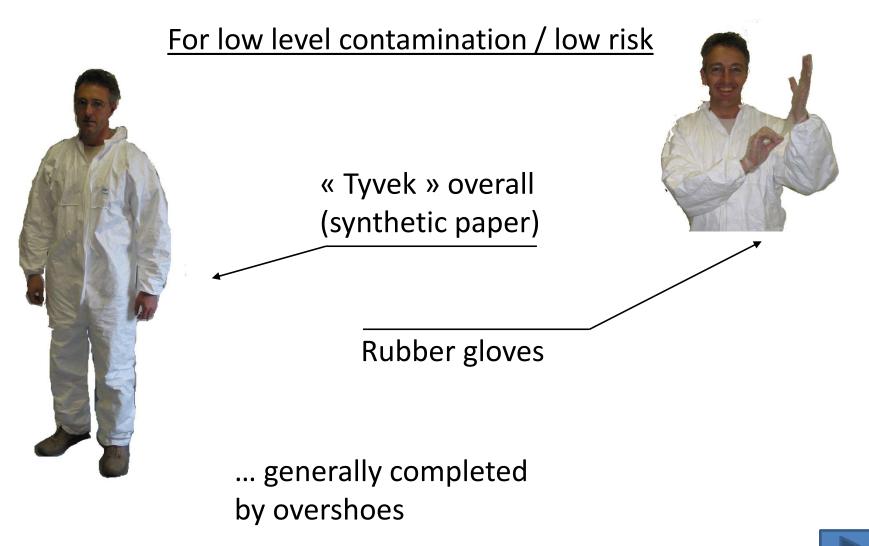
- Determination of the activity taken into the body and calculation of the committed effective dose with a standard model
- Measurements to determine the activity taken into the body:
 - direct measurement of the radiation emitted by the person using a thyroid monitor, a lung monitor or a whole body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



- Operational quantity: committed effective dose E₅₀
- 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.

Personal protection equipment against contamination



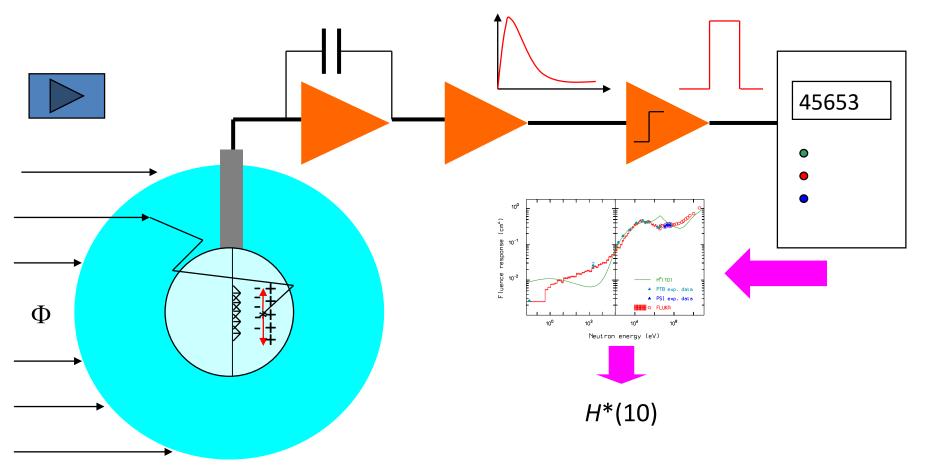


CERN

- 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 quantity
- Principles of radiation protection
 - Justification, optimization and d
 - The ALARA principle
- Protection means
- Instrumentation for measuring ionizing radiation

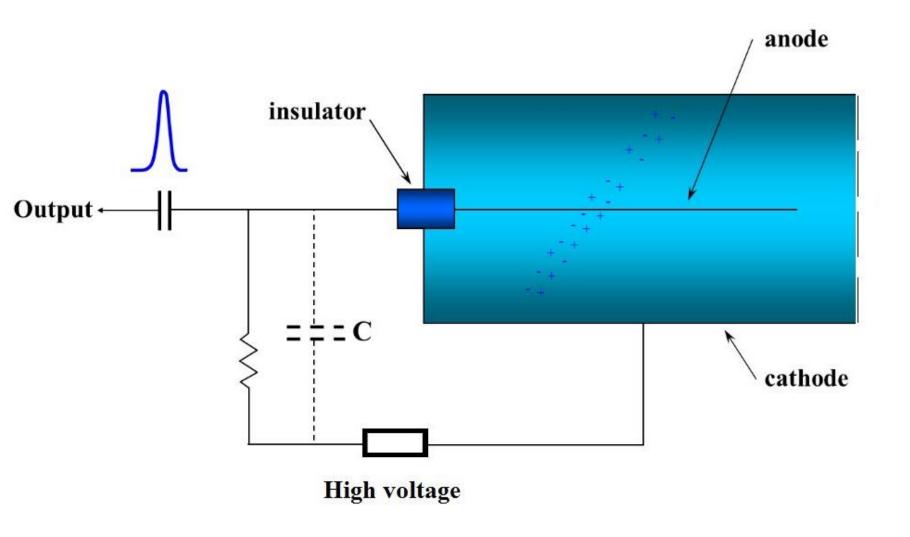
CERN

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



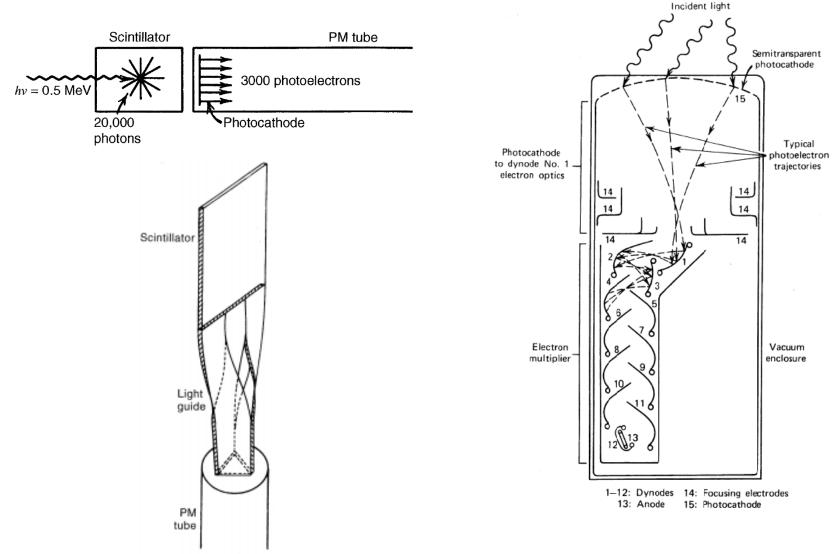
Courtesy S. Agosteo, Politecnico di Milano





Scintillating crystal coupled to a PMT



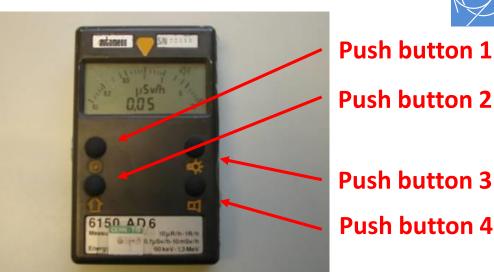


From Glenn F. Knoll, Radiation Detection and Measurement

AUTOMESS dose rate meter 6150 AD6





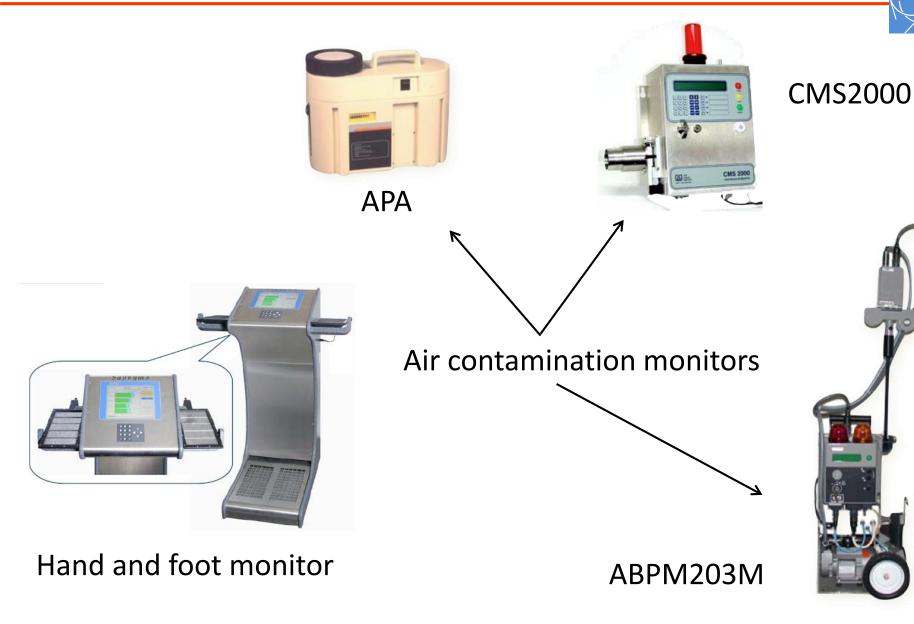


<u>Detector:</u> Geiger Müller counter <u>Range:</u> 0.5 μSv/h – 10 mSv/h <u>Energy range:</u> 60 keV – 1.3 MeV <u>Dimensions:</u> 130 mm x 80 mm x 29 mm <u>Alimentation</u>: 9 V standard battery

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

Contamination monitors





Whole body counting







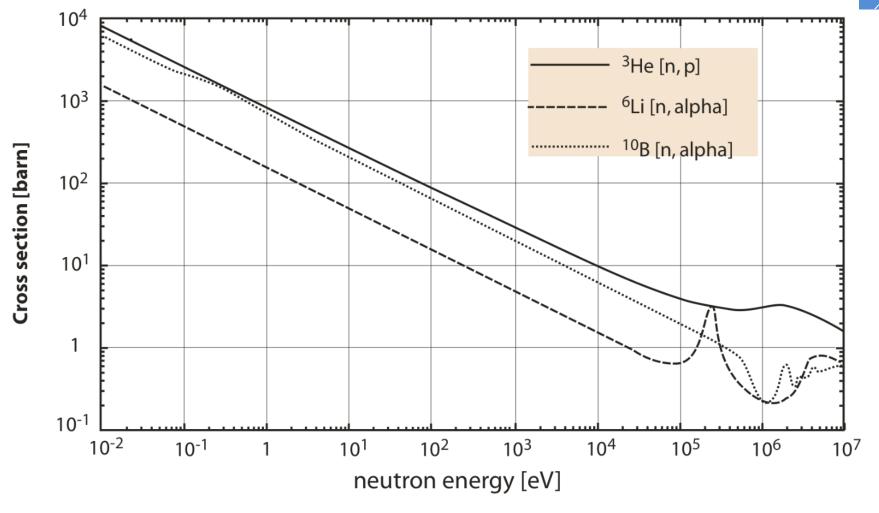




Some elements have a very large cross section for slow neutrons and can be exploited for neutron detection

1) Boron ${}^{10}B + n \rightarrow {}^{7}Li + \alpha$ ${}^{10}B + n \rightarrow {}^{7}Li^* + \alpha$ 2) Lithium ${}^{6}Li+n \rightarrow {}^{3}H + \alpha$ 3) ${}^{3}He$ ${}^{3}He + n \rightarrow {}^{3}H + p$ ${}^{2}Z.793 MeV$ ${}^{Q} = 2.310 MeV$ ${}^{Q} = 4.78 MeV$ ${}^{Q} = 764 keV$

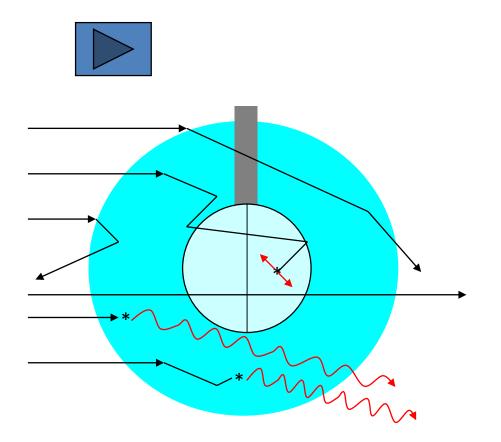
Neutron cross sections



Mean free path of thermal neutrons

- in ³He gas \approx 7 cm
- in solid $^{10}\text{B}\approx70~\mu\text{m}$



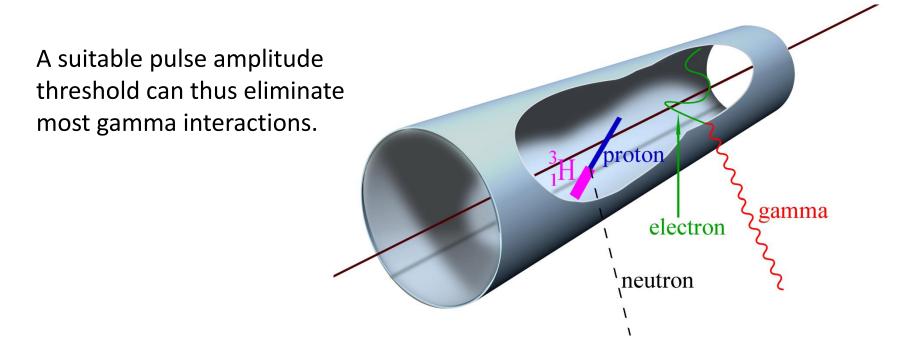


Courtesy S. Agosteo, Politecnico di Milano

CERN

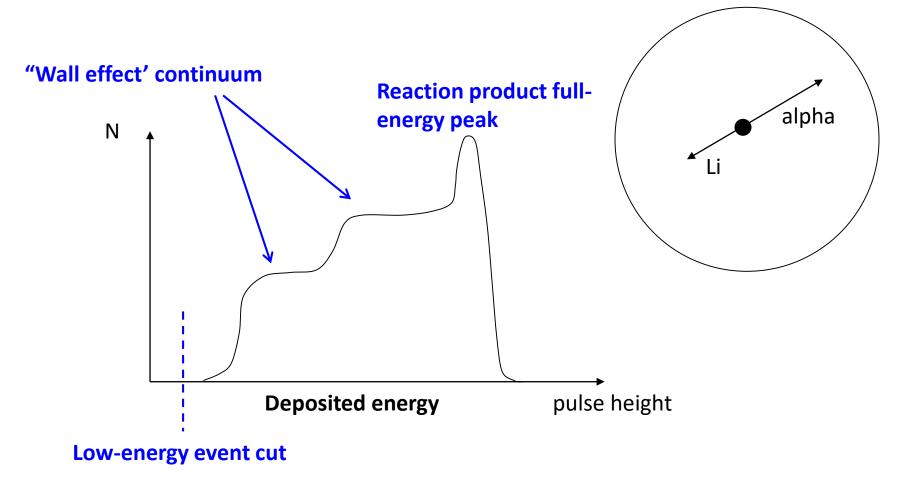
 BF_3 gas and ³He gas make detectors for slow neutrons with excellent gamma discrimination

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



Pulse height spectrum from a BF₃ proportional counter





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

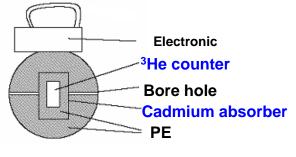
Rem counters

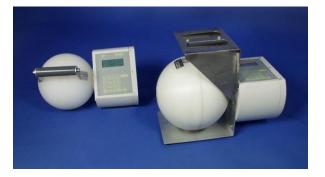
CERN

Studsvik 2202D Figure Figure

Berthold LB6411 (also LB6411Pb)







MAB SNM500(X)



Active monitoring

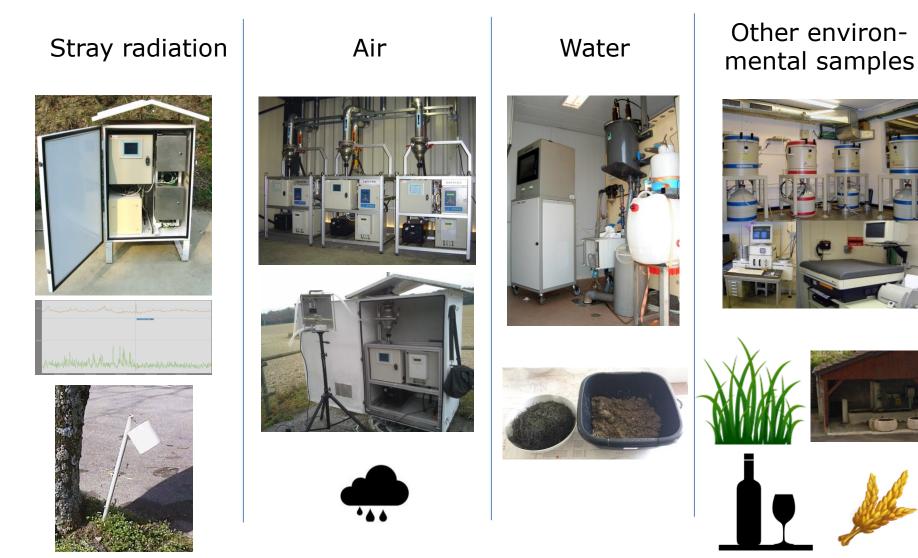
- Ambient dose rate
- Water contamination
- Airborne contamination
- Weather parameters
- Gate monitors

Passive monitoring

 Thermoluminescent dosimeters placed in the environment

Environmental 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





Site Gate Monitor

Reading of radiation levels directly available

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Radiation Alarm Unit (RAMSES)

CERN

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) <u>http://www.icrp.org/publications.asp</u>

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



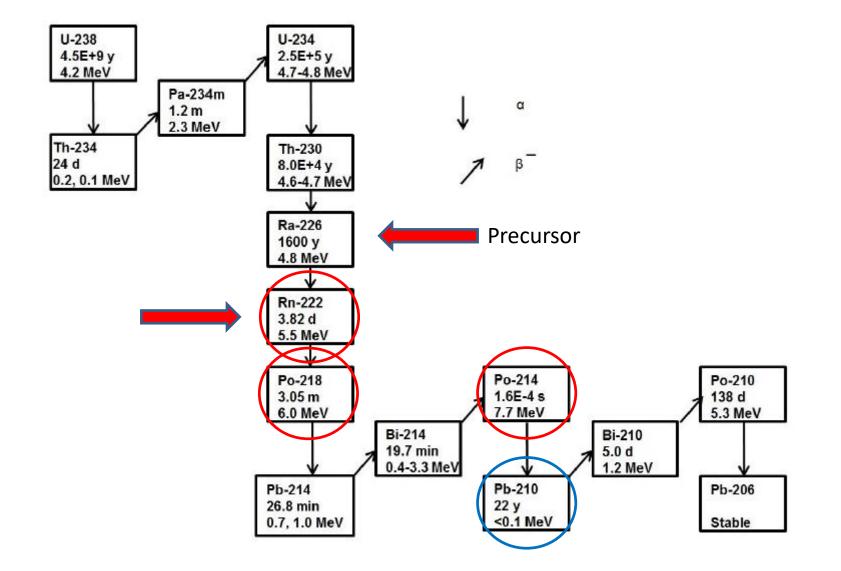
Supplementary material



Periodic Table of Elements

1	2	3	³ ²¹⁹ Rn (Actinion), ²²⁰ Rn (Thoron) and ²²² Rn (Radon)									18					
1 1 H Hydrogen 1.00794	¹ Atomic # Symbol Name Atomic Mass	С	Solid				Metals			Nonmet	als						2 ² K He Helium 4.002602
3 2 Li Lithium 6.941	² 1 4 ² 2 Be Beryllium 9.012182	Hg H	Liquid Gas		Alkali metals	Alkaline earth metals	Lanthanoi	ids metals	Poor metals	Other nonmetals	Noble ga	5 B Boron 10.811	6 ²	7 25 N Nitrogen 14.0087	8 6 O Oxygen 15.9994	9 F Fluorine 18.9984032	7 10
11 3 Na Sodium 22,98976928	12 12 12 0 12 2 2 2 2 2 2 2 2 2 2 2 2 2	Rf	Unknow	'n	stals	tals	Actinoids	-	tals		gases	13 23 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 ² 8	16 ² S Sulfur 32.085	17 Cl Chlorine 35.453	² Ar Argon 39.948
19 4 K Potassium 39.0983	² 20 Ca ² ⁸ ² ² ⁸ ² ² ² ² ² ² ² ²	21 8 Sc 32 Scandium 44.955912	22 28 Ti 10 Titanium 47.867	23 28 V 11 Vanadium 50.9415	24 28 Cr 13 Chromium 51.9961	25 Mn Manganese 54.938045	² ¹³ ¹² ¹³ Fe ¹ ¹⁰ ¹⁰	27 Cobalt 58.933195	28 28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 20 Zn 2 5.38	31 28 Ga 3 Gallium 69.723	32 2 Ge 4 Germanium 72.64	33 As Arsenio 74.92160	34 18 9 78.9	35 Br Bromine 79.904	36 28 KL Kr 18 N Krypton 83.798
37 5 Rb Rubidium 85.4678	38 2 Sr 2 Strontium 87.62	39 2 Y 18 Yttrium 88.90585	40 28 Zr 10 2 Zirconium 91.224	41 28 Nb 12 Niobium 92.90838	42 2 Mo 13 Molybdenum 95.96	43 Tc Technetium (97.9072)	⁸ ¹⁸ ¹⁴ Ruthenium 101.07	45 Rh 102.90550	46 Pd Palladium 108.42	47 Ag Silver 107.8682	48 28 Cd 18 Cadmium 112.411	49 28 In 18 Indium 114.818	50 28 Sn 18 Tin 118.710	51 28 Sb 18 Antimony 121.760	52 Te Tellurium 127.60		54 2 K Xe 18 N Xenon 131 292
55 Cs Caesium 132.9054519	² 56 ² Ba ¹⁸ ¹⁸ ¹⁸ ¹⁸ ¹⁸ ² ² ² ¹⁸	57–71	72 28 Hf ³⁸ Hafnium 2 178.49	73 28 Ta 18 18 32 11 12 180.94788	74 28 W 12 Tungsten 2 183.84	75 Re Rhenium 186.207	76 18 32 12 0smium 190.23	2 77 1 1 1 2 1ridium 192.217	78 Platinum 195.084	79 Au 1 Gold 196.966569	80 2 Hg 18 Mercury 2 200.59	81 2 TI 18 Thallium 204.3833	82 2 Pb 32 Lead 4 207.2	83 2 8 Bi 12 Bismuth 208,98040	84 28 Polonium (208.9824)	85 At Astatine (209.9871)	86 8 Rn 18 Radon 8 (222.0176)
87 Fr Francium (223)	88 2 Ra 18 Ra 28 Ra 18 18 18 18 18 18 18 18 18 18	89–103	104 2 Rf 32 Rutherfordium 10 (281) 2	105 28 Db 322 Dubnium 2 (262)	106 28 Sg 32 Seaborgium 12 (286)	107 Bh Bohrium (284)	108 18 18 12 13 12 Hassium (277)	² 109 Mt ³ Meitnerium ¹ (268)	110 Ds (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 2 Uut 32 Ununtrium 18 (284) 13	114 28 Uuq 32 Ununquadium 18 (289)	115 28 Uup 15 Ununpentum 15 (288)	116 28 Uunhexium 18 Ununhexium 18 (292)	117 Uus ^{Uhurseptum}	110 2 8 18 18 18 18 18 18 18 10 12 18 10 12 12 12 12 12 12 12 12 12 12
			F	or elem	ents wit	h no sta	able isoto	opes, the	e mass r	umber c	of the iso	tope wit	h the lon	gest hal	f-life is i	n parent	heses.
Design and Interface Copyright © 1997 Michael Dayah (michael@dayah.com). http://www.ptable.com/																	
Dte	blo		57 2 La 18 Lanthanum 2 138.90547	58 28 Ce 18 Cerium 2 140.116	59 28 Pr 21 18 Praseodymium 2 140.90765	60 Nd Neodymium 144.242	² ¹⁸ ²⁸ ²⁹ ²⁰ ²⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹	62 5 5 5 5 5 5 5 5 5 5 5 5 5	63 Eu ¹ ² ² ² ¹ ² ¹ ²	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 28 Dy Dysprosium 28 182.500	67 28 Ho 29 Holmium 184.93032	68 28 Er 30 Erbium 2 167.259	69 28 Tm 31 Thulium 2 168.93421	70 Yb ¹ ¹ ³ ¹ ³ ¹ ³	² ² ² ² ² ² ² ¹⁸ ¹⁸ ³² ⁹ ² ¹⁸ ¹⁸ ²⁹ ² ¹⁸ ¹⁸ ¹⁸ ¹⁸ ²⁹ ² ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰
	com		89 ² Ac ¹⁸ Actinium ⁹ (227)	90 28 Th 18 10 232.03806	91 28 28 28 28 28 28 28 28 28 28 28 28 28	92 U Uranium 238.02891	⁸ ¹⁸ ²² ⁹ ⁹ ¹⁹ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰ ¹⁰	² ⁸ ⁹ ⁹ ⁹ ⁹ ⁹ ⁹ ¹ ¹ ¹ ² ¹ ² ¹ ²	² Am ³ ² ² ² ³ ² ³ ² ³ ² ³ ² ³ ² ³ ² ³ ² ³ ² ³ ² ³ ² ³ ² ³ ² ³ ² ³ ² ³ ³ ² ³ ³ ³ ² ³ ³ ³ ³ ³ ³ ³ ³	96 Cm ¹ ²² ²⁴⁷	97 Bk 37 Berkelium 2 (247)	98 2 Cf 32 Californium 2 (251)	99 28 ES 18 29 Einsteinium 8 (252)	100 2 Fm 30 Fermium 2 (257) 2	101 2 Md 32 18 31 Mendelevium 2 (258)	102 No 33 Nobelium (259)	² ² ² ² ² ² ² ² ² ²

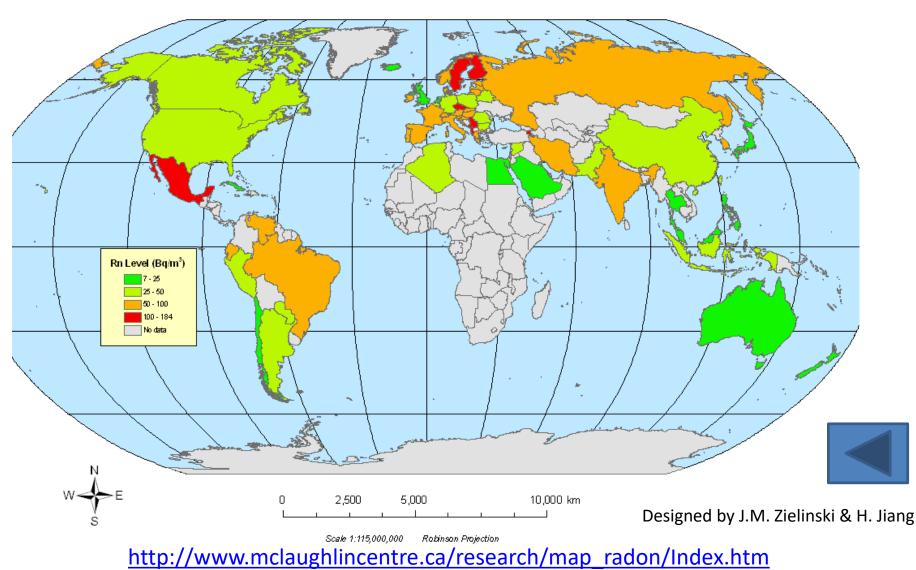






Arithmetic Mean Radon Level by Country

(Based on Data up to 2007)





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					



Classification of radiological areas at CERN

CERN

	A	Dose	Ambient do rate	ose equivalent			
	Area	limit [year]	Work place	Low occupancy	Sign		
	Non- designated	1 mSv	0.5 µSv/h	2.5 µSv/h	Dosimeter obligatory E Radiation Protection Dosimètre obligatoire E 2		
Radiation Area	Supervised	6 mSv	3 µSv/h	15 µSv/h	Dosimeter obligatory Carlos Radiation Protection Dosimètre obligatoire		
	Simple	20 mSv	10 µSv/h	50 µSv/h		G	
	Limited Stay	20 mSv		2 mSv/h		ed Area	
	High Radiation	20 mSv		100 mSv/h	HIGH RADIATION HAUTE RADIATION Dosimeters obligatory Dosimètres obligatoires	Controlled	
	Prohibited	20 mSv		> 100 mSv/h	PROHIBITED AREA ZONE INTERDITE No Entry Défense d'entrer	J	



From the 15th of March 2021, the Radiation Protection Group is implementing a new signage scheme for radiation areas to better visualise the level of the radiological risk

		Supervised Area	Simple Controlled Area	Limited Stay Controlled Area	High Radiation Controlled Area	Prohibited Controlled Area
Old signs for Radiation Areas		RADIATION ZONE SURVEILÉE Dosimister obligatory Dosimistre obligatory	RADIATION	RADIATION	RADIATION ZONE CONTRÔLÉE HIGH RADIATION HAUTER RADIATION Desimètres obligatoires Cosimètres obligatoires	RADIATION
New signs for	RADIATION	RADIATION SUPERVISED AREA ZONE SURVEILLÉE	RADIATION CONTROLLED AREA ZONE CONTROLES IMPLEMENTE CONTROLES IMPLEMENTE CONTROLES INTO	RADIATION	RADIATION CONTROLLED AREA CONTROLLED AREA CONTROLLED MEMORY ADDATON MEMORY ADDATON	RADIATION PROHIBITED AREA ZONE INTERDITE NO ENTRY DEFENSE D'ENTRER 💓 🕿
Radiation Areas	RADIATION / CONTAMINATION		CONTROLLED AREA CONTROLLED AREA CONCONTROLES BURGE CONTROLES BURGE CONTROLES CONTROLES CONTROLES BURGE CONTROL CONTROL DE CONTROLES BURGE	CONTROLLED AREA ZONE CONTROLES LINE STATUS	RADIATION CONTAMINATION CONTROLLED AREA ZONE CONTROLES	



- 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







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









- 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





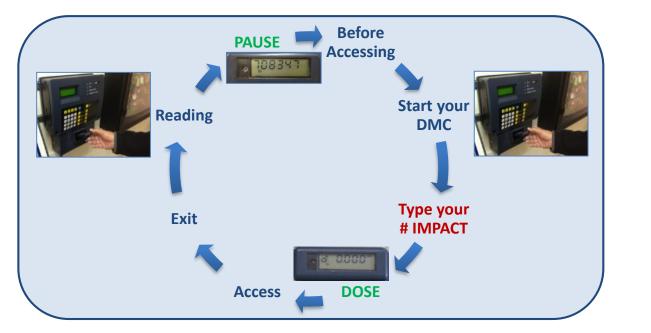


- Obligation to wear an operational dosimeter in a controlled area
- Continuous $\beta\gamma$ -dose measurement
- Instrument: DMC
- Display of Hp(10) (resolution of 1 μSv)
- Dose alarm at 2 mSv
- Dose rate alarm at 2 mSv/h
- Audible detection signal (« bip »)
- Record the dose before and after the operation

















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, ...)