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
Hundred years ago

The discovery of radiation

**Henri Becquerel (1852-1908)**

1896

Discovery of natural radioactivity

1898

Discovery of polonium and radium

Thesis of Mme. Curie – 1904

$\alpha$, $\beta$, $\gamma$ in magnetic field

**Marie Curie (1867 – 1934)**

**Pierre Curie (1859 – 1906)**
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# Periodic Table of Elements

Following is the periodic table of elements. The elements are arranged in order of increasing atomic number, with the exception of groups 1 and 2, which are arranged by increasing atomic number within their group. The table includes the following:

- **Atomic Number**: The number of protons in the nucleus of an atom.
- **Symbol**: The abbreviation used to represent the element.
- **Name**: The name of the element.
- **Group**: The vertical column to which the element belongs.
- **Period**: The horizontal row to which the element belongs.
- **Electron shell**: The principal energy level of the electron configuration.
- **Electronic configuration**: The arrangement of electrons in the atomic orbitals.
- **Mass number**: The sum of the protons and neutrons in the nucleus.
- **Isotopes**: Variants of an element with different numbers of neutrons.
- **Isotopes of the element**: A list of isotopes along with their mass numbers and natural abundance.

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

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Unstable (=radioactive) nuclides ~ 3000

Stable nuclides ~ 250

$\alpha$-decay

$\beta^+$: $p^+ \rightarrow n + e^+$

$\beta^-$: $n \rightarrow p^+ + e^-$

$\alpha$ : $^{A}X \rightarrow ^{A-4}Y + ^4\text{He}^{2+}$
Directly ionizing radiation:
- Fast charged particles (e.g., electrons, protons, alpha particles), which deliver their energy to matter directly, through many small Coulomb-force interactions along the particle’s track.

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

The deposition of energy in matter by indirectly ionising radiation is a two-step process:
- Photon → Electron
- Neutron → Proton or recoiling nuclei
Radioactivity: the phenomenon whereby atoms undergo spontaneous random disintegration, usually accompanied by the emission of ionising radiation.

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

\[ A(t) = -\frac{dN}{dt} \text{ [Bq]} \]

\[ 1 \text{ Bq} = s^{-1} \]

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

The radioactive half-life \( (T_{1/2}) \) 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)
PHOTONS
- Electromagnetic radiation
- Energy: a few keV to a few MeV
- Very penetrating
- Radiological hazard only by external irradiation

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

HEAVY CHARGED PARTICLES (protons, ions)
- External irradiation
- Enhanced biological effect (high LET radiation)
Radioactivity and ionising radiation

$\beta$, $\gamma$-emitter

$^{22}$Na (2.6 yr.) Decay Scheme
- $^0_{22}$Na $\rightarrow$ $^{22}$Ne $+$ $^0_{\beta}$ + $\gamma$-ray
- $Q$ = 2841.2 MeV
- $2^+$ $\rightarrow$ $1274.57$ MeV, 99.94%

$^{60}$Co (5.2 yr.) Decay Scheme
- $^0_{60}$Co $\rightarrow$ $^{60}$Ni $+$ $^0_{\beta}$ + $\gamma$-ray
- $Q$ = 2823.9 MeV
- $0^+$ $\rightarrow$ $1173$ MeV, 99.025%
- $2^+$ $\rightarrow$ $1332.52$ MeV, 0.057%

$^7$Be (53 day) Decay Scheme
- $^0_{7}$Be $\rightarrow$ $^7$Li $+$ $^0_{\beta}$ + $\gamma$-ray
- $Q$ = 861.815 MeV
- $1/2^-$ $\rightarrow$ $1177$ MeV, 10.52%
- $3/2^-$ $\rightarrow$ $1177$ MeV, 89.48%

Pure $\beta$-emitter

Tritium $\rightarrow$ $^3$He $+$ $^0_{\beta}$ + $\gamma$-ray

$\alpha$, $\beta$- and $\gamma$ 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!

Beta sources are usually shielded with Plexiglas, gamma sources with lead.
Production and decay of radionuclides

For a given particle, target element and nuclide

- Interaction probability, $\sigma$ (*cross section*)
- Flux (spectrum), $\Phi$
- Beam intensity, $I_p$

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

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

\[ A = A_s \left(1 - e^{-t_{irr}/\tau}\right)e^{-t_{dec}/\tau} \]

It takes about 5 half-lives to reach saturation of activity.
The **absorbed dose** is the energy deposited by a given radiation in a unit mass of matter.

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

\[ 1 \text{ Gy} = 1 \frac{\text{J}}{\text{Kg}} \]

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

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

\[ H = Q \cdot D \]

\[ 1 \text{ Sv} = 1 \frac{\text{J}}{\text{Kg}} \]

\( Q \) = 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)
Periodic Table of Elements

\[ ^{219}\text{Rn} \text{ (Actinon)}, \ ^{220}\text{Rn} \text{ (Thoron) and} \ ^{222}\text{Rn} \text{ (Radon)} \]
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

Rn-222
3.82 d
5.5 MeV

Po-218
3.05 m
6.0 MeV

Bi-214
19.7 min
0.4-3.3 MeV

Pb-214
26.8 min
0.7, 1.0 MeV

Po-214
1.6E-4 s
7.7 MeV

Bi-210
5.0 d
1.2 MeV

Pb-210
22 y
<0.1 MeV

Po-210
138 d
5.3 MeV

Pb-206
Stable

Precursor
Worldwide radon risk

Arithmetic Mean Radon Level by Country
(Based on Data up to 2007)

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

Designed by J.M. Zielinski & H. Jiang
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)

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Symbol</th>
<th>Half-life</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium-235</td>
<td>$^{235}\text{U}$</td>
<td>$7.04 \times 10^8$ y</td>
<td>0.72% of natural Uranium</td>
</tr>
<tr>
<td>Uranium-238</td>
<td>$^{238}\text{U}$</td>
<td>$4.47 \times 10^9$ y</td>
<td>99.3% of natural Uranium</td>
</tr>
<tr>
<td>Thorium-232</td>
<td>$^{232}\text{Th}$</td>
<td>$1.41 \times 10^{10}$ y</td>
<td></td>
</tr>
<tr>
<td>Potassium-40</td>
<td>$^{40}\text{K}$</td>
<td>$1.28 \times 10^9$ y</td>
<td>Earth: 0.037-1.1 Bq/g</td>
</tr>
</tbody>
</table>

...and some more:

$^{50}\text{V}, \ 87\text{Rb}, \ 113\text{Cd}, \ 115\text{In}, \ ... \ 190\text{Pt}, \ 192\text{Pt}, \ 209\text{Bi}, \ ...$
Cosmogenic radionuclides are produced by nuclear reactions of cosmic particles with stable nuclei of the atmosphere

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

More cosmogenic radionuclides: $^{10}\text{Be}$, $^{26}\text{Al}$, $^{36}\text{Cl}$, $^{80}\text{Kr}$, ...
### The radioactivity inside our body

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Total activity in human body (~ 70 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium-40</td>
<td>~ 5 kBq</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>~ 3 kBq</td>
</tr>
<tr>
<td>Tritium</td>
<td>~ 20 Bq</td>
</tr>
<tr>
<td>Polonium-210</td>
<td>~ 18 Bq</td>
</tr>
<tr>
<td>Uranium</td>
<td>~ 1 Bq</td>
</tr>
<tr>
<td>Radium</td>
<td>~1 Bq</td>
</tr>
<tr>
<td>Thorium</td>
<td>~ 0.1 Bq</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>~ 8 kBq</td>
</tr>
</tbody>
</table>
Cosmic radiation exposure versus altitude

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

- **ISS** 400 km: 20 - 30 μSv/h
- **15 km**: 10 μSv/h
- **10 km**: 5 μSv/h
- **7 km**: 1 μSv/h
- **5 km**: 0.15 μSv/h
- **Lhasa, Tibet 3.7 km**: 0.10 μSv/h
- **Mexico City, Mexico 2.25 km**: 0.10 μSv/h
- **Jura ridge 1.0 km**: 0.10 μSv/h
- **Geneva 0.38 km**: 0.10 μSv/h

Courtesy PTB, Braunschweig
Daily natural background radiation: 2-3 $\mu$Sv

Average annual dose for aircrew: 3 mSv

Max annual dose for occupationally exposed workers: 20 mSv

Chest x-ray: 10 $\mu$Sv

CT scan: up to 10 mSv

Dose per fraction in RT: 2 Sv

Estimated dose absorbed by the Russian spy Litvinenko: 18 Sv
Times change... This is what we had in the past!
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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 CH₃) 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)

Primary particle track

delta rays

Water radicals attack the DNA

OH•

Light damage - reparable

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 depend on the amount of absorbed dose
- delayed health detriment

**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

Cell membranes

indirect effects

$H_2O \rightarrow OH^+ \rightarrow H^+$

free radicals 

peroxydes, active substances 

no-repair 

uncontrolled cell death (necrosis)

deterministic

hereditary effects

annual, day, year, generation

cancer

programmed cell death (apoptosis)

mis-repair 

uncontrolled cell death (necrosis)

repair 

normal cell survival 

stochastic

direct effects

IONISATION

excitation

$OH^+$

no-repair 

repair

normal cell survival

biomolecule 

DNA lesions

uncontrolled cell death (necrosis)

deterministic

second, minute

day, year, generation

field 

physics 

chemistry 

biochemistry

time scale 

$10^{-16}s$ 

$10^{-6}s$ 

$10^{-2}s$

normal cell survival

uncontrolled cell death (necrosis)

programmed cell death (apoptosis)

hereditary effects

annual, day, year, generation
## The biological actions of radiation

<table>
<thead>
<tr>
<th>Step</th>
<th>Time of appearance</th>
<th>Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>$\sim 10^{-16}$ s</td>
<td>Energy deposition by ionisation and excitation of the atoms</td>
</tr>
<tr>
<td>Physico-chemical</td>
<td>$\sim 10^{-10}$ s</td>
<td>Production of chemical compounds (ions radicals) which diffuse in the cell</td>
</tr>
<tr>
<td>Chemical</td>
<td>$\sim 10^{-6}$ s</td>
<td>Production of molecular lesions in the DNA</td>
</tr>
<tr>
<td>Cellular</td>
<td>$\sim$ hours</td>
<td>Lesions at cellular level and cell repair involvement</td>
</tr>
<tr>
<td>Deterministic effects</td>
<td>$\sim$ weeks</td>
<td>Expression of dysfunctions at the tissues and organs level</td>
</tr>
<tr>
<td>Stochastic effects</td>
<td>$\sim$ tens of years</td>
<td>Cancer induction and induction of heritable disorders</td>
</tr>
</tbody>
</table>
Lethal dose ($LD_{50/30}$) for various organisms

Source: Martin Volkmer, Radioaktivität und Strahlenschutz, Informationskreis Kernenergie
## LD50 and effect of acute irradiation to humans

<table>
<thead>
<tr>
<th>Whole body dose (Gy)</th>
<th>Organ or tissue failure responsible for death</th>
<th>Time at which death occurs after exposure (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-5</td>
<td>Bone marrow</td>
<td>30-60</td>
</tr>
<tr>
<td>5-15</td>
<td>Intestine and lungs</td>
<td>10-20</td>
</tr>
<tr>
<td>&gt;15</td>
<td>Nervous system</td>
<td>1-5</td>
</tr>
</tbody>
</table>

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

any exposure of persons to ionizing radiation has to be justified

2) **Limitation**

the personal doses have to be kept below the legal limits

3) **Optimization**

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

Physical quantities

- Fluence, \( \Phi \)
- Kerma, \( K \) (gray)
- Absorbed dose, \( D \) (gray)

Dose equivalents calculated using absorbed dose and \( Q_L \) and simple phantoms (sphere or slab), validated by measurements and calculations.

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

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.

Protection quantities

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

Comparison using the measured and calculated values to establish relationship

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

Radiological quantities and units

Absorbed Dose $D$: energy absorbed per mass
   Unit: Gy
   \[ 1 \text{ Gy} = 1 \text{ J/kg} \]
   \( (1 \text{ Gy} = 100 \text{ rad}) \)

Equivalent Dose $H$: absorbed dose of organs weighted by the radiation weighting factor $w_R$ of radiation $R$:
   Unit: Sv
   \( (1 \text{ Sv} = 100 \text{ rem}) \)

Effective dose $E$: Sum of all equivalent doses weighted with the weighting factor $w_T$ for tissue $T$
   Unit: Sv
   \( (1 \text{ Sv} = 100 \text{ rem}) \)

\[
D = \frac{1}{m} \int EdV
\]

\[
H_T = \sum_R w_R D_{T,R}
\]

\[
E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}
\]
### Radiation weighting factors, $W_R$

<table>
<thead>
<tr>
<th>Type and energy of radiation $R$</th>
<th>$W_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons, all energies</td>
<td>1</td>
</tr>
<tr>
<td>Electrons and muons, all energies</td>
<td>1</td>
</tr>
<tr>
<td>Protons and charged pions</td>
<td>2</td>
</tr>
<tr>
<td>Alpha particles, fission fragments, heavy ions</td>
<td>20</td>
</tr>
</tbody>
</table>

#### Neutrons

The radiation weighting factor for neutrons, $W_R$, is given by:

$$W_R = \begin{cases} 
2.5 + 18.2 \ e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\
5.0 + 17.0 \ e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leq E_n \leq 50 \text{ MeV} \\
2.5 + 3.25 \ e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} 
\end{cases}$$
### Tissue sensitivity and tissue weighting factors, $W_T$

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

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

Dose equivalent (mSv)

Year


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

Annual occupational limit

Annual public limit

ICRP

ICRP 60

ICRP 103

M. Curie

Roentgen

30 Sv

700 mSv

300 mSv

150 mSv

50 mSv

20 mSv

5 mSv

1 mSv
Radiological risks

External radiation source → external exposure

Contamination

Surface

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

<table>
<thead>
<tr>
<th>Area</th>
<th>Dose limit [year]</th>
<th>Ambient dose equivalent rate Work place</th>
<th>Low occupancy</th>
<th>Sign</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-designated</td>
<td>1 mSv</td>
<td>0.5 µSv/h</td>
<td>2.5 µSv/h</td>
<td></td>
</tr>
<tr>
<td>Supervised</td>
<td>6 mSv</td>
<td>3 µSv/h</td>
<td>15 µSv/h</td>
<td></td>
</tr>
<tr>
<td>Simple</td>
<td>20 mSv</td>
<td>10 µSv/h</td>
<td>50 µSv/h</td>
<td></td>
</tr>
<tr>
<td>Limited Stay</td>
<td>20 mSv</td>
<td></td>
<td>2 mSv/h</td>
<td></td>
</tr>
<tr>
<td>High Radiation</td>
<td>20 mSv</td>
<td></td>
<td>100 mSv/h</td>
<td></td>
</tr>
<tr>
<td>Prohibited</td>
<td>20 mSv</td>
<td></td>
<td>&gt; 100 mSv/h</td>
<td></td>
</tr>
</tbody>
</table>
How you can protect yourself from radiation?
How to reduce external exposure

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 \( D = \frac{dD}{dt} \times t \)

- **Shielding**: the dose rate approximately reduces as \( \exp(-d/\lambda) \)

\( \lambda \) = shielding properties of the material

For \( \beta \) radiation: plexiglass
For \( \gamma \) 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 on 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
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

Personal dosimeter: "Legal dose"

Kodak film badge

Quartz-fiber dosimeter (ionisation chamber and electroscope)

Operational dosimeter DMC: “Operational dose”

Finger dosimeter

RADOS DIS
Personal dosimetry at CERN

- 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
Operational dosimetry at CERN

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

Before Accessing

Start your DMC

Type your # IMPACT

Read Access

Exit

PAUSE

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
Radioactive contamination at particle accelerators

- 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
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 quantities and dose limits

- **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.
Personal protection equipment against contamination

For low level contamination / low risk

« Tyvek » overall
(synthetic paper)

Rubber gloves

... generally completed by overshoes
Personal protection equipment against contamination

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
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 quantities
– Principles of radiation protection
  – Justification, optimization and dose limitation
  – 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.
Ionization chamber

Output

High voltage

= C

insulator

anode

cathode
Scintillating crystal coupled to a PMT

From Glenn F. Knoll, Radiation Detection and Measurement
AUTOMESS dose rate meter 6150 AD6

AD17 external probe

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

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

- APA
- CMS2000
- ABPM203M
- Air contamination monitors
- Hand and foot monitor
Whole body counting
Some elements have a very large cross section for slow neutrons and can be exploited for neutron detection.

1) Boron
\[ ^{10}\text{B} + \text{n} \rightarrow ^{7}\text{Li} + \alpha \quad \text{Q} = 2.793 \text{ MeV} \]
\[ ^{10}\text{B} + \text{n} \rightarrow ^{7}\text{Li}^* + \alpha \quad \text{Q} = 2.310 \text{ MeV} \]

2) Lithium
\[ ^{6}\text{Li} + \text{n} \rightarrow ^{3}\text{H} + \alpha \quad \text{Q} = 4.78 \text{ MeV} \]

3) $^{3}\text{He}$
\[ ^{3}\text{He} + \text{n} \rightarrow ^{3}\text{H} + \text{p} \quad \text{Q} = 764 \text{ keV} \]
Neutron cross sections

Mean free path of thermal neutrons
- in $^3\text{He}$ gas ≈ 7 cm
- in solid $^{10}\text{B}$ ≈ 70 µm
Moderator-type neutron detector

Courtesy S. Agosteo, Politecnico di Milano
Proportional counters for slow neutron detection

BF$_3$ gas and $^3$He gas make detectors for slow neutrons with excellent gamma discrimination.

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

A suitable pulse amplitude threshold can thus eliminate most gamma interactions.
The shape of the pulse height spectrum is due to the energy loss of the recoils in the gas.

- **Wall effect’ continuum**
- **Reaction product full-energy peak**
- **Low-energy event cut**
Rem counters

Studsvik 2202D

Berthold LB6411 (also LB6411Pb)

Eberline WENDI-2

MAB SNM500(X)
Environmental monitoring

- **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, $E < \text{some GeV}$)

**Alarm function**

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

**Air filled ionization chamber**

**No alarm function**
Operational radiation protection monitoring

Site Gate Monitor

Reading of radiation levels directly available

Radiation Alarm Unit (RAMSES)
Radiation alarm display

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

ORANGE flashing light + SOUND
WARNING ➔ Limited stay

RED flashing light + SOUND
ALARM ➔ Evacuation of the area
Passive environmental monitoring

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, 4\textsuperscript{th} 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
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
  - $\alpha$ – 4.270 MeV (4.47E9 years)
  - $\beta$ – 0.273 MeV (24.1 hour)
  - $\beta$ – 2.197 MeV (6.7 hour)
  - $\alpha$ – 4.859 MeV (245500 years)
  - $\alpha$ – 4.770 MeV (75380 years)
  - $\alpha$ – 4.871 MeV (1602 years)
  - $\alpha$ – 5.590 MeV (3.82 days)
  - ...