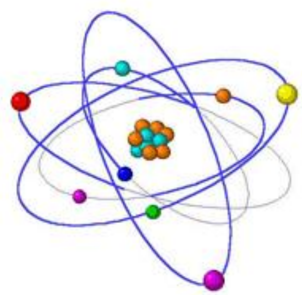
Introduction to Nuclear Engineering
ME 464



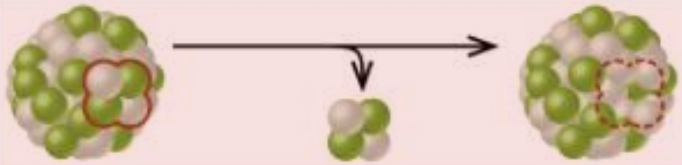
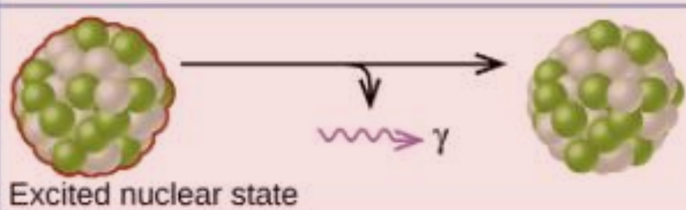
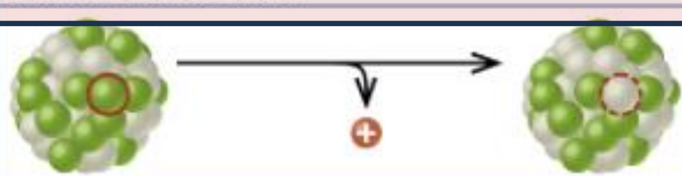
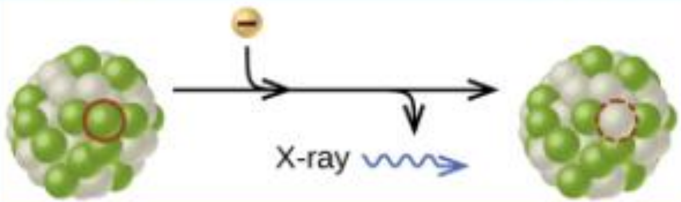
Radiation protection

15.05.2024

Radiation Protection: Outline

- ❑ Interaction of radiation with matter
- ❑ Concept of Dose, absorbed, equivalent and effective
- ❑ Origin of an average annual effective dose
  - Radionuclides in the environment
- ❑ Interaction of radiations with biological systems
  - Effect of radiations on DNA
- ❑ Radiation Shielding and Protection

Main Types of Radiation

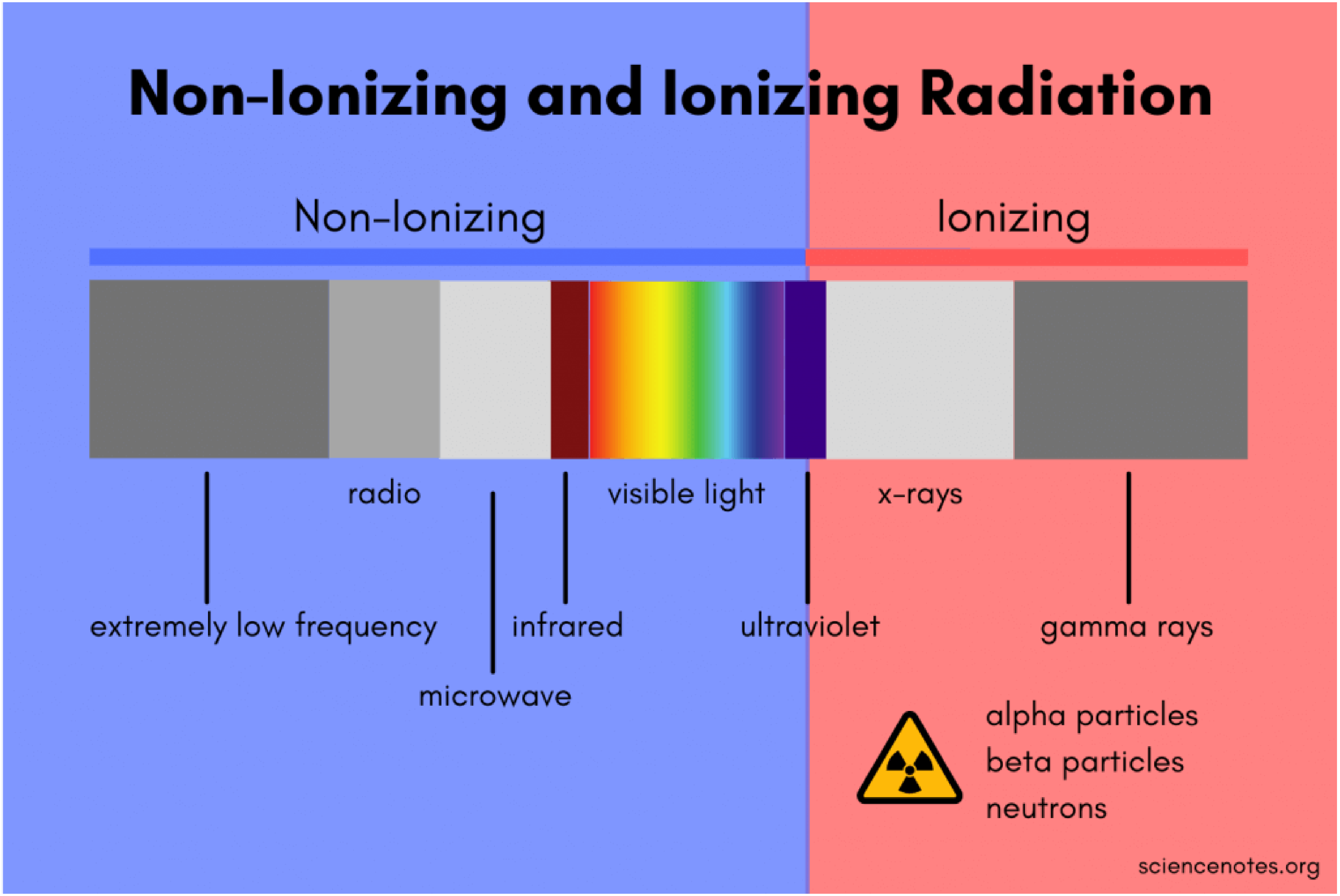
Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	${}^{A}_{Z}X \quad {}^{4}_{2}He + {}^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	${}^{A}_{Z}X \quad {}^{0}_{-1}e + {}_{Z+1}^{A}Y$		A: unchanged Z: increase by 1
Gamma decay	${}^{A}_{Z}X \quad {}^{0}_{0}\gamma + {}^{A}_{Z}Y$		A: unchanged Z: unchanged
Positron emission	${}^{A}_{Z}X \quad {}^{0}_{+1}e + {}_{Y-1}^{A}Y$		A: unchanged Z: decrease by 1
Electron capture	${}^{A}_{Z}X \quad {}^{0}_{-1}e + {}_{Y-1}^{A}Y$		A: unchanged Z: decrease by 1

Interaction of Radiation with Matter

- There are four general types of radiation generated in nuclear and atomic processes:

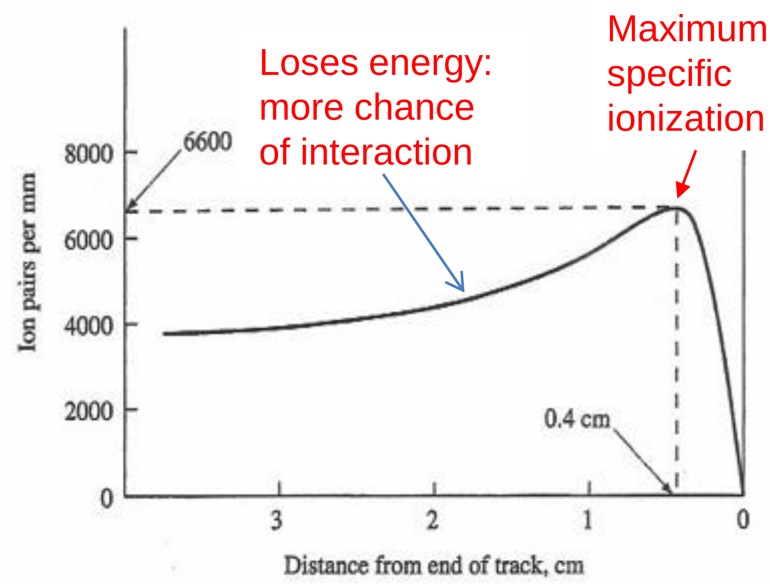
  - **Charged particles:**
    - Fast electrons: *beta*$^+$ and *beta*$^-$ from nuclear decay.
    - Heavy charged particles: all energetic ions with A ≥1 (p^+, alpha^{2+}, fission products, nuclear reaction products)

  - **Uncharged particles:**
    - Electromagnetic radiation: photons, X-rays (from electron transitions between atomic shells), gamma-rays (from nuclear transitions)
    - Neutrons: slow and fast (generated in nuclear reactions.)

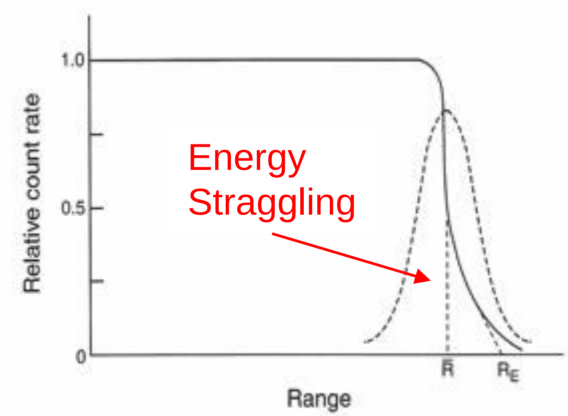

Non-Ionizing and Ionizing Radiation
Non-Ionizing
Ionizing
radio
visible light
x-rays
extremely low frequency
infrared
ultraviolet
gamma rays
microwave
alpha particles
beta particles
neutrons
sciencenotes.org

Interaction of Alpha (and Heavy Charged) Particles

- Alphas lose energy primarily by **ionizing** the atoms in the medium (i.e. energy is transferred to electrons).
- The specific ionization (number of ion-electron pairs created per cm) of alpha particles follows a **Bragg curve**.
- The range *R* is well defined and relatively abrupt, as the alpha particle continues to penetrate (with gradually lower energy) until it is finally stopped
- Rang of few cm in standard air



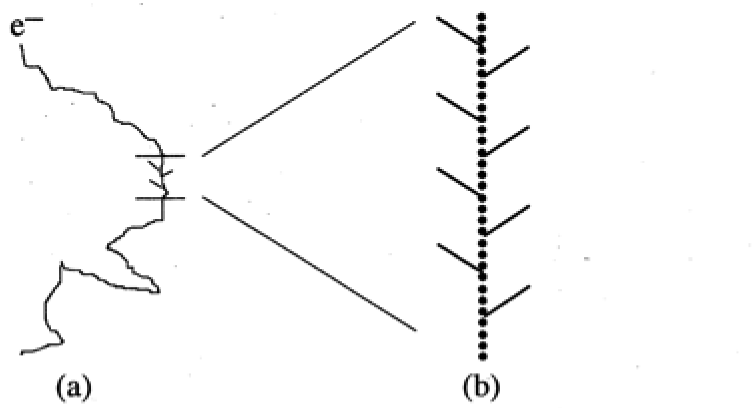
Specific ionization of an α-particle in air.



Range in air of a collimated monoenergetic source of alpha particles showing straggling that is normally distributed about the mean range at $\bar{R}$. An extrapolated range, R_E, can be obtained by extending the straight-line portion of the curve to the *x*-axis.

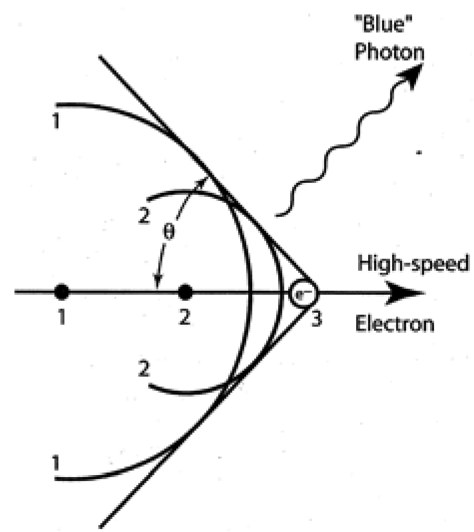
Interaction of Beta Particles with Matter

- Beta particles lose energy mostly by **ionization**
  - Direct ionization (main mechanism)
  - “Delta” rays from electrons ejected by ionization.
  - Beta particle paths are tortuous:



(a) Range and ionization path of a beta particle in an absorbing medium; (b) amplified segment of ionization track showing delta ray tracks produced by ejected electrons.

- At higher energies other mechanism become relevant:
  - **Bremsstrahlung** - occurs when beta particles are decelerated or deflected by the electric fields of nuclei in the medium, resulting in the emission of X-rays
  - **Cherenkov radiation** caused by high-speed beta particles in media if (v/c)>(1/n), n=refractive index of the medium.



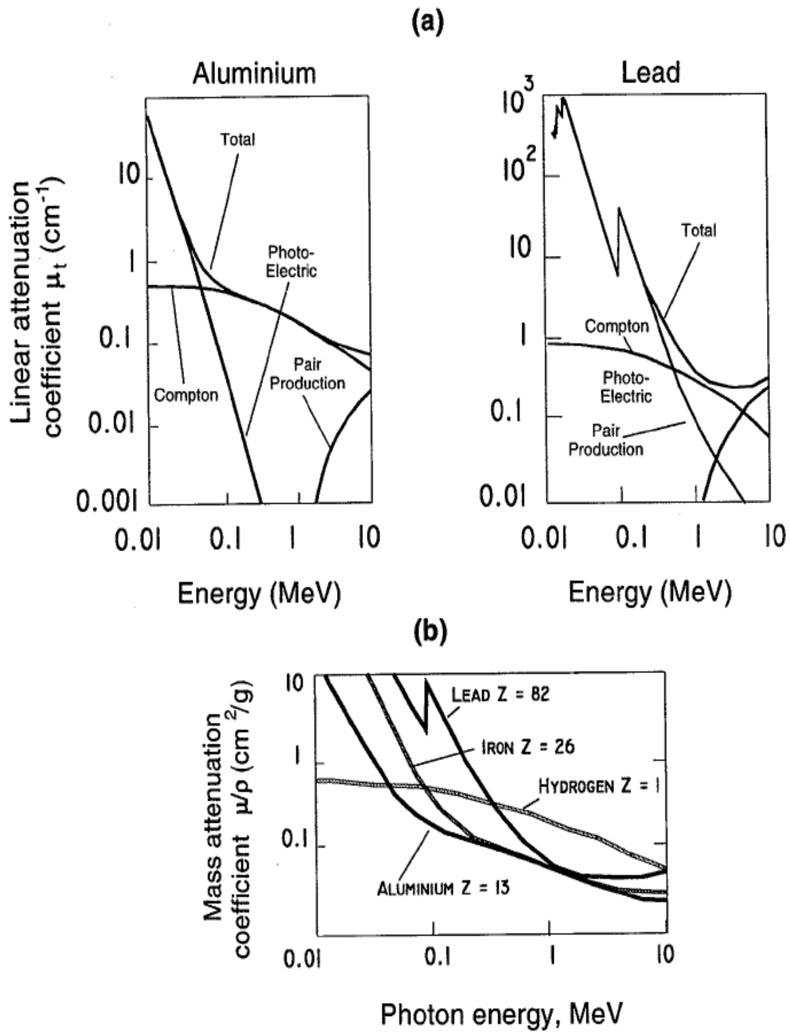
Wavefronts produced by a particle with velocity ≥ c/n constructively interfere to produce blue photons of light, or Cerenkov radiation.

Interaction of Photons with Matter

- Photons lose energy interacting with matter **mainly** by:
  - **Photoelectric effect (E < 0.5 MeV) $\sigma_{pe} \sim Z^n/E^3$ (n=4-5)**
  - **Compton Scattering (E 0.5 - 1.0 MeV) $\sigma_C \sim Z/E$**
  - **Pair Production (E > 1.022 MeV) $\sigma_{pp} \sim Z^{2\cdot}/(E)$**

- Attenuation follows exponential law with attenuation coefficient: $\mu_{tot}=\mu_{pe}+\mu_C+\mu_{pp}$

$$I(x)=I_0\, e^{-\mu x}$$



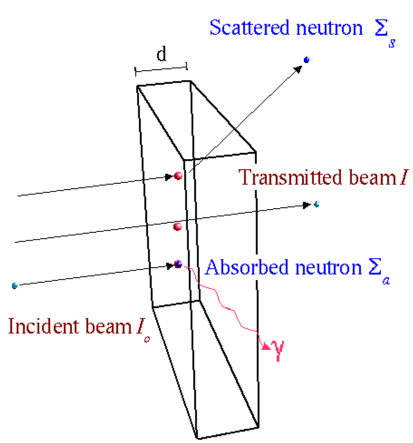
Total linear and mass attenuation coefficients (μ_t cm^{-1} and μ_m cm^2/g) for γ rays. (a) μ_t values for aluminium ($Z=13$, $\rho=2.70$ g/cm^3) and lead ($Z=82$, $\rho=11.3$ g/cm^3), showing the three mutually independent components. (b) The mass attenuation coefficient μ_m for the elements H, Al, Fe and Pb. Note the different function for hydrogen.

Neutron Interactions and Attenuation

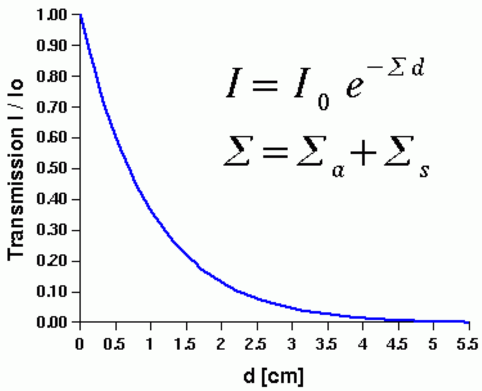
- Neutrons (n) interact with matter (nuclei) in many ways:
  - Elastic scattering: $^{A}Z(n,n)^{A}Z$; energy loss of *n* is highest for light nuclei
  - Inelastic scattering: $^{A}Z(n,n')^{A}Z^{*}$
  - Radiative capture: $^{A}Z(n,g)^{A+1}Z$
  - Nuclear reactions: $^{A}Z(n,p)$, $^{A}Z(n,a)$, $^{A}Z(n,2n)$, ...
  - Fission of heavy nuclei: $^{A}Z(n,f)$

Narrow Beam Attenuation

$$I = I_o e^{-\Sigma d}$$



Exponential Attenuation Law



Macroscopic Cross Section Σ

$$\Sigma = N\sigma \quad [cm^{-1}]$$

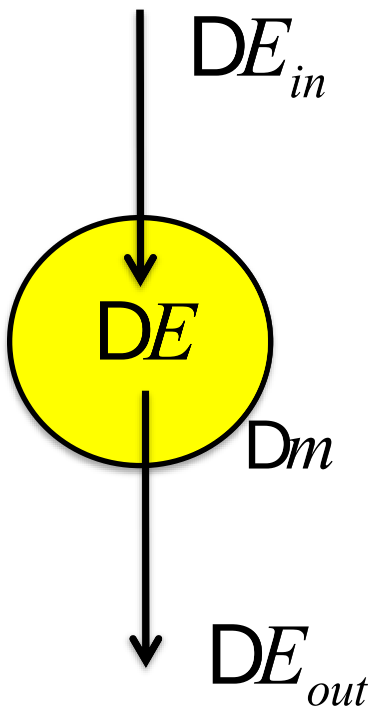
$$N = \frac{\rho}{A} N_A \quad [cm^{-3}]$$

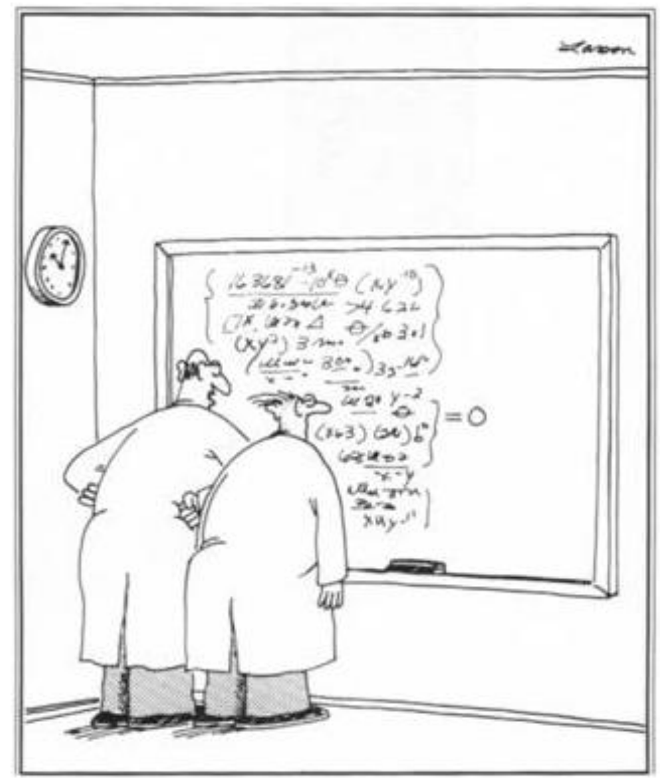
N := number density $[cm^{-3}]$
ρ := material density $[g\, cm^{-3}]$
A := atomic weight $[g\, mol^{-1}]$
N_A := Avogadro number $6.022\, 10^{23}\, [mol^{-1}]$

Radiation protection dosimetric quantities

- Absorbed dose:
  - Basic **physical quantity**
  - Energy deposited per unit mass
  - Unit: gray (1 Gy = 1 J/kg)

$$D = \lim_{Dm \to 0} \frac{DE}{Dm}$$





Exercise: absorbed dose

- What is the increase of temperature when 3.2 liters of water receive an absorbed dose of 1 Gy?

  a) c. 10 K

  b) c. 1 K

  c) c. 0.1 K

  d) c. 20 mK

  e) c. 0.1 mK

Exercise: absorbed dose

- What is the increase of temperature when 3.2 liters of water receive an absorbed dose of 1 Gy?

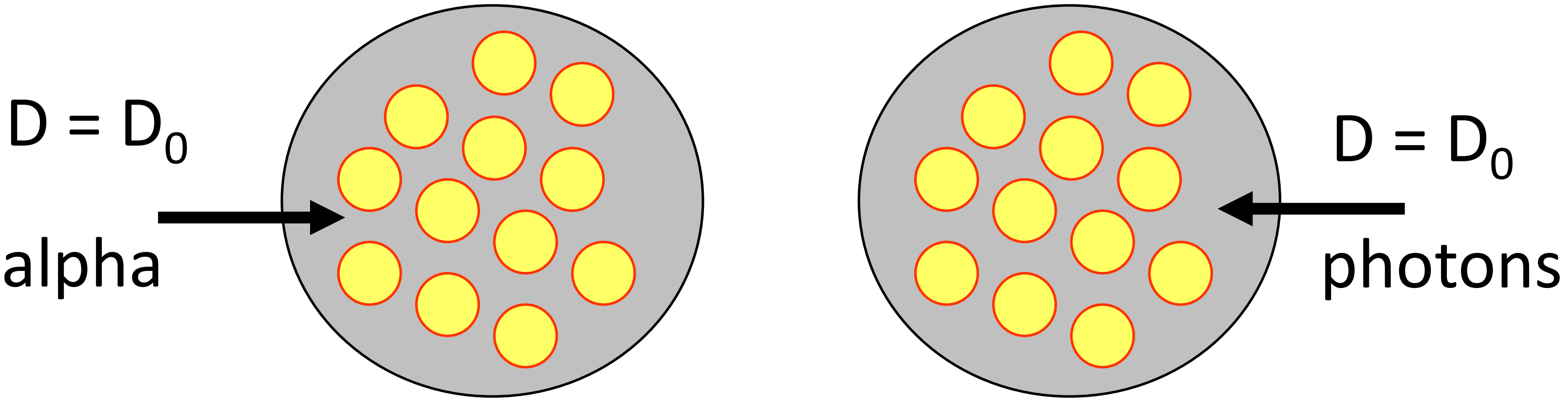
$$\Delta E = Dm = 1\ \mathrm{Gy}\ \times\ 3.2\ \mathrm{kg} = 3.2\ \mathrm{J}$$

$$\Delta T = \frac{\Delta E}{m\ c_p} = \frac{3.2\ \mathrm{J}}{3.2\ \mathrm{kg}\ \times\ 4181\,\frac{\mathrm{J}}{\mathrm{kg\ K}}} = 0.24\ \mathrm{mK}$$

$$\text{OR:}\ \ \Delta T = \frac{D}{c_p} = \frac{1\,\frac{\mathrm{J}}{\mathrm{kg}}}{4181\,\frac{\mathrm{J}}{\mathrm{kg\ K}}}$$

Exercise: dose and its biological effects

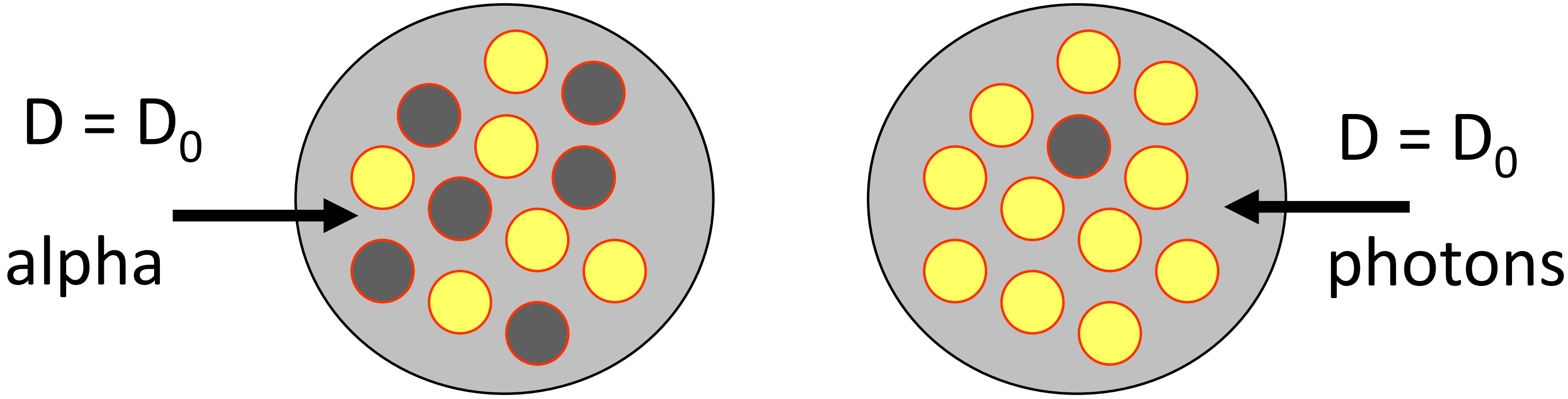
- For a given absorbed dose, what kind of radiation is the most damaging?



Exercise: dose and its biological effects

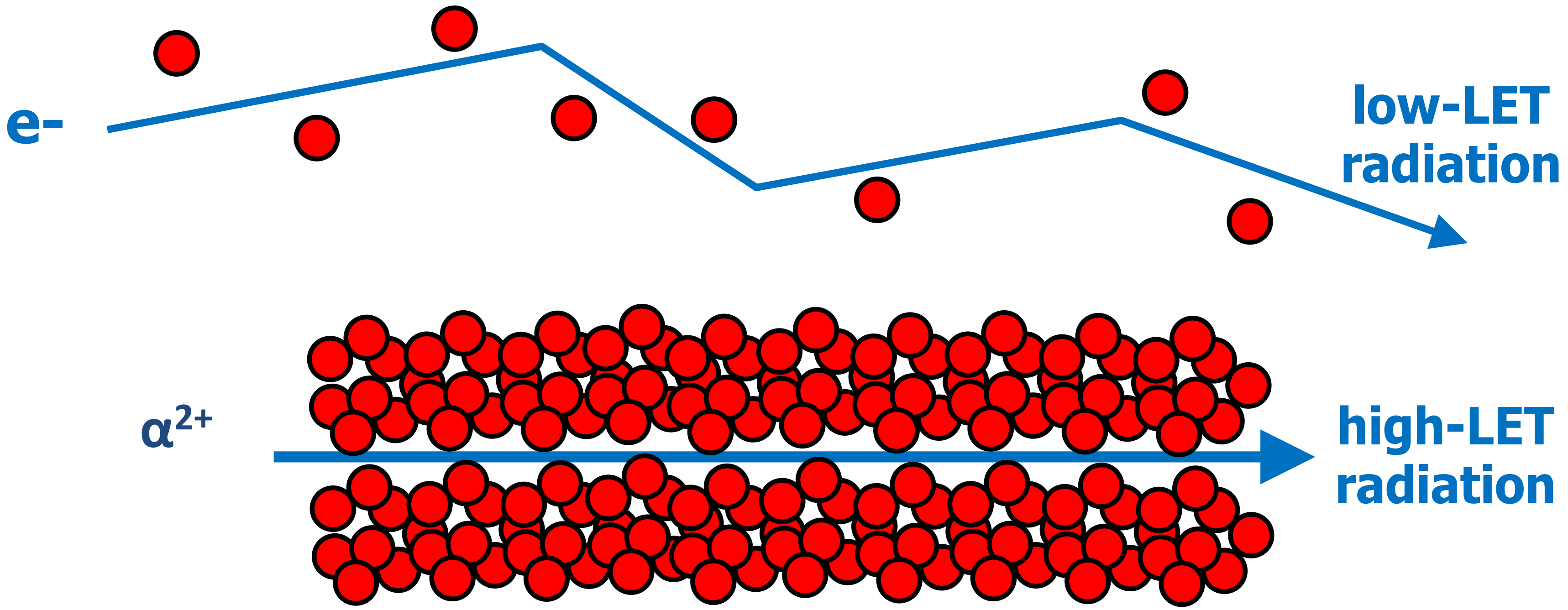
- For a given absorbed dose, what kind of radiation is the most damaging?

  - For a given absorbed dose **alpha particles** are **more damaging** than **photons** ➔ The absorbed dose is not always linked to the biological risk



Linear Energy Transfer (LET)

- LET explains the difference of biological efficiency

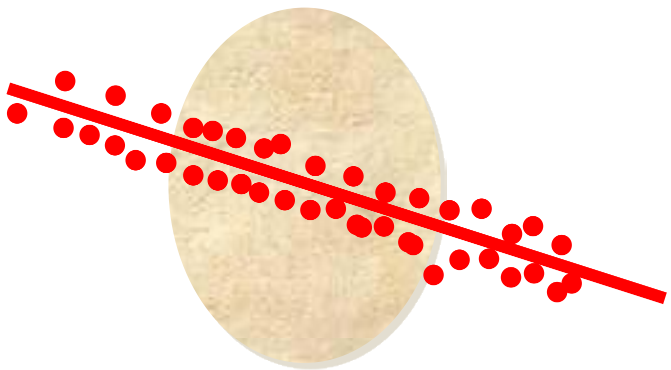


- LET: **linear energy transfer** (≈ dE_{coll}/dx)
  - Energy transferred through collision to the electrons of matter

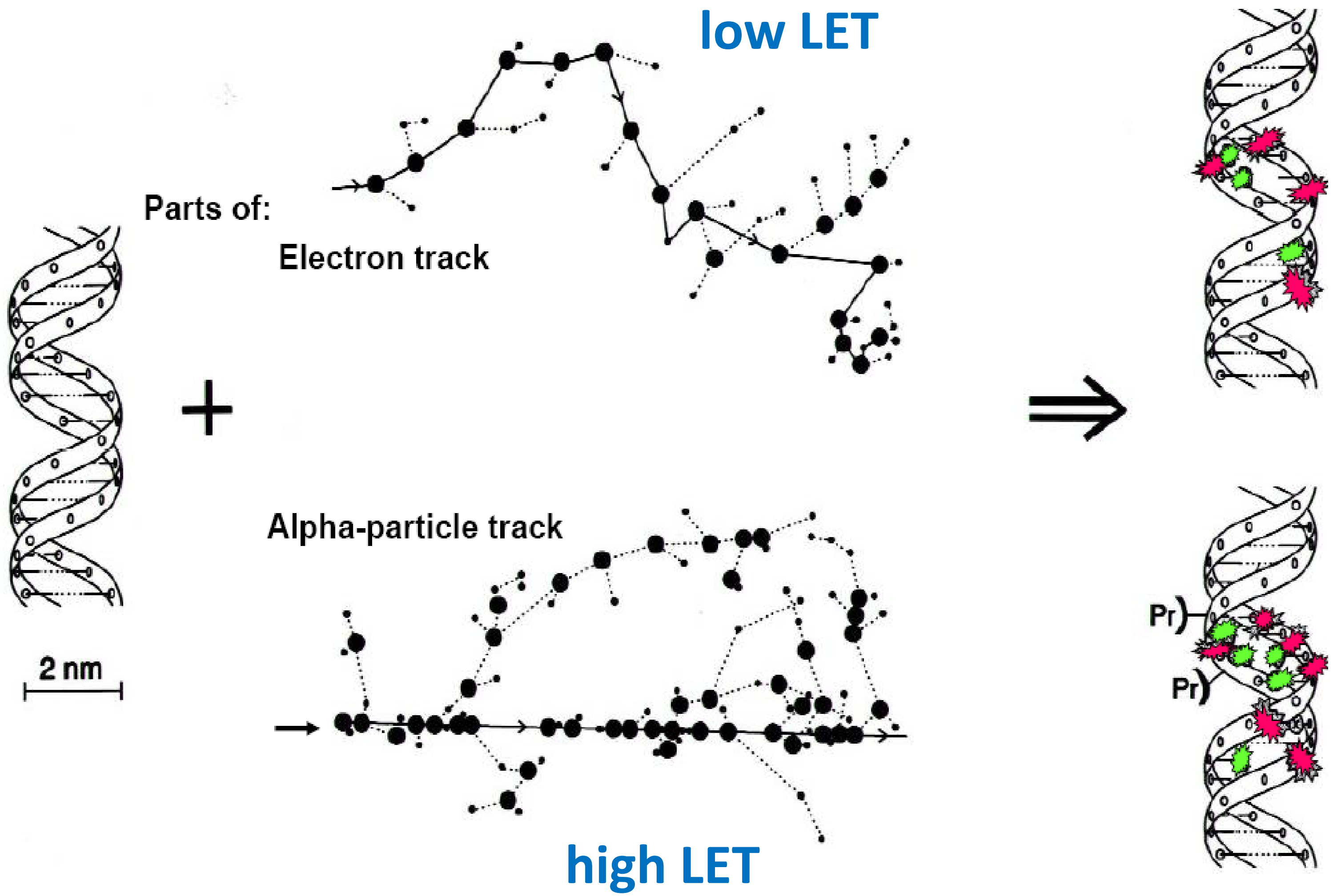
LET and biological effects

- Low LET radiation
  - Many cells lightly wounded
  - Recovery probable

- High LET radiation
  - Few cells highly injured
  - Lower probability to recover



LET and biological effects



Equivalent dose to an organ

- Radiation weighting (w_R) of the absorbed dose
  - Unit: **sievert** [Sv]

absorbed dose to the **organ T** delivered by the radiation of **quality R**

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

equivalent dose to organ T

radiation weighting factor

Radiation	w_R
Photons (all energies)	1
Electrons	1
Neutrons < 1MeV	2.5 + 18.2 exp(-ln(E)^2/6)
Neutrons > 1MeV, <50 MeV	5.0 + 17.0 exp(-ln(2E)^2/6)
Neutrons >50 MeV	2.5 + 3.25 exp(-ln(0.04E)^2/6)
Protons	2
Charged particles	20

Exercise

- A 2 MeV proton beam of intensity I=10^{10} proton/s/cm2 and a section S of 5 cm^2 is used in a radiotherapy facility. A technician of mass m 80 kg accidentally walk in front of the beam and stands there for 30s (t_{exp}).
- What are the doses (absorbed/equivalent) received by the technician?

Exercise

- A 2 MeV proton beam of intensity *I*=10^{10} proton/s/cm2 and a section *S* of 5 cm^2 is used in a radiotherapy facility. A technician of mass *m* 80 kg accidentally walk in front of the beam and stands there for 30s (t_{exp}).
- What are the doses (absorbed/equivalent) received by the technician?

$$D = E_P \cdot I \cdot S \cdot t_{exp} \, 1eV/m \qquad D = 6.10^{-3} Gy$$

$$H_T = w_T D \qquad H_T = 12 mSv$$

Effective dose (for stochastic, population level risk)

- Radiation weighting (w_T) of the absorbed dose to achieve full body dose estimate
- Unit: Sievert [Sv]

$$E = \sum_T w_T H_T$$

equivalent dose to organ T

weighting factor of organ T

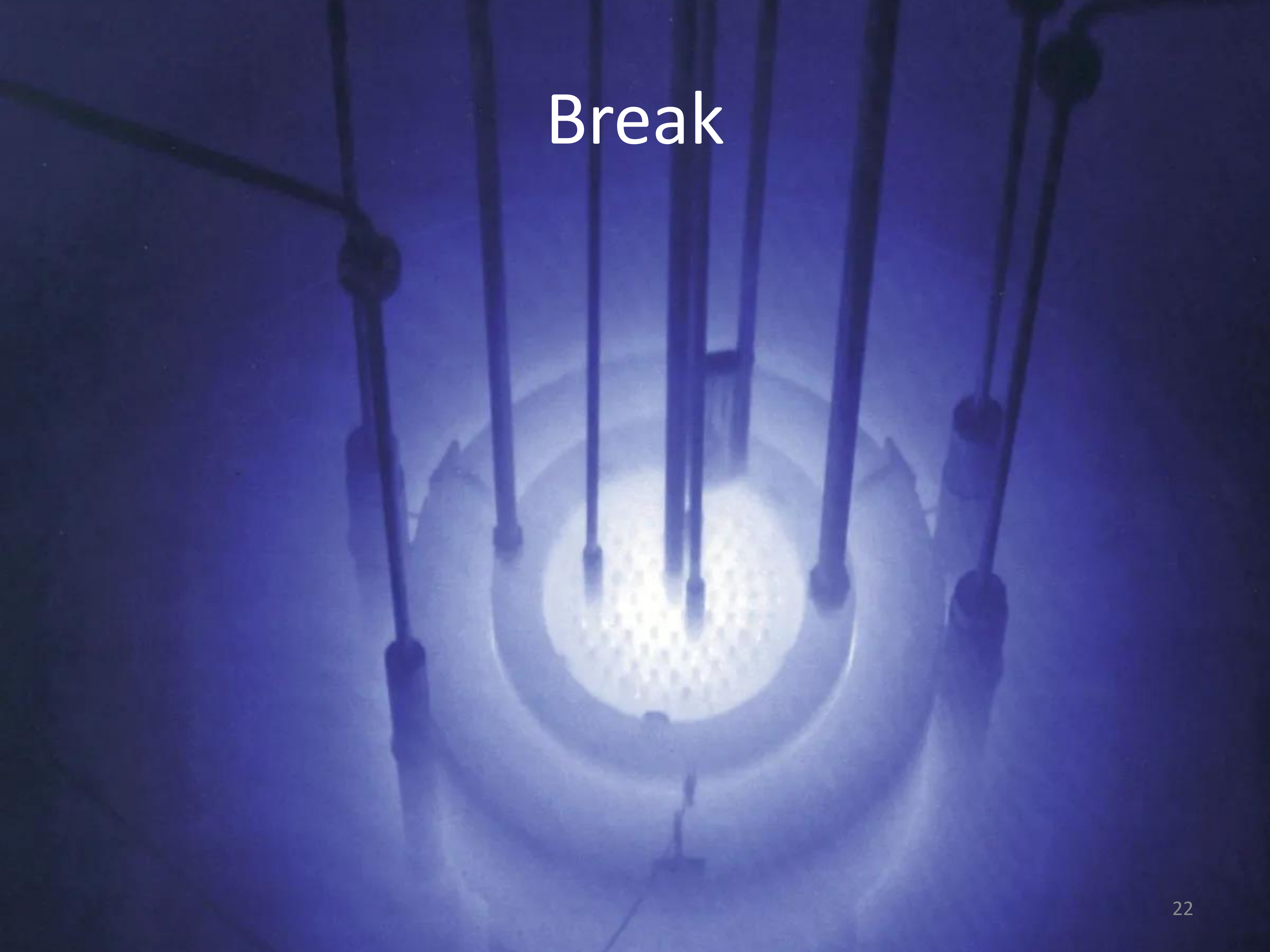
sex and age averaged

Table 3. Recommended tissue weighting factors.

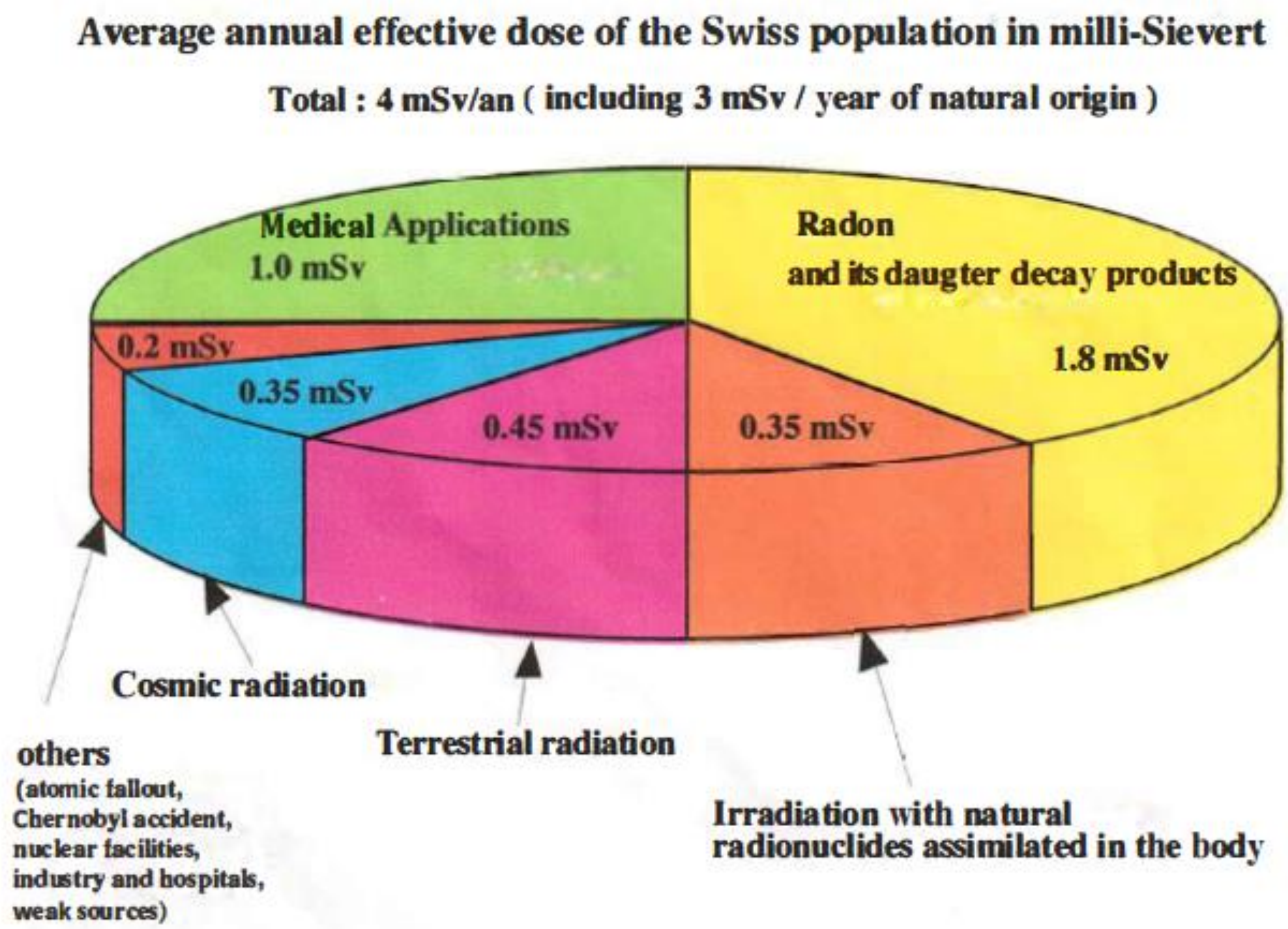
Tissue	Tissue weighting factor, w_T	Sum of w_T values
Bone-marrow (red), colon, lung, stomach, breast, remainder tissues[a]	0.12	0.72
Gonads	0.08	0.08
Bladder, oesophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04
Total		1.00

[a] Remainder tissues: Adrenals, extrathoracic (ET) region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, uterus/cervix (♀).

Break



Origin of an average annual effective dose



Ref. : *Radioactivité de l'environnement et doses de rayonnements en Suisse 2003* , Office fédéral de la santé publique, Division radioprotection, Section de surveillance de la radioactivité, ISBN 3-905235-44-7

Radionuclides in the Environment (1)

Cosmic rays and cosmogenic radionuclides

- Cosmic radiation includes high-energy protons and atomic nuclei (originate from the **Sun**, from **outside of the solar system** and from **distant galaxies)**

- Interaction of cosmic rays with atmosphere can produce radionuclides e.g.

  - ^{3}H from $^{14}N(n, t)\ ^{12}C$
  - ^{14}C from $^{14}N(n, p)\ ^{14}C$
  - ^{10}Be from interaction of p and n with ^{14}N and ^{16}O
  - ^{32}Si or ^{36}Cl from interaction of cosmic rays with ^{40}Ar

Radionuclides in the Environment (2)

Terrestrial radionuclides

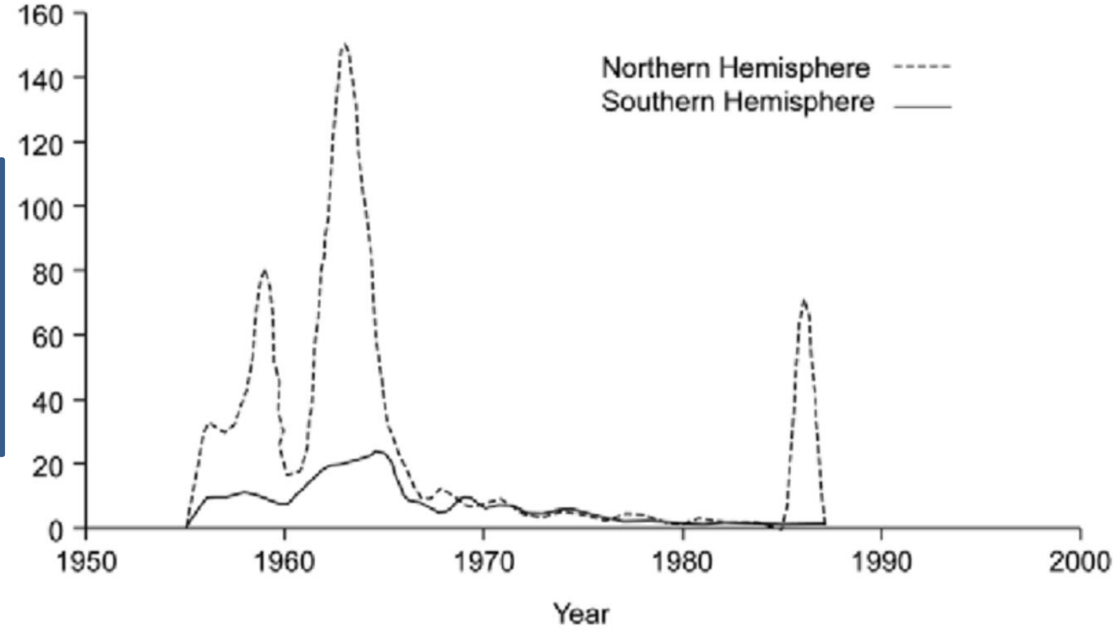
- Circa 70 naturally occurring radionuclides on Earth (most of them are heavy radioactive elements from the natural decay chains)

Decay series	Decay mode of the mother nuclide	Half-life of the mother nuclide [y]
$^{238}U \ldots ^{226}Ra \ldots ^{206}Pb$	α	$4.468 \cdot 10^9$
$^{235}U \ldots ^{207}Pb$	α (sf: $3.7 \cdot 10^{-7}$%)	$7.038 \cdot 10^8$
$^{232}Th \ldots ^{208}Pb$	α	$1.405 \cdot 10^{10}$

- Several important light elements, such as **H-3, C-14, K-40, etc.**

These radioactive species are ubiquitous, occurring in plants, animals, the air we breathe, the water we drink, the soil, etc. **For example**, in a 70 kg man one finds:

~ 4.4 kBq of K-40 & ~ 3.6 kBq of C-14.

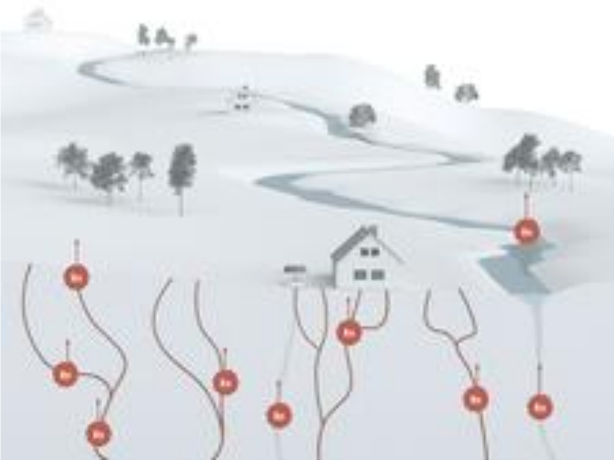

160
140
120
100
80
60
40
20
0
1950
1960
1970
1980
1990
2000
Year
Northern Hemisphere
Southern Hemisphere

Radionuclides in the Environment (3)

Radionuclides in food

- All foods contain natural radionuclides. The natural radioactivity in foods contributing to the radiation exposure to humans is mainly caused by the **K-40** and the long-lived radionuclides of the uranium-radium decay chain and the thorium decay chain.

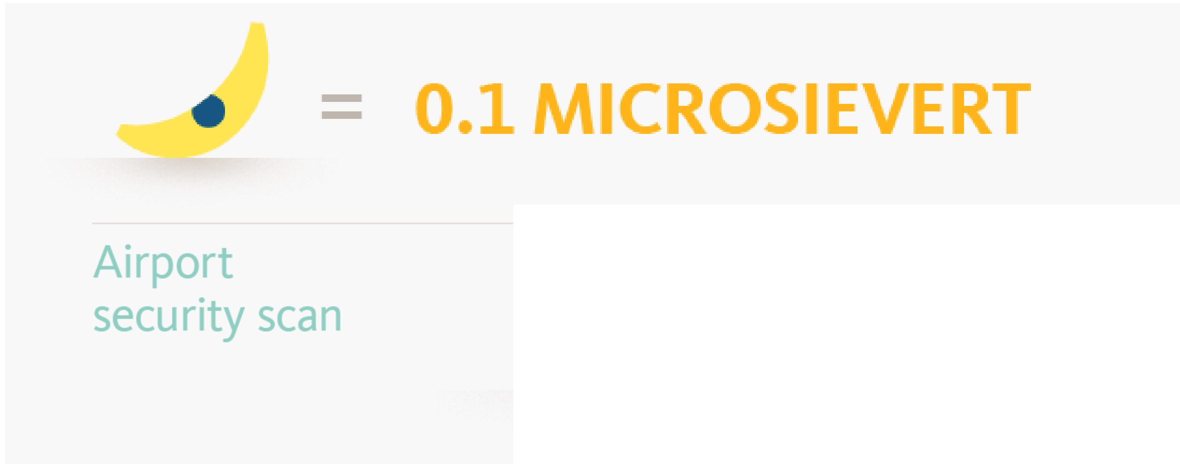
...
U-238,
U-234,
Ra-226,
Ra-228,
Pb-210,
Po-210
Th-230, Th-232 & Th-228
...



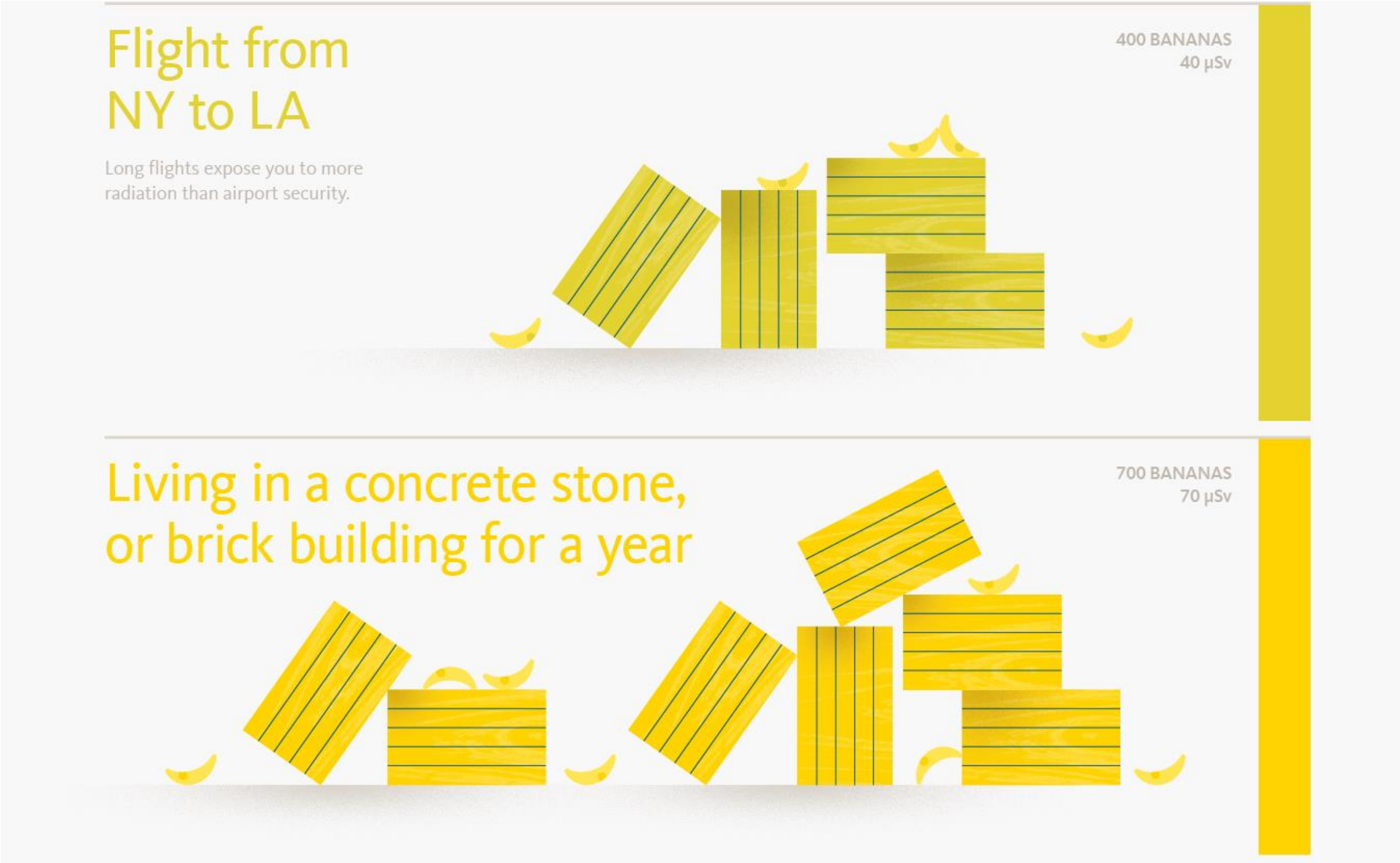
Radon decay products can deposit on leaf surfaces and be taken up in the leaves

- Among artificial radionuclides, **Cs-137** plays an important role as to food from forests, i.e. edible wild mushrooms and game, in particular wild boars.
  - **Legacy of the Chernobyl accident and the atmospheric nuclear weapons tests**

A "practical" guide to radioactive dose

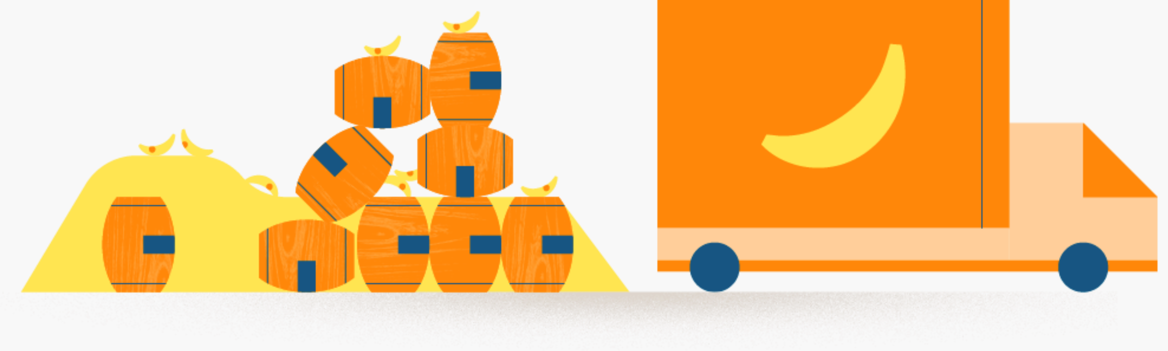


https://www.universityofcalifornia.edu/sites/default/files/uc_climatechange_illustrations_banana-radiation.png


Flight from
NY to LA
Long flights expose you to more
radiation than airport security.
400 BANANAS
40 µSv
Living in a concrete stone,
or brick building for a year
700 BANANAS
70 µSv

CT Scan

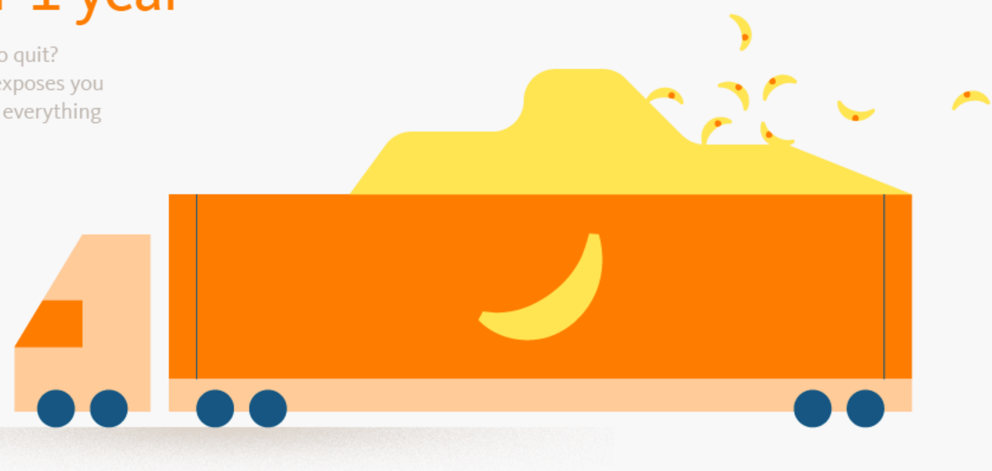
100,000 BANANAS
10,000 μSv

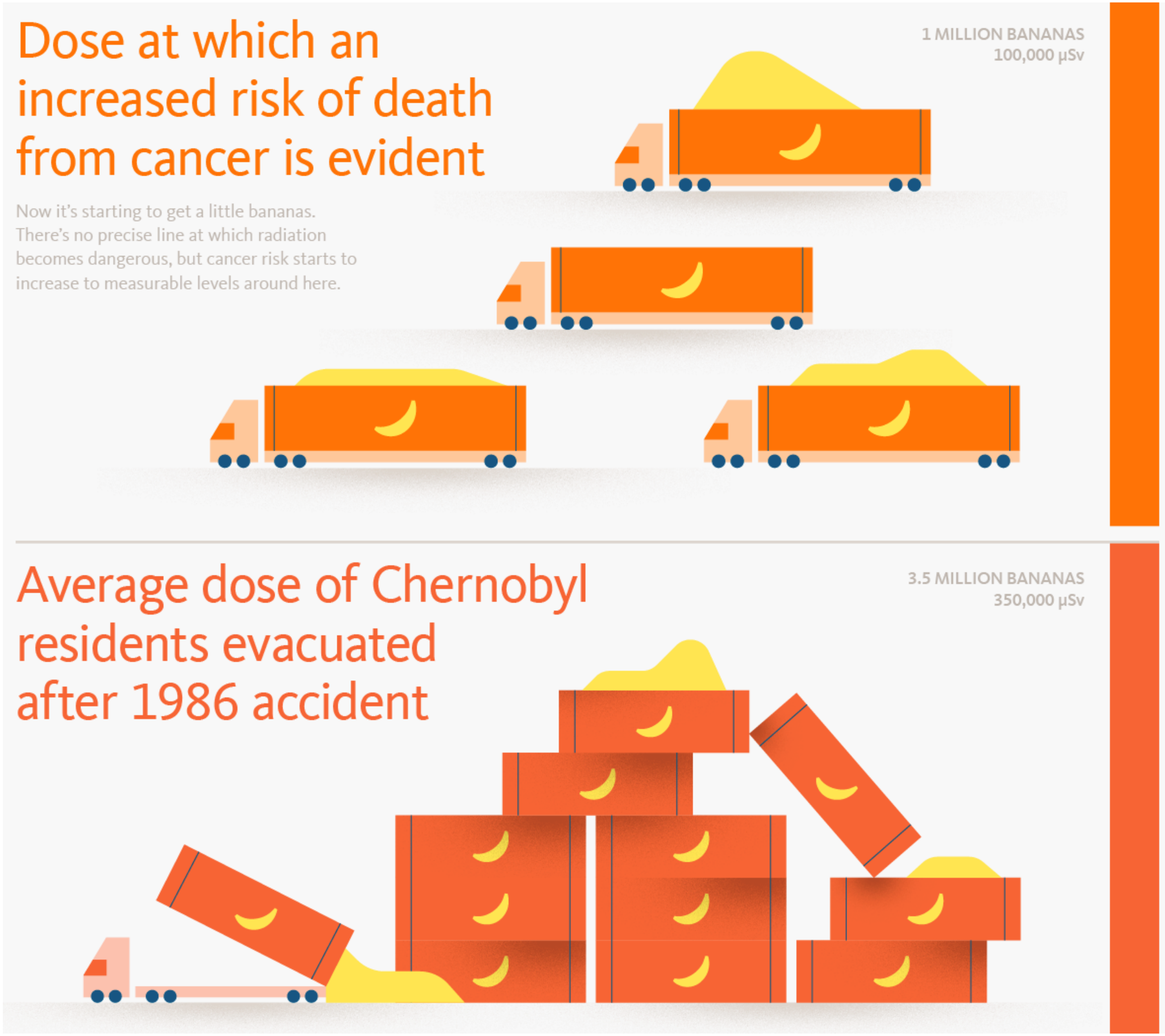


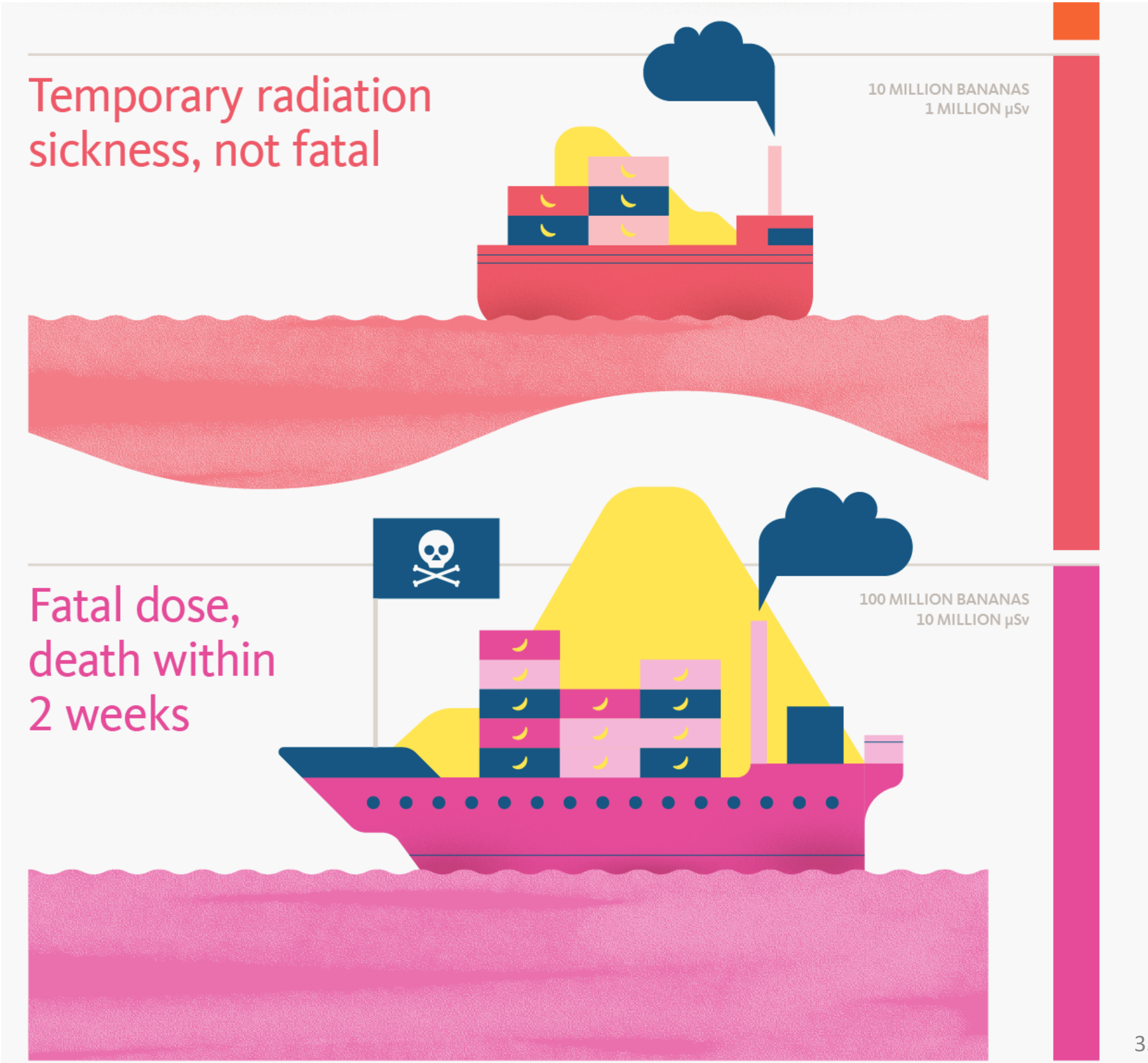
Smoking a pack of cigarettes a day for 1 year

240,000 BANANAS
24,000 μSv

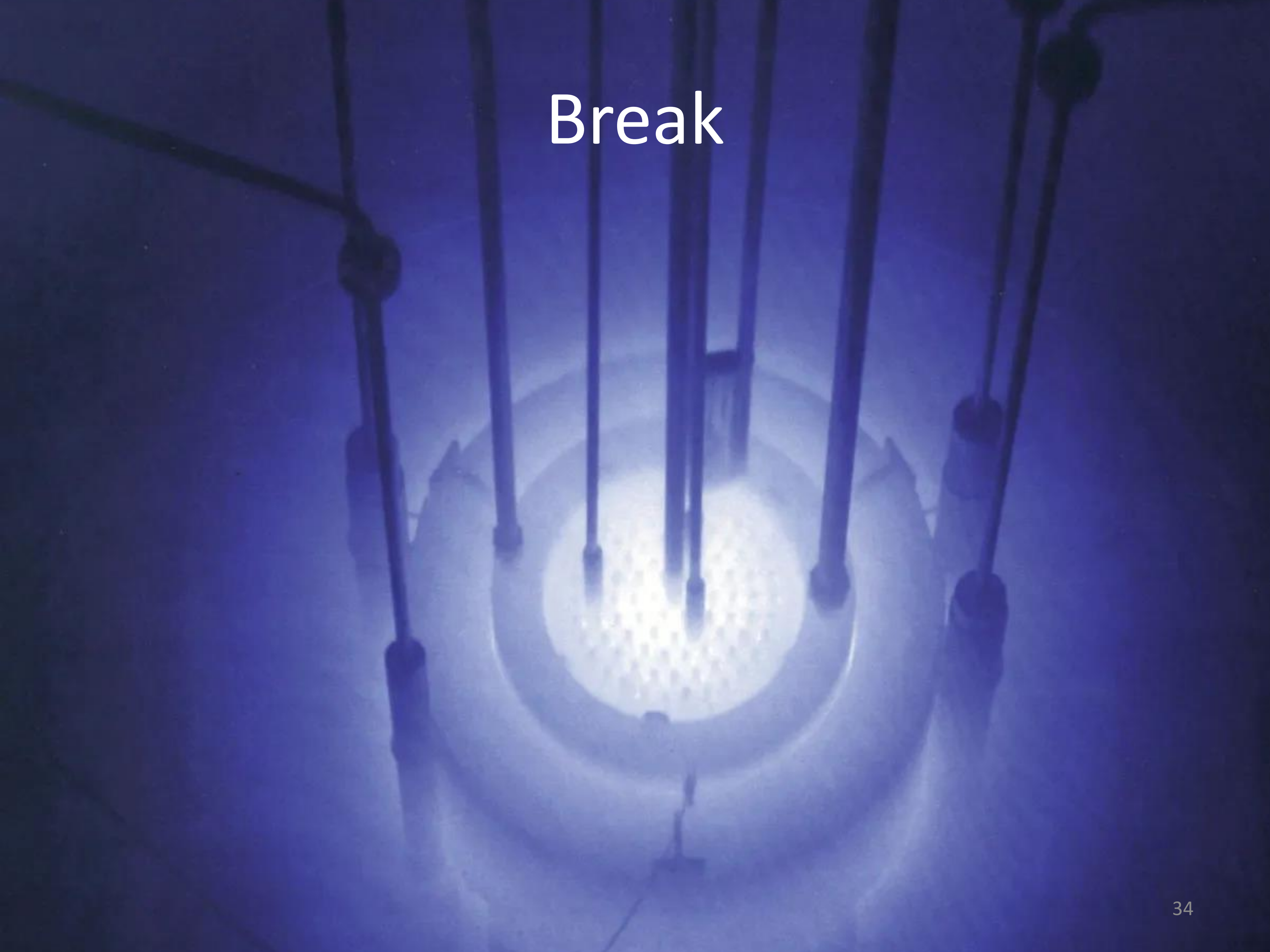
Need another reason to quit? Smoking a pack a day exposes you to more radiation than everything above put together.




Dose at which an increased risk of death from cancer is evident
Now it's starting to get a little bananas. There's no precise line at which radiation becomes dangerous, but cancer risk starts to increase to measurable levels around here.
1 MILLION BANANAS
100,000 μSv
Average dose of Chernobyl residents evacuated after 1986 accident
3.5 MILLION BANANAS
350,000 μSv


Temporary radiation sickness, not fatal
10 MILLION BANANAS
1 MILLION μSv
Fatal dose, death within 2 weeks
100 MILLION BANANAS
10 MILLION μSv

Break



Irradiation of Cells: The two Ways of Damage

- **Biological effects** are usually thought of **as effects on cells**.
- Ionizing radiation interacts with atoms by ionization.
- **The biological effects of radiation result mainly from damage to the DNA, which is the most critical target within the cell.**
- Direct Action Damage:
  - The radiation interacts **directly** with the critical target in the cell.
  - The interactions lead to the chain of physico-chemical events that will produce the biological damage.
  - This is the dominant process for high LET radiation.
- Indirect Action Damage:
  - The radiation interacts **indirectly** with other molecules: 80% water.
  - **Production of free radicals**.
  - The free radicals produce chemical damage in the critical target molecule.
  - This is the dominant process for low LET radiation (2/3 of damage).

Indirect Action Cell Damage Mechanisms

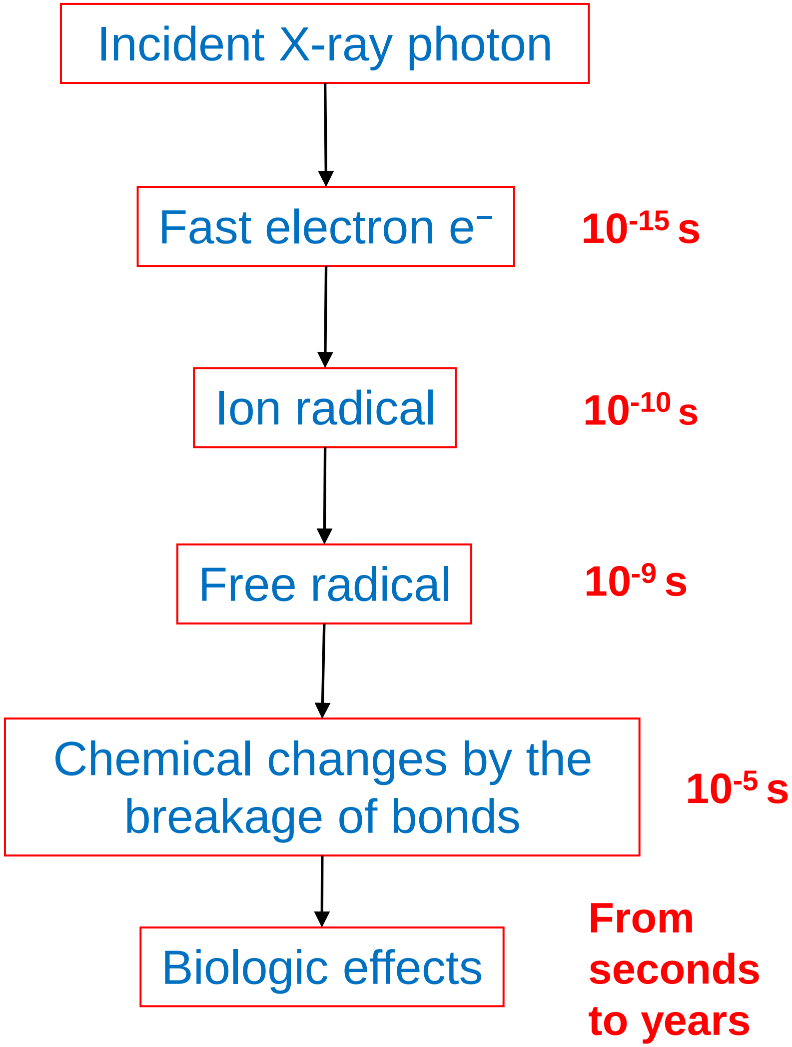
- Radiation interacts with a water molecule (80% cell is water).
- Ionization of the water molecule:

$$H_2O \rightarrow H_2O^{+} + e^{-}$$

- Ion radical forms free radical:

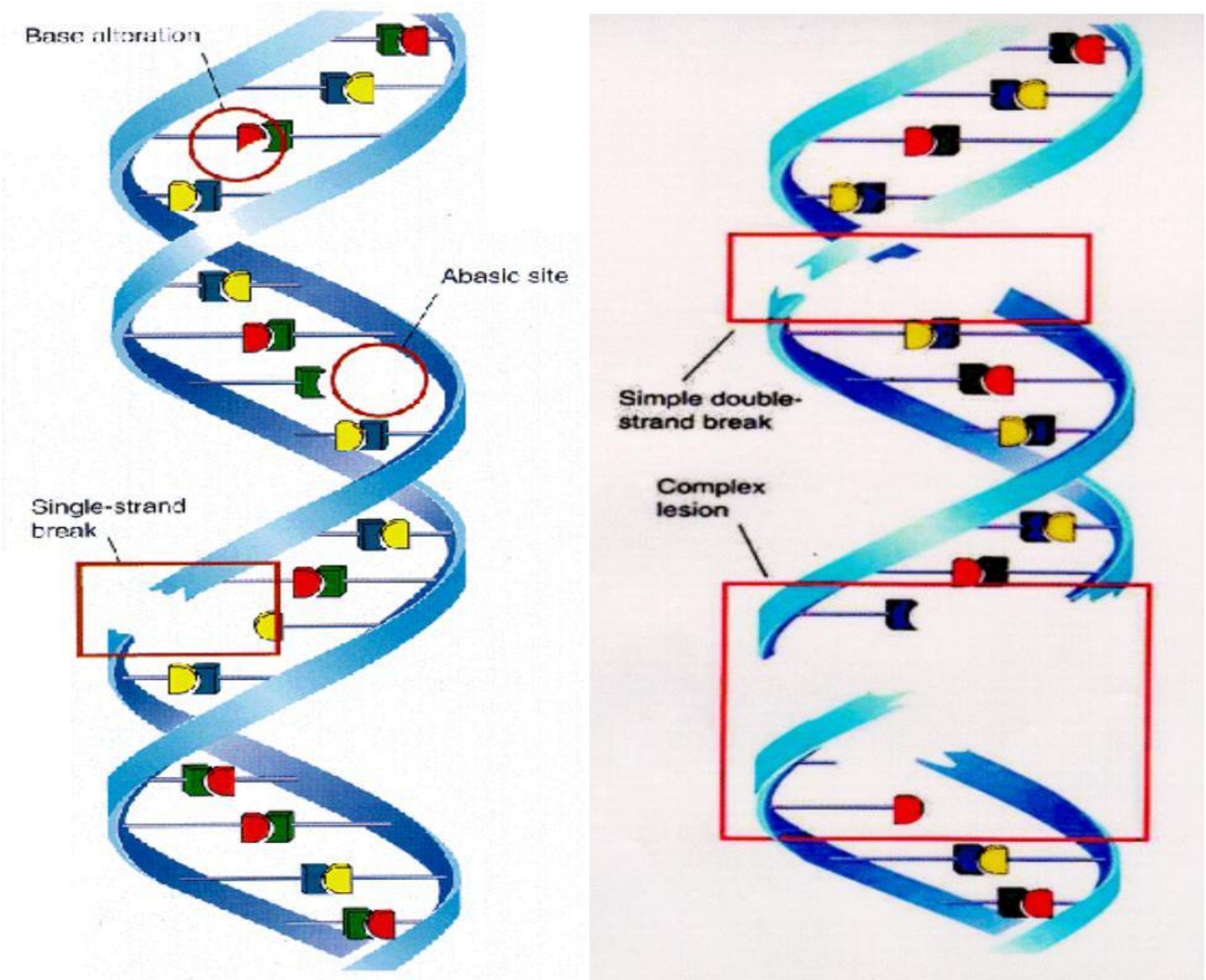
$$H_2O^{+} + H_2O \rightarrow H_3O^{+} + OH^{\bullet}$$

- Hydroxyl radical $OH^{\bullet}$ diffuses and attacks the DNA molecule.



Radiation Injury to DNA

- Base pair deletion
- Cross-linking injuries
- Single strand break
- Double strand break
- Multiple (complex) lesions



Fate of Irradiated Cells

- **No effect.**
- **Division delay.**
- **Apoptosis**: cell death before it can divide.
- **Reproductive failure**: cell death when attempting **mitosis**.
- **Genomic instability**: delayed reproductive failure.
- **Mutation**: cells survives, but contains mutation in genome.
- **Transformation**: mutation leads to carcinogenesis.
- **Bystander effects**: damaged cell induces damage in surrounding ones.
- **Adaptive response**: increased resistance to radiation.

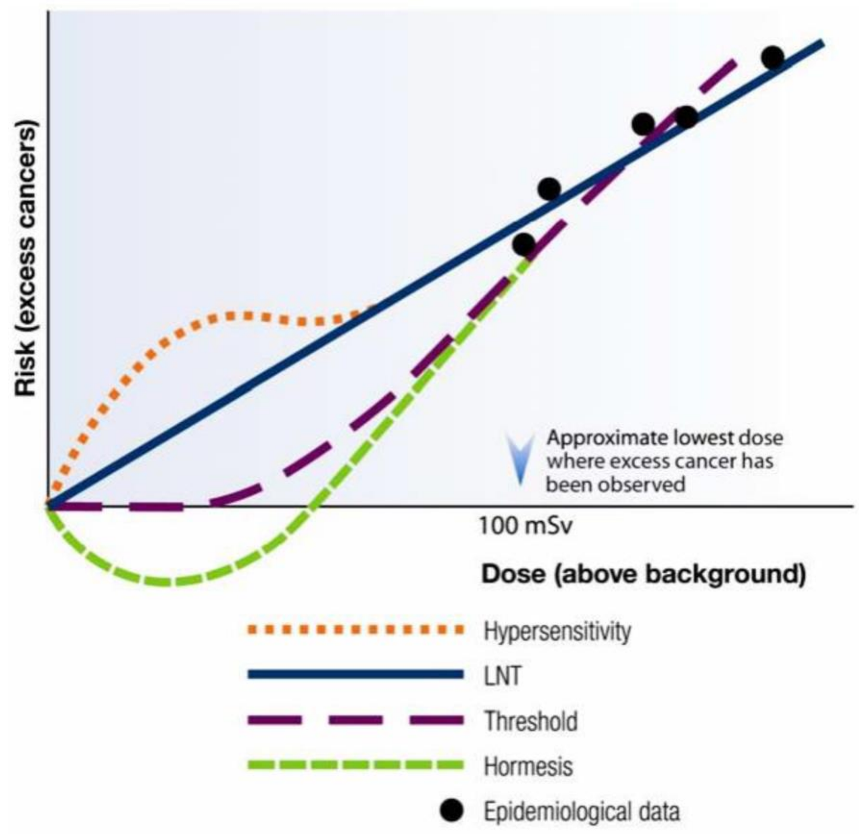
Types of Radiation Damage, Radiation Effects

- The harmful effects of radiation may be classified into:
  - ***Stochastic***: the probability of the effect increases with dose. There is no threshold, but it may be assumed that there is always a small probability the event occurring even at small doses.
  - ***Deterministic***: there is a threshold for the effect, above which the severity increases with dose.

- Related to the response of an organ or tissue to radiation:
  - ***Acute*** (after high doses): cells are killed in large quantities. Tissues and organs are damaged. Rapid body response.
  - ***Late*** (after low doses): cells are damaged or changed. Slow body response.

Stochastic Effects

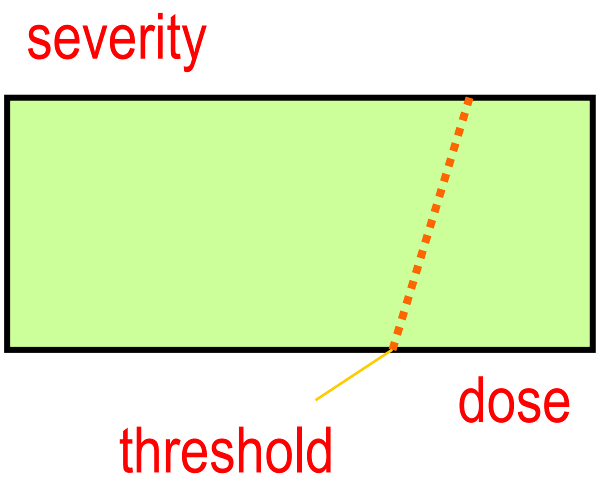
- Cancer Induction
  - The most important stochastic effect for radiation safety considerations
  - Reliable evidence through Hiroshima & Nagasaki (H&N) dataset
  - Linear pattern of risk with respect to dose
  - Controversy with respect to extrapolation to very low dose (airline pilots; inhabitants of area of high radiation background)
  - Decline of radiosensitivity with age
  - Complicated process (multi-stage, large amount of parameters)
- Hereditary Defects
  - Demonstrated during animal experiments
  - No increase of defects in patients exposed to radiations in Japan (H&N) and Chernobyl



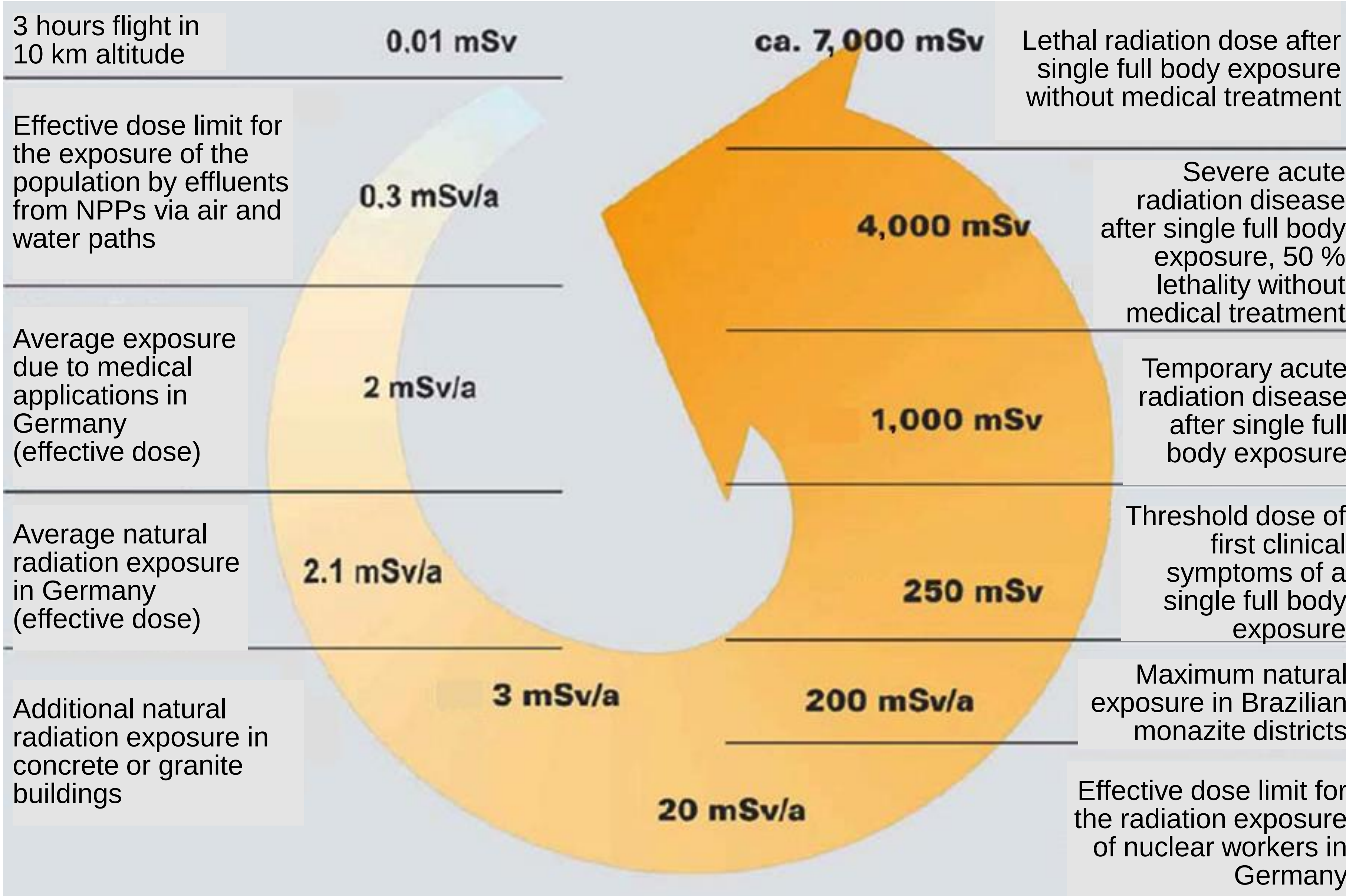
Deterministic Effects

- Due to cell killing.
- Only above dose threshold.
- Specific to tissues.
- Severity of harm is dose dependent.
- Examples:
  - Skin breakdown
  - Cataract of the lens of the eye
  - Sterility
  - Kidney failure
  - Acute radiation syndrome (whole body)

- Thresholds for deterministic effects:
  - Cataracts of eye lens: 2-10 Gy
  - Permanent sterility
    - males 3.5-6 Gy
    - females 2.5-6 Gy
  - Temporary sterility
    - males 0.15 Gy
    - females 0.6 Gy



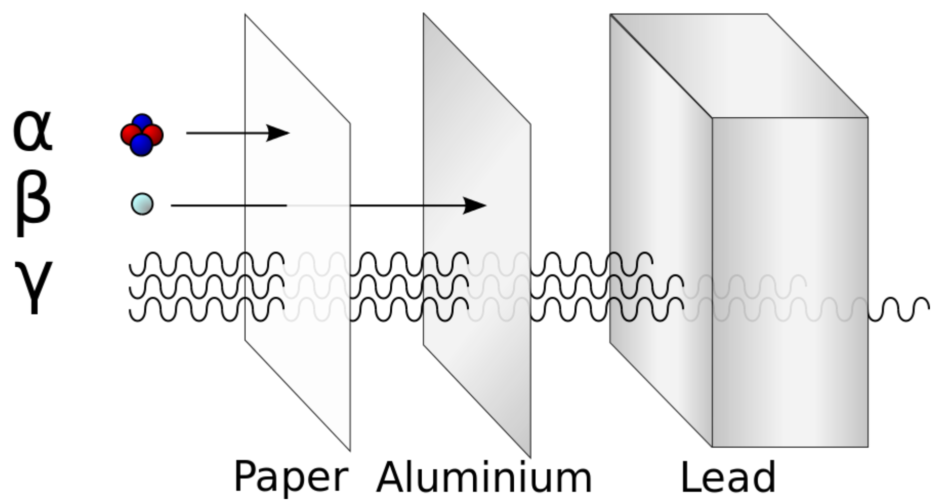
Radiation effects: Dose Ranges



Cellular Sensitivity to Radiation

- Not all cells are equally sensitive to radiation.
- Those cells actively reproducing are more sensitive:
  - DNA is exposed to damage when the cell is dividing.
  - Non reproducing cells are more resistant to radiation.
- Classify cells according to their rate of reproduction:
  - Constantly reproducing: e.g. Lymphocytes.
  - Moderate regeneration: e.g. Gastrointestinal lining cells.
  - Slowest to regenerate: e.g. Muscle and Nerve cells.
- Fast reproducing cells well oxygenated are the most susceptible:
  - Tumour at the periphery. Irradiation causes rapid shrinkage -> Fractional irradiation.
  - Foetus: the sensitivity of the developing embryo is very large.

Radiation protection principles and shielding



ALARA PRINCIPLE

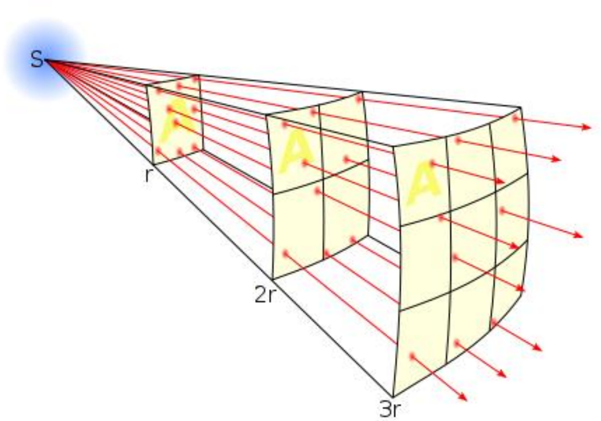
- "As Low As Reasonable Achievable": A principle of keeping radiation doses and releases of radioactive materials to the environment as low as can be achieved, based on technologic and economic considerations

  - **Factors to consider to reduce exposure**

① **Time:** Reducing the time of an exposure reduces the effective dose proportionally.

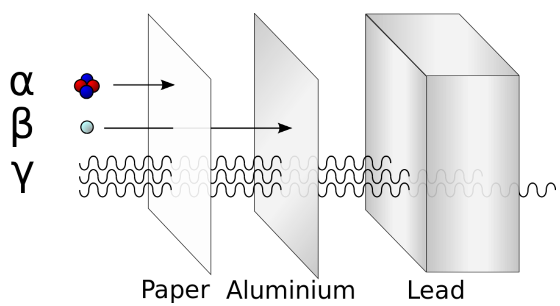
② **Distance:** Increasing distance reduces dose due to the inverse square law.

③ **Shielding:** A mass of absorbing material placed around a radioactive source, to reduce radiation levels



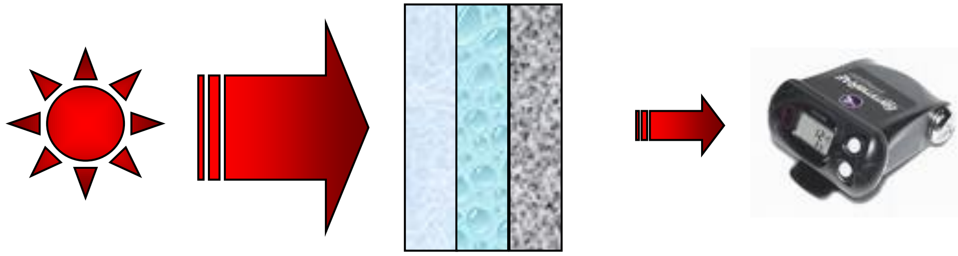
$$\frac{Intensity_1}{Intensity_2} = \frac{distance_2^2}{distance_1^2}$$

$$Intensity \propto \frac{1}{distance^2}$$



The Concept of Radiation Shielding

- Purpose of radiation shielding:
  - Reduce the radiation exposure to persons and equipment.
  - Can be used to control radiation and thus is an important aspect of Radiation Protection.
- Radiation shielding is **based upon the mechanisms by which different radiations interact** in an absorbing medium.
- **Radiation shielding is** a very **complex** discipline:
  - There are many radiation sources.
  - There is a wealth of materials and geometric configurations.



Interaction properties of radiation.

Radiation	Charge	Energy	Range in air	Range in H_2O
α particles	+2	3–10 MeV	2–10 cm	20–125 μm
β^+, β^- particles	±1	0–3 MeV	0–10 m	<1 cm
Neutrons	0	0–10 MeV	0–100 m	0–1 m
X-rays	0	0.1–100 keV	m–10 m	mm–cm
Gamma rays	0	0.01–10 MeV	cm–100 m	mm–10s of cm

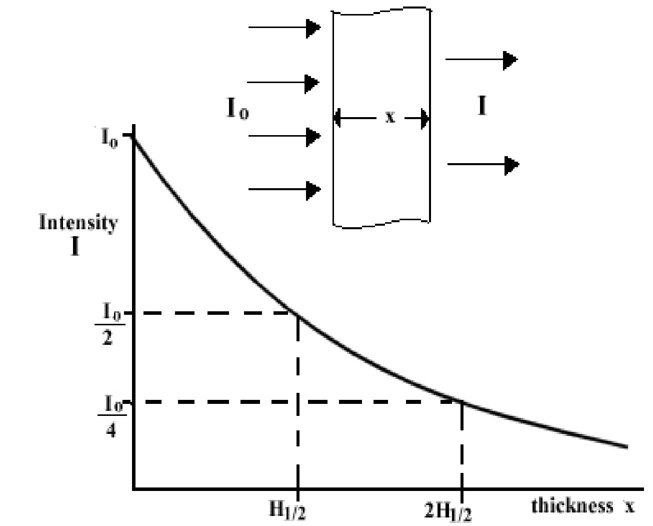
Attenuation and Range

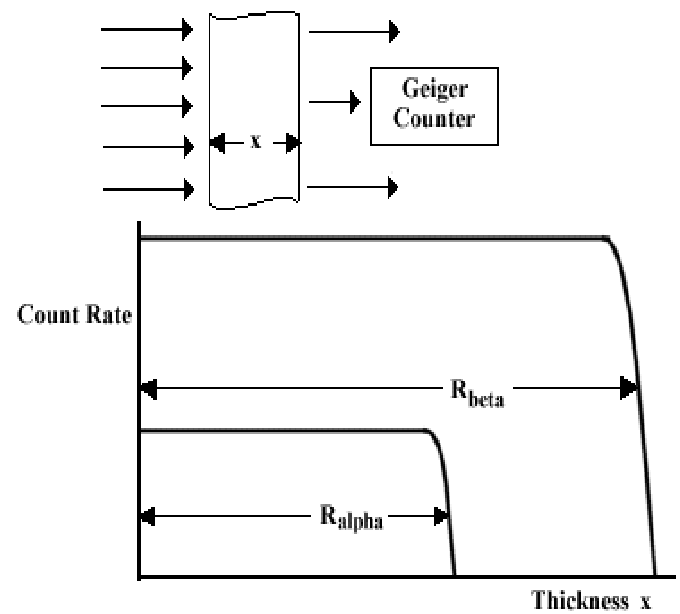
❑ Attenuation:

- A **reduction in intensity** of radiation with respect to distance traveled through a medium.

❑ Range $R_{particle}$:

- In passing through matter, charged particles ionize and thus lose energy in many steps, until their **energy is** (almost) **zero**. The distance to this point is called the range of the particle.
- The range depends on:
    1. The type of particle,
    2. its initial energy and
    3. the material which it passes through.

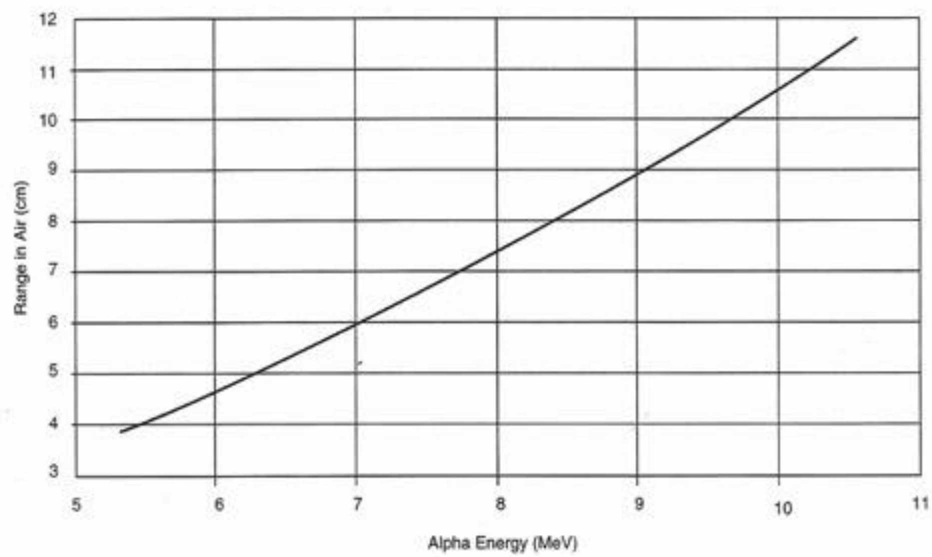




Shielding of Alpha (and Heavy Charged Particle) Sources

- Alpha particles are easy to shield due to their short and well predictable range.
- External radiation:
  - Absorbed by very **thin** layers of dense materials (range generally less than 1mm).
  - Stopped by dead skin layer.
- Internal Radiation:
  - Considerable damage to biological tissue: Large ionization.
  - High LET radiation.
- **Shielding avoids spread and contact by using fixatives on surfaces.**
- Very short range makes detection difficult:
  - Detector windows must be thin.
  - Highly contaminated areas may be missed by failing to get close enough.

Range almost linear



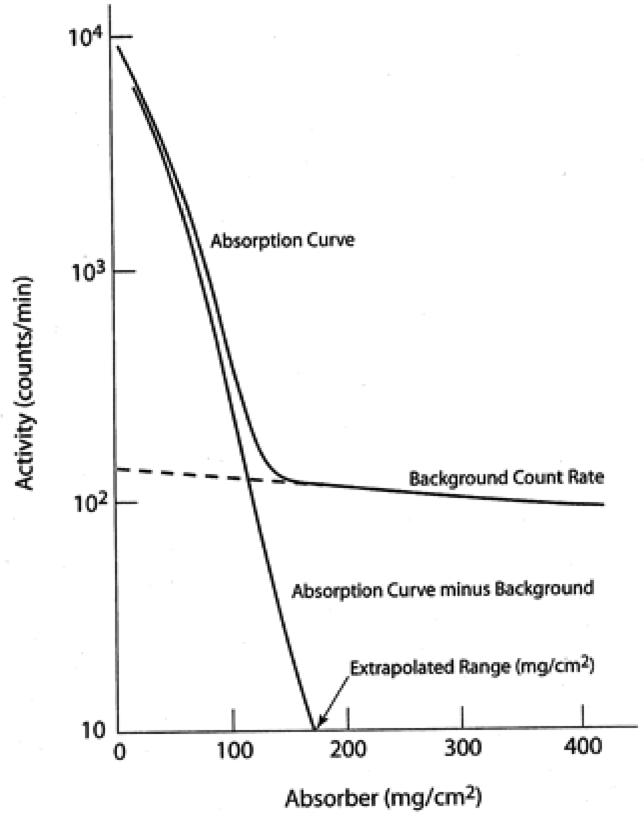
Range versus energy of alpha particles in air.

Attenuation and Range of Beta Particles

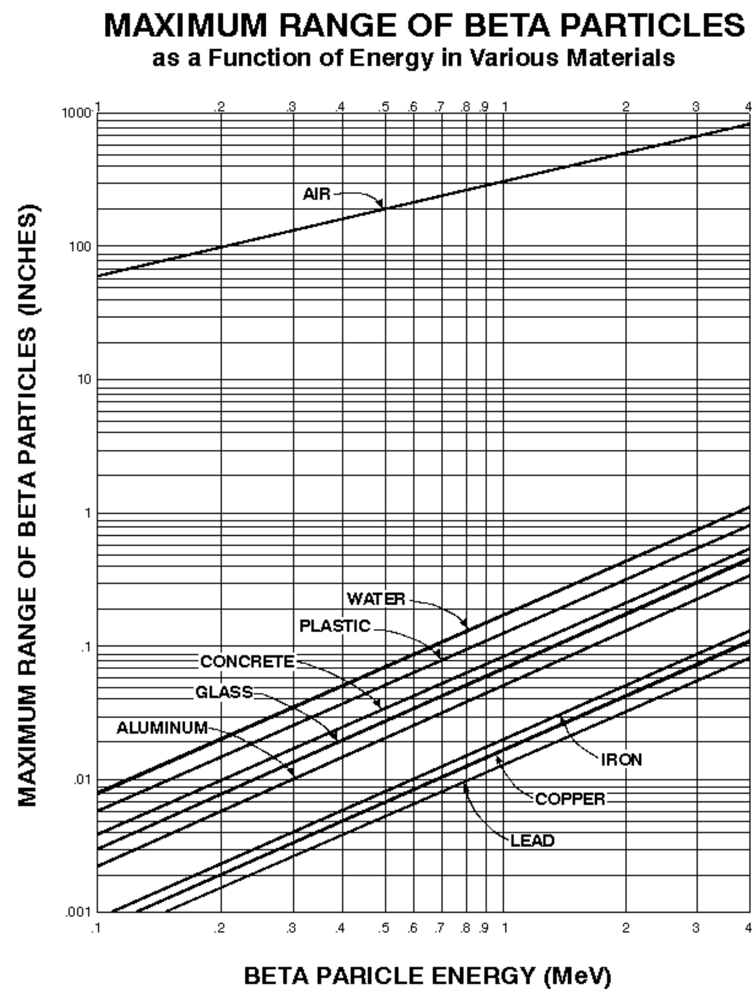
- The attenuation of beta particles in a medium is exponential:

$$I(x) = I_0\, e^{-\mu_{\beta,i}(\rho x)}$$

- The range of beta particles is short (few meters in air, tenths of mm in dense materials) and depends on their kinetic energy and Z of the material.

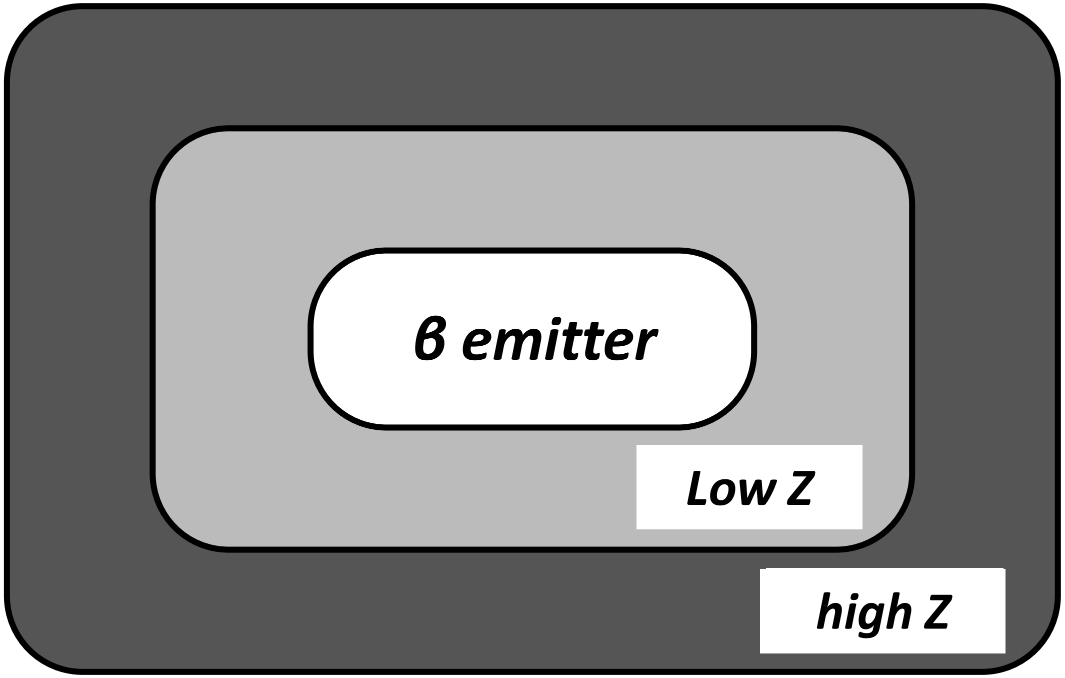


Decrease in measured activity of a beta particle source versus mg/cm² of absorber thickness that trails off into the background of the detector system. Subtraction of the background portion from the total curve yields a curve that can be extrapolated to estimate the maximum range (in mg/cm²) of the beta source.



Protection against beta radiation

- Bremsstrahlung is important for high Z materials (Pb).
- Shield design must account for the fraction of total energy transformed into photons by Bremsstrahlung.



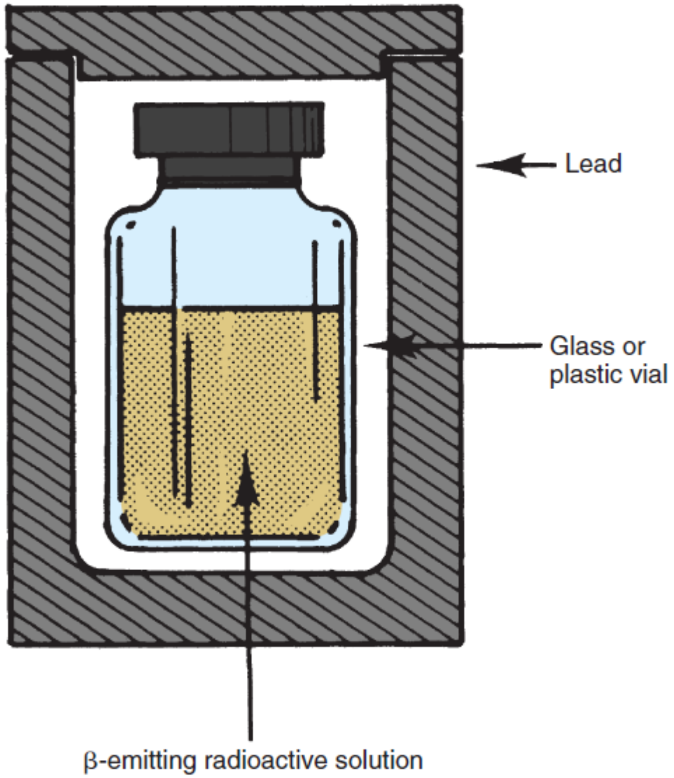


FIGURE 6-3 Preferred arrangement for shielding energetic β-emitting radioactive solution. Glass or plastic walls of a vial stop the β particles with minimum bremsstrahlung production, and a lead container absorbs the few bremsstrahlung photons produced.

Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

Shielding of Photons

- The attenuation obeys an exponential law:
- The attenuation coefficient μ (cm^{-1}) is the sum for all interactions:
  - Depends on photon energy and Z of the absorber medium:
    - => Pb is often used as shield for X-rays.
    - $BaSO_4$ is incorporated into concrete.
  - μ grows with Z because of rising importance of photoelectric effect and pair production.

Attenuation of Photons

$$I(x) = I_0 \, e^{-\mu x}$$

Half-Value Layer (HVL)

$$\frac{I(x_{1/2})}{I_o} = \frac{1}{2} = e^{-\mu x_{1/2}}$$

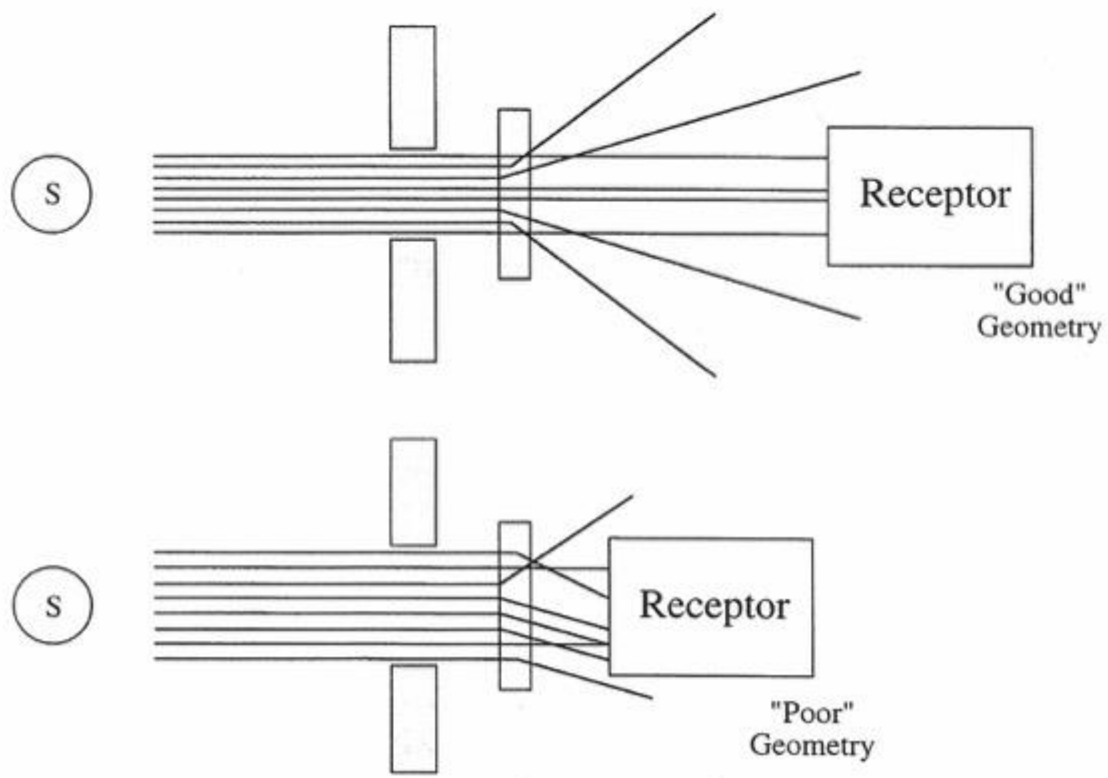
$$x_{1/2} = \mathrm{HVL} = \frac{\ln 2}{\mu}$$

Tenth-Value Layer (TVL)

$$x_{1/10} = \mathrm{TVL} = \frac{\ln 10}{\mu}$$

Attenuation of Photon Sources depends on "Geometry"

- "Good" and "Bad" geometry:
  - **"Good" geometry** (**narrow-beam**): Only non-scattered (primary) photons (that have the same energy as the original beam) reach the receptor.
  - **"Bad"** (**broad-beam**) **geometry**: Also scattered (secondary) photons of lower energy can reach the receptor and lead to a complex energy spectrum.
  - Shield design must tend to "good" geometry.



Shielding of Neutrons

- The basis is to use materials that enhance the interactions that deplete neutrons:
  - Fast neutrons:
    - **First** moderation: elastic and inelastic scattering (γ-rays).
    - **Then** absorption of thermal neutrons.
  - Thermal neutrons:
    - Absorption: (n,γ)-reactions, but not (n,2n), (n,3n), (n,f), …
- Best moderating materials are those with:
  - Low Z: higher energy loss per collision, e.g., H_2 (1/2E loss per interaction).
  - High elastic scattering X-sections.
- Best absorbing materials are those with large absorption cross sections for thermal neutrons: e.g., ^{10}B, Cd, H, Li, Gd, …
- Neutron attenuation under "good" geometry conditions:

$$I(x) = I(0)\cdot\exp(-\Sigma_t\cdot x), \qquad \Sigma_t = N\cdot\sigma_t = N\cdot(\sigma_e+\sigma_i+\sigma_\gamma+\sigma_r+\ldots)$$

- Otherwise, when the scattering of neutrons "back into the beam" plays a role, it must be taken into account (as for photons), by buildup factors, e.g., B~5.0 for 20 cm or more water or paraffin.

Shielding of Neutrons (Materials)

Hydrogenous materials (moderators)

- **Water**: (corrosion, leakage, contamination, etc.).
- **Paraffin**: (flammable). Shielding needed for the 2.225 MeV γ-photon from H neutron capture.
- **Polyethylene**: larger H/volume than water.
- **LiH**: no γ from neutron capture, but Tritium formation from ^{6}Li.

Elements used as shielding materials in NPP

- **Pb, Fe**: Capture γ-rays, ^{59}Fe activation.
- **W**: Better than Pb. Secondary γ-radiation from neutron capture.
- **U (depleted)**: best attenuator for γ-rays, low neutron capture γ, but high γ flux from fast fission reactions.
- **B**: incorporated in Boron based shields. High thermal absorption cross section.
- **Concrete and earth**: high H content; added B.
- **Cd**: large absorption X-section; high capture γ-photons (9.05 MeV).