ROYAL INSTITUTE
OF TECHNOLOGY

Nuclear Fuel Cycle 2011

Lecture 4: Interaction of Ionizing Radiation with Matter

Ionizing radiation (Nuclear radiation)

Radiation with energy > 100 eV

Ionize an atom < 15eV

Break a bond 1-5 eV

Typical decay energies

- α: 4-9 MeV
- β: 0.02-4 MeV
- γ: 0.1-2 MeV

≈ 100 000 – 1 000 000 ionizations per decay

Radiation types

- Protons and heavy ions (*e.g.* α-particles)
- Electrons (β^+ and β^-)
- Photons (γ)
- Neutrons

Absorption of ionizing radiation

- Interactions with the electrons of the absorber

- (Neutrons): Interactions with nuclei resulting in radioactive decay and

  High energy γ, resulting in pair production

Linear Energy Transfer (LET)

The energy lost per length unit

LET = -dE/dx

LET depends on the electron density of the absorber (usually proportional to the physical density)

Radiation (3 MeV)	**LET (keV/µm)**	**cm in air**
Electron	0.20	1400
Proton ($^{1}_{1}H^{+}$)	21	14
Deuteron ($^{2}_{1}H^{+}$)	34	8.8
α ($^{4}_{2}He^{2+}$)	180	1.7

Protons and heavy ions

The LET of protons and heavy ions follow the Bethe equation:

$$-\frac{dE}{dx}=\frac{4\pi z^2 e^4}{mv^2} NZ \ln\left(\frac{2mv^2}{I}\right) \Rightarrow -\frac{dE}{dx} \propto \frac{z^2}{v^2}$$

Z = absorber's atomic number

z = particle's atomic number

N = number of absorbing atoms per unit volume

v = Velocity

I = Ionization potential

m = electron mass

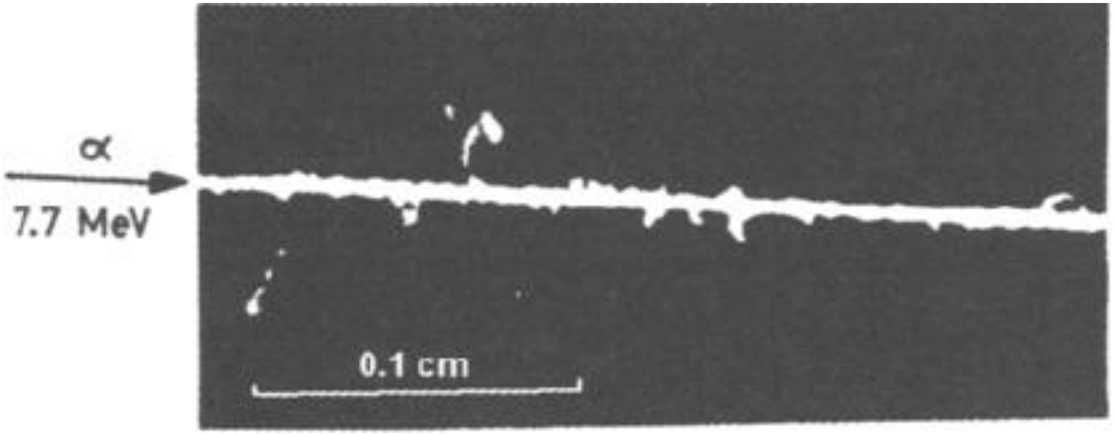
e = particle charge

α-particles

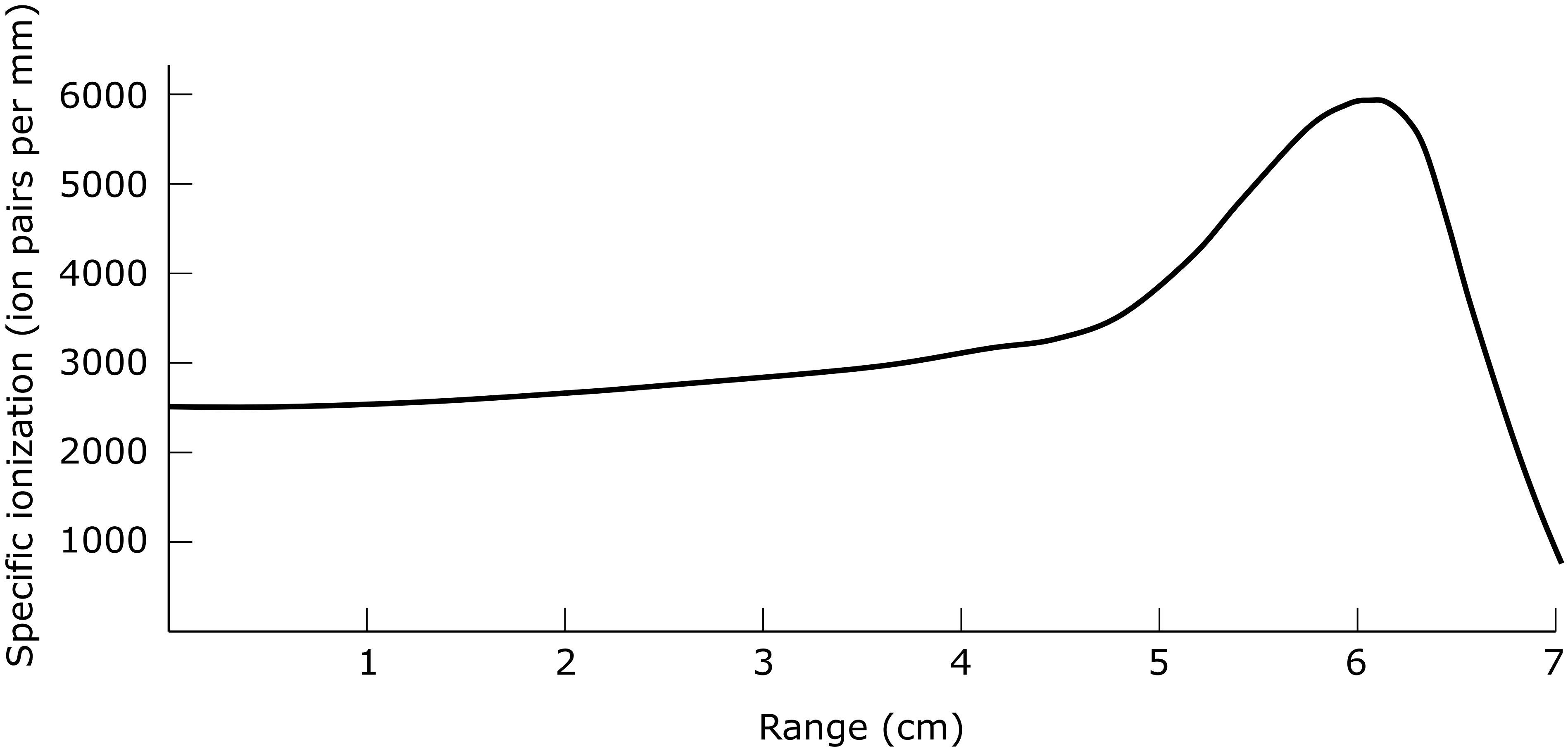
- Heavy charged particle: $^{4}_{2}\mathrm{He}^{2+}$

=> Interaction very strong (high LET)

Particles travels in a straight path, leaving a “spur” with lots of ionizations behind. The number of ionizations in an α–spur is in the order of 1 mol/liter



The Bragg curve (heavy charged particles)



β-particles (=electrons and positrons)

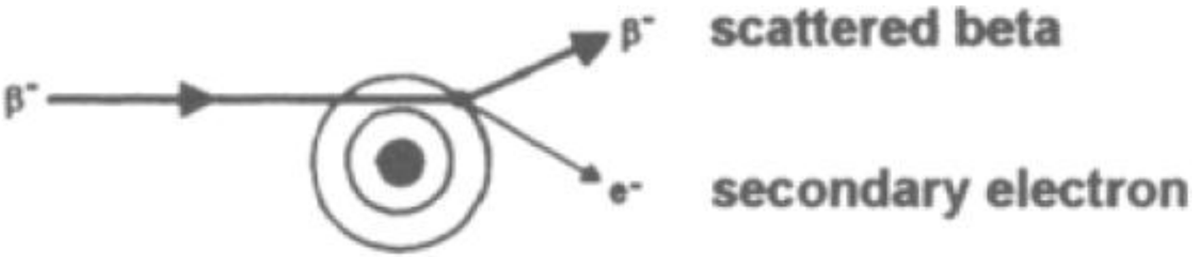
β-particles from nuclear decay have the same mass and velocity as orbital electrons and can lose much of the energy in one collision

When colliding with electrons β-particles are deflected and greatly scattered

Much higher velocity than alpha and protons
=> the range is longer

β-particles (=electrons/positrons)

ionization

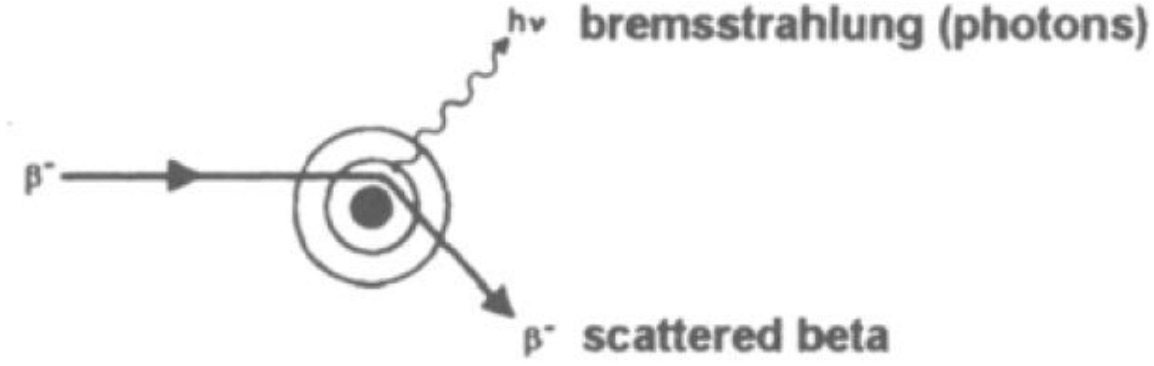


50% of the energy is lost by ionization and 50% by excitation

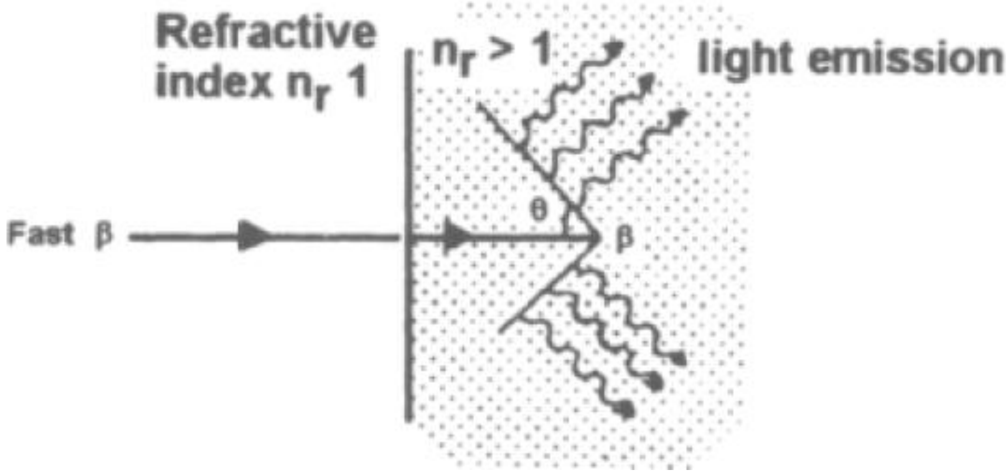
excitation

β-particles (=electrons/positrons)

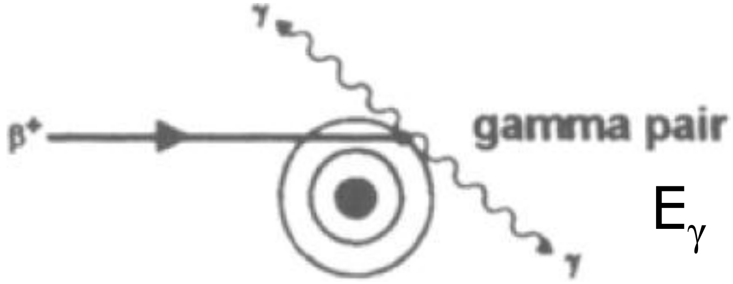
bremsstrahlung



Čerenkov radiation



positron annihilation



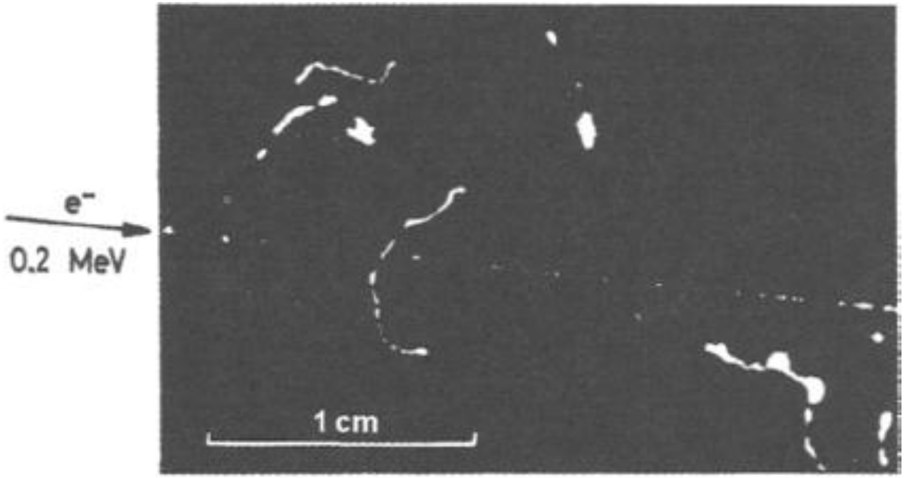
E_{γ} = 511 keV

Backscattering

β^--particles can scatter as much as 180° from the original direction.

This phenomena is called backscattering

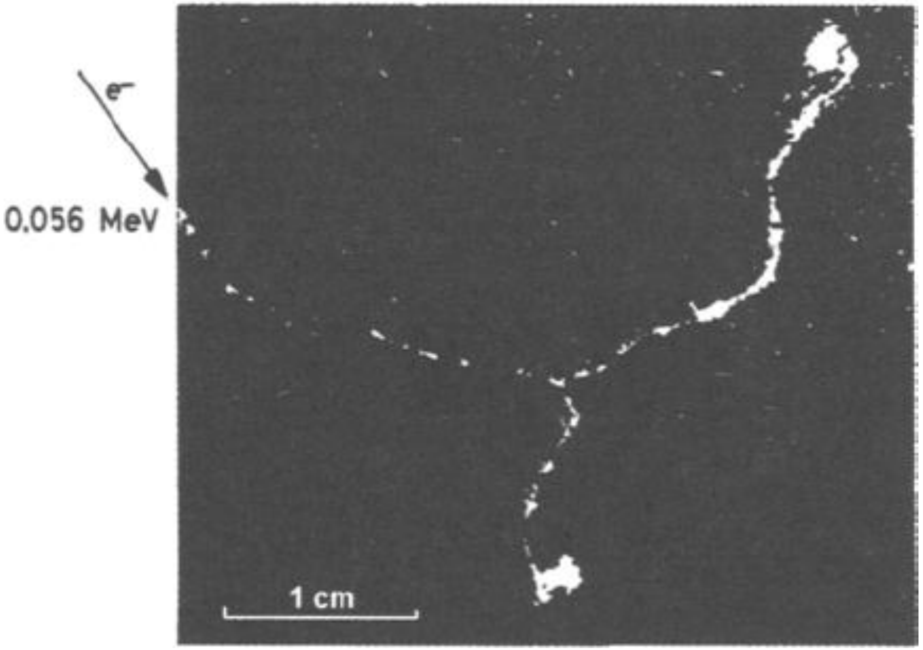
Tracks from β^--particles



Normal energy β^-

Meandering tracks

LET much lower



Low energy β^-

γ-radiation

γ-photons have no mass or charge

$\Rightarrow$ Very little interaction with absorber

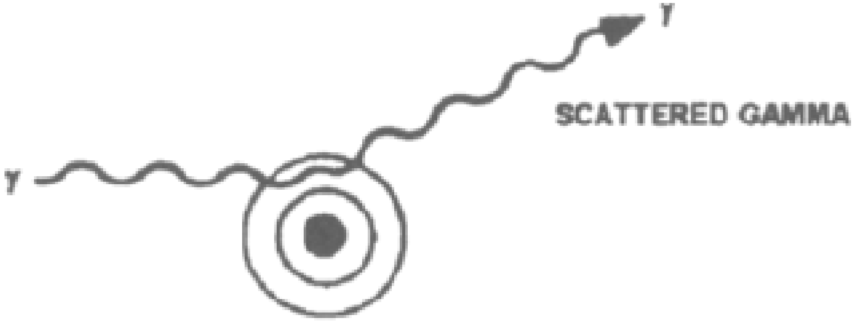
$\Rightarrow$ Long range

Unlike particles with mass, γ-photons loose all energy in one or two interactions.

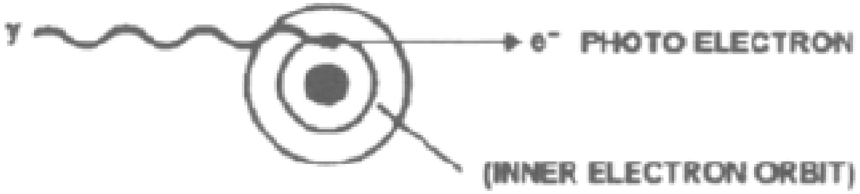
γ-photons interacts with absorber in four different ways: coherent (Rayleigh) scattering, photoelectric effect, Compton scattering and pair production

Interaction of γ-radiation

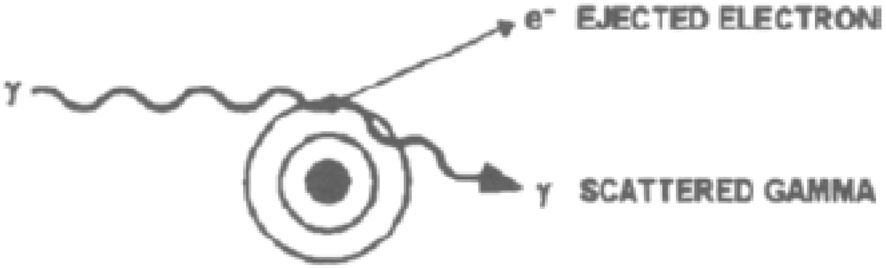
Coherent scattering
(Rayleigh scattering)



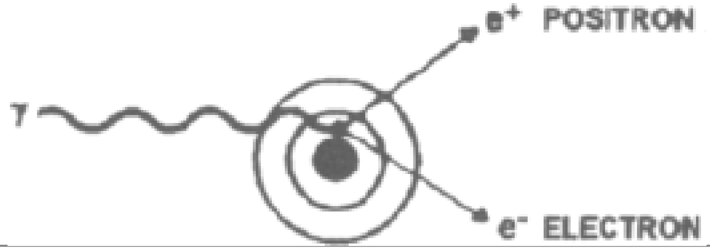
Photoelectric effect



Compton scattering



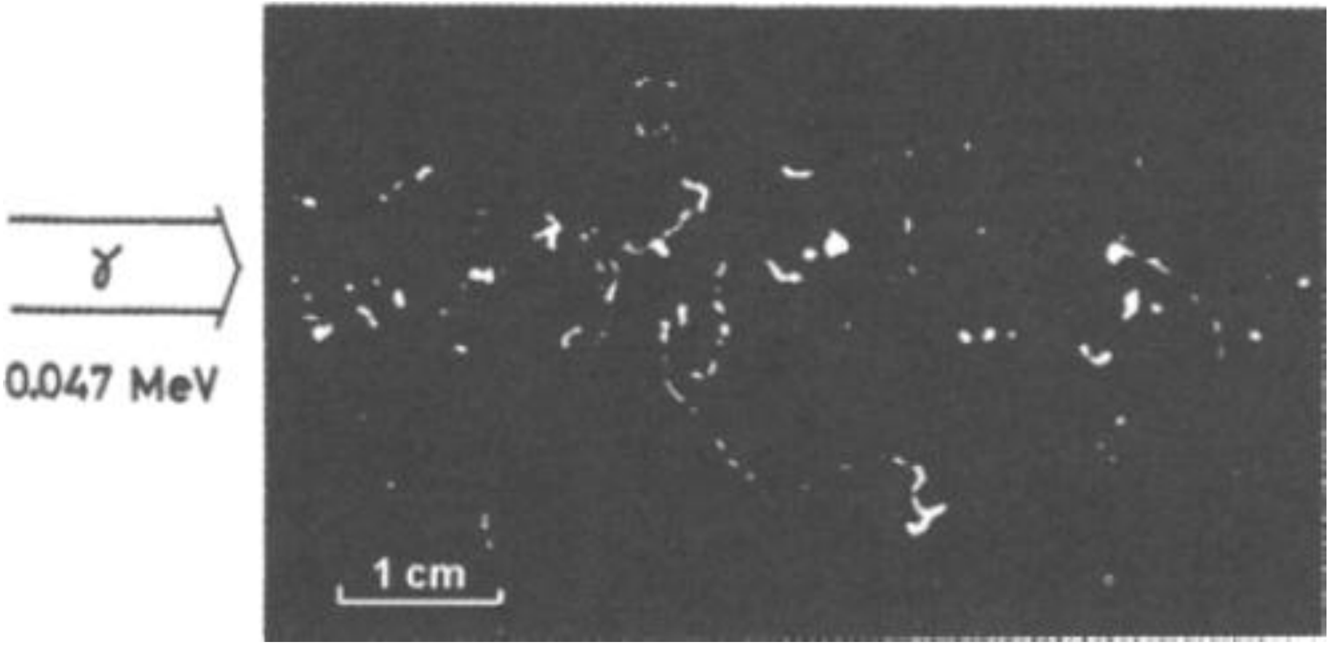
Pair production



Interaction of γ-radiation

Since a γ-photon can interact immediately and loose all energy or travel several cm before interacting the range is not possible to determine

But half-thickness can be determined



Neutrons

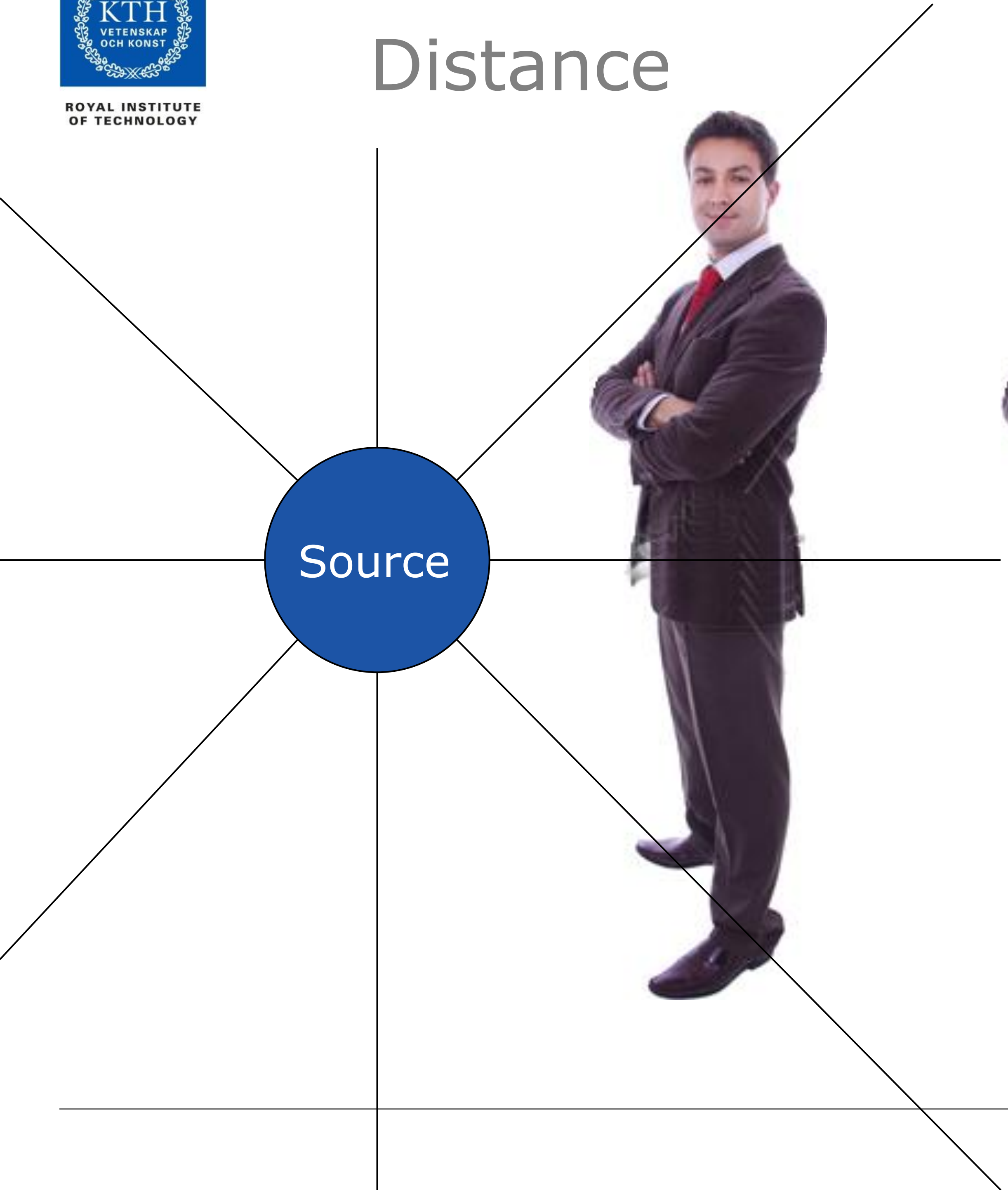
- No charge, interaction with matter similar to that of gamma (scattering).
- No range can be determined

Radiation shielding

Radiation	Relative penetration depth	Shielding	Range in water
α	1	Paper, skin	30-40 µm
β	100	3 mm Al	3-6 mm
γ	10 000	Concrete, Lead	-

Remember: The ability ability to interact (=absorb energy) of a material is proportional to its (electron) density.

Distance



Source

Dose decreases with square of distance due to geometric reasons

Absorbed dose

- Unit: Gray. 1 Gy = J/kg
- Older unit: 1 Gy = 100 rad

$$D = \frac{dE_{abs}}{dm}$$

$$E_{abs} = E_{in} - E_{out}$$

- Dose rate: Gray/s. (absorbed dose/s)

Equivalent dose

- Weights in the damage different radiation will do to tissue and organs (*i.e.* biologically significant)

- Units: 1 J/kg = 1 Sv (sievert)

- Old unit: 1 Sv = 100 rem

Equivalent dose

The equivalent dose (H_T) to an organ or tissue is the sum of mean absorbed dose $D_{T,R}$ in T, multiplied by a weighing factor w_R for each type of radiation R.

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

Radiation type & energy	**w_R**
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons of Energy E (MeV)	$5 + 17e^{\frac{-(\ln(2E))^2}{6}}$
Protons, energy > 2MeV	5
α, heavy nuclei	20

Effective Dose (Effective Equivalent Dose)

- Weights in the damage different radiation will do to specific tissues and organs (*radiation does different damage to different organs*)
- Units: 1 J/kg = 1 Sv (Sievert)
- Old unit: 1 Sv = 100 rem

Effective Dose

The equivalent dose is multiplied by a factor depending for each tissue/organ that is exposed to radiation

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

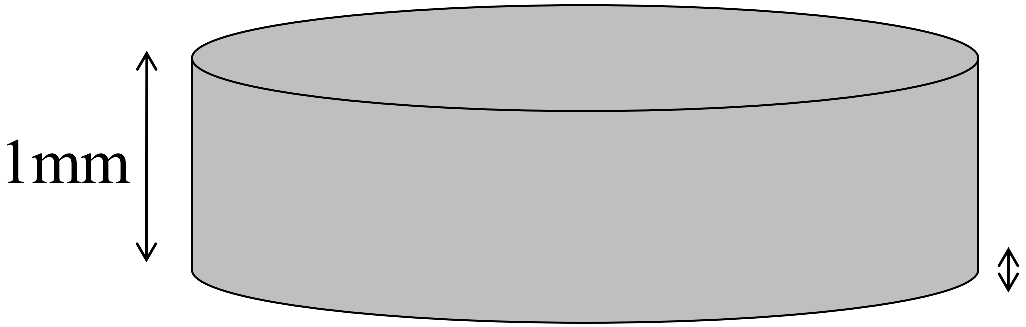
Organ or tissue	w_T	Organ or tissue	w_T
Gonads	0.20	Liver	0.05
Bone marrow (red)	0.12	Oesophagus (matstrupe)	0.05
Colon	0.12	Thyroid (Sköldkörtel)	0.05
Lung	0.12	Skin	0.01
Stomach	0.12	Bone surface	0.01
Bladder	0.05	Remainder	0.05
Breast	0.05		

Recommended dose limits

Dose limits for persons working with ionizing radiation	
Period of time	Limits of effective dose (mSv)
Annual	50
Effective dose	150
Equivalent dose to the lens of the eye	500
Equivalent dose to the skin, hands, forearms, feet and ankles	500
In addition, for 5 consecutive years, Effective dose	100

Example calculating dose rate

- A 1 mm thick radiation source of $^{238}UO_2$ (ρ_{UO2} = 11 g·cm^{-3}) is used to irradiate water. Assume that the range in H_2O is 35 μm and calculate the dose rate in the water. Assume furthermore that the range in an absorber is proportional to the density, that for geometrical reasons only 25 % of the alpha particles will reach the water and that they have lost 50 % of their energy while traversing UO_2.



Range in UO_2=35/11=3.2 μm

Assume 1cm×1cm×3.2μm

$V = 3.2\times10^{-4}$ cm^3

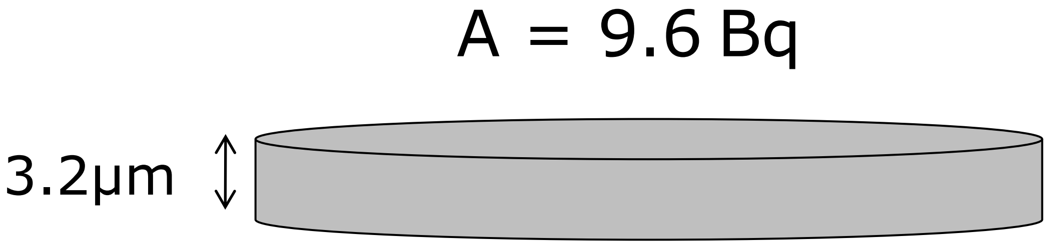
$N_U=V\times\rho/M_{UO2}\times N_A=7.85\times10^{18}$ atoms

$\lambda_U=\ln2/(4.5\times10^9\times365*24*3600)=4.9\times10^{18}$ s^{-1}

$A=N\lambda=38.35$ Bq

Only 25% will reach the water
=>A = 9.6 Bq

Example, continued



Dose rate = Absorbed energy/kg,s

E_α=4.2 MeV = 6.73×10^{-13} J (1 eV = 1.602×10^{-19} J)
50% will be lost => E = 3.36×10^{-13} J

Volume of the water = 1cm×1cm×35µm=35×10^{-4} cm^3

Mass of the water ≈ 35×10^{-7} kg

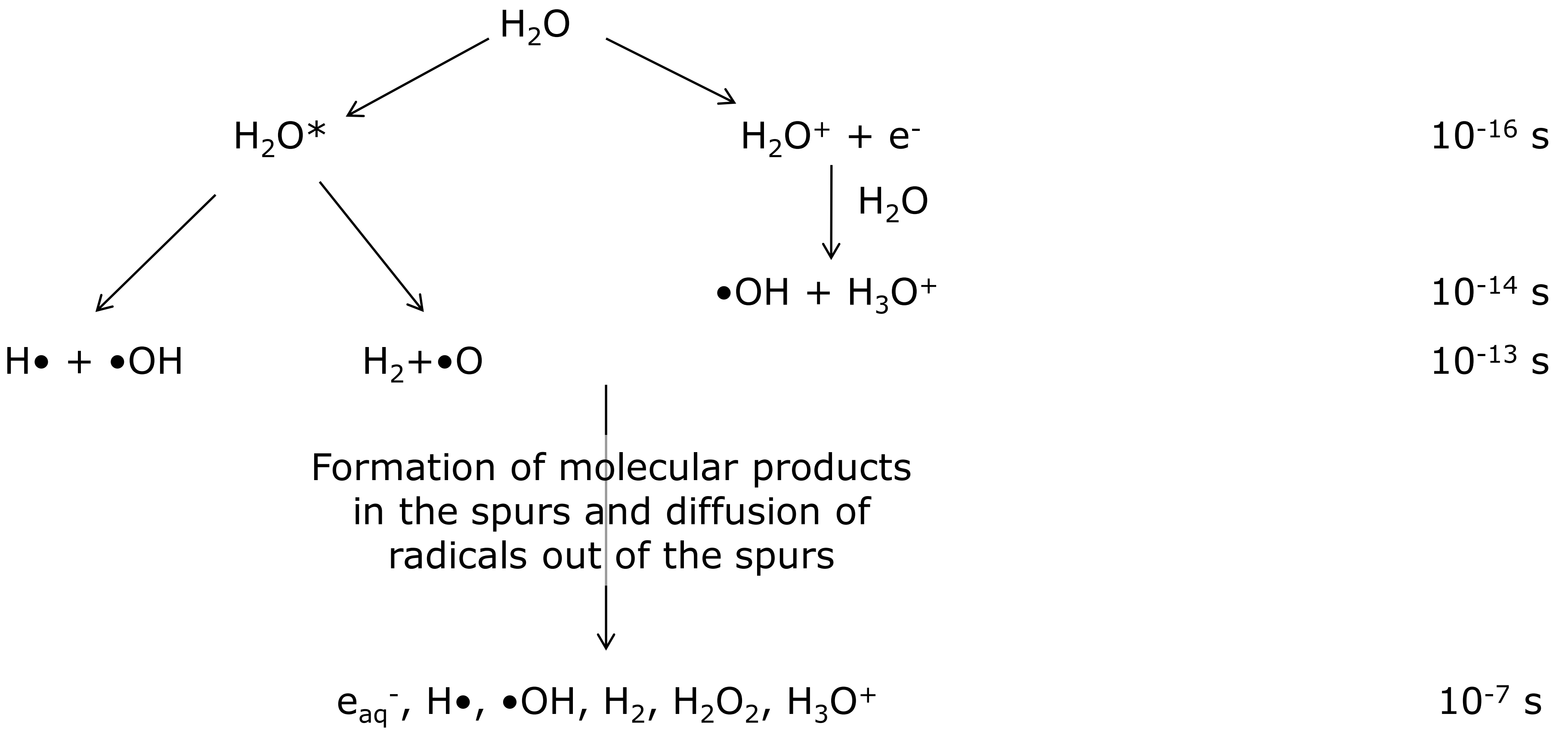
Dose rate = A×E/m= 9.6 × 3.36×10^{-13} /35×10^{-7} = 9.2×10^{-7} Gy/s

Radiation chemistry

- Radiation chemical yield
- G-value: $G_X = \frac{d[X]}{dE_{abs}}$
- Unit: mol/J
- Older unit: number of molecules/100 eV

Water Radiolysis

Event **Time scale**



H_2O

H_2O^*

$H_2O^+ + e^-$ 10^{-16} s

H_2O

$\bullet OH + H_3O^+$ 10^{-14} s

$H\bullet + \bullet OH$ $H_2 + \bullet O$ 10^{-13} s

Formation of molecular products
in the spurs and diffusion of
radicals out of the spurs

$e_{aq}^-, H\bullet, \bullet OH, H_2, H_2O_2, H_3O^+$ 10^{-7} s

LET (keV/µm) and G-values (µmol/J) for radiolysis of water

Radiation	LET	G(H_2O)	G(H_2)	G(H_2O_2)	G(e_{aq}-)	G(H•)	G(HO•)	G(HO_2•)
γ, β^-	0.24	-0.43	0.047	0.073	0.28	0.062	0.28	0.0027
α	92	-0.294	0.115	0.112	0.0044	0.028	0.056	0.007

$\Rightarrow$ Different radiation types give different products

Radiation effects in nuclear reactors

- Oxidation of metals
- Brittleness (H_2)
- Explosion ($H_2 + O_2$)