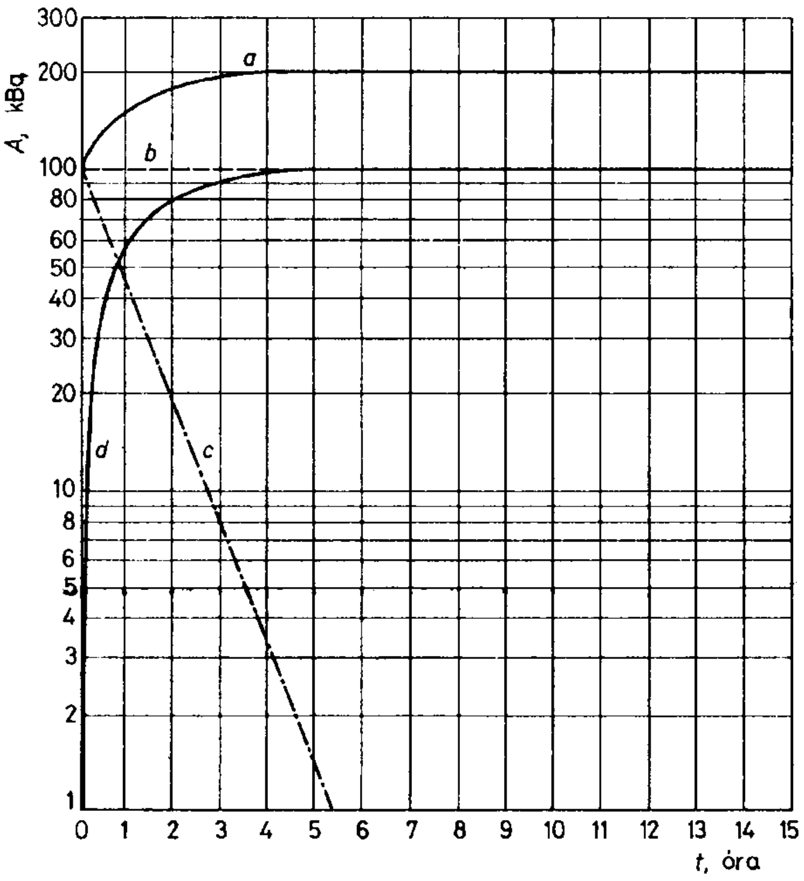
Decay chains

$$X \xrightarrow[T_{1/2,X}]{\lambda_X} Y \xrightarrow[T_{1/2,Y}]{\lambda_Y} Z_{stable}$$

$$A_Y = \lambda_Y N_Y = A_{X,0} \frac{\lambda_Y}{\lambda_Y - \lambda_X} \left(\mathrm{e}^{-\lambda_X t} - \mathrm{e}^{-\lambda_Y t} \right)$$

relation *of* λ_A and λ_B ?



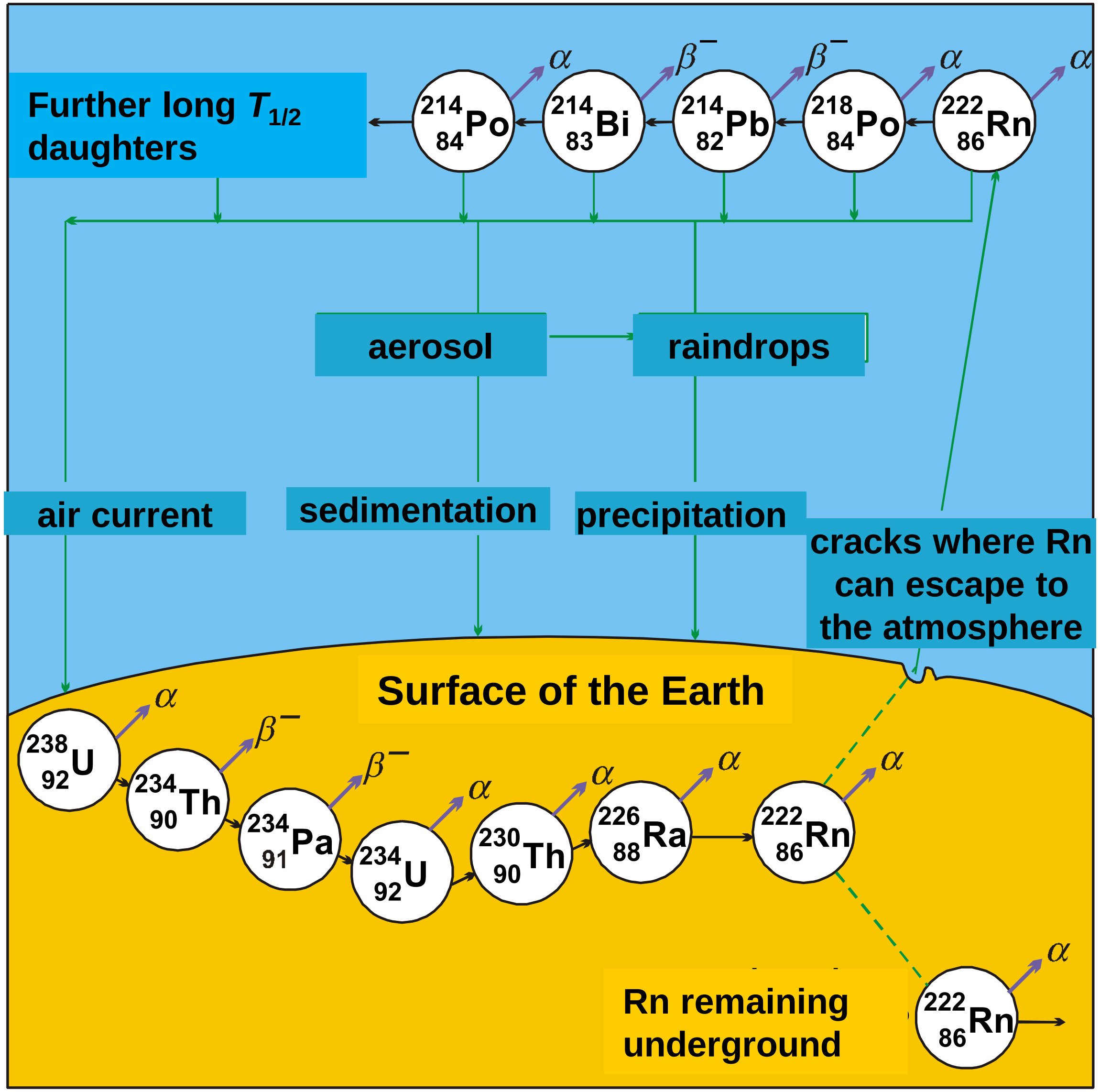
$T_{1/2,X} >> T_{1/2,Y}$

$T_{1/2,X} = 8 \cdot 10^7 h$

$T_{1/2,Y} = 0{,}8 h$

$$ {}^{90}\mathrm{Sr} \xrightarrow[28\,a]{\beta^-} {}^{90}\mathrm{Y} \xrightarrow[64\,h]{\beta^-} {}^{90}\mathrm{Zr} $$

$${}^{226}_{88}\text{Ra} \xrightarrow[1620\,\text{a}]{\alpha} {}^{222}_{86}\text{Rn} \xrightarrow[3{,}83\,\text{d}]{\alpha} \dots {}_{82}\text{Pb}$$



Further long $T_{1/2}$ daughters

aerosol

raindrops

air current

sedimentation

precipitation

cracks where Rn can escape to the atmosphere

Surface of the Earth

Rn remaining underground

When former Russian spy Alexander Litvinenko died from polonium-210 poisoning several years ago in London, it triggered a murder investigation that developed like a thriller.

Po-210 generate much heat as the atoms decay - it was used in Russian lunar landers to keep the craft's instruments warm at night.

.

^{210}Po is an α-emitter, that has a half-life of 138.4 days, E_α = 5.3 MeV

Interaction of the radiation with the matter

Particles/photons

I.		II.	III.
a	b		
p	e^+	n	γ
α	e^-		X

Partners

1. Electromagnetic field
2. Electron
3. Field of the nucleus
4. Nucleus

	Effect on	
Mechanism	**radiation**	**matter**
A) Absorption	ΔI	E_{kin}, E^*
B) Coherent scattering (only the direction is altered))	ΔI	-
C) Incoherent scattering (also exchange of *E*)	ΔI, ΔE	
elastic (no excitation)		E_{kin}
inelastic		E_{kin}, E^*

1. Ionizing radiations

The first step of the ionizing radiation in the matter:

1. Neutral excitation

$A + \text{radiation} \rightarrow A^* + \text{radiation}'$

2. External ionization

$A + \text{radiation} \rightarrow A^+ + e^- + \text{radiation}'$

3. Internal ionization

$A + \text{radiation} \rightarrow A^{*+} + e^- + \text{radiation}'$

$A^{*+} \rightarrow A^+ + X_{char}$

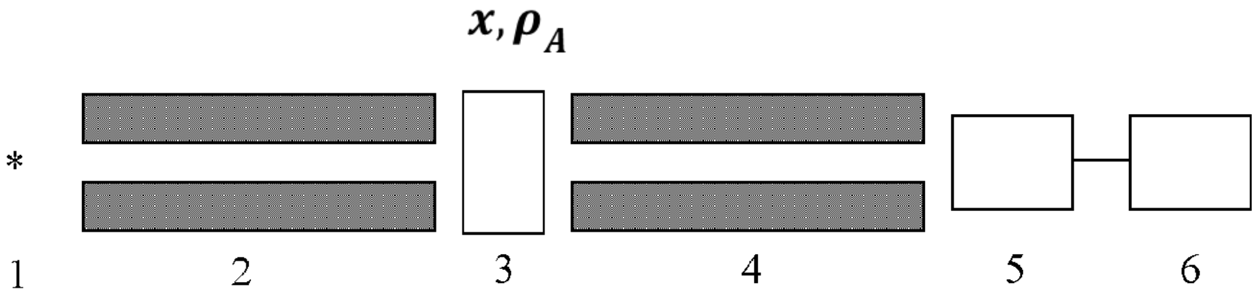
$A^{*+} \rightarrow A^{2+} + e^-_{Auger}$

4. Bremsstrahlung (breaking radiation)

$A + \text{radiation}^{\pm} \rightarrow A + X_b + \text{radiation}^{\pm\prime}$

FUNDAMETALS OF DETECTION

Quantitative description of the interaction



$$\nu = \sigma n x \rho_A$$

cross section

$$-dn = \sigma(E) n \rho_A dx$$

$$n = n_0 e^{-\sigma(E)\rho_A x}$$

$$I = \frac{n}{t}$$

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

linear absorption coefficient

$$I = I_0 e^{-\mu x} = I_0 e^{-\frac{\mu}{\rho} x \cdot \rho} = I_0 e^{-\mu_m d}$$

mass absorption coefficient

$$x_{1/2} = \frac{\ln 2}{\mu} \qquad d_{1/2} = \frac{\ln 2}{\mu_m}$$

α-radiation

Heavy, charged, high energy

With electrons: **incoherent scattering**

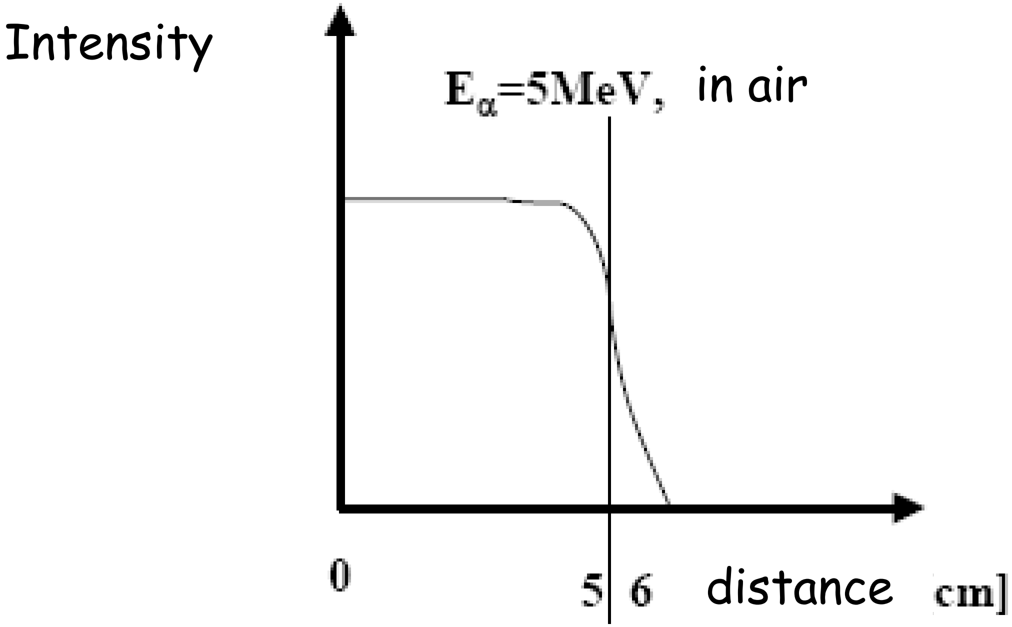
ionisation and excitation (50-50 %)

E and direction of the alpha particles is modified

With the nucleus: **Rutherford-scattering**

nuclear reaction (see later)

! Bremsstrahlung (continuous energy gamma radiation)!



β-radiation small, charged, limited energy

With electron: **incoherent scattering**

ionisation (external and internal)

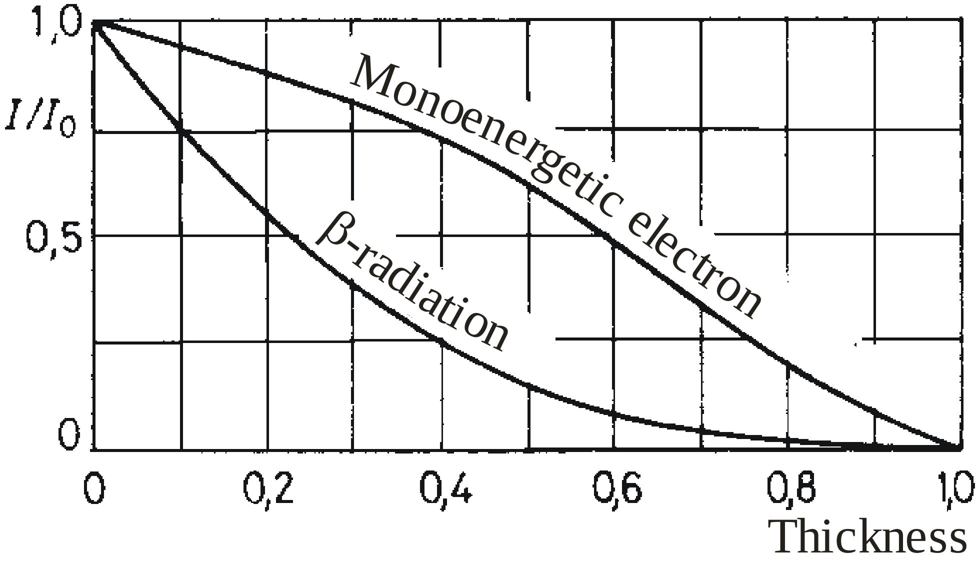
excitation

E and the direction of the radiation changes

$$\frac{\left(\frac{dE}{dx}\right)_r}{\left(\frac{dE}{dx}\right)_{ion}} = \frac{EZ}{800}$$

With the field of the nucleus: **incoherent scattering**

! Bremsstrahlung !

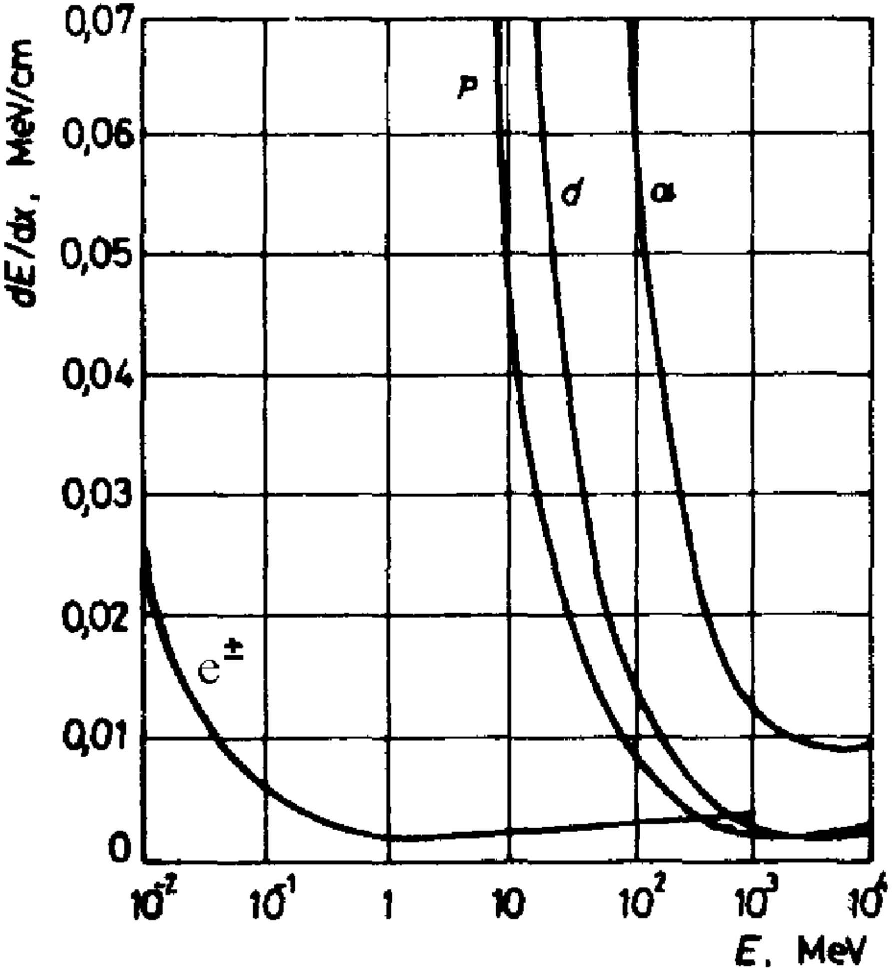


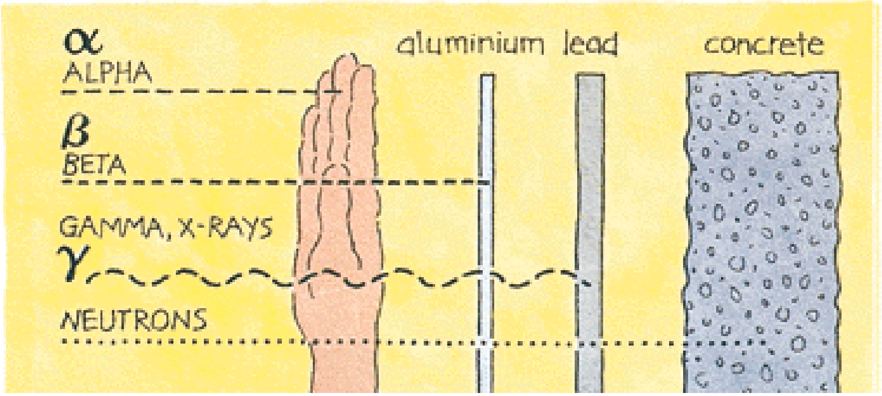
$$I = I_0 e^{-\mu x} = I_0 e^{-\mu_m d}$$

Linear/mass absorption coefficient

Linear energy transfer (LET)

air





$$dE/dx \approx 1/v^2$$

Calculate the activity of 1 kg KCl. 0.012 % of the K atoms is radioactive ^{40}K. The half life of ^{40}K is $1.13 \cdot 10^9$ years.

We prepared a ^{35}S labelled protein at 12:00, 10 September 2014. The half life of the pure β^- emitter is 88 days. This sample was measured at noon on 26 September and the intensity was found 7000 imp/s. The overall effieciency of the measurement was 22 %. Calculate the activity of the sample in the time of synthesis.

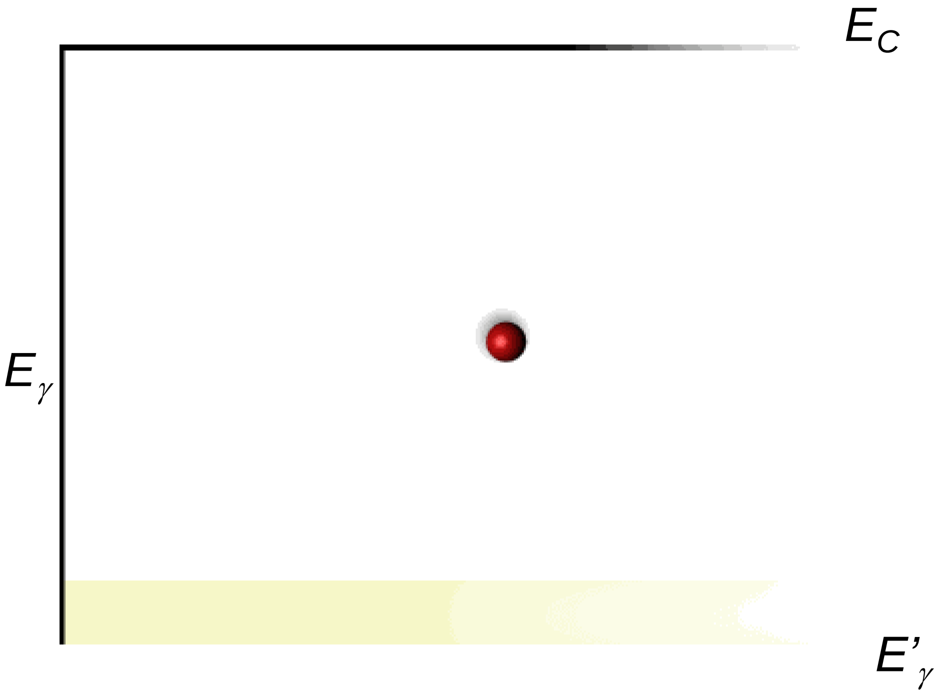
The linear absorption coefficient of gamma radiation of 660 keV in aluminum is 3,4 cm^{-1}. Calculate the half thickness. How efficiently will attenuate this radiation an 10 cm aluminum wall ?

γ-radiation

electromagnetic radiation

1. Compton-scattering

Elastic collision of the photon with an electron



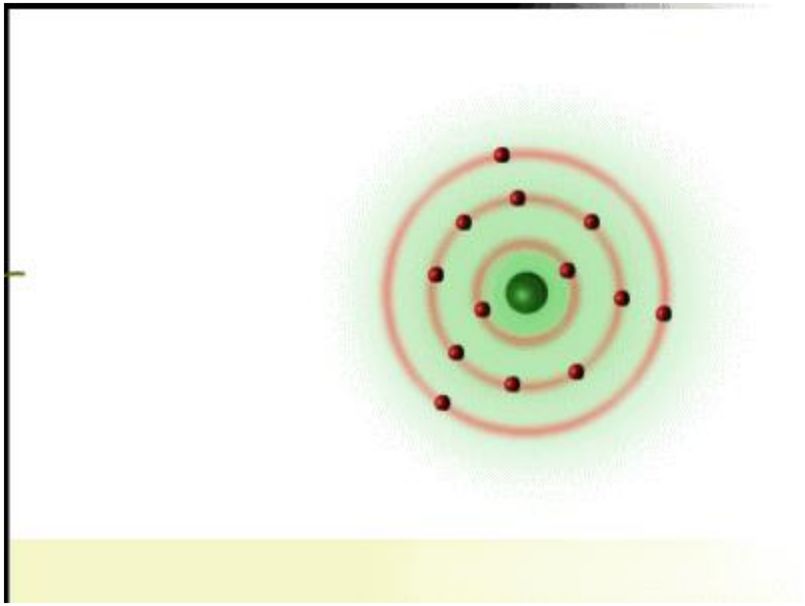
$$\mu_{C,m} = \frac{\mu_C}{\rho} = \sigma_C \frac{\rho_A}{\rho} = \sigma_C \frac{N_A Z}{A}$$

where $\sigma_C = \sigma_s + \sigma_a$

2. Photoelectric effect

$$A + \gamma \longrightarrow A^{*+} + e_{\mathrm{f}}^{-}$$

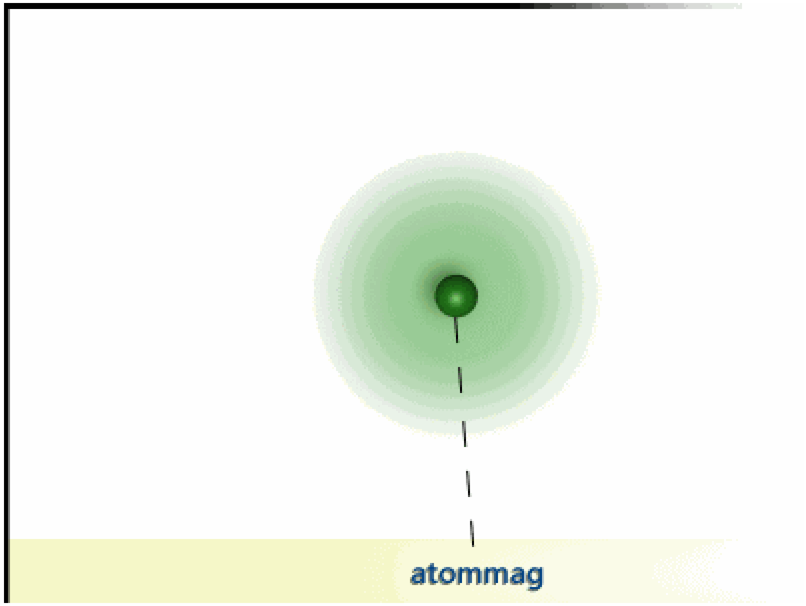
$$\begin{tikzcd}
A^{*+} \arrow[r] \arrow[dr] & A^{+} + X_{\mathrm{k}} \\
 & A^{2+} + e_{\mathrm{A}}^{-}
\end{tikzcd}$$



$$\sigma_{\mathrm{f}} \approx \mathrm{konst.}\ \frac{Z^{n}}{(h\nu)^{3}}$$

$n(E)$=4 - 5

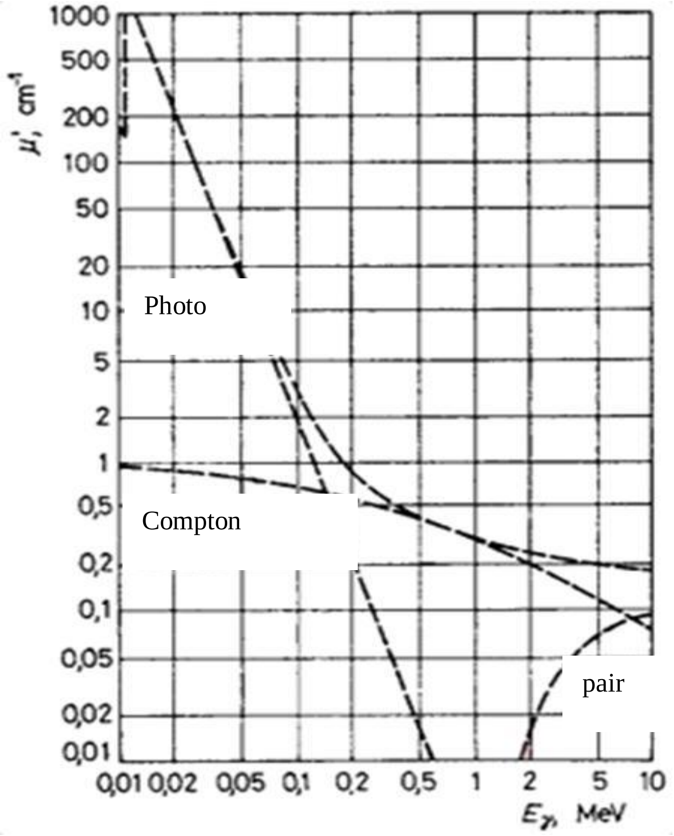
3. Pair production

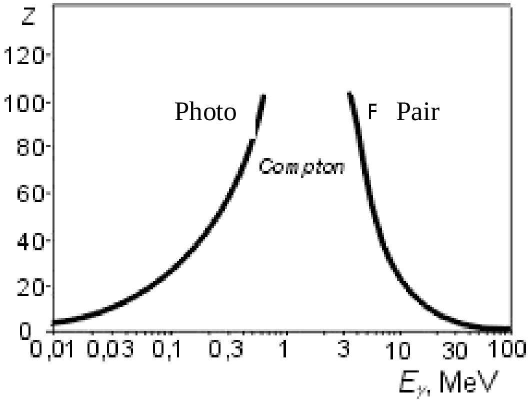


$$\sigma_p = K\left(E_\gamma - 1{,}02\right)^{2{,}2} Z^2$$

$$I = I_0 e^{-\mu d} = I_0 e^{-(\mu_C + \mu_f + \mu_p) d}$$

Germanium





2. Nuclear reactions

Cross section (~probability)

Conventional equation

$^{10}B + \alpha \rightarrow$

$^{14}N^*$

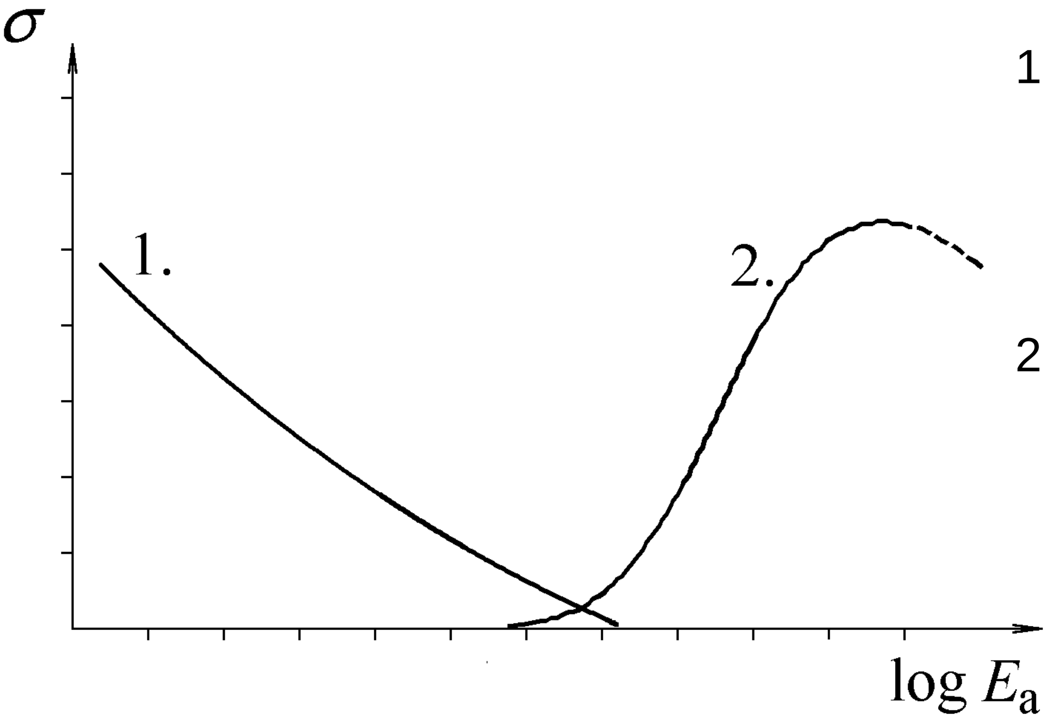
$\rightarrow {}^{10}B + \alpha$

$\rightarrow {}^{13}C + p$

$\rightarrow {}^{13}N + n$

$^{12}C + d \rightarrow$

Transition state



1.
- (n,γ)
- (n,f) ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu
- $^{10}B(n,\alpha)$
- $^{6}Li(n,\alpha)$

2.
- (γ,n)
- $(n,2n)$
- (n,α)
- (p,)
- (d,)

Tunnel effect

Kinetics of the nuclear reactions

$$\frac{dN^*}{dt} = \sigma_\mathrm{a} N\phi - \lambda N^*$$

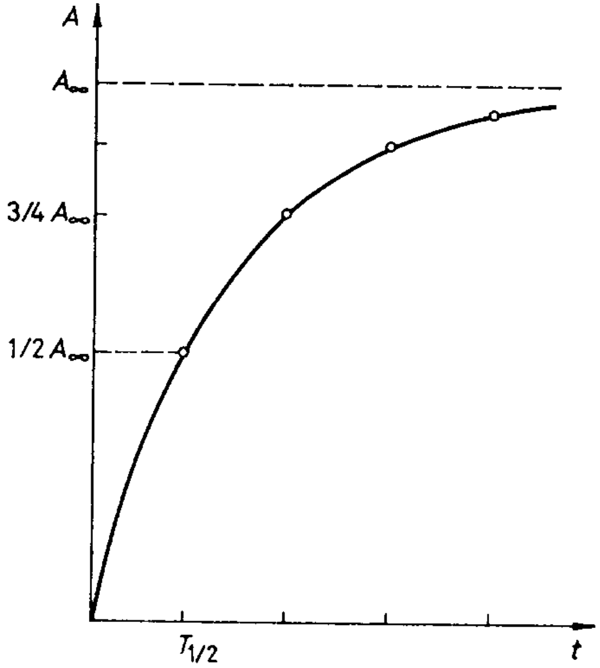
$$N^* = N^*_\infty\left[1-\exp\left(-\lambda t\right)\right]$$

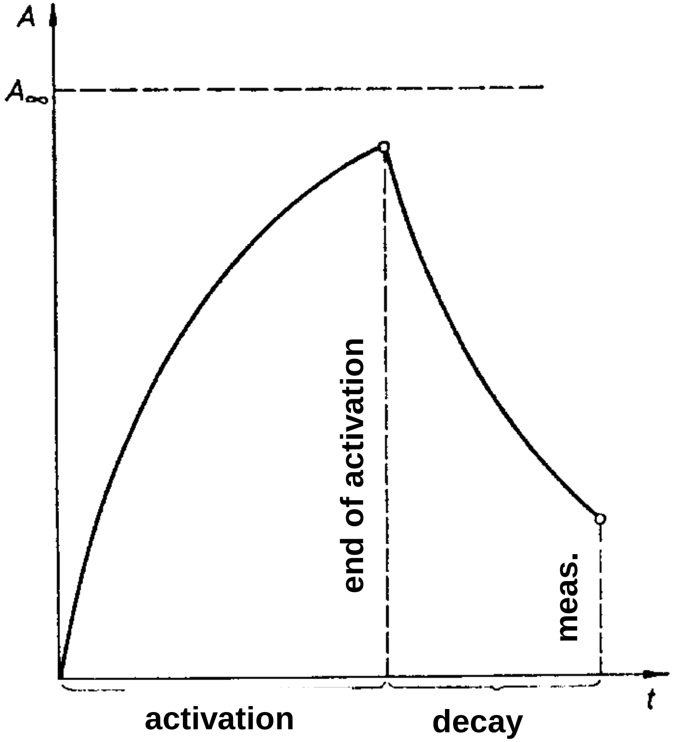
$$A = A_\infty\left[1-\exp\left(-\lambda t\right)\right]$$

$$A_\infty = \lambda N^*_\infty = \phi\sigma_a N$$

$$A' = \lambda N^* =$$

$$= A_\infty\left[1-\exp\left(-\lambda t\right)\right]\exp\left(-\lambda t_h\right)$$





We intend to obtain ^{65}Ni with neutron irradiation. Therefore, we expose 1 g of Ni (with a ^{64}Ni content of 91 %) to neutrons with a flux $\Phi=10^{12}$ 1/cm^{2}s. Thre cross section σ of the

$$^{64}\mathrm{Ni}(n,\gamma)^{65}\mathrm{Ni}$$

reaction is $1.55\cdot10^{-28}$ m^2. The half-life of ^{65}Ni is 2.52 h.

i) How long should the irradtiation last if we want to reach 80 % of the saturation activity?

ii) Estimate the ratio of the ^{64}Ni/^{65}Ni isotopes in the sample after being „cooled" for the same period as the activation lasted.

Interaction of neutrons with the matter

relatively heavy, no charge, energy ?

- elastic scattering

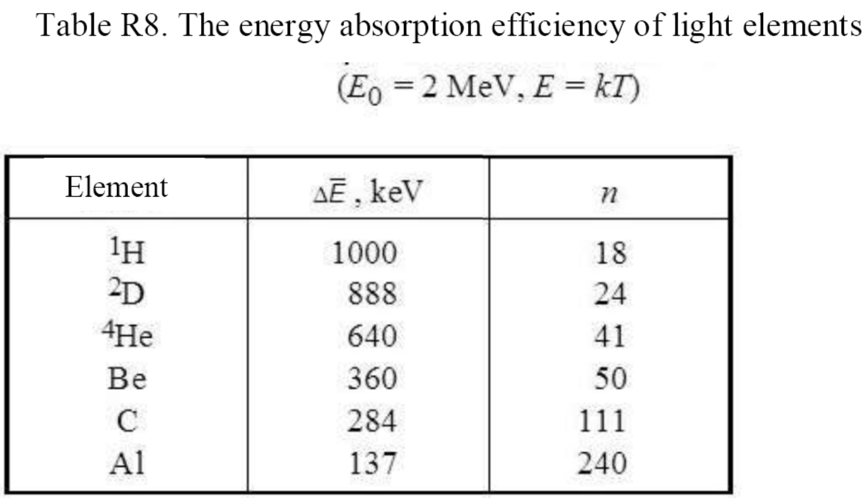


Table R8. The energy absorption efficiency of light elements

($E_0 = 2$ MeV, $E = kT$)

Element	$\Delta\bar{E}$, keV	n
^{1}H	1000	18
^{2}D	888	24
^{4}He	640	41
Be	360	50
C	284	111
Al	137	240

- inelastic scattering

Excited nucleus, hν

- neutron capture

(absorption): (n,?)

Due to the strong E dependence,

1. Slow			
a) cold		$E <$	0.025 eV
b) ***thermal***	0.025 eV	$< E <$	0.44 eV
c) resonance	0.44 eV	$< E <$	1000 eV
2. Medium	1 keV	$< E <$	500 keV
3. Fast	0.5 MeV	$< E <$	10 MeV
4. High energy	10 MeV	$< E <$	50 MeV
5. Super fast	50 MeV	$< E$	

Examples of practical relevance

(n,γ) $^{113}\mathrm{Cd}(n,\gamma)^{114}\mathrm{Cd}$ $\sigma = 6{,}31\cdot10^{-24}\ \mathrm{m}^2$

$^{135}\mathrm{Xe}(n,\gamma)^{136}\mathrm{Xe}$ $\sigma = 2{,}7\cdot10^{-22}\ \mathrm{m}^2,$

$^{149}\mathrm{Sm}(n,\gamma)^{150}\mathrm{Sm}$ $\sigma = 6{,}6\cdot10^{-24}\ \mathrm{m}^2,$

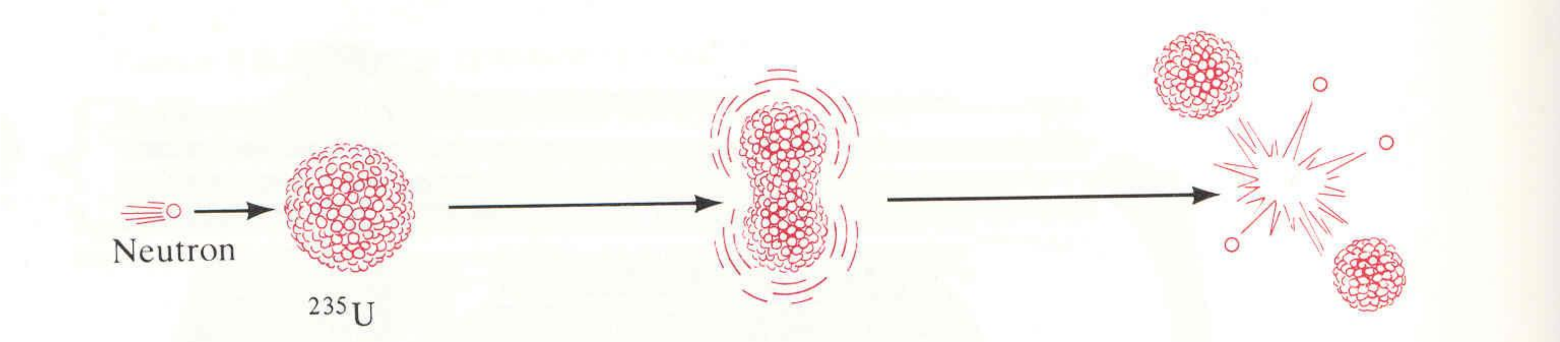
$^{157}\mathrm{Gd}(n,\gamma)^{158}\mathrm{Gd}$ $\sigma = 4{,}6\cdot10^{-23}\ \mathrm{m}^2,$

(n,α) $^{10}\mathrm{B}(n,\alpha)^{7}\mathrm{Li}$ $\sigma = 3\cdot10^{-25}\ \mathrm{m}^2$

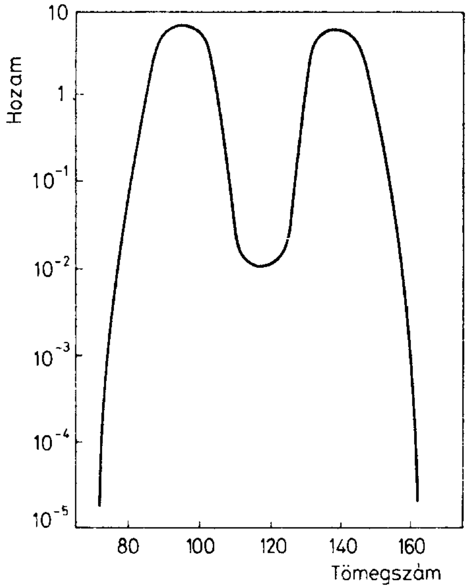
(n,f) fission

Fuel	Source of the fuel	Neutron energy needed
^{235}U	natural uranium	0.025 eV< E_{neutron} < 0.44 eV (thermal)
^{233}U	from thorium with n absorption	0.025 eV< E_{neutron} < 0.44 eV (thermal)
^{239}Pu	from ^{238}U with n absorption	0.025 eV< E_{neutron} < 0.44 eV (thermal)
^{241}Pu	from ^{238}U with n absorption	0.025 eV< E_{neutron} < 0.44 eV (thermal)
^{238}U	natural uranium	0.5 MeV< E_{neutron} < 10 MeV (fast)
^{232}Pu	natural thorium	0.5 MeV< E_{neutron} < 10 MeV (fast)

Fission (*n, f*)



$$ {}^{235}\mathrm{U} + n \xrightarrow{\left[{}^{236}\mathrm{U}\right]} 3n + {}^{90}\mathrm{Kr} + {}^{143}\mathrm{Ba} \;\; +200\ \mathrm{MeV} $$



50 ways, 300 isotopes 35 elements

$$ {}^{90}\mathrm{Kr} \xrightarrow[33\ \mathrm{s}]{\beta^{-}} {}^{90}\mathrm{Rb} \xrightarrow[2{,}7\ \mathrm{min}]{\beta^{-}} {}^{90}\mathrm{Sr} \xrightarrow[28\mathrm{a}]{\beta^{-}} {}^{90}\mathrm{Y} \xrightarrow[64\mathrm{h}]{\beta^{-}} {}^{90}\mathrm{Zr} $$

Distribution 200 MeV

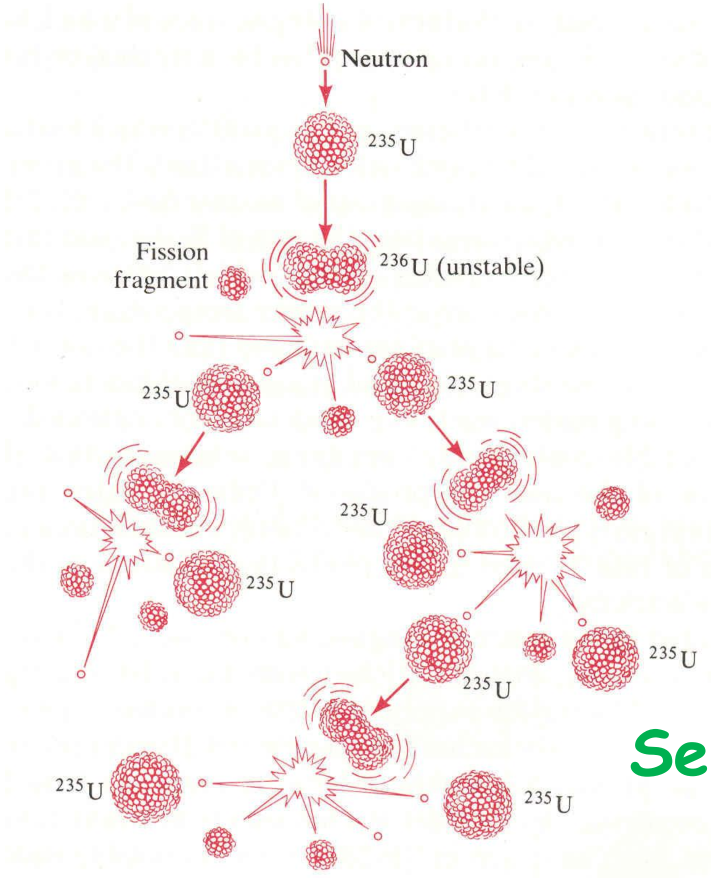
kinetic energy of fission products: ≈ 160 MeV

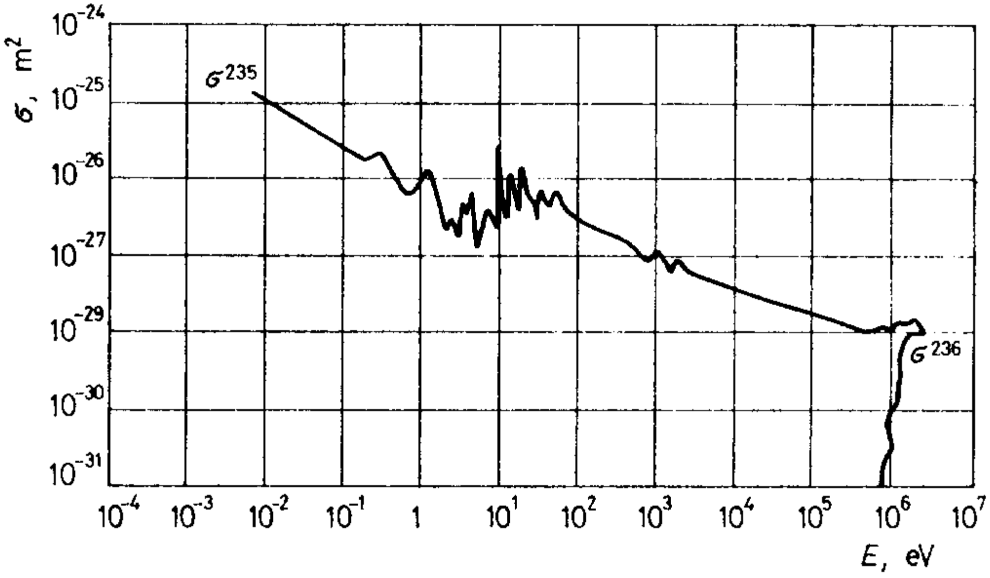
kinetic energy of the neutrons: ≈ 5 MeV

energy of the γ-rays: ≈ 5 MeV

energy of the secondary radioactive decay: ≈ 20 MeV

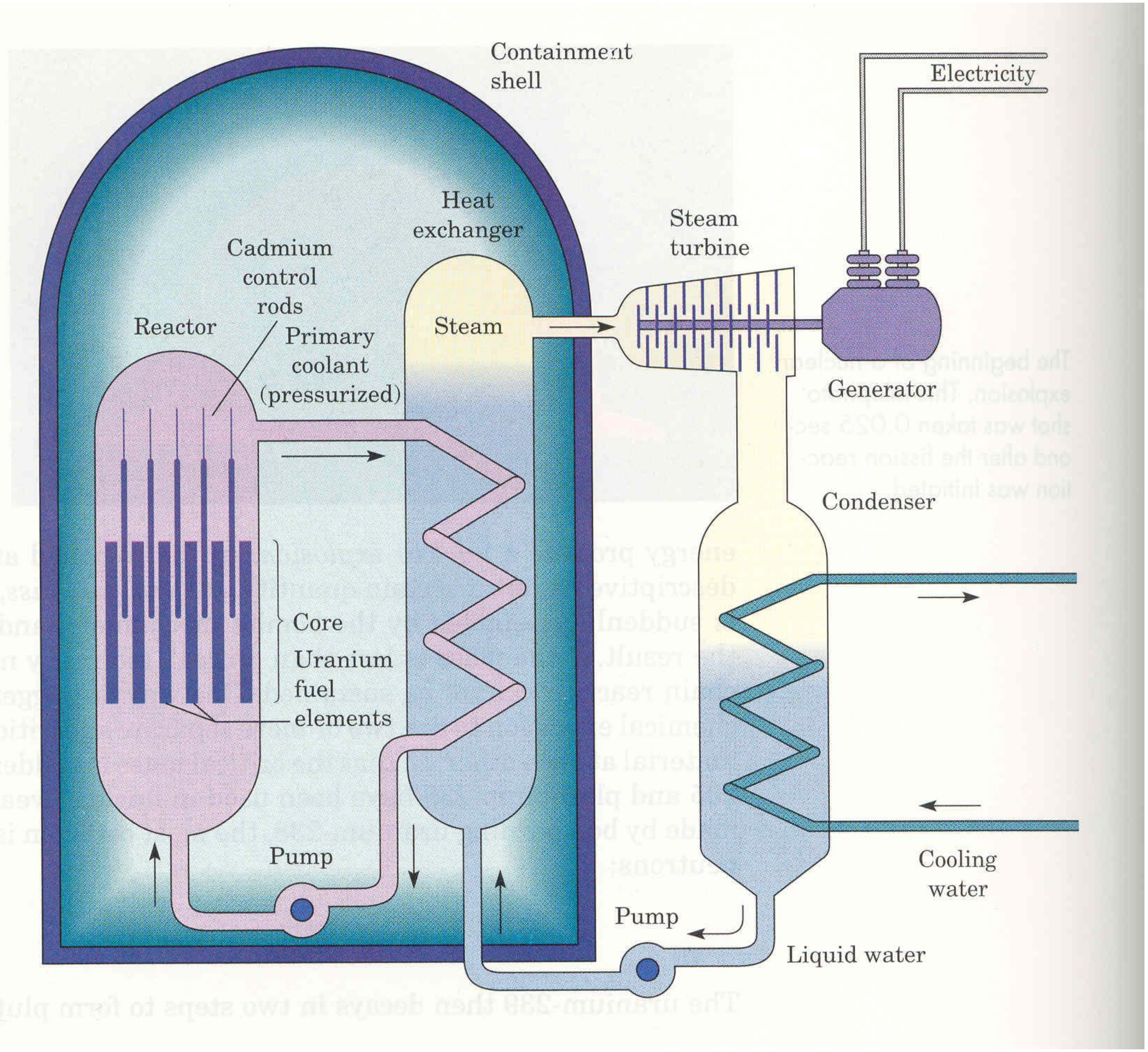
energy released at neutron capture: ≈ 10 MeV





Self-sustaining chain reaction: control

Nuclear reactor



Fuel
Moderator
Cooling system
Control