
Neutronen

CD cursus 2023-2024

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PARTREC/UMCG



rijksuniversiteit
 groningen



university of
 groningen

kvi - center for advanced
 radiation technology



PARTREC

High precision, innovation & patient comfort



umcg

PARTREC\KVI

KVI/KVI-CART

PARTREC\PARTICLE THERAPY RESEARCH CENTRE

PARTREC accelerator AGOR 190 MeV p cyclotron



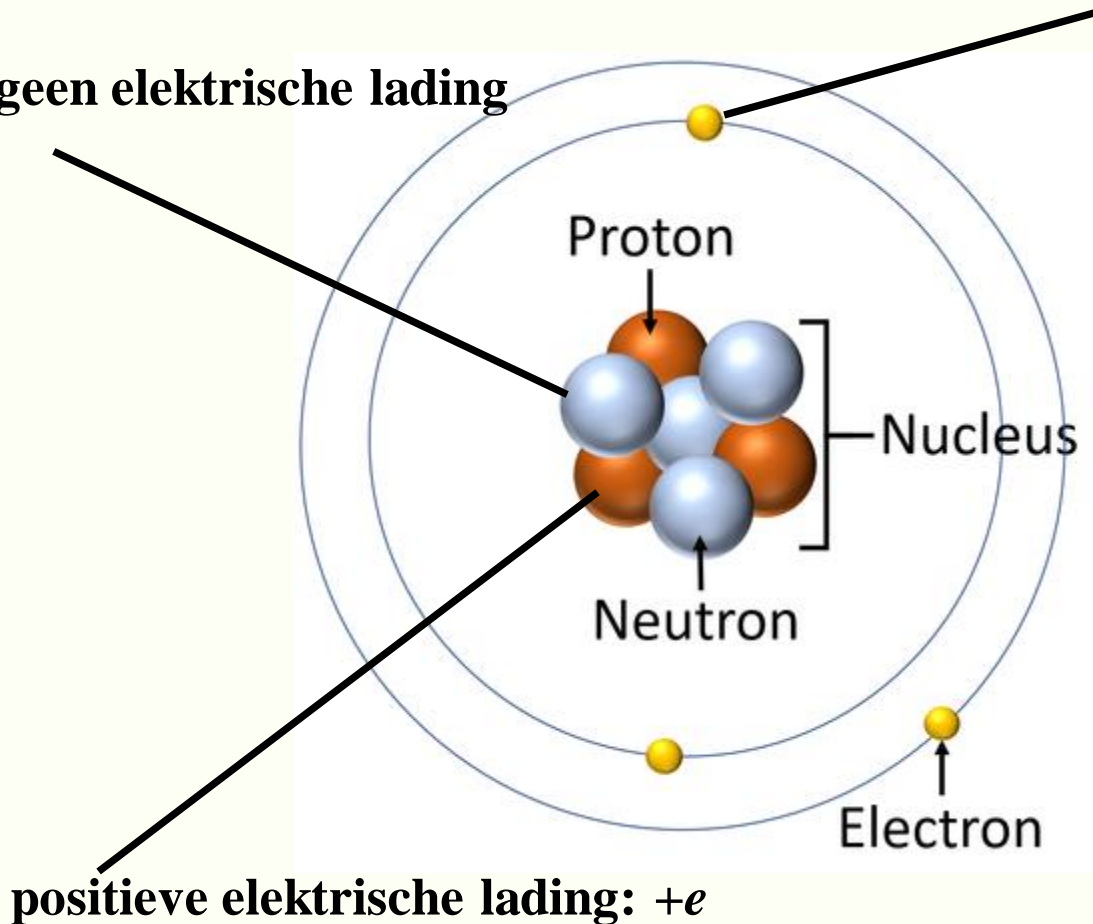
partrec

Atoom

een atoom is neutraal, er is geen netto elektrische lading

negatieve elektrische lading: $-e$

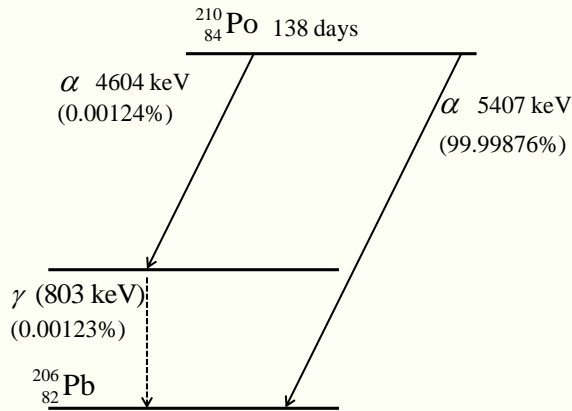
geen elektrische lading



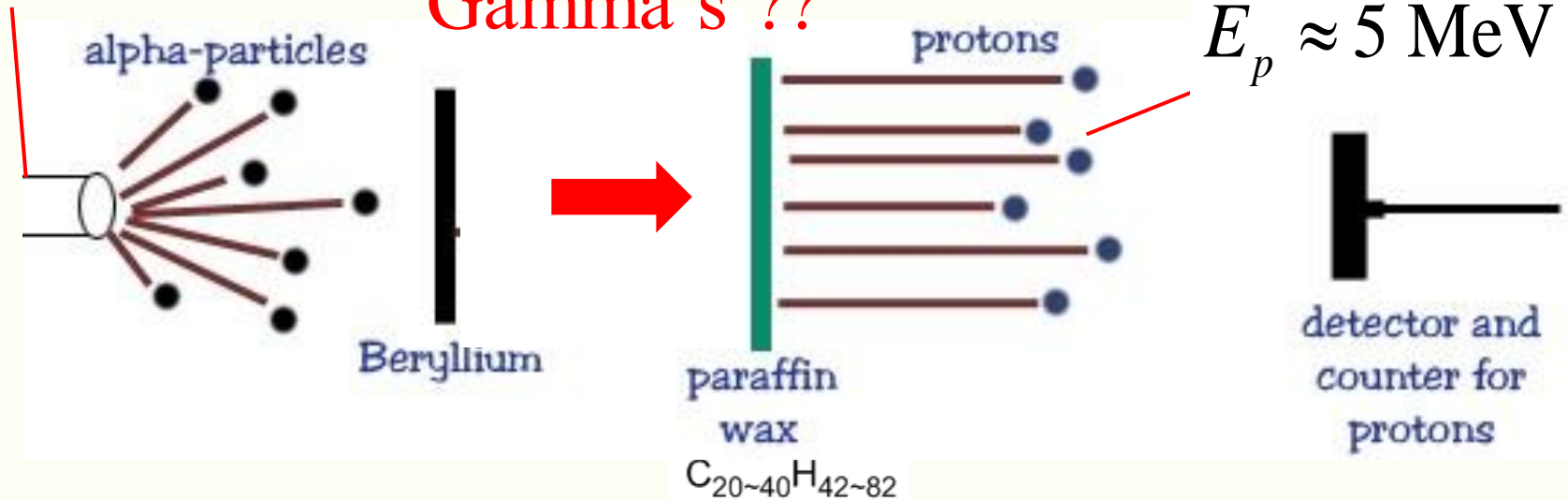
positieve elektrische lading: $+e$

Neutronen

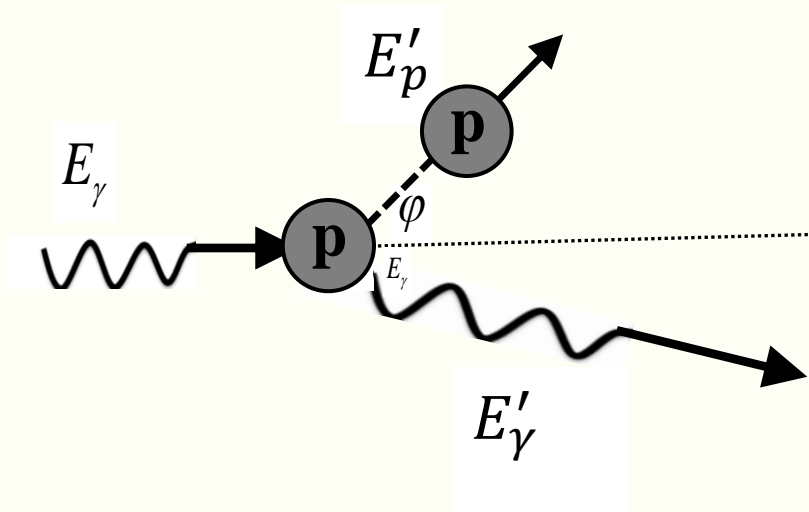
Ontdekt door Chadwick in 1932



Gamma's ??



Comptoneffect met een *proton*



$$(\Delta E)_{max} = \frac{E_\gamma}{\left(1 + \frac{m_p c^2}{2E_\gamma}\right)}$$

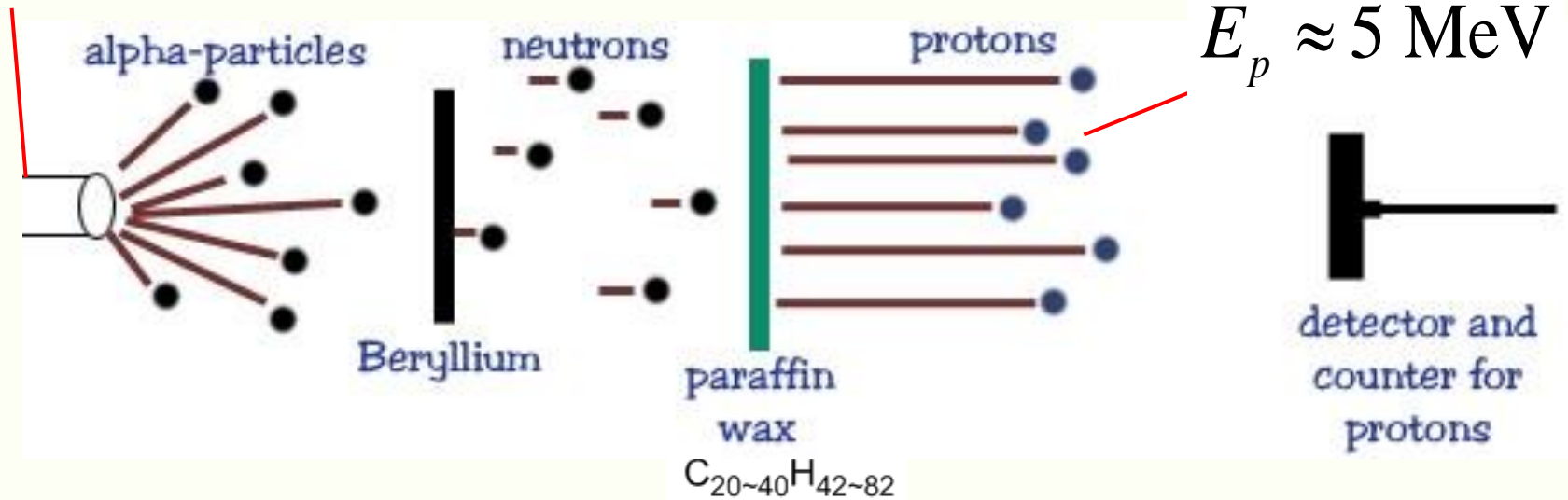
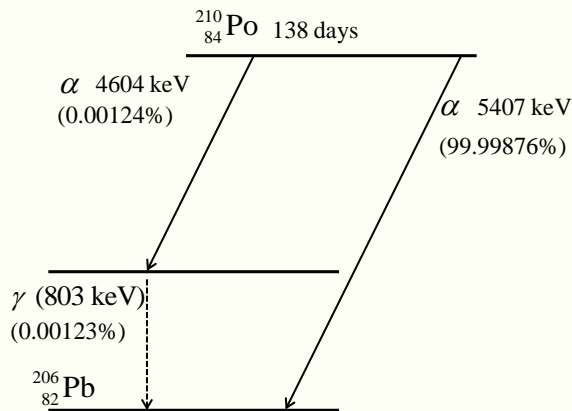
Maximum energieverdracht
aan het *proton*
(voor electron: verg. 6.27-6.28
in boek)

$$5(\text{MeV}) = \frac{E_\gamma}{\left(1 + \frac{938}{2E_\gamma}\right)} \Rightarrow E_\gamma = 46 \text{ MeV}$$

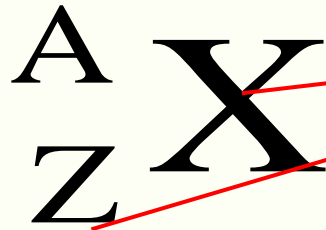
gemeten protonenergie

Neutronen

Ontdekt door Chadwick in 1932



Kernbouw



chemisch element:
H (Z=1), He (Z=2),
Li (Z=3), C (Z=6), etc

Z: atoomnummer is het aantal protonen

A: massagetal is het aantal nucleonen

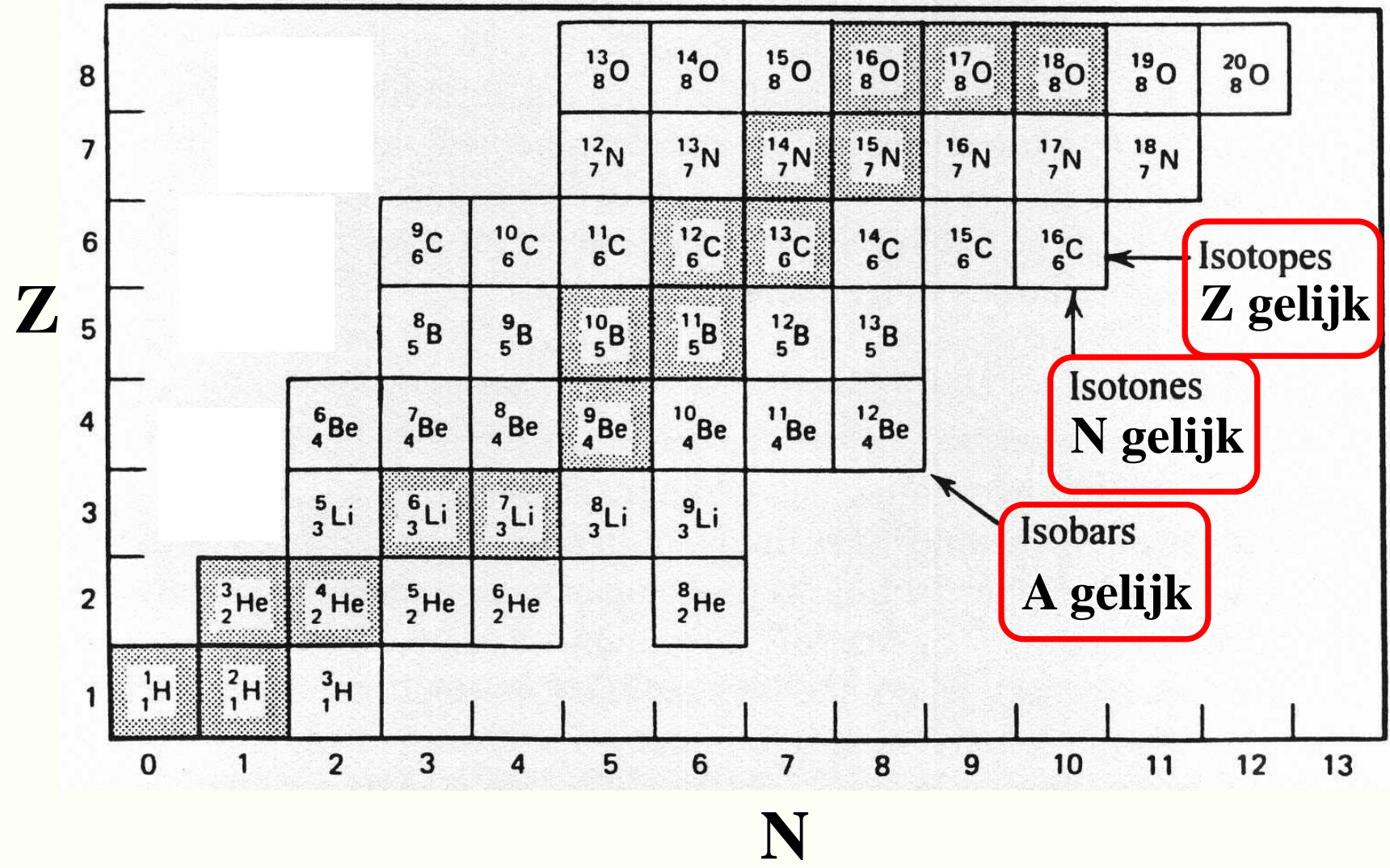
N: neutronengetal is aantal neutronen

$$A = Z + N$$

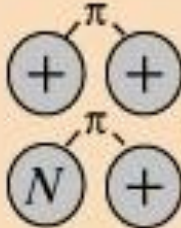
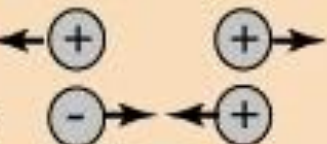
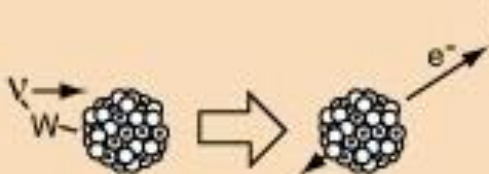
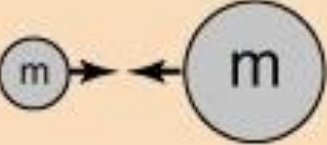
nucleonen $\left\{ \begin{array}{l} \text{protonen} \\ \text{neutronen} \end{array} \right.$



Isotopen, Isotonen, Isobaren

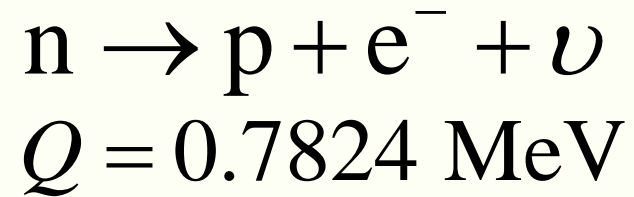
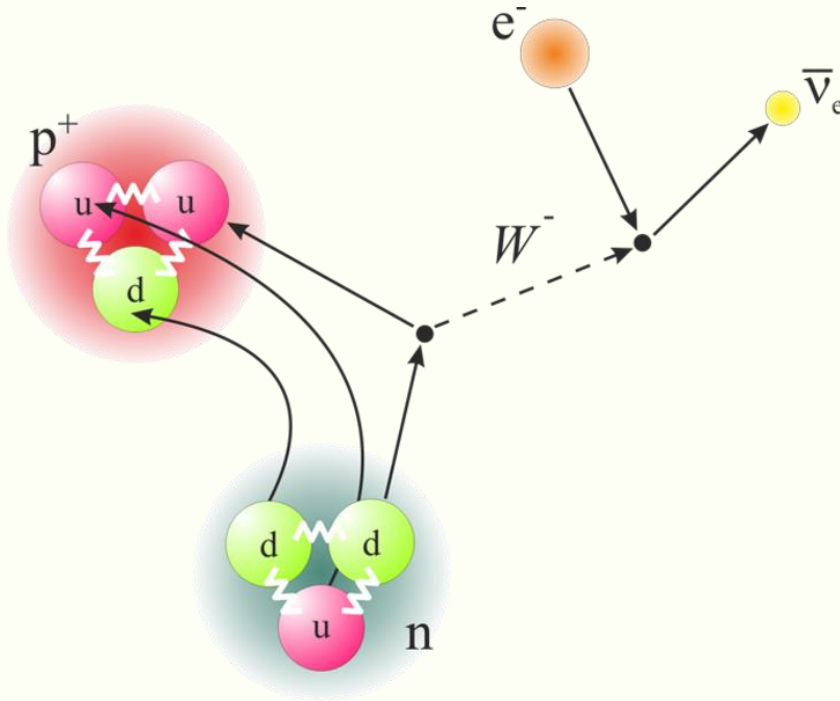


Vier fundamentele krachten

<i>Strong</i>	 <p>Force which holds nucleus together</p>	Strength 1	Range (m) 10^{-15} (diameter of a medium sized nucleus)	Particle gluons, π (nucleons)
<i>Electro-magnetic</i>		Strength $\frac{1}{137}$	Range (m) Infinite	Particle photon mass = 0 spin = 1
<i>Weak</i>	 <p>neutrino interaction induces beta decay</p>	Strength 10^{-6}	Range (m) 10^{-18} (0.1% of the diameter of a proton)	Particle Intermediate vector bosons W^+ , W^- , Z_0 , mass > 80 GeV spin = 1
<i>Gravity</i>		Strength 6×10^{-39}	Range (m) Infinite	Particle graviton? mass = 0 spin = 2

Verval van het neutron

$$T_{\frac{1}{2}} = 611 \text{ s}$$

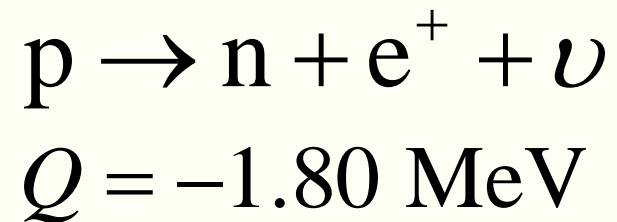


$$M_n = 939.565 \text{ MeV}$$

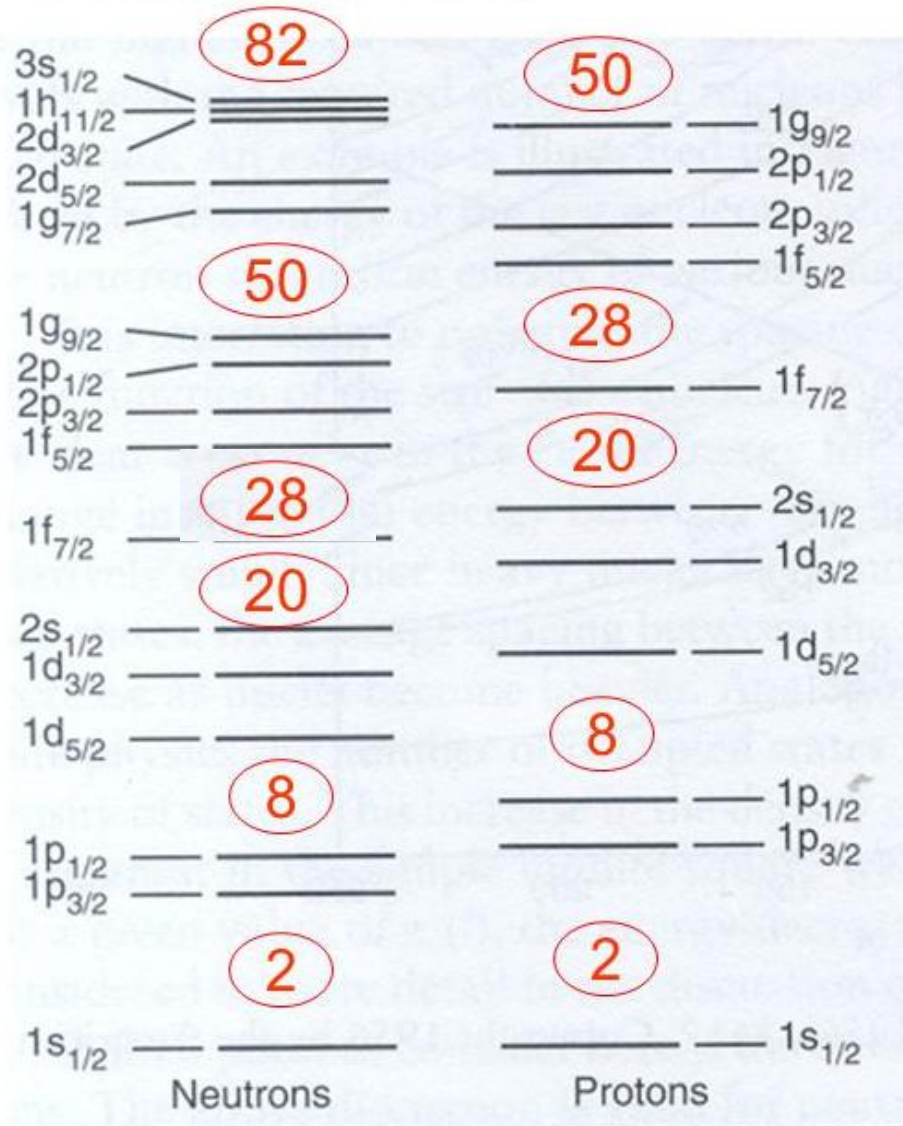
$$\left[\begin{array}{l} M_p = 938.272 \text{ MeV} \\ M_e = 0.511 \text{ MeV} \end{array} \right]$$

$$= 0.782 \text{ MeV}$$

En het proton?



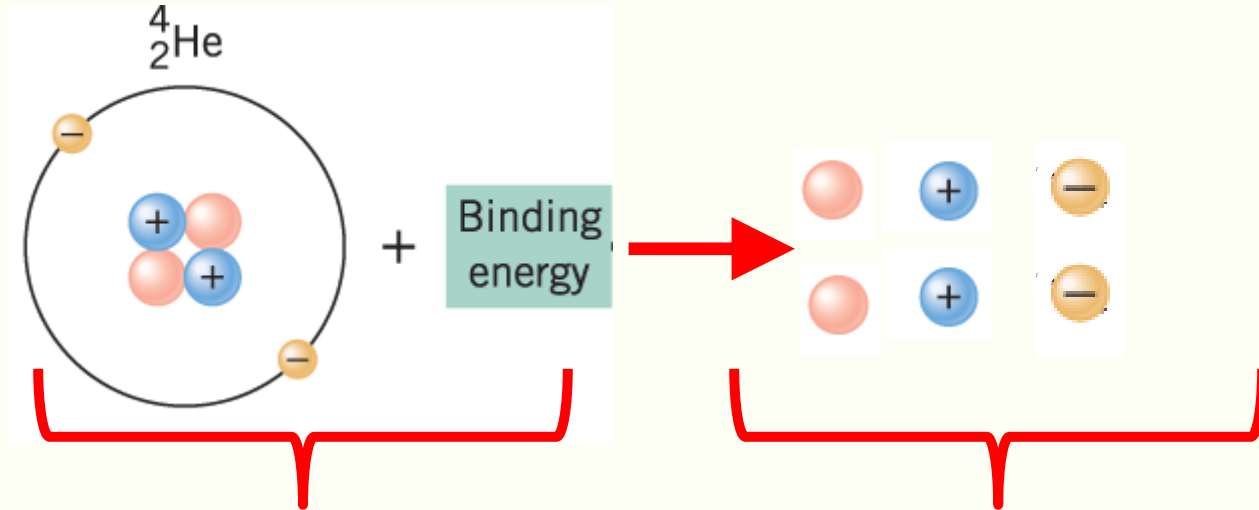
Schillenmodel van de kern



protonen en neutronen in de kern hebben discrete energieën (schillen)

De energieniveaus voor de protonen liggen hoger dan die van de neutronen door de Coulomb afstoting

Bindingsenergie van helium



$$M({}^4_2\text{He}) = 4.00260\text{u}$$

$$M(\text{p}) = 1.007276\text{u}$$

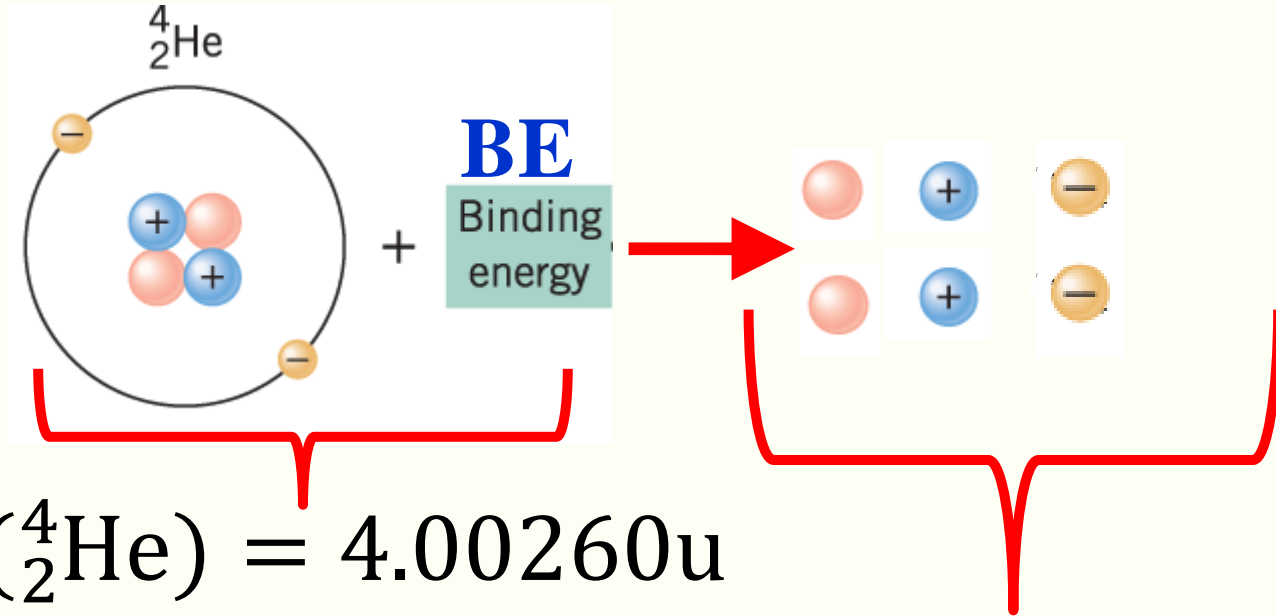
$$M(\text{n}) = 1.008664\text{u}$$

$$M(\text{e}) = 0.000550\text{u} +$$

$$2.016490\text{u} \times 2$$

$$4.03298\text{u}$$

Bindingsenergie van helium

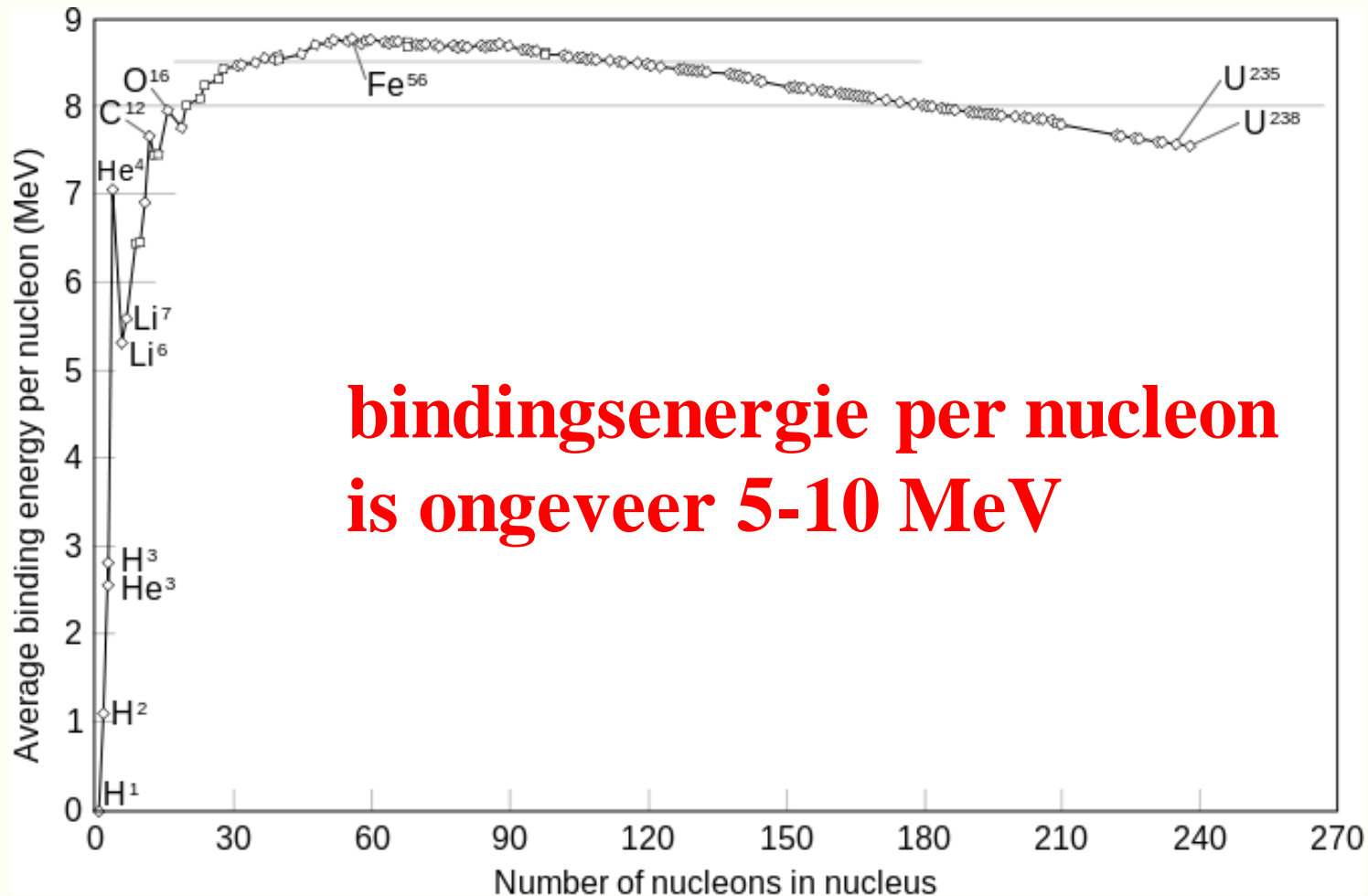


$$\text{BE} = 2M(\text{p}) + 2M(\text{n}) + 2M(\text{e}) - M({}^4_2\text{He}) = 4.03298 - 4.00260 = 0.03038\text{u} = 28.30 \text{ MeV}$$

$$1\text{u} = 931.49 \text{ MeV}$$

Bindingsenergie

$$BE({}_Z^A X) = ZM(p) + (A - Z)M(n) + ZM(e) - M({}_Z^A X)$$



Q-waarde

Q-waarde van een reactie is de energie die vrijkomt of nodig is om van de begintoestand naar de eindtoestand van de reactie te komen.



Behoud van energie; T : kinetische energie, Mc^2 : rustenergie

$$M_a c^2 + T_a + M_X c^2 = M_b c^2 + T_b + M_Y c^2 + T_Y$$

Q-waarde is het verschil tussen de kinetische energie van de eindtoestand en de begintoestand

$$Q = T_b + T_Y - T_a = \left[(M_a + M_X) c^2 - (M_b + M_Y) c^2 \right]$$

Q-waarde

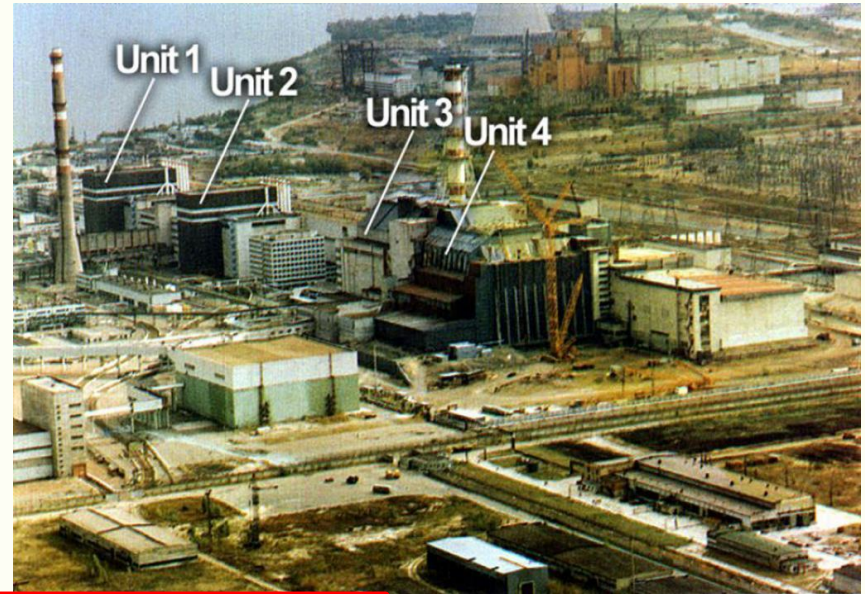
$$Q = T_b + T_Y - T_a = \left[(M_a + M_X)c^2 - (M_b + M_Y)c^2 \right]$$

$Q > 0$ **Exotherme reactie, energie komt vrij bij de omzetting van rustenergie in kinetische energie**

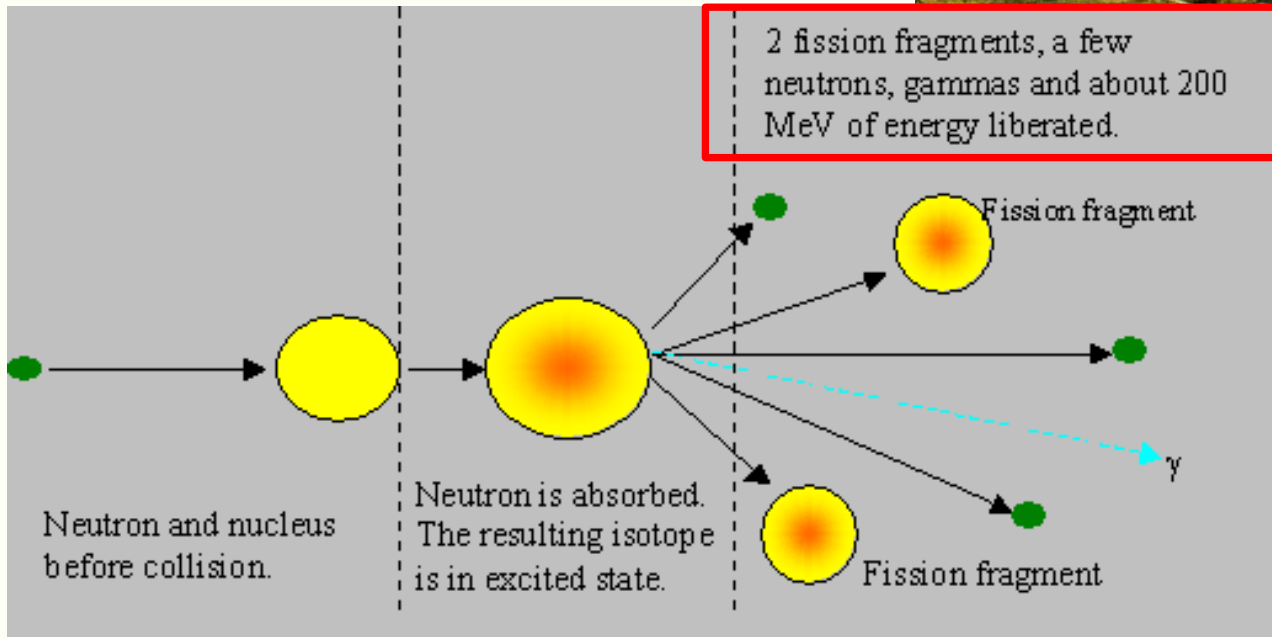
$Q < 0$ **Endotherme reactie, kinetische energie wordt omgezet in rustenergie**

Neutronenbronnen

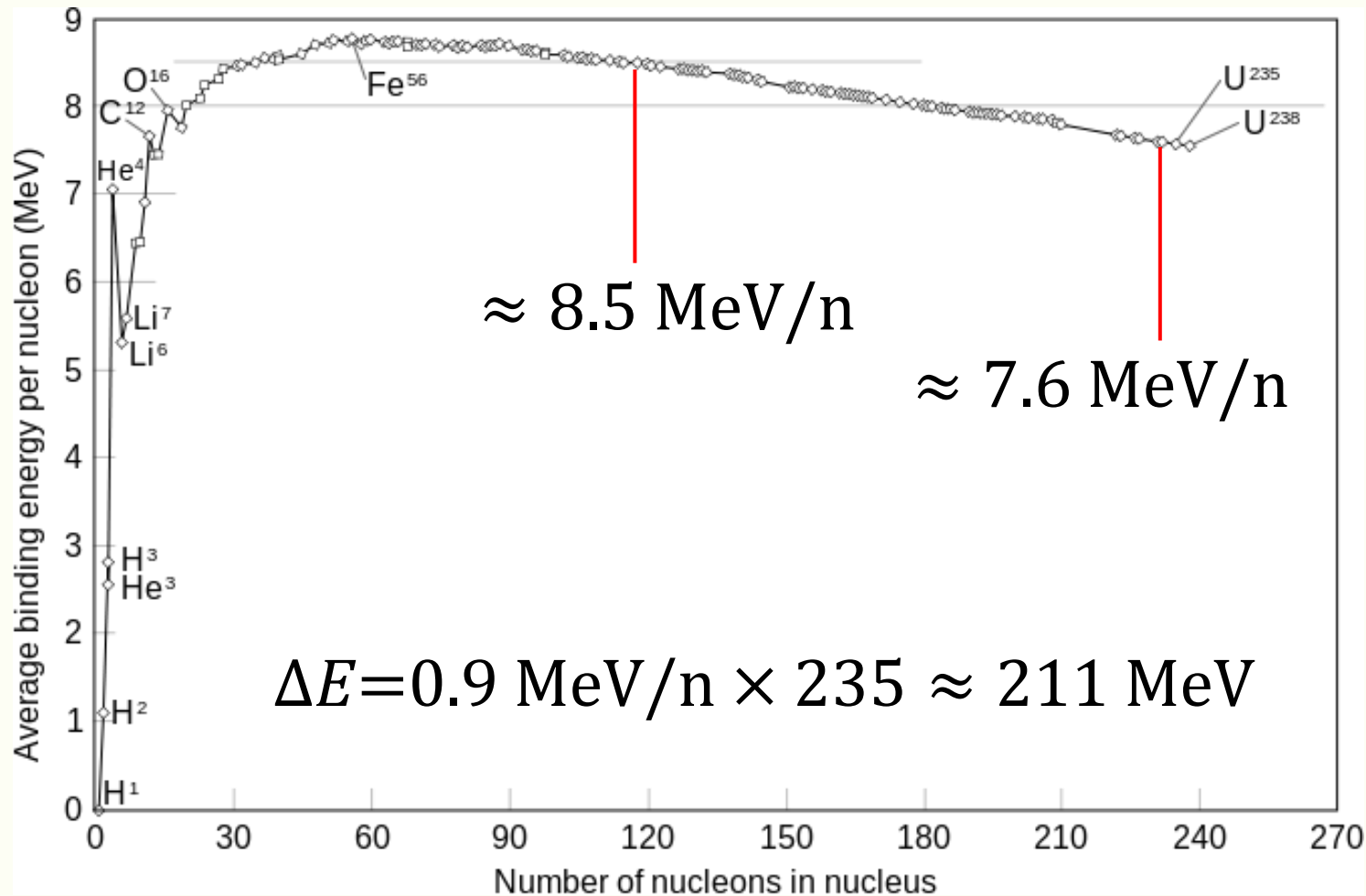
Kernreaktoren



Chernobyl

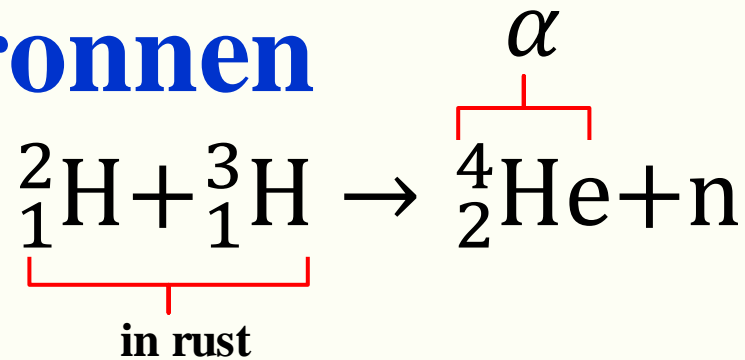


Energie uit kernsplijting



Neutronenbronnen

Kernreacties



$$Q = 17.59 \text{ MeV}$$

$$\frac{1}{2} m_{\alpha} v_{\alpha}^2 + \frac{1}{2} m_n v_n^2 = Q$$

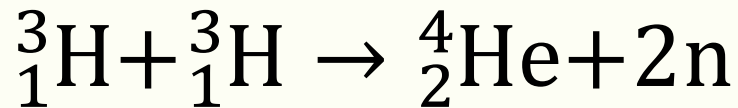
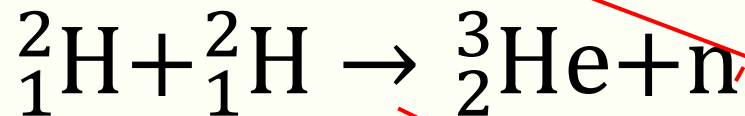
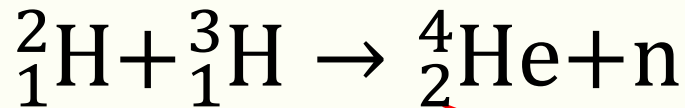
$$m_{\alpha} v_{\alpha} + m_n v_n = 0$$



$$E_n^{kin} = \frac{m_{\alpha}}{m_{\alpha} + m_n} Q = \frac{4}{5} Q \approx 14 \text{ MeV}$$

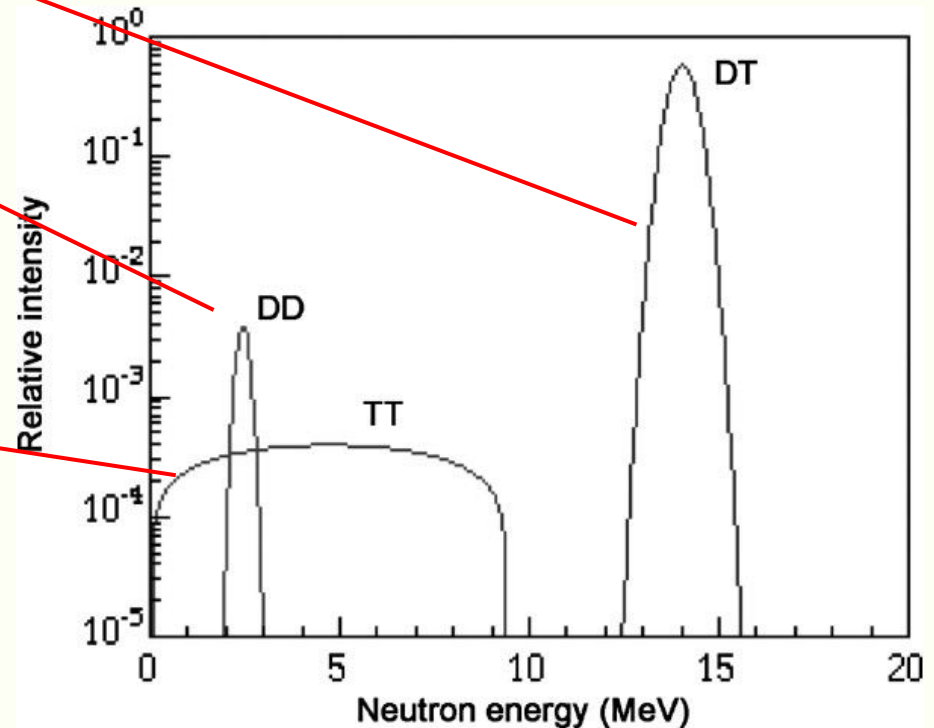
Neutronenbronnen

Kernreacties



$Q=11.4 \text{ MeV}$

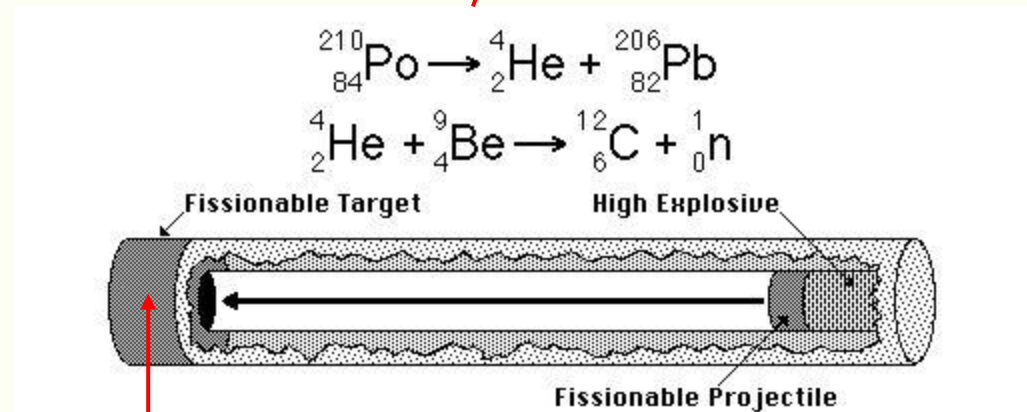
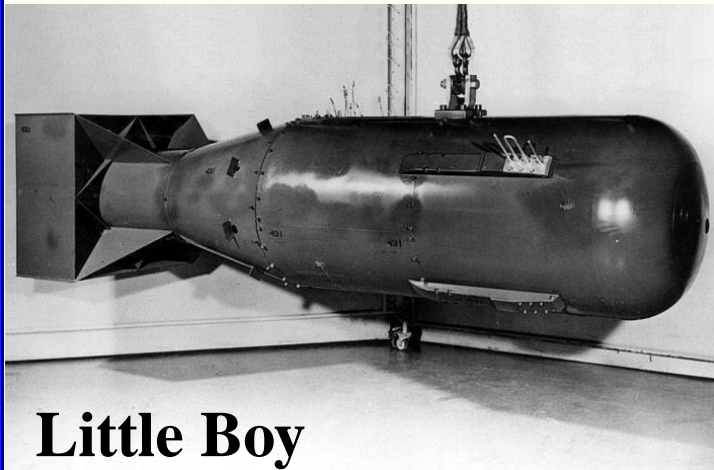
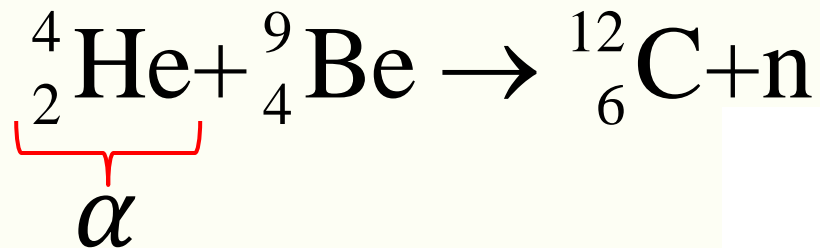
$$E_n^{kin} = \frac{m_{{}^3\text{He}}}{m_\alpha + m_{{}^3\text{He}}} Q = \frac{3}{4} Q$$
$$= \frac{3}{4} \times 3.27 = 2.45 \text{ MeV}$$



Neutronenbronnen

(alfa n) bronnen

Combinatie van een alfa-emitter (bijv. ^{210}Po , ^{226}Ra , ^{239}Pu , ^{241}Am) en een licht element (bijv. Be or B)



Positie van de Po-Be initiator

Neutronenbronnen

(alfa n) bron

Neutron source: ^{241}Am : $^9\text{Be}(\alpha, n)^{12}\text{C}$

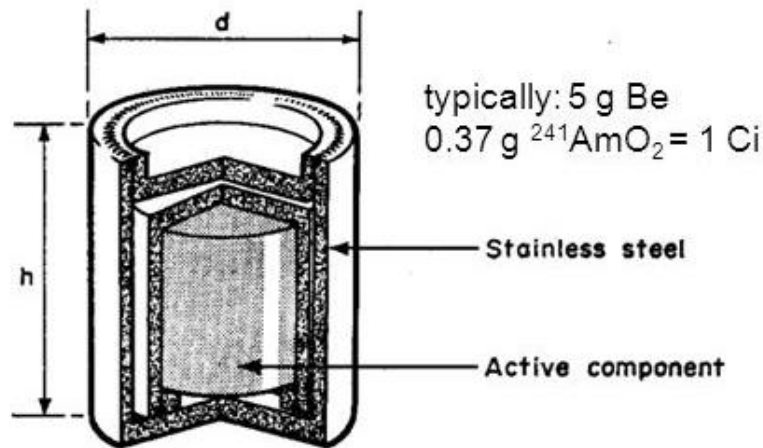
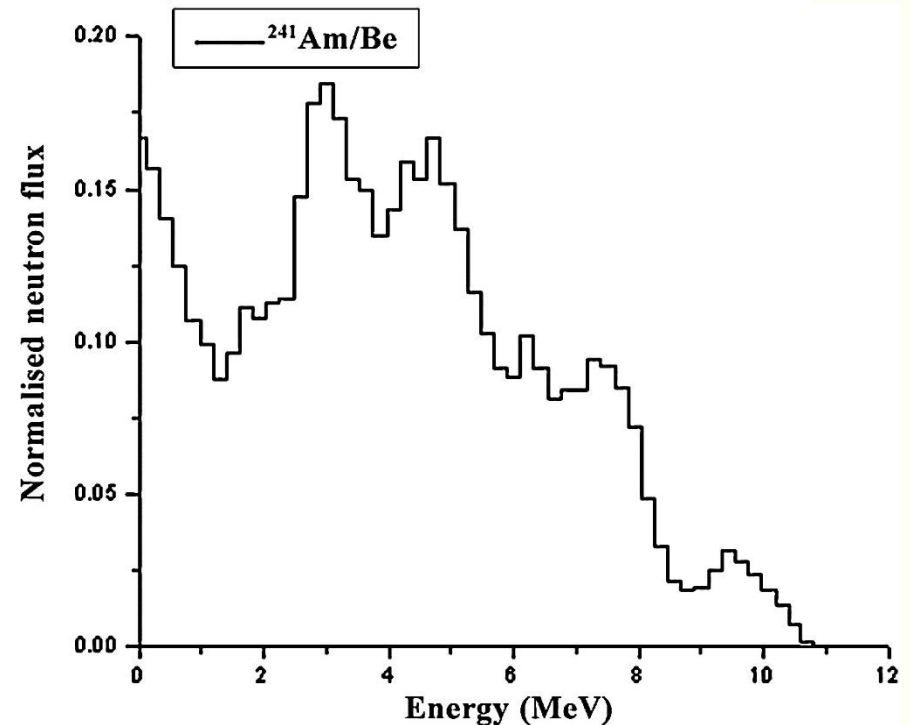


FIG. 1. Capsules used for (α, n) neutron sources:

- X1 capsule $d = 7.8 \text{ mm}$, $h = 10 \text{ mm}$;
- X2 capsule $d = 17.4 \text{ mm}$, $h = 19.4 \text{ mm}$;
- X3 capsule $d = 22.4 \text{ mm}$, $h = 31 \text{ mm}$.

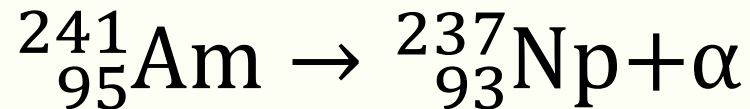
Content: Mixture of α -Emitter M and Beryllium as a fine powder or as alloy or Actinide-Boride
Yield ca. $10^{-4} \text{ n}/\alpha$ -decay
(Most α -particles are stopped without causing a nuclear reaction.)



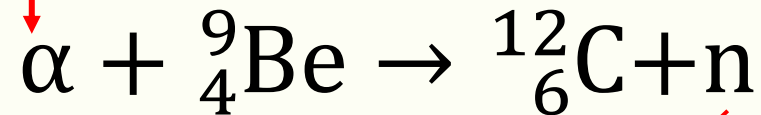
Neutronenspectrum

Neutronenbronnen

(alfa n) bron



$E_{\alpha}^{kin} \approx 5.4 \text{ MeV}$ in 97%

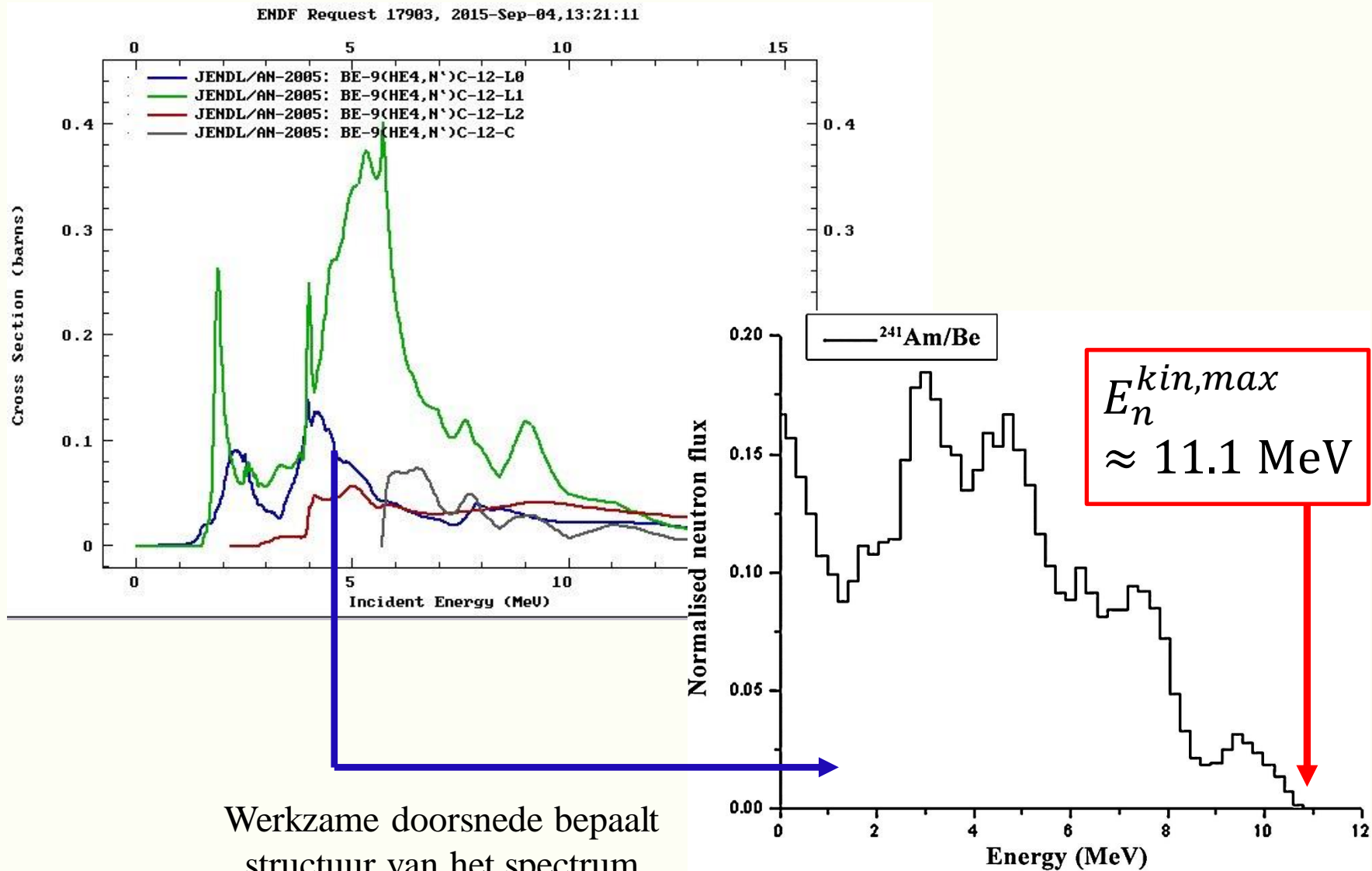


$$Q = 5.7 \text{ MeV}$$

$$E_n^{kin,max} \approx 5.4 + 5.7 = 11.1 \text{ MeV}$$

Neutronenbronnen

(alpha n) bron

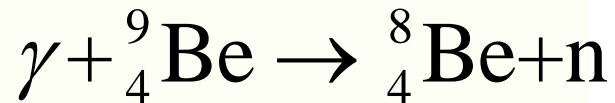


Neutronenbronnen

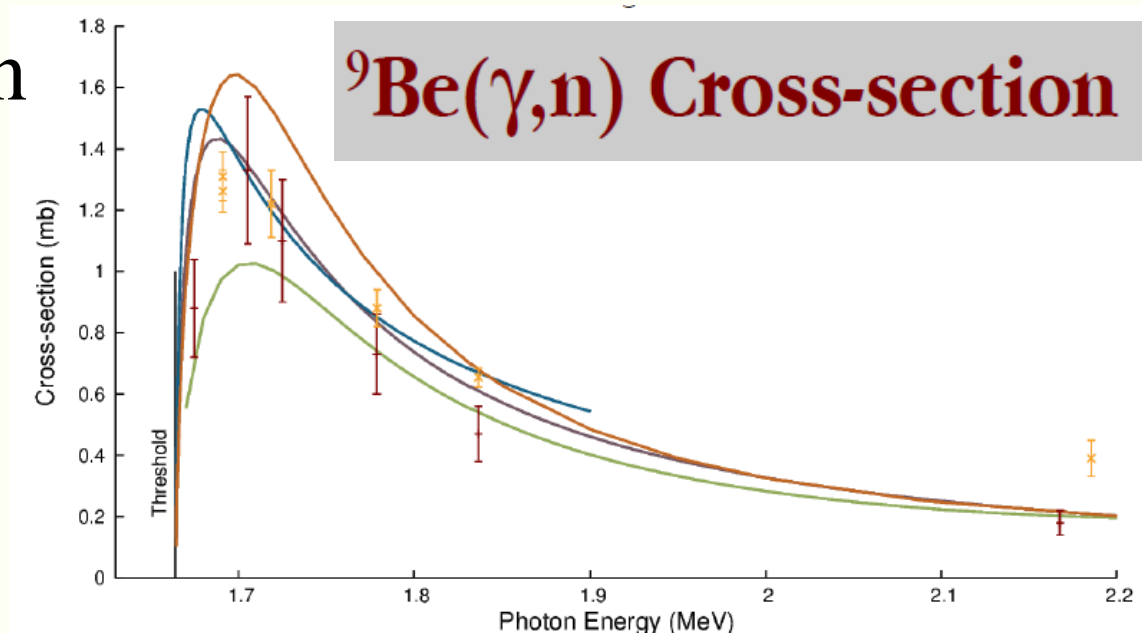
(gamma n) bronnen of foton-neutron bron

Combinatie van een gammastraler (bijv. ^{24}Na , ^{226}Ra , ^{88}Y) en een licht element (D, Be or B)

- Lichte elementen: omdat daar de drempelenergie laag is



$$Q = -1.665 \text{ MeV}$$

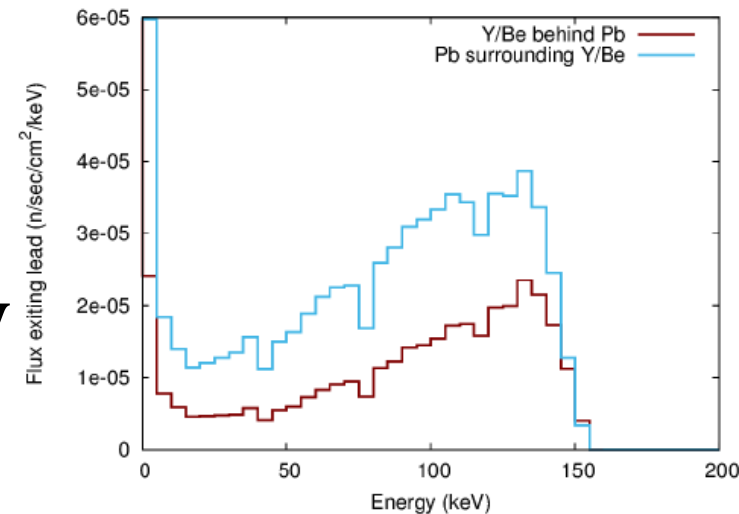


Neutronenbronnen

(gamma n) bronnen of foton-neutron bron

Radioisotope / beryllium sources

Source	Half-life	Photons	Neutron Energy
^{226}Ra	1600 y	1764 keV (15.3 %) 2204 keV (4.92 %) others (9.69 %)	89 keV 479 keV
^{124}Sb	60.2 d	1691 keV (47.6 %) 2091 keV (5.49 %) others (0.52 %)	23.5 keV 379 keV
^{88}Y	106.6 d	1836 keV (99.9 %) 2734 keV (0.71 %)	152 keV 950 keV
^{207}Bi	31.6 y	1770 keV (6.87 %)	94 keV



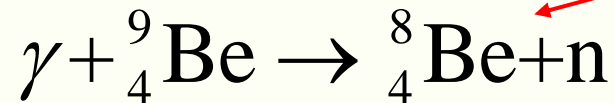
$$\Delta E = 1.836 - 1.665 = 0.171 \text{ MeV}$$

$$Q = -1.665 \text{ MeV}$$

Neutronenbronnen

(gamma n) bronnen of foton-neutron bron

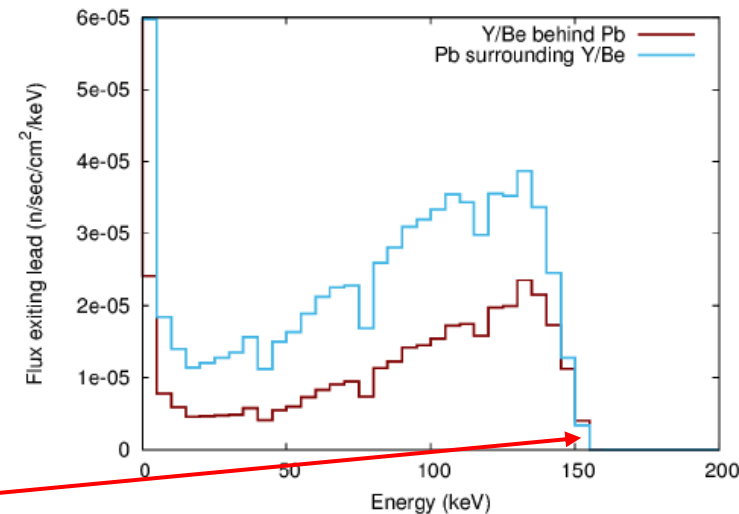
$$\Delta E = 1.836 - 1.665 = 0.171 \text{ MeV}$$



$$E_n^{kin} = \frac{m_{Be}}{m_{Be} + m_n} \Delta E =$$

$$\frac{8}{8 + 1} \Delta E = \frac{8}{9} \times 0.171$$

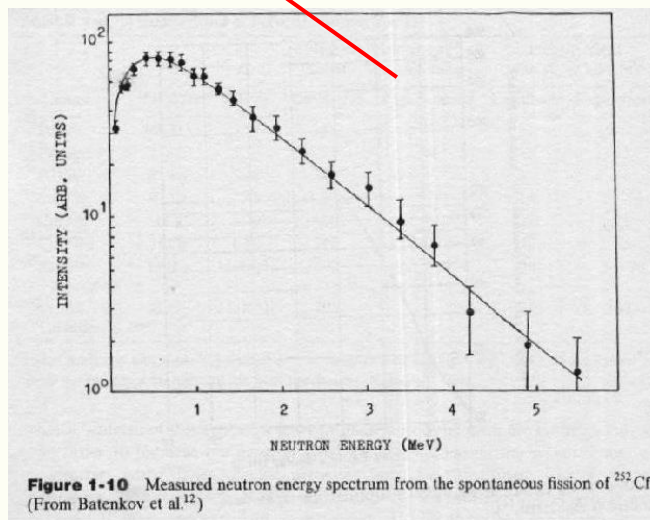
$$= 0.152 \text{ MeV} = 152 \text{ keV}$$



Neutronenbronnen

Spontane splijting bronnen

Nuclide	$T_{1/2}$ (Fission)	$T_{1/2}$ (α -decay)	neutrons/sec/gram
${}^{235}_{92}\text{U}$	1.8×10^{17} years	6.8×10^8 years	8.0×10^{-4}
${}^{238}_{92}\text{U}$	8.0×10^{15} years	4.5×10^9 years	1.6×10^{-2}
${}^{239}_{94}\text{Pu}$	5.5×10^5 years	2.4×10^4 years	3.0×10^{-2}
${}^{240}_{94}\text{Pu}$	1.2×10^{11} years	6.6×10^3 years	1.0×10^3
${}^{252}_{98}\text{Cf}$	66.0 years	2.65 years	2.3×10^{12}



**Typisch spectrum van
splijtingsneutronen**

*Zie ook ${}^{235}\text{U}$ spectrum in figuur
6.18 in boek*

Neutronbronnen

versnellers

European Spallation Source

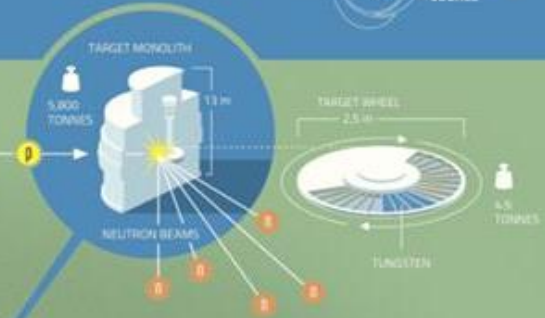


The European Spallation Source (ESS) is a multi-disciplinary research centre based on the world's most powerful neutron source. ESS will give scientists new possibilities in a broad range of research, from life science to engineering materials, from heritage conservation to magnetism. ESS is a pan-European project, with Sweden and Denmark serving as host countries. The main research facility is being built in Lund, Sweden, and the Data Management and Software Centre (DMSC) is located in Copenhagen, Denmark.



THE TARGET IS THE NEUTRON SOURCE

When the accelerated protons hit the rotating tungsten target wheel, spallation occurs and neutrons are scattered from the tungsten nucleus. The most neutrons produced are collected in the target, the "brighter" the neutron source. The neutrons are directed through moderators and neutron guides to the scientific instruments where they are used for experiments. The Target monolith consists of the Target wheel, moderators, cooling systems and shielding and weighs approximately 5,800 tonnes.



$$E_p = 2 \text{ GeV}$$

W-target wheel

Classificatie van neutronen

- **Thermisch: ongeveer 0.025 eV**
- **Langzaam: <0.5 eV**
- **Epithermisch: 0.5 eV-200 keV**
- **Snel: 200 keV-20 MeV**
- **Relativistisch: > 20 MeV**

Classificatie van neutronen

- **Thermisch: ongeveer 0.025 eV**
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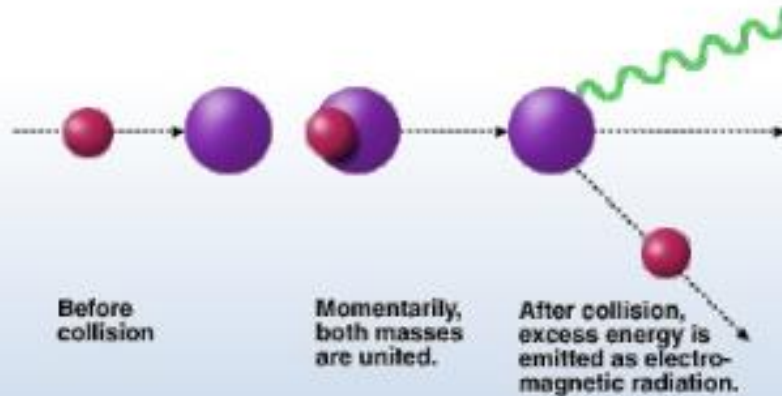
$$kT = 1.38 \cdot 10^{-23} \times 300 = 4.14 \cdot 10^{-21} \text{ J} = \frac{4.41 \cdot 10^{-21}}{1.6 \cdot 10^{-19}} \Rightarrow$$

$$kT = 0.025 \text{ eV}$$



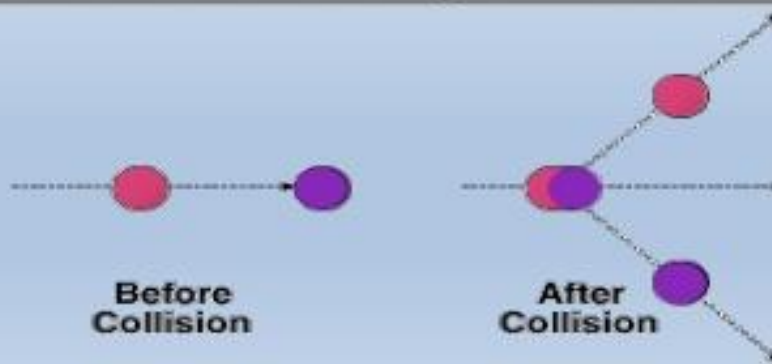
Wisselwerking van neutronen

Inelastic Scattering of Neutrons



$$E_{kin}(\text{in}) \neq E_{kin}(\text{out})$$

Elastic Scattering of Neutrons



$$E_{kin}(\text{in}) = E_{kin}(\text{uit})$$

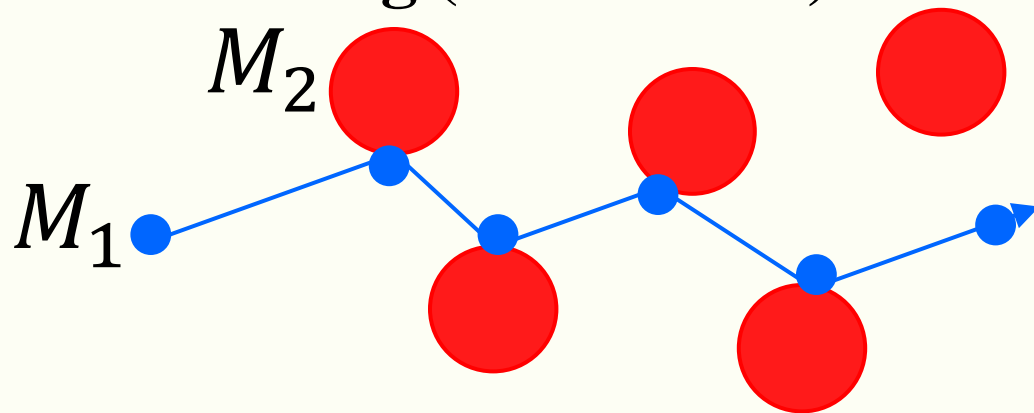
Wisselwerking van neutronen

Wisselwerking

- **Thermisch:** elastische botsingen, vangst
- **Langzaam:** elastische botsingen, vangst, $\sigma \sim 1/\sqrt{E}$
- **Epithermisch:** elastische botsingen, vangst, resonanties
- **Snel:** elastische en inelastische botsingen, vangst
- **Relativistisch:** inelastische botsingen, spallatie

Wisselwerking

Afremmen van neutronen door elastische verstrooiing (modereren)



T : kinetische energie van het inkomende deeltje

$$\Delta E_{max} = \frac{4M_1M_2T}{(M_1 + M_2)^2} = \frac{4m_nM_N T}{(m_n + M_N)^2}$$

neutron kern

Verg. 6.32
boek

**Gemiddelde energieverdracht
ongeveer helft van het maximum**



Wisselwerking


Afremmen van neutronen door elastische verstrooiing (modereren)

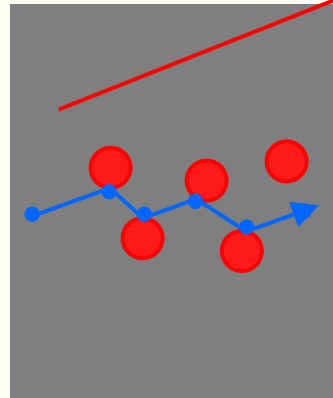
$$\Delta E_{max} = \frac{4m_n M_N T}{(m_n + M_N)^2}$$

$$\Delta E_{max}(H) = \frac{4 \times 1 \times 1 \times T}{(1 + 1)^2} = T$$

Nucleus	$\frac{\Delta E_{max}}{T}$
${}^1_1\text{H}$	1.000
${}^2_1\text{H}$	0.889
${}^4_2\text{He}$	0.640
${}^9_4\text{Be}$	0.360
${}^{12}_6\text{C}$	0.284
${}^{16}_8\text{O}$	0.221
${}^{56}_{26}\text{Fe}$	0.069
${}^{118}_{50}\text{Sn}$	0.033
${}^{238}_{92}\text{U}$	0.017


Neutronmoderatie


$$E_n = 1 \text{ MeV}$$


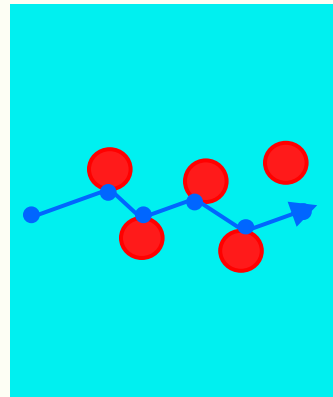


Grafiet (C)


Hoeveel botsingen heb je gemiddeld nodig?

$$E_n = 0.025 \text{ eV}$$


$$E_n = 1 \text{ MeV}$$


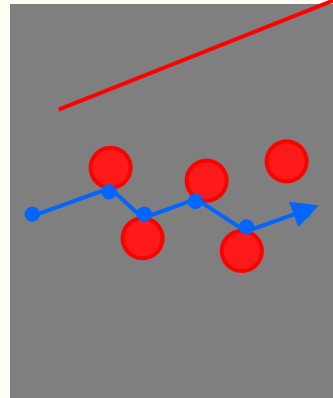


Water (H)

$$E_n = 0.025 \text{ eV}$$


Neutronmoderatie

$$E_n = 1 \text{ MeV}$$



Hoeveel botsingen heb je gemiddeld nodig?

$$E_n = 0.025 \text{ eV}$$



Grafiet (C)

$$\Delta E_{max} = \frac{4m_n M_N T}{(m_n + M_N)^2} = \frac{4 \times 1 \times 12}{(1 + 12)^2} E_n^0 = 0.284 E_n^0$$

$$\Delta E_{avg} = \frac{1}{2} \times \underbrace{0.284 E_n^0}_a = \frac{1}{2} a E_n^0$$

Neutronmoderatie


$$\Delta E_{avg} = \frac{1}{2} a E_n^0$$

Na 1 botsing: $E_n^1 = E_n^0 - \frac{1}{2} a E_n^0 = E_n^0 \left(1 - \frac{1}{2} a\right)$

Na 2 botsingen: $E_n^2 = E_n^1 \left(1 - \frac{1}{2} a\right) = E_n^0 \left(1 - \frac{1}{2} a\right)^2$

Na k botsingen: $E_n^k = E_n^0 \left(1 - \frac{1}{2} a\right)^k$

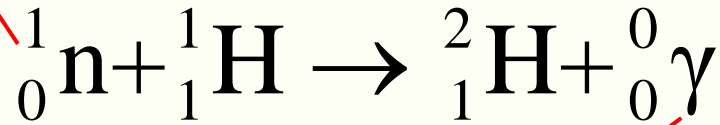
0.025 eV **1 MeV** **0.284**

 $k = 114$ grafiet

$a = 1$  $k = 25$ water

Neutronen-reacties

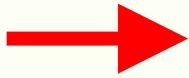
thermisch neutron



$$Q = 2.2245 \text{ MeV}$$

neutronvangstreactie

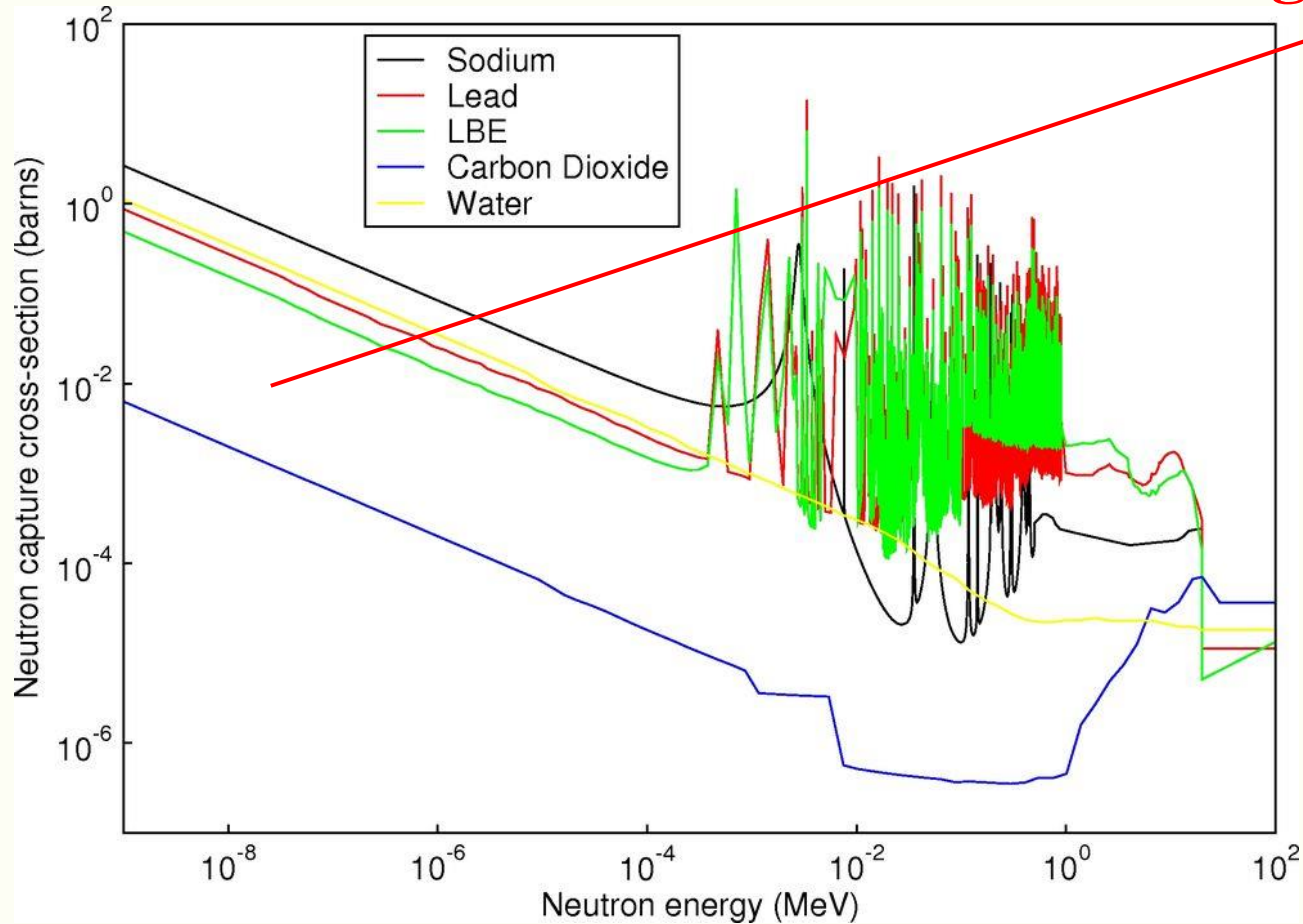
thermische neutronen



dosis tgv gamma's en
1.3 keV terugstootenergie

Neutronen-reacties

in dit gebied tot
ongeveer 1 keV



$$\sigma \propto \frac{1}{v_n} \propto \frac{1}{\sqrt{E_n}}$$

werkzame doorsnede voor neutronvangst

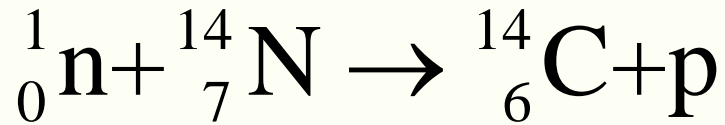
neutronvangst werkbare doorsnede voor thermische neutronen

Nuclide	Weight % in tissue	Neutron capture cross-section*
H	10.0	0.332
C	18.0	0.0034
N	3.0	1.82
O	65.0	1.8×10^{-4}
Na	0.11	0.43
Mg	0.04	0.053
P	1.16	0.18
S	0.20	0.53
Cl	0.16	32.68
K	0.20	2.1
Ca	2.01	0.4
Fe	0.01	2.57

* Neutron cross section (σ) in barns ($b = 10^{-24} \text{ cm}^2$).

**elementen
zoals ze
voorkomen in
het menselijk
lichaam**

Neutronen-reacties

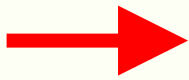


$$Q = 0.626 \text{ MeV}$$

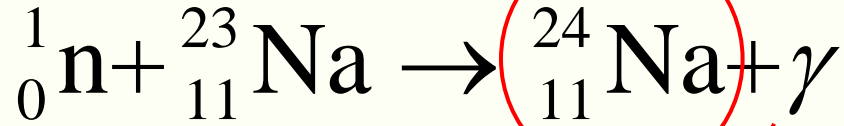
dosis tgv ${}^{14}\text{C}$ en p

$$E_p \approx 0.6 \text{ MeV}$$

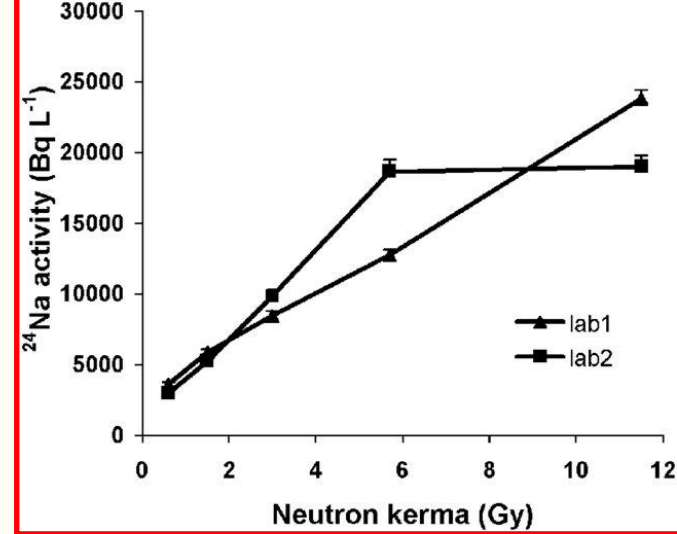
thermische neutronen



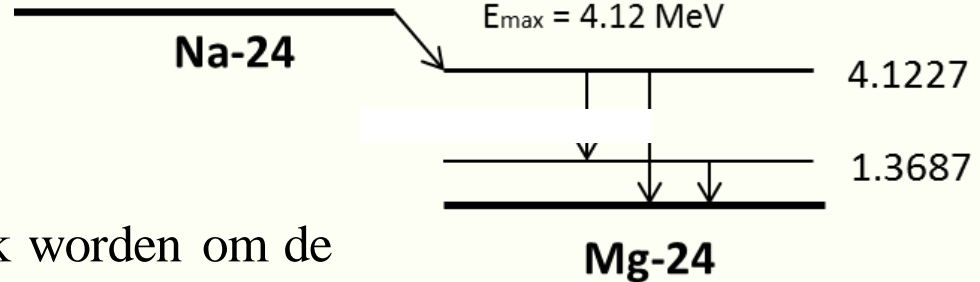
Neutronen-reacties



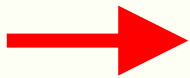
$Q = 6.961 \text{ MeV}$ prompt gamma's



$T_{1/2} = 15.0 \text{ h}$



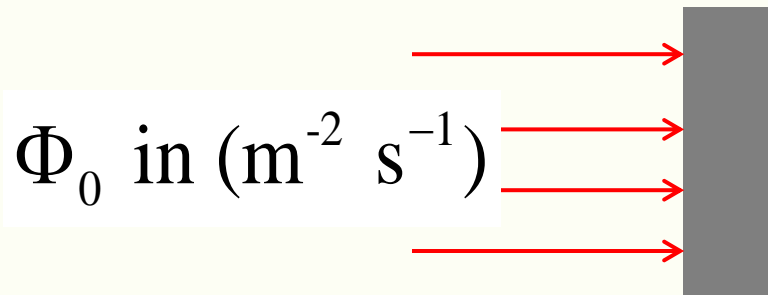
thermische neutronen



kan gebruik worden om de opgelopen dosis te schatten aan de hand van metingen aan bloedmonsters na de blootstelling

$E_{\gamma} = 2.75 \text{ MeV (99.99\%)}$
 $E_{\gamma} = 1.37 \text{ MeV (99.98\%)}$

Neutronactivering



N_T : aantal atomen in target T
 σ : werkzame doorsnede (in m^2)

$n + T \rightarrow D$ (radioactief: vervalconstante λ in s^{-1})

$$\frac{dN_D}{dt} = \Phi_0 \sigma N_T - \lambda N_D$$

↑
productie

↑
verval

$$\frac{dN_D}{dt} = \Phi_0 \sigma N_T - \lambda N_D$$

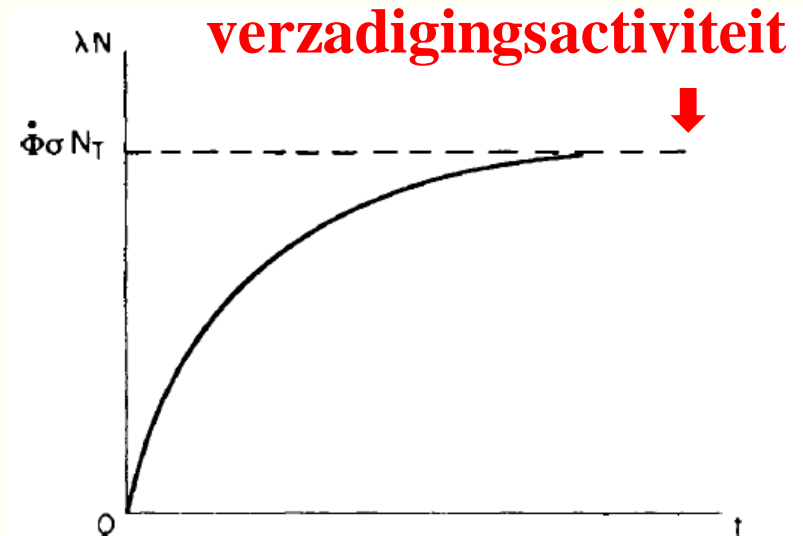
$$N_D(t) = Ae^{-\lambda t} + B = A(1 - e^{-\lambda t})$$

$$N_D(0) = 0 = A + B \Rightarrow A = -B$$

$$\cancel{\lambda A e^{-\lambda t}} = \Phi_0 \sigma N_T - \lambda A(1 - \cancel{e^{-\lambda t}}) \Rightarrow A = \frac{\Phi_0 \sigma N_T}{\lambda}$$

$$N_D(t) = \frac{\Phi_0 \sigma N_T}{\lambda} (1 - e^{-\lambda t})$$

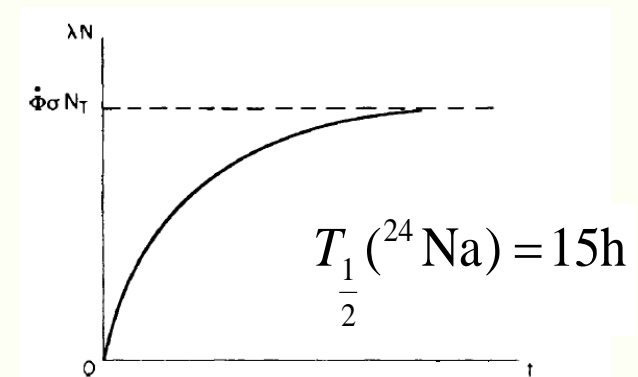
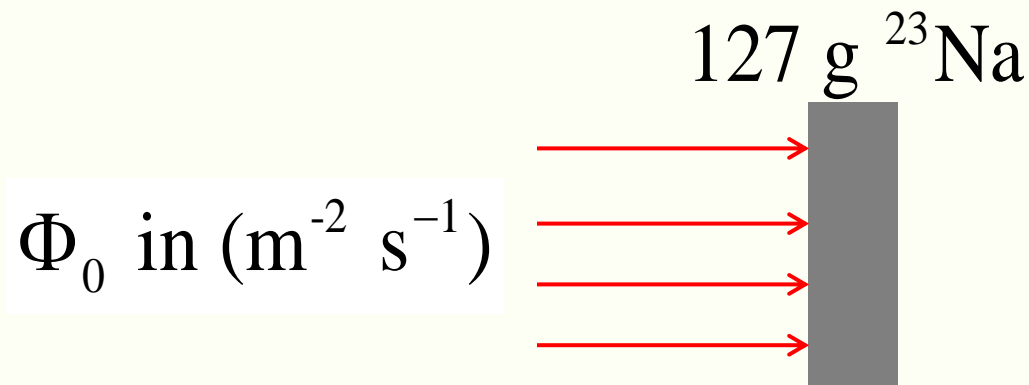
$$A_D(t) = \Phi_0 \sigma N_T (1 - e^{-\lambda t})$$



Neutronactivering

Een plaatje met 127 g ^{23}Na (100% puur) wordt in een bundel thermische neutronen geplaatst. De thermische neutronflux is $1.19 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$. De werkzame doorsnede voor de vangst van thermische neutronen ($^{23}\text{Na}(n,\gamma)^{24}\text{Na}$) is 0.53 barn.

- Bereken de verzadigingsactiviteit
- Bereken de ^{24}Na activiteit na 24 uur bestraling
- Hoeveel ^{23}Na atomen zijn “opgebruikt” in die 24 uur

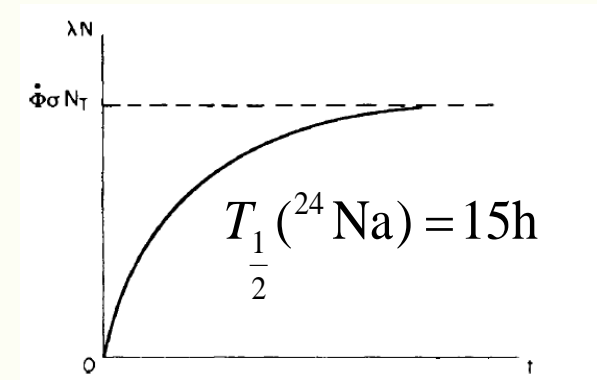


Neutronactivering

Een plaatje met 127 g ^{23}Na (100% puur) wordt in een bundel thermische neutronen geplaatst. De thermische neutronflux is $1.19 \cdot 10^4 \text{ cm}^{-2} \text{ s}^{-1}$. De werkzame doorsnede voor de vangst van thermische neutronen ($^{23}\text{Na}(n,\gamma)^{24}\text{Na}$) is 0.53 barn.

a) Bereken de verzadigingsactiviteit

$$A_D(t) = \underbrace{\Phi_0 \sigma N_T}_{\text{}} (1 - e^{-\lambda t})$$



$$= \underbrace{1.19 \cdot 10^4}_{\Phi_0} \times \underbrace{0.53 \cdot 10^{-24}}_{\sigma} \times \underbrace{\frac{127}{23} \times 6 \cdot 10^{23}}_{N_T} = 20.9 \text{ kBq}$$

Neutronactivering

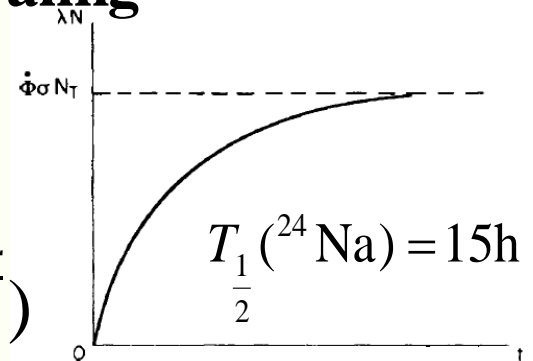
Een plaatje met 127 g ^{23}Na (100% puur) wordt in een bundel thermische neutronen geplaatst. De thermische neutronflux is $1.19 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$. De werkzame doorsnede voor de vangst van thermische neutronen ($^{23}\text{Na}(n,\gamma)^{24}\text{Na}$) is 0.53 barn.

b) Bereken de ^{24}Na activiteit na 24 uur bestraling

$$A_D(t) = \Phi_0 \sigma N_T (1 - e^{-\lambda t})$$

$$A_D(24\text{h}) = 20.9 \text{ kBq} \times \left(1 - e^{-\frac{\ln(2) \times 24}{15}}\right)$$

$$A_D(24\text{h}) = 14.0 \text{ kBq}$$



Neutronactivering

Een plaatje met 127 g ^{23}Na (100% puur) wordt in een bundel thermische neutronen geplaatst. De thermische neutronflux is $1.19 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$. De werkzame doorsnede voor de vangst van thermische neutronen ($^{23}\text{Na}(n,\gamma)^{24}\text{Na}$) is 0.53 barn.

c) Hoeveel ^{23}Na atomen zijn “opgebruikt” in die 24 uur

Snelheid waarmee ^{23}Na wordt opgebruikt is:

$$\Phi_0 \sigma N_T = 20.9 \cdot 10^3 \text{ } ^{23}\text{Na} \text{ per seconde}$$

Na 24 uur zijn er:

$$20.9 \cdot 10^3 \times 24 \times 3600 = 1.8 \cdot 10^9 \text{ } ^{23}\text{Na} \text{ atomen gebruikt}$$

Dosimetrie van neutronen

- Neutronen zijn indirect ioniserend, **dus neutronen interacties resulteren niet in electronen**
- Secondaire deeltjes kunnen ioniseren, p, α , d, t
- Secondaire deeltjes zijn zwaar en geladen, dus geen remstraling (zoals bij fotonen)

KERMA **K**inetic **E**nergy **R**eleased in **M**atter

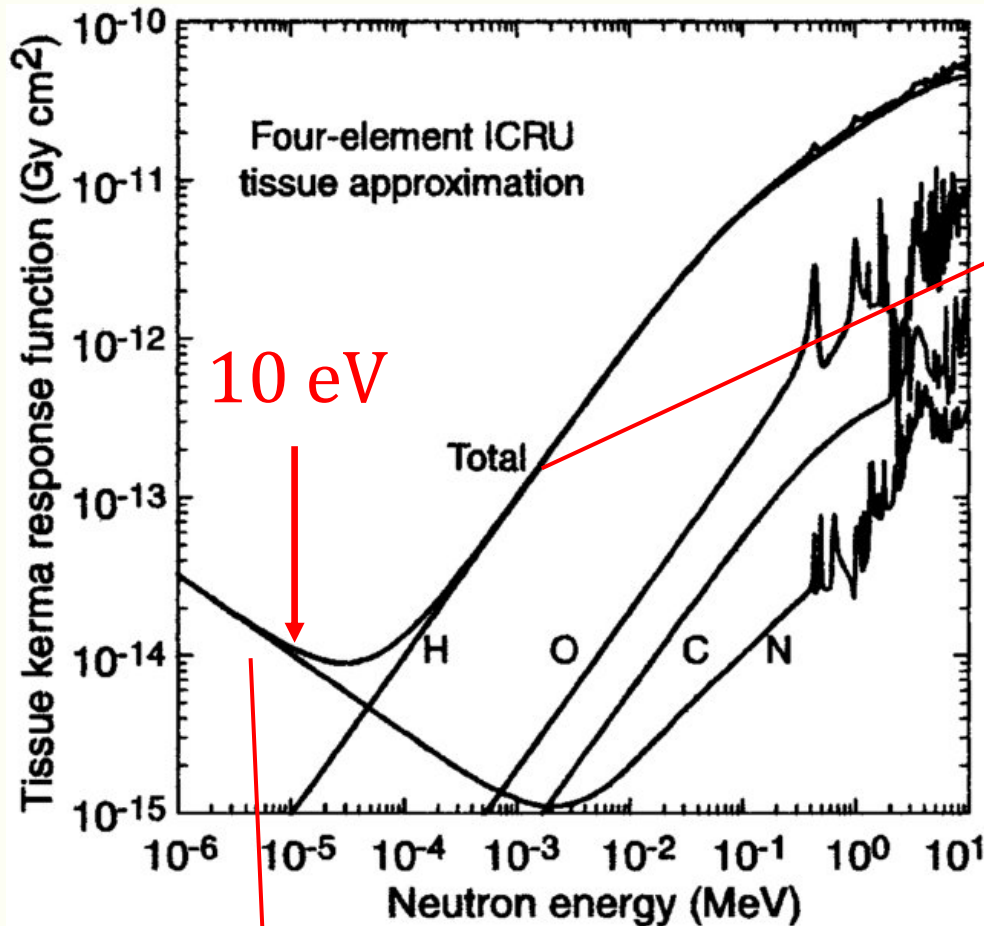
$$K = E_n \Phi \frac{\mu_{tr}}{\rho} = E_n \Phi \frac{\mu}{\rho} \frac{\Delta E}{E_n} = E_n \Phi \frac{\sigma}{A} N_a \frac{\Delta E}{E_n}$$

massieke energie-
overdrachts-
coëfficiënt

massieke
verzwakkings-
coëfficiënt

werkzame
doorsnede
wisselwerking

Dosimetrie van neutronen



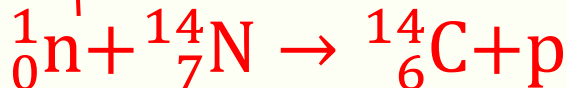
elastische verstrooiing aan H

$$\Delta E_{avg}(H) = 0.5E_n$$

$\Delta E \sim E_n$ en $\sigma \approx const.$
Fig 6.19 boek

K

Φ



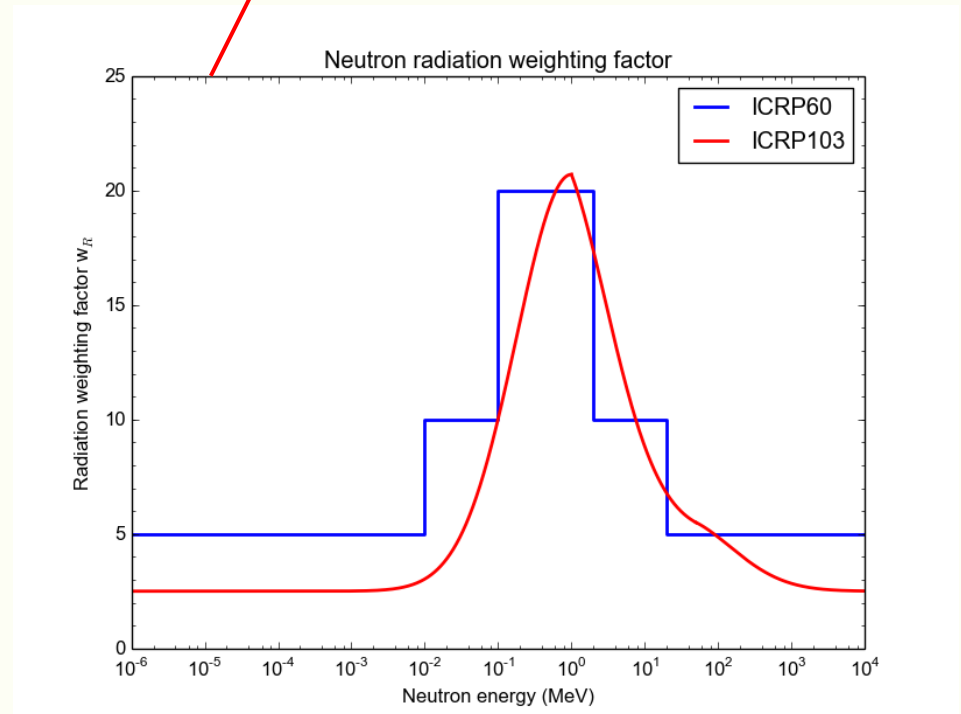
$$\Delta E = 0.6 \text{ MeV and } \sigma \sim \frac{1}{\sqrt{E_n}}$$

Dosimetrie van neutronen

Effectieve dosis E

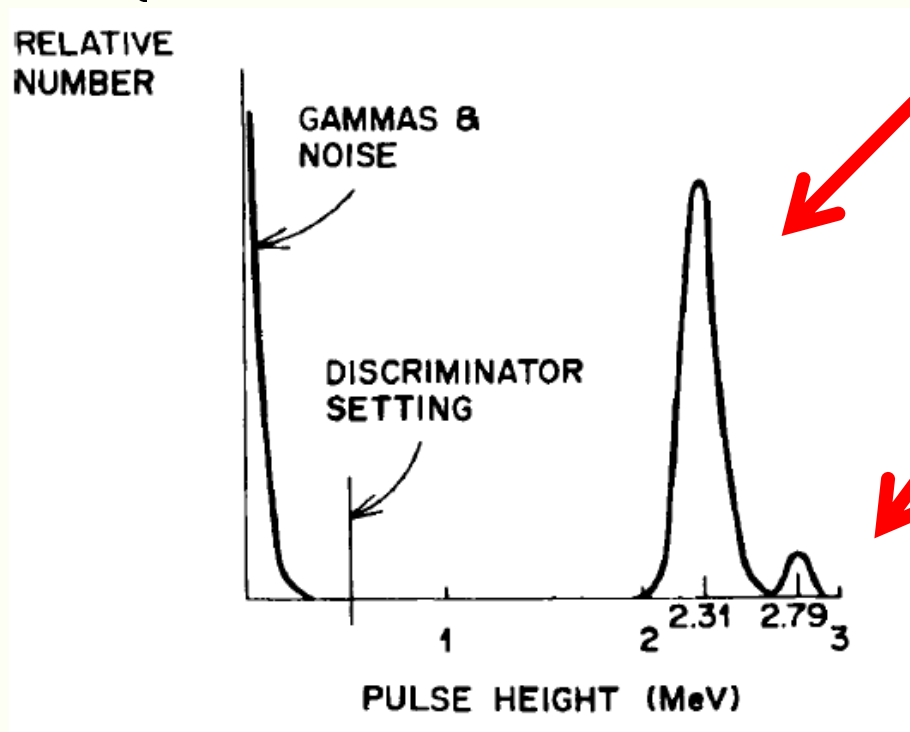
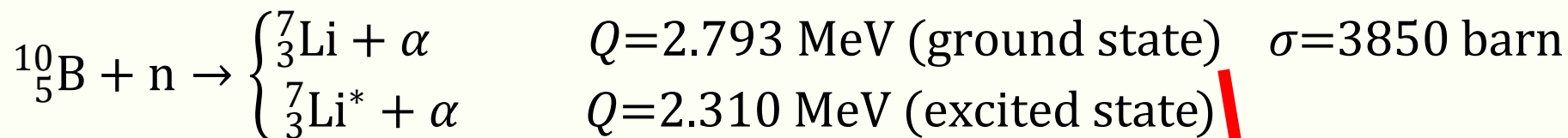
$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}$$

**stralingsweegfactor
hangt af van de
neutronenergie**



Detectie van langzame neutronen

$^{10}\text{B}(n, \alpha)$ -reactie

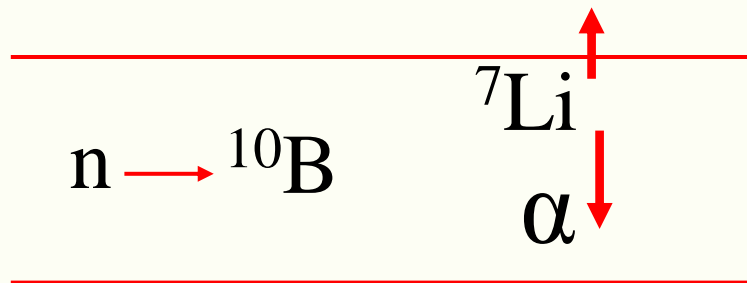
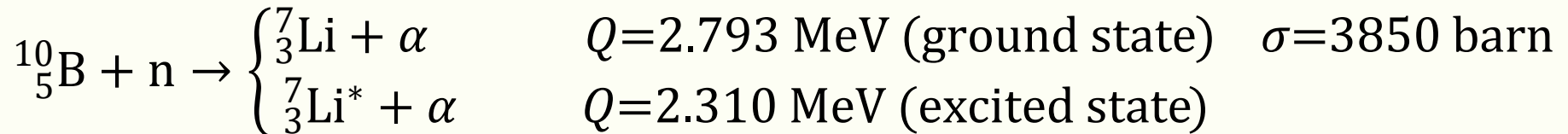


96%

4%

“Ideale”
proportionele
teller met BF_3
gas

Detectie van langzame neutronen

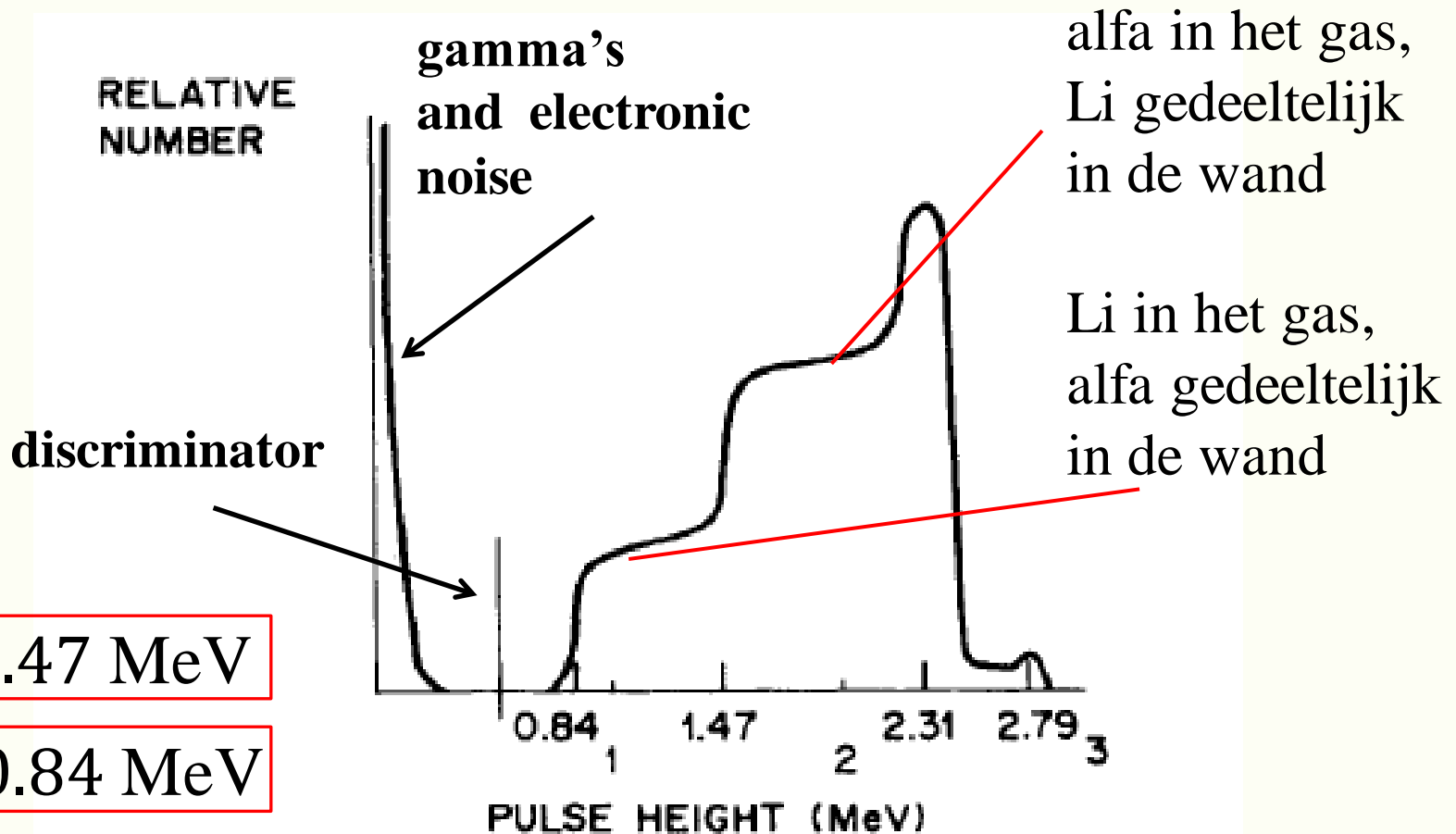


**proportionele
telbuis met
 BF_3 gas**

$$E_{\alpha} = \frac{m_{\text{Li}}}{m_{\alpha} + m_{\text{Li}}} Q = \frac{7}{11} \times 2.31 = 1.47 \text{ MeV}$$

$$E_{\text{Li}} = 2.31 - 1.47 = 0.84 \text{ MeV}$$

Detectie van langzame neutronen

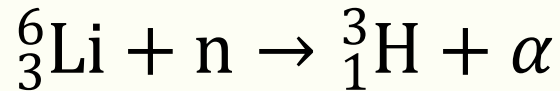


$$E_{\alpha} = 1.47 \text{ MeV}$$

$$E_{Li} = 0.84 \text{ MeV}$$

Detectie van langzame neutronen

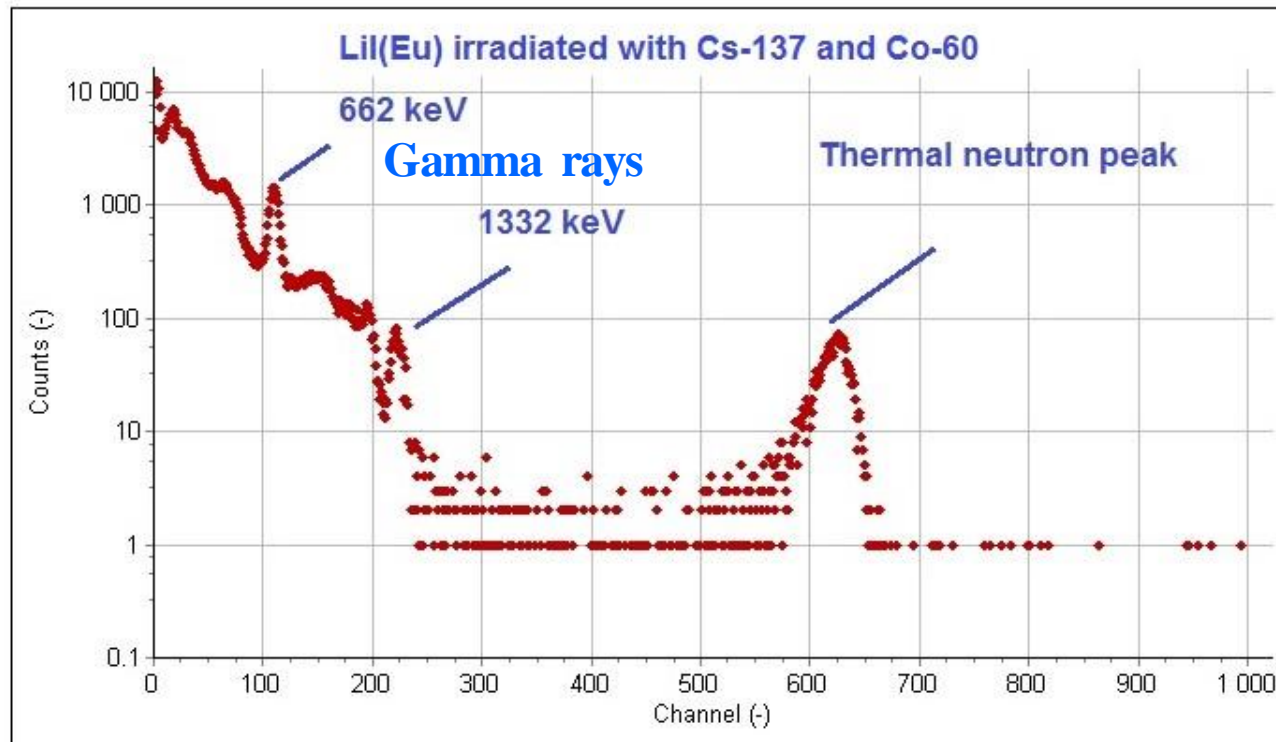
${}^6\text{Li}(n, \alpha)$ -reactie



$Q=4.78$ MeV $\sigma=940$ barn

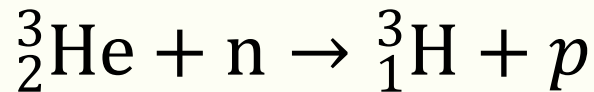
goede γ -discriminatie

minder efficient, **kristal**



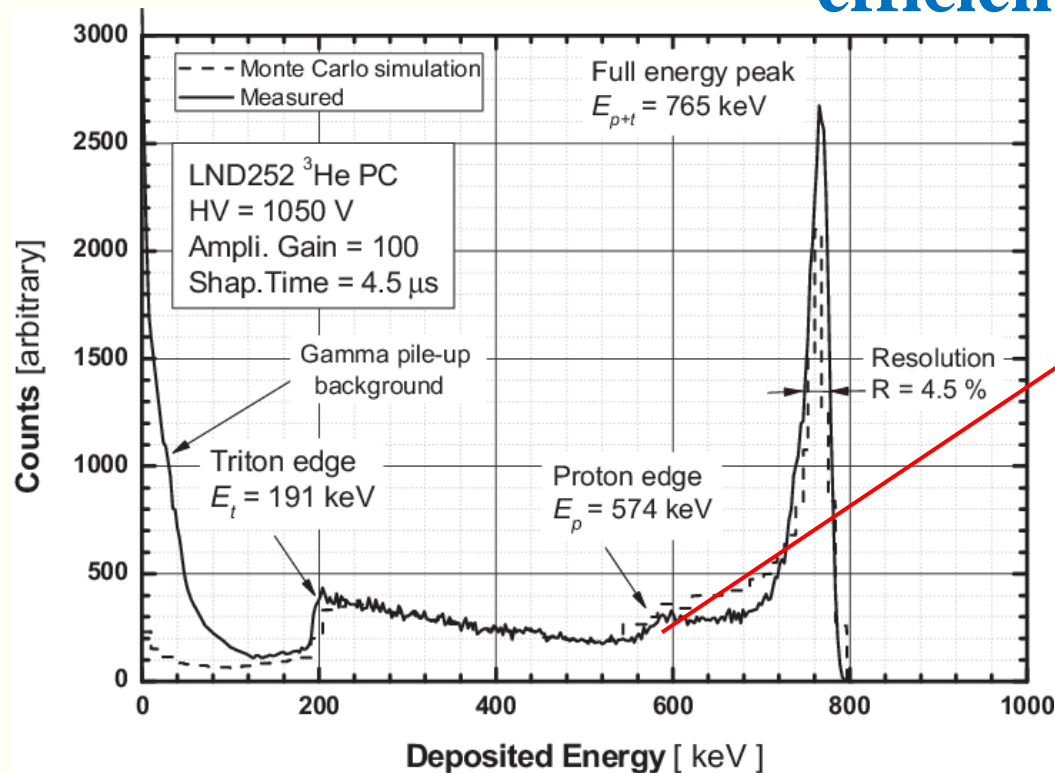
Detectie van langzame neutronen

${}^3\text{He}(n, p)$ -reactie



$$Q = 0.764 \text{ MeV} \quad \sigma = 5330 \text{ barn}$$

slechte γ -discriminatie
efficiënt

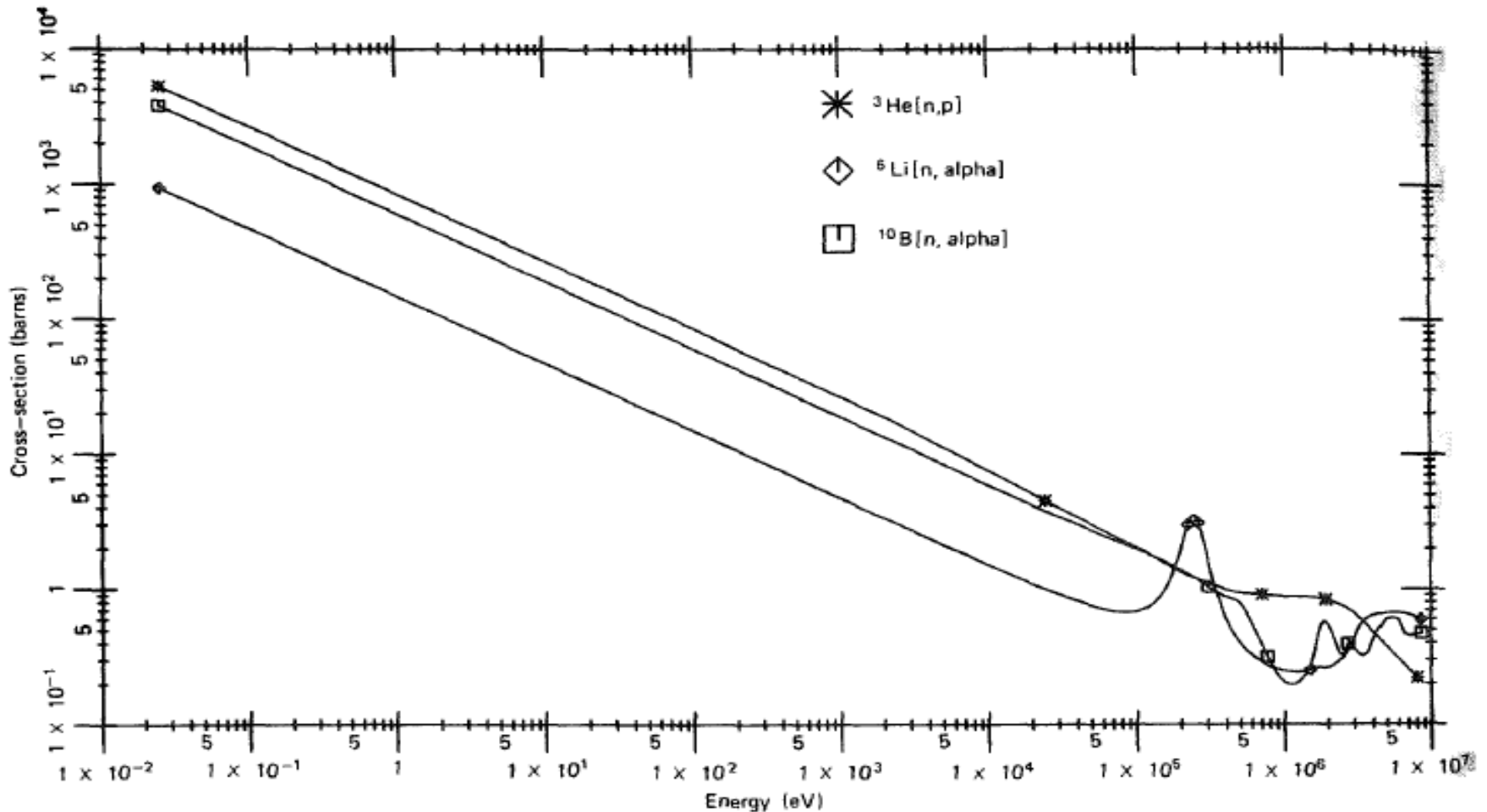


$$E_p = \frac{m_t}{m_p + m_t} Q = \frac{3}{4} \times 0.764 = 0.574 \text{ MeV}$$

$$E_t = Q - E_p = 0.191 \text{ MeV}$$

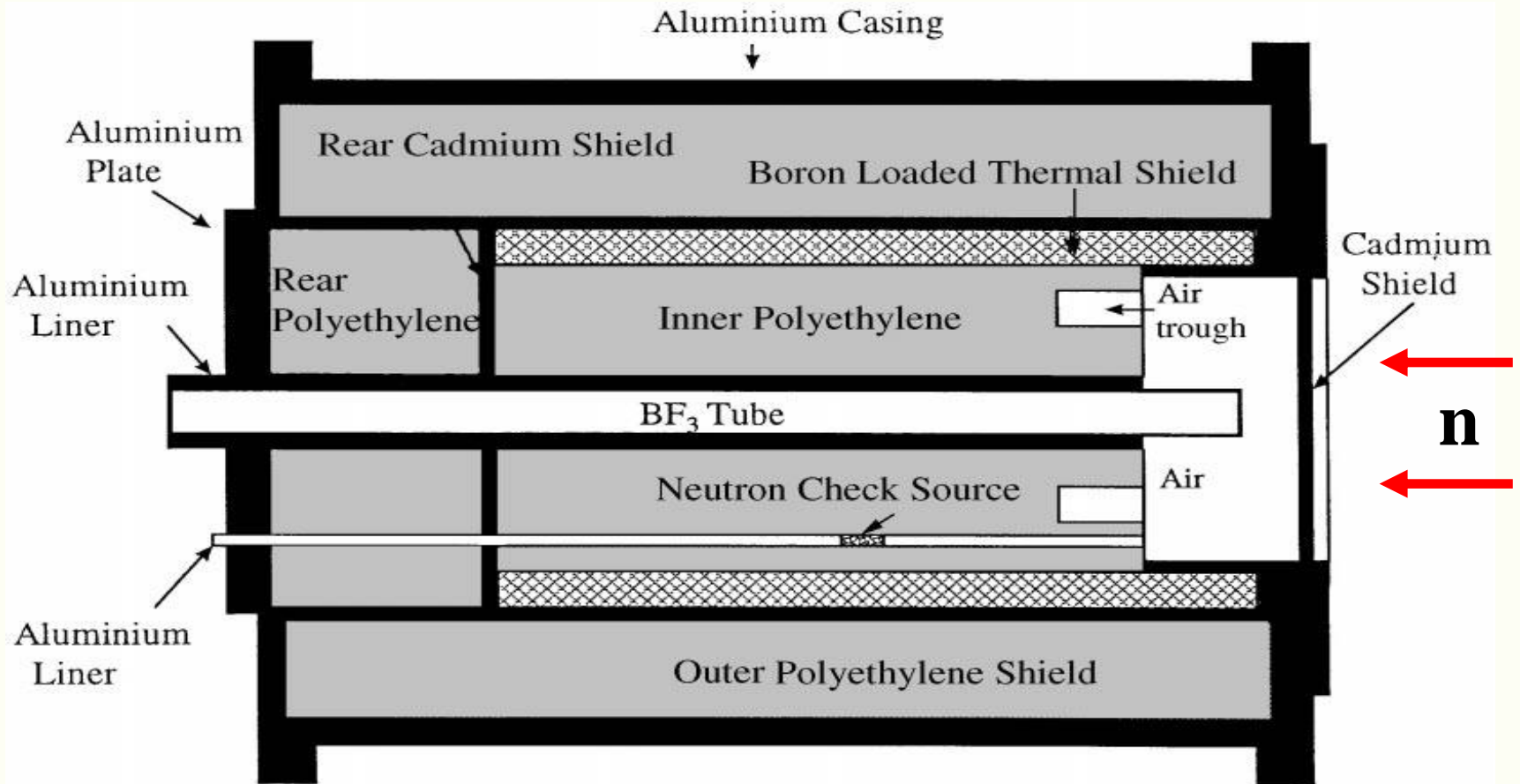
Detectie van snelle neutronen

werkzame doorsnede wordt snel kleiner voor hogere energieën



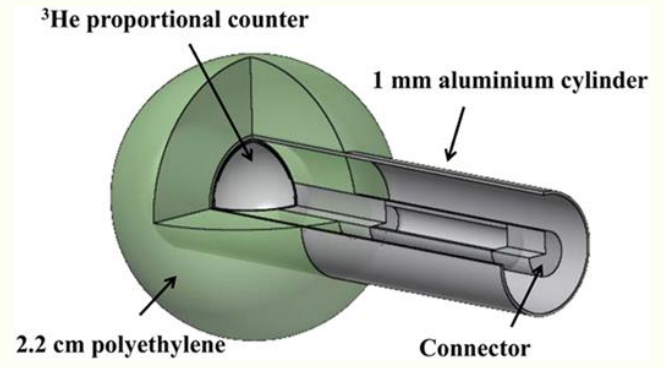
Detectie van snelle neutronen

Long counter

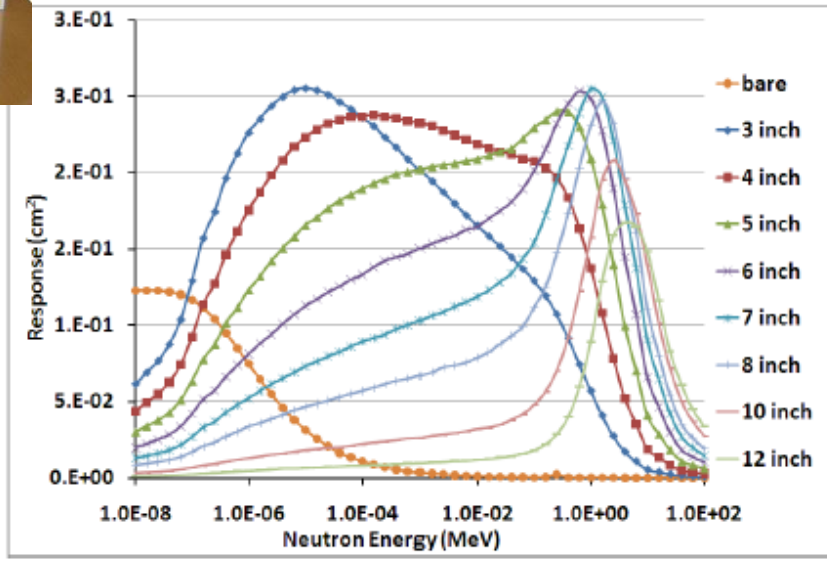


Neutronenspectroscopie

PE bollen van verschillende diameter

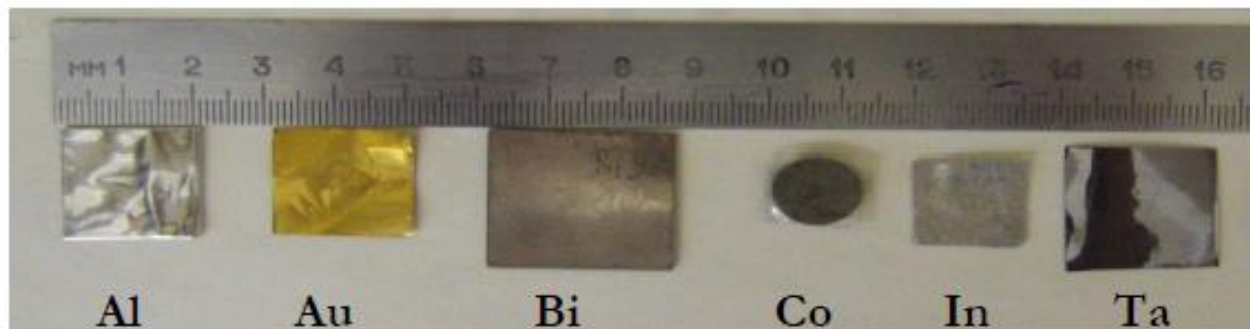


Bonner spheres



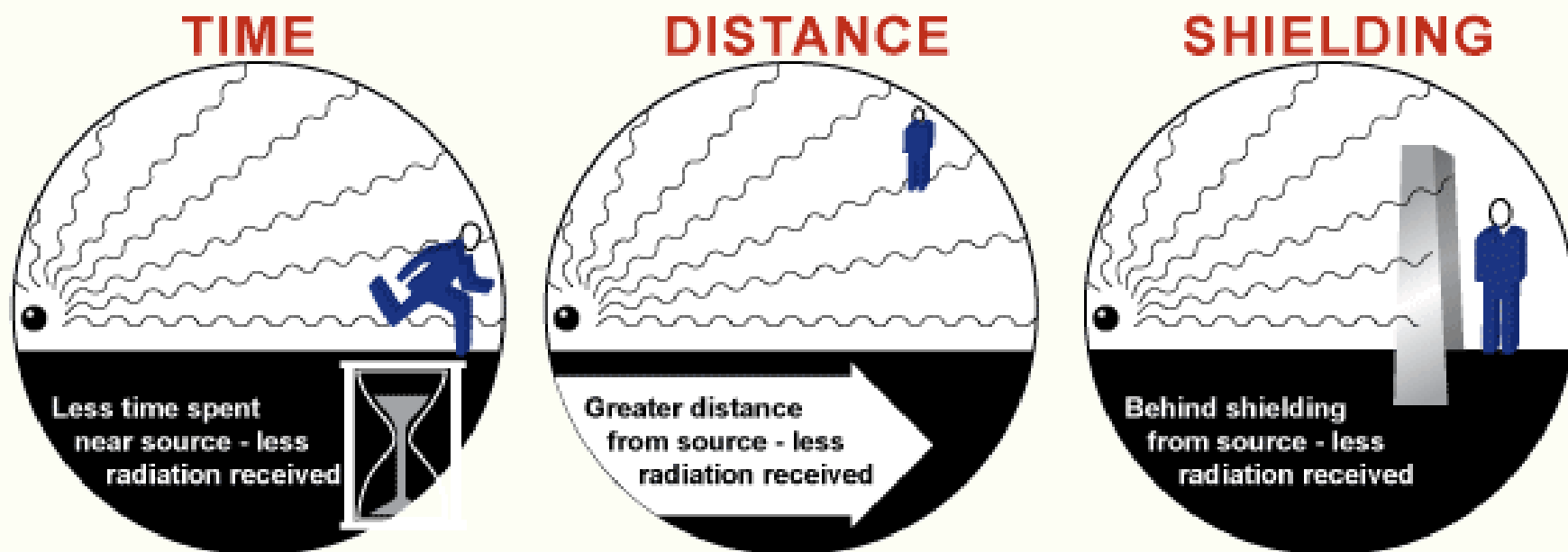
Activatiefolies

Reaction	Effective Threshold (MeV)
$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$	0.5
$^{58}\text{Ni}(n,p)^{58}\text{Co}$	1.9
$^{27}\text{Al}(n,p)^{27}\text{Mg}$	3.8
$^{56}\text{Fe}(n,p)^{56}\text{Mn}$	4.9
$^{59}\text{Co}(n,\alpha)^{56}\text{Mn}$	5.2
$^{24}\text{Mg}(n,p)^{24}\text{Na}$	6.0
$^{197}\text{Au}(n,2n)^{196}\text{Au}$	8.6



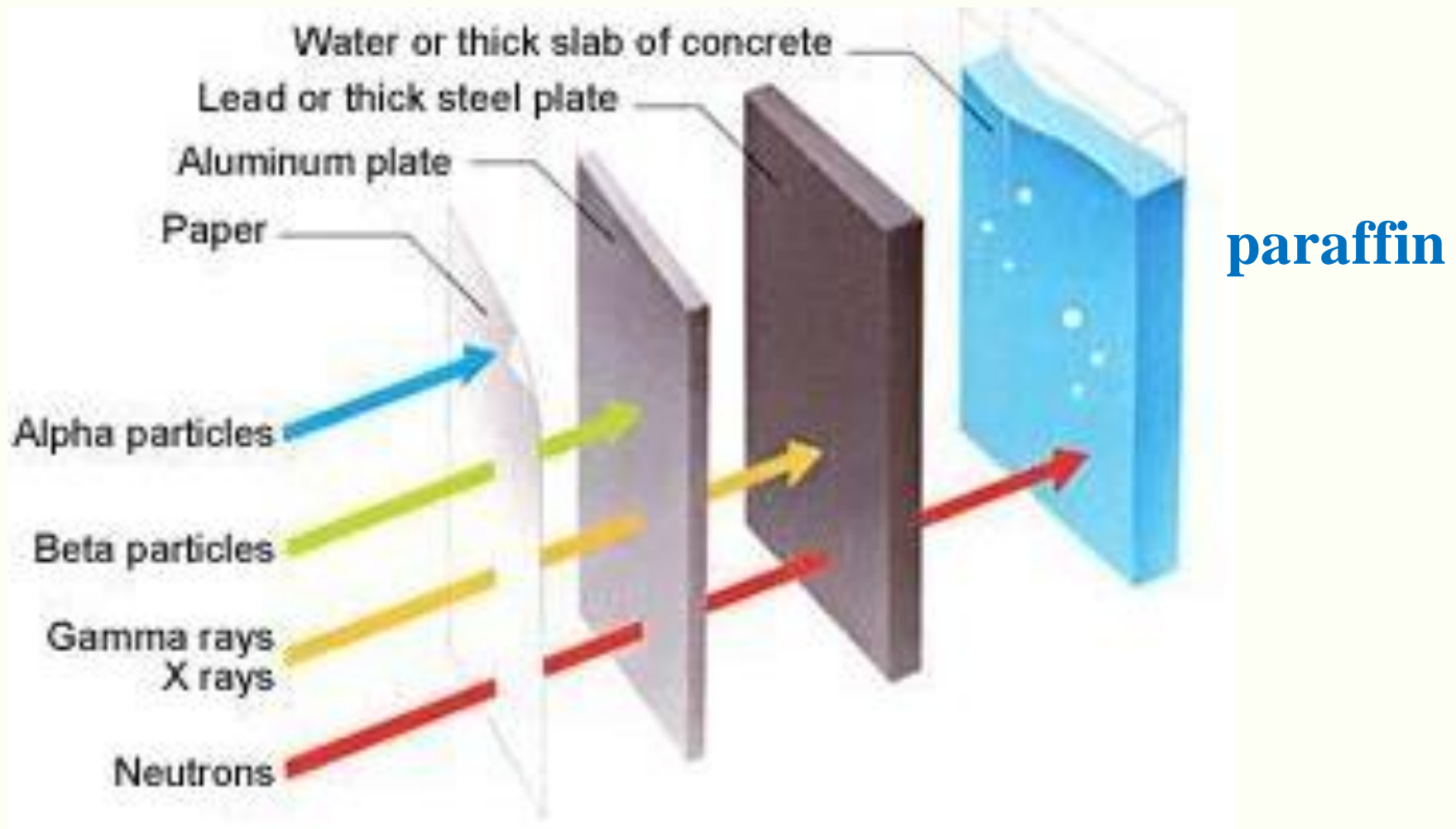
Afscherming

Drie manieren om dosis te verlagen

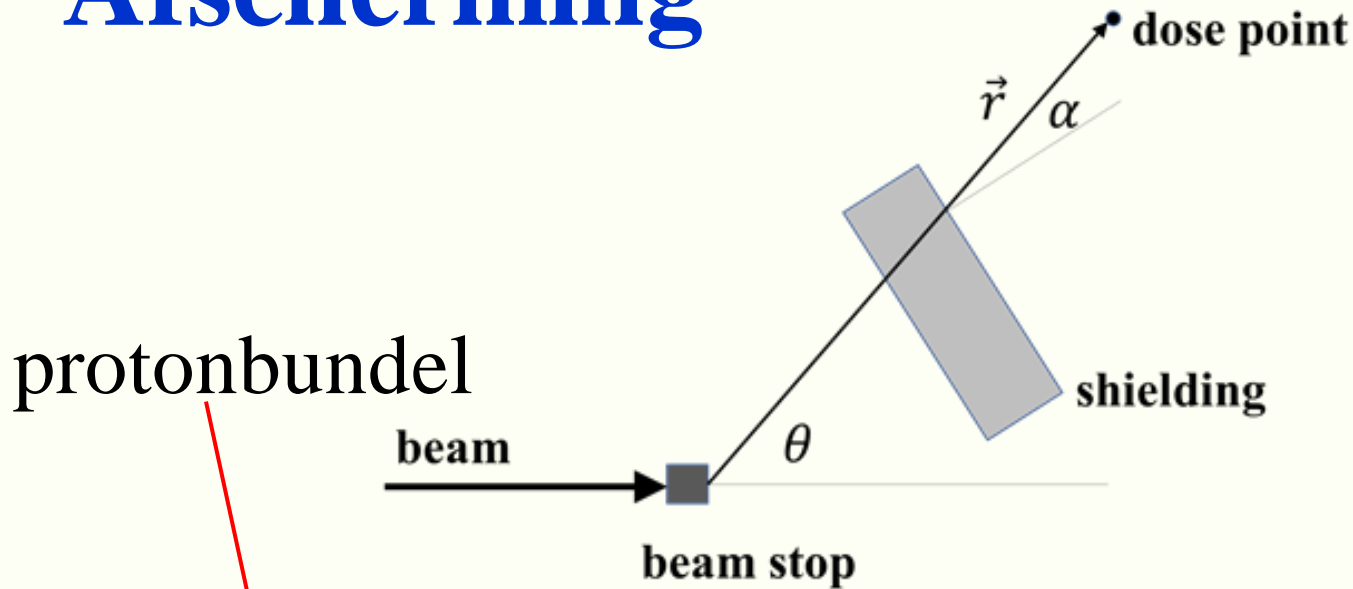


Gelden ook voor neutronen!!

Afscherming



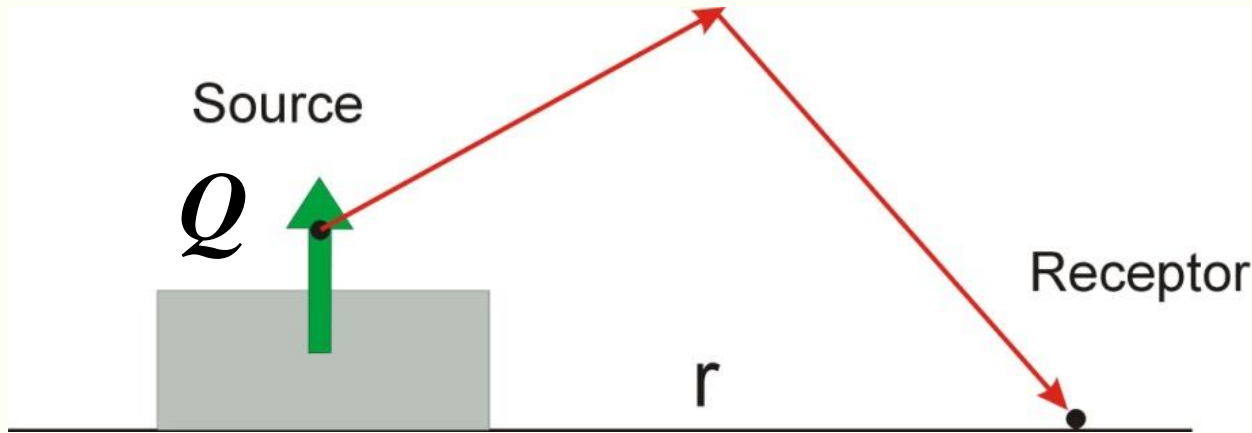
Afscherming



$$H \left(E_p, \vec{r}, m_{st}, m_{sh}, \theta, \frac{d}{\lambda} \right) = \frac{H_0(E_p, m_{st}, \theta)}{\vec{r}^2} e^{-\left(\frac{d}{\lambda(E_p, m_{st}, m_{sh}, \theta) \cos(\alpha)} \right)}$$

Monte Carlo simulaties

Skyshine



Skyshine neutron-fluëntie $\Phi(r)$ op afstand r v.d. bron:

$$\Phi(r) = \frac{Q}{4\pi r^2} e^{-r/\lambda}$$

