Physics of Detectors - So Se 2009

Notiztitel 15.04.2009

1. Interaction of radiation with matter

1.1 Heavy charged particles

- heavy $\hat{=}$ $\geq m(\text{proton})$
- charged $\hat{=}$ $\neq$ neutron

$\left(\begin{array}{l} m(p) \sim 938\ MeV/c^2 \\ m(\mu^-) \sim 106\ MeV/c^2 \\ m(e^-) \sim 0{,}511\ MeV/c^2 \end{array} \right)$

- main interaction: Coulomb with atomic electrons
- maximum energy transferred per collision

$$\Delta E/_{\text{nucleon}} = 4E \cdot \frac{m(\text{target})}{m(\text{projectile})} \sim E \cdot \frac{(4 \cdot 0{,}5\ MeV)}{1000\ MeV}$$

$$\simeq \frac{1}{500} E(\text{projectile})$$

$\curvearrowright$ many interactions necessary to loose substantial amount of energy

(a) STOPPING POWER

$$S = -\frac{dE}{dx} \quad \curvearrowright \text{ Bethe formula}$$

$$-\frac{dE}{dx} = \frac{4\pi \cdot e^4 \cdot z^2}{v^2 \cdot m_0} \cdot N \cdot Z \left[\ln \frac{2m_0 v^2}{I} \underbrace{- \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2}}_{\text{vanishes for } v \ll c} \right]$$

v $\hat{=}$ velocity projectile
$z \cdot e$ $\hat{=}$ charge projectile
m_0 $\hat{=}$ rest mass electron $= 511\ keV/c^2$
$Z \cdot e$ $\hat{=}$ charge absorber
I $\hat{=}$ average ionization potential $\sim 10\ eV \cdot Z$ (Bloch, empirical)

$N \mathrel{\hat{=}}$ number density of absorber electrons $(\propto \varrho)$

$\Rightarrow$ mainly $\dfrac{z^2}{v^2} \cdot \underbrace{N}_{\sim \varrho/A} \cdot Z \sim \dfrac{z^2}{E} \cdot N \cdot Z$ — E: projectile energy

$\Rightarrow$ large stopping power for

- small velocities
- large z of projectile
- large Z and density of absorber

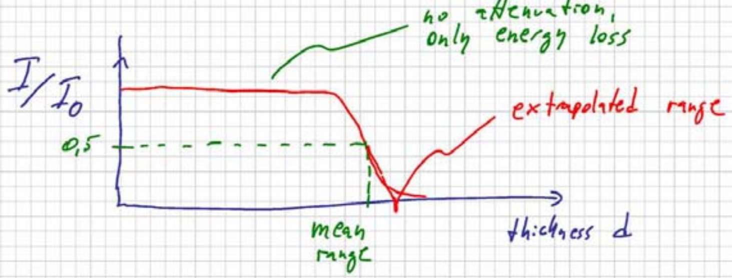
- Bethe formula fails at very low projectile energies (ion captures e^- and becomes neutral)

(b) BRAGG CURVE

- Energy straggling

(c) PARTICLE RANGE

Let projectile beam with intensity I_0 pass through absorber with variable thickness → measure intensity I



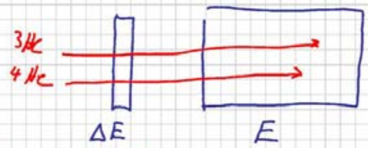
- Range straggling, typically a few %

(d) ENERGY LOSS IN THIN ABSORBERS

$$\Delta E = -\left(\frac{dE}{dx}\right)_{avg.} \cdot d$$

energy averaged over thickness d

- ↗ $\Delta E - E$ detectors



	ΔE
3He	75 keV
4He	90 keV

$E = 10$ MeV

- energy loss in target

1.2 Fast electrons

20.04.09

- fast ~ MeV
- m(projectile) = m(absorber electrons)

↗ large deviations from straight path possible

(a) STOPPING POWER $\left(\frac{dE}{dx}\right)_{total} = \left(\frac{dE}{dx}\right)_{coll} + \left(\frac{dE}{dx}\right)_{rad}$

$$-\left(\frac{dE}{dx}\right)_{coll} = \frac{2\pi e^4}{v^2 \cdot m_0} \cdot N \cdot Z \left(\ln \frac{m_0 v^2 \cdot E}{2 I^2 (1-\beta^2)} - \ln \dots (\beta) \right)$$

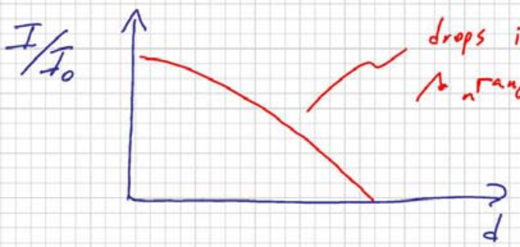
collisional losses

$$\beta = v/c$$

$$-\left(\frac{dE}{dx}\right)_{rad} = \frac{N \cdot E (Z+1) \cdot e^4}{137 \; m_0^2 c^4} \left(4 \ln \frac{2E}{m_0 c^2} - \frac{4}{3} \right)$$

- ↗ Fig. 1.8 $\frac{(dE/dx)_{rad}}{(dE/dx)_{coll}} \simeq \frac{Z \cdot E/MeV}{700}$

(b) ELECTRON RANGE



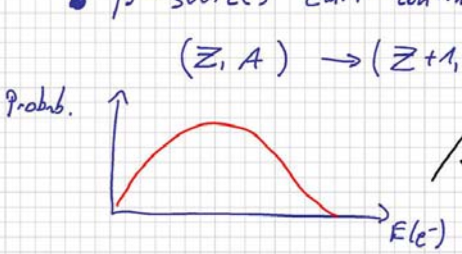
drops immediately

↗ „range" less defined

→ Fig. 1.9

- β^- - sources emit continuous energy spectrum

$$(Z, A) \to (Z+1, A) + e^- + \bar{\nu}_e$$



$$\Rightarrow I/I_0 = e^{-n d}$$

absorption coefficient

- backscattering (large deflection angles)

- (e^-) and for (heavy ions)

reality more complex $\to$

tables, graph, simulation (SRIM $\to$ heavy ions; GEANT $\to$ all particles)

1.3 Gamma rays

1.3.1 PHOTOELECTRIC ABSORPTION

Gamma transfers energy to atomic electron

$$E_{e^-} = E_\gamma - E_b$$

↳ Binding energy of e^- in shell (typically keV)

One ionized absorber atom remains

$\Rightarrow$ shell vacancy quickly filled

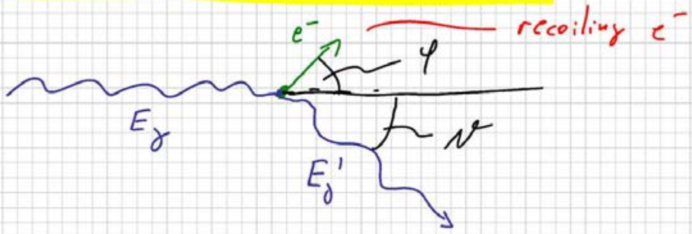
$\Rightarrow$ X-ray photons, Auger - electrons

Absorption probability per atom

$$P_{abs} \propto \frac{Z^n}{E_\gamma^{3,5}} \qquad n \sim 4-5$$

1.3.2 COMPTON SCATTERING

22.04.09



Conservation of linear momentum and energy

$$E_\gamma' = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1-\cos\vartheta)} \qquad m_0 c^2 = 511\ \mathrm{keV}$$

- Probability of Compton scattering increases linearly with Z
- Angular distribution of scattered γ-rays:

  $\rightarrow$ Klein-Nishina formula

$$\frac{d\sigma}{d\Omega} = Z \cdot r_0^2 \left(\frac{1}{1+\alpha(1-\cos\vartheta)}\right)^2 \left(\frac{1+\cos^2\vartheta}{2}\right)\left(1 + \frac{\alpha^2(1-\cos\vartheta)^2}{(1+\cos^2\vartheta)\cdot\left[1+\alpha(1-\cos\vartheta)\right]}\right)$$

$\alpha = \frac{E_\gamma}{m_0 c^2}$ $\quad r_0$ = classical electron radius $2{,}8 \times 10^{-15}$ m

→ Fig. 1.12

1.3.3 PAIR PRODUCTION

If $E_\gamma \geq \underbrace{2\, m_0 \cdot c^2}_{1022 \text{ keV}}$ → e^+e^- production possible

in the field of a nucleus.

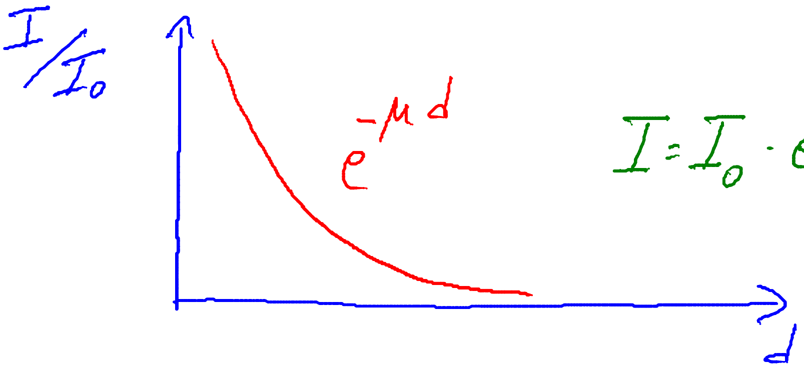
With $E_{kin}(e^+) + E_{kin}(e^-) = E_\gamma - 1022$ keV

- e^+ annihilates with e^- from atom → two 511 keV photons

$e^+ e^-$ → 

- Probability raises sharply with energy and scales $\sim Z^2$

1.3.4 Attenuation of γ rays



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

$\mu = \mu(\text{Photoeffect}) + \mu(\text{Compton}) + \mu(\text{Pair})$

(linear attenuation coefficient)

- MEAN FREE PATH (before interaction)

$$\lambda = 1/\mu$$

- MASS ATTENUATION COEFFICIENT

$$\mu_{mass} = \mu/\rho$$

$$\Rightarrow \quad I = I_0 \cdot e^{-(\mu/\rho)\,\rho \cdot d}$$

mass thickness, e.g. mg/cm^2

1.4 Neutrons

Interaction with nuclei of absorber material via strong interaction

$\Rightarrow$ n has to be in 10^{15} m range

(a) elastic scattering $A(n,n')A$ (mainly if $E_n \sim$ MeV)

(b) inelastic scattering $A(n,n')A^*$ (later e.g. γ-emission)

(c) radiative capture $A(n,\gamma)B$ (usually $1/v$-dependence plus resonances)

(d) other reactions (n,p), (n,d), (n,α)

(e) fission (n,f) (usually with thermal neutrons)

E_n	classification
100 keV - MeV	fast
0,1 eV - 100 keV	epithermal
1/40 eV	thermal, slow
μeV - meV	cold, ultracold

- neutron cross section

$$\sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic} + \sigma_{reaction} + \dots$$

$$\Sigma_{tot} = N \cdot \sigma_{tot}$$

N: number of nuclei/volume

$$I = I_0 \cdot e^{-\Sigma_{tot} \cdot d}$$