Some recommended exercises

1 Look at the classical derivation of the the Bethe-Bloch formula

2 Kinematics of Compton scattering and (e+e-)-pair creation

3 Cerenkov threshold for electrons in water

4 Estimate the nuclear interaction length in Iron
(Fe, A=56; ρ=7.8 g/cm^3)

1 The number of particles in a elm shower is proportional to the Energy. If we can measure the number of particles in a shower, how will the energy resolution scale with energy ?

2 Movement of a charged particle in a magnetic field. If the curvature is measured, how well can we measure the momentum of the charged particle ?

Bibliographie

Text books :

– C. Grupen, Particle Detectors, Cambridge University Press, 1996
– G. Knoll, Radiation Detection and Measurement, 3rd ed. Wiley, 2000
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– K. Kleinknecht, Detectors for particle radiation , 2nd edition, Cambridge Univ. Press, 1998
- D. Green, The physics of <<<particle Detectors, Cambridge Univ. Press 2000
- S. Tavernier, Experimental Techniques in Nuclear and particle Physics, Springer 2010
- G. Lutz, Semiconductor Radiation Detectors, Springer, 1999
- W. Blum, L. Rolandi, Particle Detection with Drift Chambers, Springer, 1994
– R. Wigmans, Calorimetry, Oxford Science Publications, 2000

Review Articles

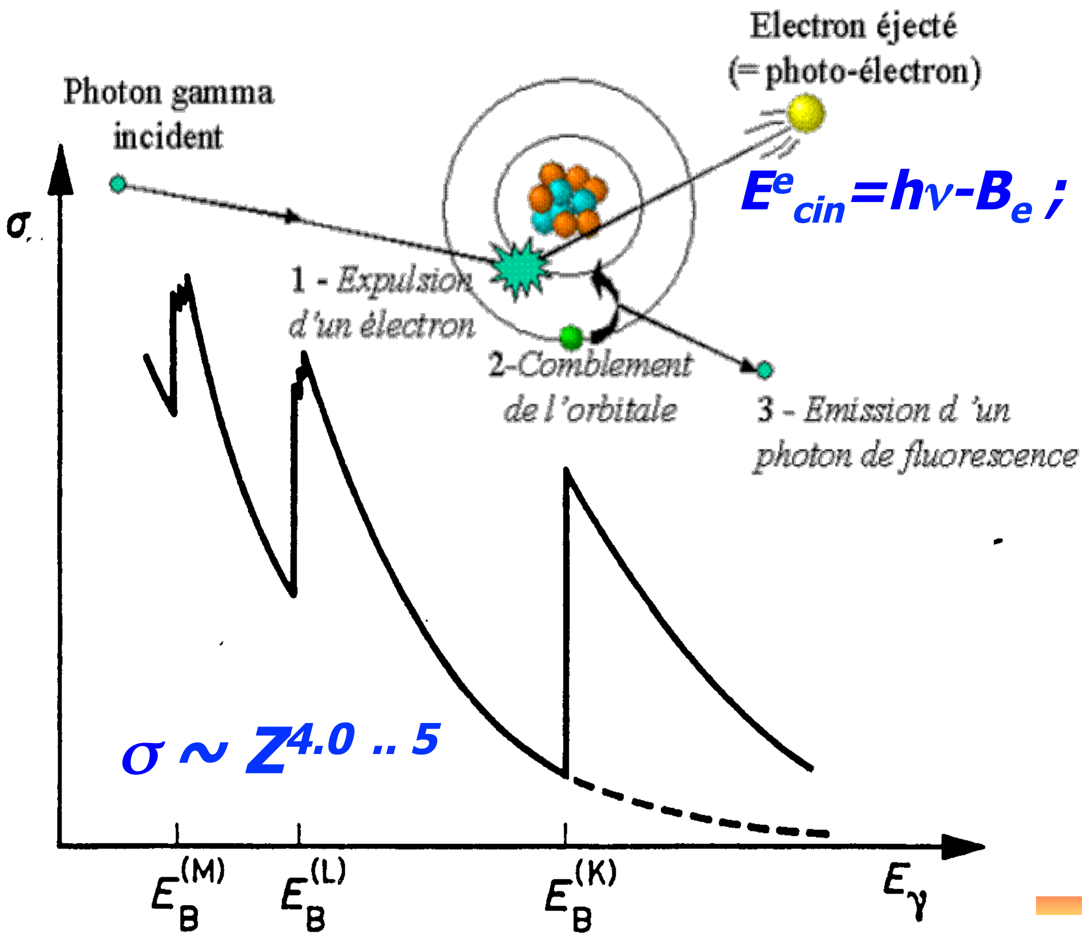
– Experimental techniques in high energy physics, T. Ferbel (editor), World Scientific, 1991.
– Instrumentation in High Energy Physics, F. Sauli (editor), World Scientific, 1992.
– Many excellent articles can be found in Ann. Rev. Nucl. Part. Sci.
……

Summer student lectures and academic training

- Particle Detectors - Principles and Techniques: C. D'Ambrosio, T. Gys, C. Joram, M. Moll and L. Ropelewski, CERN Academic Training Programme 2004/2005 …..
- Summer Student Lectures 2010, Werner Riegler, CERN,
- Summer Student Lectures 2012, Detectors for Particle Physics, D. Bortoletto, Purdue University
- Particle detection and reconstruction at the LHC (I), African School of Physics, Stellenbosch, South Africa, August 2010 (D. Froidevaux, CERN)
- Particle detectors and large HEP experiments, L. Serin LAL/Orsay & IN2P3/ CNRS, lecture at the European Summer Campus 2011, Strasbourg France
- Physics of Particle Detection, ICFA, Instrumental school, South Africa 2001, Claus Grupen, University of Siegen
- ….

Photo-electric effect

$$\sigma^{K}_{p.e.}\Big|_{atom} = \sqrt{\frac{32}{\left(E_\gamma / m_e c^2\right)^7}} \cdot Z^5 \alpha^4 \times \underbrace{\left(\frac{8}{3}\pi r_e^2\right)}_{} \times \text{corrections}$$



$E^e_{cin} = h\nu - B_e$;

$\sigma \sim Z^{4.0\ ..\ 5}$

- At high *Z*, the hole in the K-shell is filled by an electron under the emission of a fluorescence x-ray of energy $E_\gamma = E_K - E_{L,M,N}$
- At low Z, Auger electrons occur: electrons of higher shells (L) are ejected with energy

$E_{Auger} = E_K - 2E_L$

Compton-effect

Scattering of a gamma on a "free" electron

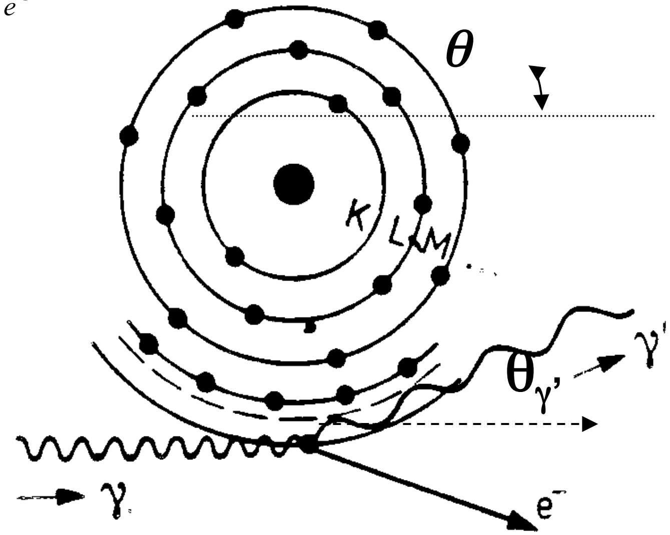
$$h\nu' = \frac{h\nu}{1+\varepsilon(1-\cos\theta_{\gamma'})};$$

$$\varepsilon = h\nu / m_e c^2$$

$$T_e = h\nu - h\nu'$$

$$\Delta\lambda = \lambda' - \lambda = \frac{hc}{m_e c^2}\left(1-\cos\theta_{\gamma'}\right)$$

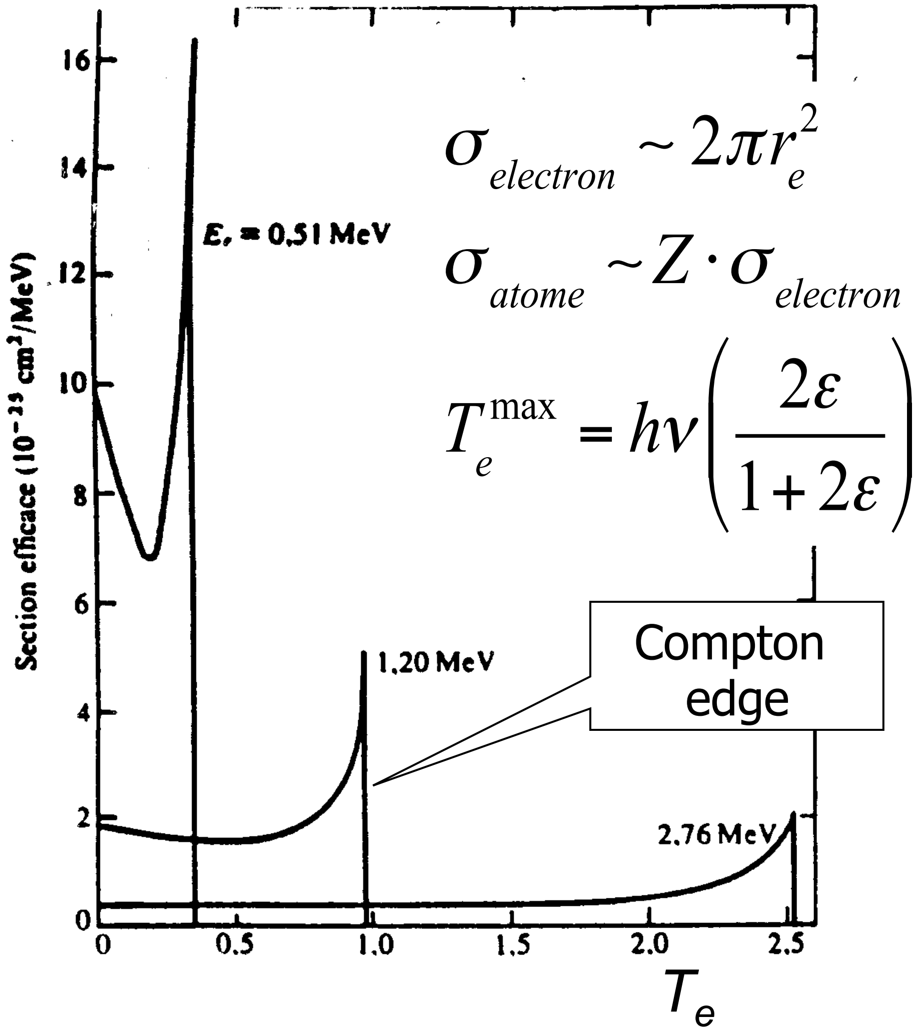
$$\lambda_c = \frac{\hbar c}{m_e c^2}$$ Compton wave lenth of an electron



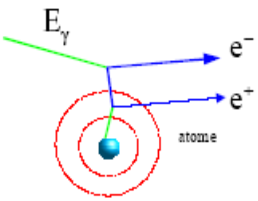
$$\sigma_{electron} \sim 2\pi r_e^2$$

$$\sigma_{atome} \sim Z \cdot \sigma_{electron}$$

$$T_e^{max} = h\nu\left(\frac{2\varepsilon}{1+2\varepsilon}\right)$$



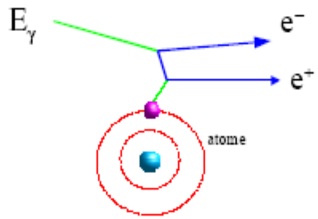
Creation of electron positron pairs



Dans le champ du noyau

$$E_\gamma \geq 2m_e + \frac{2m_e^2}{m_N}$$

$$m_N \gg m_e \Rightarrow E_\gamma \geq 2m_e$$

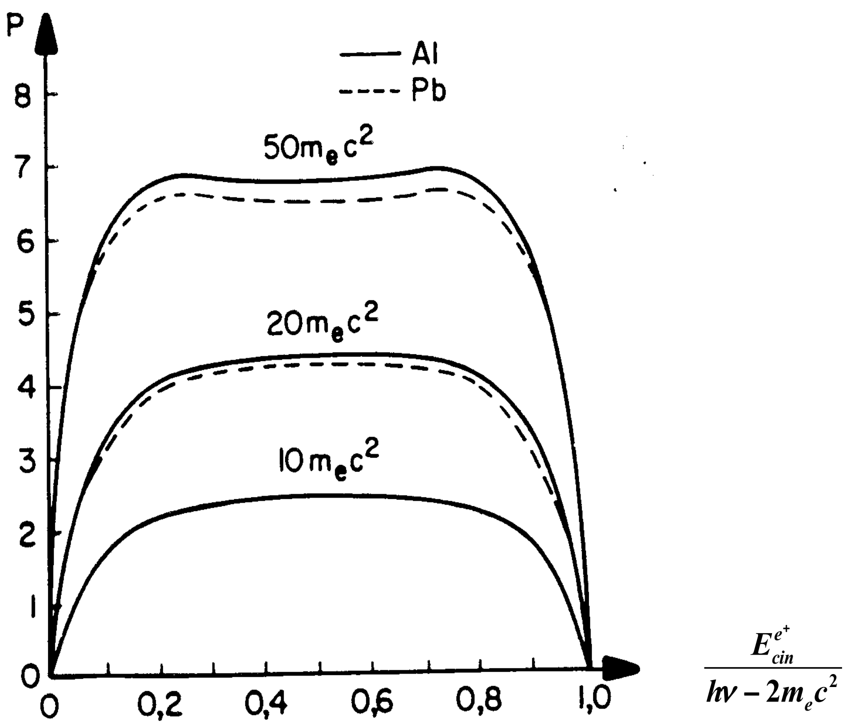


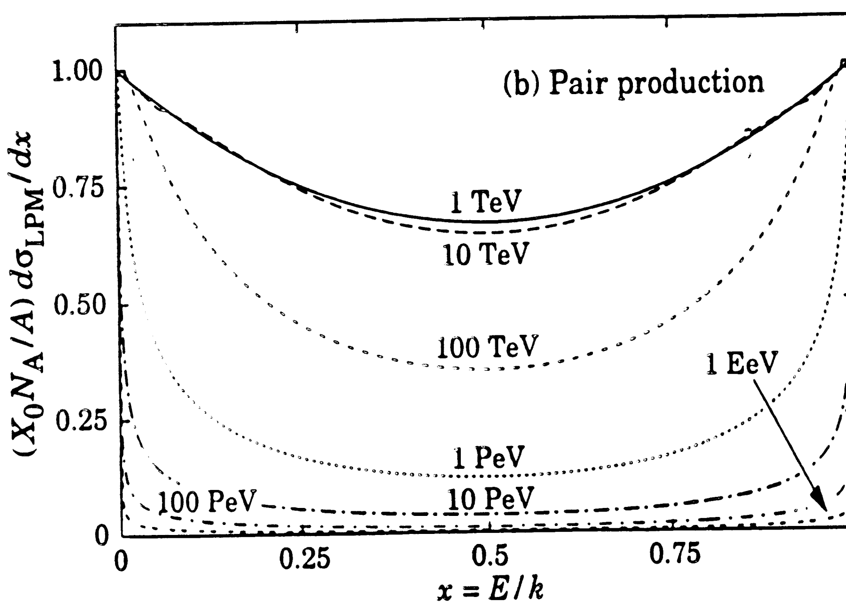
Dans le champ d'un électron

$$E_\gamma \geq 4m_e$$

$$\sigma_{pair} \approx \frac{7}{9}\frac{A(g)}{N_A}\cdot\frac{1}{X_0} \sim Z(Z+1)$$

$$\mu_{pair} = \frac{N_A}{A}\sigma_{pair} \approx \frac{7}{9}\frac{1}{X_0} \;;\; \lambda_{pair} = \frac{1}{\mu_{pair}} = \frac{9}{7}X_0$$





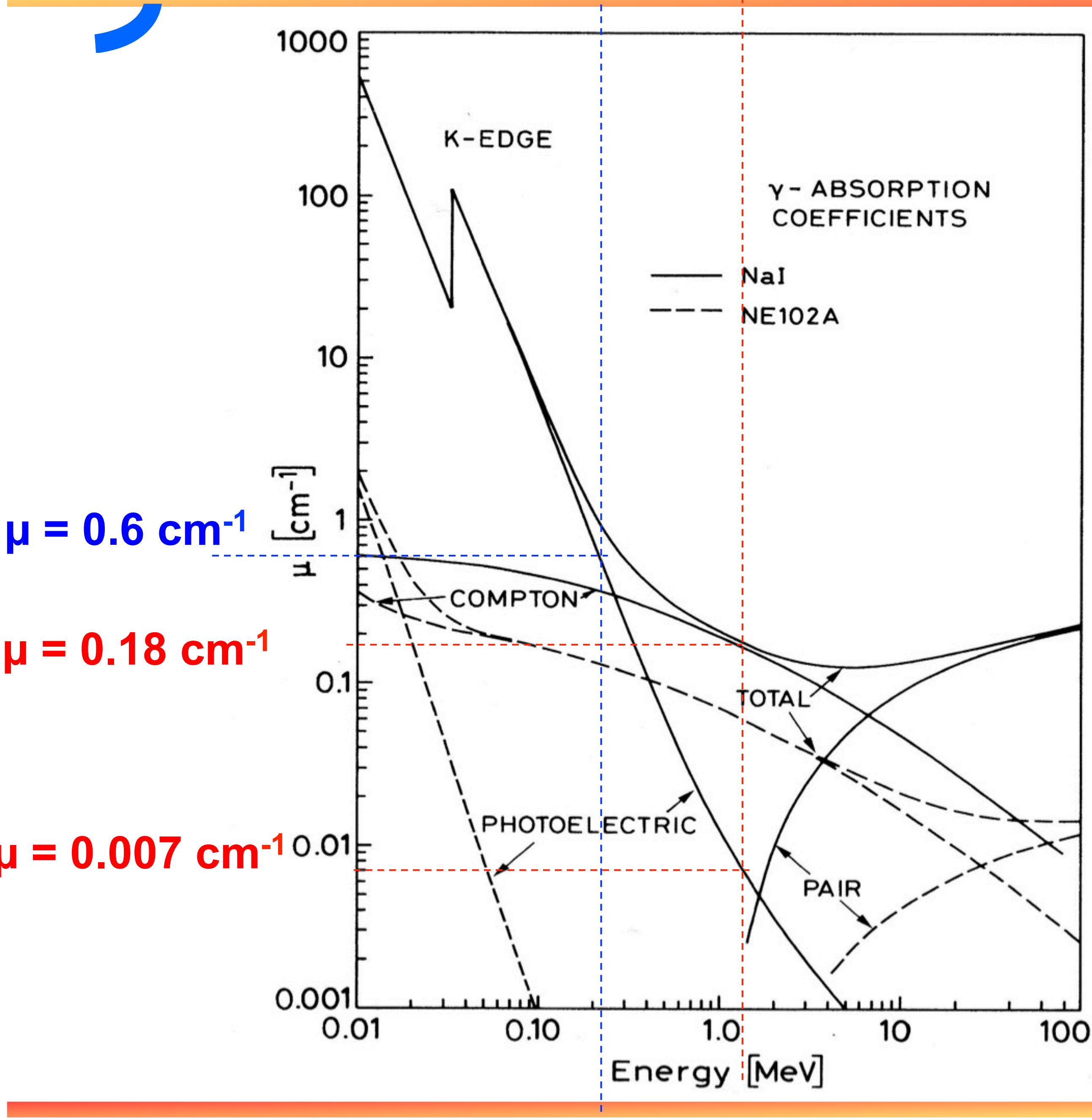


Photo-electric effect

Absorption of γ

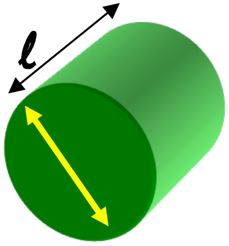
Compton scattering

scattering γ –> γ'

Creation of (e^+e^-) pairs

Absorption of γ

NaI (Tl)



- Reference/standard of efficiency: $\varepsilon = 1{,}22 \times 10^{-3}$
    - Cylindrical detector NaI(Tl), 7,62(∅) x 7,62(ℓ) cm^3
    - Source of ^{60}Co (1,33 MeV) at 25 cm

Properties of NaI:

- Z = 53 high ⇒ good efficiency
- Relatively short decay time (230 ns)
- intense signal
- Relative good energy resolution
- But NaI is very hygroscopic!!

Exercise : verify efficiency!

Efficiency of a detector
(valid in general!!)

- **Absolute or total efficiency**

$$\varepsilon_{tot} = \frac{\left(\text{particles or gammas}\right)\ \text{registered}}{\left(\text{particles or gammas}\right)\ \text{emmitted}}$$

  – This depends on the geometry between the source and the detector (its distance and opening, its solid angle)

$$\varepsilon_{tot} = \underbrace{\left[1 - \exp\left(\frac{-S_p}{\lambda}\right)\right]}_{\text{probability of an interaction}} \times \underbrace{\frac{\Delta\Omega}{4\pi}}_{\text{probability of an emmission in the solid angle of the detector}}$$

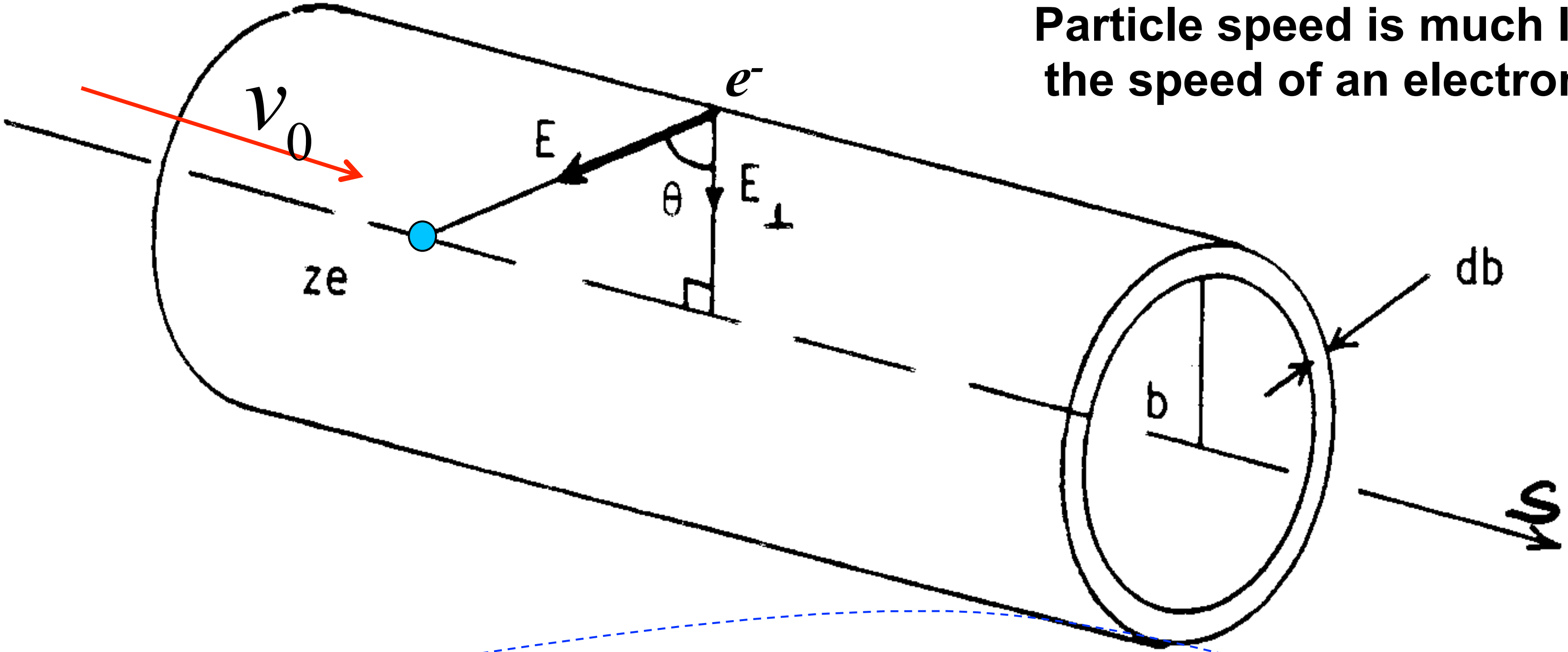
$$\varepsilon_{tot} \cong \varepsilon_{\text{int}} \times \varepsilon_{geom}$$

$$\lambda = \text{attenuation length;} \left\{\frac{1}{\lambda} = \sigma \cdot n_b\right\};\ S_p = \text{Depth of the detector}$$

- **Intrinsic efficiency**

$$\varepsilon_{\text{int}} = \frac{\left(\text{particles or gammas}\right)\ \text{"registered"}}{\left(\text{particles or gammas}\right)\ \text{in the acceptance of the detector}}$$

Interaction of charged "heavy" particles with the electrons of matter



Particle speed is much larger than the speed of an electron bound to a nucleus

$$-\frac{dE}{ds} = -\int_0^\infty \frac{dE}{db}\,db = \frac{4\pi z^2 e^4 k^2}{m_e v_0^2} n_e \ln\frac{b_{max}}{b_{min}}$$

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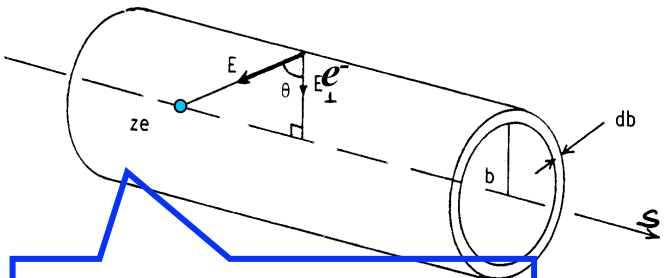


Cylinder of surface A and volume V

Classical calculation by Bohr:

Momentum transfer Δp to the electron;

Energyloss of particle = - energy transfer to electron ΔE;

n_e = electron density

$$\Delta p_e = \int_{-\infty}^{\infty} F\,dt = e\int_{-\infty}^{\infty} \mathfrak{E}_\perp\,dt = \frac{e}{v_0}\int_{-\infty}^{\infty} \mathfrak{E}_\perp\,ds; \quad \mathfrak{E}_\perp = \text{electric field}$$

$$GAUSS: \iiint_V \operatorname{div}\vec{\psi}\,dx\,dy\,dz = \oint_A \vec{\psi}\,d\vec{a}; \quad \vec{\psi} = \text{vector field}$$

$$\iint_A \mathfrak{E}_\perp\,da = \iiint_V \operatorname{div}\vec{\mathfrak{E}}\,dx\,dy\,dz = \frac{1}{\varepsilon_0}\iiint \rho\,dx\,dy\,dz = \frac{ze}{\varepsilon_0}; \quad \operatorname{div}\vec{\mathfrak{E}} = \frac{\rho}{\varepsilon_0}$$

$$da = 2\pi b\,ds\;; \quad 2\pi b\int_{-\infty}^{\infty} \mathfrak{E}_\perp\,ds = \frac{ze}{\varepsilon_0}$$

$$\Delta p_e = \frac{2}{4\pi\varepsilon_0}\frac{ze^2}{bv_0} = 2k\frac{ze^2}{bv_0}; \qquad k = \frac{1}{4\pi\varepsilon_0}$$

$$\Delta E = -\Delta E_e = -\frac{(\Delta p_e)^2}{2m_e} = -2\frac{z^2e^4}{b^2m_e}\left(\frac{k}{v_0}\right)^2$$

$$-dE(b) = \Delta E(b)n_e dV = 4\pi n_e\frac{z^2e^4}{m_e}\left(\frac{k}{v_0}\right)^2\frac{db}{b}ds; \quad (dV = 2\pi b\,db\,ds)$$

$$-\frac{dE}{ds} = -\int_0^{\infty}\frac{dE}{db}db = 4\pi n_e\frac{z^2e^4}{m_e}\left(\frac{k}{v_0}\right)^2\ln\left(\frac{b_{max}}{b_{min}}\right)$$

Classical calculation by Bohr, b_{min} and b_{max}

$b_{\min}$: Maximal energy transfer to electron

$$T_e^{\max} = 2 m_e v_0^2 \gamma^2 = 2 \frac{z^2 e^4}{b_{\min}^2 m_e} \left(\frac{k}{v_0} \right)^2$$

$$b_{\min} = \frac{z \cdot e^2 k^2}{\gamma m_e v_0^2}; \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}; \ \beta = \frac{v_0}{c}; \ v_0 = \text{particle speed !}$$

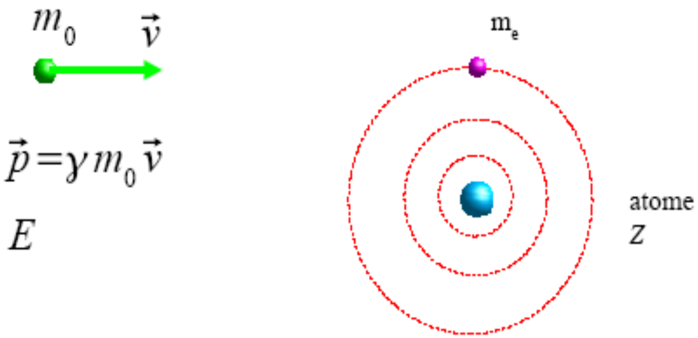
$b_{\max}$: interaction time $\ll$ Orbit time $\bar{T}$

$$\frac{b_{max}}{\gamma v_0} \ll \bar{T}$$

$$b_{max} = \gamma v_0 \bar{T}$$

$$-\frac{dE}{ds} = -\int_0^\infty \frac{dE}{db} db = \frac{4\pi z^2 e^4 k^2}{m_e v_0^2} n_e \ln \frac{\gamma^2 m_e v_0^3 \bar{T}}{z^2 e^2 k^2}$$

Maximal energy transfer of charged "heavy" particles to the electrons of matter



$$T_e^{\max} = E_e^{\max} - m_e c^2 = \frac{2 m_e^2 c^2 \beta^2 \gamma^2}{\left(E_{CM} / m_0 c^2\right)^2}$$

$$v \gg v_e \simeq Z\alpha c$$

$$E_{CM} = \left(m_0^2 c^4 + m_e^2 c^4 + 2 m_e c^2 E\right)^{\frac{1}{2}}$$

$$p_e^{CM} = p \frac{m_e c^2}{E_{CM}}$$

$$E_e^{CM} = (E + m_e c^2) \frac{m_e c^2}{E_{CM}}$$

$$\gamma^{CM} = \frac{E + m_e c^2}{E_{CM}}; \ \beta^{CM} = \frac{pc}{E + m_e c^2}$$

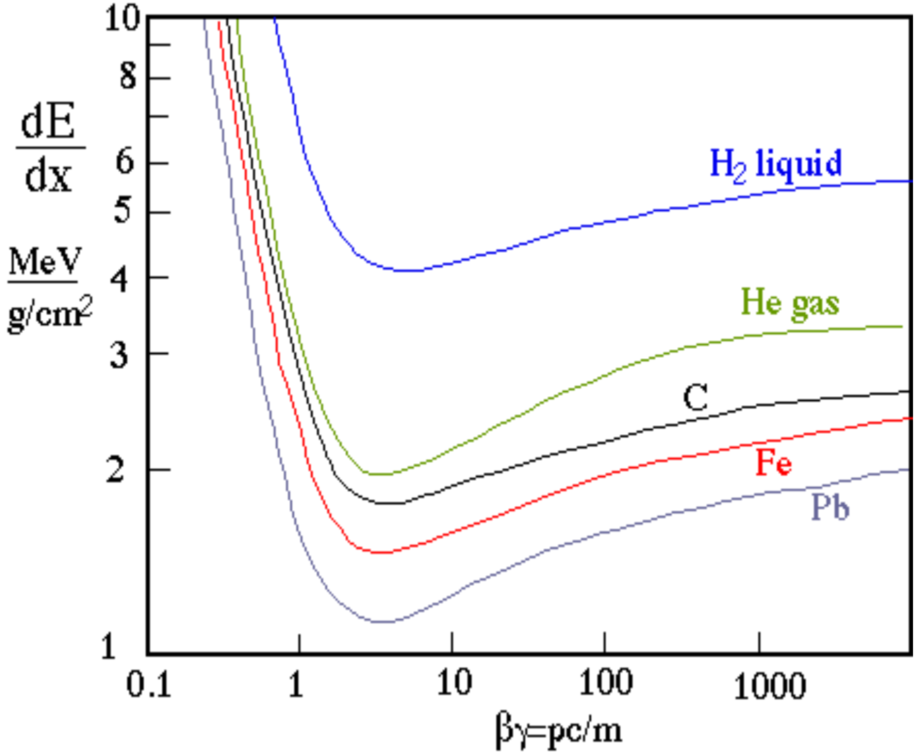
$$m_0 \gg m_e; \ 2\gamma m_e / m_0 \ll 1$$

$$T_e^{\max} = 2 m_e c^2 \beta^2 \gamma^2$$

$$m_0 = m_e$$

$$T_e^{\max} = \frac{E^2 - m_e^2 c^4}{m_e c^2 + E} = E - m_e c^2 = T_e = T_0$$

Bethe – Bloch formula



$$-\frac{dE}{dx} = -\frac{1}{\rho}\frac{dE}{ds}$$

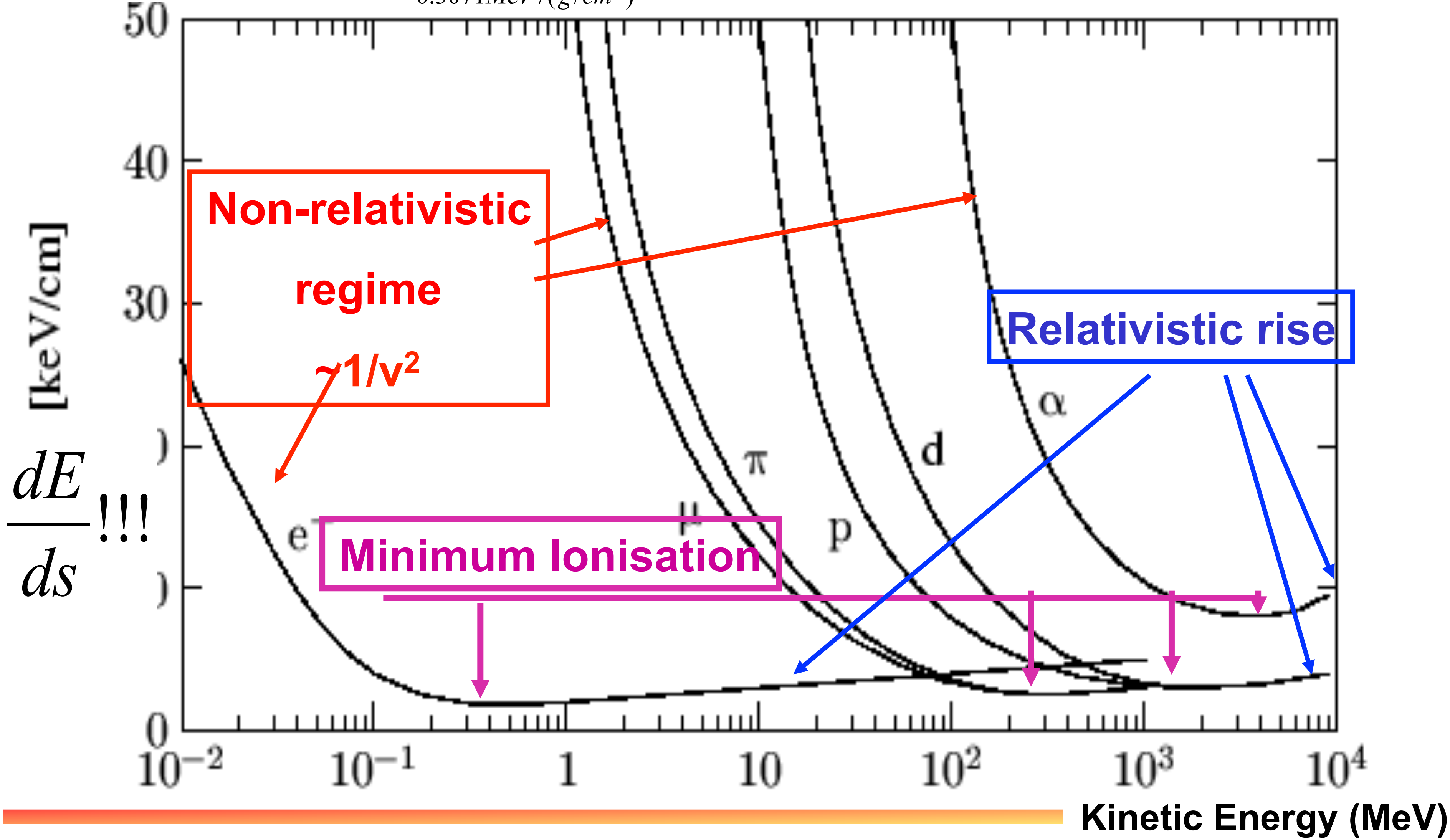
$$n_e = N_A \cdot \rho \cdot \frac{Z}{A}$$

$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2} = \frac{\alpha\hbar c}{m_e c^2}$$

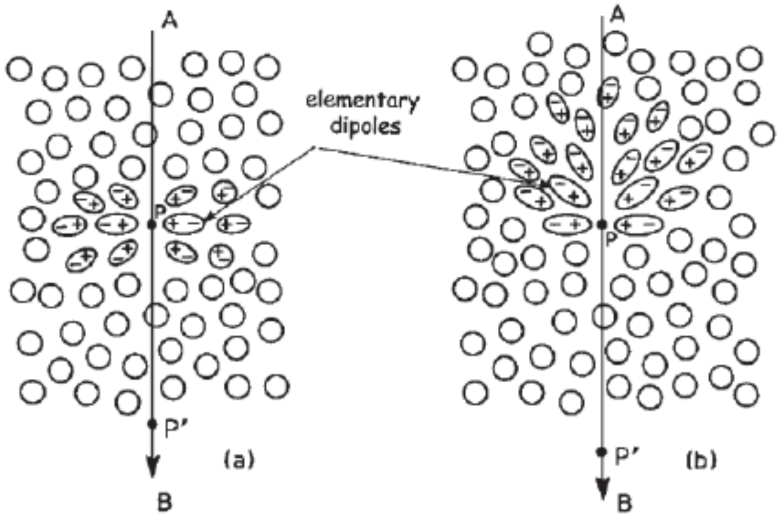
$$-\frac{1}{\rho}\frac{dE}{ds} = -\frac{dE}{dx} = \underbrace{4\pi N_{Av} r_e^2 m_e c^2}_{0.3071 MeV/(g/cm^2)} \frac{Z}{A} z^2 \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2 \cdot T_e^{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$

Density- *shell correction*

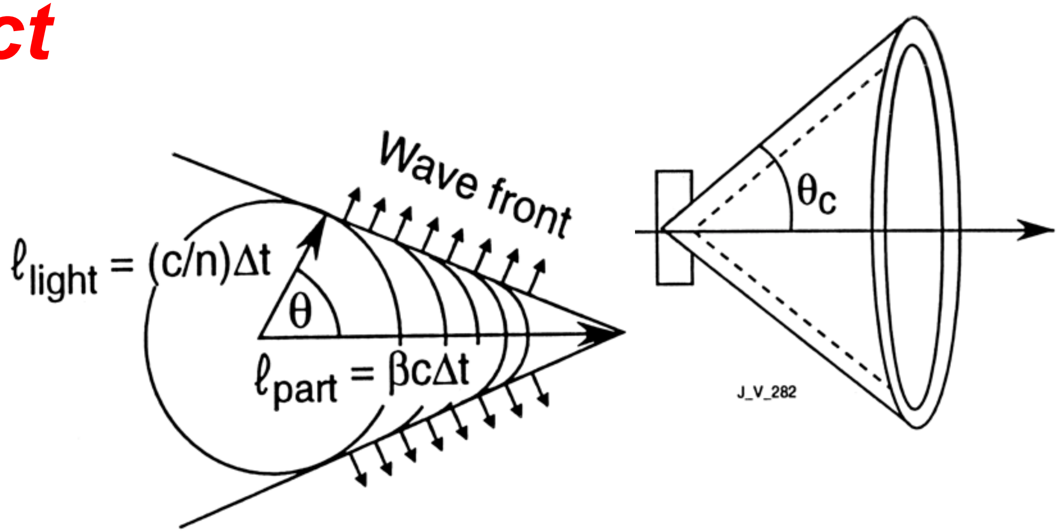
$$-\frac{1}{\rho}\frac{dE}{ds} = -\frac{dE}{dx} = \underbrace{4\pi N_{Av} r_e^2 m_e c^2}_{0.3071 MeV/(g/cm^2)} \frac{Z}{A} z^2 \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2 \cdot T_e^{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$



Cerenkov effect



$v_p/c < c/n(\lambda)$ $v_p/c > c/n(\lambda)$



$$v = \beta c > c / n$$

$$\cos\theta_C = \frac{c \cdot \Delta t / n}{\beta c \cdot \Delta t} = \frac{1}{\beta n}$$

$$\Rightarrow \beta > \frac{1}{n} \; ; \cos\theta_c^{max} = \frac{1}{n}$$

$$\lambda_{photons} \approx 200 - 700\, nm$$

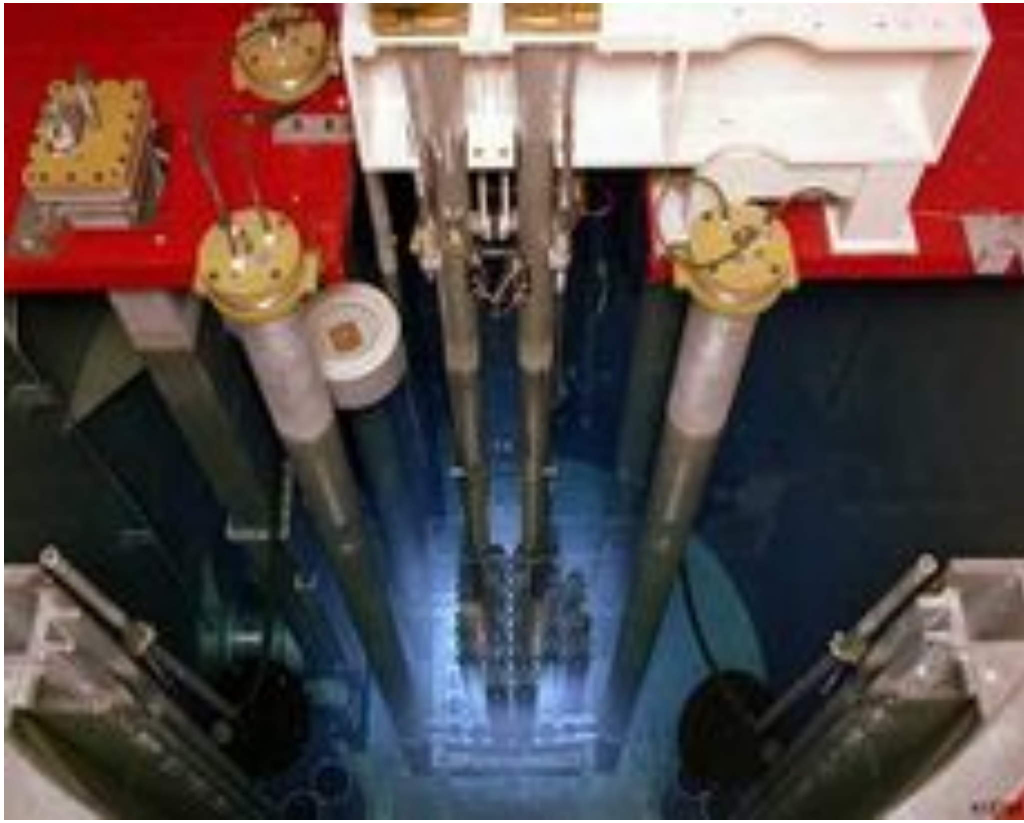
$$\frac{d^2 N_{h\nu}}{dE_{h\nu} dx} \approx 370 \sin^2\theta_C \; eV^{-1} cm^{-1}$$

- **Coherent superposition of the radiation of the atoms**
- **Mainly blue light**
- **Very few photons**
- **Very small energy loss**
- **Identification of particles!**

Exercise

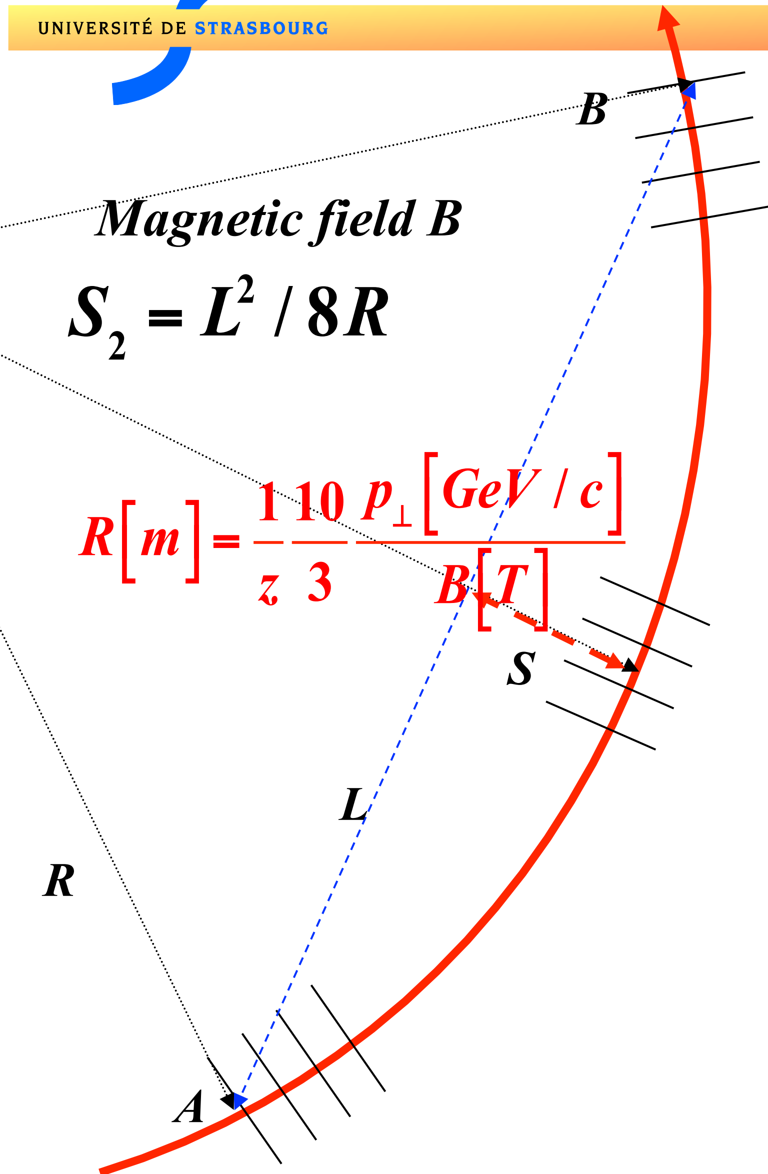
Blue light in a reactor

1. **What produces the light?**
2. **Water *n*=1.333. calculate the minimal energy of an electron to produce Cerenkov light**



Reconstruction of transv…e momentum in a magn… field

Exercise !!!



$$S_2 = L^2 / 8R$$

$$R[m] = \frac{1}{z}\frac{10}{3}\frac{p_\perp[GeV/c]}{B[T]}$$

- Movement of a charge z in a uniform magnetic field
- Momentum resolution *dp/p*
- Spatial resolution of the sagitta *dS/S*

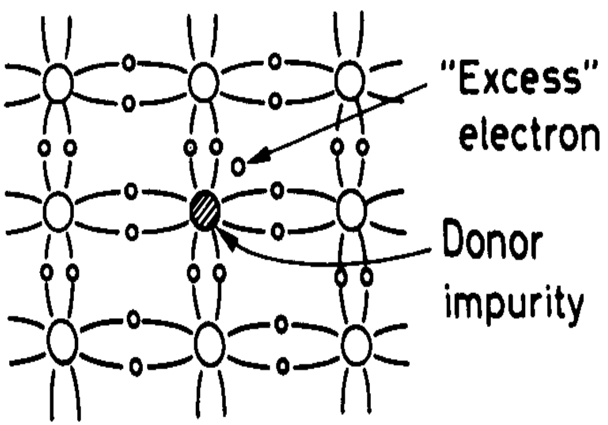
$$\frac{dS}{S} = \frac{dp_\perp}{p_\perp} = \frac{80}{3 \cdot z}\frac{1}{BL^2}p_\perp dS$$

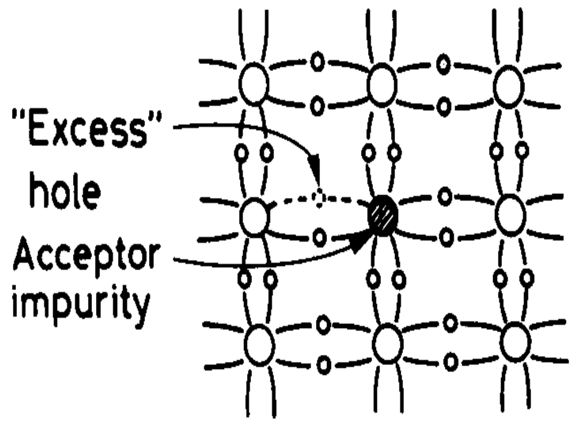
$$[B] = Tesla;\ [L] = m; [p_\perp] = GeV/c$$

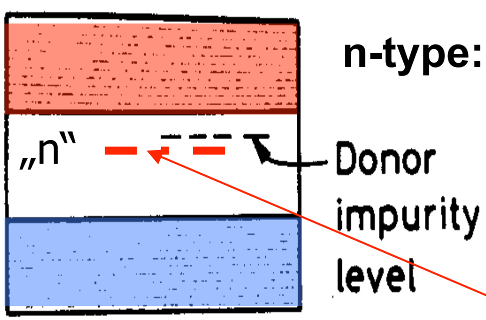
If the trajectory is measured with *N* points:

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3 \cdot BL^2}\sqrt{720/(N+4)} \qquad \text{(for } N \geq \sim 10\text{)}$$

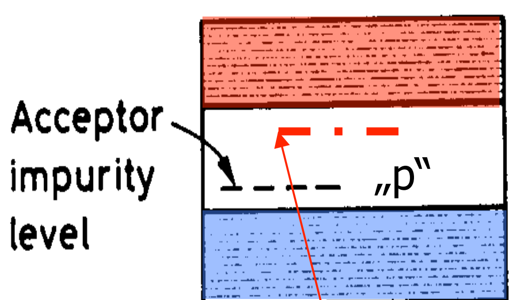
„Doped“ Semi-conductors



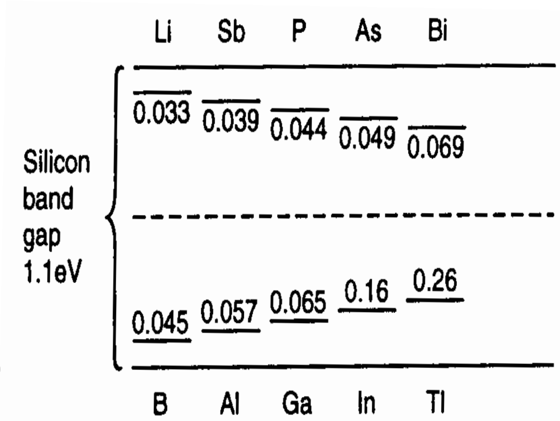




n-type: $N_D > N_A \approx 0$



p-type: $N_A > N_D \approx 0$



Energy levels within the band gap corresponding to various n- and p-type dopants [6]

Intrinsic: 1.5 $10^{10}/cm^3$ (N_A = 6.022 $10^{23}/cm^3$!!)
n, p : $10^{13}/cm^3$
n^+, p^+ : $10^{20}/cm^3$

Impurities

- **traps**
- **recombination**

W.Dulinski

Semi-conductor detectors

Material	E_g [eV]	w [eV]	Mobility (velocity/E)		τ_e [s]	τ_h [s]	density	Z [a.m.u]
			μ_e [cm^2/Vs]	μ_h [cm^2/Vs]			g/cm^3	
C (diamond)	5.5	13	1800	1200	$2\ 10^{-9}$	$2\ 10^{-9}$	3.515	6
Si	1.12	3.61	1350	480	$5\ 10^{-3}$	$5\ 10^{-3}$	2.33	14
Ge	0.67	2.98	3900	1900	$2\ 10^{-5}$	$2\ 10^{-5}$	5.32	32
GaAs	1.42	4.70	8500	450	$5\ 10^{-8}$	$5\ 10^{-8}$	5.32	31,33
CdTe	1.56	4.43	1050	100	$1\ 10^{-6}$	$1\ 10^{-6}$		48,52
HgI_2	2.13	4.20	100	_	$1\ 10^{-6}$	$2\ 10^{-6}$		53,80

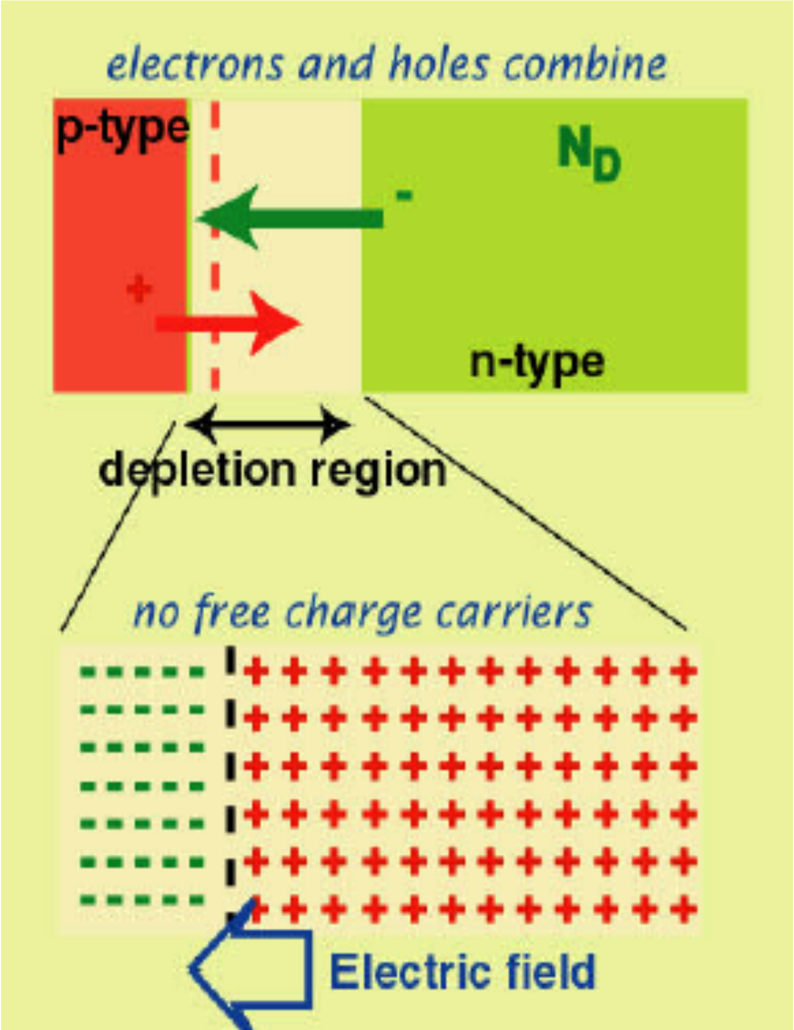
$$\frac{dN}{N} = \frac{1}{\sqrt{N}}\ ;\ \ E \sim N;\quad N = \text{numb. of (e,h))}$$

Parameters Values for Materials Used in Fabricating Semiconductor Radiation Sensors [3]

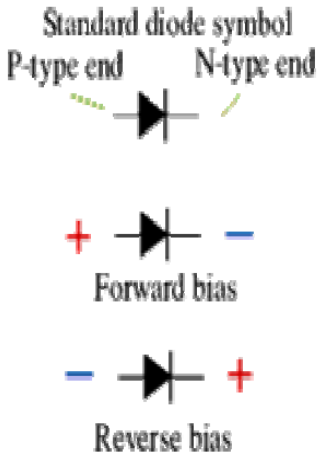
W.Dulinski

Junction p-n

Formation of a depletion zone



G.Hall

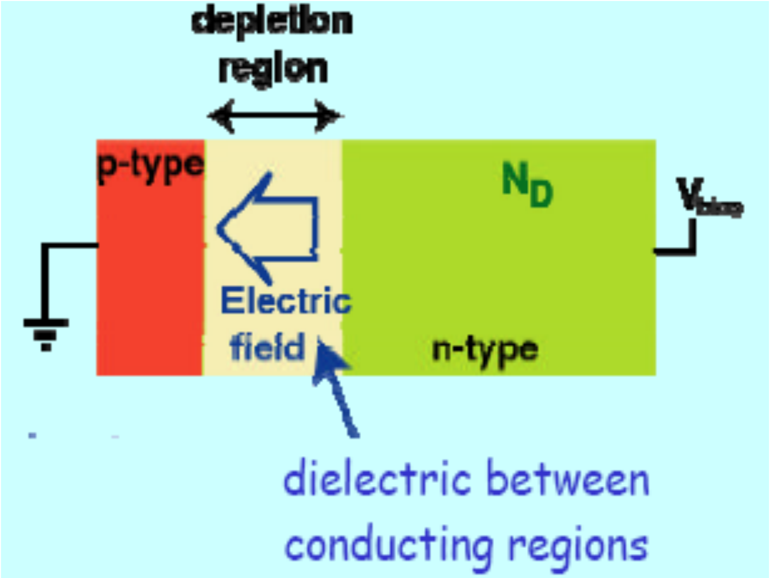


Direct Polarisation

- **conduction**
- $I \sim I_0[\exp(qV/kT) - 1]$

Inverse Polarisation

- **increase of depletion zone**
- **reduction of capacitance**



Inverse Polarisation

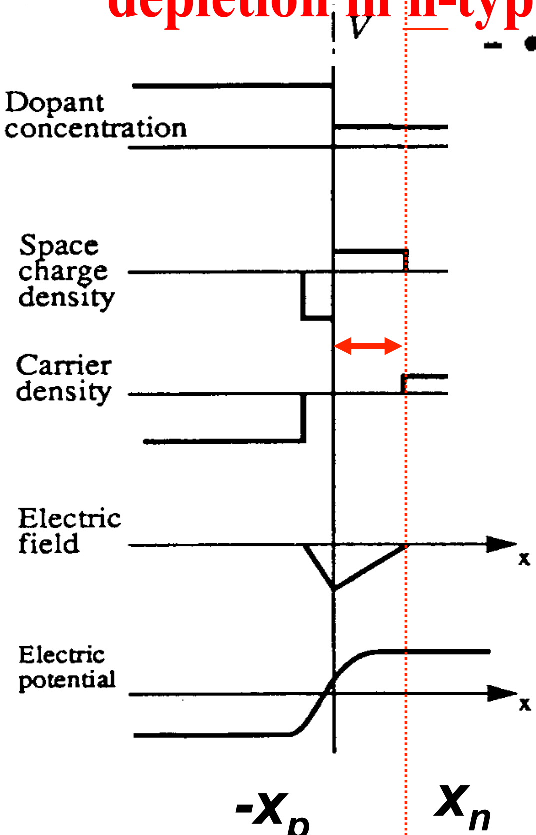
$$d\Big|_{V_{bias}} = x_n + x_p = \sqrt{\frac{2\varepsilon\left(\phi_0 + V_{bias}\right)}{e}\frac{\left(N_A + N_D\right)}{N_A N_D}}$$

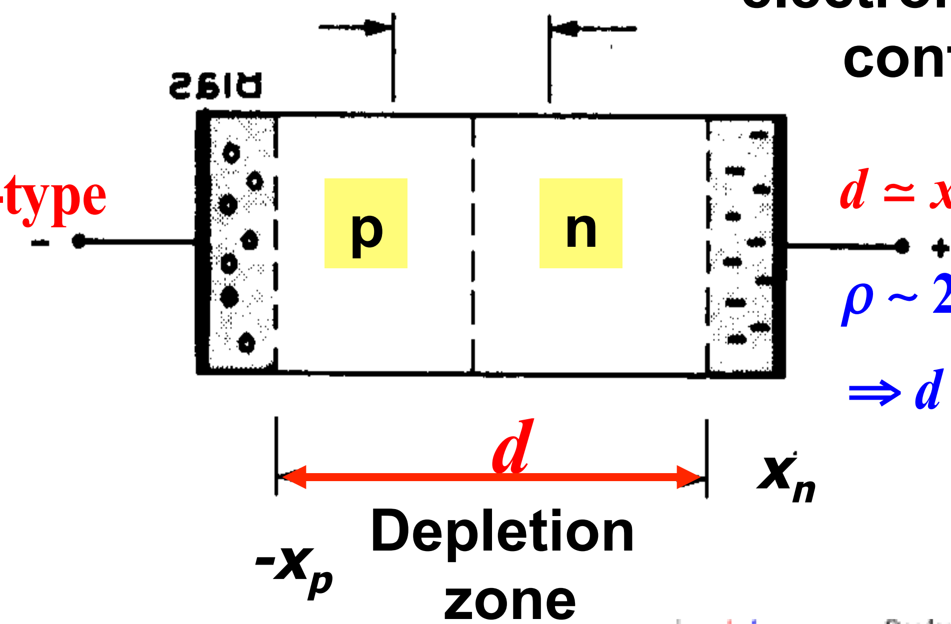
Holes move to « - »

electrons move to contact "+"

$N_A \gg N_D$

depletion in n-type

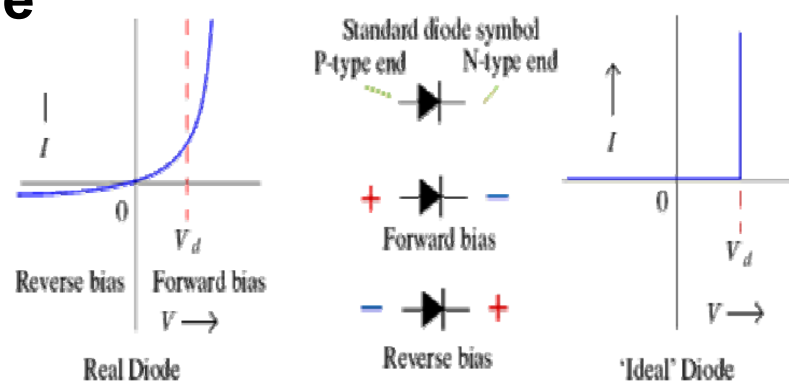




$$d \simeq x_n \approx 0.53\sqrt{\rho_n \phi_0}\ \mu m$$

$$\rho \sim 2 \cdot 10^4\ \Omega cm,\ \phi_0 \sim 1V$$

$$\Rightarrow d \sim 75\ \mu m$$



Surface barrier detectors

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Interaction des particules chargées avec le silicium

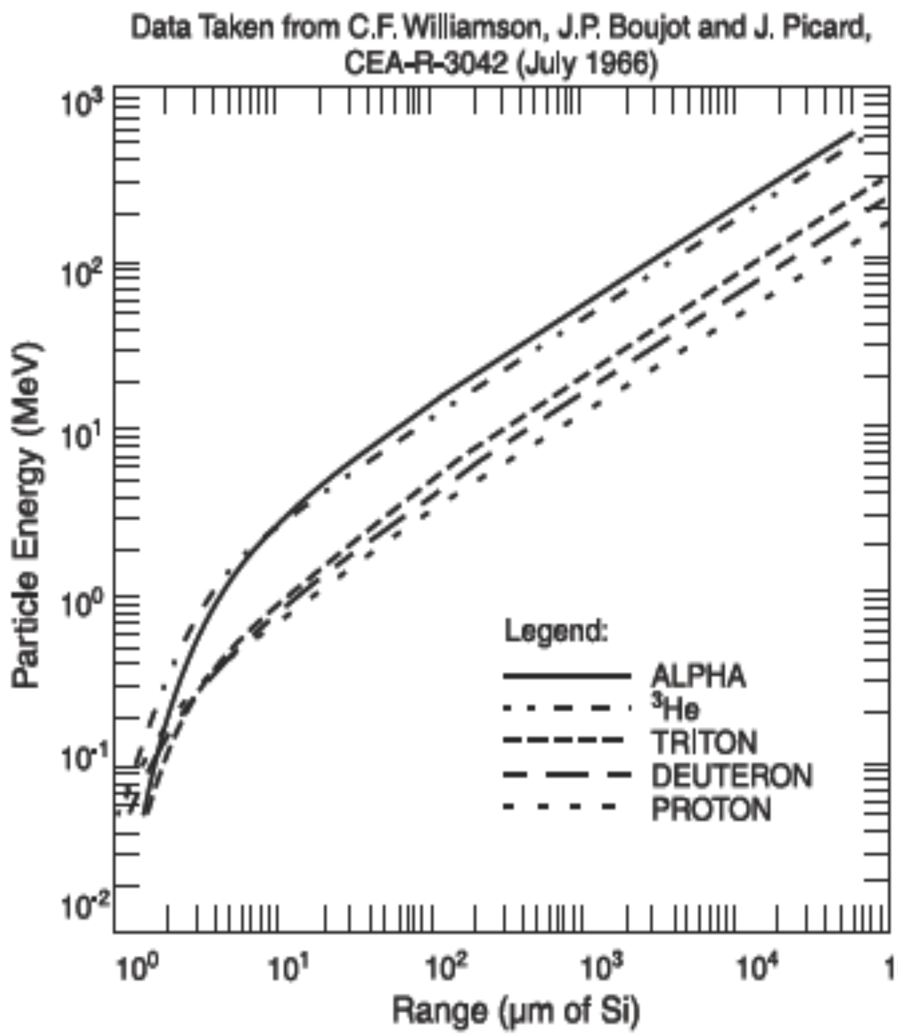
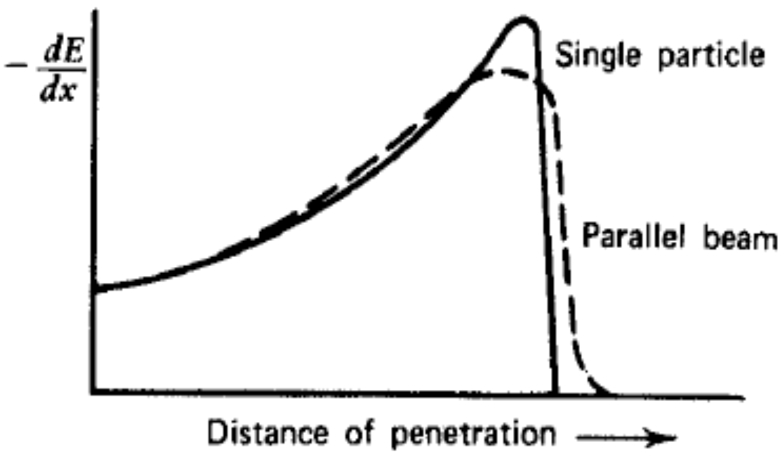


Figure 1.10 Range-Energy Curves in Silicon



Identification of masses

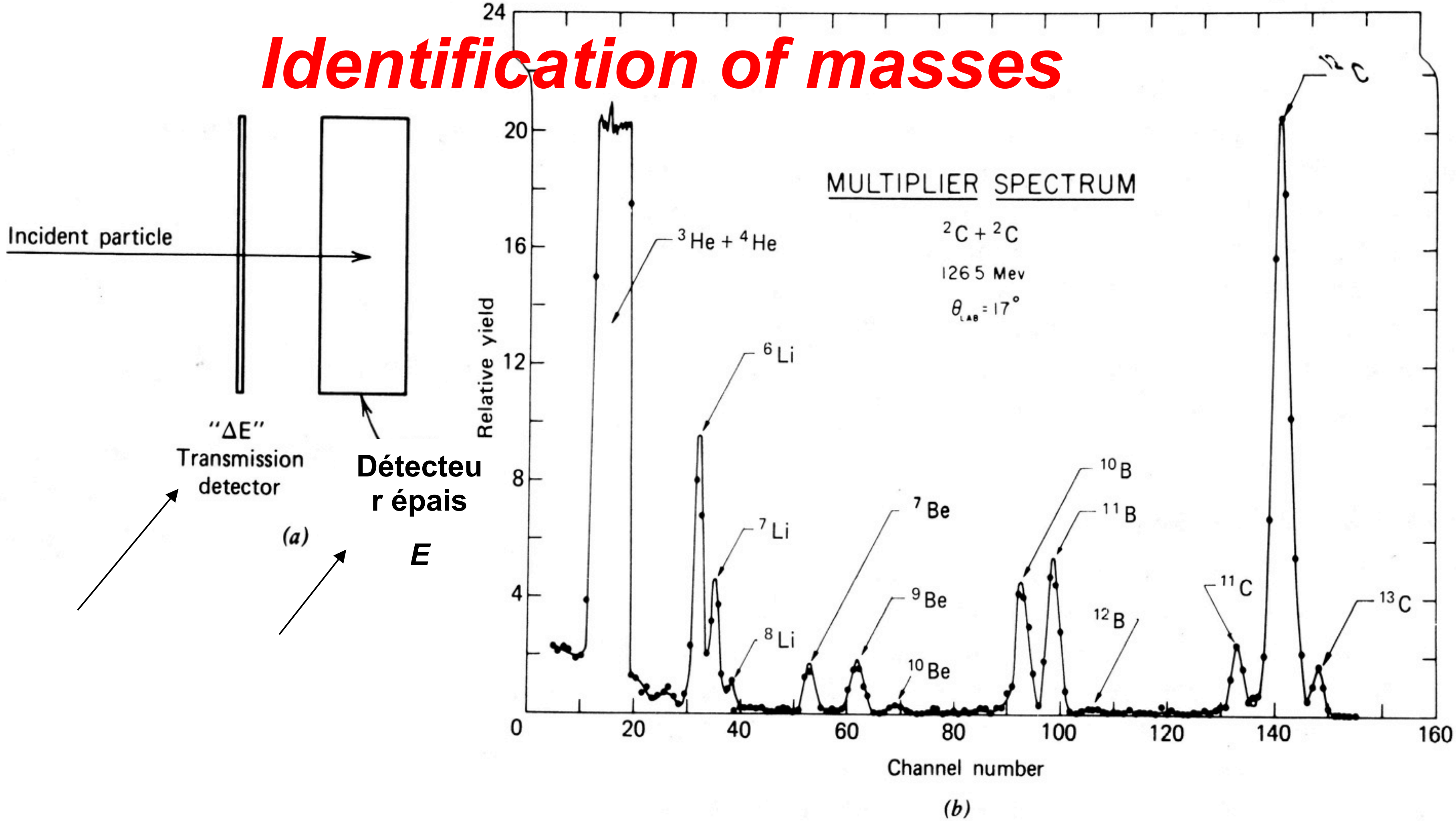


Figure 11-16 (a) A particle identifier arrangement consisting of tandem ΔE and E detectors operated in coincidence. (b) Experimental spectrum obtained for the $\Delta E \cdot E$ signal product for a mixture of different ions. (From Bromley.[90])