

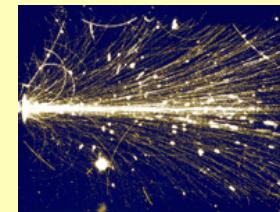
## **2 Particle Interaction with Matter**

**Detectors for Particle Physics**

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## 2.0 Content



2.0 Introduction

2.1 Charged particles

2.1.1 Energy loss through  
collision (heavy particles)

2.1.2 Energy loss of electrons  
and positrons

2.1.3 Bremsstrahlung

2.1.4 Cherenkov radiation

2.1.5 Transition radiation

2.2 Photons

2.2.1 Photo effect

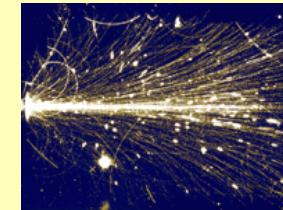
2.2.2 Compton scattering

2.2.3 Pair production

2.3 Hadronic interactions

2.4 Neutrinos

## 2.0 Particles



Many (hundreds) particles known, see PDG (Particle Data Group):

## Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3 or 4 star status are included in the [Baryon Summary Table](#). Due to insufficient data or uncertain interpretation, the other entries in the table are not established baryons. The names with masses are of baryons that decay strongly. The spin parity  $J^P$  (when known) is given with each particle. For the strongly decaying particles, the  $J^P$  values are considered to be part of the name.

## Meson Summary Table

See also the table of suggested  $q\bar{q}$  quark-model assignments in the Quark Model section.

- Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.

LIGHT UNFLAVORED ( $S = C = B = 0$ )		STRANGE ( $S = \pm 1, C = B = 0$ )		CHARMED, STRANGE ( $C = S = \pm 1$ )		$c\bar{c}$	
$f^0(J^P)$	$f^0(J^P)$	$f^0(J^P)$	$f^0(J^P)$	$f^0(J^P)$	$f^0(J^P)$	$f^0(J^P)$	
$\bullet \pi^\pm$	$1^-(0^-)$	$\pi_0(1670)$	$1^-(2^-)$	$\bullet K^+$	$1/2(0^-)$	$D_s^+$	$0(0^-)$
$\bullet \pi^0$	$1^+(0^-)$	$\phi(1680)$	$0^-(1^-)$	$\bullet K^0$	$1/2(0^-)$	$D_s^+$	$0(?)^?$
$\bullet \eta$	$0^+(0^-)$	$\rho_1(1690)$	$1^+(3^-)$	$\bullet K_S^0$	$1/2(0^-)$	$\phi_{s0}(2317)^{\pm}$	$0(0^+)$
$\bullet \zeta(500)$	$0^+(0^-)$	$\rho_1(1700)$	$1^+(1^-)$	$\bullet K_L^0$	$1/2(0^-)$	$\phi_{s0}(2460)^{\pm}$	$0(1^+)$
$\bullet \rho(770)$	$1^+(1^-)$	$\omega_2(1700)$	$1^+(2+)$	$K_N^*(800)$	$1/2(0^+)$	$\phi_{s0}(2536)^{\pm}$	$0(1^+)$
$\omega(782)$	$0^-(1^-)$	$\phi_1(1710)$	$0^+(0+)$	$\bullet K^*(892)$	$1/2(0^-)$	$D_{s0}(2573)$	$0(?)^?$
$\eta(958)$	$0^+(0^-)$	$\eta(1760)$	$0^+(0-)$	$K_0(1270)$	$1/2(1^+)$	$D_{s1}^*(7200)^{\pm}$	$0(1^-)$
$\chi(980)$	$0^+(0+)$	$\pi_1(1800)$	$1^-(0+)$	$K_0(1400)$	$1/2(0^+)$	$D_{s1}^*(2860)^{\pm}$	$0(?)^?$
$\omega_b(980)$	$1^-(0+)$	$\psi_1(1810)$	$0^+(2+)$	$\bullet K^*(1410)$	$1/2(1^+)$	$D_{s1}^*(3040)^{\pm}$	$0(?)^?$
$\bullet \omega_0(1020)$	$1^-(0^-)$	$X(1835)$	$?^-(?)^+$	$\bullet K_1(1430)$	$1/2(0^+)$	BOT I TOME (B = ±)	
$\bullet h_1(1170)$	$0^+(0^-)$	$\phi_1(1850)$	$0^-(3^-)$	$\bullet K_1(1430)$	$1/2(2^+)$	BOT II TOME (B = ±)	
$b_1(1235)$	$1^+(1^-)$	$\eta_1(1870)$	$0^-(2-)$	$K_1(1460)$	$1/2(0^-)$	$\bullet B^\pm$	$1/2(2^-)$
$\bullet a_1(1260)$	$1^-(1+)$	$\phi_1(1880)$	$1^-(2-)$	$K_1(1580)$	$1/2(2^-)$	$\bullet B^\pm$	$1/2(2^-)$
$\bullet f_2(1270)$	$1^+(1+)$	$\rho_1(1900)$	$1^-(1-)$	$K_1(1630)$	$1/2(2^?)$	$\bullet B^{*0}/B^0$	ADMIXTURE
$\bullet f_1(1285)$	$0^+(3+)$	$\psi_2(1910)$	$0^+(2+)$	$K_1(1650)$	$1/2(1^+)$	$\bullet B^{*0}/B^0/B^+$	$b$ -baryon
$\eta(1295)$	$0^-(0+)$	$\psi_1(1950)$	$0^+(2+)$	$\bullet K^*(1680)$	$1/2(1^+)$	ADMIXTURE	
$\pi(1300)$	$1^-(0+)$	$\rho_1(1990)$	$1^-(3-)$	$K_1(1770)$	$1/2(2^+)$	$V_b$ and $V_{ub}$ CKM Matrix Elements	
$\bullet a_2(1320)$	$1^+(2+)$	$\rho_1(2010)$	$0^+(2+)$	$\bullet K_1(1780)$	$1/2(3^-)$	$\bullet A^{*0}$	$1/2(2^-)$
$\bullet f_1(1370)$	$0^+(0+)$	$\psi_2(2020)$	$0^+(0+)$	$K_1(1820)$	$1/2(2^-)$	$\bullet A^{*+}$	$1/2(2^-)$
$h_1(1380)$	$?^-(1^-)$	$\phi_1(2040)$	$1^+(4+)$	$K_1(1830)$	$1/2(0^-)$	$\bullet B^{*0}$	$?^?(?)^?$
$\pi_1(1400)$	$1^-(1+)$	$\phi_1(2050)$	$0^+(4+)$	$K_1^*(1950)$	$1/2(0^+)$	$\bullet B^{*0}_1(5732)$	$?^?(?)^?$
$\eta(1405)$	$0^+(0+)$	$\pi_2(2100)$	$1^-(2-)$	$K_1^*(1980)$	$1/2(2^+)$	$\bullet B_1(5721)^0$	$1/2(1^+)$
$\bullet f_1(1420)$	$0^+(1+)$	$\psi_2(2100)$	$0^+(9+)$	$\bullet K_1(2045)$	$1/2(4^+)$	$\bullet B_2^*(5747)^0$	$1/2(2^+)$
$w(1420)$	$0^-(1-)$	$\psi_2(2150)$	$0^+(2+)$	$K_1(2250)$	$1/2(0^-)$	BOT II TOME, STRANGE	
$f_1(1430)$	$0^+(2+)$	$\rho_1(2150)$	$1^-(1-)$	$K_1(2320)$	$1/2(3^+)$	$\bullet B_2^0$	$0(0^-)$
$\bullet a_3(1450)$	$1^-(1+)$	$\phi_1(2170)$	$0^-(1-)$	$K_1^*(2380)^0$	$1/2(0^+)$	$\bullet B_2^*$	$0(1^-)$
$\bullet \rho(1450)$	$1^+(1-)$	$\psi_2(2200)$	$0^+(9+)$	$K_1(2500)$	$1/2(4^+)$	$\bullet B_{s1}(5830)^0$	$0(1^+)$
$\eta(1475)$	$0^+(0+)$	$\psi_2(2220)$	$0^+(2+)$	$K_1(3100)$	$?^?(?)^?$	$\bullet B_{s2}^*(5840)^0$	$0(2^+)$
$\bullet f_1(1500)$	$0^+(0+)$					$\bullet B_{s2}^*(5850)^0$	$?^?(?)^?$
$f_1(1510)$	$0^+(1+)$	$\eta(2225)$	$0^+(9-)$			CHARMED ( $C = \pm 1$ )	
$f_1^*(1525)$	$0^+(2+)$	$\rho_1(2250)$	$1^-(3-)$			BOT I TOME, CHARMED ( $B = \pm 1, S = \mp 1$ )	
$f_1(1565)$	$0^+(2+)$	$\rho_1(2300)$	$0^+(2+)$	$\bullet D^+$	$1/2(0^-)$	BOT II TOME, CHARMED ( $B = \pm 1, S = \mp 1$ )	
$\rho(1570)$	$1^-(1-)$	$\psi_2(2300)$	$0^+(4+)$	$\bullet D^0$	$1/2(0^-)$	$\bullet B^0$	$0(0^-)$
$h_1(1595)$	$0^+(1-)$	$\psi_2(2330)$	$0^+(9+)$	$\bullet D^*(2007)^0$	$1/2(1^+)$	BOT II TOME, CHARMED ( $B = \pm 1, S = \mp 1$ )	
$\pi_1(1600)$	$1^-(3-)$	$\phi_1(2340)$	$0^+(2+)$	$\bullet D^*(2010)^{\pm}$	$1/2(1^+)$	$\bullet B^0$	$0(0^-)$
$\alpha_1(1640)$	$1^-(1+)$	$\rho_1(2360)$	$1^-(5-)$	$\bullet D^*(2400)^0$	$1/2(0^+)$	BOT II TOME, CHARMED ( $B = \pm 1, S = \mp 1$ )	
$\chi_1(1640)$	$0^+(1+)$	$\phi_1(2450)$	$1^-(6+)$	$\bullet D^*(2400)^{\pm}$	$1/2(0^+)$	$\bullet D_1(2420)^0$	$1/2(1^+)$
$\eta_2(1645)$	$0^+(2+)$	$\psi_2(2510)$	$0^+(6+)$	$\bullet D_1(2420)^{\pm}$	$1/2(0^+)$	$D_1(2420)^{\pm}$	$1/2(2^2)$
$\omega(1650)$	$0^-(1-)$			$D_1(2420)^0$	$1/2(2^2)$	$D_1(2420)^{\pm}$	$1/2(2^2)$
$\omega_2(1670)$	$0^-(3-)$			$D_1(2420)^0$	$1/2(2^2)$	$D_1(2420)^{\pm}$	$1/2(2^2)$
OTHER LIGHT							
Further States							
$\eta_0(1S)$							$\eta_0(1S)$
$\bullet J/\psi(1S)$							$\eta_0(1S)$
$\chi_0(1P)$							$\chi_0(1P)$
$\chi_1(1P)$							$\chi_1(1P)$
$\chi_2(1P)$							$\chi_2(1P)$
$\chi_0(2P)$							$\chi_0(2P)$
$\chi_1(2P)$							$\chi_1(2P)$
$\chi_2(2P)$							$\chi_2(2P)$
$\chi_0(3P)$							$\chi_0(3P)$
$\chi_1(3P)$							$\chi_1(3P)$
$\chi_2(3P)$							$\chi_2(3P)$
$\gamma(4S)$							$\gamma(4S)$
$\chi_0(4P)$							$\chi_0(4P)$
$\chi_1(4P)$							$\chi_1(4P)$
$\chi_2(4P)$							$\chi_2(4P)$
$\chi_0(5P)$							$\chi_0(5P)$
$\chi_1(5P)$							$\chi_1(5P)$
$\chi_2(5P)$							$\chi_2(5P)$
$\chi_0(6P)$							$\chi_0(6P)$
$\chi_1(6P)$							$\chi_1(6P)$
$\chi_2(6P)$							$\chi_2(6P)$
$\chi_0(7P)$							$\chi_0(7P)$
$\chi_1(7P)$							$\chi_1(7P)$
$\chi_2(7P)$							$\chi_2(7P)$
$\chi_0(8P)$							$\chi_0(8P)$
$\chi_1(8P)$							$\chi_1(8P)$
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$\chi_0(9P)$							$\chi_0(9P)$
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$\chi_2(10P)$							$\chi_2(10P)$
$\chi_0(11P)$							$\chi_0(11P)$
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$\chi_1(20P)$							$\chi_1(20P)$
$\chi_2(20P)$							$\chi_2(20P)$
$\chi_0(21P)$							$\chi_0(21P)$
$\chi_1(21P)$							$\chi_$

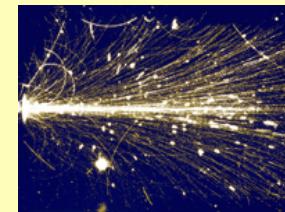
# Leptons

- e
  - $\mu$
  - $\tau$
  - $\nu_e$
  - $\nu_\mu$
  - $\nu_\tau$

## Gauge bosons

- $\gamma$
  - $W^{+/-}$
  - Z
  - g
  - H

## 2.0 Particle Measurements



**Particles can only be measured in the detector, if they**

### 1. Life long enough after creation to reach the detector

The majority of particle states are short lived.

Track length:  $l_{\text{track}} = v\tau = c\beta\gamma\tau_0$  with  $\tau_0$  being the lifetime at rest.

From the hundreds of particles only few particles (and their antiparticles) have track lengths long enough to measure them:

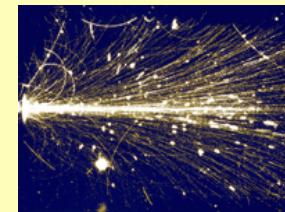
	$\gamma$	$p$	$n$	$e^\pm$	$\mu^\pm$	$\pi^\pm$	$K^\pm$	$K_0 (K_S/K_L)$
$\tau_0$	$\infty$	$\infty$	$\infty$	$\infty$	$2.2 \mu s$	$26 \text{ ns}$	$12 \text{ ns}$	$89 \text{ ps} / 51 \text{ ns}$
$l_{\text{track}}$ ( $p=1\text{GeV}$ )	$\infty$	$\infty$	$\infty$	$\infty$	$6.1 \text{ km}$	$5.5 \text{ m}$	$6.4 \text{ m}$	$5 \text{ cm} / 27.5 \text{ m}$

+ Neutrinos (but interact only weakly)

### 2. Interact with the detector

→ deposition of energy  $dE/dx$  → transferred into a detector signal

## 2.0 Energy loss - $dE/dx$



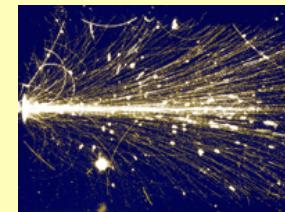
Particles interact differently with matter. Important for detectors is the energy loss per path length. The total energy loss per path length is the sum of all contributions.

$$-\left(\frac{dE}{dx}\right)_{\text{tot}} = -\left(\frac{dE}{dx}\right)_{\text{coll}} - \left(\frac{dE}{dx}\right)_{\text{rad}} - \left(\frac{dE}{dx}\right)_{\text{pair}} - \left(\frac{dE}{dx}\right)_{\text{photoeff}} - \left(\frac{dE}{dx}\right)_{\text{compton}} - \left(\frac{dE}{dx}\right)_{\text{hadron}} \dots$$

Depending on the particle type, the particle energy and the material some processes dominate, others do not occur. For instance only charged particles will interact with electrons of the atoms and produce ionisation, etc.

In the following I will try to work out those processes important for particle detection in high energy physics experiments.

## 2.1 Charged Particles



For charged particles the electromagnetic interaction is dominating!

Charged particles penetrating matter can initiate the following processes:

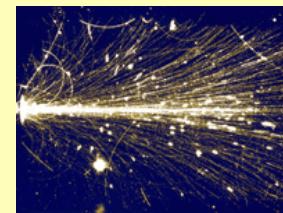
- ★ Ionization of atoms
- ★ Excitation of atoms
- ★ Bremsstrahlung (only relevant for electrons and positrons)
- ★ Cherenkov radiation
- ★ Transition radiation

All these processes cause energy loss of the penetrating particles. The relative contribution of these various processes to the total energy loss depends on the kinetic energy of the particle, the detector material, etc.

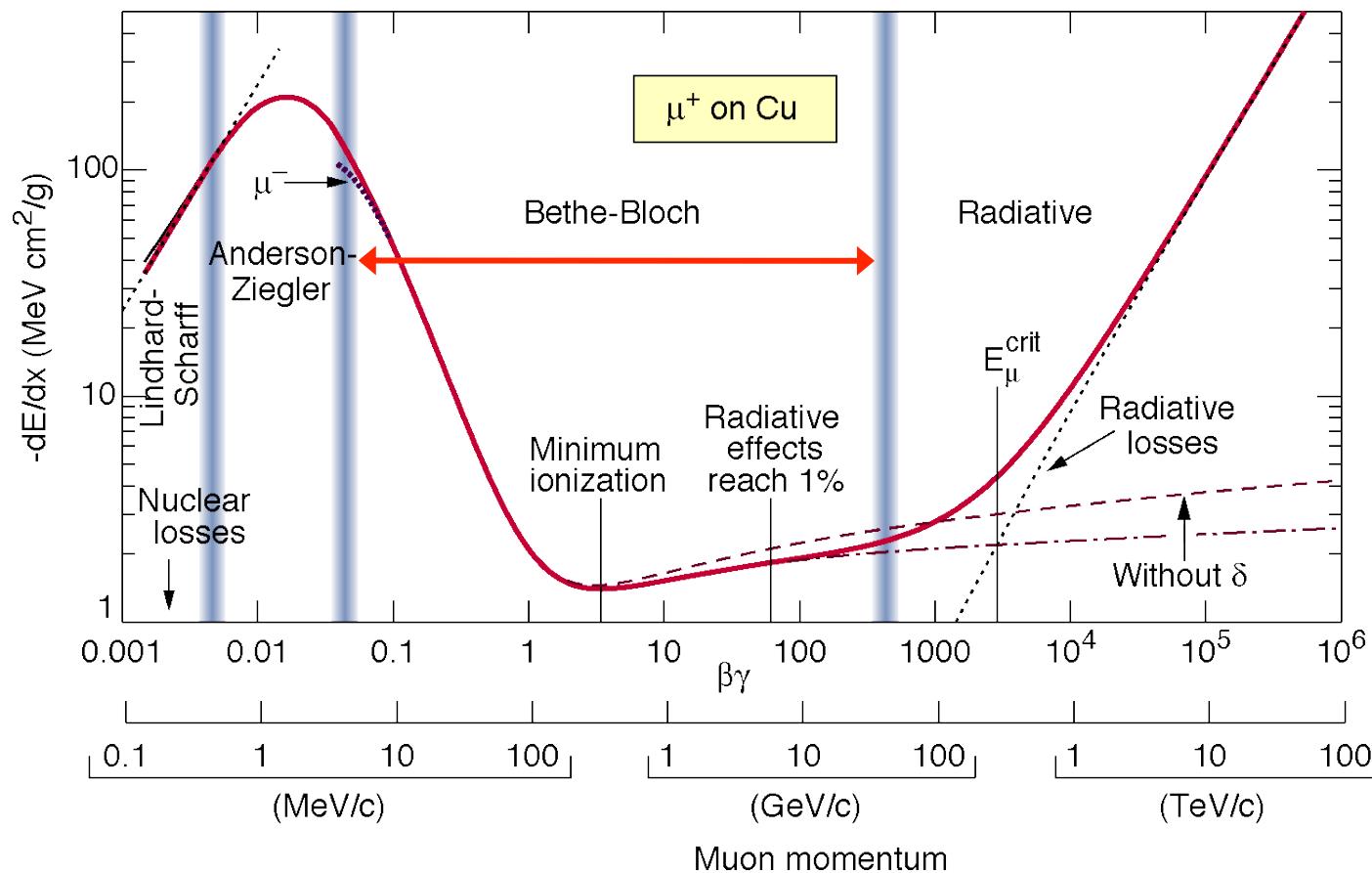
**Important: The detection of neutral particles is usually done via the production and subsequent detection of secondary charged particles.**

## 2.1 Interaction of charged particles

### Energy loss $dE/dx$ as a function of momentum , energy



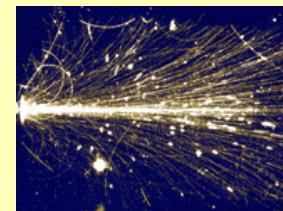
Total energy loss  $-dE/dx$  for muons in cooper:



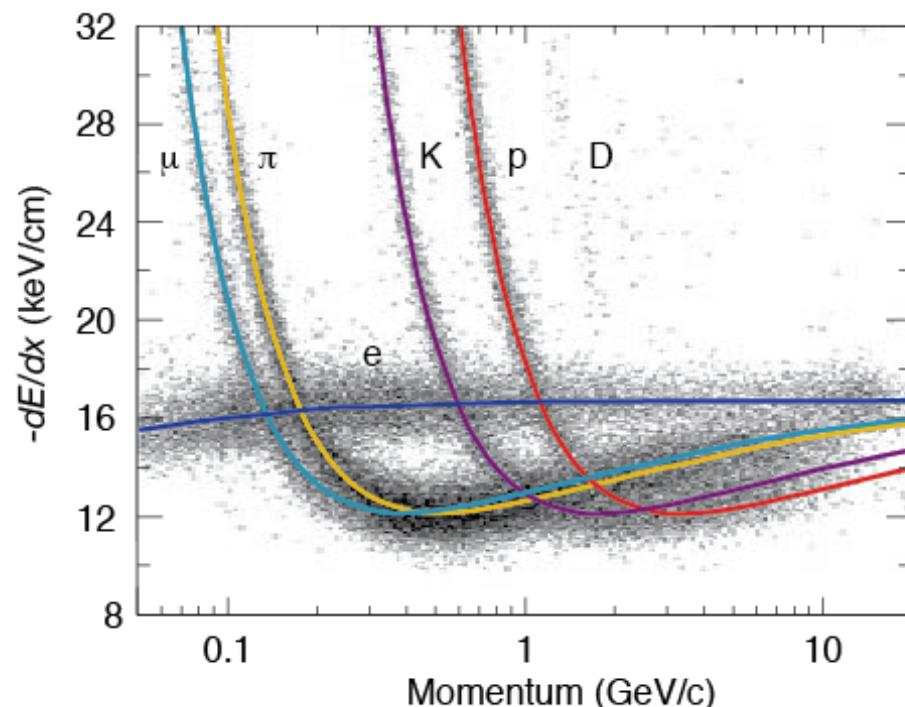
Particle Data Group, *Review of Particle Physics*, Physics Letters B 592 (2004)

## 2.1 Energy loss of charged particles

### $dE/dx$ for different particles



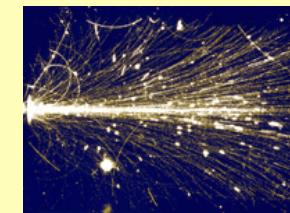
Total energy loss  $-dE/dx$  for different particles measured in the PEP4/9 TPC (Ar–CH<sub>4</sub> = 80:20 @ 8.5 atm):



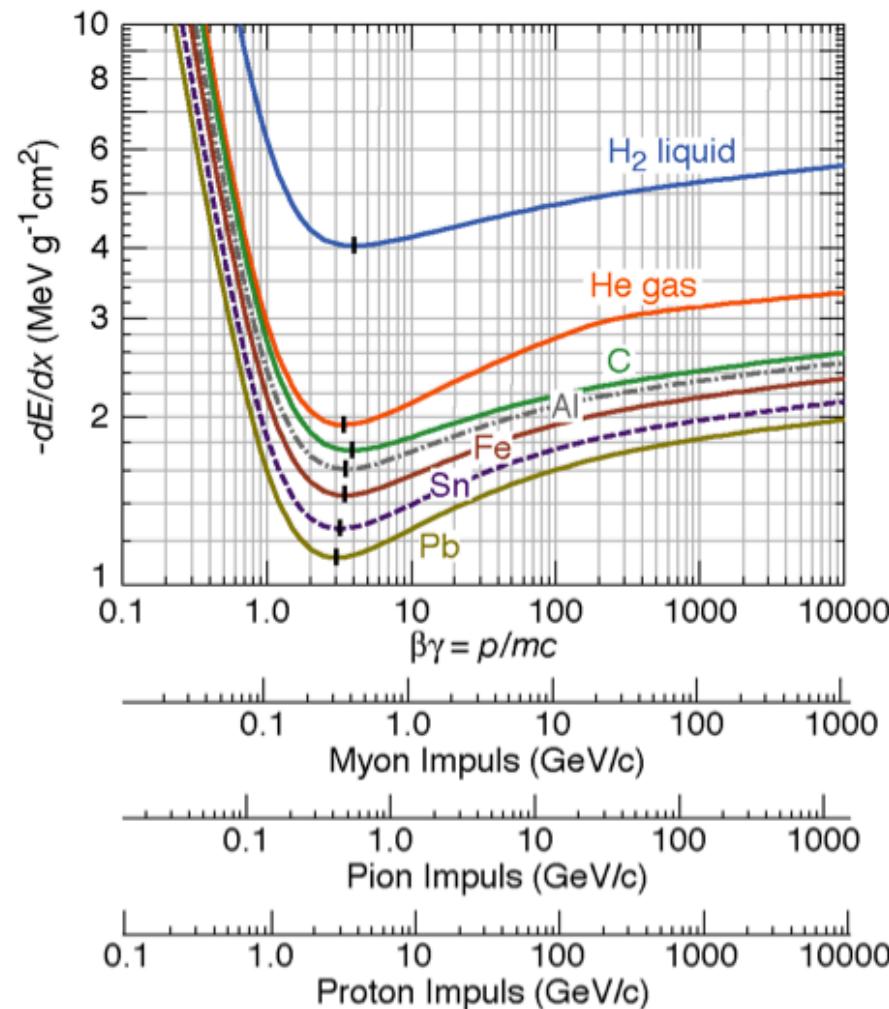
- ★  $dE/dx$  for heavy particles in this momentum regime is well described by Bethe-Bloch formula, i.e. the dominant energy loss is collision with atoms.
- ★  $dE/dx$  for electrons does not follow Bethe-Bloch formula. The dominant process is bremsstrahlung.

Carsten Niebuhr, DESY Summer Student Lecture, 2004

## 2.1 Energy loss of charged particles $dE/dx$ in different material

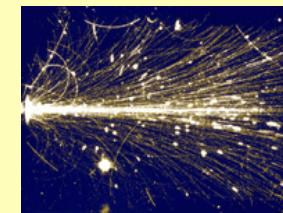


Specific energy loss rate  $\frac{1}{\rho} \frac{dE}{dx}$  for muons, pions and protons in different materials:



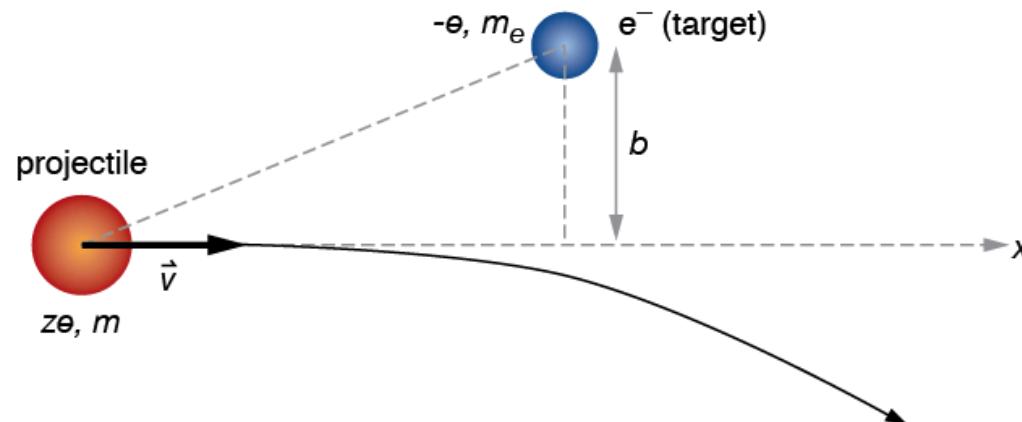
Particle Data Group, *Review of Particle Physics*, Physics Letters B **592** (2004)

## 2.1.1 Energy loss of heavy charged particles Bohr's classical formula



Ansatz to derive classical formula of Bohr:

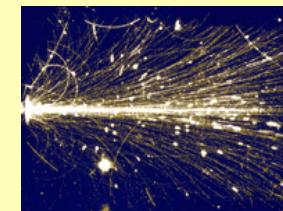
Energy loss  $dE/dx$  of a **heavy** ( $m \gg m_e$ ), charged particle through the scattering on an electron of the target atoms.



Assumptions:

- ★ Electrons of the atoms are in rest, i.e. the original orbit movement and the recoil after collision are neglected.
- ★ Binding of electrons to the nucleus is neglected. (i.e. energy transfer  $\gg$  binding energy)

## 2.1.1 Energy loss of heavy charged particles Bohr's classical formula

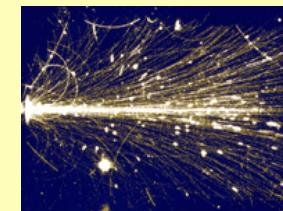


Bohr's classical formula for the energy loss rate through collision/excitation of heavy charged particles:

$$-\left(\frac{dE}{dx}\right)_{\text{coll}} = \frac{4\pi z^2 e^4}{m_e v^2} N_A \rho \frac{Z}{A} \ln \frac{\gamma^2 m_e v^3}{ze^2 \bar{v}}$$

$N_A$  ... Avogadro constant  
 $\rho$  ... Target density  
 $Z$  ... Atomic number of target  
 $A$  ... Nuclear number of target

## 2.1.1 Energy loss of heavy charged particles Bethe-Bloch(-Sternheimer) formula



The quantum mechanically correct description of the energy loss is the **Bethe-Bloch(-Sternheimer) formula**:

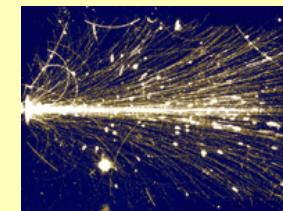
$$-\left(\frac{dE}{dx}\right)_{\text{coll}} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z z^2}{A \beta^2} \cdot \left[ \ln\left(\frac{2m_e c^2 \gamma^2 \beta^2 W_{\max}}{I^2}\right) - 2\beta^2 - \delta - 2 \frac{C}{Z} \right]$$

$$\beta = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}, \quad r_e = \frac{1}{4\pi\epsilon_0} \cdot \frac{e^2}{m_e c^2} \dots \text{classic e}^- \text{- radius}$$

- $z$  ... Charge of penetrating particle  
 $Z, A$  ... Atomic and nuclear number of the target  
 $\rho$  ... Target density,  $N_A$  ... Avogadro constant  
 $I$  ... mean ionisation potential (material constant of the target)  
 $W_{\max}$  ... max. energy transfer in a single collision  
 $\delta$  ... Density correction (Polarisation effect,  $\delta \approx 2 \cdot \ln \gamma + K$ )  
 $C$  ... Shell correction (important for small particle velocities)

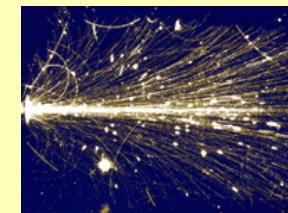
## 2.1.1 Bethe-Bloch Formula

### Comments



- ★ The energy loss is a **statistical process** (see later).
- ★ Bethe-Bloch formula is an excellent description in the range  $0.1 < \gamma\beta < 100$ .
- ★ The  $dE/dx$  curve following Bethe-Bloch-Sternheimer has 3 regions:
  1. At low energies a **( $1/\beta$ )<sup>2</sup> drop** to a minimum (appr.  $\beta\gamma$  3–3.5). Particles at this point are called **minimum ionising particles (mip)**.
  2. At higher energies a **logarithmic rise** follows.
  3. At very high energies a **plateau** is reached.
- ★ The energy loss is often given as  $\frac{1}{\rho} \frac{dE}{dx}$  with length in [cm] and the density  $\rho$  in [g/cm<sup>3</sup>]).
- ★ The value in these units varies only weakly with the absorber material and is app. **2 MeVg<sup>-1</sup>cm<sup>2</sup>** for a mip. (H:  $\approx 4$  MeVg<sup>-1</sup>cm<sup>2</sup>, U:  $\approx 1$  MeVg<sup>-1</sup>cm<sup>2</sup>)

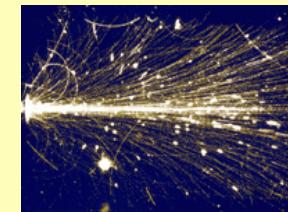
## 2.1.1 Statistics of the energy loss Landau distribution



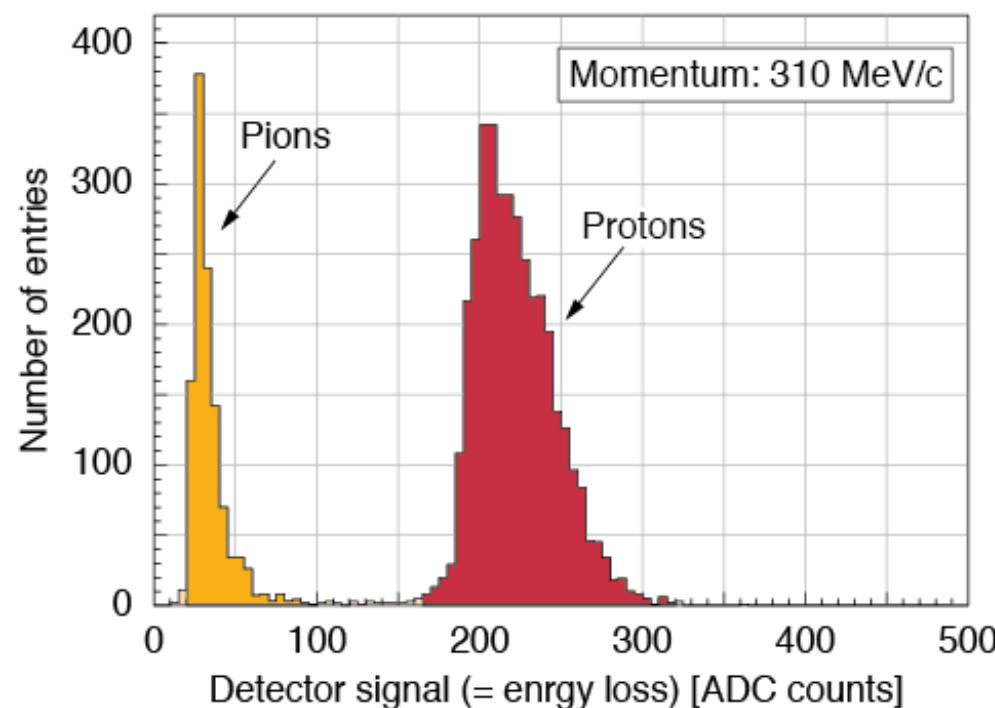
- ★ The energy loss is a **statistical process**. Number of collisions and energy loss varies from particle to particle
- ★ The distribution is usually **asymmetric**. Collisions with a small energy transfer are more probable than those with a large energy transfer.
- ★ The tail at very high energy loss values are caused by rare collisions with small impact parameters. In these collisions  $e^-$  with high energies (keV), are produced, so-called  **$\delta$ -electrones**.
- ★ A result of the asymmetric is that the mean energy loss is larger than the most probable energy loss.
- ★ For **thin absorber** the energy loss can be described by the **Landau distribution**.
- ★ For thick absorbers the Landau distributions goes slowly into a Gaussian distribution.

## 2.1.1. Statistics of the energy loss

### Examples

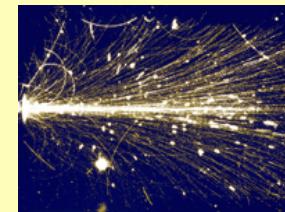


Measurements of the energy loss for pions and protons (equal momentum of 310 MeV/c) in a thin silicon detector:



W. Adam et al., CMS note 1998/092 (1998)

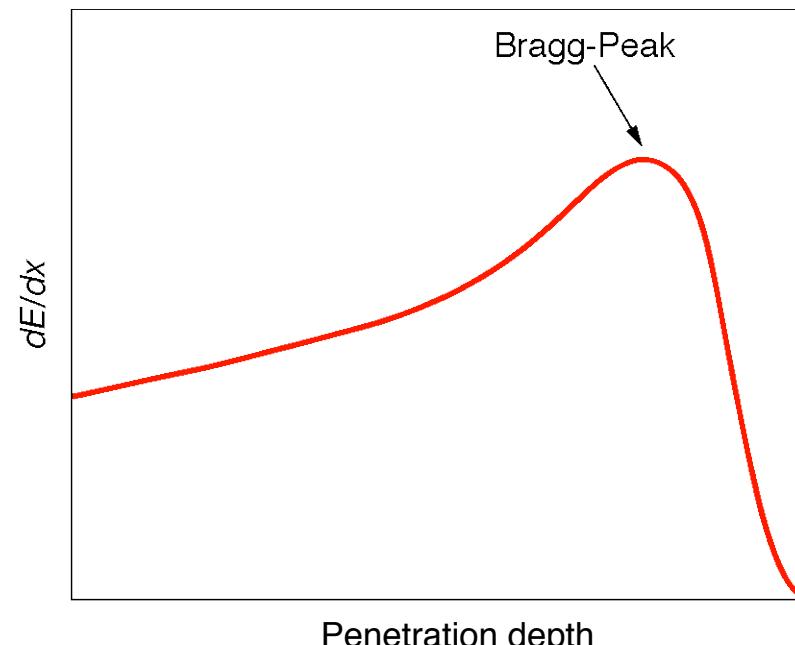
## 2.1.1. Bragg Curve and Bragg Peak



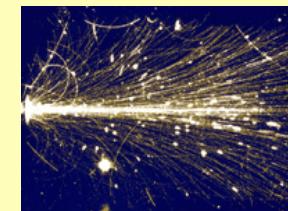
- ★ Energy loss as function of the penetration depth is called **Bragg Curve**.
- ★ Due to the energy loss along the flight path the projectile slows down
  - the energy loss increases (remember Bethe-Bloch curve!)
  - Largest energy loss near the end of the track = **Bragg Peak**

Used in particle therapy of cancer, to concentrate the effect of light ion beams on the tumor while minimizing the effect on the surrounding healthy tissue.

Example of a Bragg Curve (schematic):



## 2.1.2 Energy loss of electrons and positrons



Electrons and positrons are special because of their low masses:

$$m_e \approx 511 \text{ keV}/c^2 \quad (m_\mu \approx 106 \text{ MeV}/c^2)$$

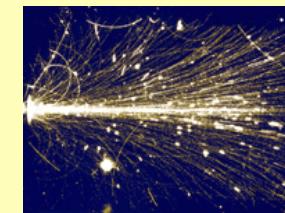
In addition to the energy loss through collision/excitation the energy loss through bremsstrahlung is important.

$$-\left(\frac{dE}{dx}\right)_{\text{tot}} = -\left(\frac{dE}{dx}\right)_{\text{coll}} - \left(\frac{dE}{dx}\right)_{\text{rad}}$$

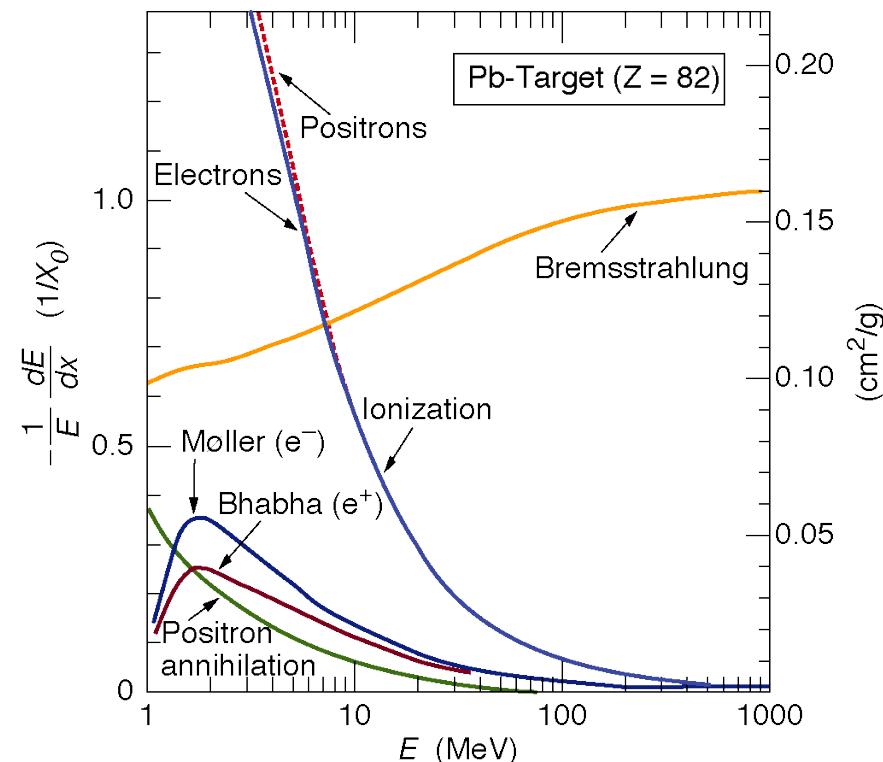
The Bethe-Bloch formula needs to be modified:

1. Because of the low masses  $e^\pm$  are deflected.
2. The collision of electrons with the electrons of the target is between quantum mechanical undistinguishable particles.

## 2.1.2 Energy loss of electrons and positrons



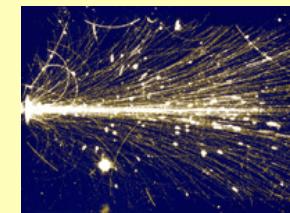
Relative energy losses for electrons and positrons:



- ★ Ionisation losses decrease logarithmically with  $E$  (and increase linear with  $Z$ )
- ★ Bremsstrahlung increases appr. linear with  $E$  (and quadratically with  $Z$ )
- **Bremsstrahlung is the dominant process for high energies ( $>1 \text{ GeV}$ ).**

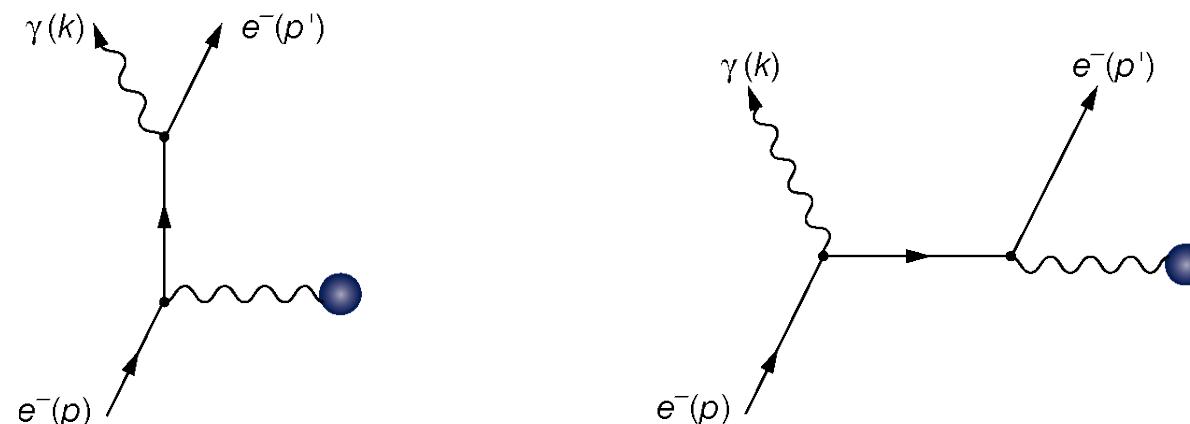
Particle Data Group, *Review of Particle Physics*,  
Physics Letters B 592 (2004)

## 2.1.3 Bremsstrahlung Principle

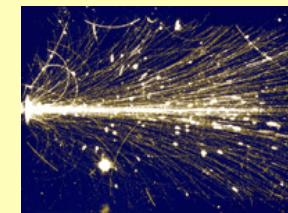


A charged particle deflected in an electric field (e.g. the Coulomb field of an atom) emits Bremsstrahlung:

Feynman-diagrams:



## 2.1.3 Bremsstrahlung Approximation



For high energies the energy loss through radiation can be approximated as:

$$-\frac{dE}{dx} \Big|_{\text{rad}} = 4\alpha \rho N_A \frac{Z(Z+1)}{A} z^2 \left( \frac{1}{4\pi\epsilon_0} \cdot \frac{e^2}{mc^2} \right)^2 E \cdot \ln(183 Z^{-1/3})$$

$\alpha$  ... fine structure constant    $\alpha \sim 1/137$

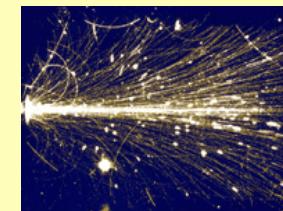
Important:

$$-\left(\frac{dE}{dx}\right)_{\text{rad}} \propto \frac{E}{m^2}$$

- The loss through bremsstrahlung of the second lightest particle the muon is 40 000 smaller than the one of electrons/positrons.

## 2.1.3 Bremsstrahlung

Radiation length  $X_0 - 1$



The radiation length  $X_0$  is the distance in which the energy of the particle is reduced by  $1/e$  ( $\approx 63.2\%$ ) due to bremsstrahlung:

$$E(x) = E_0 \cdot \exp\left(-\frac{x}{X_0}\right)$$

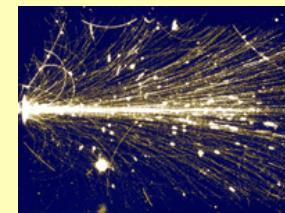
Rough approximation:  $X_0$  (g/cm<sup>2</sup>)  $\approx 180 A/Z^2$

**The thickness of materials (detectors) is often given in units of  $X_0$ .  
→ Radiation loss per thickness becomes material independent.**

This definition is only meaningful for energies above the critical energy of the material. The critical energy is the energy at which the loss through ionization equals the loss through bremsstrahlung.

## 2.1.3 Bremsstrahlung

### Radiation length $X_0$ – 2

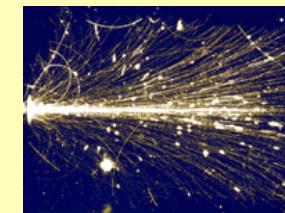


The radiation length is often also given normalized to the target density ( $\rho X_0 \rightarrow X_0$ ) in units of [g/cm<sup>2</sup>]:

Material	$X_0$ (g/cm <sup>2</sup> )	$X_0$ (cm)
H <sub>2</sub> O	36.1	36.1
Air (NTP)	36.2	30050
H <sub>2</sub>	63	7·10 <sup>5</sup>
C	43	18.8
Polystyrol	43.8	42.9
Fe	13.8	1.76
Pb	6.4	0.56

Examples from.: – C. Grupen, *Teilchendetektoren*, BI-Wissenschaftsverlag, 1993  
– W.R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, Springer, 1987  
– K. Kleinknecht, *Detektoren für Teilchenstrahlung*, B.G. Teubner, 1992  
– D.H. Perkins, *Introduction to High Energy Physics*, Addison-Wesley, 1987

## 2.1.4 Cherenkov Radiation Principle

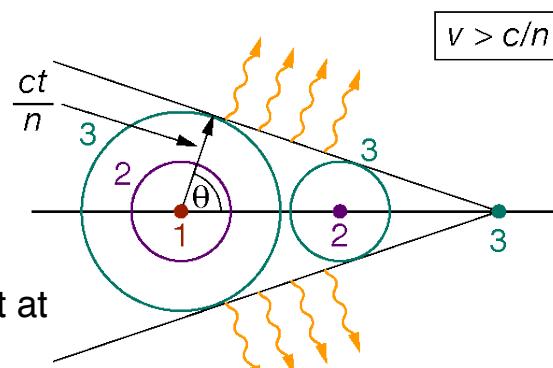
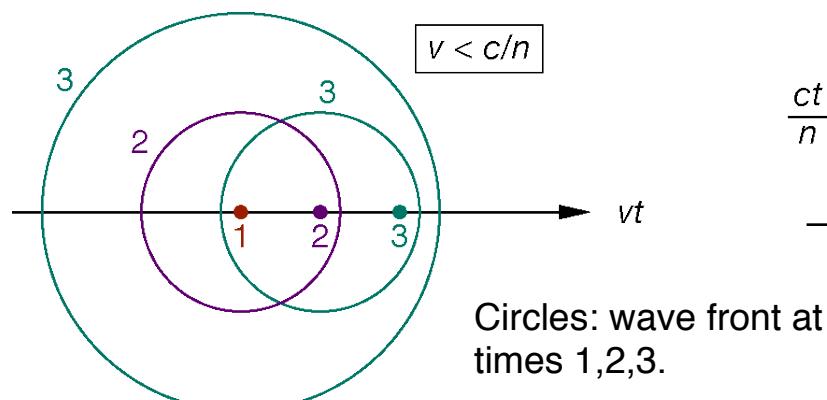


Cherenkov radiation is emitted if the particles velocity  $v$  is larger than the velocity of light in the medium.

$$v > \frac{c}{n} \quad \begin{aligned} c &\dots \text{speed of light in vacuum} \\ n &\dots \text{refraction index} \end{aligned}$$

An electromagnetic „shock“ wave develops. The coherent wave front has a conical shape and the photons are emitted under an angle:

$$\cos \theta_C = \frac{1}{\beta n} \quad \text{with } \beta = v/c$$

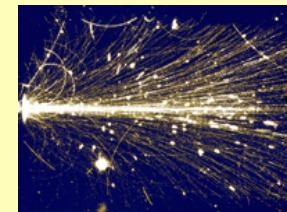


$$\theta_{\max} = \arccos \frac{1}{n}$$

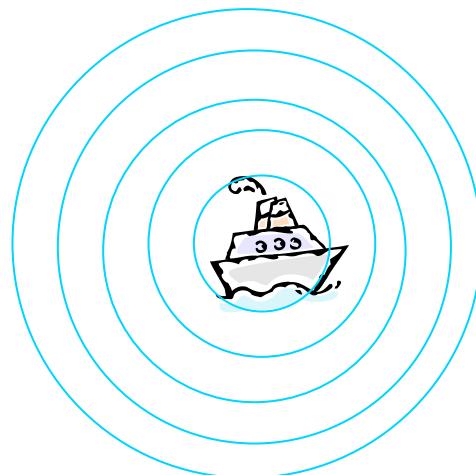
‘saturated’ angle ( $\beta=1$ )

## 2.1.4 Cherenkov Radiation

### Propagating waves -1

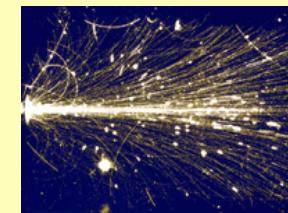


- ★ A stationary boat bobbing up and down on a lake, producing waves

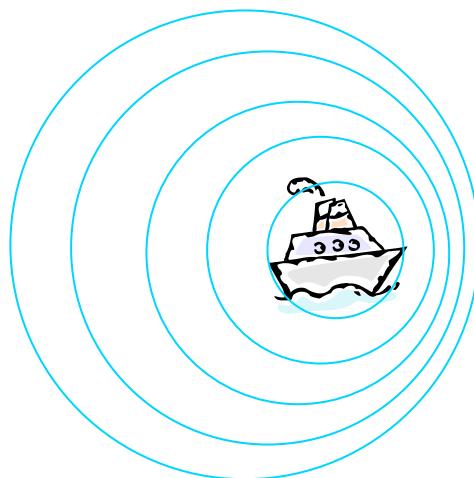


## 2.1.4 Cherenkov Radiation

### Propagating waves -2



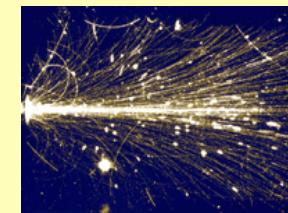
- ★ Now the boat starts to move, but slower than the waves



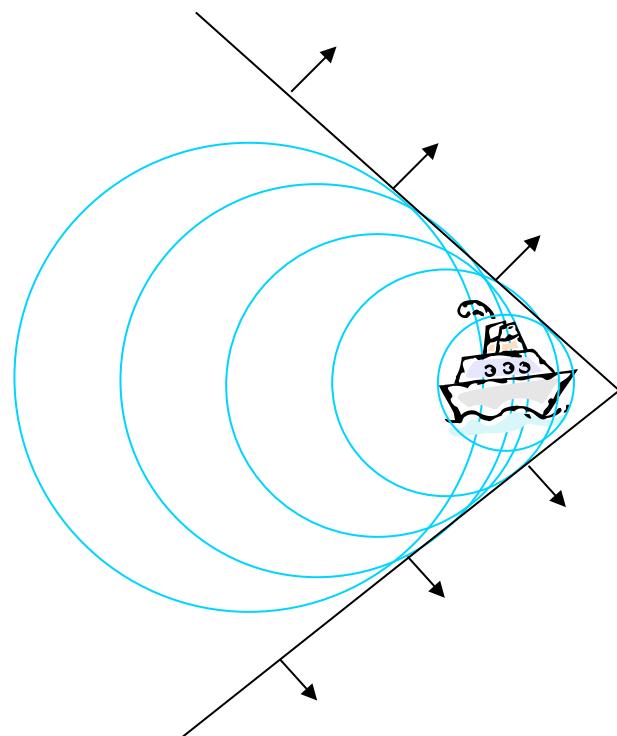
No coherent wavefront is formed

## 2.1.4 Cherenkov Radiation

### Propagating waves -3

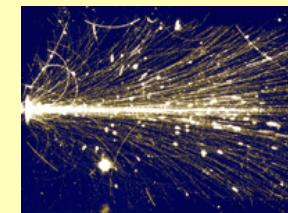


- ★ Next the boat moves faster than the waves

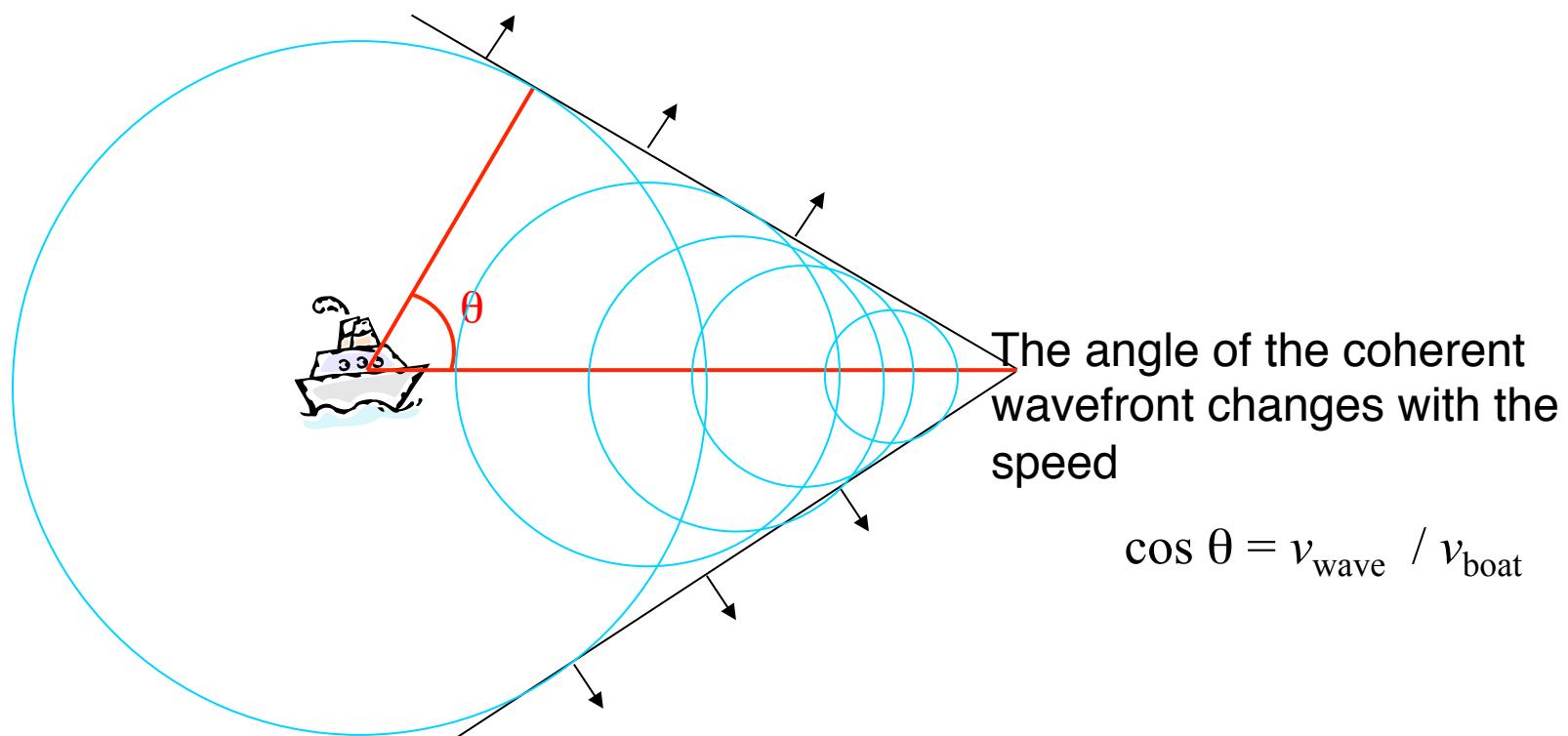


## 2.1.4 Cherenkov Radiation

### Propagating waves -4

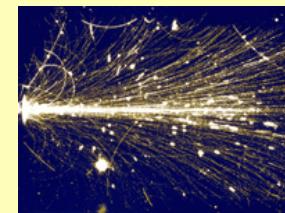


- ★ Finally the boat moves even faster



## 2.1.4 Cherenkov Radiation

Photons per unit length and wavelength/energy



$$\frac{d^2N}{dxd\lambda} = \frac{2\pi z^2 \alpha}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2}\right) = \frac{2\pi z^2 \alpha}{\lambda^2} \sin^2 \theta_c$$

$$\frac{d^2N}{dxd\lambda} \propto \frac{1}{\lambda^2}$$

with  $\lambda = \frac{c}{\nu} = \frac{hc}{E}$

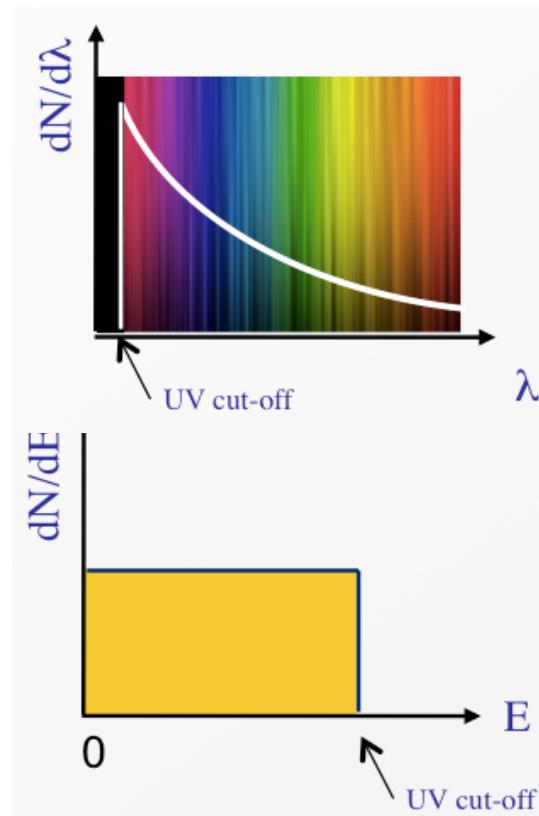
$$\frac{d^2N}{dxdE} = \text{const.}$$

$$\frac{dN}{dx} = 370/\text{cm} \sin^2 \theta \cdot \Delta E_{\text{detector}}$$

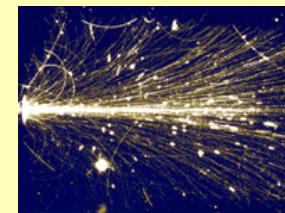
$\Delta E$ ...energy interval  
in which the  
detector is sensitive

$$\frac{dE}{dx} \Big|_{\text{Cherenkov}} \approx 1 \text{ keV/cm} \approx 0.001 \cdot \frac{dE}{dx} \Big|_{\text{Ionization}}$$

Cherenkov effect is a weak light source.  
Only few photons are produced.



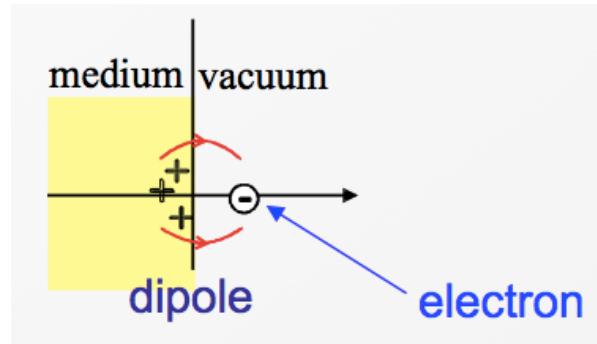
## 2.1.5 Transition Radiation Principle



A charged particle emits transition radiation traversing the boundary between two materials with different dielectric constants  $\epsilon$ .

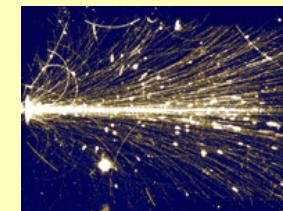
- In the material with low  $\epsilon$  the polarisation effect is small.  
→ the electric field of the moving charge has a large extension
- In the material with high  $\epsilon$  the polarisation effect is larger.  
→ the electric field of the moving charge has a smaller extension

The reallocation of charges and the associated changes of the electric field cause transition radiation.



## 2.1.5 Transition Radiation

### Emission angle and energy



The direction of the emitted photons (X rays) is in the direction of the moving particle within a cone. The opening angle is:

$$\cos \theta_t \approx \frac{1}{\gamma} \quad \text{with} \quad \gamma = \frac{1}{\sqrt{1-v^2/c^2}}$$

A particle with charge  $ze$  moving from vacuum into a material (plasma frequency  $\omega_p$ ) emits transition radiation with energy:

$$E_t = \frac{1}{3} \alpha z^2 \gamma \hbar \omega_p$$

→ Measuring the energy allows to determine  $\gamma$  and consequently the velocity of the particle

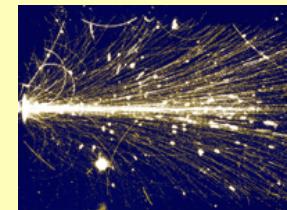
Radiated energy proportional to  $\gamma$

→ only high energy  $e^+/e^-$  emit transition radiation of detectable intensity → particle ID

→ Lorentz transformation causes radiation to be extremely forward peaked, photons stay close to the charged particle track

## 2.1.5 Transition Radiation

### Photons per boundary

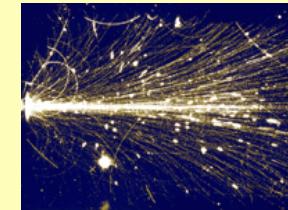


However, quantum efficiency is small. For typical photon energies the average number of photons emitted at a single boundary is:

$$\langle N \rangle = \frac{E_T}{\hbar\omega} \propto \alpha \approx \frac{1}{137}$$

→ Need detector with many boundaries!

## 2.2 Interaction of Photons



Important processes are:

- ★ Photoeffekt
- ★ Compton scattering
- ★ Pairproduction of  $e^+e^-$

These processes create charged particles and/or transfer energy to charged particles → photon detection via charged particle detection!

Note: These processes absorb or scatter single photons and remove them from the photon beam. The energy of the photons remains unchanged (exception is Compton scattering). This is a big difference to the interaction of charged particles!

The attenuation of a photon beam is exponential

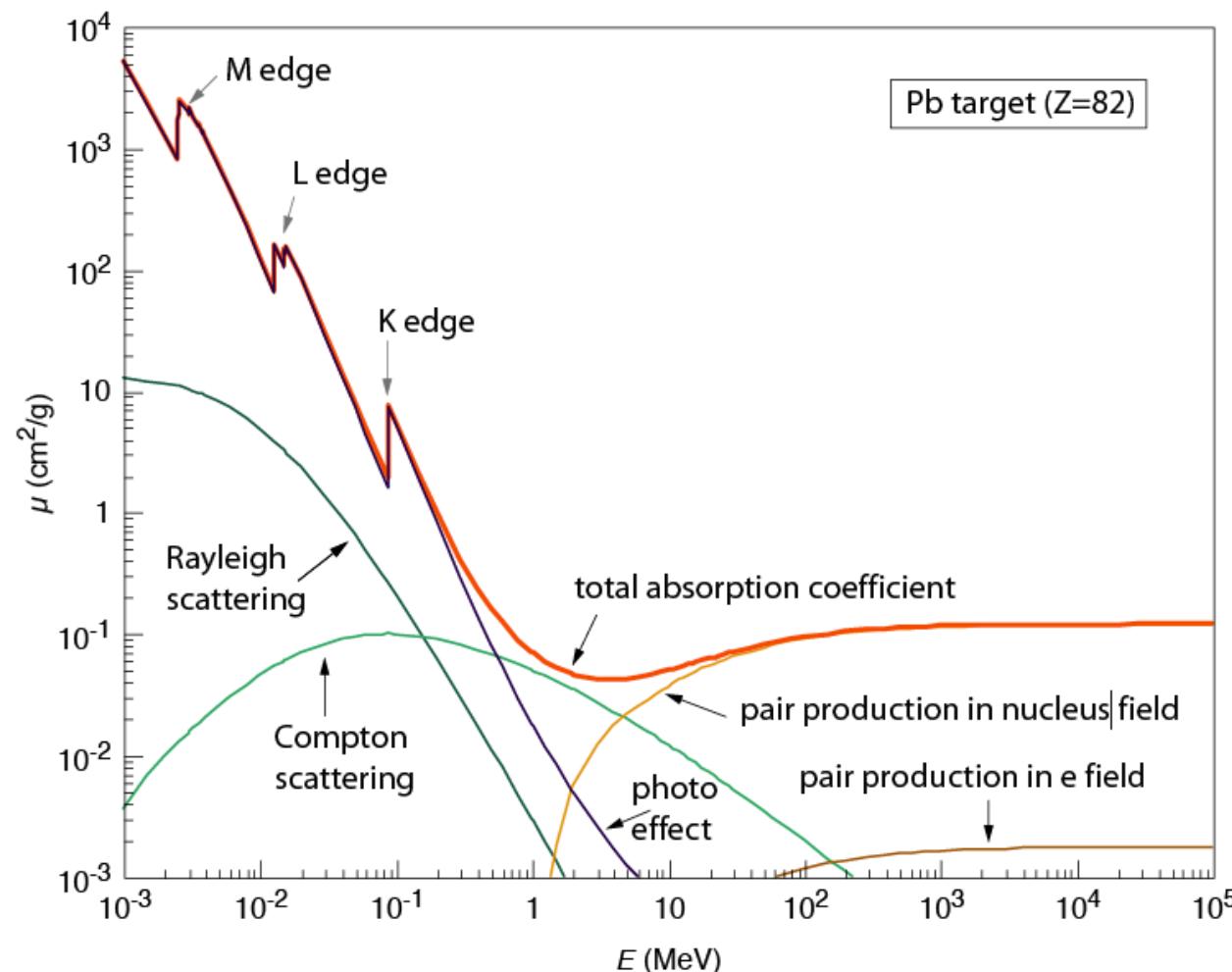
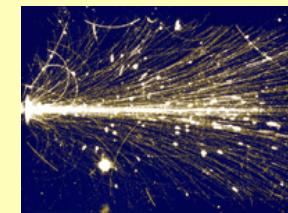
$$I(x) = I_0 \cdot e^{-\mu x}$$

With  $\mu$  defined as the mass absorption coefficient containing the cross sections  $\sigma_i$  of all relevant processes

$$\mu = \frac{N_A \rho}{A} \sum_i \sigma_i$$

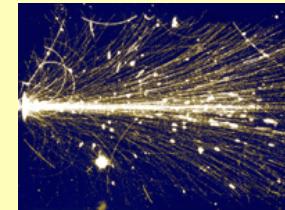
## 2.2 Interaction of Photons

### Mass absorption coefficient

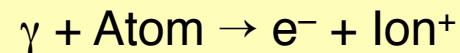


<http://physics.nist.gov/PhysRefData/> calculated using XCOM  
(Photon Cross Sections Database)

## 2.2.1 Photoeffect



The photon is absorbed by an electron from the atoms shell. The transferred energy liberates the electron:



The energy of the electron is:

$$E_e = E_\gamma - \Phi \quad \text{with} \quad \begin{aligned} E_e &\dots \text{kinet. energy of the emitted electron} \\ E_\gamma &\dots \text{energy of the photons, } E_\gamma = h\nu \\ \Phi &\dots \text{binding energy of the electron} \end{aligned}$$

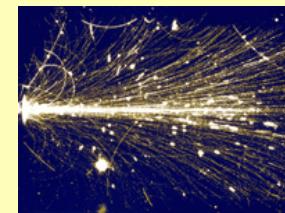
Cross section (approximation for high photon energies):

$$\sigma_{\text{photo}} = \frac{3}{2} \alpha^4 \sigma_0 Z^5 \frac{m_e c^2}{E_\gamma} \propto \frac{Z^5}{E_\gamma}$$

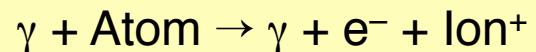
$\sigma_0$  Thomson cross section (elastic scattering of photons on electrons)

Strong dependence on the material with  $Z^5$  !

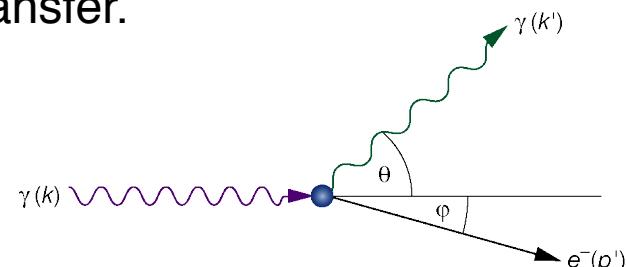
## 2.2.2 Compton Scattering



Compton scattering is the scattering of photon on a “quasi” free electron  
(Photon energy is large compared to the binding energy of the electron).



The photon is deflected and wave length of the photon changes due to the energy transfer.



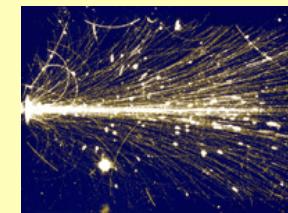
$$\Delta\lambda = \lambda' - \lambda = \frac{\hbar}{m_e c} (1 - \cos \theta)$$

Klein-Nishina formula for the angle dependent cross section :

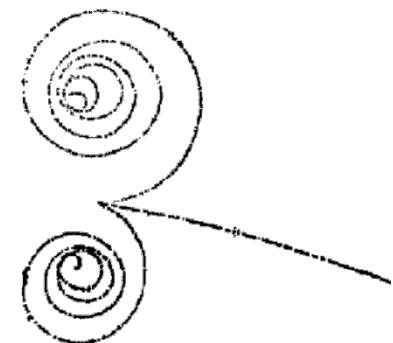
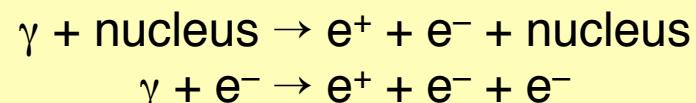
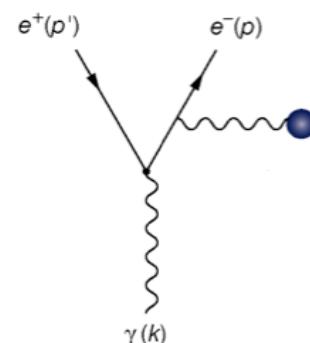
$$\frac{d\sigma_c}{d\Omega} = \frac{r_e^2}{2} \frac{1}{[1 + \kappa(1 - \cos \theta)]^2} \left( 1 + \cos^2 \theta + \frac{\kappa^2 (1 - \cos \theta)^2}{1 + \kappa(1 - \cos \theta)} \right)$$

$\kappa = E_\gamma / m_e c^2$   
“reduced” photon energy

## 2.2.4 Pair production Principle



Pair production is the generation of an electron positron pair by a photon in the field of a nucleus or an electron (the later is suppressed).



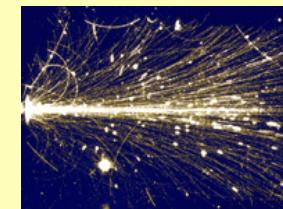
The minimum photon energy for pair production is the sum of the rest mass of the  $e^-e^+$  pair and the recoil energy, i.e.:

$$E_\gamma \geq 2m_e c^2 + 2 \frac{m_e^2}{m_{\text{Stoßpartner}}} c^2 > 1.022 \text{ MeV} \quad (= 2 \times \text{electron mass})$$

This is the dominant process for photon interaction at high energies!

## 2.2.4 Pair production

### Cross section and mean free path length



In the high energy approximation the cross section reaches an energy independent value:

$$\sigma_{\text{pair,nucl}} = 4\alpha r_e^2 Z^2 \left[ \frac{7}{9} \ln\left(\frac{183}{Z^{1/3}}\right) - \frac{1}{54} \right] \quad \text{for } \frac{E_\gamma}{m_e c^2} > \frac{1}{\alpha Z^{1/3}}$$

$\sigma_{\text{pair}}$  independent of energy!

The mean free path length in matter is the inverse of the cross section multiplied with  $A/N_A \rho$

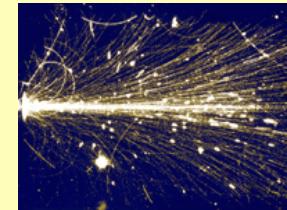
$$\lambda_{\text{pair}} = \frac{A}{N_A \rho} \frac{1}{\sigma_{\text{pair,atom}}}$$

Compared to the radiation lenght

$$\lambda_{\text{pair}} = \frac{9}{7} X_0$$

The similarity is no surprise, considering the equivalency of the two processes Bremsstrahlung and pair production (compare Feynman diagrams).

## 2.3 Hadronic Interactions



Interaction of charged and neutral hadrons.

Neutral hadrons, e.g. neutrons, have no charge, → interact hadronically (and weakly) only.

The hadronic (strong) interactions take place between the hadron and the nuclei of the materials.

- ★ Strong interaction has a short range
- Small probability for a reaction
- **Neutrons are therefore very penetrating**

The total cross section is the sum of all contributions

$$\sigma_{\text{total}} = \sum_i \sigma_i = \sigma_{\text{elastic}} + \sigma_{n,n' \text{ (inelastic)}} + \sigma_{\text{capture}} + \sigma_{\text{fission}} + \dots$$

Define collision and absorption length

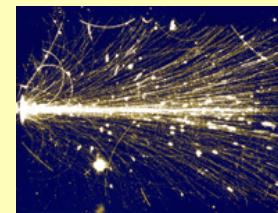
$$\sigma_{\text{inelastic}} = \sigma_{\text{total}} - \sigma_{\text{elastic}}$$

$$\lambda_t = \frac{A}{N_A \rho} \frac{1}{\sigma_{\text{total}}}$$

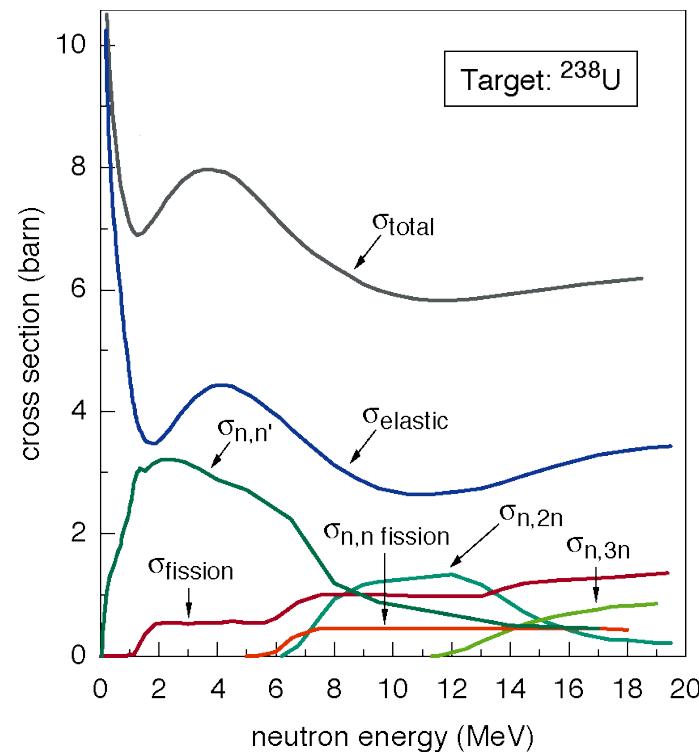
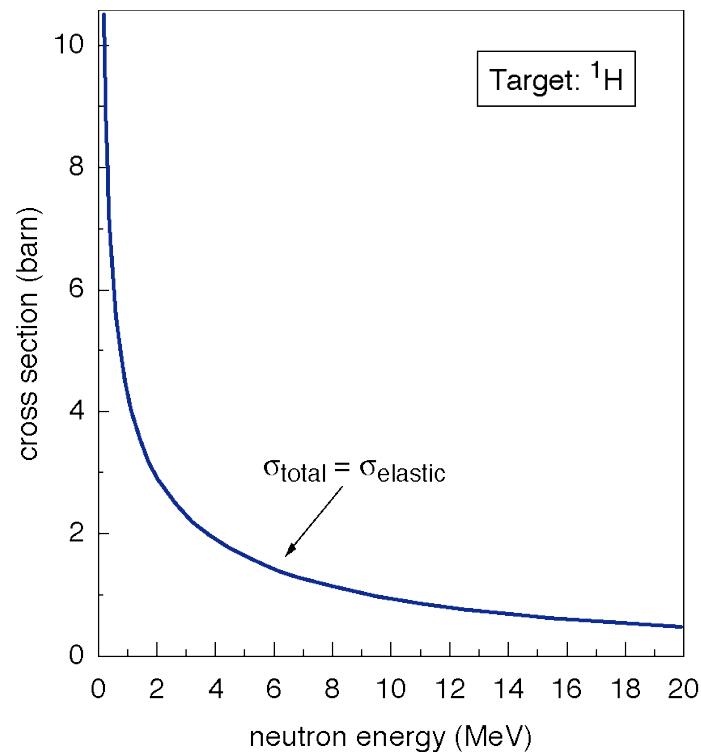
$$\lambda_a = \frac{A}{N_A \rho} \frac{1}{\sigma_{\text{inelastic}}}$$

## 2.3 Hadronic Interactions

### Cross sections for neutrons



Hadronic cross sections for high energy neutrons in hydrogen and uranium (not all possible reaction shown):

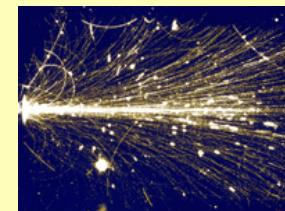


[http://www-nds.iaea.org:8080/exfor/  
endf00.htm](http://www-nds.iaea.org:8080/exfor/endf00.htm) calculated  
using ENDF (Evaluated Nuclear Data File)

Again, these processes create charged particles (e.g. proton recoil, debris) →  
neutron detection via charged particle detection!

## 2.3 Hadronic Interactions

### Cross sections, collision and absorption lengths

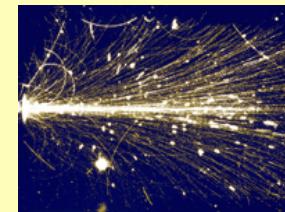


Values for high energy neutrons ( $\approx 100$  GeV) in various materials:

Material	$\sigma_{\text{tot}}$ (barn)	$\sigma_{\text{inelastic}}$ (barn)	$\lambda_t \rho$ (g/cm <sup>2</sup> )	$\lambda_a \rho$ (g/cm <sup>2</sup> )	$\lambda_t$ (cm)
H <sub>2</sub>	0.0387	0.033	43.3	50.8	516.7
C	0.331	0.231	60.2	86.3	26.6
Al	0.634	0.421	70.6	106.4	26.1
Fe	1.120	0.703	82.8	131.9	10.5
Cu	1.232	0.782	85.6	134.9	9.6
Pb	2.960	1.77	116.2	194	10.2
Air (NTP)			62.0	90.0	~51500
H <sub>2</sub> O			60.1	83.6	60.1
Polystyrol			58.5	81.9	56.7

C. Grupen, *Teilchendetektoren*, BI-Wissenschaftsverlag, 1993

## 2.4 Neutrinos



Neutrinos interact only via the weak force. The cross section for interaction is therefore extremely small.

E.g. for 200 GeV neutrinos:  $\sigma_{\text{total}} = 1.6 \cdot 10^{-36} \text{ cm}^2 = 1.6 \text{ pbarn}$

Detection efficiency:

$$\varepsilon = \sigma N_a = \sigma \rho \frac{N_A}{A} d$$

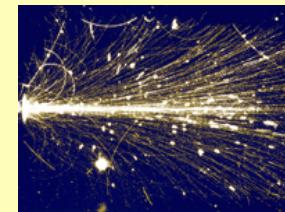
$N_a$ ...area density

$N_A$ ...Avogadro's number

1 m Iron:  $\varepsilon \sim 5 \cdot 10^{-17}$ , 1 km water:  $\varepsilon \sim 6 \cdot 10^{-15}$

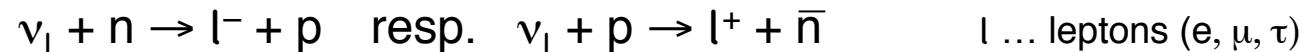
- ★ To compensate for the small cross section very large detector systems or very intense neutrino fluxes are needed.
- ★ In collider detectors reconstruct missing energy and momentum (missing *transverse E<sub>T</sub>*, p<sub>T</sub> in hadron collider experiment). The detector has to be hermetically to reconstruct the energy, momentum vector sums of all particle from the reaction. Missing energy, momentum is a sign of an escaping neutrino (or other weakly interacting particles).

## 2.4 Neutrino Detectors



Very large detectors systems (ktons – Mtons): water (ice), liquid scintillators, liquid Argon

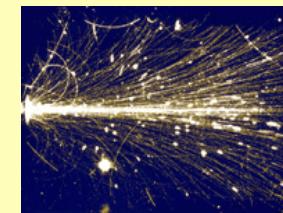
The following reactions are used to detect neutrinos:



Examples for neutrino experiments:

- ★ Gran Sasso National Laboratory (LNGS), several experiments (e.g. Opera, Icarus) <http://www.lngs.infn.it/>
- ★ Super-Kamiokande (Mozumi Mine, Gifu, Japan)  
<http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/super-kamiokande.html>
- ★ Sudbury Neutrino Observatory (SNO, Creighton Mine, Ontario, Kanada)  
<http://www.sno.phy.queensu.ca/>
- ★ IceCube (Amundsen-Scott South Pole Station, Antarktis)  
<http://icecube.wisc.edu/>

## 2.4 Neutrino Detection in Collider Experiments



### Missing Energy and Momentum

Nevertheless, it is important to detect and reconstruct neutrinos. For instance to identify W-Bosons:  $W^\pm \rightarrow l^\pm + \nu_l$      $l \dots \text{Lepton (e, } \mu, \tau)$

A W boson decaying in an electron and a neutrino seen in CMS:

