2 Particle Interaction with Matter

Detectors for Particle Physics

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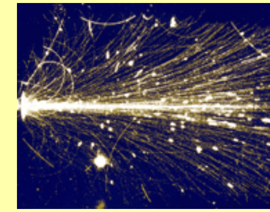
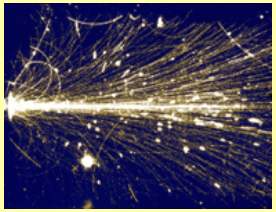
(slides by Manfred Krammer)

2.0 Content



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 names.

p	$1/2^+$	****	$\Delta(1232)$	$3/2^+$	****	Σ^+	$1/2^+$	****	Ξ^0	$1/2^+$	****	Λ_c^+	$1/2^+$	****
n	$1/2^+$	****	$\Delta(1600)$	$3/2^+$	***	Σ^0	$1/2^+$	****	Ξ^-	$1/2^+$	****	$\Lambda_c(2595)^+$	$1/2^-$	***
$N(1440)$	$1/2^+$	****	$\Delta(1620)$	$1/2^-$	****	Σ^-	$1/2^+$	****	$\Xi(1530)$	$3/2^+$	****	$\Lambda_c(2625)^+$	$3/2^-$	***
$N(1520)$	$3/2^-$	****	$\Delta(1700)$	$3/2^-$	****	$\Sigma(1385)$	$3/2^+$	****	$\Xi(1620)$		*	$\Lambda_c(2765)^+$		*
$N(1535)$	$1/2^-$	****	$\Delta(1750)$	$1/2^+$	*	$\Sigma(1480)$		*	$\Xi(1690)$		***	$\Lambda_c(2880)^+$	$5/2^+$	***
$N(1650)$	$1/2^-$	****	$\Delta(1900)$	$1/2^-$	**	$\Sigma(1560)$		**	$\Xi(1820)$	$3/2^-$	***	$\Lambda_c(2940)^+$		***
$N(1675)$	$5/2^-$	****	$\Delta(1905)$	$5/2^+$	****	$\Sigma(1580)$	$3/2^-$	*	$\Xi(1950)$		***	$\Sigma_c(2455)$	$1/2^+$	****
$N(1680)$	$5/2^+$	****	$\Delta(1910)$	$1/2^+$	****	$\Sigma(1620)$	$1/2^-$	*	$\Xi(2030)$	$\geq \frac{5}{2}?$	***	$\Sigma_c(2520)$	$3/2^+$	***
$N(1685)$		*	$\Delta(1920)$	$3/2^+$	***	$\Sigma(1660)$	$1/2^+$	***	$\Xi(2120)$		*	$\Sigma_c(2800)$		***
$N(1700)$	$3/2^-$	***	$\Delta(1930)$	$5/2^-$	***	$\Sigma(1670)$	$3/2^-$	****	$\Xi(2250)$		**	Ξ_c^+	$1/2^+$	***
$N(1710)$	$1/2^+$	***	$\Delta(1940)$	$3/2^-$	**	$\Sigma(1690)$		**	$\Xi(2370)$		**	Ξ_c^0	$1/2^+$	***
$N(1720)$	$3/2^+$	****	$\Delta(1950)$	$7/2^+$	****	$\Sigma(1750)$	$1/2^-$	***	$\Xi(2500)$		*	$\Xi_c'^+$	$1/2^+$	***
$N(1860)$	$5/2^+$	**	$\Delta(2000)$	$5/2^+$	**	$\Sigma(1770)$	$1/2^+$	*				$\Xi_c'^0$	$1/2^+$	***
$N(1875)$	$3/2^-$	***	$\Delta(2150)$	$1/2^-$	*	$\Sigma(1775)$	$5/2^-$	****	Ω^-	$3/2^+$	****	$\Xi_c(2645)$	$3/2^+$	***
$N(1880)$	$1/2^+$	**	$\Delta(2200)$	$7/2^-$	*	$\Sigma(1840)$	$3/2^+$	*	$\Omega(2250)^-$		***	$\Xi_c(2790)$	$1/2^-$	***
$N(1895)$	$1/2^-$	**	$\Delta(2300)$	$9/2^+$	**	$\Sigma(1880)$	$1/2^+$	**	$\Omega(2380)^-$		**	$\Xi_c(2815)$	$3/2^-$	***
$N(1900)$	$3/2^+$	***	$\Delta(2350)$	$5/2^-$	*	$\Sigma(1915)$	$5/2^+$	****	$\Omega(2470)^-$		**	$\Xi_c(2930)$		*
$N(1990)$	$7/2^+$	**	$\Delta(2390)$	$7/2^+$	*	$\Sigma(1940)$	$3/2^-$	***				$\Xi_c(2980)$		***
$N(2000)$	$5/2^+$	**	$\Delta(2400)$	$9/2^-$	**	$\Sigma(2000)$	$1/2^-$	*				$\Xi_c(3055)$		**
$N(2040)$	$3/2^+$	*	$\Delta(2420)$	$11/2^+$	****	$\Sigma(2030)$	$7/2^+$	****				$\Xi_c(3080)$		***
$N(2060)$	$5/2^-$	**	$\Delta(2750)$	$13/2^-$	**	$\Sigma(2070)$	$5/2^+$	*				$\Xi_c(3123)$		*
$N(2100)$	$1/2^+$	*	$\Delta(2950)$	$15/2^+$	**	$\Sigma(2080)$	$3/2^+$	**				Ω_c^0	$1/2^+$	***
$N(2120)$	$3/2^-$	**				$\Sigma(2100)$	$7/2^-$	*				$\Omega_c(2770)^0$	$3/2^+$	***
$N(2190)$	$7/2^-$	****	Λ	$1/2^+$	****	$\Sigma(2250)$		***						
$N(2220)$	$9/2^+$	****	$\Lambda(1405)$	$1/2^-$	****	$\Sigma(2455)$		**				Ξ_{cc}^+		*
$N(2250)$	$9/2^-$	****	$\Lambda(1520)$	$3/2^-$	****	$\Sigma(2620)$		**						
$N(2300)$	$1/2^+$	**	$\Lambda(1600)$	$1/2^+$	***	$\Sigma(3000)$		*				Λ_b^0	$1/2^+$	***
$N(2570)$	$5/2^-$	**	$\Lambda(1670)$	$1/2^-$	****	$\Sigma(3170)$		*				$\Lambda_b(5912)^0$	$1/2^-$	***
$N(2600)$	$11/2^-$	***	$\Lambda(1690)$	$3/2^-$	****							$\Lambda_b(5920)^0$	$3/2^-$	***
$N(2700)$	$13/2^+$	**	$\Lambda(1800)$	$1/2^-$	***							Σ_b	$1/2^+$	***
			$\Lambda(1810)$	$1/2^+$	***							Σ_b^*	$3/2^+$	***
			$\Lambda(1820)$	$5/2^+$	****							Ξ_b^0, Ξ_b^-	$1/2^+$	***
			$\Lambda(1830)$	$5/2^-$	****							$\Xi_b(5945)^0$	$3/2^+$	***
			$\Lambda(1890)$	$3/2^+$	****							Ω_b^-	$1/2^+$	***
			$\Lambda(2000)$		*									
			$\Lambda(2020)$	$7/2^+$	*									
			$\Lambda(2100)$	$7/2^-$	****									
			$\Lambda(2110)$	$5/2^+$	***									
			$\Lambda(2325)$	$3/2^-$	*									
			$\Lambda(2350)$	$9/2^+$	***									
			$\Lambda(2585)$		**									

Meson Summary Table

See also the table of suggested $q\overline{q}$ 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 ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(500)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $a_2(1320)$	$1^-(2^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$f_0(2020)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $a_4(2040)$	$1^-(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_4(2050)$	$0^+(4^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $f_1(1420)$	$0^+(1^{++})$	$f_0(2100)$	$0^+(0^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $a_0(1450)$	$1^-(0^{++})$	• $\phi(2170)$	$0^-(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	$f_0(2200)$	$0^+(0^{++})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $f_0(1500)$	$0^+(0^{++})$	$\eta(2225)$	$0^+(0^{-+})$
$f_1(1510)$	$0^+(1^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
• $f_2'(1525)$	$0^+(2^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$f_4(2300)$	$0^+(4^{++})$
$\rho(1570)$	$1^+(1^{--})$	$f_0(2330)$	$0^+(0^{++})$
$h_1(1595)$	$0^-(1^{+-})$	• $f_2(2340)$	$0^+(2^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	$\rho_5(2350)$	$1^+(5^{--})$
$a_1(1640)$	$1^-(1^{++})$	$a_6(2450)$	$1^-(6^{++})$
$f_2(1640)$	$0^+(2^{++})$	$f_6(2510)$	$0^+(6^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$		
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

OTHER LIGHT

Further States

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K_S^0	$1/2(0^-)$
• K_L^0	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(0^-)$
$D(2600)$	$1/2(?^?)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2750)$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)

	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)$	$0(?^?)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{sJ}^*(2860)^\pm$	$0(?^?)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$
• $B_1(5721)^0$	$1/2(1^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

• $B_c^\pm$	$0(0^-)$

$c\overline{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^+(1^{++})$
• $\chi_{c0}(2P)$	$0^+(0^{++})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^\pm$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4430)^\pm$	$?(?^?)$
• $X(4660)$	$?^?(1^{--})$

$b\overline{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$?^?(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$?^?(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_b(3P)$	$?^?(?^{?+})$
• $\Upsilon(4S)$	$0^-(1^{--})$
$X(10610)^\pm$	$?^+(1^+)$
$X(10650)^\pm$	$?^+(1^+)$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

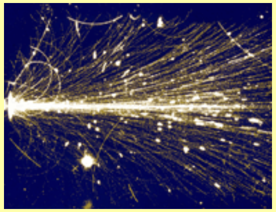
Leptons

- e
- μ
- τ
- ν_e
- ν_μ
- ν_τ

Gauge bosons

- γ
- $W^{+/-}$
- Z
- g
- H

2.0 Particle Measurements



Particles can only be measured in the detector, if they

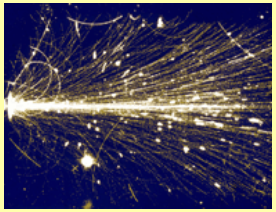
1.Life long enough after creation to reach the detector
The majority of particle states are short lived.
Track length: $l_{track} = v\tau = c\beta\gamma\tau_0$ with τ_0 being the lifetime at rest.
From the hundreds of particles only few particles (and their antiparticles) have track lengths long enough to measure them:

	γ	**p**	**n**	$e^\pm$	$\mu^\pm$	$\pi^\pm$	$K^\pm$	K_0 (K_S/K_L)
τ_0	∞	∞	∞	∞	2.2 μs	26 ns	12 ns	89 ps / 51 ns
l_{track} (p=1GeV)	∞	∞	∞	∞	6.1 km	5.5 m	6.4 m	5 cm / 27.5 m

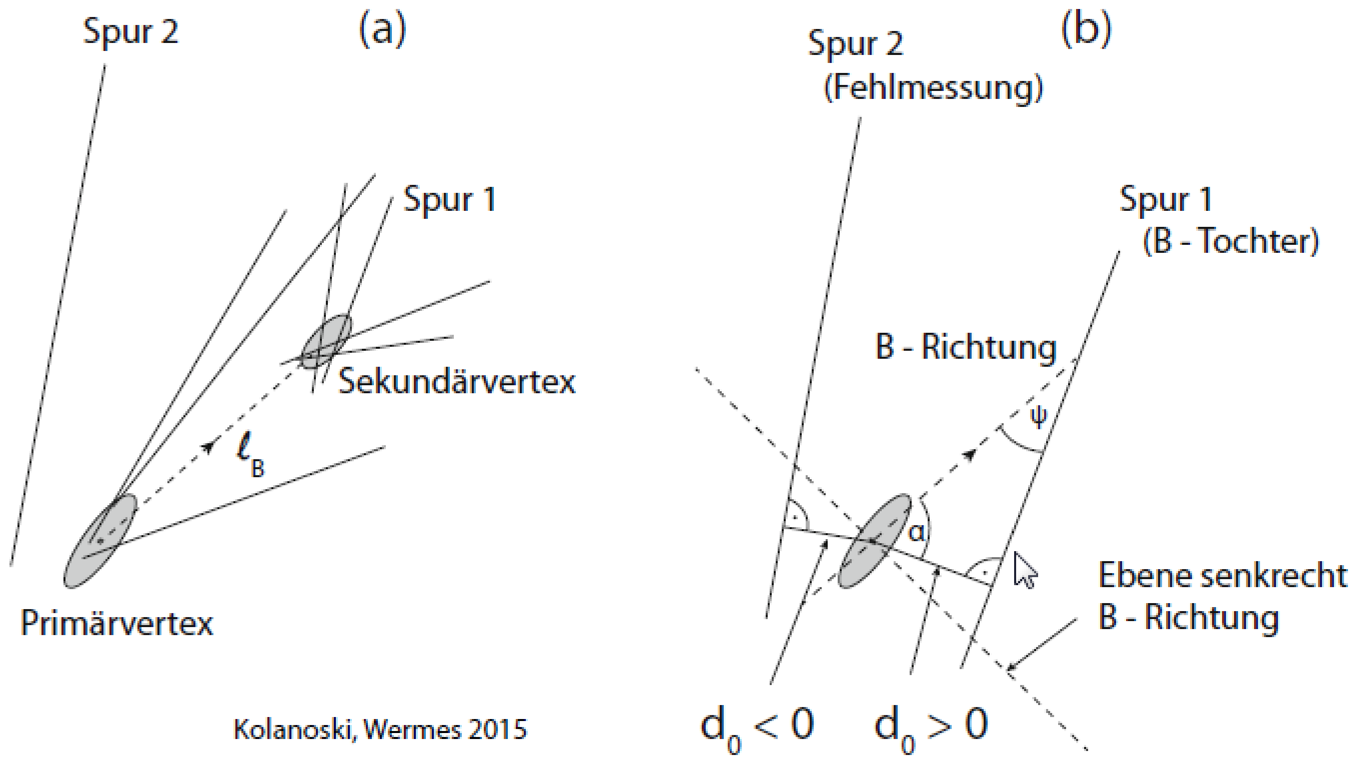
+ Neutrinos (but interact only weakly)

2. Interact with the detector
➔ deposition of energy dE/dx ➔ transferred into a detector signal

2.0 Particle Measurements

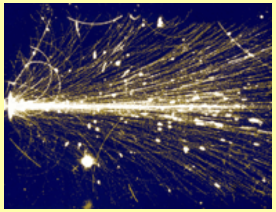


- Detection of particles with ps lifetime

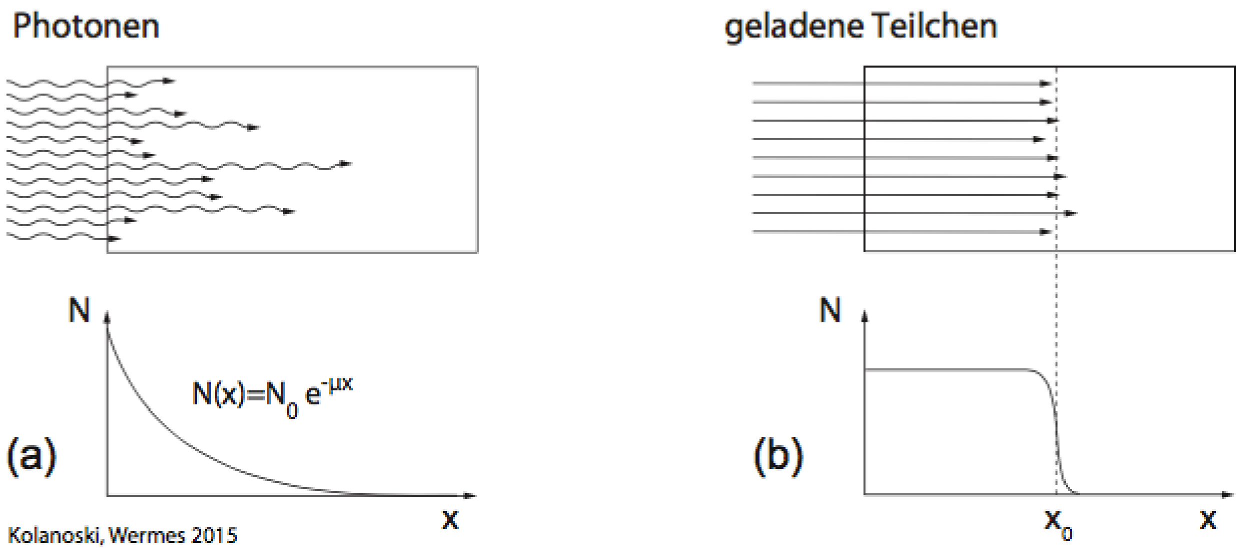


d_0…..impact parameter

2.0 Energy loss photons vs. charged particles



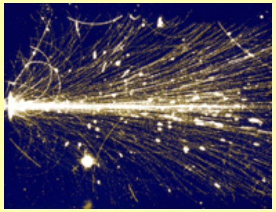
Number of particles as function of depth



(a) Particle loss by absorption (typical of photons) leads to an exponential decay of the beam intensity

(b) Energy loss through matter for charged particles results in a limited range with a relatively localized drop in intensity.

2.1 Charged Particles



For charged particles the electromagnetic interaction is dominating!

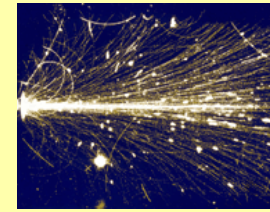
Charged particles penetrating matter can initiate the following processes:

- 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.

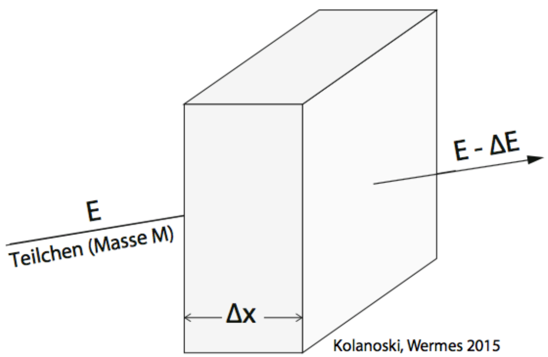
Important: The detection of neutral particles is usually done via the production and subsequent detection of secondary charged particles.

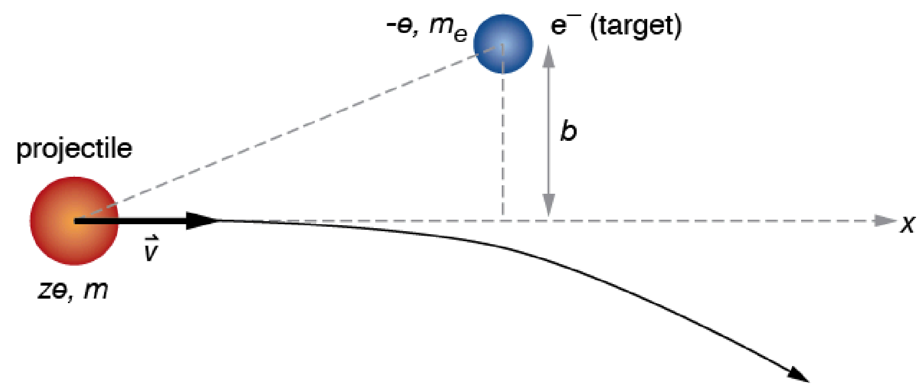
2.1.1 Energy loss of heavy charged particles Bohr‘s classical formula



Ansatz to derive classical formula of Bohr:

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

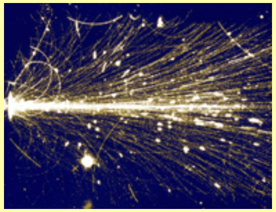




Assumptions:

- 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 >> binding energy)

2.1.1 Energy loss of heavy charged particles **Bohr‘s classical formula**



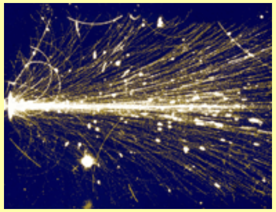
Bohr‘s classical formula for the energy loss rate through collision/excitation of heavy charged particles:

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

N_A … Avogadro constant
ρ … Target density
Z … Atomic number of target
A … Nuclear number of target

Calculated using perturbation theory

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:

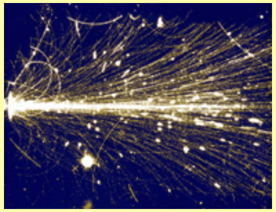
$$-\left(\frac{dE}{dx}\right)_{\text{coll}} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2} \cdot \left[\ln\left(\frac{2 m_e c^2 \gamma^2 \beta^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$

$$\beta = \frac{v}{c},\ \gamma = \frac{1}{\sqrt{1-\beta^2}},\ r_e = \frac{1}{4\pi\varepsilon_0}\cdot\frac{e^2}{m_e c^2}\ \ldots \text{classic } e^- \text{-radius}$$

z	…	Charge of penetrating particle
Z, A	…	Atomic and nuclear number of the target
ρ	…	Target density, N_A … Avogadro constant
I	…	mean ionisation potential (material constant of the target); $I=16Z^{0.9}$ [eV] if $Z>1$
W_{max}	...	max. energy transfer in a single collision
δ	…	Density correction (Polarisation effect, $\delta \approx 2 \cdot \ln\gamma + K$)
C	…	Shell correction (important for small particle velocities)

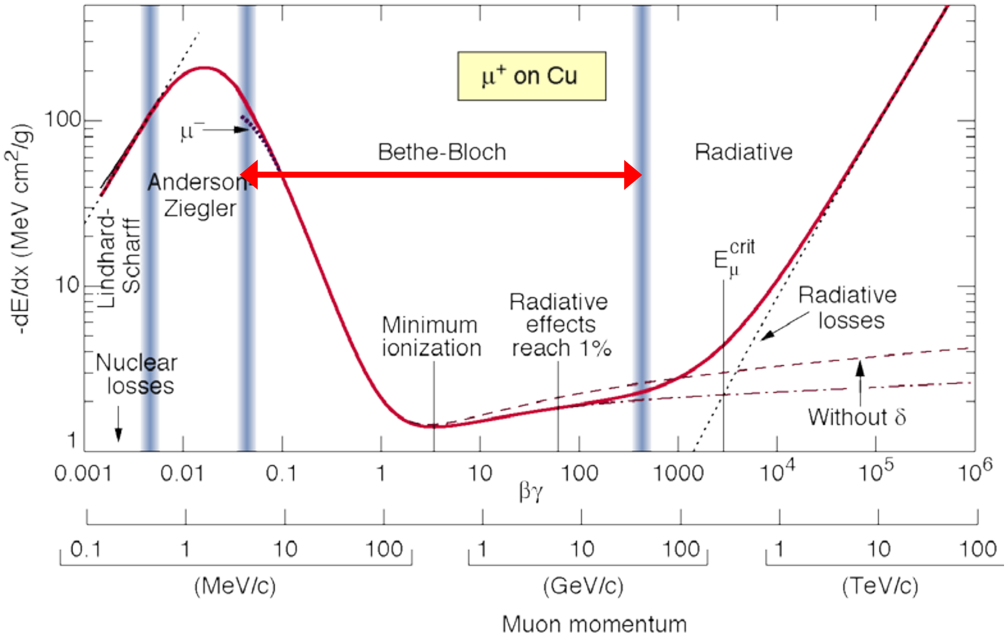
2.1 Interaction of charged particles

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



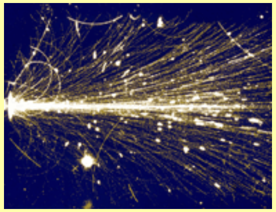
- Bethe-Bloch formula is an excellent description in the range $0.1 < \beta\gamma < 100$.
- The *dE/dx* curve following Bethe-Bloch-Sternheimer has 3 regions:
  - At low energies a $(1/\beta)^2$ drop to a minimum (appr. $\beta\gamma$~3–3.5). Particles at this point are called minimum ionising particles (mip).
  - At higher energies a logarithmic rise follows.
  - At very high energies a radiative losses due to bremsstrahlung start do dominate over ionisation

Total energy loss *-dE/dx* for muons in copper:



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

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

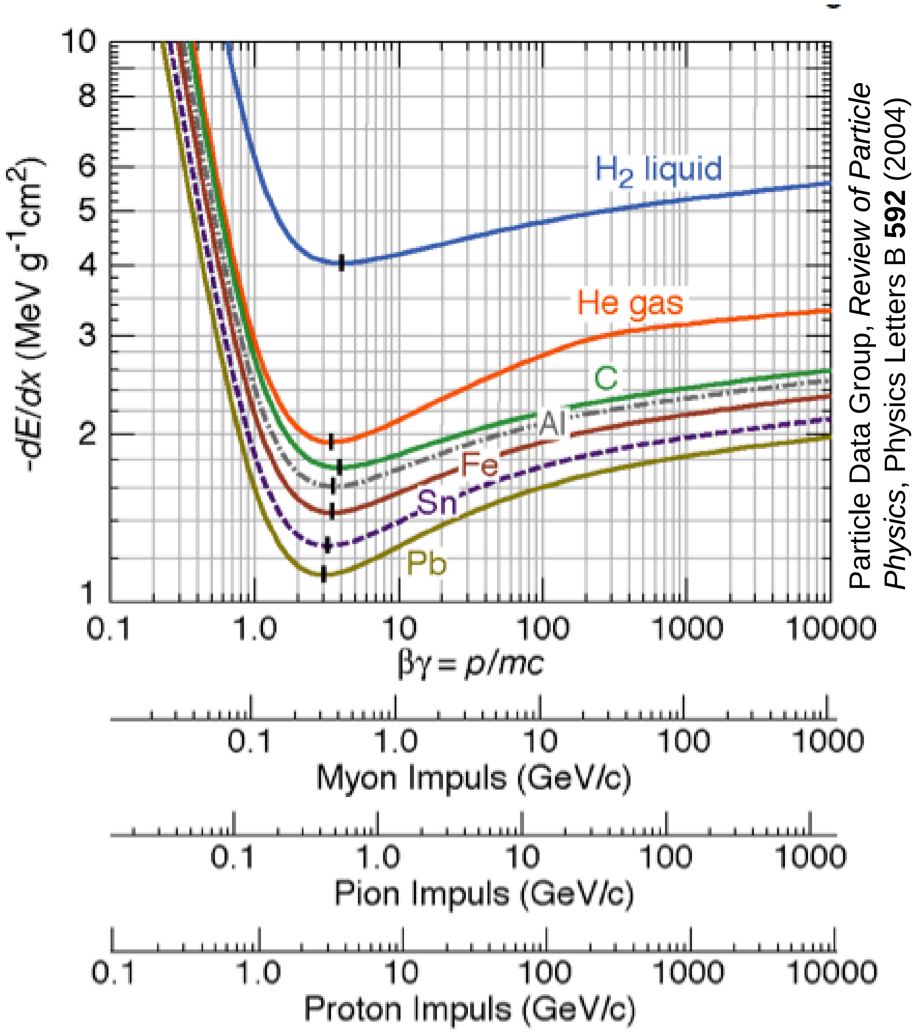


- Specific energy loss rate for muons, pions and protons in different materials is shown in figure on the right
- The energy loss is often given as

$$\frac{1}{\rho}\frac{dE}{dx}$$

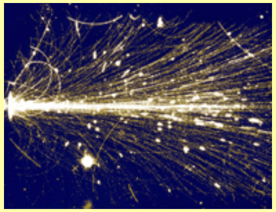
with length in [cm] and the density ρ in [g/cm^3]).

- The value in these units varies only weakly with the absorber material and is
- app. **2 MeVg^{-1}cm^2** for a mip. (H: ≈ 4 MeVg^{-1}cm^2,U: ≈ 1 MeVg^{-1}cm^2)

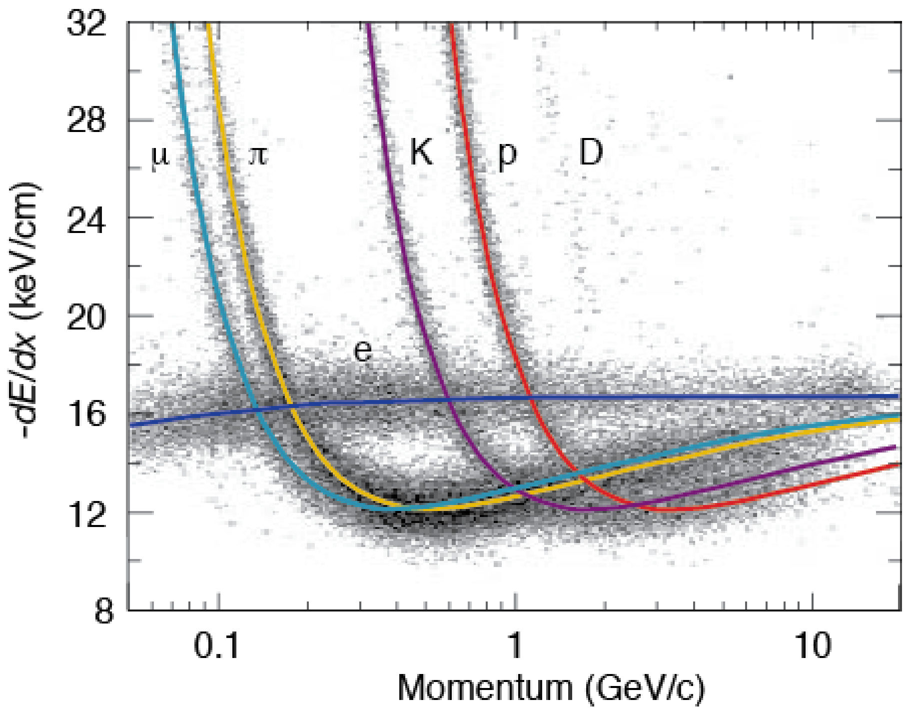


2.1 Energy loss of charged particles

dE/dx for different particles



Total energy loss *-dE/dx* for different particles measured in the PEP4/9 TPC (Ar–CH4 = 80:20 @ 8.5 atm):

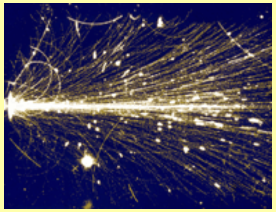


Carsten Niebuhr, *DESY Summer Student Lecture*, 2004

- *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.
- The energy loss is a statistical process (see later).

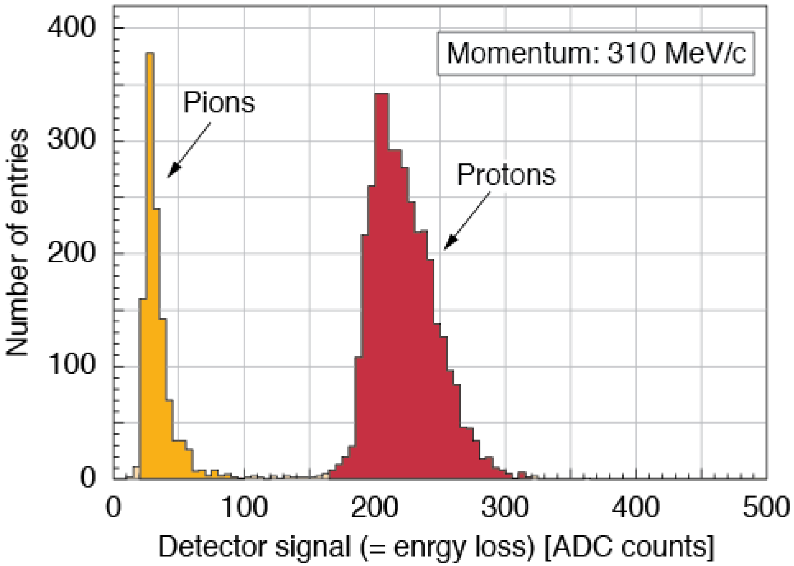
2.1.1 Statistics of the energy loss

Landau distribution



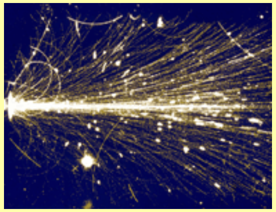
- Energy loss of the incident particle corresponds to deposited energy in absorber material
- The energy loss is a statistical process. Number of collisions and energy loss varies from particle to particle
- The distribution is usually asymmetric. Collisions with a small energy transfer are more probable 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 δ-electrons.
- 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.

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)

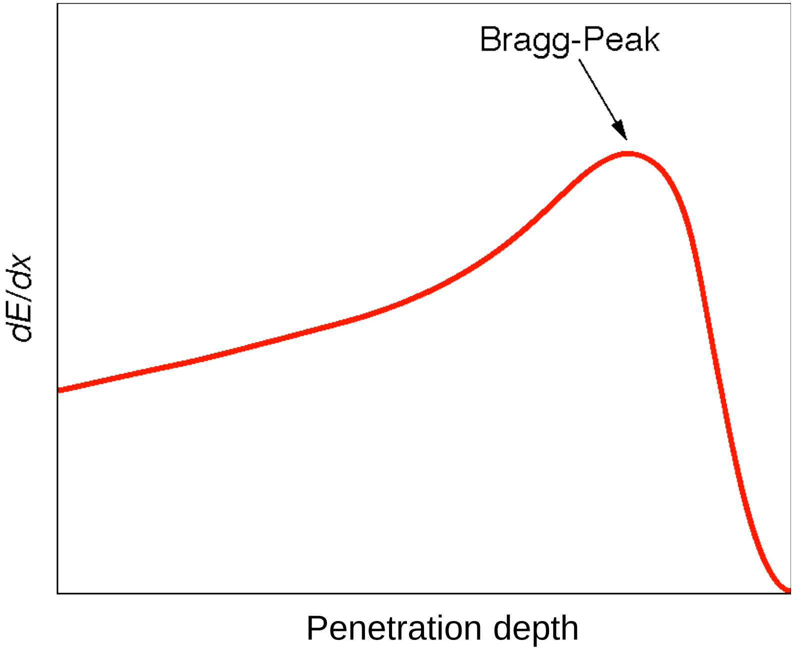
2.1.1. Bragg Curve and Bragg Peak



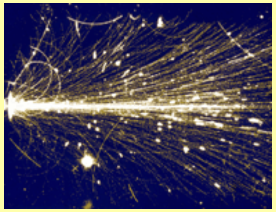
- Energy loss as function of the penetration depth is called Bragg Curve.
- Due to the energy loss along the flight path the projectile slows down
  ➔ the energy loss increases (remember Bethe-Bloch curve!)
  ➔ Largest energy loss near the end of the track = Bragg Peak

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:

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

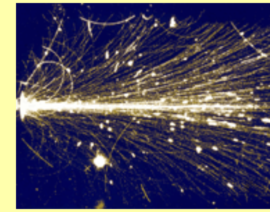
In addition to the energy loss through collision/excitation the energy loss through bremsstrahlung is important.

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

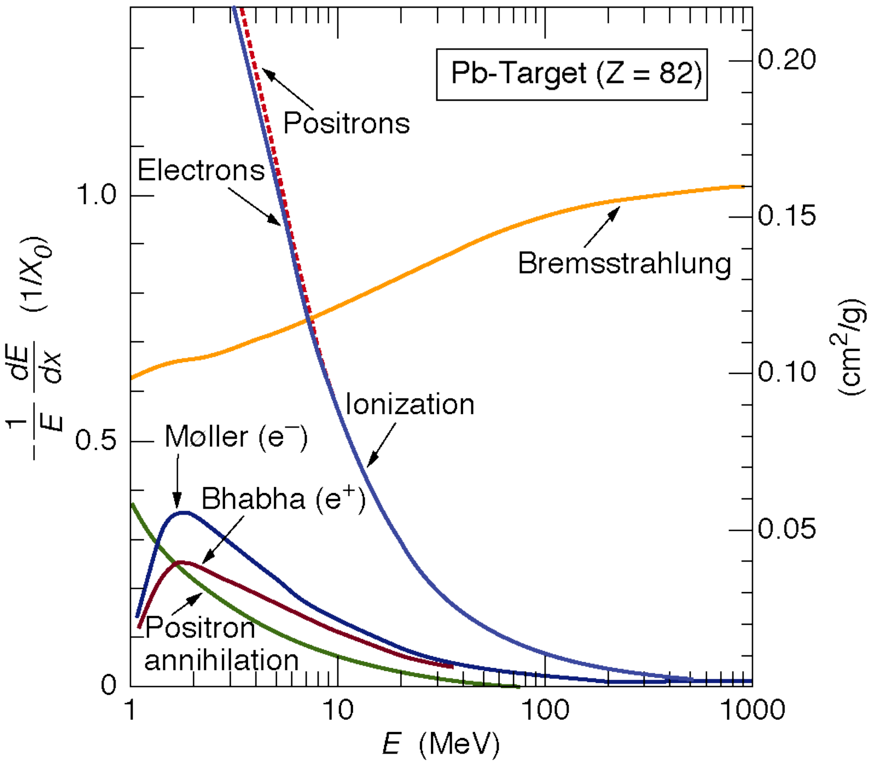
The Bethe-Bloch formula needs to be modified:

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



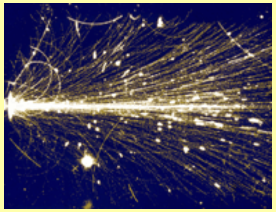
Relative energy losses for electrons and positrons:



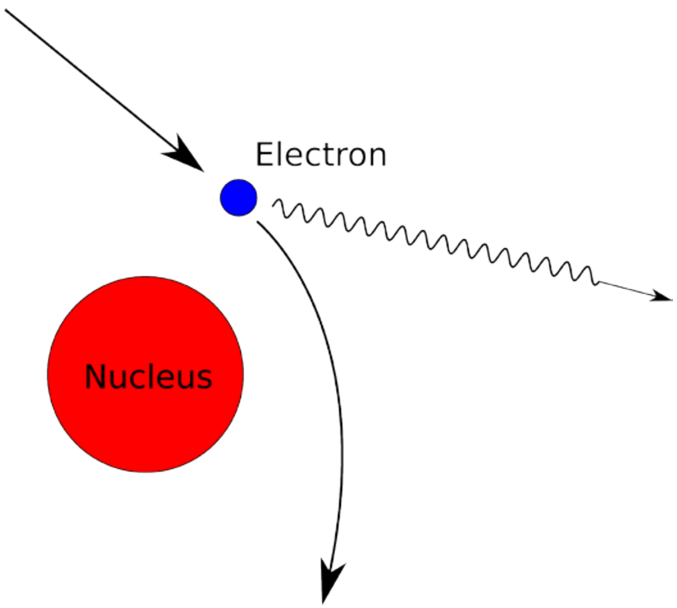
Particle Data Group, *Review of Particle Physics*, Physics Letters B **592** (2004)

- Ionisation losses decrease logarithmically with E (and increase linear with Z)
- Bremsstrahlung increases appr. linear with E (and quadratically with Z)
- Bremsstrahlung is the dominating process for high energies (>1 GeV).

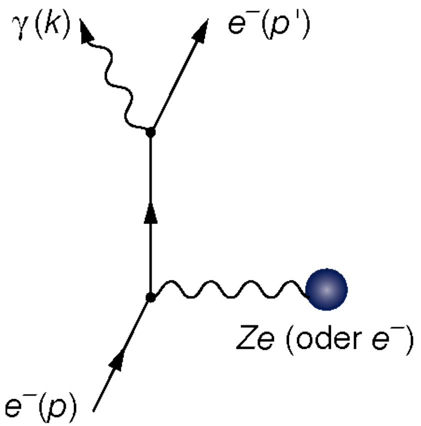
2.1.3 Bremsstrahlung
Principle



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



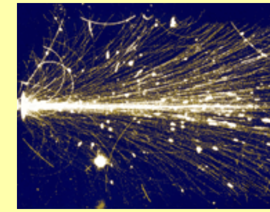
Feynman-diagram:



Similar radiation: X-rays, synchrotron radiation

2.1.3 Bremsstrahlung

Approximation



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

$$\boxed{-\left.\frac{dE}{dx}\right|_{\text{rad}} = 4\alpha\,\rho N_A\,\frac{Z(Z+1)}{A}\,z^2\left(\frac{1}{4\pi\varepsilon_0}\cdot\frac{e^2}{mc^2}\right)^2 E\cdot\ln\left(183\,Z^{-1/3}\right)}$$

α … fine structure constant $\alpha \sim 1/137$

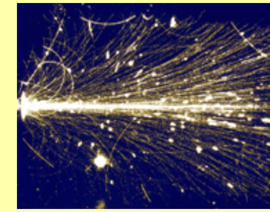
Important:

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

➲ The loss through bremsstrahlung of the second lightest particle (the muon) is 40 000 smaller than the one of electrons/positrons. ($m_u/m_e=200$)

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 (≈63.2%) due to bremsstrahlung:

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

$$\frac{1}{X_0} \approx 4\alpha\left(\frac{\rho N_A}{A}\right) Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}$$

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

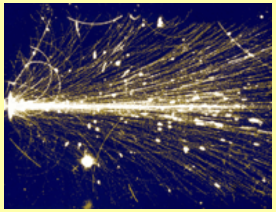
Probability P that a photon creates an e/h pair within one radiation length:

$$P \approx \sigma_{Paar}\left(\frac{\rho N_A}{A}\right) X_0 \approx \frac{7}{9}$$

Mean free path of a photon is:

$$\lambda_{Paar} \approx \frac{9}{7} X_0$$

2.1.3 Bremsstrahlung
Radiation length X_0 – 2



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

Material	$\boldsymbol{X_0}$ (g/cm^2)	X_0 (cm)
H_2O	36.1	36.1
Air (NTP)	36.2	30050
H_2	63	$7 \cdot 10^5$
C	43	18.8
Polystyrol	43.8	42.9
Fe	13.8	1.76
Pb	6.4	0.56

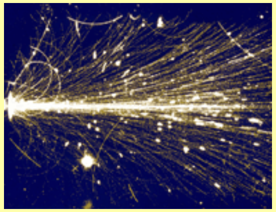
Rough approximation:

X_0 (g/cm^2) ≈ 180 A/Z^2

(e.g. Fe=14, C=60)

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



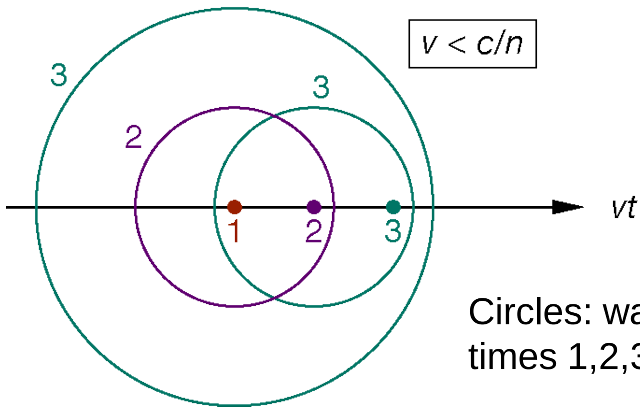
Cherenkov radiation is emited if the particles velocity v is larger then the velocity of light in the medium.

$$v > \frac{c}{n}$$

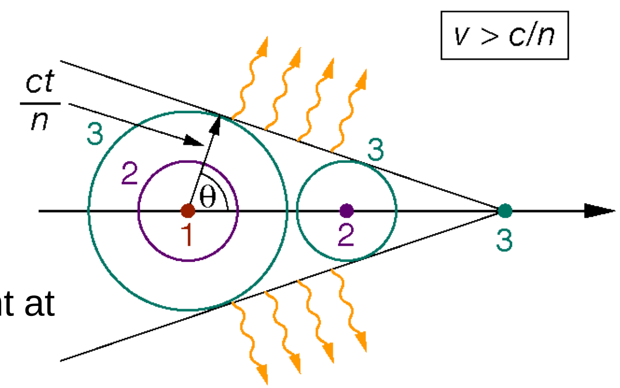
c … speed of light in vacuum
n … refraction index

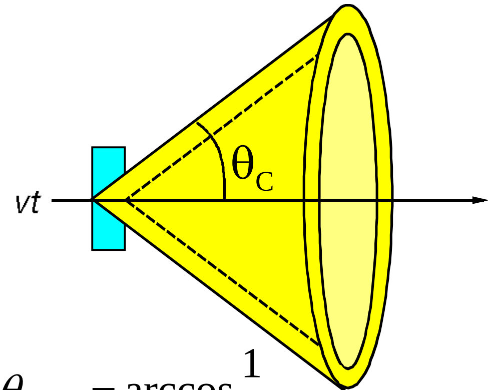
An electromagnetic „shock“ wave develops. The coherent wave front has a conical shape and the photons are emitted under an angle:

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



Circles: wave front at times 1,2,3.

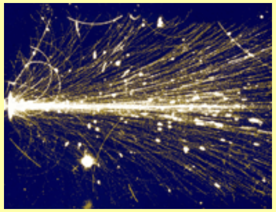




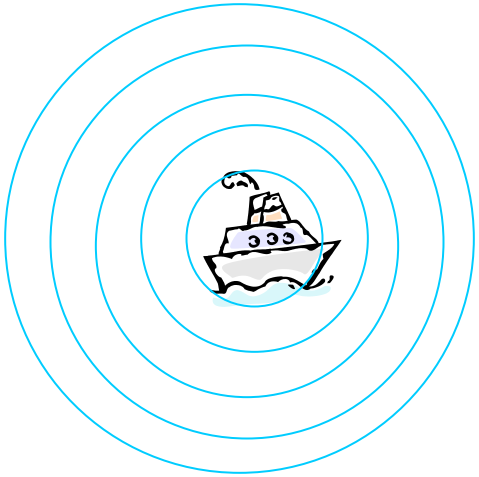
$$\theta_{\max} = \arccos\frac{1}{n}$$

‘saturated’ angle (β=1)

2.1.4 Cherenkov Radiation
Propagating waves -1

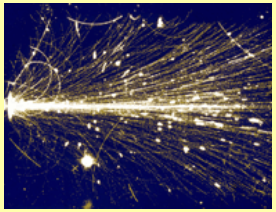


- A stationary boat bobbing up and down on a lake, producing waves

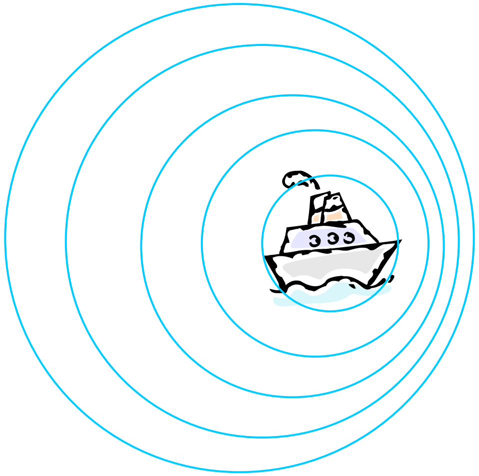


2.1.4 Cherenkov Radiation

Propagating waves -2

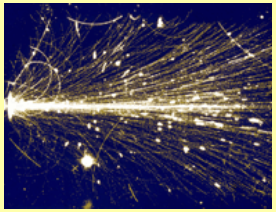


- Now the boat starts to move, but slower than the waves

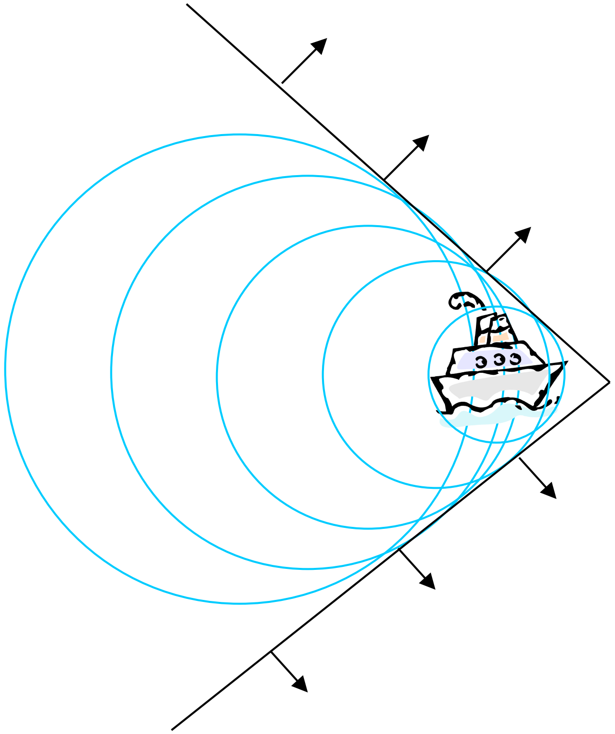


No coherent wavefront is formed

2.1.4 Cherenkov Radiation
Propagating waves -3



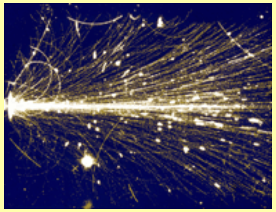
- Next the boat moves faster than the waves



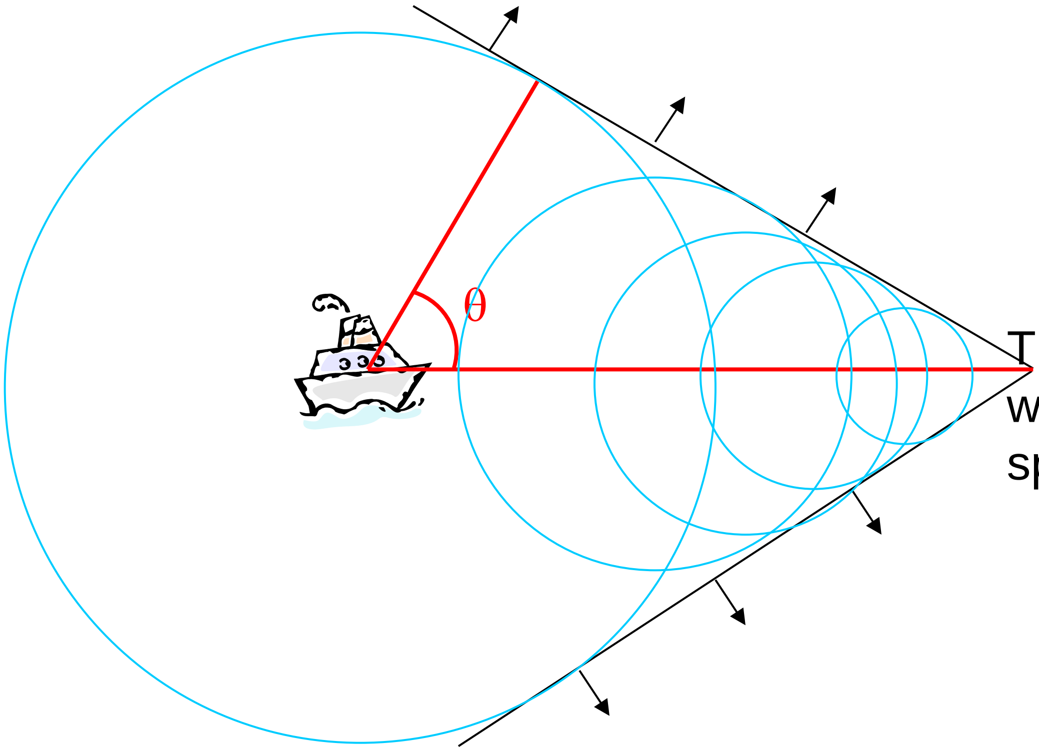
A coherent wavefront is formed

2.1.4 Cherenkov Radiation

Propagating waves -4



- Finally the boat moves even faster

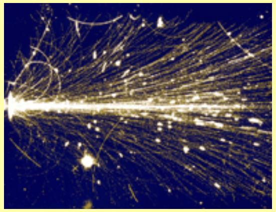


The angle of the coherent wavefront changes with the speed

$$\cos \theta = v_{\text{wave}} \ / \ v_{\text{boat}}$$

2.1.4 Cherenkov Radiation

Photons per unit length and wavelength/energy

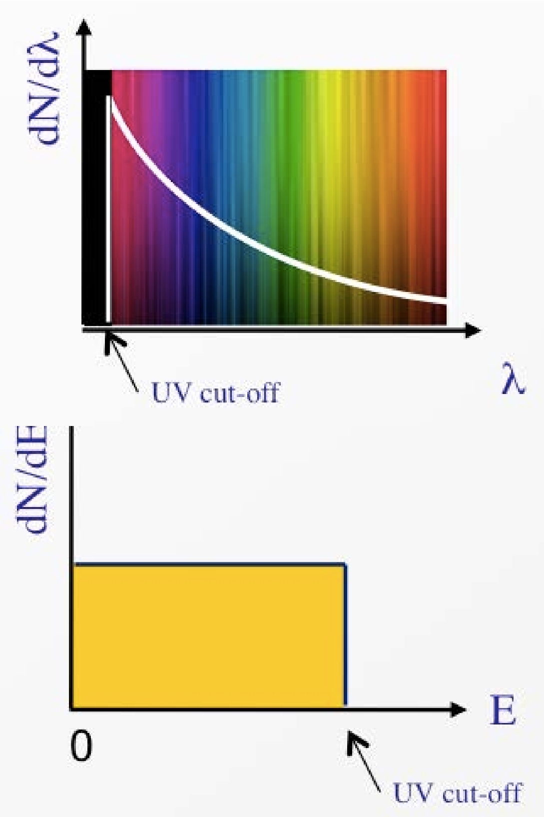


$$\frac{d^2N}{dxd\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1-\frac{1}{\beta^2 n^2}\right) = \frac{2\pi z^2\alpha}{\lambda^2}\sin^2\theta_C$$

$$\frac{d^2N}{dxd\lambda} \propto \frac{1}{\lambda^2} \quad \text{with} \quad \lambda = \frac{c}{\nu} = \frac{hc}{E} \qquad \boxed{\frac{d^2N}{dxdE} = const.}$$

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

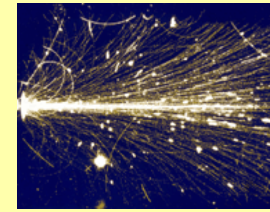
ΔE…energy interval in which the detector is sensitive



$$\boxed{\left.\frac{dE}{dx}\right|^{\text{Cherenkov}} <\approx 1\,\text{keV/cm} \approx 0.001\cdot\left.\frac{dE}{dx}\right|^{\text{Ionization}}}$$

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

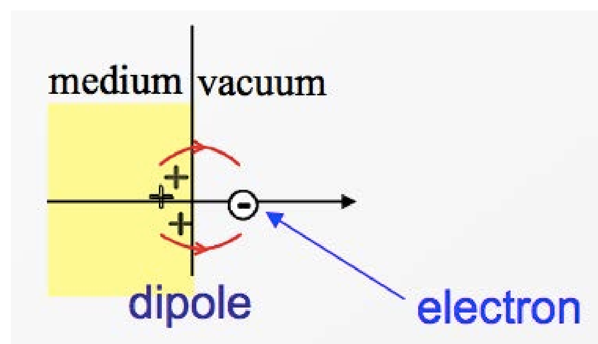
2.1.5 Transition Radiation
Principle



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

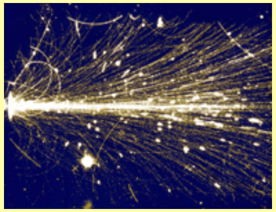
- In the material with low ε the polarisation effect is small.
  → the electric field of the moving charge has a large extension
- In the material with high ε the polarisation effect is larger.
  → the electric field of the moving charge has a smaller extension

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



2.1.5 Transition Radiation

Emission angle and energy



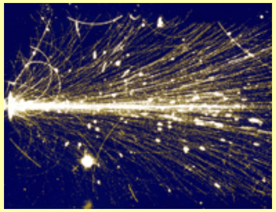
The direction of the emitted photons (X rays) is in the direction of the moving particle within a cone. The opening angle is:

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

Intensity: $\boxed{I \propto \gamma}$

- Measuring the intensity allows to determine γ and consequently the velocity of the particle
- 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

2.2 Interaction of Photons



Important processes are:

- Photo effect
- Compton scattering
- Pair production 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

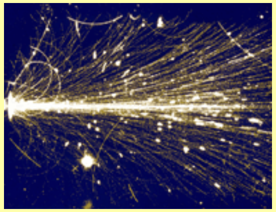
$$\boxed{I(x) = I_0 \cdot e^{-\mu x}}$$

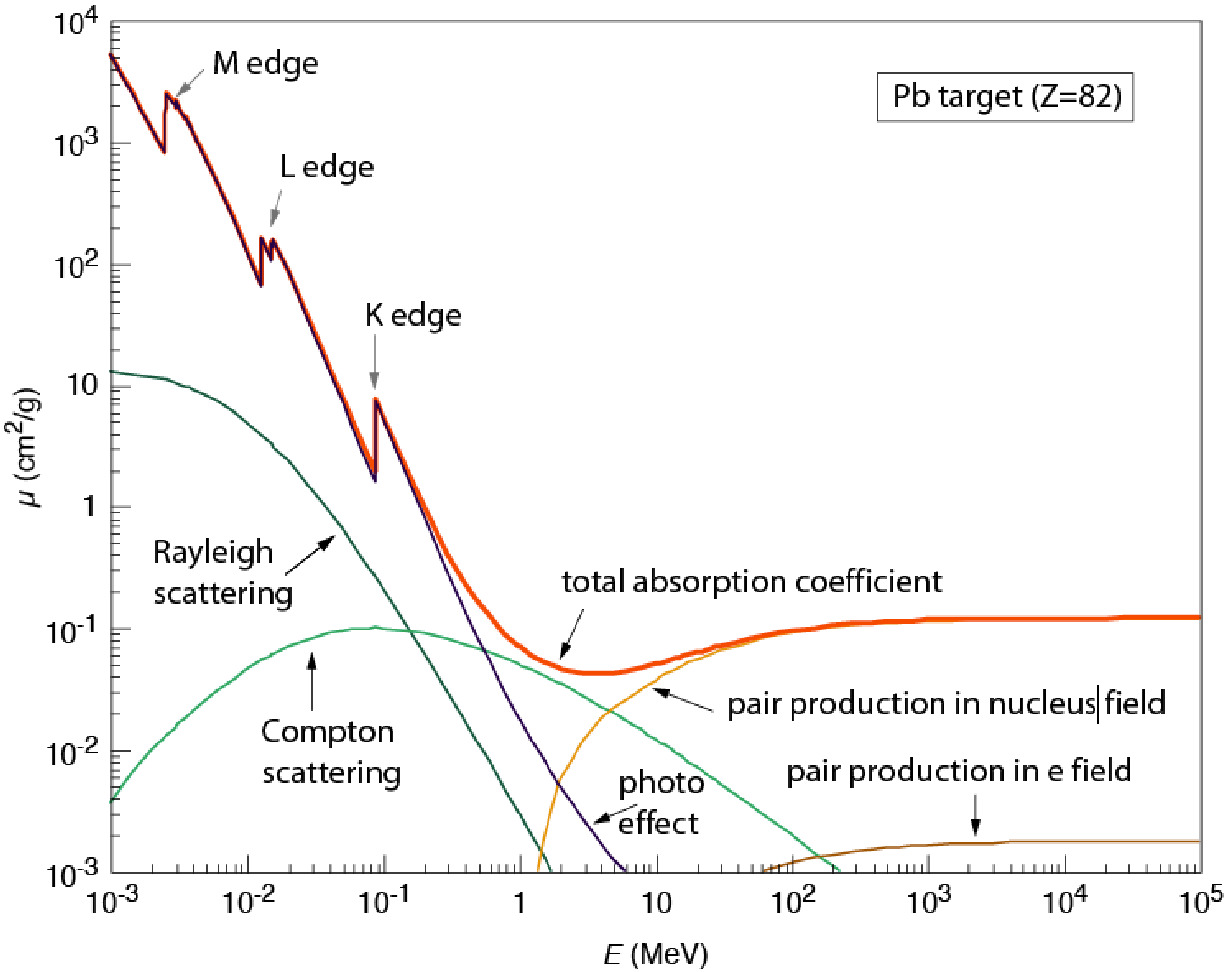
With µ defined as the **mass absorption coefficient** containing the cross sections σ_i of all relevant processes

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

2.2 Interaction of Photons

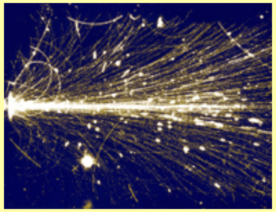
Mass absorption coefficent





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

2.2.1 Photo effect



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

$$\gamma + \text{Atom} \rightarrow e^{-} + \text{Ion}^{+}$$

The energy of the electron is:

$$E_e = E_\gamma - \Phi$$

with

E_e … kinet. energy of the emitted electron

E_γ … energy of the photons, $E_\gamma = h\nu$

Φ … binding energy of the electron

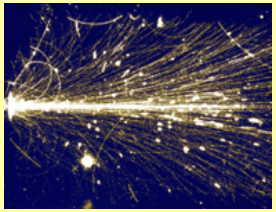
Cross section (approximation for high photon energies):

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

σ_0 Thomson cross section (elastic scattering of photons on electrons)

Strong dependence on the material with Z^5 !

2.2.1 Photo effect

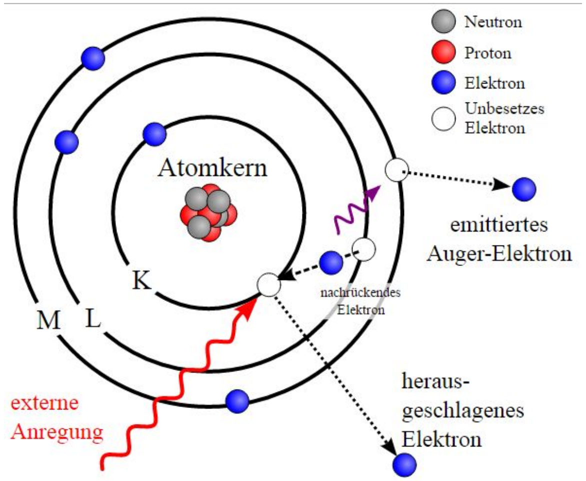


Ionisation of atom creates secondary effects:

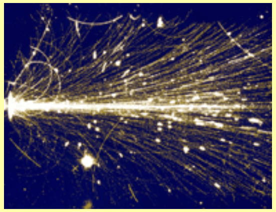
- Characteristic x-rays
- Auger electrons

When the vacant electron is filled up

- $E_{auger} << E_{photoeffect}$



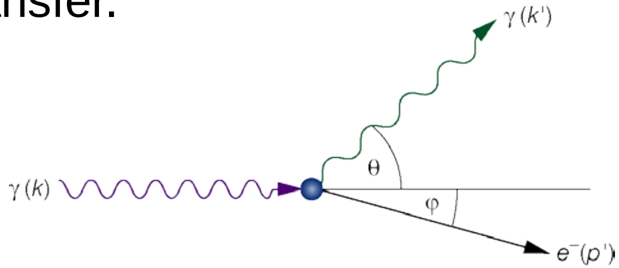
2.2.2 Compton Scattering



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

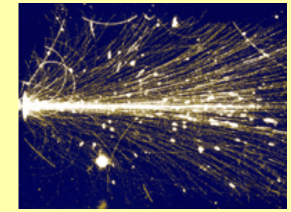
$$\boxed{\gamma + \text{Atom} \rightarrow \gamma' + e^- + \text{Ion}^+}$$

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



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

2.2.2 Compton Scattering



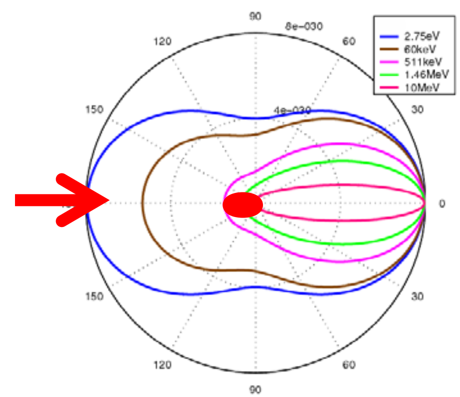
Energy E‘ of the scattered photon depends on the scattering angle θ and photon energy E:

$$E' = E \cdot P(E,\Theta) \quad with \quad P(E,\Theta) = \frac{1}{1 + \frac{E}{m_e c^2}(1-\cos\Theta)}$$

Klein-Nishina formula for the angle dependent cross section :

$$\boxed{\frac{d\sigma_c}{d\Omega} = \frac{r_e^2}{2} P(E,\theta)\left(1 - P(E,\theta)\sin^2\Theta + P(E,\theta)^2\right)}$$

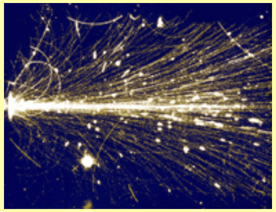
$$d\Omega = \sin\Theta d\Theta d\phi$$



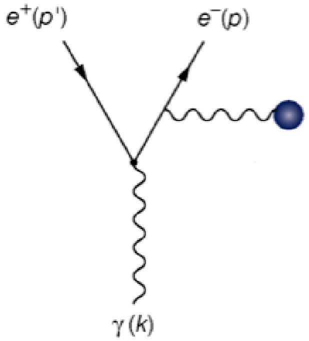
For photon energies << $m_{e:}$ $\quad P(E,\theta) \xrightarrow{E=0} 1$

$$\frac{d\sigma_c}{d\Omega} = \frac{r_e^2}{2}\left(1 + \cos^2\Theta\right)$$

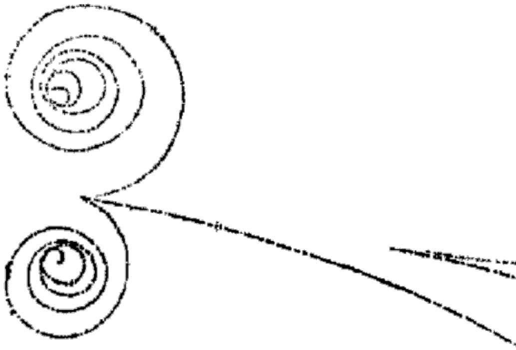
2.2.4 Pair production
Principle



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).



γ + nucleus → $e^+ + e^-$ + nucleus
$\gamma + e^- \rightarrow e^+ + e^- + e^-$



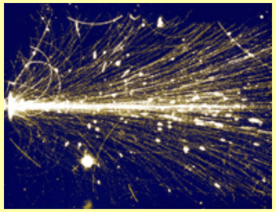
The minimum photon energy for pair production is the sum of the rest mass of the e^-e^+ pair and the recoil energy, i.e.:

$$E_\gamma \geq 2m_e c^2 + 2\frac{m_e^2}{m_{\text{nucleus}}}c^2 \quad > 1.022\text{MeV}$$ (= 2 x 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:

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

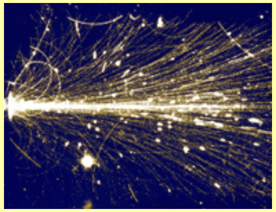
σ_{pair} independent of energy!

$$\sigma_{\text{pair,nucl}} \approx 4\alpha r_e^2 Z^2 \frac{7}{9}\ln\left(\frac{183}{Z^{1/3}}\right) = \frac{7}{9}\cdot\frac{A}{N_A}\cdot\frac{1}{X_0}$$

Compared to the radiation length $\boxed{\lambda_{pair} = \frac{9}{7} X_0}$

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

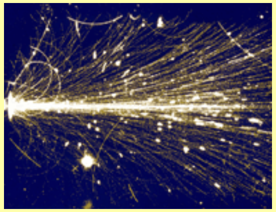
The total cross section is the sum of all contributions

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

Define collision and absorption length

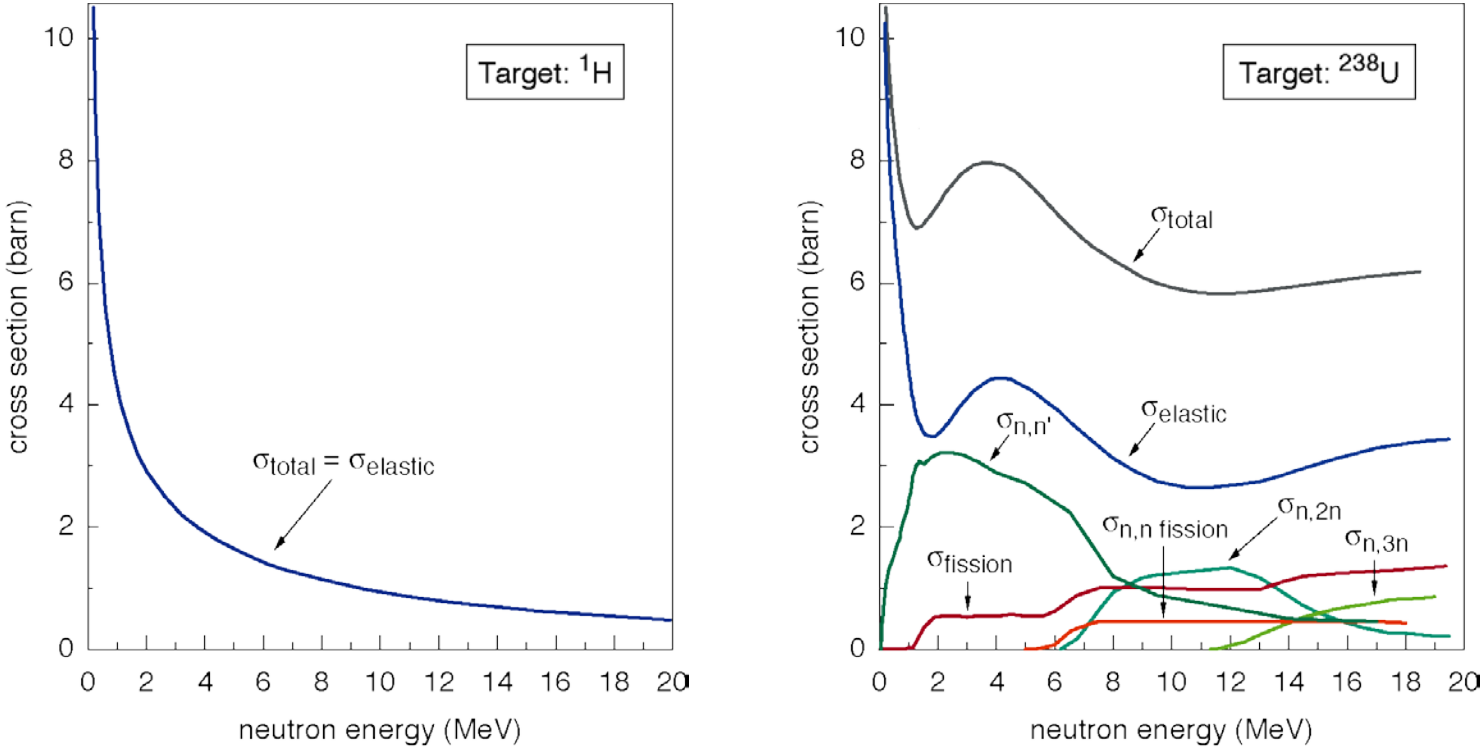
$$\lambda_t = \frac{A}{N_A \rho} \frac{1}{\sigma_{\text{total}}} \qquad \lambda_a = \frac{A}{N_A \rho} \frac{1}{\sigma_{\text{inelastic}}}$$

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



Cross sections for neutrons

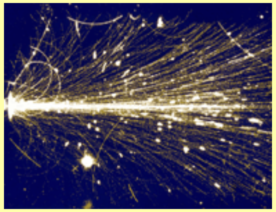
Hadronic cross sections for high energy neutrons in hydrogen and uranium (not all possible reaction shown):



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

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

2.4 Neutrinos



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

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

Detection efficiency:

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

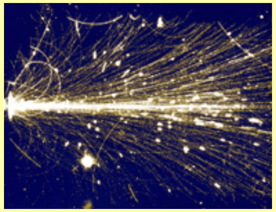
N_a…area density
N_A…Avogadro's number

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_T, p_T 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

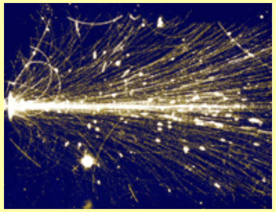
The following reactions are used to detect neutrinos:

$$\nu_l + n \to l^- + p \quad \text{resp.} \quad \nu_l + p \to l^+ + \bar{n} \qquad l \ldots \text{leptons } (e, \mu, \tau)$$

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/

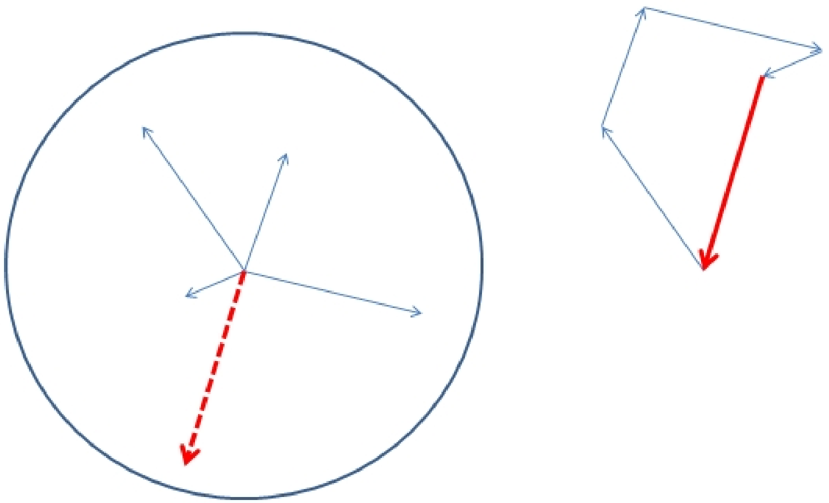
2.4 Neutrino Detection in Collider Experiments



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 … Lepton (e, μ, τ)

Sum of all transverse momenta must be zero:



2.0 Content