JENNIFER2 SUMMER SCHOOL ON PARTICLE PHYSICS AND DETECTORS

20-27 ~~6-15~~ July 2020

KEK, ~~Tsukuba~~, Japan REMOTE

Particle Detectors 01

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Outline

01

- Introduction
- A tour of particle-matter interactions
  - Heavy charged particles
  - Electron and positrons
  - Hadrons
  - Neutrinos

02

- Detector technologies
  - Gas ionization detectors
  - Semiconductor detectors
  - Scintillators and photodetectors

03

- Modern detector systems
  - Tracking/vertexing
  - Particle identification
  - Calorimetry
- Conclusion

Introduction

What’s all about

Particle detectors

- Particle detectors are the basic tools to observe phenomena in the ultra small field of high energy physics.
- Most particles decay after a very short time, depending on the kind of interaction that causes the decay
  - Strong interactions - $< 10^{-22}\ s$
  - Electromagnetic interactions - $10^{-20} - 10^{-14} s$
  - Weak interactions - $> 10^{-13}\ s$
- Only long-lived particles can be observed directly in detectors, the parent particles must be reconstructed indirectly:

Particle measurement - preconditions

Particles can be measured if

a) They live long enough to reach the detector. $l_{\text{track}} = \beta\gamma c\tau_0$

- τ_0 is the lifetime at rest; l_{track} is the average track length for a particle of 1GeV/c momentum.

	γ	p	n	$e^\pm$	$\mu^\pm$	$\pi^\pm$	$K^\pm$	$K^0(K_S/K_L)$
m (MeV)	0	938	939	.511	105	140	494	498
τ_0 (ns)	∞	∞	∞	∞	2200	26	12	0.089/51
l_{track}@1GeV(m)	∞	∞	∞	∞	6100	5.5	6.4	0.05/27.5

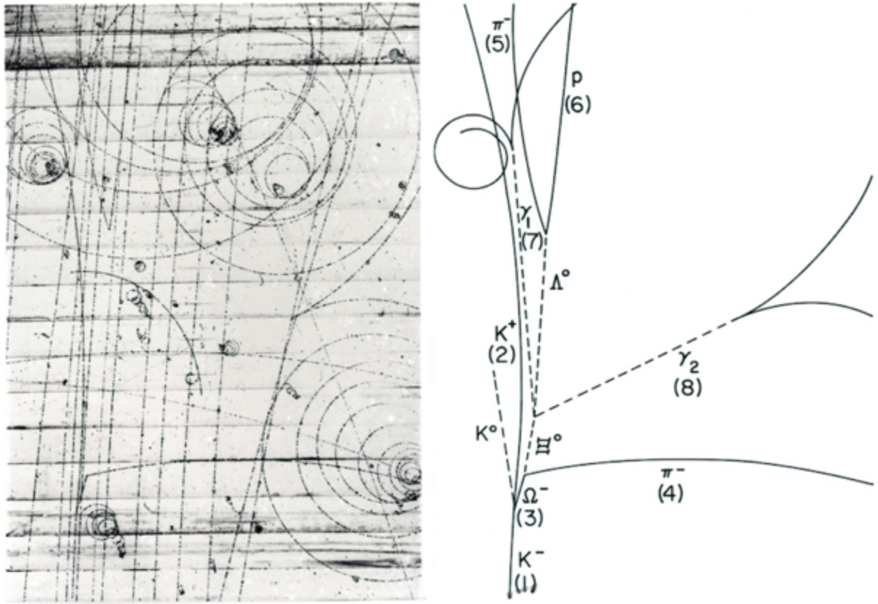
- + neutrinos: stable, but with very weak interaction

b) They interact with the detector and produce a detectable signal

Particle measurement - requirements

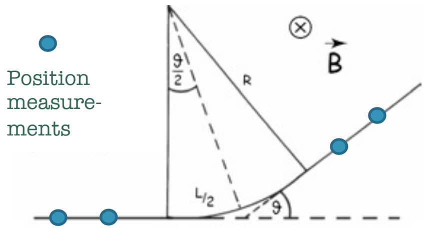
- Ideally one would like to measure all the properties of a particle produced in an experiment:
  - particle type, momentum p, energy E, mass m, charge q, life time τ, spin, decay modes, …
- Ideally one would like to make the measurement without modifying the particle trajectory or energy
  - Although some modifications are unavoidable to produce a detectable signal
- For short-lived particles, obtain information by the properties of the daughters

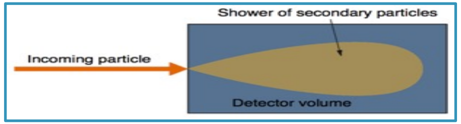
Bubble chamber image of Ω^- discovery

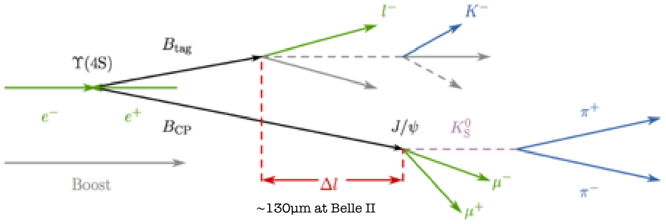


Particle measurement – properties

Momentum p	Radius of curvature in magnetic field p=qRB
Charge q	Direction of deflection in magnetic field up/down, right/left
Energy E	Full energy absorption in a calorimeter ∝ released charge, produced light
Lifetime τ	Measurement of decay length Extrapolation of daughter particles
Velocity β	Time of flight measurement, dE/dx, Cherenkov emission threshold or angle
Mass m / Identity	Calculated from E, p or p, β $m^2 = E^2 - p^2$ $\quad p = m\beta/\sqrt{1-\beta^2}$







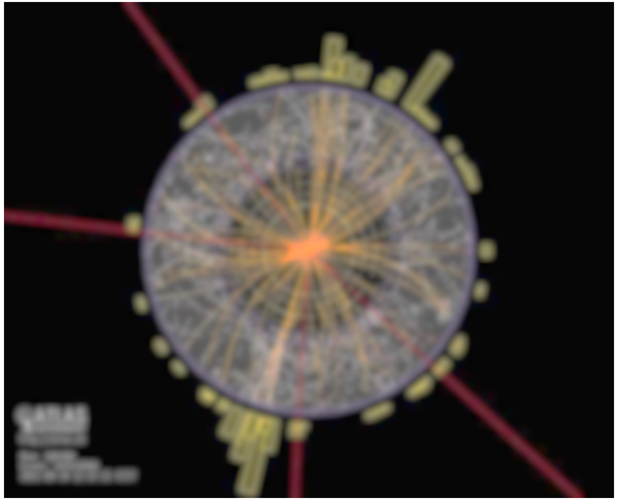
Form vertex from daughter particles

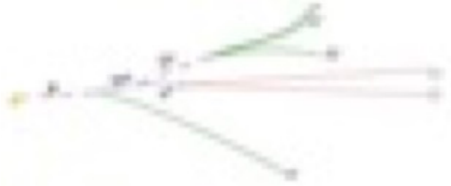
Units

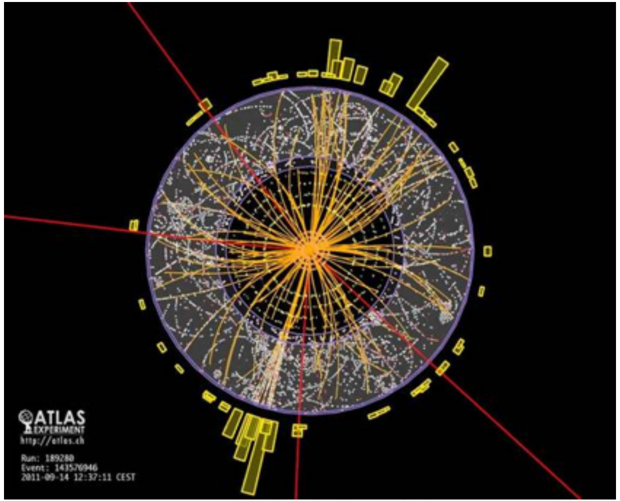
Quantity	HEP units	SI Units
length	1 fm	10^{-15} m
energy	1 GeV	$1.602 \cdot 10^{-10}$ J
mass	1 GeV/c^2	$1.78 \cdot 10^{-27}$ kg
$\hbar$=h/2	$6.588 \cdot 10^{-25}$ GeV s	$1.055 \cdot 10^{-34}$ Js
c	$2.988 \cdot 10^{23}$ fm/s	$2.988 \cdot 10^{8}$ m/s
$\hbar$c	0.1973 GeV fm	$3.162 \cdot 10^{-26}$ Jm

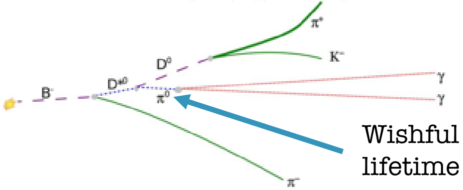
Natural units ($\hbar$ = c = 1)	
mass	1 GeV
length	1 GeV^{-1} = 0.1973 fm
time	1 GeV^{-1} = $6.59 \cdot 10^{-25}$ s

WE NEED EYES TO SEE









Wishful thinking: π^0 lifetime too short

Detectors are our eyes

Classification of detectors

By physical mechanism

- Ionization detectors
- Scintillation detectors
- Cherenkov detectors
- (Transition radiation det.)

By detector material

- Gas filled detectors
- Liquid filled detectors
- Solid state detectors

By measured property

- Charged particles charge, position and momentum (tracking/vertexing)
- Particle total energy (calorimetry)
- Particle type (Particle IDentification)

By purpose/experiment

- Fixed target detectors
- Collider detector
- Massive neutrino detectors

Sources

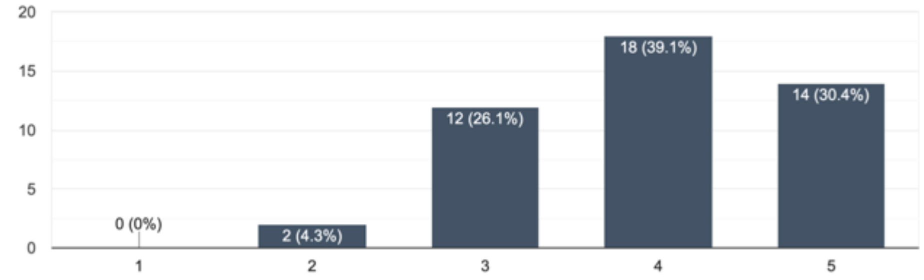
- Books:
  - S.N.Ahmed – Physics and Engineering of Radiation Detectors, Elsevier 2015
  - W.R. Leo – Techniques for Nuclear and Particle Physics Experiments, Springer 1994
  - G.F. Knoll – Radiation detection and measurement, Wiley 1989
  - K.Kleinknecht – Detectors for Particle Radiation, Cambridge, 1998
  - C.Grupen – Particle Detectors, Cambridge, 2009
  - C.W.Fabjan, J.E.Pilcher – Instrumentation in elementary particle physics, World Scientific, 1988
  - T.Ferbel, ed. – Experimental Techniques in High Energy Physics, World Scientific, 1991
  - F.Sauli, ed. – Instrumentation in High Energy Physics, World Scientific, 1992
  - R.Wigmans – Calorimetry: Energy Measurement in Particle Physics, Oxford Scholarship Online, 2018
  - W.Blum , W.Riegler, L.Rolandi – Particle Detection with Drift Chambers, Springer 2008
  - R.K.Bock, A.Vasilescu – The Particle Detector BriefBook, Springer 1998
- Lessons
  - E. Garutti Slides at DESY
  - H.-C. Schultz-Coulon & J. Stachel Slides at Heidelberg
- Particle Data Group - The Review of Particle Physics https://pdg.lbl.gov/

Thanks for answering the survey

- It looks like a large majority would like to hear about particle-matter interactions, at least as a refresher

How familiar are you with particle-matter interactions ?

46 responses



How would you like Part_01 to be presented ?

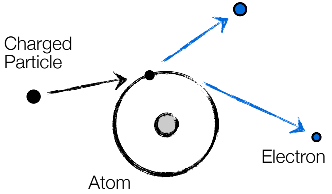
46 responses

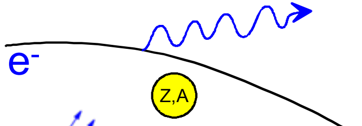
A tour of particle-matter interactions

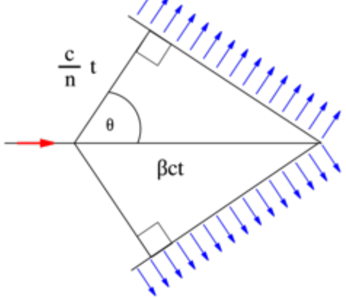
A very quick overview of how particles interact with matter

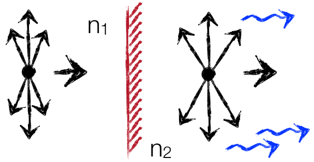
Charged particles interactions

- Atomic excitation / ionization
  - Incident particle excites or ionizes an atom
  - Produces charge or light through de-excitation
- Bremstrahlung (only e^-, e^+)
  - Incident e^-, e^+ is deflected in nucleus electric field, radiating a photon
- Cherenkov radiation (fast particles)
  - EM shock wave produced by particle traveling faster than light in medium
- (Transition radiation – very high energy)
  - Relativistic particle electric field re-arrangement at boundary of different permittivity causes photon irradiation





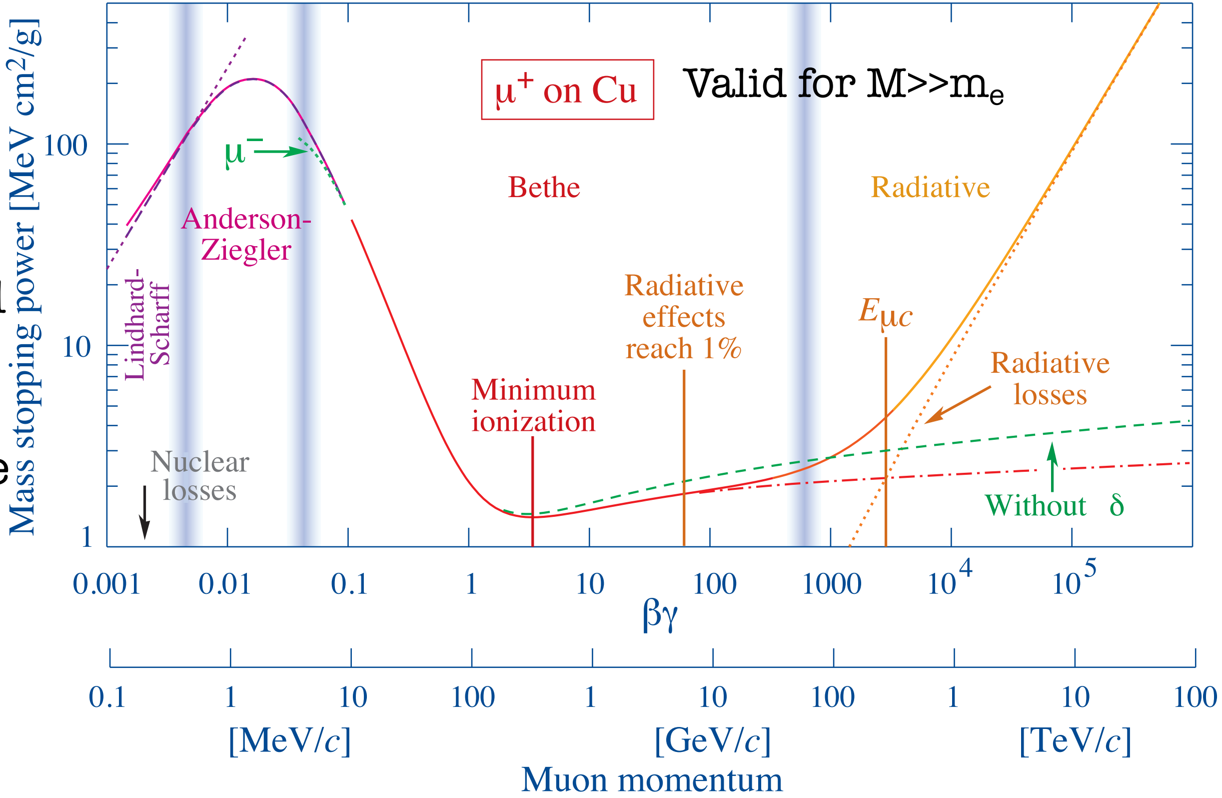




Drawings thanks to H.-C. Schultz-Coulon

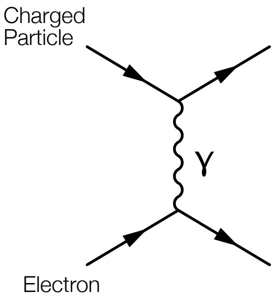
Ionization energy loss -dE/dx: a summary

Mass stopping power: thickness is measured in g/cm² = (distance)*(density) to remove dependence on material density



-dE/dx: Bethe-Bloch

- Loss of heavy particles ($M >> m_{electron}$) dominated by elastic scattering with atomic electrons --> Bethe-Bloch formula



$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307 \text{ MeV g}^{-1} \text{ cm}^2$

$W_{max} = 2 m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma\, m_e/M + (m_e/M)^2)$

[Max. energy transfer in single collision]

z : Charge of incident particle
M : Mass of incident particle

Z : Charge number of medium
A : Atomic mass of medium

I : Mean excitation energy of medium
δ : Density correction [transv. extension of electric field]

$N_A = 6.022 \cdot 10^{23}$
[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm
[Classical electron radius]

$m_e = 511$ keV
[Electron mass]

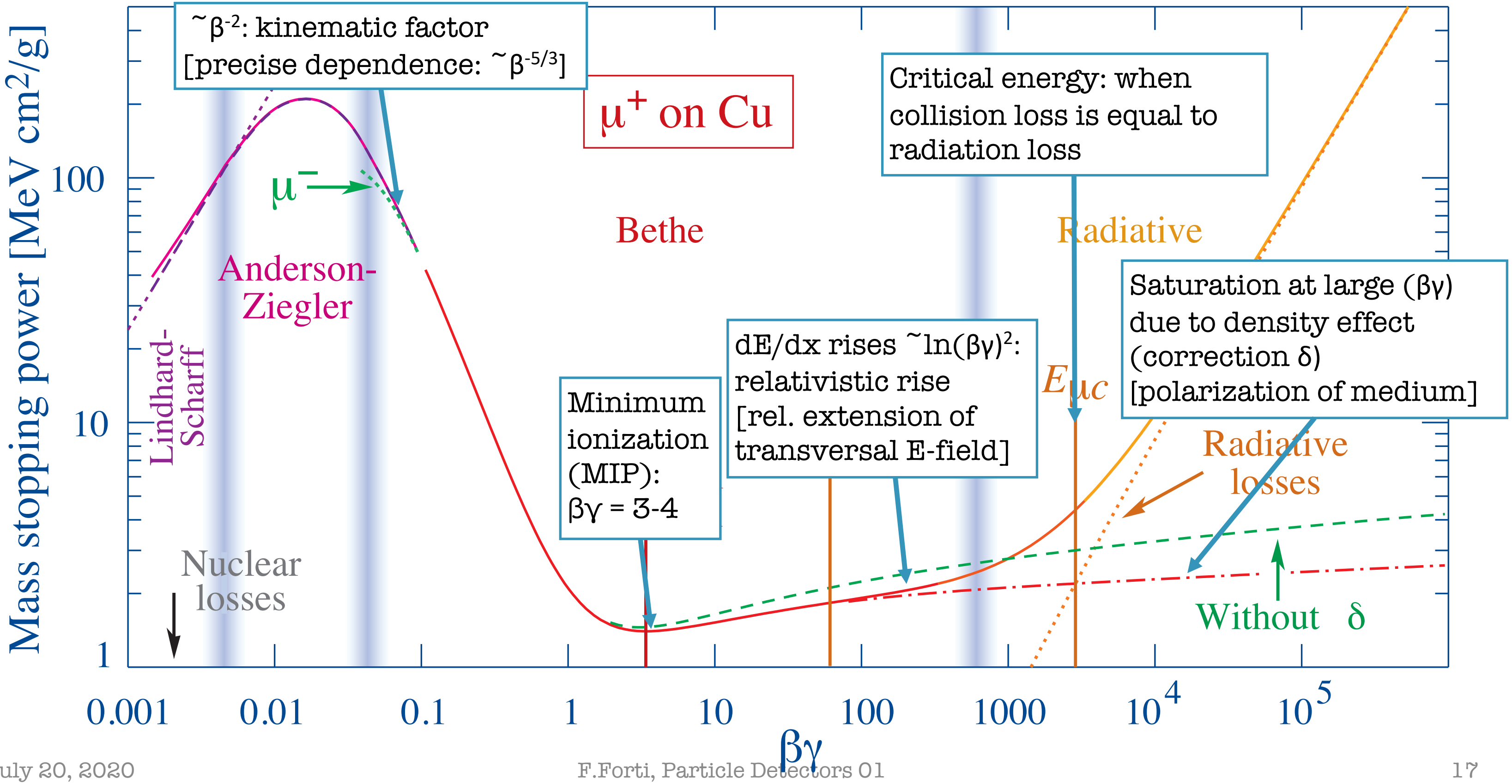
$\beta = v/c$
[Velocity]

$\gamma = (1-\beta^2)^{-2}$
[Lorentz factor]

Validity:

$.05 < \beta\gamma < 500$
$M > m_\mu$

Main features of dE/dx



~β^{-2}: kinematic factor [precise dependence: ~$\beta^{-5/3}$]

Critical energy: when collision loss is equal to radiation loss

Saturation at large (βγ) due to density effect (correction δ) [polarization of medium]

dE/dx rises ~$\ln(\beta\gamma)^2$: relativistic rise [rel. extension of transversal E-field]

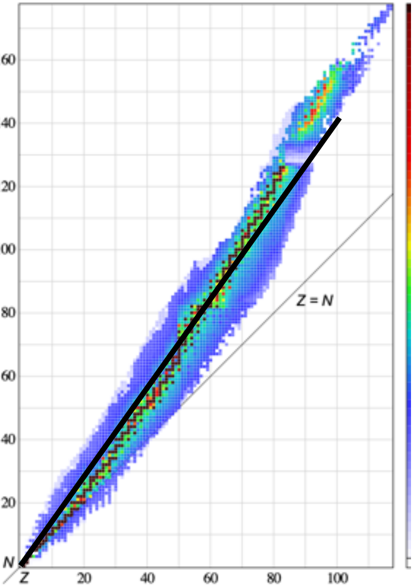
Minimum ionization (MIP): βγ = 3-4

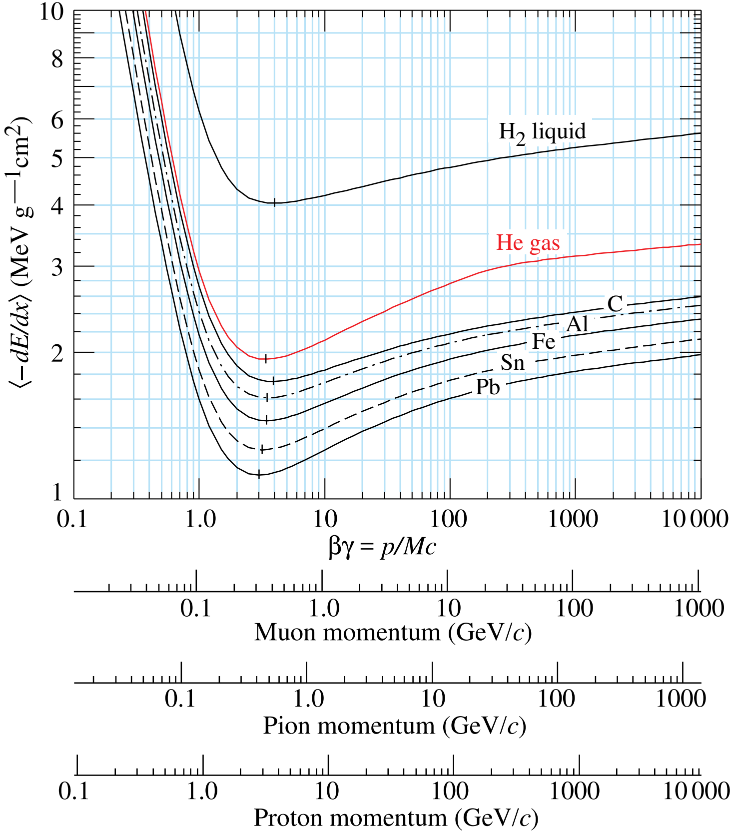
-dE/dx dependence on material

$$\left\langle -\frac{dE}{dx}\right\rangle = K z^2 \boxed{\frac{Z}{A}} \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 W_{\max}}{\boxed{I^2}} - \beta^2 -\right.$$

- Main dependence is Z/A ~0.4

- Fairly constant for most materials
- -dE/dx(MIP) about 1-2 MeV/(g/cm^2)

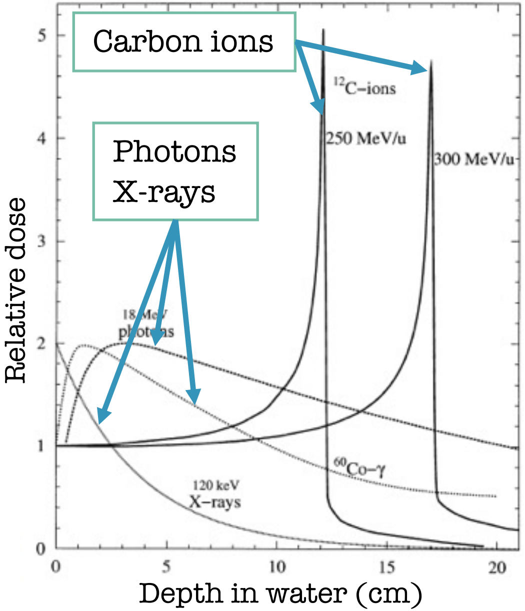


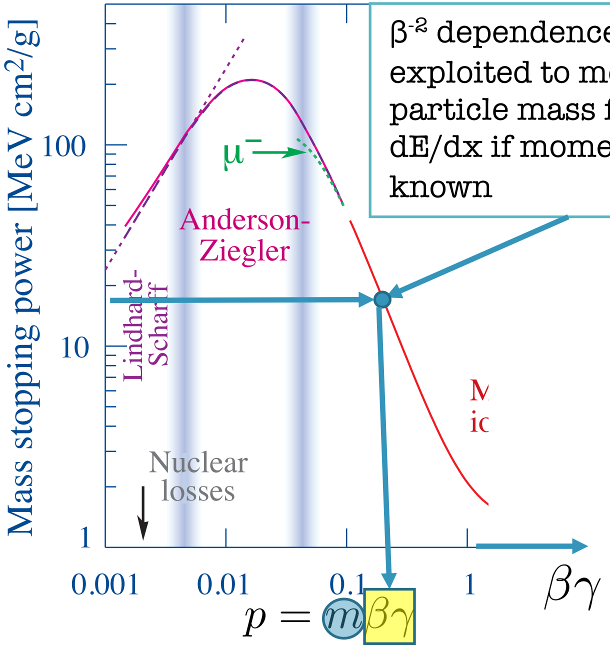


Energy loss at small momenta

- Because of the large increase in –dE/dx at small momentum, charged particle release most of their energy at the end of their track
- → Bragg peak

Very important for cancer treatment selectiveness: give the dose only where it is needed





$p = m\beta\gamma$

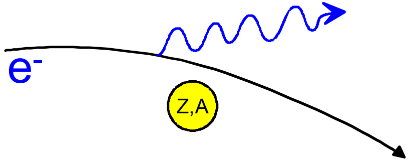
β^{-2} dependence can be exploited to measure particle mass from dE/dx if momentum is known

Energy loss of electron and positrons

- Differences in ionization:
  - Incident and target particles have the same mass (e- and e+)
  - Incident and target particles are identical particles (e- only)
- → modification to Bethe Bloch formula
  - (simplified):

$$-\left\langle \frac{dE}{dx} \right\rangle_{Ionization} \propto \ln(E)$$

- For E>10-30MeV the dominating process is Bremstrahlung
  - Radiation of a photon from an electron accelerated in the field of an atom



$$e^- + N \rightarrow e^- + N + \gamma$$

Bremsstrahlung and Radiation length

- The energy loss through Bremsstrahlung can be written as

$$-\frac{dE}{dx} = 4\alpha N_A \frac{z^2 Z^2}{A} \left(\frac{1}{4\pi\epsilon_0} \frac{e^2}{mc^2} \right)^2 E \ \ln \frac{183}{Z^{\frac{1}{3}}}$$

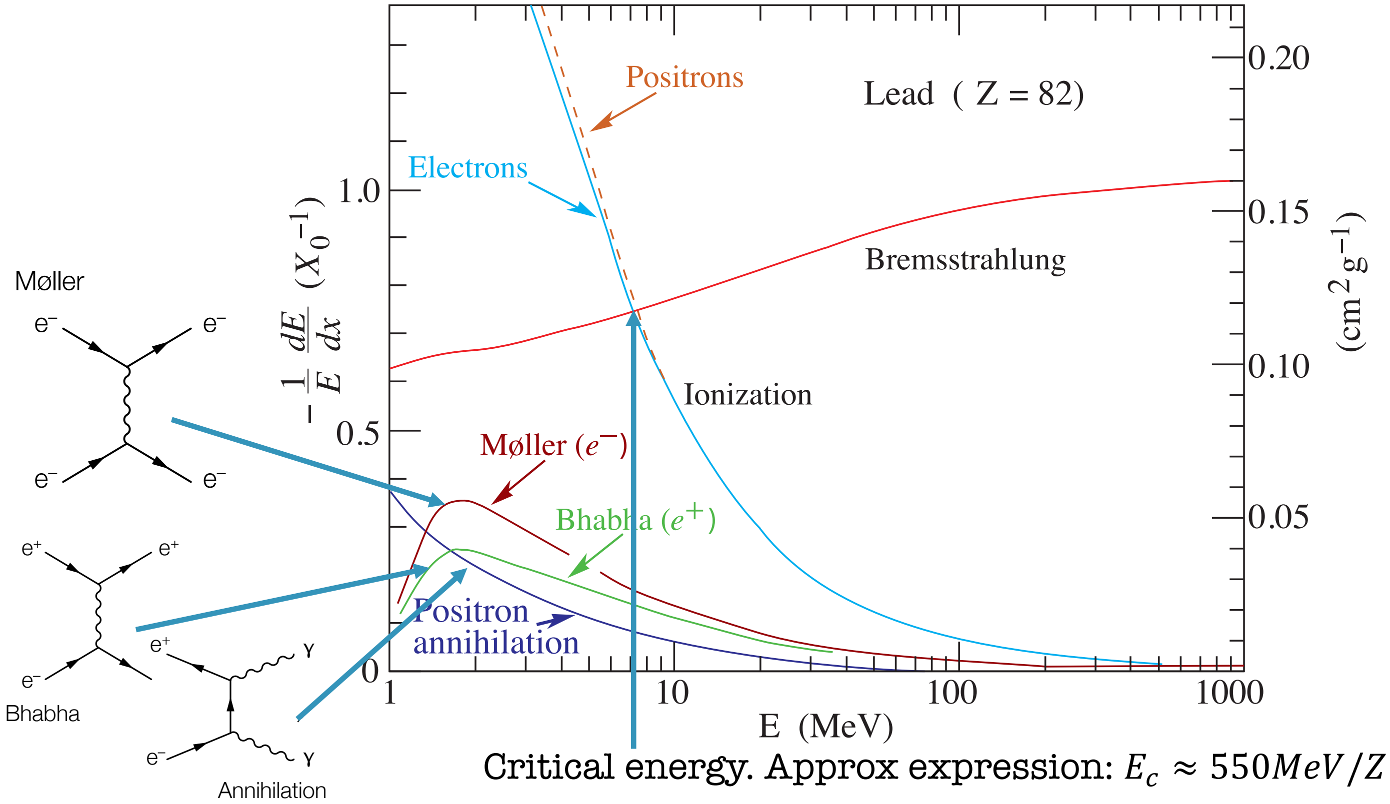
- Features:
  - Proportional to $\frac{E}{m^2} \implies$ only relevant for electrons or very energetic muons.

$$-\frac{dE}{dx} = \frac{E}{X_0} \implies E(x) = E_0 e^{-x/X_0} \qquad X_0 = \frac{A}{4\alpha N_A \ Z^2 r_e^2 \ \ln \frac{183}{Z^{\frac{1}{3}}}}$$

  - X_0 is called "radiation length" = distance after which electron energy is reduced to 1/e.
    - r_e is the classical electron radius
    - Formula gives X_0 in g/cm^2

$$r_e = \frac{1}{4\pi\epsilon_0} \frac{e^2}{mc^2} = 2.8 \text{ fm}$$

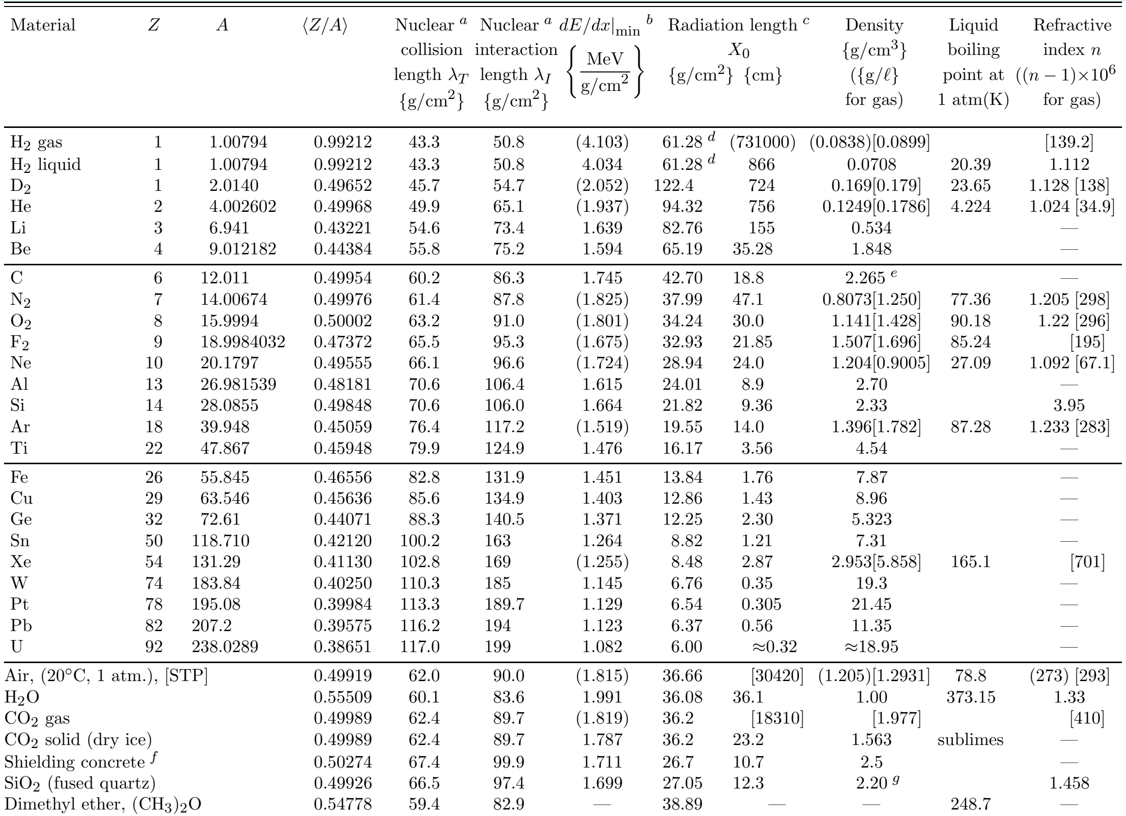
Energy loss of e^-e^+ summary



Critical energy. Approx expression: $E_c \approx 550MeV/Z$

Material properties

https://pdg.lbl.gov/2020/reviews/rpp2020-rev-atomic-nuclear-prop.pdf
https://pdg.lbl.gov/2020/AtomicNuclearProperties/index.html



Material	Z	A	$\langle Z/A\rangle$	Nuclear [a] collision length λ_T $\{g/cm^2\}$	Nuclear [a] interaction length λ_I $\{g/cm^2\}$	$dE/dx\|_{\mathrm{min}}$ [b] $\left\{\frac{\mathrm{MeV}}{g/cm^2}\right\}$	Radiation length [c] X_0 $\{g/cm^2\}$	$\{cm\}$	Density $\{g/cm^3\}$ ($\{g/\ell\}$ for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times10^6$ for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H_2O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33
CO_2 gas			0.49989	62.4	89.7	(1.819)	36.2	[18310]	[1.977]		[410]
CO_2 solid (dry ice)			0.49989	62.4	89.7	1.787	36.2	23.2	1.563	sublimes	—
Shielding concrete [f]			0.50274	67.4	99.9	1.711	26.7	10.7	2.5		—
SiO_2 (fused quartz)			0.49926	66.5	97.4	1.699	27.05	12.3	2.20 [g]		1.458
Dimethyl ether, $(CH_3)_2O$			0.54778	59.4	82.9	—	38.89	—	—	248.7	—

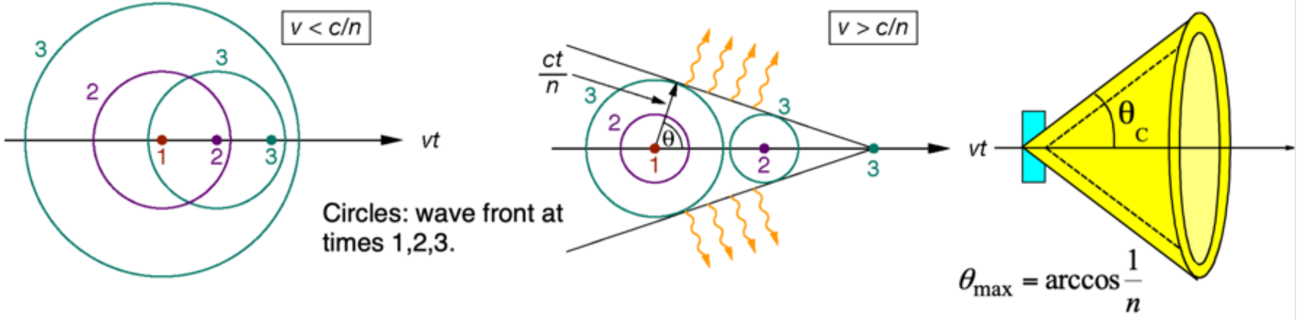
Cherenkov radiation

- Cherenkov radiation is emitted if the particle's velocity is larger than the speed of light in medium of refractive index n

$$\beta > \frac{1}{n}$$

- A coherent conical wave front develops (shock wave). Cherenkov photons are emitted at a specific angle.

$$\cos\theta_c = \frac{1}{n\beta}$$



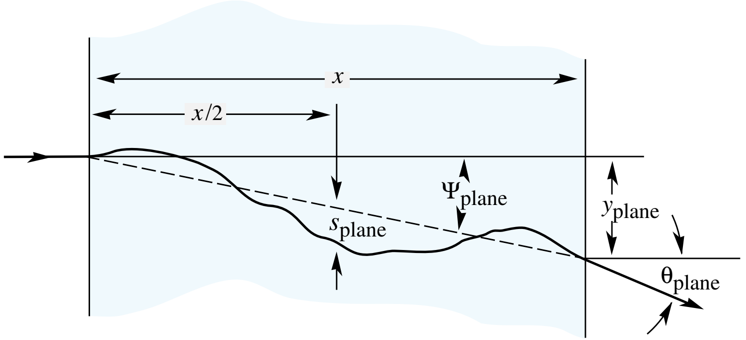
Circles: wave front at times 1,2,3.

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

- It can be used as a yes/no threshold or to measure the photons angle and find β.
- Amount of enery lost by Cherenkov radiation negligible.

Collateral damage: multiple scattering

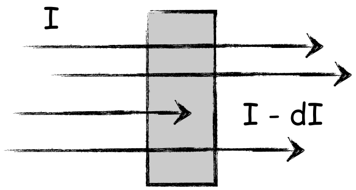
- Particles going through a material are subject to many scattering events from the Coulomb field of the nuclei
- Results in uncertainties in direction when traversing material
- X_0 = radiation length



$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}}\theta_{\text{space}}^{\text{rms}}$$

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}}\left[1 + 0.088 \log_{10}\left(\frac{x\, z^2}{X_0 \beta^2}\right)\right]$$

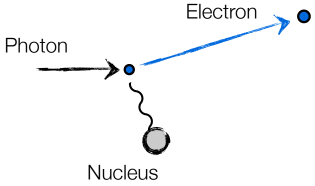
Photons



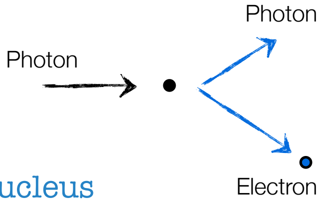
- In photon interactions the interacting photon is lost.
- The energy of the non-interacting photons is unchanged
  - Very different from charged particle interactions
- The electron produced in the interaction can then be detected
- The photon beam intensity is exponential: $I(x) = I_0 e^{-\mu x}$
  - μ (cm^2/g) is the mass absorption coefficient including all processes
  - The mean free path is $\rho\lambda = 1/\mu$

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

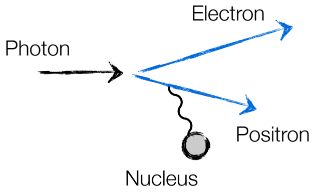
- Photoelectric effect
  - The photon is absorbed by an atomic electron which is ionized



- Compton effect
  - The photon scatters off an electron, resulting in an ionized electron and photon with different energy



- Pair production
  - The photon produces a e^+e^- pair in the field of the nucleus



Drawings thanks to H.-C. Schultz-Coulon

Photoelectric effect

- The photon is absorbed by an electron from the atoms shell. The transferred energy ionizes the electron

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

- The energy of the electron is $E_e = E_\gamma - \Phi$ where Φ is the binding energy of the electron.
- Cross section for high photon energy
  - σ_0 is the Thomson cross section for elastic scattering of photons on electrons

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

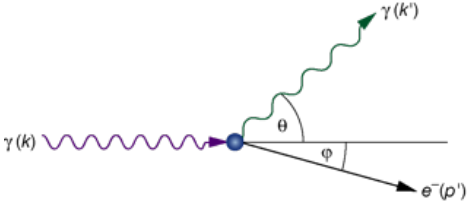
Very strong material dependence: Z^5

Compton effect

- In Compton scattering the photon energy is large compared to the binding energy of the electron

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

- The emerging photon has longer wavelength and different direction wrt the incident photon



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

Klein-Nishina formula for the angle dependent cross section :

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

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

Pair production

- A photon can produce e^+e^- pair in the field of the nucleus

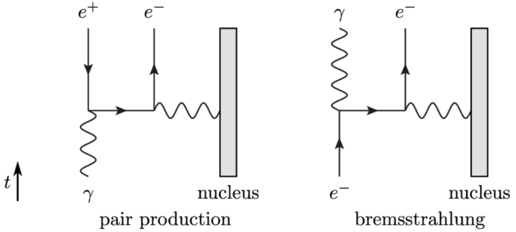
$$\gamma + \text{nucleus} \rightarrow e^- + e^+ + \text{nucleus}$$

- Mimimum photon energy: $E_\gamma > 2m_e + (\text{recoil energy}) > 1.022\text{Mev}$
- At high energy pair production is dominant. Cross section is independent of energy:

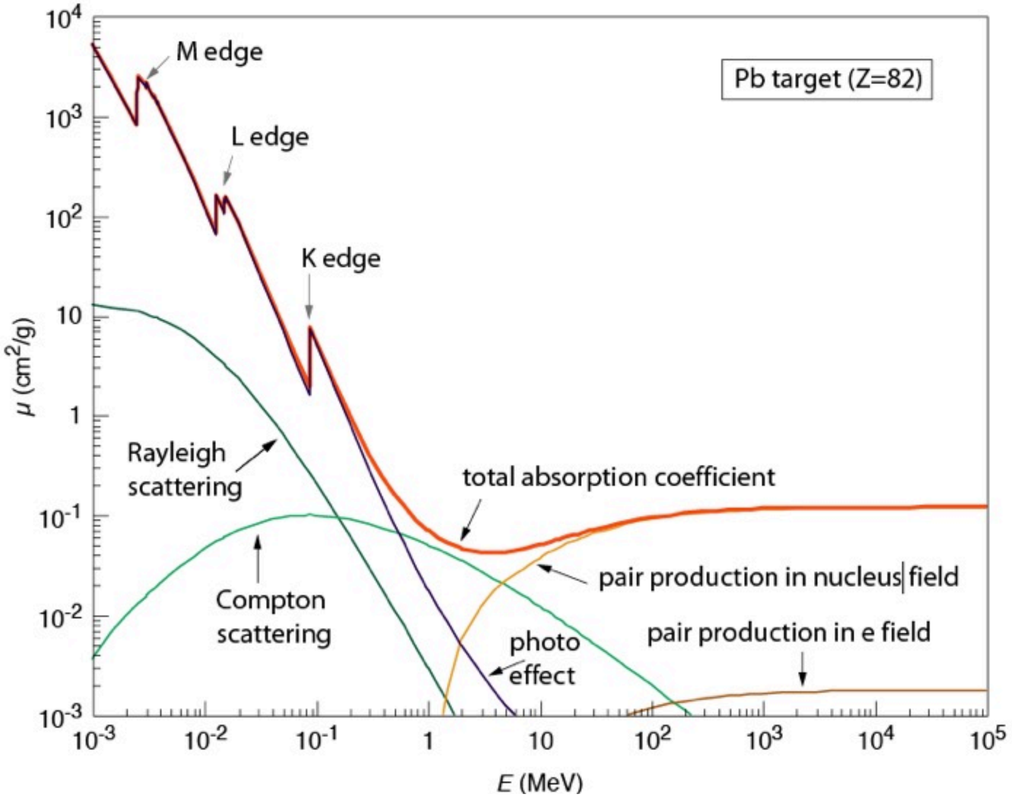
$$\boxed{\sigma_{\text{pair,nucl}} = 4\alpha r_e^2 Z^2 \left[\frac{7}{9}\ln\left(\frac{183}{Z^{1/3}}\right) - \frac{1}{54}\right] \quad \text{for} \quad \frac{E_\gamma}{m_e c^2} > \frac{1}{\alpha Z^{1/3}}}$$

- Mean free path for pair production is related to radiation length: same diagram as Bremsstrhlung

$$\rho\lambda_{\text{pair}} = \frac{A}{N_A \sigma_{\text{pair}}} \quad ; \quad \rho\lambda_{\text{pair}} = \frac{9}{7}X_0$$



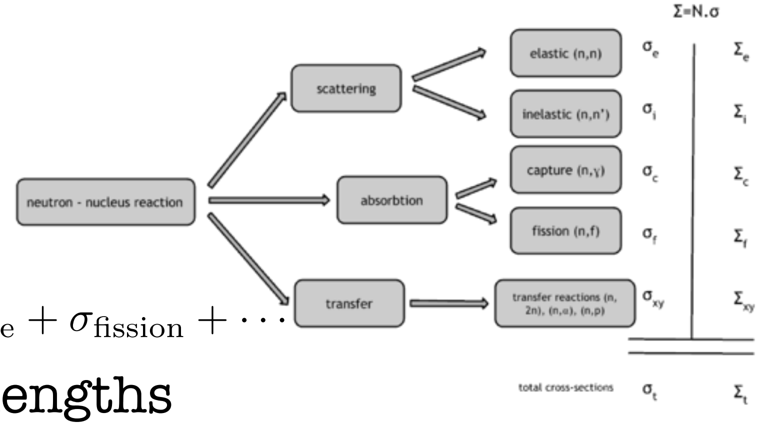
Photon absorption summary



Hadronic interactions

- Neutral hadrons (neutrons, K0) interact only hadronically with the nuclei of the materials
  - Strong interaction has a short range
  - Small probability of a reaction
  - Neutrons are very penetrating
- Many processes are possible

$$\sigma_{\text{total}} = \sum_i \sigma_i = \sigma_{\text{elastic}} + \sigma_{\text{n,inelastic}} + \sigma_{\text{capture}} + \sigma_{\text{fission}} + \cdots$$



- Define the collision and absorption lengths

$$\rho\lambda_{\text{t}} = \frac{A}{N_A \sigma_{\text{total}}} \quad ; \quad \rho\lambda_{\text{a}} = \frac{A}{N_A \sigma_{\text{inelastic}}} \quad ; \quad \sigma_{\text{total}} = \sigma_{\text{elastic}} + \sigma_{\text{inelastic}}$$

- All these process create charged particles (proton recoil, nuclear debris) that can be detected

Neutron interactions

Values for high energy neutrons (≈ 100 GeV) in various materials:

Material	σ_{tot} (barn)	$\sigma_{inelastic}$ (barn)	$\lambda_t \rho$ (g/cm^2)	$\lambda_a \rho$ (g/cm^2)	λ_t (cm)
H_2	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_2O			60.1	83.6	60.1
Polystyrol			58.5	81.9	56.7

Neutrinos

- Neutrinos interact only weakly. The cross section is extremely small.
- Typical reactions used:

$$\nu_{e,\mu,\tau} + n \to (e,\mu,\tau)^- + p \quad ; \quad \bar{\nu}_{e,\mu,\tau} + p \to (e,\mu,\tau)^+ + n$$

- For instance, the probability ε of interaction of 200 GeV neutrinos is:

1 m of iron $\varepsilon \sim 5 \cdot 10^{-17}$ 1 km of water $\varepsilon \sim 6 \cdot 10^{-15}$

- Very large detector systems or very intense neutrino fluxes are required to have a signal
  - ktons / Mtons of water, ice, liquid Argon, liquid scintillator, Fe/detector sandwich ….

Take away summary

- What happens ? Only long-lived particles are observerd
- Charged particles → ionization, Cherenkov, radiation
- Neutral particles → interact and produce charged particles
- Photon → photoelectric, Compton, pair production
- Neutron, Kaon → hadronic interactions
- Neutrinos → weak interactions

- What signal do we observe ? Charge or light

- What properties can we measure ? Momentum, Charge, Lifetime, Energy, Velocity, Mass.

End of part 01