Particle Physics Instrumentation

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The 2011 CERN – Latin-American School of High-Energy Physics Natal, Brazil, 23 March - 5 April 2011

Lecture1/3 Detector Systems, Interaction of particles with Matter

On Tools and Instrumentation

"New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson, Imagined Worlds

 \rightarrow New tools and technologies will be extremely important to go beyond LHC



Physics Nobel Prices for Instrumentation

- 1927: C.T.R. Wilson, Cloud Chamber
- **1939:** E. O. Lawrence, Cyclotron & Discoveries
- **1948:** P.M.S. Blacket, Cloud Chamber & Discoveries
- **1950:** C. Powell, Photographic Method & Discoveries
- **1954:** Walter Bothe, Coincidence method & Discoveries
- 1960: Donald Glaser, Bubble Chamber
- **1968:** L. Alvarez, Hydrogen Bubble Chamber & Discoveries
- **1992:** <u>Georges Charpak, Multi Wire Proportional Chamber</u>

The 'Real' World of Particles

E. Wigner:

"A particle is an irreducible representation of the inhomogeneous Lorentz group"

Spin=0,1/2,1,3/2 ... Mass>0

Annals of Mathematics Vol. 40, No. 1, January, 1939

ON UNITARY REPRESENTATIONS OF THE INHOMOGENEOUS LORENTZ GROUP*

BY E. WIGNER

(Received December 22, 1937)

1. Origin and Characterization of the Problem

It is perhaps the most fundamental principle of Quantum Mechanics that the system of states forms a *linear manifold*,¹ in which a unitary scalar product is defined.² The states are generally represented by wave functions³ in such a way that φ and constant multiples of φ represent the same physical state. It is possible, therefore, to normalize the wave function, i.e., to multiply it by a constant factor such that its scalar product with itself becomes 1. Then, only a constant factor of modulus 1, the so-called phase, will be left undetermined in the wave function. The linear character of the wave function is called the superposition principle. The square of the modulus of the unitary scalar product (Ψ, φ) of two normalized wave functions Ψ and φ is called the transition probability from the state Ψ into φ , or conversely. This is supposed to give the probability that an experiment performed on a system in the state φ , to see whether or not the state is Ψ , gives the result that it is Ψ . If there are two or more different experiments to decide this (e.g., essentially the same experiment,

E.g. in Steven Weinberg, The Quantum Theory of Fields, Vol1

The 'Real' World of Particles

W. Riegler:

"...a particle is an object that interacts with your detector such that you can follow it's track,

it interacts also in your readout electronics and will break it after some time,

and if you a silly enough to stand in an intense particle beam for some time you will be dead ..."





Looking at your hand by scattering light off it is the same thing as looking at the nucleons by scattering alpha particles (or electrons) off it.

Before discussing the working principles of detectors let's have a look at a few modern \rightarrow

Particle Detector Systems

The Giants at LHC



The Giants at LHC





pp Collisions







ALICE Particle ID Alice uses ~ all known techniques! π/K TPC + ITS K/p (dE/dx)*e/π* e /π π/K TOF K/p π/K **HMPID** K/p (RICH) 5 p (GeV/c) 2 0 π/K TPC (rel. rise) π /K/p K/p TRD e/π PHOS γ / π^0 100 p (GeV/c) 10

Heavy Ion Collisions, Nov. 2010



First ZZ \rightarrow 4 μ Event



[N. Pastrone, Talk at Bormio Winter Meeting, 2011]

Small is Beautiful

ALPHA



GB Andresen et al. Nature 000, 1-4 (2010) doi:10.1038/nature09610





AMANDA

Antarctic Muon And Neutrino Detector Array

AMANDA



South Pole





W. Riegler/CERN



Look for upwards going Muons from Neutrino Interactions. Cherekov Light propagating through the ice.

 \rightarrow Find neutrino point sources in the universe !





W. Riegler/CERN

AMANDA





Up to now: No significant point sources but just neutrinos from cosmic ray interactions in the atmosphere were found.

→ Ice Cube for more statistics – data taking stating May 2011 !

The Ice Cube neutrino observatory is designed so that 5,160 optical sensors view a cubic kilometer of clear South Polar ice.



CERN Neutrino Gran Sasso

(CNGS)

CNGS

If neutrinos have mass:



Muon neutrinos produced at CERN. See if tau neutrinos arrive in Italy.



CNGS Project

CNGS (CERN Neutrino Gran Sasso)

- A long base-line neutrino beam facility (732km)
- send v_{μ} beam produced at CERN
- detect v_{τ} appearance in OPERA experiment at Gran Sasso



 \rightarrow direct proof of $v_{\mu} - v_{\tau}$ oscillation (appearance experiment)





CNGS



CNGS



Radial Distribution of the v_{μ} **-Beam at GS**



Neutrinos at CNGS: Some Numbers

For 1 year of CNGS operation, we expect:

protons on target	2 x 10 ¹⁹
pions / kaons at entrance to decay tunnel	3 x 10 ¹⁹
$\mathbf{v}_{\boldsymbol{\mu}}$ in direction of Gran Sasso	10 ¹⁹
ν_{μ} in 100 m² at Gran Sasso	3 x 10 ¹⁴
ν_{μ} events per day in OPERA	≈ 2500
ν _τ events (from oscillation)	≈ 2

Basic unit: brick

56 Pb sheets + 56 photographic films (emulsion sheets)

Lead plates: massive target Emulsions: micrometric precision





^{10.2} x 12.7 x 7.5 cm³





First observation of CNGS beam neutrinos : August 18th, 2006





Scintillator planes 5900 m² 8064 7m long drift tubes





3050 m² Resistive Plate Counters 2000 tons of iron for the two magnets

The Brick Manipulator System (BMS) prototype: a lot of fun for children and adults !



Tests with the prototype wall



The robotised "Ferrari" for insertion/extraction of bricks with vacuum grip by Venturi valve



"Carousel" brick dispensing and storage system

First Tau Candidate seen!

Hypothesis:

τ (parent) → hadron (daughter) + $π_0$ (decaying instantly to $γ_1$, $γ_2$)+ $ν_τ$ (invisible)





AMS Alpha Magnetic Spectrometer

Try to find Antimatter in the primary cosmic rays. Study cosmic ray composition etc. etc.

Launch to Space Station with the last Shuttle flight scheduled for April 19, 2011 7:48 PM Eastern !

Check out the countdown: http://ams-02project.jsc.nasa.gov



Will be installed on the space station.





A state of the art particle detector with many 'earth bound' techniques going to space !






How can a particle detector distinguish the hundreds of particles that we know by now ?

htlp://pag.lbl.gov

~ 180 Selected Particles

D, W^t, Z', Q, E, M, J, Ve, Vm, Vy, TC^t, TC°, y, fo(660), g(20), w (782), y' (1558), to (380), Qo (380), \$(1020), ha (1170), ba (1235), $\alpha_1(1260), f_2(1270), f_1(1285), \gamma(1295), \pi(1300), \alpha_2(1320),$ 10 (1370), 1, (1420), w (1420), y (1440), a, (1450), g (1450), $f_{0}(1500), f_{2}'(1525), \omega(1650), \omega_{3}(1670), \pi_{2}(1670), \phi(1680),$ Q3 (1690), Q (1700), fp (1710), TC (1800), \$\$ (1850), \$\$ (2010), a4 (2040), \$4 (2050), \$2 (2300), \$2 (2340), K2, K°, KS, KL, K*(892), K, (1270), K, (1400), K* (1410), K, (1430), K, (1430), K* (1680), K, (1770), K* (1780), K, (1820), K, (2045), D* D°, D* (2007). D* (2010)^t, D, (2420)°, D, (2460)°, D, (2460)^t, D, D, (2 Ds, (2536)*, Ds, (2573)2, B*, B°, B*, B°, B*, B°, Bt, Me (15), J/4(15), $\chi_{co}(1P), \chi_{c1}(1P), \chi_{c1}(1P), \psi(2S), \psi(3770), \psi(4040), \psi(4160),$ ψ (4415), γ (15), χ_{10} (1P), χ_{10} (1P), χ_{50} (1P), γ (25), χ_{10} (2P), X12 (2P), T (35), T(45), T (10860), T (11020), D, n, N(1440), N(1520), N(1535), N(1650), N(1675), N(1680), N(1700), N(1710), $N(1720), N(2190), N(2220), N(2250), N(2600), \Delta(1232), \Delta(1600),$ A(1620), A(1700), A(1905), A(1910), A(1920), A(1930), A(1950), $A(2420), \Lambda, \Lambda(1405), \Lambda(1520), \Lambda(1600), \Lambda(1670), \Lambda(1690),$ Λ (1800) Λ (1810) Λ (1820) Λ (1830) Λ (1890) Λ (2100) Λ $\Lambda(2110), \Lambda(2350), \Sigma^{+}, \Sigma^{\circ}, \Sigma^{-}, \Sigma(1385), \Sigma(1660), \Sigma(1670),$ $\Sigma(1750), \Sigma(1775), \Sigma(1915), \Sigma(1940), \Sigma(2030), \Sigma(2250), \Xi^{\circ}, \Xi^{-},$ \equiv (1530), \equiv (1690), \equiv (1820), \equiv (1950), \equiv (2030), Ω , Ω (2250), $\Lambda_{c}^{\dagger}, \Lambda_{c}^{\dagger}, \Sigma, (2455), \Sigma_{c}(2520), \Xi_{c}^{\dagger}, \Xi_{c}^{\circ}, \Xi_{c}^{\prime}, \Xi_{c}^{\circ}, \Xi(2645)$ = (2780), = (2815), ~ ~ ~ ~ ~ ~ ~ ~ <u>L</u>, = <u>L</u>, <u>E</u>, <u>t</u>

There are Many move

W. Riegler/CERN

These are all the known 27 particles with a lifetime that is long enough such that at GeV energies they travel more than 1 micrometer.

All Povhichs with C3 > Jum @ GeV Level			19
Particle Mass (nel)Lifetimes	s) C Y	
r TT (vā, dī) 140	2.6.10-8	7.8 m	
K= (us, us) 494	1.2.10-8	3.7 m	
K° (ds, ds) 497	5.7. 10-8 8.9.10-11	15.5m 2.7 cm	
$D^{\pm}(c\bar{a},\bar{c}a)$ 1869	1.0-10-12	315 pm	
D° (cū, vē) 1864	4.1.10-13	123 pm	
$D_s^{\dagger}(c\bar{s},\bar{c}s)$ 1969	4.9.10-13	147 mm "	-
BI (w.j.j.) 5279	1.7.10-12	502 mm	Je contry
B° (60,03) 5279	1.5 - 10-12	462 um	Vention
B's (s5, 5b) 5370	1.5.10-12	438 pm	
Bt (c5, 25) ~6400	~ 5.10-13	150 pm	
p (uud) 938.3	> 1033 Y	~	
n (udd) 939,6	885.75	2.655.10	⁸ Km
N° (uds) 1115.7	2.6.10-10	7.89 cm	
$\sum^{+}(uus)$ 1189.4	8.0.10-11	2.404 cm	
Z (das) 1197.4	1.5.10-10	4.434 cm	
∃°(uss) 1315	2.9.10-10	8.71cm	
E (dss) 1321	1.6.10-10	4.91cm	
0-(00) 1629	8 2 10-11	7461	
$A^{+}(uAe) = 2285$	~ 2. 10-13	60 mm	
= + (use) 2466	4.4.10-13	132 m	
- (Acs) 2422	~1.10=43	29	
$O^{\circ}(ssc) = 2688$	6.0.10-14	19 mm	
Λ_b (uab) 5620	1.2-10-12	368pm	

W. Riegler/CERN

From the 'hundreds' of Particles listed by the PDG there are only ~27 with a life time cs >~ 1 mm i.e. they can be seen as 'tracks' in a Detector.

~ 13 of the 27 have cs < 500 pm i.e. only mm range at Gev Energies. -> "short" Ivochs measured with Emulsions or Verkx Detectors.

Fron the ~ 14 remaining porticles et, mt, y, TCt, Kt, Ko, pt, n

are by far the most frequent ones

A porticle Dekelor nux be able to identify and measure Energy and Momenta of Hese <u>8</u> porticles.

The 8 Particles a Detector must be able to Measure and Identify

 $\begin{array}{c} \mathcal{Q}^{\pm} & m_{e} = 0.511 \, MeV \\ \mu^{\pm} & m_{\mu} = 105.7 \, \Pi eV \sim 200 \, me \\ \gamma & m_{\pi} = 0, \, Q = 0 \end{array} \end{array} \\ \begin{array}{c} \mathsf{EM} \\ \mathsf{M} \\ \mathsf{M$

The Difference in Mass, Charge, Interection is the key to the Identification

The 8 Particles a Detector must be able to Measure and Identify

TRACKING

- · Electrons ionite and show Bremsstrahling due to the small mess
- · Photons don't ionise but show Peir Production in high Z Makerial. From Ken on equal to et
- · Charged Hodrons ionite and show Hadron Shower in dense holeriel.
- Neutral Hodrons don't ionize and show Hodron shower in Bense Moterial
- · Myons ionite and don't shower



CALORIMETERS

MUONS

Detector Physics

Precise knowledge of the processes leading to signals in particle detectors is necessary.

The detectors are nowadays working close to the limits of theoretically achievable measurement accuracy – even in large systems.

Due to available computing power, detectors can be simulated to within 5-10% of reality, based on the fundamental microphysics processes (atomic and nuclear crossections).

Particle Detector Simulation

Electric Fields in a Micromega Detector



Very accurate simulations of particle detectors are possible due to availability of Finite Element simulation programs and computing power.

Follow every single electron by applying first principle laws of physics.

For Gaseous Detectors: GARFIELD by R. Veenhof Electric Fields in a Micromega Detector



Electrons avalanche multiplication





Particle Detector Simulation

I) C. Moore's Law: Computing power doubles 18 months.

II) W. Riegler's Law: The use of brain for solving a problem is inversely proportional to the available computing power.

 \rightarrow I) + II) = ...



Knowing the basics of particle detectors is essential ...

Interaction of Particles with Matter

Any device that is to detect a particle must interact with it in some way \rightarrow almost ...

In many experiments neutrinos are measured by missing transverse momentum.

E.g. e^+e^- collider. $P_{tot}=0$, If the Σp_i of all collision products is $\neq 0 \rightarrow$ neutrino escaped.



Claus Grupen, Particle Detectors, Cambridge University Press, Cambridge 1996 (455 pp. ISBN 0-521-55216-8) W. Riegler/CERN

Interaction of Particles with Matter



Electromagnetic Interaction of Particles with Matter



Interaction with the atomic electrons. The incoming particle loses energy and the atoms are <u>excited</u> or <u>ionized.</u>

Interaction with the atomic nucleus. The particle is deflected (scattered) causing <u>multiple scattering</u> of the particle in the material. During this scattering a <u>Bremsstrahlung</u> photon can be emitted. In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as <u>Cherenkov Radiation</u>. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called <u>Transition radiation</u>.

While the charged particle is passing another charged particle, the Coulomb Force is acting, resulting in momentum transfer

$$F_y = \frac{Z_1 Z_2 e_0^2}{4\pi\varepsilon_0 (b^2 + v^2 t^2)} \frac{b}{\sqrt{b^2 + v^2 t^2}} \qquad \qquad \Delta p = \int_{-\infty}^{\infty} F_y(t) dt = \frac{2Z_1 Z_2 e_0^2}{4\pi\varepsilon_0 v b}$$

The relativistic form of the transverse electric field doesn't change the momentum transfer. The transverse field is stronger, but the time of action is shorter

$$F_{y} = \frac{\gamma Z_{1} Z_{2} e_{0}^{2} b}{4\pi\varepsilon_{0} (b^{2} + \gamma^{2} v^{2} t^{2})^{3/2}} \qquad \Delta p = \int_{-\infty}^{\infty} F_{y}(t) dt = \frac{2Z_{1} Z_{2} e_{0}^{2}}{4\pi\varepsilon_{0} v b}$$
The transferred energy is then
$$\Delta E = \frac{(\Delta p)^{2}}{2m} = \frac{Z_{2}^{2}}{m} \frac{2Z_{1}^{2} e_{0}^{4}}{(4\pi\varepsilon_{0})^{2} v^{2} b^{2}}$$

$$\Delta E(electrons) = Z_{2} \frac{1}{m_{e}} \frac{2Z_{1}^{2} e_{0}^{4}}{(4\pi\varepsilon_{0})^{2} v^{2} b^{2}} \qquad \Delta E(nucleus) = \frac{Z_{2}^{2}}{2Z_{2} m_{p}} \frac{2Z_{1}^{2} e_{0}^{4}}{(4\pi\varepsilon_{0})^{2} v^{2} b^{2}} \qquad \frac{\Delta E(electrons)}{\Delta E(nucleus)} = \frac{2m_{p}}{m_{e}} \approx 4000$$

\rightarrow The incoming particle transfer energy only (mostly) to the atomic electrons !

3/23/11

Ionization and Excitation

Target material: mass A, Z₂, density ρ [g/cm³], Avogadro number N_A



$$dE = -\int_{b_{min}}^{b_{max}} n_e \Delta E dx 2b\pi db = -\frac{4\pi Z_2 Z_1^2 m_e c^2 r_e^2}{\beta^2} \frac{N_A \rho}{A} \int_{b_{min}}^{b_{max}} \frac{db}{b}$$

With $\Delta E(b) \rightarrow db/b = -1/2 dE/E \rightarrow E_{max} = \Delta E(b_{min}) E_{min} = \Delta E(b_{max})$

$$\frac{dE}{dx} = -2\pi r_e^2 m_e^2 c^2 \frac{Z_1^2}{\beta^2} \frac{N_A Z_2 \rho}{A} \int_{E_{min}}^{E_{max}} \frac{dE}{E} \qquad = \qquad -2\pi r_e^2 m_e^2 c^2 \frac{Z_1^2}{\beta^2} \frac{N_A Z_2 \rho}{A} \ln \frac{E_{max}}{E_{min}} \frac{dE}{E}$$

$E_{min} \approx I$ (Ionization Energy)



$$E^{k'}_{max} = \frac{2mc^2 p^2 c^2}{(m^2 + M^2)c^4 + 2m\sqrt{p^2 c^2 + M^2 c^4}} = 2mc^2 \beta^2 \gamma^2 F \qquad F = \left(1 + \frac{2m}{M}\sqrt{1 + \beta^2 \gamma^2} + \frac{m^2}{M^2}\right)^{-1}$$

3/23/11

Classical Scattering on Free Electrons

$$\frac{1}{\rho}\frac{dE}{dx} = -2\pi r_e^2 m_e c^2 \frac{Z_1^2}{\beta^2} N_A \frac{Z}{A} \ln \frac{2m_e c^2 \beta^2 \gamma^2 F}{I}$$

This formula is up to a factor 2 and the density effect identical to the precise QM derivation \rightarrow

Bethe Bloch Formula



Bethe Bloch Formula

$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2 m_e c^2 \frac{Z_1^2}{\beta^2} N_A \frac{Z}{A} \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2 F}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

For Large $\beta\gamma$ the medium is being polarized by the strong transverse fields, which reduces the rise of the energy loss \rightarrow density effect

At large Energy Transfers (delta electrons) the liberated electrons can leave the material. In reality, E_{max} must be replaced by E_{cut} and the energy loss reaches a plateau (Fermi plateau).

Characteristics of the energy loss as a function of the particle velocity ($\beta\gamma$)

The specific Energy Loss $1/\rho dE/dx$

- first decreases as $1/\beta^2$
- increases with ln γ for β =1
- is ~ independent of M (M>> m_e)
- is proportional to Z_1^2 of the incoming particle.
- is ≈ independent of the material (Z/A ≈ const)
- shows a plateau at large βγ (>>100)
- •dE/dx \approx 1-2 x ρ [g/cm³] MeV/cm



Für Z>1, I ≈16Z ^{0.9} eV



Discovery of muon and pion



Cosmis rays: dE/dx α Z²



Bethe Bloch Formula

Bethe Bloch Formula, a few Numbers:

For Z \approx 0.5 A 1/ ρ dE/dx \approx 1.4 MeV cm ²/g for $\beta\gamma \approx$ 3

Example : Iron: Thickness = 100 cm; ρ = 7.87 g/cm³ dE ≈ 1.4 * 100* 7.87 = 1102 MeV

→ A 1 GeV Muon can traverse 1m of Iron



This number must be multiplied with ρ [g/cm³] of the Material \rightarrow dE/ dx [MeV/cm]

Energy Loss as a Function of the Momentum

Energy loss depends on the particle velocity and is ≈ independent of the particle's mass M.

The energy loss as a function of particle Momentum P= Mcβγ IS however depending on the particle's mass

By measuring the particle momentum (deflection in the magnetic field) and measurement of the energy loss on can measure the particle mass

→ Particle Identification !



$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2 m_e c^2 Z_1^2 \frac{p^2 + M^2 c^2}{p^2} N_A \frac{Z}{A} \left[\ln \frac{2m_e c^2 F}{I} \frac{p^2}{M^2 c^2} - \frac{p^2}{p^2 + M^2 c^2} \right]$$

Energy Loss as a Function of the Momentum



Measure momentum by curvature of the particle track.

Find dE/dx by measuring the deposited charge along the track.

→Particle ID

Range of Particles in Matter

Particle of mass M and kinetic Energy E₀ enters matter and looses energy until it comes to rest at distance R.





Energy Loss by Excitation and Ionization

Range of Particles in Matter

Average Range:

Towards the end of the track the energy loss is largest \rightarrow Bragg Peak \rightarrow Cancer Therapy



Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhny, Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino Fig. 2 (bottom right). Cross sections of (a) the Great Pyramid of Cheops and (b) the Pyramid of Chephren, showing the known chambers: (A) Smooth limestone cap, (B) the Belzoni Chamber, (C) Belzoni's entrance, (D) Howard-Vyse's entrance, UN descending passageway, (F) ascending passageway, (G) underground chamber, (/-1) Grand Gallery, (b) King's Chamber, (l) Queen's Chamber, (K) center line of the pyramid.

6 FEBRUARY 1970





Fig. 13. Scatter plots showing the three stages in the combined analytic and visual analysis of the data and a plot with a simulated chamber, (a) Simulated "x-ray photograph" of uncorrected data. (b) Data corrected for the geometrical acceptance of the apparatus. (c) Data corrected for pyramid structure as well as geometrical acceptance. (d) Same as (c) but with simulated chamber, as in Fig. 12.

W. Riegler, Particle Detectors Luis Alvarez used the attenuation of muons to look for chambers in the Second Giza Pyramid → Muon Tomography

He proved that there are no chambers present.



Intermezzo: Crossection

Crossection σ : Material with Atomic Mass A and density $\,\rho$ contains n Atoms/cm^3

$$n[\rm{cm}^{-3}] = \frac{N_A[\rm{mol}^{-1}]\,\rho[\rm{g/cm}^3]}{A[\rm{g/mol}]} \qquad N_A = 6.022 \times 10^{23}\,\rm{mol}^{-1}$$

E.g. Atom (Sphere) with Radius R: Atomic Crossection $\sigma = R^2 \pi$

A volume with surface F and thickness dx contains N=nFdx Atoms. The total 'surface' of atoms in this volume is N σ . The relative area is $p = N \sigma/F = N_A \rho \sigma /A dx =$ Probability that an incoming particle hits an atom in dx.



 $\circ \circ$

⊮dx

What is the probability P that a particle hits an atom between distance x and x+dx ? P = probability that the particle does NOT hit an atom in the m=x/dx material layers and that the particle DOES hit an atom in the m^{th} layer

$$P(x)dx = (1-p)^m p \approx e^{-m} p = \exp\left(-\frac{N_A\rho\sigma}{A}x\right) \frac{N_A\rho\sigma}{A}dx = \frac{1}{\lambda}\exp\left(-\frac{x}{\lambda}\right)dx \qquad \lambda = \frac{A}{N_A\rho\sigma}dx$$

Mean free path
$$= \int_0^\infty x P(x) dx = \int_0^\infty \frac{x}{\lambda} e^{-\frac{x}{\lambda}} dx = \lambda$$

Average number of collisions/cm
$$= \frac{1}{\lambda} = \frac{N_A \rho \sigma}{A}$$

Intermezzo: Differential Crossection



Differential Crossection: $\frac{d\sigma(E, E')}{dE'}$

→ Crossection for an incoming particle of energy E to lose an energy between E' and E'+dE'

Total Crossection:
$$\sigma(E) = \int \frac{d\sigma(E, E')}{dE'} dE'$$

Probability P(E) that an incoming particle of Energy E loses an energy between E' and E'+dE' in a collision:

$$P(E, E')dE' = \frac{1}{\sigma(E)} \frac{d\sigma(E, E')}{dE'} dE'$$

Average number of collisions/cm causing an energy loss between E' and E'+dE' = $\frac{N_A \rho}{A} \frac{d\sigma(E, E')}{dE'}$

Average energy loss/cm:

$$\frac{dE}{dx} = -\frac{N_A \rho}{A} \int E' \frac{d\sigma(E, E')}{dE'} dE'$$

3/23/11

W. Riegler, Particle Detectors

Fluctuation of Energy Loss

Up to now we have calculated the average energy loss. The energy loss is however a statistical process and will therefore fluctuate from event to event.



 $P(\Delta)$ = ? Probability that a particle loses an energy Δ when traversing a material of thickness D

We have see earlier that the probability of an interaction ocuring between distance x and x+dx is exponentially distributed

$$P(x)dx = \frac{1}{\lambda}\exp\left(-\frac{x}{\lambda}\right)dx \qquad \lambda = \frac{A}{N_A\rho\sigma}$$

Probability for n Interactions in D

We first calculate the probability to find n interactions in D, knowing that the probability to find a distance x between two interactions is $P(x)dx = 1/\lambda \exp(-x/\lambda) dx$ with $\lambda = A/N_A \rho \sigma$

Probability to have no interaction between 0 und D:

$$P(x > D) = \int_D^\infty P(x_1) dx_1 = e^{-\frac{D}{\lambda}}$$

Probability to have one interaction at x_1 and no other interaction:

$$P(x_1, x_2 > D) = \int_D^\infty P(x_1) P(x_2 - x_1) dx_2 = \frac{1}{\lambda} e^{-\frac{D}{\lambda}}$$

Probability to have one interaction independently of x_1 :

$$\int_0^D P(x_1, x_2 > D) = \frac{D}{\lambda} e^{-\frac{D}{\lambda}}$$

Probability to have the first interaction at x_1 , the second at x_2 the $n^{th} \in x_n$ and no other interaction:

$$P(x_1, x_2...x_n > D) = \int_D^\infty P(x_1)P(x_2 - x_1)...P(x_n - x_{n-1})dx_n = \frac{1}{\lambda^n}e^{-\frac{D}{\lambda}}$$

Probability for *n* interactions independently of $x_1, x_2...x_n$

$$\int_{0}^{D} \int_{0}^{x_{n-1}} \int_{0}^{x_{n-1}} \dots \int_{0}^{x_{1}} P(x_{1}, x_{2}..., x_{n} > D) dx_{1}...dx_{n-1} = \frac{1}{n!} \left(\frac{D}{\lambda}\right)^{n} e^{-\frac{D}{\lambda}}$$

Probability for n Interactions in D

For an interaction with a mean free path of λ , the probability for n interactions on a distance D is given by

$$P(n) = \frac{1}{n!} \left(\frac{D}{\lambda}\right)^n e^{-\frac{D}{\lambda}} = \frac{\overline{n}^n}{n!} e^{-\overline{n}} \qquad \overline{n} = \frac{D}{\lambda} \qquad \lambda = \frac{A}{N_A \rho \sigma}$$

 \rightarrow Poisson Distribution !

If the distance between interactions is exponentially distributed with an mean free path of $\lambda \rightarrow$ the number of interactions on a distance D is Poisson distributed with an average of $\bar{n}=D/\lambda$.

How do we find the energy loss distribution ?

If f(E) is the probability to lose the energy E' in an interaction, the probability p(E) to lose an energy E over the distance D ?

$$\begin{split} f(E) &= \frac{1}{\sigma} \frac{d\sigma}{dE} \\ p(E) &= P(1)f(E) + P(2) \int_0^E f(E-E')f(E')dE' + P(3) \int_0^E \int_0^{E'} f(E-E'-E'')f(E'')f(E')dE''dE' + \dots \\ F(s) &= \mathcal{L}\left[f(E)\right] = \int_0^\infty f(E)e^{-sE}dE \\ \mathcal{L}\left[p(E)\right] &= P(1)F(s) + P(2)F(s)^2 + P(3)F(s)^3 + \dots \\ &= \sum_{n=1}^\infty P(n)F(s)^n = \sum_{n=1}^\infty \frac{\overline{n}^n F^n}{n!} e^{-\overline{n}} = e^{\overline{n}(F(s)-1)} - 1 \approx e^{\overline{n}(F(s)-1)} \\ p(E) &= \mathcal{L}^{-1}\left[e^{\overline{n}(F(s)-1)}\right] = \frac{1}{2\pi i} \int_{\sigma-i\infty}^{\sigma+i\infty} e^{\overline{n}(F(s)-1)+sE} ds \end{split}$$

Fluctuations of the Energy Loss

Probability f(E) for loosing energy between E' and E'+dE' in a single interaction is given by the differential crossection $d\sigma$ (E,E')/dE'/ σ (E) which is given by the Rutherford crossection at large energy transfers



Excitation and ionization

Scattering on free electrons



Landau Distribution

Landau Distribution

 $P(\Delta)$: Probability for energy loss Δ in matter of thickness D.

Landau distribution is very asymmetric.

Average and most probable energy loss must be distinguished !

Measured Energy Loss is usually smaller that the real energy loss:

3 GeV Pion: $E'_{max} = 450 \text{MeV} \rightarrow \text{A}$ 450 MeV Electron usually leaves the detector.



Landau Distribution



LANDAU DISTRIBUTION OF ENERGY LOSS:

PARTICLE IDENTIFICATION Requires statistical analysis of hundreds of samples

Particle Identification



Rigidity



Bremsstrahlung

A charged particle of mass M and charge $q=Z_1e$ is deflected by a nucleus of charge Ze which is partially 'shielded' by the electrons. During this deflection the charge is 'accelerated' and it therefore radiated \rightarrow Bremsstrahlung.



Bremsstrahlung, Classical

$$\frac{de'}{d_{A}c_{A}} = \left(\frac{22_{1}z_{2}}{4\pi\epsilon_{o}}\frac{e^{2}}{p^{-t_{a}}}\right)^{2} \frac{1}{(2\sin\theta)^{u}} \quad p = M_{0}p$$

$$\stackrel{H}{=} R_{U}k_{0}ford \quad Scattering$$

$$Written in Terns of Horechen Transfer \quad Q^{2}\cdot 2p^{2}(1-c_{0}\theta)$$

$$\frac{de'}{dQ} = 8\pi \left(\frac{3_{1}z_{2}}{4\pi\epsilon_{o}}\frac{e^{2}}{p^{2}}\right)^{2} \cdot \frac{1}{Q^{2}}$$

$$\stackrel{P}{=} \sum_{m} \left(\frac{3_{1}z_{2}}{2}\frac{e^{2}}{p^{2}}\right)^{2} \cdot \frac{1}{Q^{2}}$$

$$\frac{dE}{Qx} = \frac{N_{A}}{A} \cdot \frac{16}{3} d \cdot \frac{2}{2} \cdot \left(\frac{2\pi^{2}e^{2}}{4\pi\epsilon_{o}}\frac{1}{m\epsilon_{o}}\right)^{2} \cdot \frac{1}{E} \cdot \ln \frac{Q_{nev}}{Q_{nin}}$$

$$\frac{dE}{dx} = \frac{N_{A}}{A} \cdot \frac{16}{3} d \cdot \frac{2}{2} \cdot \left(\frac{2\pi^{2}e^{2}}{4\pi\epsilon_{o}}\frac{1}{m\epsilon_{o}}\right)^{2} \cdot \frac{1}{E} \cdot \ln \frac{Q_{nev}}{Q_{nin}}$$

$$\frac{dE}{dx} = \frac{N_{A}}{4\pi\epsilon_{o}}\frac{16}{3} d \cdot \frac{2}{2} \cdot \left(\frac{2\pi^{2}e^{2}}{4\pi\epsilon_{o}}\frac{1}{m\epsilon_{o}}\right)^{2} \cdot \frac{1}{E} \cdot \ln \frac{Q_{nev}}{Q_{nin}}$$

A charged particle of mass M and charge $q=Z_1e$ is deflected by a nucleus of Charge Ze.

Because of the acceleration the particle radiated EM waves \rightarrow energy loss.

Coulomb-Scattering (Rutherford Scattering) describes the deflection of the particle.

Maxwell's Equations describe the radiated energy for a given momentum transfer.

 \rightarrow dE/dx

Bremsstrahlung, QM



Proportional to Z²/A of the Material.

Proportional to Z₁⁴ of the incoming particle.

Proportional to ρ of the material.

Proportional 1/M² of the incoming particle.

Proportional to the Energy of the Incoming particle \rightarrow

E(x)=Exp(-x/X₀) – 'Radiation Length'

 $X_0 \propto M^2 A / (\rho Z_1^4 Z^2)$

 X_0 : Distance where the Energy E_0 of the incoming particle decreases $E_0Exp(-1)=0.37E_0$.

Critical Energy

such as copper to about 1% accuracy for energies between about 6 MeV and 6 GeV



For the muon, the second lightest particle after the electron, the critical energy is at 400GeV.

The EM Bremsstrahlung is therefore only relevant for electrons at energies of past and present detectors.

Critical Energy: If dE/dx (Ionization) = dE/dx (Bremsstrahlung)

Myon in Copper: p ≈ 400GeV Electron in Copper: p ≈ 20MeV
Pair Production, QM



For $E_{\gamma} >> m_e c^2 = 0.5 MeV$: $\lambda = 9/7X_0$

Average distance a high energy photon has to travel before it converts into an $e^+ e^-$ pair is equal to 9/7 of the distance that a high energy electron has to travel before reducing it's energy from E₀ to E₀*Exp(-1) by photon radiation.



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Bremsstrahlung + Pair Production → EM Shower



Statistical (quite complex) analysis of multiple collisions gives:

Probability that a particle is defected by an angle θ after travelling a distance x in the material is given by a Gaussian distribution with sigma of:

$$\Theta_0 = \frac{0.0136}{\beta cp [\text{GeV/c}]} Z_1 \sqrt{\frac{x}{X_0}}$$

- X₀... Radiation length of the material
- Z₁... Charge of the particle
- p... Momentum of the particle



Magnetic Spectrometer: A charged particle describes a circle in a magnetic field:

$$\vec{B} \otimes L = R \cdot \Theta$$

$$L = R \cdot \Theta$$

$$S = R(1 - \cos \frac{R}{2}) \sim R \frac{\Theta^2}{8} = \frac{L^2}{8R} \rightarrow R = \frac{L^2}{8S}$$

$$\Delta p = 0.3 \text{ B } \Delta R = 0.3 \text{ B } \frac{L^2}{8s^2} \Delta S$$

$$\Delta s = \frac{G^2}{1N^2} \quad G_{\pi} = \frac{\rho \cdot h}{\sqrt{N^2}} \cdot \frac{3.3 \cdot 8 \text{ p} [\frac{G \cdot V}{2}]}{\text{B}[T] \cdot L^2 [m^2]}$$

$$E \cdot g: p = 10 \quad \frac{G \cdot V}{2}, \quad B = 1T, \ L = 1n, \ G' = 200 \text{ pm}, \ N = 25$$

Limit → Multiple Scattering

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ATLAS Muon Spectrometer: N=3, sig=50um, P=1TeV, L=5m, B=0.4T

 $\Delta p/p \sim 8\%$ for the most energetic muons at LHC



Cherenkov Radiation

If we describe the passage of a charged particle through material of dielectric permittivity is (using Maxwell's equations) the differential energy crossection is >0 if the velocity of the particle is larger than the velocity of light in the medium is

$$\frac{d\sigma}{dE} = \frac{\alpha}{\beta^2 \pi} \frac{A}{N_A \rho Z_2 \hbar c} \left(\beta^2 - \frac{1}{\epsilon_1} \right) \quad \rightarrow \quad \frac{N_A \rho Z_2}{A} \frac{d\sigma}{d\omega} \frac{d\omega}{dE} = \frac{\alpha}{c} \left(1 - \frac{1}{\beta^2 n^2} \right) \qquad n = \sqrt{\epsilon_1} \qquad E = \hbar \omega$$

$$\frac{dE}{dx d\omega} \frac{1}{\hbar} = \frac{\alpha}{c} \left(1 - \frac{1}{\beta^2 n^2} \right) \qquad \rightarrow \qquad \frac{dN}{dx d\lambda} = \frac{2\pi \alpha}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2} \right) \qquad \omega = \frac{2\pi c}{\lambda}$$

N is the number of Cherenkov Photons emitted per cm of material. The expression is in addition proportional to Z_1^2 of the incoming particle. The radiation is emitted at the characteristic angle \mathbb{W}_c , that is related to the refractive index n and the particle velocity by



Cherenkov Radiation



If the velocity of a charged particle is larger than the velocity of light in the netion $t > \frac{\pi}{n}$ (n... Representive Index of Natural) if emits 'Grenkor' radiation at a characteristic angle of $\cos \theta_{c} = \frac{\pi}{N/3}$ ($B = \frac{\pi}{c}$) $\frac{dN}{dx} \sim 2\pi d Z_{n}^{2} (1 - \frac{\pi}{D^{2}n^{2}}) \frac{\lambda_{2} - \lambda_{n}}{\lambda_{3} \cdot \lambda_{n}}$ = Number of emitted Pholons / large with λ between λ_{n} and λ With $\lambda_{n} - 400 \text{ nm}$ $\lambda_{n} = 700 \text{ nm}$ $\frac{dN}{dx} = 430 (1 - \frac{\pi}{D^{2}n^{2}}) [\frac{1}{cm}]$

Maleriel	n-1	13 thromold	7 threshold
solid Sodium	3.22	0.24	1.029
lead gloss	0.67	0.60	1.25
water	0.33	0.75	1.52
silica aerogel	0.025-0.075	0.93-0.976	2.7 - 4.6
air	2.93-10-4	0.9957	41.2
He	3.3.10-5	0.99997	123

Ring Imaging Cherenkov Detector (RICH)

25

20

15 F

10



	n	θ_{max} (deg.)	$N_{ph} (eV^{-1} cm^{-1})$
air*	1.000283	1.36	0.208
isobutane*	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4



There are only 'a few' photons per event \rightarrow one needs highly sensitive photon detectors to measure the rings!



Transition Radiation



When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called <u>Transition radiation</u>.

Transition Radiation

Radiation (~ keV) enitted by ultra - relativistic Porticles when they traverse the boarder of 2 noteriols of different Dielectric Permittivity (En, Ez) Vecuum En En Ho q -q (nirror Chorge) Mesium Clamical Picture 9= Z1e I = 3 d Zn (hwp) p Radield Evergy por Travilian thep plane Frequery of Ke Medium ~ 20 eV for Styrene About holf the Elevary is voliced between 0.1 theop < two theop E.g. p=1000 2-20 keV X-Rays $N_{\gamma} \sim \frac{2}{3} \checkmark Z_{1}^{2} \sim 5 \cdot 10^{-3} \cdot Z_{1}^{2}$ n- Dependera from hardening roker than Nn

Emission Angle ~ 7

The Number of Photons can be increased by placing many fails of Polerial.



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Electromagnetic Interaction of Particles with Matter

Ionization and Excitation:

Charged particles traversing material are exciting and ionizing the atoms.

The average energy loss of the incoming particle by this process is to a good approximation described by the Bethe Bloch formula.

The energy loss fluctuation is well approximated by the Landau distribution.

Multiple Scattering and Bremsstrahlung:

The incoming particles are scattering off the atomic nuclei which are partially shielded by the atomic electrons.

Measuring the particle momentum by deflection of the particle trajectory in the magnetic field, this scattering imposes a lower limit on the momentum resolution of the spectrometer.

The deflection of the particle on the nucleus results in an acceleration that causes emission of Bremsstrahlungs-Photons. These photons in turn produced e+e- pairs in the vicinity of the nucleus, which causes an EM cascade. This effect depends on the 2nd power of the particle mass, so it is only relevant for electrons.

Electromagnetic Interaction of Particles with Matter

Cherenkov Radiation:

If a particle propagates in a material with a velocity larger than the speed of light in this material, Cherenkov radiation is emitted at a characteristic angle that depends on the particle velocity and the refractive index of the material.

Transition Radiation:

If a charged particle is crossing the boundary between two materials of different dielectric permittivity, there is a certain probability for emission of an X-ray photon.

 \rightarrow The strong interaction of an incoming particle with matter is a process which is important for Hadron calorimetry and will be discussed later.

Electromagnetic Interaction of Particles with Matter



Now that we know all the Interactions we can talk about Detectors !

Interaction with the atomic electrons. The incoming particle loses energy and the atoms are <u>excited</u> or <u>ionized</u>.

3/23/11

Interaction with the atomic nucleus. The particle is deflected (scattered) causing <u>multiple scattering</u> of the particle in the material. During this scattering a <u>Bremsstrahlung</u> photon can be emitted. In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as <u>Cherenkov Radiation</u>. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called <u>Transition radiation</u>.

Now that we know all the Interactions we can talk about Detectors !

