Physics of Particle Detectors

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Exercise 1: Interaction of radiation with matter

1) Explain the characteristic features of the Bethe-Bloch equation (BB). For which value of $\beta\gamma$ does the BB equation have a minimum? How is a particle with this specific $\beta\gamma$ called? What is the typical value of dE/dx at the minimum? Does BB rule X-ray interactions?

2) Where is the minimum of dE/dx in terms of momentum p for muons (m_μ=105.7 MeV), pions (m_π=140 MeV), kaons (m_K=494 MeV) and protons (m_p=938 MeV)?

3) Calculate the energy loss of a minimum ionizing particle (MIP) in silicon and argon.

Note: $\rho(Si) = 2.329\ g/cm^3$; $\rho(Ar) = 0.001662\ g/cm^3$

4) Typically a silicon sensor on a hybrid pixel detector is 300 μm thick and a drift chamber about 1 m long. How much energy is deposited in each detector, if a minimum ionizing particle traverses it perpendicularly?

5) The energy needed to form an electron-hole (electron-ion) pair by ionization is called w-value. The w-value for silicon is 3.6 eV and for argon is 26 eV. Determine the number of electron-hole (electron-ion) pairs created in the previously mentioned silicon detector and drift chamber by a MIP.

6) The radiation length is commonly used to determine the amount of material traversed by particles in a detector, i.e. its *thickness*. The detector thickness expressed in units of X_0 is called the material budget. Calculate the material budget of a 300 μm thick silicon detector and of a 1 m thick drift chamber filled with argon.

Note: $X_0(Si) = 21.82\ g/cm^2$, $\rho = 2.329\ g/cm^3$; $X_0(Ar) = 19.55\ g/cm^2$, $\rho = 0.001662\ g/cm^3$

7) How many electron-hole pairs are created by a MIP traversing perpendicularly a fully depleted 300 μm thick silicon detector? Choose either:

(a) Approximately 31000 electrons
(b) Approximately 31000 electrons if the MIP is a proton and 10% higher if the particle is an electron, due to the relativistic rise
(c) Depends on the pixel pitch as p/$\sqrt{12}$

Exercise 2: Particle identification

1) What is the opening angle of Cherenkov light for a particle with velocity v , if the speed of

light in that medium is v_{light}?

2) A Cherenkov detector filled with Freon114 (n=1.0014) is used for charged pion detection (m_π=139 MeV):

2.1) Calculate the pion threshold energy

2.2) Calculate the angle of the Cherenkov light emitted by pions with a total energy of 5 GeV

3) A Cherenkov detector is under construction for a particle physics experiment where charged pions, charged kaons and protons are created with the same total energy of 1 GeV. Two Cherenkov materials are available in the storage of the laboratory: perfluorobutane (n(C_4F_{10})=1.00153) and water (n(H_2O)=1.33).

3.1) Which material should be used to detect charged pions (m_π=139 MeV) and why?

3.2) Can charged kaons (m_K=494 MeV) and protons (m_p=938 MeV) with total energies of 1 GeV also be detected with this same material?

Exercise 3: Electromagnetic calorimeters

1) Explain the terms 'radiation length' X_0, 'critical energy' E_c and 'Moliere radius' R_M

2) How does an electromagnetic (EM) shower evolve as a function of the penetration depth in a homogeneous EM calorimeter (see figure below)? What is the difference between an incoming photon and an incoming electron/positron? When does the shower end?

3) In the following some important quantities are derived, using the simplified shower model shown in the figure. Assume that in every branching two particles with equal energies are produced.

3.1) What is the number of particles $N(t)$ as a function of the penetration length t (measured in units of the radiation length $t = x/X_0$)?

3.2) What is the average energy of a particle (electron or positron or photon) E_i(t) as a function of the penetration length t? Note that: $\sum_i E_i(t) = E_0$

3.3) What is the maximum length t_{max} of an EM shower? How does t_{max} depend on the energy of the incoming particle E_0?

4) Electrons with an energy of 1600 MeV penetrate a lead-fluoride calorimeter ($X_0 = 0.93\ cm$, $E_c = 9.04\ MeV$):

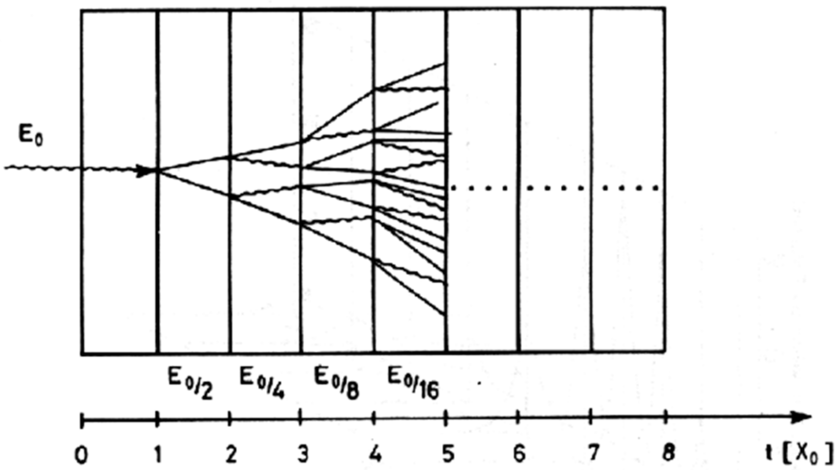
4.1) Using the simplified shower model just discussed, what is the number of shower particles at a depth of 3.72 cm?

4.2) What is the average photon energy at this depth?

4.3) Calculate the depth (in cm) where the shower maximum is reached (assume the volume to be sufficiently large to contain the shower).

5) Now consider a 'sampling calorimeter'. What is different with respect to the homogeneous calorimeter? Does the energy resolution change?

6) What is the difference for hadronic showers instead?



Exercise 4: The ATLAS detector

1) The ATLAS detector is a typical example of detector for collider experiments in HEP. Looking at the figure below, discus what sub-detectors it is made of, what the task of the different sub-detectors is and how different particles are 'seen' in the detector.

2) Explain in your own words how muons are identified in ATLAS. Which role play the calorimeters? How are muons distinguished from charged pions?

3) What possible reasons are there why a single particle traversing a pixel silicon detector creates signals on more than one pixel? Name at least two reasons.

4) How do you think you could improve the performance of this detector?