Chapter 1

Detectors for Particle Physics

1.1 Recap: interaction of particles with matter

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The way we identify particles is through their interaction with matter. So, we can detect:

- Charged particles based on ionization, breamsstrahlung, Cherenkov effect.
- γ-rays based on photoelectric/Compton effect and pair production.
- Neutrons based on strong interaction.
- Neutrinos based on weak interaction.

We will give only a phenomenological treatment since the goal is to be able to understand the implications for detector design.

1.1.1 Interactions involving the electrons and heavier particles

Interaction through ionization

A relativistic charged particle with a mass much greater that the mass of the electron, when passing through the matter, is subject to a loss of energy due to the interaction with atomic electrons. These ones can be substracted from the atom and then can be detected. From the total charge collected by the electrodes of a detector, it is possible to know the original interacting particle. The equation that describes this interaction and the loss of energy is the **Bethe-Bloch Equation** (in natural units):

$$-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = K\rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\frac{1}{2}\log\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} - \frac{C}{z}\right] \tag{1.1}$$

where the meaning of the various symbols is given in Table 1.1. A plot showing the stopping power in function of the factor $\beta\gamma$ is given in Figure 1.1. In particular, from this plot we can see some interesting characteristics of the energy loss process. In the first part, the particle loses more energy when the its velocity is slower, so the trend is $\sim \frac{1}{\beta^2}$. When the energy increases, a minimum is met, whose x-axis value is approximately the same for every material. The right part of the plot with respect to this minimum shows a gain in the energy loss which is due to relativistic effects.

Breamsstrahlung energy loss

The Bethe-Bloch formula is valid for particles much heavier than the electron. For this kind of particles, we have that relativistic effects even at low energies, since its mass is lower in comparison with the other particles. So, the electron loses energy through ionization (at lower energies) and **breamsstrahlung**, namely *braking radiation*, when deflected by another charged particle (at higher energies). The different materials that the electron can pass through, are characterized by their **radiation length** X_0,

Symbol	**Physical meaning**
K	Constant [0.307075 $\mathrm{MeVg^{-1}cm^2}$]
ρ	Density of the absorber
Z	Atomic number of absorber
A	Atomic mass of absorber
z	Atomic number of incident particle
β	Particle velocity in units of c
γ	Relativistic factor derived from β
T_{max}	Maximum energy transfer in a single collision
I	Ionization potential of the absorber

Table 1.1: Bethe-Bloch formula: meaning of all the symbols figuring in its expression.

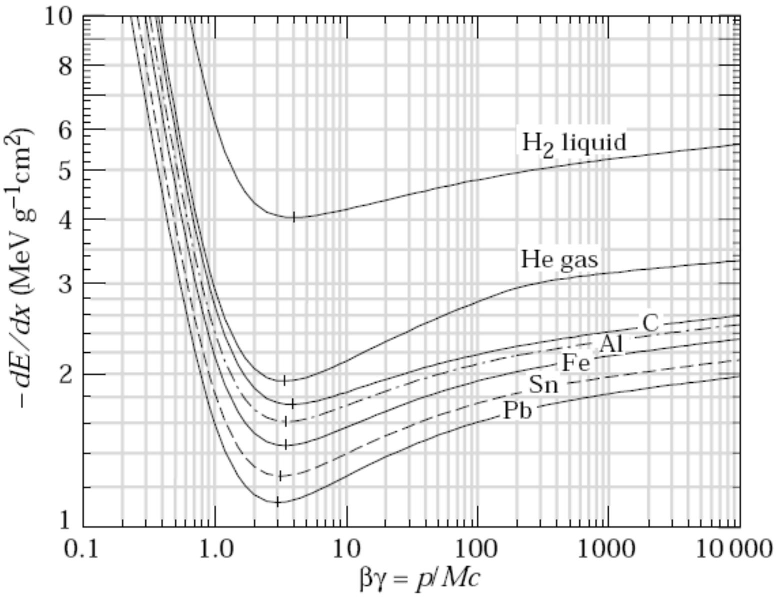

Figure 1.1: Few examples for different materials of Bethe-Bloch formula.

which is a quantity empirically defined as the distance covered by an electron beam before its energy decreases by a factor $\frac{1}{e}$ (63%.). It is measured in g/cm^2 and an approximation of its expression is:

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \log \frac{183}{Z^{\frac{1}{3}}}} \tag{1.2}$$

After the passage of one X_0, electron has lost all but $(1/e)^{\mathrm{th}}$ of its energy, namely 63%.
The critical energy E_C is the energy for which:

$$\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{ion}} = \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{rad}} \tag{1.3}$$

An approximation is:

$$E_C \approx \frac{600\ \mathrm{MeV}}{Z} \tag{1.4}$$

1.1.2 Total energy loss for electrons

Ionization losses decrease logarithmically with E and increase linearly with Z. Bremsstrahlung increases approximately linearly with E and is the dominant process at high energies.

1.1.3 Interaction of photon with the matter

Photon lose energy by:

- Photoelectric effect on atoms at low energy.
- Compton effect important at intermediate range.
- Pair production.

In our case pair production is dominant:

$$\sigma_{\text{pair}} = \frac{7}{9}\frac{N_A}{A}\frac{1}{X_0} \tag{1.5}$$

1.2 Detectors: gaseous, scintillators and

1.2.1 Ionization in gas detectors

Primary ionization:

$$\text{Particle} + X \longrightarrow X^+ + e^- + \text{Particle} \tag{1.6}$$

Secondary ionization:

$$X + e^- \longrightarrow X^+ + e^- + e^- \tag{1.7}$$

The relevant parameters to evaluate the number of particles produced are the ionization energy E_i, the average energy/ion pair W_i and the average number of ion pairs (per cm) n_T. In particular:

$$\langle n_T \rangle = \frac{L \left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle}{W_i} \tag{1.8}$$

with L the thickness of the material. Typical values for E_i are
Concerning the diffusion, it is significantly modified by the presence of a magnetic field, with transverse and longitudinal orientation depending on it. By measuring the bending of the particle, we are able to infer the momentum of the particle itself. The electric field influences only the longitudinal diffusion and not the transverse diffusion.
The electrons can undergo to a multiplication process called townsend avalanche. Given the number of electrons at the position x, $n(x) = n_0 e^{\alpha x}$, we have the gain:

$$G = \frac{n(x)}{n_0} = e^{\alpha x} \tag{1.9}$$

where α can depend on x.
There are four regions of work:

- Geiger-Muller coun

1.2.2 Multiwire proportional chambers

Signal generations: electron drift to closest wire, gas amplification near wire that creates avalanche

1.2.3 Drift chambers

In this case we can have two dimensional informations through time measurments, namely drift time measurement. It starts by an external detector such as a scintillator counter. Electrons drift to the anode in the field created by anode and cathode. The electron arrival at the anode stops in the time measurement.

$$x = \int_0^{t_D} v_D \mathrm{d}t \tag{1.10}$$

We build the detector with a known drift velocity. We can introduce field wires

1.2.4 Semiconductor detectors

Semiconductor detectors have the following characteristics:

- High density (respect to gas detectors), so large energy loss in a short distance
- A small diffusion effect, so position resolution of less than 10 μm
- Low ionization energy, so it is easier to produce particles.

The materials employed for their construction are:

- Germanium, which needs to be operated at a very low temperature (77 K) due to small band gap.
- Silicon, which can operate at room temperature.
- Diamond, resistent to very hard radiations, low signal and high cost.

Silicon detectors are based on a p-n junction with reverse bias applied to enlarge the depletion region. The potential barrier becomes higher so that the diffusion across the junction is suppressed and the current across the junction is very small ("leakage current").
Such a detector can be built in strips. By segmenting the implant we can reconstruct the position of hte transversing particle in one dimension. We have a higher field close to the collecting electrodes where most of the signal is induced. Strips can be read with dedicated electronics to minimize the noise. To have 2-dimensional measurements, double sided silicon detector are used. A type of silicon detector still in development is the pixel detector (for 3-dimensional measurements).
Noise contributions can be leakage current and electronics readout.
Position resolution is the spread of the reconstructed position minus the true position. For example:

$$\sigma = \frac{\text{pitch}}{\sqrt{12}} \qquad \text{One strip cluster} \tag{1.11}$$

$$\sigma = \frac{\text{pitch}}{1.5\frac{S}{N}} \qquad \text{Two strip cluster} \tag{1.12}$$

1.3 Track reconstruction

Track reconstruction is used to determine momentum of charged particles by measuring the bending of a particle trajectory in a magnetic field