Chapter 10

Interaction of Particles with Matter

A scattering process at an experimental particle physics facility is called an *event*. Stable particles emerging from an event are identified and their momenta measured by their interactions in the material media of a suitably constructed detector.[1] Unstable particles are identified by adding the 4-momenta of their daughters, if they can be isolated with sufficient confidence. Particle identification can be either a unique assignment, or a broader classification. In this chapter we shall discuss some fundamental characteristics of how different kinds of particles interact with different kinds of material. In the next chapter we will see how this knowledge is utilized to design detectors.

Electromagnetic interactions are most heavily relied upon for particle detection. A charged particles loses energy as it tries to make its way through a material medium. Several phenomena contribute to this process, and their relative importance depends on the properties of the particle and of the medium. For energies of interest to us, the most important phenomenon, for any charged particle other than electrons, is ionization. In addition to ionization, electrons also lose a significant fraction of their energies by photon emission (a.k.a *bremsstrahlung*). Being electrically neutral, photons do not cause ionization, but at high energies, they transfer their energy to a medium by such electromagnetic interactions as the photoelectric effect, Compton scattering, and production of electron-positron pairs. Another important process is the Coulomb scattering of a charged particle with atomic nuclei, which is responsible for *multiple scattering*. We will discuss these first.

There are other electromagnetic processes that are used in particle identification, but less generally. These include scintillation, Cerenkov radiation, and transition radiation. These will be discussed separately along with some special

[1] Here "stable" is defined by the time it takes for a high-energy particle (K.E.$>\sim$1 GeV) to traverse distances comparable to the dimensions of the detector. Therefore, a high-energy muon is a stable particle for our purpose.

applications of the general effects mentioned above. Strong and weak nuclear interactions of particles in matter will be discussed in subsequent sections.

10.1 Electromagnetic Interaction of Particles with Matter

A rigorous treatment of electromagnetic interactions based on QED has been done to a good extent. For subtle effects, empirical parametrizations of extensive data give reasonably good basis for interpolation. Details of these procedures are beyond our scope. We will only summarize the key results.

10.1.1 Energy Loss by Ionization

The form of the rate of energy loss by ionization can be seen from a semi-classical argument. The mean rate of energy loss, or *stopping power*, of moderately relativistic charged particles other than electron by ionization and atomic excitation of a material medium is given by the Bethe-Bloch equation, which follows from a quantum treatment of energy loss based on a first-order Born approximation, with some reasonable simplifying assumptions:

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left(\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right). \tag{10.1}$$

(see "Passage of particle through matter" in `http://pdg.lbl.gov` for definitions of various terms). The first two terms in the parentheses depend on the particle velocity β, while the last one reflects a modest *density effect*.

The Bethe-Bloch formula is a good approximation (accurate to $\sim$1%) for particles with $\beta\gamma = \dfrac{p}{Mc}$ in the range of about 0.05 to 500. At lower energies various corrections need to be taken into account, while at higher energies radiative losses dominate. The effect of the sign of the particle's charge, known as the "Barkas effect" begins to enter the picture only near the lower boundary of the Bethe-Bloch region.[2] Except in hydrogen, particles of the the same velocity have similar rates of energy loss in different materials, decreasing at a slow rate with increasing Z. The stopping power functions are characterized by broad minima whose position drops from $\beta\gamma = 3.5$ to 3.0 as Z goes from 7 to 100. In practical cases, most relativistic particles (e.g. cosmic-ray muons) have mean energy loss rates close to the minimum, and are said to be minimum ionizing particles, or MIP's.

Equation 10.1 can be integrated to find the total (or partial) "continuous slowing-down approximation" (CSDA) range R for a particle which loses energy only through ionization and atomic excitation. Since for a given medium, $\frac{dE}{dx}$ depends only on β, R/M is a function of E/M or pc/M in the Bethe-Bloch region

[2] In principle, one might expect some particle-antiparticle asymmetry, since the detector is made entirely of matter, with no trace of antimatter.

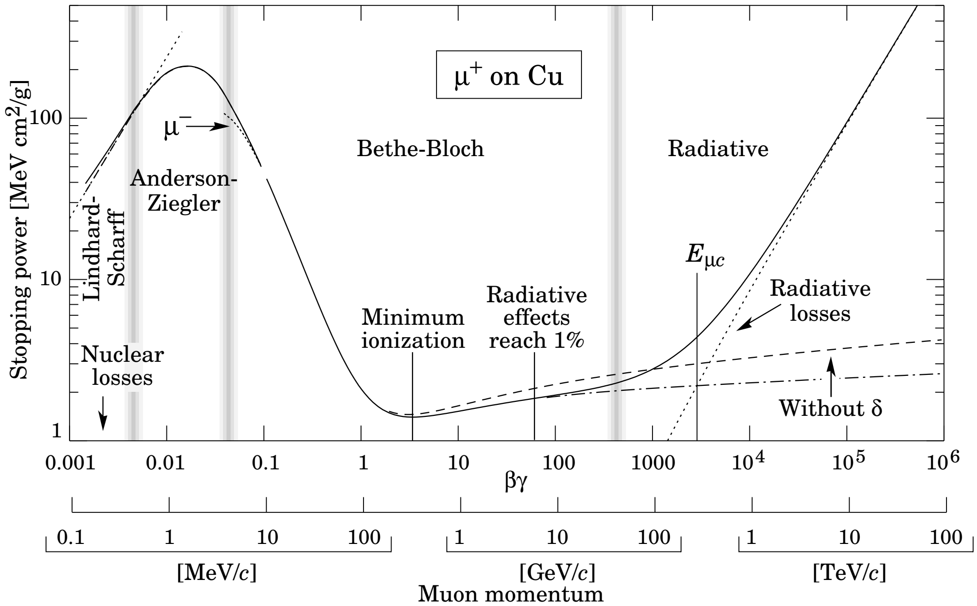

Figure 10.1: Stopping power ($= \langle -dE/dx \rangle$) for μ^+'s in Cu as a function of $\beta\gamma = p/Mc$ ove 9 orders of magnitude in momentum (12 orders in KE). Solid curves indicate the total stopping power. Vertical bands indicate boundaries between different approximations.

In practice, range is a useful concept only for low-energy hadrons, for which it is typically less than the *interaction length* (defined as the length through which the probability of the hadron not participating in a strong nuclear interaction drops by a factor of e), and for muons below a few hundred GeV (above which radiative effects dominate).

For a particle with mass M and momentum $M\beta\gamma c$, $T_{\max}$ is given by

$$T_{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}. \tag{10.2}$$

The determination of the mean excitation energy is the principal non-trivial task in the evaluation of the Bethe-Bloch formula. Estimates based on fits to experimental measurements for various charged particles are used.

The simplifying assumptions used in the derivation of Eq. 10.1 begin to lead us astray in regions of low energy. Atomic shell corrections are necessary when the velocity of the incident particle becomes comparable to the velocity of the bound electrons. Above the upper boundary of the Bethe-Bloch region, it is necessary to account for radiation, kinematics, and the structure of the incident particle.

The energy transferred to electrons increases with the incident particle energy. Secondary "knock-on" electrons with $T \gg I$ are known as δ *rays.* The number of δ rays produced with energy greater than T_0 in a thickness x is

$$N(T \geq T_0) = \int_{T_0}^{T_{\max}} \xi \frac{dT}{T^2} = \xi \left(\frac{1}{T_0} - \frac{1}{T_{\max}} \right), \tag{10.3}$$

where

$$\xi = \frac{2\pi n_e Z^2 e^4}{M\beta^2} x. \tag{10.4}$$

So, for $T_0 \ll T_{\max}$, the number of energetic δ rays falls off inversely with the energy and that the parameter ξ is the energy above which there will be, on average, one δ ray produced. As such, it represents a "typical" value of energy loss in the material.

Usually, δ rays of appreciable energy are rare, but occassionally they can carry energies of $O(1 \text{ GeV})$, sufficient to start a process that requires independent treatment. A δ ray with kinetic energy T_e and corresponding momentum p_e is produced at an angle θ given by

$$\cos\theta = \frac{T_e}{p_e} \frac{p_{\max}}{T_{\max}}, \tag{10.5}$$

where $p_{\max}$ is the momentum of an electron with the maximum possible energy transfer $T_{\max}$.

Several other processes, such as Cerenkov radiation, transition radiation, brensstrahlung, and pair-production also become important at high energies.

10.1.2 Fluctuations in Ionization Energy Loss

Equation 10.1 only gives the mean energy lost by a charged particle per unit thickness of matter (*absorber*). The actual amount of energy lost by a charged particle that has traversed a given thickness of absorber will vary due to the stochastic nature of the process. For moderatly relativistic incident charged particles, collisions with small energy transfers are much more likely than those with large transfers. As a result, the single-collision spectrum is highly skewed and the $\frac{dE}{dx}$ distribution has a long tail on the high energy side. The probability density function $f(\Delta; \beta\gamma, x)$ describing the distribution of energy loss Δ in absorber thickness x is called the "Landau distribution". If $\chi(W, x)dW$ is the probability that a particle loses an energy between W and $W + dW$ after crossing a thickness x of the absorber, then

$$\chi(W, x)dW = \frac{1}{\xi} f_L(\lambda), \tag{10.6}$$

where

$$\begin{aligned}
&\lambda = \tfrac{1}{\xi}\left(W - \xi \left(\ln \tfrac{\xi}{\epsilon'} + 1 - c_{\mathrm{E}} \right) \right), \\
&\ln \epsilon' = \ln \frac{(1-\beta^2)I^2}{2mv^2} + \beta^2, \\
&C_{\mathrm{E}} = 0.577 \quad \text{(Euler's constant)}.
\end{aligned} \tag{10.7}$$

The quantity ϵ' is the low energy cutoff of possible energy losses, chosen by Landau so that the mean energy loss agreed with the Bethe-Bloch theory. The function $f_L(\lambda)$ can be expressed as

$$f_L(\lambda) = \frac{1}{\pi} \int_0^\infty \exp\left(-u(\ln u + \lambda)\right) \sin\left(\pi u\right) du. \tag{10.8}$$

The most probable value of the energy loss is given by

$$W_{\mathrm{MP}} = \xi \left(\ln \frac{\xi}{\epsilon'} + 0.198 + \delta \right). \tag{10.9}$$

The full width at half maximum (FWHM) of the distribution is 4.02ξ.

The Landau formula an approximation based on the assumptions that successive collisions are statistically independent, that the absorber medium is homogeneous, and that the total energy loss is small compared to the incident particle's energy. Experimental energy loss distributions in gases are broader than predicted by the Landau formula. Still, pulse height spectra of high-energy charged particles in gaseous proportional chambers follow the general form of the distribution. More elaborate "straggling" functions that provide a better fit are available, but the Landau distribution often serves well enough. When $\xi/E_{\max}$ is $O(0.01)$ or less, the number of δ rays with energies near $E_{\max}$ is small, and single large energy loss events give an asymmetric high-energy tail to the energy loss distribution. The distribution approaches a Gaussian for $\xi/E_{\max}$ of $O(1)$ or more, when the number of δ rays with energies near $E_{\max}$ is large.

Physicists often relate total energy loss to the number of ion pairs produced near the particle's track. This relation becomes complicated for extremely relativistic particles due to the wandering of energetic δ rays whose ranges exceed the dimensions of the fiducial volume. The mean local energy dissipation per ion-pair produced, W, is essentially constant for moderately relativistic particles, but increases at slower particle speeds. For gases, W can be highly sensitive to trace amounts of contaminants or dopants. Also, ionization yields in practical cases may be influences by such factors as subsequent recombination.

Because of fluctuations in energy loss, a beam of particles of fixed energy will have a distribution of ranges in a thick absorber. This is another manifestation of the straggling phenomenon. The two fluctuations are related by

$$\langle (E - \bar{E})^2 \rangle = \left(\frac{dE}{dx} \right)^2 \langle (R - \bar{R})^2 \rangle. \tag{10.10}$$

The range distributions of moderately relativistic hadrons in metals are nearly Gaussian. For a pure, monoenergetic beam of particles, the fractional straggling σ_R/R increases with Z of the absorber. The fractional straggling in a given absorber decreases with increasing kinetic energy and approaches a value $\sigma_R/R \approx \frac{1}{2}\sqrt{m_e/M}$ at high energy, where M is the mass of the incident particle.