Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

DSE2T (Nuclear and Particle Physics)

Topic – Interaction of Nuclear Radiation with Matter (Part – 1)

Introduction:

Most modern experiments rely on the application of a variety of exceedingly sophisticated electronic and computer tools. These tools provide the means for automatically preselecting interactions of greatest interest and of handling of enormous volumes of scientific data. We begin with the principles underlying the detection of different kinds of particles. In order to be detected, an object must leave some trace of its presence. It means, it must deposit energy in its wake. Ideally, detectors should help us observe particles without affecting them in any measurable way, but as we will see, this is not always possible. Independent of the sizes or shapes of particle detectors, their operation is usually based on the electromagnetic interactions of particles with matter. Energetic charged particles, for example, can ionize atoms, and thereby release electrons that can subsequently be accelerated to produce small detectable currents. Most electrically neutral particles can also interact with matter and transfer some or all of their energies to the charged nuclei or to the atomic electrons of the medium, which in turn can yield detectable electric signals. Particles such as neutrinos have no electromagnetic interactions, and therefore have very low probabilities for colliding in matter (that is, having small cross sections). They are therefore especially difficult to detect. We will now discuss some of the more straightforward ways in which particles can deposit or transfer their energies in matter.

The choice of material to use for radiation detectors depends on the type of radiation we are trying to detect and on the information about that radiation we are trying to gather. For alpha particles from radioactive decays or charged particles from nuclear reactions at low (MeV) energies, very thin detectors are sufficient, as the maximum range of these particles in most solids is typically less than 100 pm. For electrons, such as those emitted in beta decay, a detector of thickness 0.1 to 1 mm is required, while for gamma rays the range is large and even detectors of 5 cm thickness may not be sufficient to convert energetic photons (MeV or above) into an electronic pulse.

Interaction of Heavy Charged Particles:

Although Coulomb scattering of charged particles by nuclei (mostly known as *Rutherford scattering*) is an important process in Nuclear Physics, it has very little influence on the loss in energy of a charged particle as it travels through the detector material. Because the nuclei of the detector material occupy only about 10^{-15} of the volume of their atoms, it is roughly 10^{15} times more probable for the particle to collide with an electron than with a nucleus. The dominant mechanism for energy loss by charged particles is therefore Coulomb scattering by the *atomic electrons of the detector*.

Conservation of energy and momentum in a head-on elastic collision between a heavy particle of mass M and an electron of mass m (which is assumed to be at rest for the sake of this simplified discussion) gives for the loss in kinetic energy of the particle

$$\Delta E = E\frac{4Mm}{(M+m)^2} \approx E\frac{4m}{M} \text{ since } M \gg m$$

For a 5 MeV alpha particle (typical of those emitted in radioactive decay), this formula gives us a value of 2.7 keV. A few immediate conclusions are crucial to note down.

(1) It takes many thousands of such events before the particle loses all its energy. A head-on collision gives the maximum energy transfer to the electron. In most collisions, the energy loss of the particle will be much smaller.

(2) In a glancing collision between an electron and a heavy particle, the heavy particle is deflected by a negligible angle, and so the particle follows very nearly a straight-line path.

(3) Because the Coulomb force has infinite range, the particle interacts simultaneously with many electrons and thus loses energy gradually but continuously along its path. After travelling a certain distance, it has lost all of its energy. This distance is called the *range of the particle*. The range is

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Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

determined by the type of particle, type of material and energy of the particle. Fig. 1 shows cloud-chamber tracks of alpha particles from the decay of ^{210}Po, there is a rather well-defined distance beyond which there are no particles. Usually we work with the mean range, defined so that one-half the particles have longer ranges and one-half shorter; the variation about the mean is very small, at most a few percent, so the mean range is a useful and precisely defined quantity.

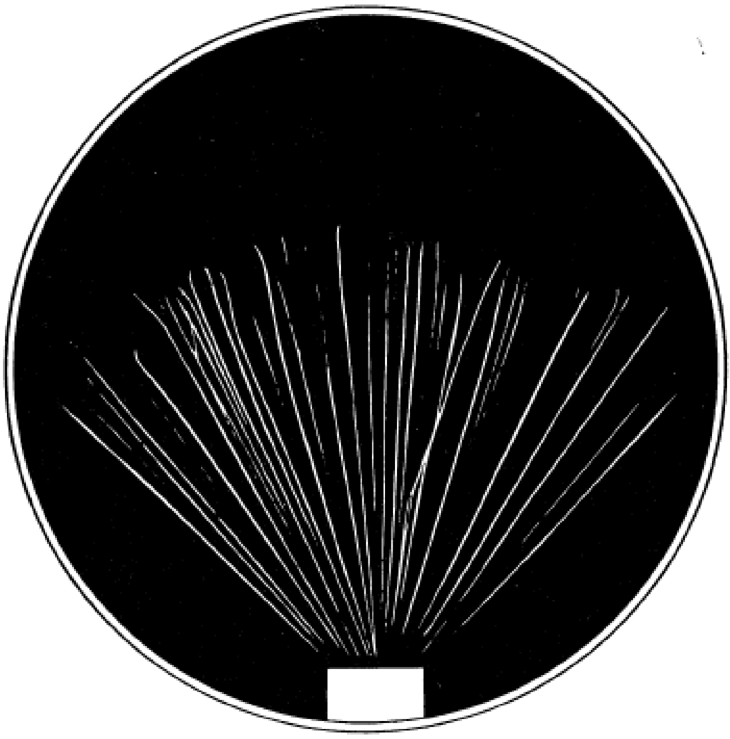

Fig. 1

(4) The energy needed to ionize an atom (i.e. to remove an electron) is of the order of ~10 eV. Thus many collisions will transfer enough energy to an electron to ionize the atom. If the electron is not given enough energy to produce an ion, the atom is sent into a higher excited state, which quickly gets relaxed back to the ground state. Furthermore, electrons given energies in the keV region (which are known as delta rays) can themselves produce ions by collisions, resulting in even more secondary electrons. To determine the energy lost by the particle, we must include the primary and secondary electrons as well as the atomic excitations.

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

Stopping Power. A convenient variable that describes the ionization properties of any material is the stopping power $S(E)$, which is defined as the amount of kinetic energy lost by any incident object per unit length of path traversed in the medium (this is often termed *ionization-energy loss*, or simply *energy loss*). We, can therefore write

$$S(E) = -\frac{dE}{dx} = n_{ion}\bar{I}$$

where E is the energy of the particle, n_{ion} is the number of electron-ion pairs formed per unit path length due to ionization and $\bar{I}$ denotes the average energy needed to ionize an atom in the medium. For large atomic numbers (Z), $\bar{I}$ can be approximated as $\approx 10Z$ expressed in eV units. The negative sign in the previous equation simply reflects the fact that a particle's energy decreases as it moves along x axis, that is the change in kinetic energy between x and $x + dx$, denoted as $dE = E(x + dx) - E(x)$ is negative. For any given medium, the stopping power is, in general, a function of the energy of the incident particle, and it must also depend on the particle's electric charge. We will see later that the dependence on energy becomes very weak for relativistic particles.

Bethe - Bloch Relation. Because the stopping power involves only electro-magnetic interactions, it can be calculated quite reliably. Hans Bethe and Felix Bloch in 1930 derived the following expression of stopping power for relativistic particles

$$S(E) = \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{4\pi Q^2 N_A Z\rho}{mc^2\beta^2 A}\left[\ln\left(\frac{2mc^2\beta^2}{\bar{I}(1-\beta^2)}\right) - \beta^2\right] \text{ in SI unit}$$

where c is the velocity of light, $v = \beta c$ is the velocity of the particle, Q is its electric charge, Z, A, and ρ are the atomic number, atomic weight and density of the stopping material, N_A is Avogadro number, $\bar{I}$ is the average ionization energy explained before and m and e are the mass and charge of an electron.

For energetic particles produced in accelerator experiments, the relativistic corrections are usually substantial and the previous relation must be used in its given form. However, in natural alpha-decay of nuclei, the emitted alpha-particles have kinetic energies of the order of a few MeV, and because of their

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Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

large mass (≈ 4000 MeV/c^2) the relativistic corrections in the relation can be ignored (or $\beta \to 0$), which simplifies $S(E)$ to

$$S(E) = \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{4\pi Q^2 N_A Z\rho}{mv^2 A}\left[\ln\left(\frac{2mv^2}{\bar{I}}\right)\right].$$

Because of the β^{-2} dependence in Bethe - Bloch Relation, at low particle velocities, the ionization loss is quite sensitive to particle energy. In fact, this dependence on v^{-2} suggests that particles of different rest mass (M) but same momentum (p) can be distinguished because of their different rates of energy loss. Although $S(E)$ has no explicit dependence on particle mass, for any fixed momentum, the effect of mass comes in through

$$S(E) = S(v) \propto \frac{1}{v^2} = \frac{M^2}{p^2(1-\beta^2)}.$$

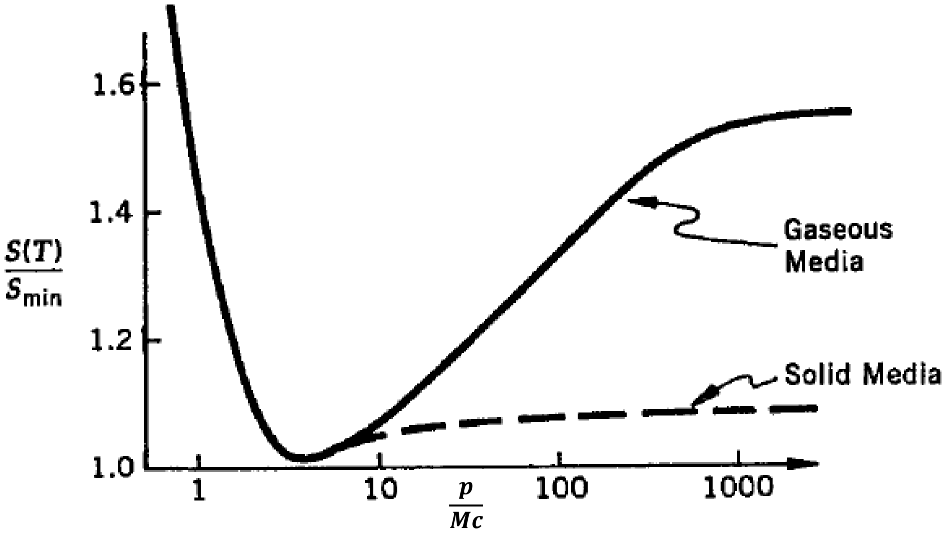

Fig. 2

We see that at low velocities ($\beta \to 0$), particles of same momentum but different mass will display significantly different energy loss. Independent of particle mass, the stopping power decreases with increasing particle velocity, and $S(E)$ displays a rather shallow minimum when $\frac{p}{Mc} \approx 3$ (that is, the minimum occurs at higher momenta for more massive particles). This minimum in the relation is due to the convolution of the decrease in $S(E)$ caused by the

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Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

β^{-2} dependence and the rise caused by the $\ln\left(\frac{1}{1-\beta^2}\right)$ term that is due to relativistic effects (shown in Fig. 2). The relativistic $\ln\left(\frac{1}{1-\beta^2}\right)$ rise in $S(E)$ for $\frac{p}{Mc} > 3$ (or $v > 0.96c$) eventually saturates because of the presence of long-range inter-atomic screening effects (which have been ignored in the Bethe - Bloch calculation). The total increase in ionization is rarely greater than 50% beyond the value measured for a "minimum-ionizing" particle, namely a particle that has $v \approx 0.96c$. The relativistic rise is best observed in gaseous media, and is only a several percent effect for dense materials. Nevertheless, this can be used to distinguish different particle types through their small differences in energy loss in gaseous detectors for energies corresponding to $v > 0.96c$.

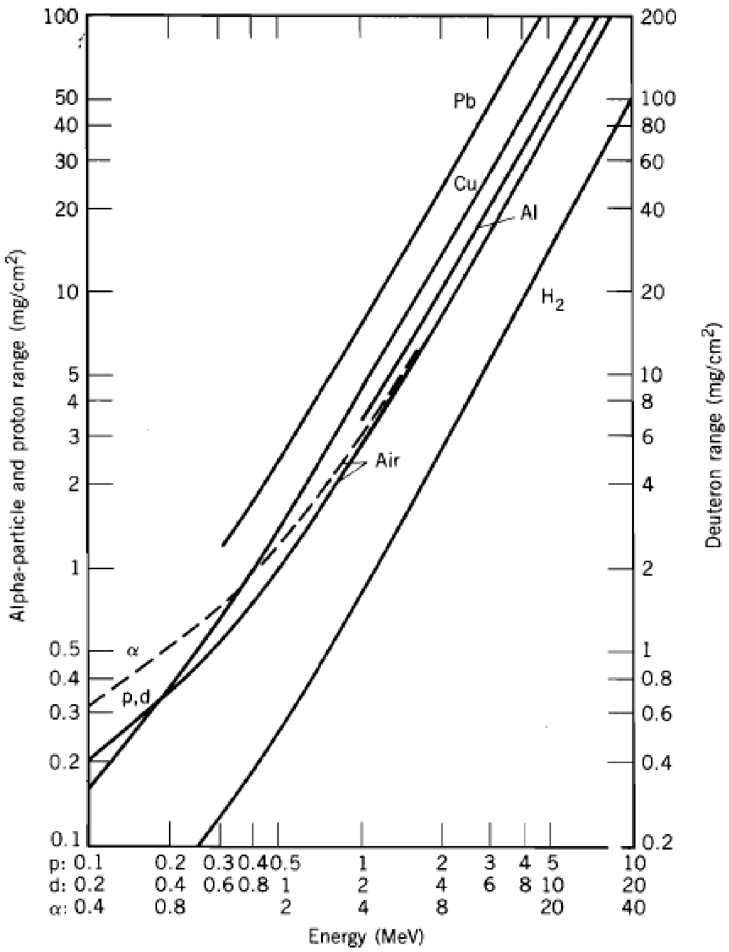

Fig. 3

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Range. Once we know the stopping power, we can calculate the expected range R of any particle in the medium, that is, the distance it will travel before it runs out of kinetic energy (T) and comes to a halt. Therefore we write

$$R = \int_0^R dx = \int_T^0 \frac{dx}{dE} dE = \int_0^T \frac{1}{(-\frac{dE}{dx})} dE = \int_0^T \frac{1}{S(E)} dE$$

At low energies, two particles of same kinetic energy but different mass can have substantially different ranges. For example, an electron with a kinetic energy of 5 MeV has a range that is several hundred times that of an alpha-particle of the same kinetic energy. At high energies, where the range becomes essentially proportional to energy, the difference in path lengths for particles of same kinetic energy becomes less pronounced. Fig. 3 shows the relationship between range and energy for air and for some other commonly encountered materials.

Interaction of Electrons: Bremsstrahlung:

Electrons interact through Coulomb scattering with the atomic electrons, just like heavy charged particles. There are, however, a number of important differences, namely

(1) Electrons, particularly those emitted in beta decay, travel at relativistic speeds.

(2) Electrons will suffer large deflections in collisions with other electrons, and therefore will follow erratic paths. The range will therefore be very different from the length of the path that the electron follows.

(3) In head-on collisions of one electron with another, a large fraction of the initial energy may be transferred to the struck electron. In fact, in electron-electron collisions we must take into account the identity of the two particles. After the collision, it is impossible to figure out which electron was incident and which was struck.

(4) Because the electron may suffer rapid changes in the direction and the magnitude of its velocity, it is subject to large accelerations, and accelerated

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Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

charged particles must radiate electromagnetic energy. Such radiation is known as *Bremsstrahlung* (a German word which means braking radiation).

Energy Loss. Bremsstrahlung is an important mechanism for energy loss, especially for ultra-relativistic electrons. It can also become significant for more massive particles, but only beyond 10^{12} eV or TeV energy scales. Thus for the total energy loss by electrons traversing matter we can write schematically the sum of two contributions.

$$\left(-\frac{dE}{dx}\right) = \left(-\frac{dE}{dx}\right)_c + \left(-\frac{dE}{dx}\right)_r$$

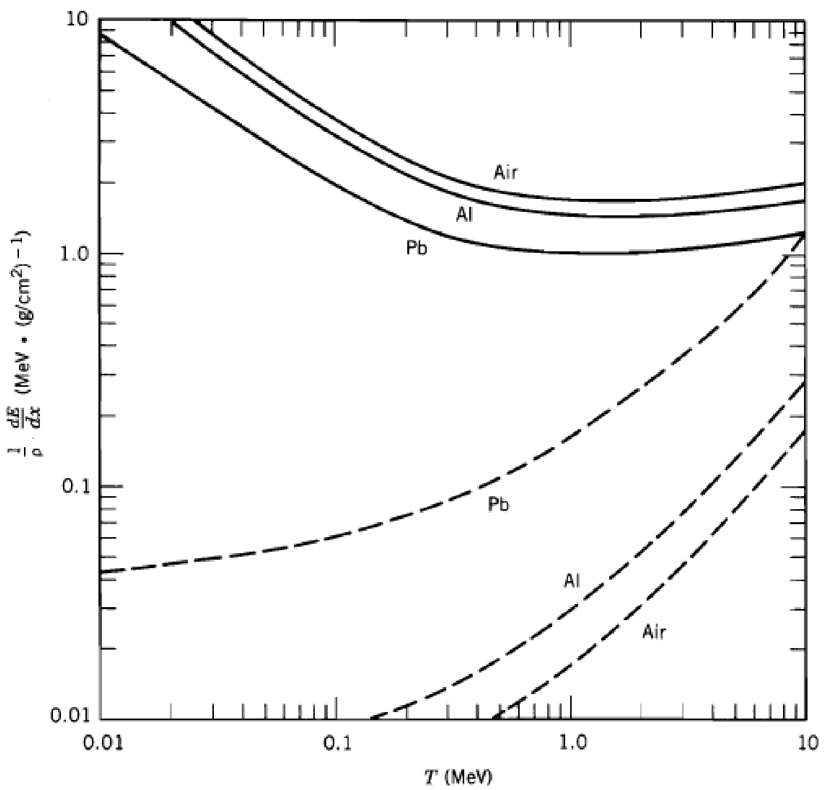

Fig. 4

Here $\left(-\frac{dE}{dx}\right)_c$ is the energy loss term due to collision or ionization discussed earlier and $\left(-\frac{dE}{dx}\right)_r$ is the energy loss term due to radiation or bremsstrahlung. To estimate the relative contributions of the two terms we can form their ratio, which in the relativistic region is approximately

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Narajole Raj College, Narajole.

$$\frac{\left(-\frac{dE}{dx}\right)_r}{\left(-\frac{dE}{dx}\right)_c} \approx \frac{T+mc^2}{mc^2}\frac{Z}{1600}$$

where Z is the atomic number of the medium, m is the rest mass of the electron (projectile), and T is its kinetic energy in MeV.

Radiation Length. The radiation term is thus significant only at high energy and in heavy materials. Fig. 4 shows the relative contributions for air, aluminum and lead. For most materials used as electron detectors, the radiative contribution is small. Moreover, there is very little variation of the collisional losses with electron energy. At high energies, the ionization loss is constant (saturated by the density effect) and the radiation dominates the total energy loss in the previous equation. According to our result, the radiated energy at high energies is proportional to the energy of the electron and for this regime it is useful to define the *radiation length* (X_0), which is the distance that an electron travels before its energy drops to $\frac{1}{e}$ of its initial value. Therefore we write,

$$\left(-\frac{dE}{dx}\right)_r = \frac{T}{X_0}$$

$$\text{or } \left(-\frac{dT}{dx}\right)_r = \frac{T}{X_0}$$

Except for smallest Z values, the above expressions provide quite satisfactory approximations for calculating ionization-energy loss for any high energy particle of unit charge, and the radiation loss for high-energy electrons. Integrating this relation between an initial kinetic energy T_0 and some later value T, we obtain, $T = T_0 e^{-\frac{x}{X_0}}$.

Thus, energetic electrons radiate most of their energy within several radiation lengths of the material. This characteristic behaviour is particularly important in the design of electron detectors. More massive ultra-relativistic charged particles that do not radiate lose their energy through nuclear (strong) collisions or just through ionization loss.

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Assistant Professor,
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Narajole Raj College, Narajole.

This concludes part 1 of this e-report.

The discussion will be continuing in the part 2 of this e-report.

Reference(s):

Introduction to Nuclear and Particle Physics, A. Das & T. Ferbel, World Scientific

Introductory Nuclear Physics, Kenneth S. Krane, John Wiley & Sons

(All the figures have been collected from the above mentioned references)