CHAPTER II

INTERACION OF COSMIC RADIATIONS

The primary cosmic radiation undergoes both electromagnetic and nuclear interactions in the atmosphere which will be discussed in more detail as follows.

1. Electromagnetic Interactions. (5)

A. Charged Particles. When a charged particle passes through a medium it can lose energy by two main processes.

(i) Collision processes. The collision process results in elastic scattering, excitation and ionization. The total energy loss due to collision processes must be calculated in two parts. Firstly, there are the losses due to small transfer of energy. The electron, which is ejected after such a collision has energy smaller than $E < 10^4 - 10^5$ ev. . This corresponds to a distant collision Secondly, if the energy transferred during the collision is large, we treat the collision as one between the incident particle and a free electron. This corresponds to a close collision. The total rate of energy loss by collision (ionization loss) for both classes is given by the relation,

$$-\frac{dE}{dx} = \frac{2\,C\,m_e\,c^2 z^2}{\beta^2}\left[\ln\left\{\frac{4\,m_e^2\,c^4\beta^4}{(1-\beta^2)^2\,I^2(Z)}\right\} - 2\,\beta^2\right], \quad (1)$$

where $C = \pi N \frac{Z}{A} r_e^2$, N = Avogadro's number, A = atomic weight of the absorber, Z = atomic number, z = charge of the particle,

$r_e = \frac{e^2}{m_e c^2}$ is the classical electron radius,

I (Z) is the average ionization potential,

c = velocity of light

$\beta = \frac{v}{c}$, v = velocity of the particle.

The probability of collision is expressed by

$$\phi_{col}(E, E')\, dE' = 2\pi N \frac{Z}{A} r_e^2 \frac{m_e c^2 E^2 dE}{(E-E')^2 E'^2} \left[1 - \frac{E'}{E} + \left(\frac{E'}{E}\right)^2\right]^2 P(E,E'), \quad (2)$$

where $\phi_{col}(E, E')$ is differential collision probability of an electron of kinetic energy E, traversing a thickness of dx g cm^{-2}, to transfer an energy between E' and $E' + dE'$ to an atomic electron. For negatron-negatron collision $P(E, E') = 1$ and for positron-negatron collision

$$P(E, E') = \left[1 - \frac{2E'}{E} + 2\left(\frac{E'}{E}\right)^2\right].$$

(ii) Bremsstrahlung. Bremsstrahlung is the emission of electromagnetic radiation when a charged particle is accelerated in the electric field of the nucleus. This phenomenon is occurred a close collision with a distance smaller than atomic nuclei. If the distance from the nucleus is large compared with the nuclear radius, the screening effect of the outer electrons is often important, This effect is calculated by Bethe and Heitler (6). The theory indicated that the influence of screening on a radiation process in which an electron of kinetic energy E produced a photon of energy E' is determined by the quantity :

$$\gamma = 100 \frac{m_e c^2}{U} \frac{v}{1-v} Z^{-\frac{1}{3}} , \qquad (3)$$

where total electron energy $U = E + m_e c^2$,

and the fraction photon energy $v = \frac{E'}{U}$.

The screening effect is greater the smaller is γ , for $\gamma \approx 0$ the effect is complete screening.

We can examine the average energy loss due to bremsstrahlung. Consider a fast electron of energy E passing through a medium of atomic number Z, and atomic weight A. The average rate of radiation loss is given by the relation

$$-\left(\frac{dE}{dx}\right)_{rad} = 4\alpha \frac{N}{A} Z^2 r_e^2 E \ln\left(183 Z^{-\frac{1}{3}}\right), \qquad (4)$$

for $U \gg 137 m_e c^2 Z^{-\frac{1}{3}}$,

where $\alpha = \frac{2\pi e^2}{hc} = \frac{1}{137}$ is the fine structure constant,

N is Avogadro's number.

It is convenient to collect all the constants and parameters of the medium together and write,

$$\frac{1}{X_o} = 4\alpha \frac{N}{A} Z^2 r_e^2 \ln\left(183 Z^{-\frac{1}{3}}\right) . \qquad (5)$$

X_o has a dimension of a length in g/cm^2 and is called radiation length of the medium.

Thus, from eq. (4) we obtained

$$-\left(\frac{dE}{dx}\right)_{rad} = \frac{E}{X_o} .$$

From this equation we find that if the energy of electron before entering an absorber is E_o, its energy, on average, after penetrating a distance x is :

$$E = E_0 \, e^{-\frac{x}{X_0}} , \qquad (6)$$

X_0 is thus the distance after which, on average, the electron energy will have fallen to $\frac{1}{e}$ of its original value.

The probability $\phi_{rad}(E, E') \, dE' \, dx$ for an electron of kinetic energy E traversing a thickness of dx g cm^{-2} to emit a photon with energy in the range E' and $E' + dE'$ may be written as

$$\phi_{rad}(E, E') \, dE' = 4 \alpha \frac{N}{A} Z^2 r_e^2 \frac{dE'}{E} F \, (U, v) , \qquad (7)$$

where $F \, (U, v)$ is screening factor,

$\phi_{rad}(E, E')$ is called the differential radiation probability of electrons.

For high energy electrons the complete screening approximation is used, that is $\gamma \to 0$, and the function $F \, (U , V)$ is

$$F \, (U , v) = \left[1 + (1 - v)^2 - \frac{2}{3} (1 - v) \right] \ln 183 \, Z^{-\frac{1}{3}} + \frac{1}{9}(1 - v). \qquad (8)$$

From Fig. 2 it is seen that for high energy electrons the fractional energy loss by radiation is far greater than the loss by collision. This figure also show the difference between these quantities for two different absorbers, that is,air and lead .

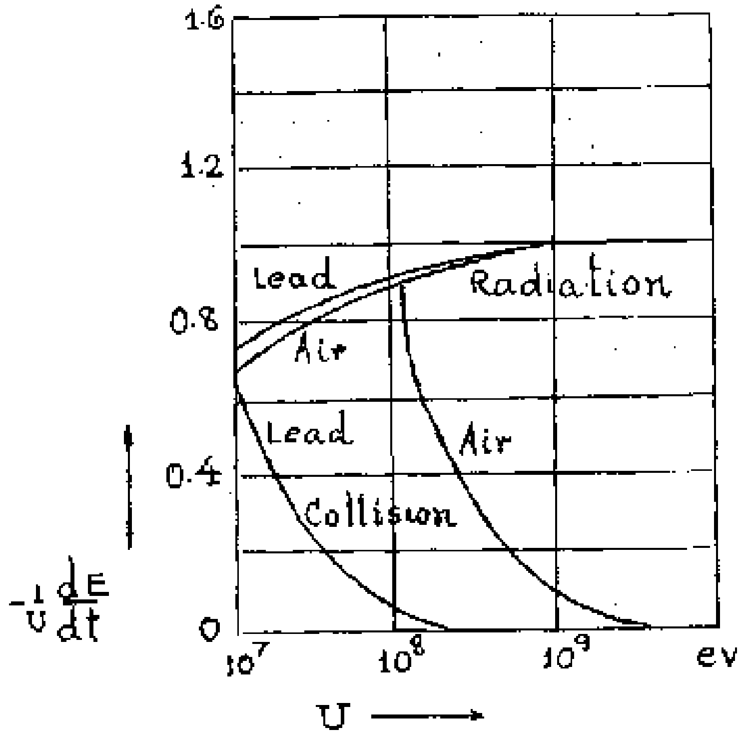

Fig. 2 : Fractional Energy Loss by Collision, $-\frac{1}{U}\left(\frac{dE}{dt}\right)_{col}$, and Fractional Energy Loss by Radiation, $-\frac{1}{U}\left(\frac{dE}{dt}\right)_{rad}$, for Electrons, per Radiation Length of Air or Lead.

B. Photon. There are three dominant processes which occur when a γ - ray passes through matter.

(i) Photoelectric effect. This involves the complete absorption of a γ - ray by a bound electron. The energy of the incident photon is used to remove an electron from one of the atomic shells and leaves it either in one of the previously unoccupied bound states or in an ionized bound state. The probability of this process occurring is very high for γ - ray energies close to the ionization energy. However, the cross section for the photoelectric effect decreases rapidly with increasing energy and will be assumed negligible when we discuss in the field of high energies.

(ii) Compton effect. The Compton effect can be described as an elastic collision between a photon and a free electron initially at rest. When the incident photon is scattered by a free electron, the scattered photon has a lower energy. The energy and momentum lost by the photon are carried away by the recoil electron. After being scattered several times the energy of the γ - ray will be reduced to a value at which it can be absorbed by the photoelectric effect.

By using principle of conservation of energy and momentum we get,

$$E' = \frac{E\, m_e c^2}{m_e c^2 + E\,(1 - \cos\theta)} \quad \text{, Compton formula} \qquad (9)$$

where E' is the energy of scattered photon,

E is the energy of incident photon,

θ is the angle at which the photon scattered.

The probability of Compton scattering carried out by Klein and Nishina (7) gave the result below.

If $\phi_{com}(E, E')\, dE'\, dx$ is the probability for a photon of energy E traversing a thickness dx g cm^{-2} to undergo a Compton collision in which the scattered photon has an energy between E' and $E' + dE'$. The expresion is obtained

$$\phi_{com}(E, E')\, dE' = \frac{C\, m_e c^2}{E} \frac{dE'}{E'} \left[1 + \left(\frac{E'}{E}\right)^2 - \frac{E'}{E} \sin^2\theta\right] , \qquad (10)$$

which holds for $\frac{m_e c^2}{2} < E' < E$.

The total probability for the occurence of Compton scattering per g cm^{-2}, when $E >> m_e c^2$ is given by

$$\int_{\frac{m_e c^2}{2}}^{E} \phi_{com}(E,E')\, dE' = C\, \frac{m_e c^2}{E} \left[\ln \frac{2E}{m_e c^2} + \frac{1}{2} \right] . \qquad (11)$$

It is sometimes convenient to consider the total probability of Compton effect per radiation length. It is called μ_{com} ,

$$\mu_{com} = X_o \int_{m_e c^2}^{E_o} \phi_{com}(E,E')\, dE' . \qquad (12)$$

Fig. 3 shows the plot of μ_{com} as a function of energy for air.

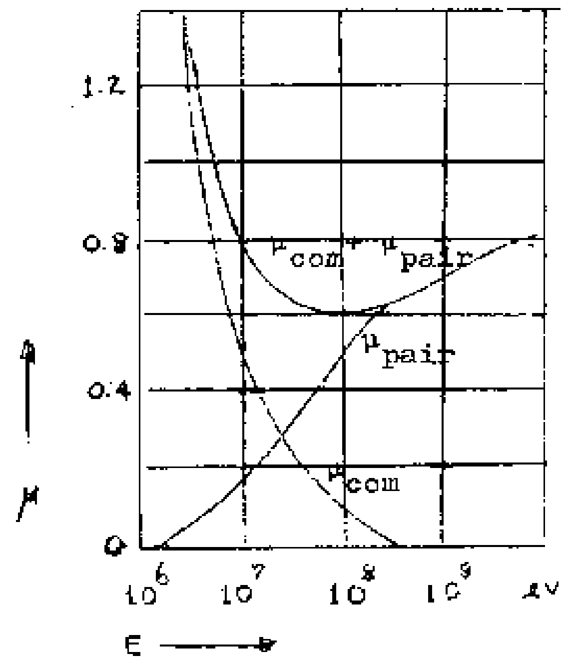

Fig. 3: The Total Probability per Radiation Length of Air for Compton Scattering (μ_{com}), for Pair Production (μ_{pair}), and for either Effect (μ_{com} + μ_{pair})

(iii) Pair production. When a photon has energy greater than $2 m_e c^2$ (1.02 Mev.) it can raise an electron from the highest negative energy state into the lowest positive energy state. The latter is what we regard as a negative electron or negatron and the hole remaining in the high negative energy state behaves as a positively charged electron or positron. Therefore, the incident photon with energy $\geq 2m_e c^2$ is absorbed and a positive and negative electrons simultaneously come into existence. The excess over the threshold energy appears as the kinetic energy of the two particles.

This theory of pair production is closely related to that of radiation process. In the case of process occurred at relatively large distance in the Coulomb field, the electric field of the nucleus is screened by the outer electrons. The influence of screening is determined from

$$\gamma = 100 \frac{m_e c^2}{E} \frac{1}{v(1 - v)} Z^{-\frac{1}{3}} , \qquad (13)$$

where $v = \frac{E' + m_e c^2}{E}$ is the fractional energy of the positron.
The screening is negligible when $\gamma \gg 1$, and $\gamma \simeq 0$ is referred to complete secreening.

The probability $\phi_{pair} (E, E') dE' dx$ of a photon traversing a thickness dx $g\ cm^{-2}$ of absorber, will produce an electron pair with the kinetic energy of the positron between E' and $E' + dE'$. The differential probability to produce electron pair has been shown by Bethe and Heitler for $E \gg m_e c^2$ as :

$$\phi_{pair}(E, E')\, dE' = 4\alpha \frac{N}{A} Z^2 r_e^2 \frac{dE'}{E} G(E, v), \qquad (14)$$

where E = energy of the incident photon,

E' = energy of the positron,

$v = \frac{E'}{E}$,

and $G(E, v)$ is a screening factor.

The expression one takes for the screening factor $G(E, v)$ depends on the value of γ, but the function $G(E, v)$ varies only slowly with E and v. For very high energy photon we have said that complete screening is appropriate and for this special case

$$G(E, v) = \left[v^2 + (1 - v)^2 + \frac{2}{3} v (1 - v) \right] \ln (183\, Z^{-\frac{1}{3}}) - \frac{1}{9} v(1-v). \qquad (15)$$

It is possible to obtain the total probability for a photon with energy E to produce a pair within a thickness dx g cm^{-2} by integrating the eq. (14) and give

for $m_e c^2 \ll E \ll 137\, m_e c^2 Z^{-\frac{1}{3}}$

$$\int_0^{E - 2m_e c^2} \phi_{pair}(E, E')\, dE' = 4\alpha N \frac{Z^2}{A} r_e^2 \left[\frac{7}{9} \ln\left(\frac{2E}{m_e c^2}\right) - \frac{109}{54} \right], \qquad (16)$$

$E \gg 137\, m_e c^2 Z^{-\frac{1}{3}}$

$$\int_0^{E - 2m_e c^2} \phi_{pair}(E, E')\, dE' = 4\alpha \frac{N}{A} Z^2 r_e^2 \left[\frac{7}{9} \ln (183\, Z^{-\frac{1}{3}}) - \frac{1}{54} \right], \qquad (17)$$

Thus, the total probability for pair production per radiation length is

$$\mu_{pair}(E) = X_0 \int_0^{E - 2m_e c^2} \phi_{pair}(E, E')\, dE', \qquad (18)$$

where X_o is the radiation length which is the same as radiation loss.

In the case of complete screening, the total probability for pair production per radiation length has the constant value

$$\mu_o = \frac{7}{9} - \frac{b}{3} ,$$

where $b = \frac{1}{18 \ln (183 Z^{-\frac{1}{3}})}$, and is very slowly varying function of Z which may be taken as 0. 0135 for all element with $Z >> 4$.

From these three processes one can see that, for low energy photon (< 0.1 Mev.) the photoelectric effect is the predominant process, but this falls off rapidly for increasing energy, and in the range 0.5 - 5 Mev. the Compton effect is the most important process. The probability that a γ- ray will produce a pair of electron increased quite rapidly for energies in excess of 1 Mev., but the increase is more gradual at higher energies. Fig. 3 shows that for high energies pair production is the dominant process for γ - ray interaction.

2. Nuclear Interactions.

When a nucleon strikes a nucleus a variety of processes can occur, depending on the energy of the nucleon, the size of the nucleus, etc.. The processes are divided into two phenomena.

A. Absorption Process. The incident nucleon is absorbed by the nucleus and a new compound nucleus is formed. This compound nucleus will usually fall to a state of lower energy with the emission of radiation and, perhaps, new particles.

B. Scattering Process. It is subdivided into two kinds.

(i) Elastic scattering. The momentum and kinetic energy are conserved and therefore, there is a billiard - ball type of collision.

(ii) Inelastic scattering. Some of the kinetic energy of the incident nucleus is absorbed by the nucleus, which is then raised to an excited state. There follows the emission of this energy in the form of γ - rays, α-particles, etc. . This is called evaporation process. If the energy of the incident nucleon is high enough, new particles mainly π-mesons may be generated in a collision with an individual nucleon in the nucleus. Then secondary particles are emitted very quickly, before the recoil energy of the struck nucleon is distributed through the nucleus and the evaporation precess begins.

At low energy the interaction is essentially with the nucleus as a whole. The characteristic of the interaction then depend critically upon the nuclear structure and the energy.

At high energy the interaction is between the incident particle and at most, a few of the individual nucleons of the target nucleus. The exact structure of the nucleus is unimportant. It is in this field of high energy, i. e. the region of energy well above that available from the emission of radioactive nuclei, that cosmic ray studies have yielded so many important advances. The exact theory of some nuclear interaction are still not known. Many theoretical physicists have been attempted to explain by using many models.

Cross section and interaction length. The probability of a particular nuclear reaction is usually expressed in terms of an effective area of cross section of the nucleus. There will be a value of the cross section for each type of interaction : scattering, absorption, etc., and each is represented by an area, associated with each nucleus, such that if an incoming particle penetrates this area the interaction will take place.

The geometric cross section σ_g is defined as πR^2 , where R is the nuclear radius. The relation $R = 1.35 A^{\frac{1}{3}} 10^{-13}$ cm. is sufficiently accurate for most purposes, i.e $\sigma_g = 0.0573 A^{\frac{2}{3}}$ barns. The geometric cross section does not include the size of the colliding particle so that for this reason, and others, the total cross section for a particular interaction differs somewhat from the geometric value. However, at high energy general feature of most interactions is that the cross section approaches geometric cross section.

Corresponding to each cross section σ, there is an interaction length, L, equal to the average distance in g cm^{-2}, travelled by a particle between collision. The relation between L and σ is

$L = \frac{A}{N \sigma}$, where N is Avogadro's number, and A is the atomic weight. Thus, the geometric interaction length is given by

$$L = \frac{A}{N\, 0.0573\, A^{\frac{2}{3}}} = 29.0\ A^{\frac{1}{3}}\ g/cm^2 .$$

If N_0 particles are incident on an absorber of thickness x g cm^{-2}, the number of particles which emerge without having interacted, N, is given by

$$N = N_o e^{-\frac{x}{L}} .$$

However, cosmic rays contain many kinds of particles , they may be able to produce nuclear interactions depending on their cross sections. The charged particles can undergo both electro - magnetic and nuclear interactions but for a high energy proton the ionization is so small that can be neglected. By exclusion from many experiments the particles mainly responsible for nuclear interaction in cosmic ray phenomena are protons, neutrons, and π-mesons. They also depend on the abundance in the atmosphere. Electrons and photons present in the atmosphere are not responsible for any large fraction of the observed nuclear interaction. They mostly undergo electromagnetic interaction. By the decaying of unstable particles such as π-mesons and these processes of interaction the cascade showers are formed. The detail of cascade theory can be seen in Reference (8) or others.