CHAPTER II

Nuclear and Electromagnetic Interactions of Particles

II.1 General Remarks.

There are two different kinds of the interactions of high energy particles with matter. One is the electromagnetic interactions , the other is nuclear interactions. The examples of the electromagnetic interactions are the collisions between the particles with atomic electrons , the production of photons by charged particles and the materialization of photons. The examples of nuclear interactions are the collisions between neutrons and neutrons, neutrons and protons, and protons and protons. High energy nuclear interaction is sometimes called the spallation reaction.

In the electromagnetic interactions, we would consider a charged particle passing near an atom. According to Rossi(6), if the distance of closest approach is large, the interaction will involve the passing particle and the atom as a whole. In this case, an excitation or an ionization of the atom is considerably the most important. If the distance is closer to the order of the atomic dimension, the interaction is between the passing particle and one of the atomic electrons. The phenomenon is called the knock-on process. When the distance is smaller than the atomic radius, the passing particle will be deflected by the atomic field, this phenomenon is called scattering.

II.2 Interaction of Cosmic Ray Particles with Particles of the Medium.

a. Ionization The atom that loses one or more electrons is said to be ionized. The energy required to ionize the atom is called the ionization energy. The ionization may be caused by radiations or collisions. When cosmic ray particles pass through a medium, its energy may be lost by ionization. According to Richtmyer(11), the ionization loss is given by the relation,

$$-\frac{dE}{dX} = BZ^2 f(V)$$

where B is a known constant, Ze is the charge of incident particle, f(V) is a function of its velocity which varies as $\frac{1}{V^2}$.

b. Scattering When a charged particle passes near a nucleus it will change the direction of motion known as scattering. According to Rossi(4), Rutherford scattering formula is given by the relation;

$$P(\theta)d\Omega = \frac{4NZ^2 r_e^2}{A} \left(\frac{m_e c}{\beta p}\right)^2 \frac{d\Omega}{\theta^4}$$

where r_e is the radius of electron and m_e is the mass of electron.

$P(\theta)d\Omega$ represent the probability of scattering of a particle of momentum p and velocity βc traversing a thickness of 1 gm cm^{-2} of the medium and undergoing a collision with the target nucleus which deflects the trajectory of the particle into the solid angle $d\Omega$ at an angle θ to the original motion. N is the Avogadro's number. The probability is dependent of Ze, charge of the target nucleus. Therefore the heavy nucleus has more probability of scattering than the light nucleus. The energy of the incident particle implies a related momentum transfer, leading to multiple scattering.

c. ~~Bremsstrahlung~~ Bremsstrahlung is the radiation loss of the incident particles. The emission of radiation is due to the acceleration or retardation in the atomic fields. Consider a particle of mass m passing near a nucleus with impact parameter b, according to Rossi(4), the radiation loss Q is related by;

$$Q = \alpha \frac{N}{A} Z^2 \left(\frac{m_e}{m}\right)^2 r_e^2 \log \frac{b_{max}}{b_{min}}$$

where α is the fine-structure constant, r_e is the electronic radius, the energy of the incident particle of mass $m = m_e$, will be lost more than that of the heavier particles, so that bremsstrahlung is to be expected in case of high energy electrons.

6. Nuclear Collisions: Cosmic ray particle may lose its energy by inelastic and elastic collision with the nuclei of the medium. If the incident particle approaches a nucleus, it may be absorbed by the nucleus to form spallation reaction. The spallation reaction is responsible for the formation of stars.

II.3 Cosmic Ray Stars.

Cosmic ray stars are seen in photographic emulsions and in cloud chambers. Events have been observed in which several tracks meeting at a point somewhat like a star in shape. The stars are related to nuclear disintegrations. The tracks of the stars, called the prongs, are caused by ionizing particles produced in the nuclear disintegrations. Neutral particles leave no trace in the nuclear emulsions. The nuclei which produce stars in the emulsions are probably those of silver or of bromine. The reactions that cause the formation of nuclear stars are sometimes called "Spallation Reaction".

II.4 Spallation Reactions

Spallation reaction is a type of nuclear reactions in which several small particles are ejected from the nucleus. This reaction is being produced only with particle of high energy of order 100 MeV or more, incident upon a nucleus. The reaction is divided into two steps. The first step is the nuclear cascade collisions of the nucleons inside the nucleus, which is the cause of direct emission from the nucleus of one or several particles. According to Serber(4) and Fermi (5)this step is in the time of order of 10^{-22} sec after the incident particles have been absorbed. The second step is nuclear evaporation, which takes time of the order of 10^{-21} sec.

In such process, a high energy incident particle, which may be, say a 5 BeV proton, collides with the target nucleus produces a large star. If a neutron of 200 MeV hits a nucleus it will probably cause a small star in which two or four nucleons may be evaporated isotropically.

The star may be initiated from the high energy photons of about 100 MeV. For example, Baldwin and Klaiber (12) had obtained 4- prong stars produced in a cloud chamber by gamma ray beam from betatron operated at 100 MeV.

II.5 Nuclear Cascade Collisions and Nuclear Evaporations.

Spallation reaction is clearly explained by using Fermi gas model as shown by Segrè (13). The nucleus of a nucleons in this model are contained in a well of constant diameter and length. The well depth V_0 is determined by the Fermi kinetic energy E_F, and the nucleon binding energy E_B, i.e.,

$$V_0 = -E_F - E_B$$

The charged particles are affected by the Coulomb barrier V_c

$$V_c = \frac{Z_1 Z_2 e^2}{R}$$

where Z_1 and Z_2 are number of electronic charge of the nucleus and the particle respectively. The nuclear radius is denoted by R.

A high energy particle can initiate within the nucleus a cascade collisions. According to Wilson (20) particles with energy below about 1 BeV have a very low probability of generating other particles, meaning that only elastic collisions are important. However, some of the nucleons will have succeeded in escaping after relatively few collisions. The escaping nucleons or particles usually cause gray tracks, i.e., those tracks with specific ionization between 1.4 g_{min} and 10 g_{min}, and are mostly protons, neutrons and clusters of deuterons.

Some of the nucleons can transfer energy further to other particles in the nucleus. The excitation energy of the nucleus at the end of the cascade, E^0, was shown by N. Metropolis, H.Divin and Stern (25), to be

$$E^{0} = E_{1} - \sum_{i=0}^{n} E_{i} - (n-1)B$$

where E_1 is the energy of the incoming particle (in the laboratory system), n is the number of out going particles, and B is the average binding energy of the n out going particles. The excitation energy content of the nucleus may be compared with the heat energy of a liquid droplet. The disintegration is analogous to a process of evaporation.

The excited nucleus is considered to be heated to a nuclear temperature T in the unit of MeV. According to [illegible](24), the temperature is varied as $(E^{0})^{1/2}$, so that

$$E^{0} = KAT^{2}$$

where A is the total number of nucleons in the nucleus, K is a constant of nearly 0.1 .

The nucleons and particles of atomic number 5 to 10, i.e., protons, neutrons, alpha particles and heavier nuclei are evaporated out off the nucleus. These nucleons and the particles usually cause black tracks of specific ionization greater than 10 G_{min} in the emulsions. The particles must have excitation energy more than their binding energies.

The probability of neutrons being emitted with energy between E and E+dE was shown by Weisskopf(16), as given

$$P(E)dE = \frac{E}{\theta^2} \exp\left(-\frac{E}{\theta}\right) dE$$

where θ is the nuclear temperature measured in each unit of MeV.

The probability of charged particles is,

$$P(E)dE = \frac{E - V_c}{\theta^2} \exp -\left(\frac{E - V_c}{\theta}\right) dE$$

where V_c is the Coulomb barrier.

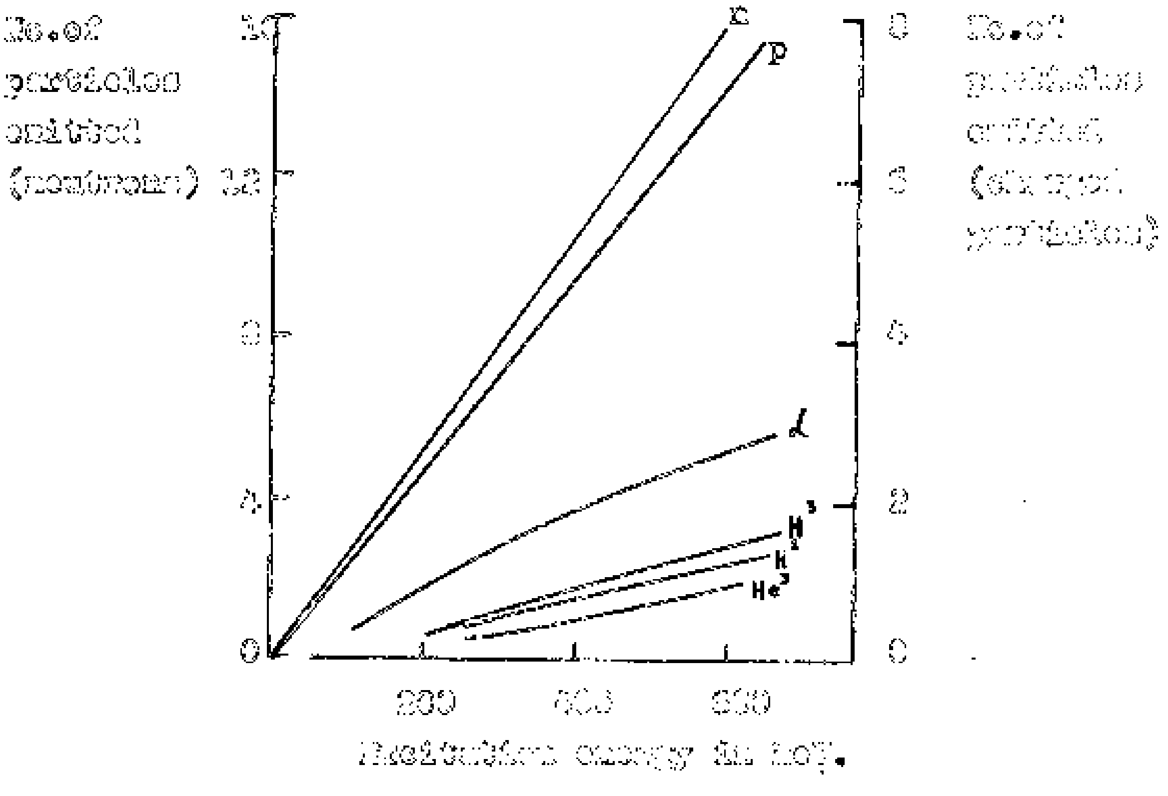

Fig. II . The number of evaporated particles as a function of initial excitation energy [after Segrè (15)]

II.6 Probability of Emission for Various Types of Evaporated Particles.

The ratio of emission for various types of evaporated particles as shown in Wilson(30) is as follows:

$$\frac{W(\alpha)}{W(p)} = 0.35 \pm 0.12$$

$$\frac{W(d)}{W(t)} = 0.50$$

$$\frac{W(H^2 + H^3)}{W(H^1 + H^2 + H^3)} = 0.21 \pm 0.10 \quad \text{for } n < 7 \text{ prongs}$$

$$= 0.07 \pm 0.03 \quad \text{for } n > 7 \text{ prongs}$$

where $\frac{W(\alpha)}{W(p)}$ denotes the ratio of emission of alpha particles to protons, $\frac{W(d)}{W(t)}$ denotes the ratio of emission of deuterons to tritons.

At low excitation energy (< 10 MeV) [illegible] than alpha particles [illegible]. The frequency of [illegible] emission at various excitation energies [illegible] in Wilson(30) is as follows:

Excitation energy [illegible]

Compound frequency per [illegible] 00.0%.

The frequency with which [illegible] were found to be emitted is as follows:

Z	3	4	5	6	7	8	9	10
Number	1449	70419	1786	1026	[illegible]	[illegible]	[illegible]	[illegible]

where Z denotes the atomic number of the critical fragments.