CHAPTER I

INTRODUCTION

It is now a wellknown fact that the great part of radioactivity in nature is due to cosmic rays. The following is an account of some of the more interesting historical and experimental aspects of cosmic rays.

(I.a) Historical Account

In 1899-1900, Elster and Geitel (1) and C.T.R. Wilson (2) Observed the rate at which electronic charge was lost by the electroscope. Wilson took the precaution of connecting the other end of the insulating support to a source of potential equal to the initial potential of the electroscope, so that leakage along the support would tend to maintain the charge. The observed loss of charge could therefore only be due to its neutralization by ions collected out of the air. The conductivity of the air enclosed in the electroscope was found to be permanent, in spite of the continual removal of ions from it by electric field. From this fact it may be infered that the ions are continually being regenerated in the air by some agency. Rutherford and Cook (3) found that the rate of collapsing of the gold leaf was long when the electroscope was shielded with brick. Lead shielding also caused the electroscope a long time of collapsing. It can be estimated that there are 10 ions pairs of positive and negative charges in one c.c. of air at ground level.

In 1911, Hess (4), a Canadian, and in 1914 Kolhorster (5), a German, found by sending a balloon in to the air, that the intensity of the rays increases at higher altitudes. To explain the effect Hess proposed the novel hypothesis that it was caused by penetrating radiation falling upon the earth from the outer ~~s~~ space. The observation of Hess and Kolhorster may be regarded as the main discovery of cosmic rays, but the name "cosmic rays" was due to Millikan and Cameron (in 1925)

(I.b) Classification of Cosmic Rays

Cosmic rays are complicated, but the following main classifications may be made:

1. Primary cosmic rays: The rays coming from the outer atmosphere are primary cosmic rays. About 85% are protons, the rest consisting of α -particles, and a small amount of nuclei of other elements. These particles have energies in the range from 10^9 to 10^{18} electron volts. The energy spectrum of protons obeys approximately the following empirical law:

$$N(E) = \frac{A}{(E + 5.3)^{1.75}}$$

where E is the kinetic energy in Bev., N(E) the number of proton energy greater than E, and A is a constant.

2. Secondary cosmic rays: When primary cosmic rays enter the atmosphere and penetrate to a certain depth, they collide with nitrogen and oxygen nuclei. A nuclear reaction occurs and

new particles are produced. These new particles are called "secondary cosmic rays". The protons and neutrons in secondary cosmic rays are called the nucleonic components of cosmic rays. The new particles usually produced in the first nuclear reaction are pi-mesons. These are unstable and decay, in the time of micro-second. These pi-mesons constitute the meson component of cosmic rays. A Charged pi-meson decays into a mu-meson and a neutrino ($\pi^{\pm} \longrightarrow \mu^{\pm} + \nu$). The neutral pi-meson decays into two photons. ($\pi^{0} \longrightarrow \gamma + \gamma$)

Secondary cosmic rays exist in a region between 15 and 30 k.m. altitude. One primary cosmic ray particle can produce many billion secondary particles. The number of secondary cosmic ray particles at sea level is approximately 1 particle per c.c. per second. Secondary particles of high energy can produce nuclear reactions times after times. These reactions are called "Extensive Air Shower" or "Cosmic Showers".

3. Soft and hard components: Among high secondary cosmic ray particles, some have high energies. They, therefore, have little nuclear radiation loss and almost no nuclear reaction, they can travel great distances through the atmosphere, and constitute what is called the hard component of cosmic rays. (mostly high energy gamma rays and μ-meson.) Lower energy particles have more nuclear radiation loss and travel shorter distances. They are called "the soft component of cosmic rays", made up mostly of electrons.

4. Nuclear interaction component: This component has the ability to interact with a target nuclei, resulting, some-times, in what are called cosmic ray stars. A cosmic ray star may consist of particles such as neutrons, protons, pi-mesons, K-mesons and hyperons etc., originating from a common centre.

(I.c) Cosmic Ray Variations

1. Geomagnetic effect (East-West Asymmetry): Stormer (6), Epstein (7), Vallarta, Lemartre (8) and others observed the behavior of charged particles moving in the earth's magnetic field, and they had formulated a theory explaining the behaviors of charged particles in the earth's magnetic field. The followings are the summations as described by Stormer (6) and Vallarta(8). The external field of the earth is represented by a dipole (of magnetic moment 8.1×10^{25} gauss-cm), located at the earth's center. The north pole is at the earth's south pole, the dipole south pole at the earth's north pole. The points where dipoles emerge from the earth are located at 78.5°N, 69.0° W. and 78.5°S, 111.0°E. The geomagnetic equator thus is tilted 11.5° with respect to the geographic equator and crosses the geographic equator at 159°W and 21°E. The geomagnetic field is proportional to the cube of the radius of the earth. The resultant field at the earth surface is about 0.3 - 0.6 gauss at equator.

A magnetic field exerts a force upon a moving charged particle. The force is perpendicular to both the direction of motion of the particle and the direction of the earth's magnetic lines of force. This force equals $\vec{F} = e\,\vec{v} \times \vec{B}$

where $\vec{v}$ = the velocity of the particle of charge e

$\vec{B}$ = the magnetic field.

The magnitude of the force equals

$$F = e\,v\,B \sin\theta$$

where θ is the angle between the direction of motion and the direction of the magnetic lines of force. As the force is always perpendicular to the direction motion the force does not affect the velocity of the particle, but it influences the direction of motion only. Hence a particle moving at right angles to the lines of force does not move along a straight line, but along a circle with radius r such that

$$p = B\,e\,r$$

where p is the momentum of the particle.

If a particle moves parallel to the direction of the magnetic field, then no force is exerted on the particle. This second mode of motion of a charged particle in a homogeneous magnetic field is to move in a straight line along the line of force.

If a particle moves in a direction neither parallel nor perpendicular to the lines of force of a homogeneous magnetic field, then the actual orbit will be a spiral.

An electrically charged particle approaching the earth will, in general, be deflected by the magnetic field of the earth, and will move along a more or less complicated orbit.

Some particles moving initially towards the earth, will be deflected away, and thus prevented from reaching the earth. Other particles which would not have reached the earth normally will be attracted by the magnetic field and fall upon the earth. A particle which moves parallel to a magnetic line of force, is not deflected at all. A particle which moves in the equatorial plane of the earth's equivalent dipole, crosses the earth's lines of force at right angles and is, therefore, curved. The curvature of the orbit increases as the momentum of the particle decreases. If the particle has a sufficiently low momentum, it will be turned away before reaching the earth's surface. But the deflection of the magnetic field doesnot only deflect away particles, it also turns some particles towards the earth.

In order to get an idea of the net effect of the magnetic field of the earth on cosmic ray intensity, the concept of forbidden and allowed directions were introduced. It was noticed by Stormer that particles approaching a magnetic dipole from outside space cannot approach in arbitrary directions. At any fixed point P in the vicinity of a dipole we have directions in which no particle coming from outside can approach. Those are called forbidden directions. The directions which are not forbidden are called allowed directions, and are the directions in which a point P can be approached by a particle coming from the outside. We note that the forbidden directions of a point refer to particles of given momentum. It is clear that for particles of sufficiently high momentum we can neglect the magnetic deflection, and all directions of approach to a point P will be allowed. Similarly, for particles of sufficiently low momentum all directions of approach to a point P will be forbidden. A direction which is called "forbidden" does not mean that it is blocked absolutely in the sense just explained. It means that the direction cannot be approached by particles coming from remote parts of space. As cosmic ray particles have their origin far away from the earth, they cannot approach along a forbidden. If a cosmic ray does not come from infinity, but, say, from the upper atmosphere, then it can approach the earth's surface both in allowed and in forbidden directions.

A few typical trajectories for particles of the same momentum but with different impact parameters approaching the earth in the magnetic equatorial plane are illustrated schematically in Fig. 1.

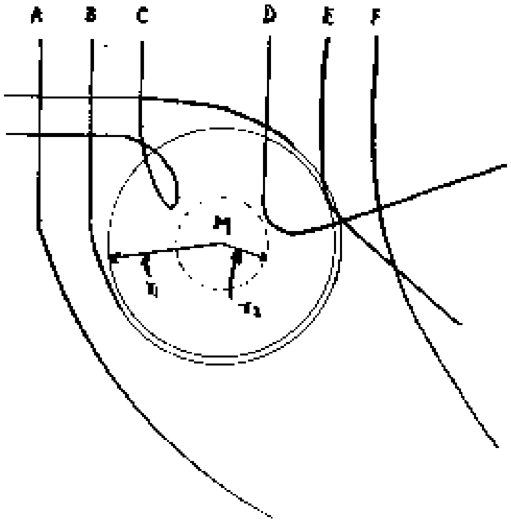

Fig. 1

Of these, one, labeled B, has the interesting property that it approaches a circle concentric with the magnetic dipole axis: in principle, particles with an impact parameter slightly less than this one can traverse the circle many times before flying off in an orbit of type B or plunging inward on such a path as C. The radius r_1 of the critical circle is evidently given by $p = B e r_1$. For impact parameters less than that corresponding to trajectory B, the particles excute loops inside the critical circle (C and D are examples); the one of these which reaches closest to the center-an orbit lying close to B - gets into a radius $r_2 = 0.414 r_1$. It can be seen from the figure that the trajectories cross r_1 at all angles but touch r_2 only tangentially. The radius of r_1 in Fig. 1 changes as the momentum of the particles under consideration is varied. Conversely, to represent the trajectias of particles of a specified momentum in their relation to the surface of the earth, we choose $r_1 = r_e$. (r_e = the radius of the earth.) For equatorial plane $B = M/r_1^3$, thus $p = Me/r_e^2$. The dipole moment of the earth $M = 8.1 \times 10^{25}$ gauss cm.^{3} Taking the radius of the earth $r_e = 6.4 \times 10^8$ cm. and $e = 4.8 \times 10^{-10}$ esu.

$$p = \frac{8.1 \times 10^{25} \times 4.8 \times 10^{-10}}{(6.4 \times 10^8)^2} \quad \mathrm{erg}/c$$

$$= \frac{8.1 \times 10^{25} \times 4.8 \times 10^{-10}}{(6.4 \times 10^8)^2 \; 1.6 \times 10^{-12}} \quad \mathrm{ev}/c$$

$$= 59500 \quad \mathrm{MeV}/c.$$

$$= 59.5 \quad \mathrm{Bev}/c.$$

The above unit is called 1 Stormer. From the argument of the preceding paragraph it may be seen that particles travelling in the equatorial plane with momenta greater than 59.5 Bev/c and having critical radii smaller than the earth's radius can be allowed. If on the other hand, the scale is so chosen that the earth's radius is equal to r_2, the particle momentum is

$$59.5 \times (.414)^2 = 10 \quad \text{Bev/c}$$

Particles with momenta less than 10 Bev/c will be forbidden. Particles with momenta just 10 Bev/c will arrive from the western horizon if they are positively charged and from the eastern horizon if they are negatively charge.

The trajectories for particles not moving in the equatorial plane, including those which arrive at higher latitudes, are considerably more complicated.

As the momenta of the particles is increased above the minimum appropriate to the latitude in question, particles begin to arrive above the atmosphere within a certain cone of directions near the horizon; this cone opens from the west if the particles carry a positive charge, from the east if they are negative. As the momentum rises the cone enlarges. This cone is usually called the Stormer cone. The open angle of the Stormer cone varies from zero to π. For a fixed momentum the smallest opening angle is at the equator; it opens up gradually when approaching the geomagnetic pole. At a certain latitude the cone closes completely, and for higher latitudes, all direction of approach are allowed. By application of Liouville's theorem, it can be shown that for particles approaching the earth in allowed direction the flux of particles arriving per unit solid angle is the same as the flux at original intensity at infinity.

The allowed directions are out side the Stormer cone. These directions can be approached by particles coming from infinity, provided they could move unhampered through the solid earth. As particles cannot move through the solid earth, there are directions outside the Stormer cone blocked by the solid earth. The effect in which particles in allowed directions in geometrical sense are blocked by the solid earth is called "Shadow effect". Therefore, in order to find out all allowed directions, it is necessary to determine which parts of the Stormer cone which lie in the earth's shadow. There is no earth shadow at the equator. The shadow effect sets in at both sides the equator, and it is most pronounced near the poles. Never theless, even at the poles, only a small part of the region outside the cone is covered by shadow. The most important effect of the shadow is that it renders the allowed cone asymmetric with respect to the North-South directions.

The magnetic field of the earth effects not only the directions of cosmic rays but also the total intensity of the rays. The forbidden cones for positively charged particles point towards the east and therefore, for positive primaries the intensity from the east is more strongly reduced than the intensity from the west. The effect is called east-west asymmetry.

The east-west asymmetry observed at sea-level show that the primaries of the meson component are predominantly positively charged. On the other hand no east-west effect was found at great altitudes. At great altitudes the soft component is predominant. Therefore the lack of east-west asymmetry at great altitudes shows that the asymmetry found at low altitudes is only shown by the hard component, while the soft component has a symmetrical distribution. The primaries of the soft component must, therefore, contain equal numbers of positive and of negative primaries.

2. Latitude effect: As indicated before, the lower the momentum of a cosmic ray particle, the less its ability to penetrate the geomagnetic field. The momentum limit (the minimum original momentum of a particle able to reach the earth's surface) is called the geomagnetic cut off. The geomagnetic cut off decreases with increasing latitude. The number of particles crossing a unit area per unit time at any point at the earth surface (ion density) remains approximately constant from the polar regions and down to a certain latitude. Below this, ion intensity decreases rapidly until it reaches a minimum in the equatorial region. This minimum point coincides with the dip equator, i.e. the locus of all points with zero dip.

3. Altitude effect: The secondary cosmic rays occur in the region 15 and 30 k.m. altitude. They are subjected to absorption processes on their way from this region down to the

lower atmosphere. Cosmic ray absorption depends on the mass of the air between the point of production of the ray and the point of recording it. Thus at the place where the secondary cosmic rays are produced, the ionizing particles are maximum (including both the primary and secondary particles). From this point of production the ion intensity is reduced gradually down to the earth's surface and is comparatively low at sea level.

Measurements under water and in mines have been summarized by E.P. George (9) and P.H. Barrett etal. (10). They have found that intensity does not vary as a simple exponential function of depth, but varies in accordance with absorption coefficient which decreases rapidly with increasing depth. Most cosmic ray interaction below the earth's surface are due to the mu-meson component of cosmic rays in this region.

4. <u>Seasonal variation</u>: Many observers have measured the seasonal variation of cosmic ray intensity at various points on the earth's surface and above the earth's surface. Results of these finding indicate that seasonal variation is complicated phenomena.

(I.e) Method of Detection

There are, in general, 7 or 8 methods of observing and measuring cosmic rays including the Ionization Chamber, Proportional and G.M. Counters, Wilson Cloud Chamber, Bubble Chamber, Scintillation Counter, Cerenko Detector, Spark Chamber and

Nuclear Emulsion Plates. The methods of detection depend on ionizing collisions by cosmic ray particles with the nuclei of a detecting medium. Charged particles of cosmic rays can be detected directly by these instruments but neutral particles can be detected only indirectly through the intermediary of secondary charged particles produced by collision of neutral cosmic ray particles with nuclei of the detecting medium.

A nuclear emulsion consists of silver halide crystals mixed with gelatin placed on a glass plates. This emulsion can recorded permanently the trajectory of ionizing particles which pass through it. The mechanism of detection is as follows: the interaction of ionizing particles with halide crystal grains in the emulsion results in the formation of silver specks within the crystal grains. The silver specks serve as a latent image which may later be rendered visible by the development of the emulsion. In the development process the silver specks act as catalyst for the action of weak reducing agents, the process thereby depositing additional silver atoms from the same crystal. The deposite silver appears black in a microscope The unionized silver halide crystals are unaltered in the development bath and are late removed in fixing bath.

Nuclear emulsions suitable for such work are manufactured commercially, for example, by Eastman Kodak in the United States and by Fuji Company in Japan. These emulsions have a high bromide concentration, about 8 times the concentration used in normal photographic films.

The thickness of the film are about 25 to 1000 microns. The sensitivity of an emulsion depends on the grain size, the smaller grain sizes giving more sensitivity. For Kodak N T_4 and Ilford G.5 the range of diameter of the grains are from 0.4 to 0.27 microns and the number of available grains per unit path length (100 microns) of undeveloped emulsions are 176 and 275 respectively.

(I.f) The Events in Nuclear Emulsions

The images which a nuclear emulsion have recorded can be classified as follows:-

1. The track of an ejected particle: The image of an ejected particle is a line. The track of high energy particle gives nearly a straight line, and that of the low energy is zigzagged, because of scattering.

2. Decayed event: The track of a parent charged particle decayed at rest is thicker than that of it daughter. If the particle decayed in flight, the daughter would appear with a greater or smaller velocity than the parent according to the line of motion of the parent at the instant of decay.

3. Stars: A group of tracks originated isotropically in the same point are called a "Star". The occurance of a star is due to the disintegration of a nucleus by collision. In studying

the disintegrations produced in "electron-sensitive" emulsions exposed at mountain altitudes, Brown et.al. (11) classified the tracks of secondary particles originating from star-like collisions into 3 types, according to the grain density within the track (g) as compared with g min, the grain density of a relativistic particle of charge (e) (in practice $g_{min.}$ = the grain density of high energy electron which is about 12.5 grains per 50 microns):

a. Tracks of heavily ionizing particles- (N_h):

Heavily ionizing particle tracks may be sub-devided into "black" and "grey" tracks, of which the number are designated N_b and N_g respectively. Most of the "black" track are due to the evaporation of nuclei obviously excited by collision with a cosmic ray particle, with a specific ionization greater than 10 $g_{min.}$ 'Grey' tracks are those with specific ionization between 1.4 $g_{min.}$ and 10 $g_{min.}$, most of them due to neucleons emitted from a target nucleus, mostly protons, but with an admixture of deuterons and particles of mass number 3.

b. Tracks of 'shower' particles (N_s):

These tracks are of grain density smaller than 1.4 $g_{min.}$ Most of shower particles are pi-mesons of kinetic energy greater than 80 MeV.; but there is a small portion of protons of kinetic energy greater than 500 MeV., of charged K-mesons, of anti-protons and of hyperons among them.

c. Tracks of primary particles of 'stars':

This is the track of a singly charged, relativistic particle passing thru a medium, antecedent to any collision with a target nucleus.

The primay particle is represented by P for proton, α for alpha-particle and n for neutral particles. The symbol for a star shower is represented by $N_h + N_s.x$, where x, the symbol for the parent particle, may be a proton, neutron, α - particle, etc.

(I.g) Nuclear Evaporation Theory.

The evaporation theory for the production of the secondary particles was derived by Bohr and Kalckar (12) and extended by Bethe (13) and by Weisskopf (14). A crude statement of this theory leads to the following expression for the energy spectrum of neutrons emitted:

$$N(E)\, dE = \text{const.}\ \frac{E}{T^2}\ \text{exp.}\ (-E/T)\ dE.$$

where $N(E)\, dE$ = the no. of neutrons with energy in dE at E

T = the temperature of the nucleus measured in the same units as the energy E. The relation between T and the total excitation energy depends on the particular nuclear model assumed. For charged particles (protons, alpha-particles the energy spectrum is :

$$N(E)\, dE = \text{const.}\ \frac{E - V_0'}{2}\ \text{exp.}\ -(E - V_0')/T \quad dE$$

where V_0' = the height coulomb barrier, measured in energy units.

The theory was applied by Bagge (15) and in greater detail by Harding et.al. (16) to the low energy particles observed in stars. They found, using the Fermi gas model of the nucleus and making the allowance for cooling and barrier penetration, that the theory gave a good account of the energy spectrum. The evaporation theory has recently been extended further by Le Coutuer (17) by calculating the thermal expansion of the nucleus and the effect of the neutron excess. Le Coutuer has obtained the energy distribution of evaporated particles and has calculated the probability for the emission of protons, neutrons, deuterons, tritrons, 3 He , and α -particles as a function of excitation energy. Since the excited nucleus is assumed to be always in approximate thermodynamic equilibrium the calculations have not been extended beyond energies of order of 600 MeV. Thus the maximum star size to which the theory can be applied is about 14 prongs. Since this model can only be applied to the heavy nuclei, stars which originate in light nuclei (C,N,O) should be excluded. The exclusion applies to all stars less than 6 prongs. Thus the theory can be applied only to starn between 6 and 14 prongs, but in actual fact a short extension of this prong limit is permissible.

(I.h) Cosmic Ray Components Causing the Formation of Stars at Ground Level.

Near the top of tha atmospher, there are primary and secondary cosmic rays. The number of protons and neutrons decrease with altitude, but the number of photons and electrons increase rapidly with altitude and reach a maximum somewhere between 13 and 20 kms above the earth's surface. Below this maximum the electron-photon component begins to decrease rapidly with decreasing altitude. Since mu-mesons do not undergo radiation losses comparable to those of electrons and do not undergo nuclear collision as do proton and neutrons, mu-meson component become more and more abundance as the altitude decreases. The observation by a number of coincidences cosmic ray telescopes with chunks of lead 15 c.m. thick placed between the counters at sea level showed that a few percent of the particles entering the telescopes were mu-meson of kinetic energy greater than 2×10^8 e.v. At high altitude nuclear interaction due to mu-meson is a small fraction of the total number of interactions due to all cosmic ray particles. All underground reactions are caused by cosmic ray particles other than mu-mesons. Thus mu-mesons caused only a very small fraction of the total number of nuclear interactions arising in the atmosphere, above earth's surface and in the region below the earth's surface. Experiment made by many observers confirm the conclusion that electrons and photons are not responsible for a large fraction of nuclear interactions observed either above or below the earth's surface. By eliminating electrons photons and mu-mesons, the result points to the conclusion that protons, neutrons, and pi-mesons are likely to cause these interactions. All of these latter particles have large nuclear cross-section. The relative number of nuclear interactions due to these particles depend not only on the nuclear cross-section but also on their relative abundance in the atmosphere. Neutrons disappear only by nuclear interaction. Protons, on the other hand, lose energy by ionization at low energy. (less than 500 MeV.) Thus at low energy protons are absorbed resulting in the fact that protons enter into nuclear interaction less than neutrons. This conclusion is in agreement with the cloud chamber experiments by Hazen (18) and Powell (19) also in agreement with the electron sensitive emulsion experiments by many observers, for example, Brown et. al. (11) and Page (20). Pi-mesons are observed in large fraction in cascade showers. The positive pi-meson disappears rapidly by spontaneous decay into positive mu-mesons. The negative fast pi-mesons can cause nuclear interaction at high altitude. The negative slow pi-mesons can cause nuclear disintegration in the capture by protons and deuterons, but only in small fraction, because of their short mean life. Therefore, except at very high energies, pi-mesons must be scare in the atmosphere.