THE COSMIC RAY STORY

B V Sreekantan

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NATIONAL INSTITUTE OF ADVANCED STUDIES

Indian Institute of Science Campus
Bangalore - 560 012 India.

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Philosophy of Science Unit
National Institute of Advanced Studies
Bangalore

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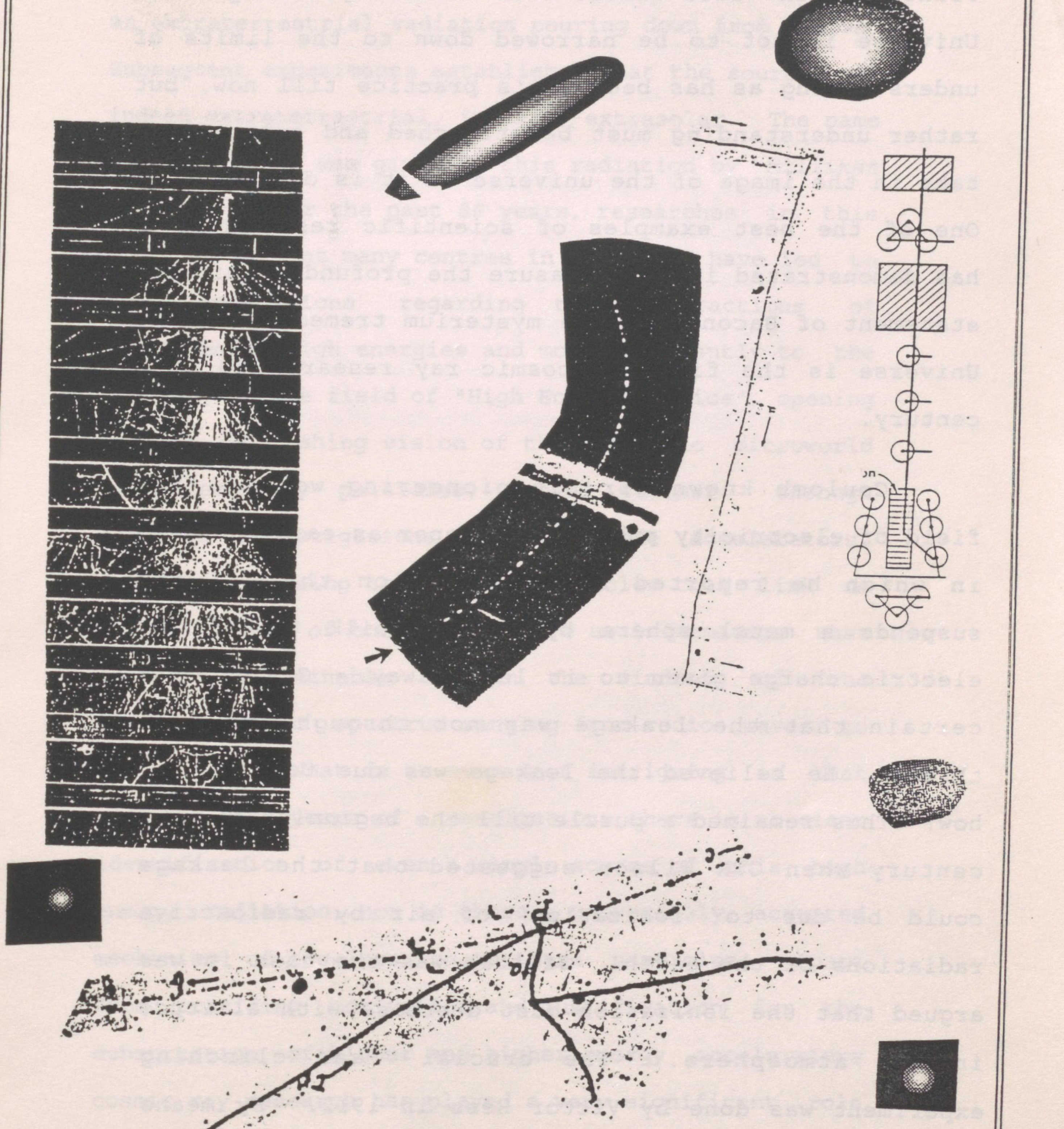

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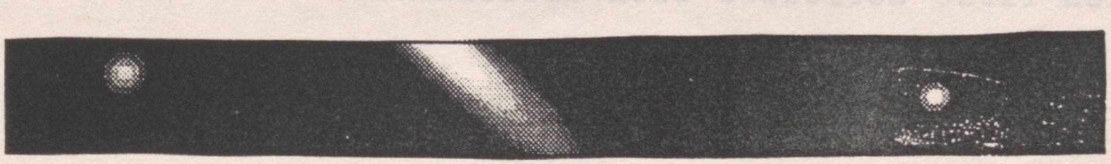

Preface

One of the founding fathers of modern science Francis Bacon said almost four hundred years ago "The Universe is not to be narrowed down to the limits of understanding as has been man's practice till now, but rather understanding must be stretched and enlarged to take in the image of the universe as it is discovered". One of the best examples of scientific research that has demonstrated in full measure the profundity of this statement of Bacon and "the mysterium tremedum" of the Universe is the field of cosmic ray research in this century.

Coulomb known for his pioneering work in the field of electricity published a paper as early as 1785 in which he reported his observation that if one suspends a metal sphere by a long silk thread any electric charge given to it leaks away. Coulomb was certain that the leakage was not through the silk thread. He believed the leakage was due to air, but how? This remained a puzzle till the beginning of this century when CTR Wilson suggested that the leakage could be due to 'ionization' of air by radioactive radiations of the earth. If this was the case it was argued that the ionization must decrease with altitude in the atmosphere. The crucial and clinching experiment was done by Victor Hess in 1912. By means of a manned balloon experiment he proved that the ionization first decreased with altitude and then went on increasing as one soared to higher and higher altitudes. This led Hess to conclude that either there is radioactive matter at higher altitudes or there is an extraterrestrial radiation pouring down from above. Subsequent experiments established that the source was indeed extraterrestrial, in fact, extrasolar. The name `cosmic rays' was given to this radiation by Millikan in 1925. Over the past 86 years, researches in this field pursued at many centres in the world have led to many revelations regarding the interactions of particles at high energies and most importantly to the spawning of the field of "High Energy Physics", opening up the astonishing vision of the subatomic microworld of elementary particles, probed further through detailed investigations with man-made accelerators. Cosmic rays being the charged particles that link us with the rest of the cosmos, give us information that is not obtainable through the windows of the electromagnetic spectrum ranging from radio waves to gamma rays. What is however most intriguing is that even after 86 years of investigations there is no clear identification of even a single source of this high energy radiation, nor is there a universally accepted mechanism of acceleration of these particles. Apart from providing motivation and justification for the construction of higher and higher energy accelerators cosmic ray research has played a very significant role also in the development of a variety of particle detectors and control and measurement electronics that had to be operated in widely different environments like balloon altitudes, high mountains, deep underwater and underground levels and more recently under deep layers of ice in the Antartic.

In this book an attempt is made to high-light these many aspects of cosmic ray research in a historical perspective and narrate "the story of cosmic rays" which as will be seen has many a time the complexion of a detective story. In the fifth chapter of the book an account is given of the Indian contribution to this field which has been long lasting, wide ranging and always in the forefront of the field. The vision of few individuals D.M. Bose, Homi Bhabha and Vikram Sarabhai in the 40's in initiating research in this field in India and creating the conditions for a sustained activity resulted in attracting a large number of young scientists to enter this field and make, over the years, outstanding contributions on many aspects of the radiation. Some of these scientists whose name will become apparent as one reads the fifth chapter not only contributed to the cosmic ray field but also shouldered major responsibilities in the development of scientific and technological activities in the post independent era. At the beginning of each Chapter there is an "overview" which essentially summarises the contents of the chapter and links it up with the general theme of the book, namely a narration of the Story of Cosmic Rays. Some of the technical terms that appear in the text are briefly explained in the glossary.

I have had the pleasure and privilege of doing research in the field of cosmic rays for almost fifty years now as a member of the Tata Institute of Fundamental Research and therefore familiar with most of the developments in the field as they happened. Nevertheless, in writing this book I have been inspired to a great extent by the very lucidly written book "cosmic Rays" by one of the pioneers of cosmic ray research Bruno Rossi, in whose laboratory at MIT, Boston, I had the privilege of working in cosmic rays and space sciences on several occasions. In presenting the Indian contribution my own preferences and biases are bound to have crept in for which of course I apologize. The field of Cosmic Ray Research is still replete with many fundamental questions to be answered - in particular questions relating to the origin and acceleration of these particles and the happenings at the highest energy end of the cosmic ray spectrum. The book would have served its purpose if it motivates some young scientists to enter this field and take up the challenge to solve some of the outstanding problems.

I would like to thank the National Institute of Advanced Studies for all the facilities provided for writing this book, and the National Book Trust of India for inviting me to write the book.

B.V. SREEKANTAN
National Institute
of Advanced Studies

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Chapter 1

Discovery and Nature of Cosmic Rays

Overview

In this Chapter, we begin the story of Cosmic rays by describing the peculiar circumstances that led to its discovery through a series of observations first at ground level and then at different altitudes right upto balloon altitudes, and the gradual identification of a primary component that is pouring down the atmosphere at all places and at all times, a secondary component that is produced in the atmosphere by the primary component by processes that the scientists became aware of for the first time. We describe the controversy that raged for several decades in the 20's and 30's regarding the identification of the nature of the primary, the global expeditions to measure the cosmic ray intensity at different latitudes, the recognition that came about that the primary radiation is dominently a charged radiation. Then we go on to the analysis of the radiation encountered at mountain altitudes and sea level by newly developed techniques of Geiger-Muiller Counter telescopes provided with coincidence circuits and magnetic cloud chambers triggered randomly as well as by counter controlled systems. These lead to the recognition of (i) a 'soft component' which is easily absorbed in, a few centimeters of lead and arrives most frequently as a 'shower' of particles (ii) a "penetrating component" that is charged and penetrates even a meter of lead. The quantum mechanical theories of radiation loss by charged particles, the theory of the 'electron' by Dirac helped to explain the nature of the soft component as comprising electrons and gamma rays resulting from bremstrahlung and pair production processes that take place in the atmosphere leaving open the question about their initial source and relation to the primary radiation.

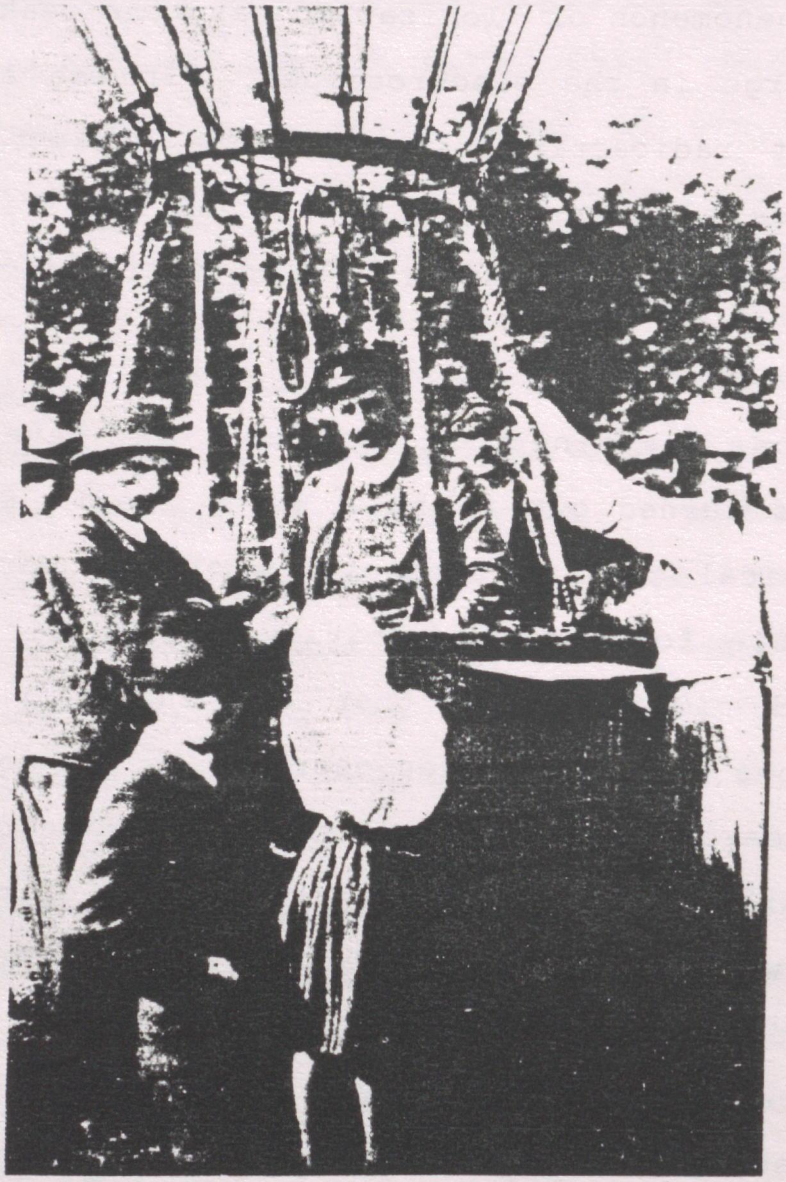
Chapter One

1.1 A mysterious penetrating ionizing radiation:

The famous french scientist well known for his pioneering work in the field of electricity, Coulomb had noticed that an electrically charged metal sphere suspended by a silk thread in air leaked away its electric charge in a short time. He had published a paper on this observation in 1785. In the early part of this century, similar observations had been made using a simple electroscope that comprised just two thin metal leaves that were clamped at one end and were free to move at ther other. Whenever an electric charge was placed on the leaves, the two separated forming an inverted "V" due to repulsion. What was most interesting was that this phenomenon of leakage happened at all places wherever observation was made and at all times - during day as well as night, and even when the electroscope was heavily shielded. One of the reasons that Coulomb himself had hinted at, was that the leakage may be due to the conductivity of the sorrounding air. What made the air conducting was the mystery.

The years 1895, 1896 and 1897, known as the 'hat trick years' of physical sciences, became memorable for the discovery of three new phenomena - discovery of X-rays (1895), discovery of Radioactivity (1896) and discovery of the electron (1897). A very important observation that was made was that in the vicinity of these radiations the air became conducting - the reason being, the neutral atoms of air were separated into positive and negative 'Ions' due to the action of these radiations. It was CTR Wilson who saw the connection between this phenomenon of 'Ionization' and the leakage of elctric charge in the electroscopes. It was soon discovered that radioactive minerals were present in small quantities all over the earth. The mysterious leakage phenomenon was thus attributed to radioactivity of the earth.

As it has happened in science on several occasions, this turned out to be a wrong lead. Some who were skeptical about radioactivity of the earlth being responsible for the conductivity of the air at all places and times, argued that the intensity of ionisation of the air should then decrease as one moves away from the earth. A novel and enterprising effort was made by Father Wulf, a jesuit priest who climbed the Eiffel tower in Paris in 1910 with his newly designed electroscope; and he did notice that the ionization decreased with height from the ground though not very convincingly. Gockel sent up the electroscope in a ballon and reached higher heights. Again the results were not sufficiently convincing to rule out radioactivity. The most crucial experiments were carried out by Victor Hess. On 7th August 1912, Victor Hess and his assistants got into a Gondola and went up



Victor Hess in the Gondola in which he went up to an altitude of 16,000 ft. for measurement of Cosmic ray intensity in 1912.

Fig 1.1

carried by a baloon to altitudes higher than 13,000 ft. (Fig 1.1) and floated for several hours and recorded the intensity at different altitudes. Surprisingly, the intensity decreased first as expected and then went on increasing with altitude. A new phenomenon had been discovered.

The elegant experimental results of Victor Hess established the presence of an extra-terrestrial radiation that caused inonization of the air. The intensity of the radiation was higher at higher altitudes in the atmosphere. The inonization was the same during day and night indicating that the source of this radiation was presumably extrasolar. These observations however did not give any clue to the nature of this radiation.

The renowned scientist Robert Millikan, who became famous for his ingenious `oil drop' experiment for the measurement of the charge on the electron, put forward the hypothesis that cosmic rays were high energy gamma rays that had origin in the process of synthesis of heavy elements in outer space. He termed them "the birth cries" of sysnthesis of heavy elements (hydrogen to helium and so on). He was essentially guided by the fact that among the radiations known in the early part of the century the alpha-particles, the beta-particles (electrons), the gamma-rays and the protons, the most penetrating were the gamma-rays which

Arthur Compton's first experiment in Cosmic Rays was done because Sir Ernest Rutherford had started wondering why radium was radioactive. Mme. Curie had suggested that this might be due to the capture of Cosmic Rays by radium.

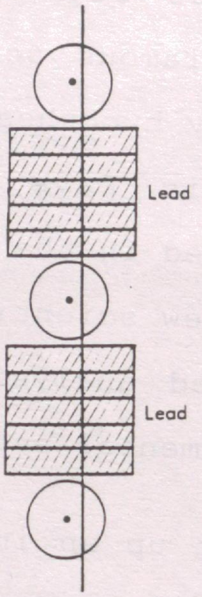
"So in 1921, I put a little radium in an electroscope and carried it with me on mule back down Bright Angel Trail to the bottom of the Grand Canyon. There the Cosmic Rays were feebler than at the top, but radioactivity of radium remained unchanged. Mme. Curie's guess was wrong. But not all our guesses have been wrong" Compton.

"I am inclined to think that Wilson's attraction to think thunder cloud as a source of Cosmic Radiation owes much to an experience he had as a young man. One summer walking on holiday in Scottish hills he was near one of the summits of Ben Nevis when there was muttering of distant thunder. Suddenly his hair stood on end and he immediately ran down the scree slope. A few seconds later a flash of lightning stuck near where he was standing. This experience, he said many years later, deeply impressed him with the power latent in a thunder cloud and the rapidity with which electric field associated with it could change." Hess.

caused ionization not directly but through the electrons they knocked out from the outer shells of the atoms. However, it turned out that both the hypotheses namely the process of synthesis of heavy elements in nearby outer space and the identification of cosmic rays with gamma-rays were not supported by later experiments. Another equally famous scientist Arthur Compton challenged the gamma-ray hypothesis of Millikan and proposed that the Cosmic Rays were charged particles. This controvery raged in the 20's and early 30's of this century. Quite a few scientists in Europe, Soviet Union and U.S.A. started analysing the Cosmic ray beam with very novel experimental set-ups.

Bothe and Kohlhorster set up an ingenious device - two Geiger Muiller counters one above the other and established that most of the cosmic ray particles were charged penetrating particles (i) because they caused simultaneous discharges in both the counters, and (ii) they passed through a 4.1 cm gold plate placed in between the counters.

An Italian scientist Bruno Rossi opened up a new method of investigation in cosmic ray research by developing what has come to be known as "the Rossi Coicidence Technique". This enabled for the first time an electronic way of recording the passage of charged particles through any number of counters and establishing their simultaneity within a short interval



Experimental arrangement used to demonstrate penetrating power of cosmic-ray particles. The number of lead bricks between counters can be varied to form an absorber as much as 1 meter thick. Only charged particles capable of traversing the absorber produce coincidences.

Fig 1.2

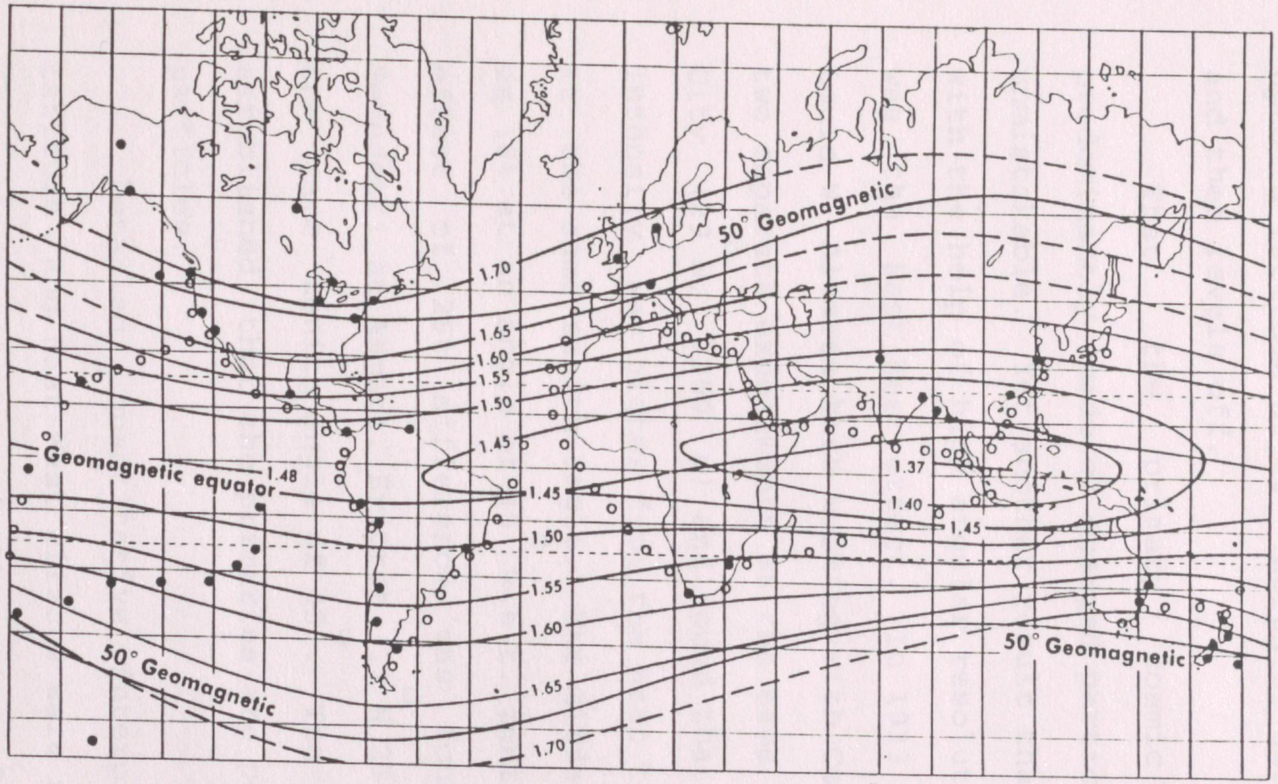
of time, thus reducing the contribution of extraneous chance events that constituted a background in all such experiments. The Rossi Coincidence and anti-coincidence circuits are the precursors to the "And", "Or" circuits of digital computers. As we shall see the Rossi Coincidence Technique provided another major break through - counter controlled cloud chamber technique introduced by Blackett for recording pre-selected types of cosmic ray events in cloud chambers. Though the experiments of Bothe and Kohlhorster and later of Bruno Rossi established that the cosmic rays observed at Seal Level and mountain altitudes were predominently charged particles, (Fig 1.2) it was not certain that the so called primary particles that arrived at the top of the atmosphere from outside were charged particles. The suspicion had begun that the particles encountered at the lower levels in the atmosphere were secondary to a primary radiation. The exact mechanism how the secondary particles arose was not known. The cosmic ray problem became compounded. One had to establish the nature of secondary particles unambiguously, the nature of the primary particles (charged or neutral) and the modality of origin of the secondaries.

1.2 The Geomagnetic Field and Cosmic Rays

The first question whether the primary cosmic rays were charged or neutral (gamma-rays) was settled by making use of the fact that the entire earth acts like a bar magnet with the associated magnetic field being strongest at the poles and weakest at the equator.

In 1927, a Dutch physicist, Clay had carried an ionization chamber aboard a ship which made a journey from Leiden in Holland to Java in Indonesia (Dutch EAst Indies then). The ship travelled through the Suez Canal route. Clay noticed that the intensity of ionization dipped by several percent near the equator. Contrary to this observation, Millikan and his associates found practically no change between Bolivia (19^{O}S latitude) and Pasadena (34^{O}N) in California, or between Pasadena and Churchill 59^{O}N) in Canada. Similarly Bothe and Kohlhorster failed to detect any variation with latitude in the North Sea. However, the Swedish physicist Axel Corlin had noticed a small latitude effect in the Baltic Sea. These observations namely, lack of laltitude effect were claimed by Millikan to support his primary gamma-ray hypothesis.

In 1930, Arthur Compton organised eight expeditions to different parts of the World carrying identical instruments for a world wide survey of cosmic ray intensity. (Fig 1.3) The latitude effect of cosmic radiation was unambiguously established. Further experiments by Compton and his collaborators and Millikan and his collaborators at high altitudes both at high mountain altitudes and high balloon altitudes



Isocosms, or curves of equal cosmic-ray intensity, according to A. H. Compton. The numbers on the curves give the intensity of the cosmic radiation level, as measured by the number of ion pairs they produce in 1 cm^3 of air at standard temperature and pressure. Dots show locations where measurements were made. The graph also shows the geomagnetic equator and two geomagnetic parallels (50° N and S). (From a paper in *Review of Scientific Instruments*, vol. 7, p. 70, 1936.)

Fig 1.3

showed that the latitude effect was very much more pronounced at higher altitudes. (Fig 1.4) One other interesting feature that can be noticed from the figure is so-called "knee effect". The intensity increases upto a latitude of 40° (North or South) from equator and then levels off.

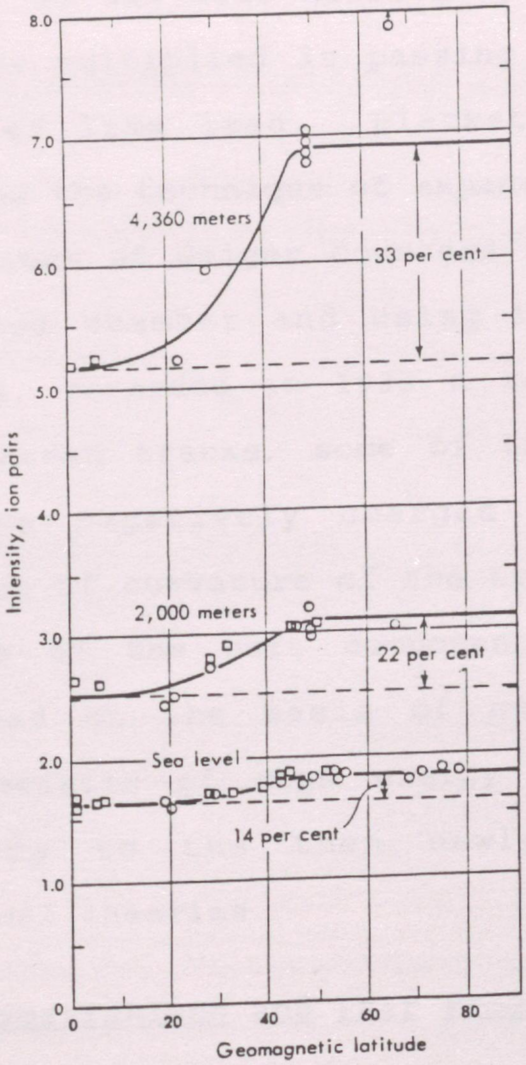
That the primary cosmic radiation was predominantly made of charged particles was therefore unmistakable. Yet another result that was established with the help of high angular resolution GM telescopes was the East West effect. In 1933 T.H. Johnson and Louis W. Alvarez both working with Compton carried out two separate experiments at the same location in Mexico City (29° N, 2250 m) and found that the cosmic ray intensity was higher from the West than from the East at the same zenith angle. The difference was as much as 10% at an angle of 45° w.e.t. zenith. A much larger effect of 26% difference was found by Rossi and Benedetti at Asmara, Eritrea (11° N 2370m above S.L.) at the same zenith angle of 45°. The East-West effect established that the primaries are positively charged particles.

Detailed quantitative interpretation of the latitude and East-West effects were made possible by the pioneering study of the motion of charged particles in the geomagnetic field by the Norwegian geophysicist Carl Stormer. The famous phenomenon of aurora borealis

- luminous colourful displays - the northern lights - attribued to the incidence of clusters of charged particles on the atmosphere at the time of magnetic storms on the Sun, had inspired Stormer to undertake these difficult calculations of the trajectories of charged particles in the geomagnetic field sorrounding the earth. More sophisticated calculations particularly relevant to cosmic ray studies were made by George E. Lemaitre of Belgium and Manuel S. Vallarta of Mexico and their students. The mechanical computer developed by Vannevar Bush at the Massachusetts Institute of Technology, Boston, came in handy in these computations of trajectories.

1.3 The Soft Component of Cosmic Rays:

Detailed analysis of the cosmic ray phenomena at sea level and mountain altitudes revealed the presence of two components. These experiments were carried out with Geiger-Muiller Counter telescopes and randomly triggered and later counter controlled cloud chambers. One of the components which came to be known as the 'soft component' was characterised by the fact that it was easily absorbed in a few cms of lead. It was also noted that this component quite frequently came in bursts of several particles practically all of which were soft. The simultaneous triggering of three or more Geiger counters placed in a horizontal plane in such a way that a single particle could not pass



Cosmic-ray intensity as a function of geomagnetic latitude at three different altitudes. The intensity is measured by the number of ion pairs produced by cosmic rays in 1 cm³ of air at normal temperature and pressure. (From A. H. Compton, *The Physical Review*, vol. 43, p. 387, 1933.)

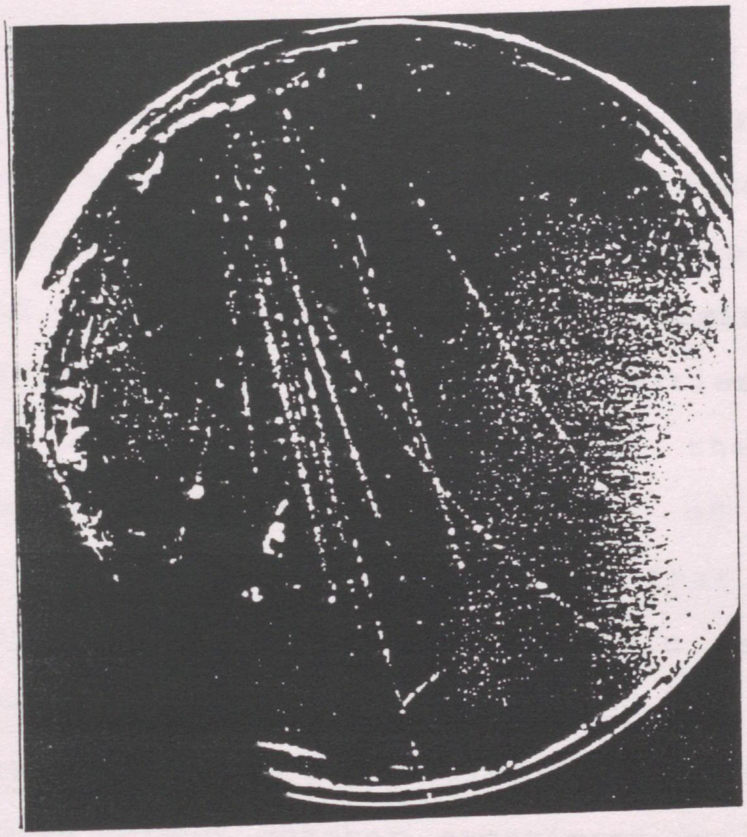
Fig 1.4

through all of them, first established the presence of such 'showers'. Skobeltsyn in the soviet union obtained cloud chamber photographs of such shower events, in a magnetic cloud chamber. The tracks were fairly straight indicating the particles were of high energy. It was also noticed by Rossi that these soft particles multiplied in passing through small amounts of matter like lead. Blackett and Occhialini who developed the technique of expanding the cloud chambers by a system of Geiger counters placed above and below the cloud chamber and using the Rossi coincidence circuits, recorded in 1933 a remarkable shower event with sixteen tracks, some of them positively charged and some negatively charged as indicated by the direction of curvature of the tracks (Fig 1.5). These features of the soft component of cosmic rays were explained on the basis of new physical phenomena characteristic of high energy electrons and photons according to the then newly developing quantum mechanical theories.

1.4 Bremstrahlung and Pair Production:

It was known that whenever a high energy charged particle like an electron was brought to rest suddenly or accelerated or its direction changed, there was emission of radiation. In 1934, Bethe and Heitler, who were then in England, calculated the energy loss of charged particles passing in the neighbourhood of the coulomb force of nuclei inside the atoms using the newly developing quantum theory and came to the surprising conclusion that the energy radiated could be an appreciable fraction of the energy of the particle itself. Their calculations also showed that the radiation loss is much higher and more frequent in the case of light mass particles like the electrons and the energy loss increased rapidly with energy. They also calculated the energy and mass dependent cross section for this process of emission of radiation which has the name ‘bremstrahlung radiation’

Another very interesting development that had taken place around the same time was the formulation of the quantum mechanical wave equation for the electron by the cambridge theoretical physicist Paul Dirac. Dirac’s theory of the electron had led to an important result that there should be in nature particles which are counterparts of the negatively charged electrons. Though initially the counterpart was confused with the Proton, soon it became evident that the anti or counter particle should have the same mass as the electron, but should have positive charge instead of negative charge. It was also predicted that such positive and negative electron pairs would be produced in the passage of high energy gamma-rays in the neighbourhood of nuclei.



Photograph obtained by Blackett and Occhialini with their counter-controlled cloud chamber. The chamber is situated between the poles of an electromagnet. Sixteen separate tracks of secondary particles enter the chamber simultaneously; they originate above the chamber, being produced, apparently, in the copper coils of the magnet (not shown in the picture). The curvature of the tracks is caused by the magnetic field; the tracks of positive particles curve to the right, the tracks of negative particles to the left. [From P. M. S. Blackett and Giuseppe Occhialini, *Proceedings of the Royal Society (London)*, vol. A139, p. 699, 1933.]

Fig 1.5

Chapter 2

Fundamental Particles Galore

(Overview)

In this Chapter, we start with the discovery of the "positron", the anti-particle of the electron with a magnetic cloud chamber by Carl Anderson in 1932, while analysing the Cosmic ray beam at Pasadena. This discovery confirmed the predictions of the quantum-relativistic electron theory of Dirac, according to which a high energy gamma-ray would materialise into an electron and positron pair in passing through matter. This coupled with bremstrahlung emission led to the 'Cascade theory' of Bhabha and Heitler, also of Carlson and Oppenheimer. The Cascade theory beautifully explained the 'Soft component', of cosmic rays, and further led to the prediction that the penetrating component' encountered in cosmic rays required the presence of particles of mass much higher than the electron. This prediction was again confirmed by another cloud chamber experiment by none other than Carl Anderson himself in collaboration with Neddermeyer. The mass of this particle was about 100 electron masses. An interesting aspect was that this new particle given the name meson was unstable and spontaneously decayed into an electron and two neutrinos. The mean lifetime was measured to be about two microseconds. The identification of the meson with the penetrating component solved the mystery of the penetrating component and its unstable nature resolved some of the anomalies observed on the absorption properties of the penetrating component in dense and extended media.

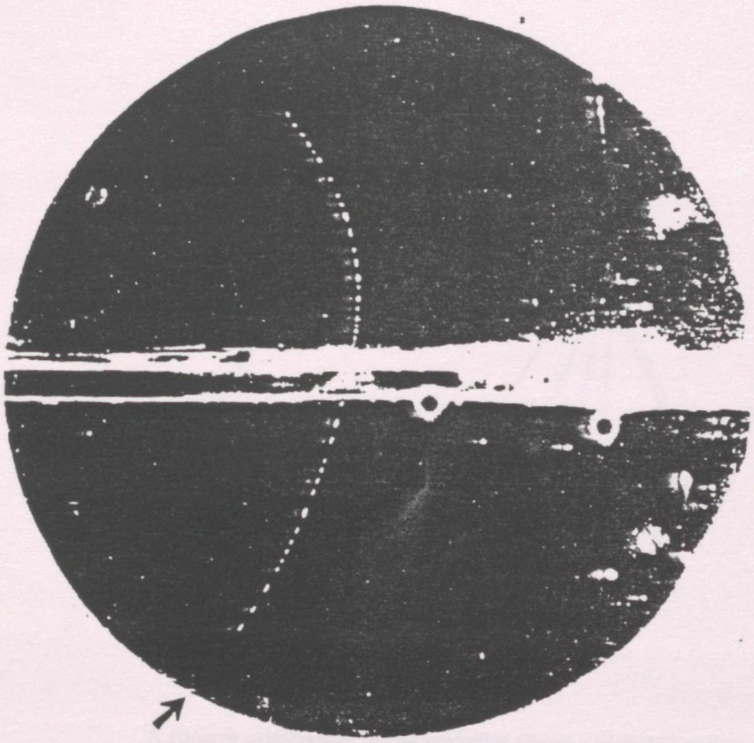
Around the time of the discovery of the meson, the Japanese Physicist Yukawa had proposed that the nuclear forces that held together protons and neutrons inside nuclei, were mediated by a heavy mass particle. The hasty identification of the meson discovered by Anderson with the Yukawa particle led to complications described in this chapter. The problem got resolved with the discovery of the Pi-meson by Powell and his collaborators. It became clear that it is the Pi-meson that is the Yukawa particle and the Anderson meson which was given the name mu-meson resulted from the decay of the Pi-meson.

The act of production of Pi-mesons in large numbers in collisions of high energy particles was caught both in mountain and Sea Level Cloud chamber experiments as well as in nuclear emulsion stacks exposed at balloon altitudes. This was followed by the discovery that in these collisions not only pi-mesons are produced, but also other types of mesons and hyperons, though in much smaller numbers. These were extremely short lived and decayed into other particles. A special feature that was noticed was that these new particles were always produced in association as a particular pair of particles. This led to the recognition of another quantum number called "Strangeness". The new exciting field of 'Elementary Particle Physics' was born.

Chapter 2

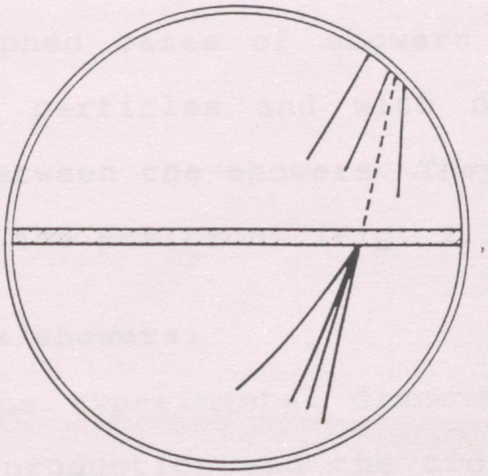
2.1 Discovery of the Positron by Carl Anderson

In 1932, Carl Anderson had set up a cloud chamber in a magnetic field of 24,000 gauss to analyse the nature of the cosmic ray beam at sea level at the California Institute of Technology in Pasadena. One of the cloud chamber photographs he recorded is shown in the Figure (2.1). The lone charged particle that enters the cloud chamber from the bottom passes through the lead plate at the centre of the chamber, loses some of its energy as indicated by the increased curvature of the track in the top half of the chamber. The direction of bending established that the charge of the particle was positive. The magnetic rigidity of the track had changed from 2.1 X 10^6 gauss.cm to 7.6 X 10^4 gauss.cm and the ionization density had not changed sufficiently to identify the particle as the then known only positively charged particle - the proton. Anderson concluded that the particle was the counterpart of the electron. An interesting aspect of this event is that normally one would have expected that the positron being part of the cosmic ray beam would have shown itself in the first instance as a particle coming from the top of the chamber, since the general directions of cosmic ray particles are from top to bottom. In this major discovery of a new particle, Nature had planned differently. The positron went from below to the top!



The positron, or positive electron, was identified as the particle that entered the cloud chamber from below and produced the track curving sharply to the left after traversing the lead plate. The photograph, taken by Anderson in 1932, definitely established the existence of positrons. (From a paper in *The Physical Review*, vol. 43, p. 491, 1933.)

Fig 2.1



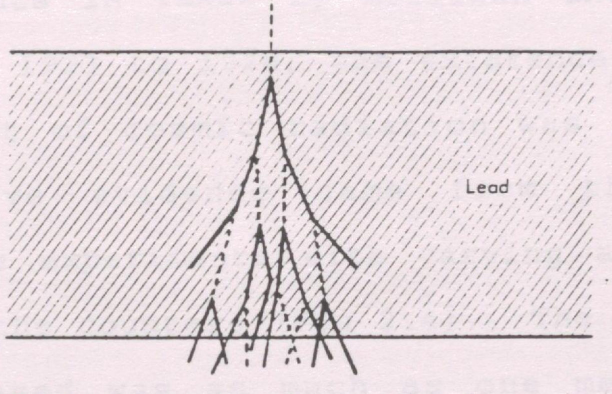
A shower originating in the material above a cloud chamber contains a nonionizing link or photon (dashed line), which produces a secondary shower in the horizontal metal plate across the chamber. [Traced from a photograph published by Blackett and Occhialini, *Proceedings of the Royal Society* (*London*), vol. A139, p. 699, 1933.]

Fig 2.2

Anderson was not aware of the theoretical developments that had taken place in Cambridge, England, predicting the possible production of positrons in the materialization of high energy gamma-rays. In Cambridge itself Blackett and Occhialini had been operating a magnetic cloud chamber with a central plate similar to the arrangement of Anderson. They had photographed cases of showers with both positive and negative particles and with non-ionizing (gamma-ray) links between the showers. They however missed the discovery of the positron! (Fig. 2.2)

2.2 Cascade showers:

With the experimental discovery of the positron and of pair production and the cross sections for the production of bremstrahlung and pair production made available by Bethe and Heitler the stage was set for the theoretical recognition of another dimension to these two processes, namely the development of what came to be known as "electromagnetic cascade showers". This was achieved almost simultaneously by two groups of scientists, Bhabha and Heitler in U.K. and Carlson and Oppenheimer in the United States. In a cascade shower, a high energy electron gives rise to a high energy photon in passing through any matter, lead, water, air, etc. and the high energy photon gives rise to a positron-electron pair further down by the pair production mechanism. The two electrons give rise to more photons by bremstrahlung and the process of pair production repeats. Thus a single electron (or photon) multiplies into a large number of secondary photons and electrons in passing through matter (Fig. 2.3). The multiplication ceases only when the energy of the bremstrahlung photons fall below a critical energy of a ~ 1 Mev equal to the sum of the rest energy of an electron and a positron. As discussed earlier, the cross section for bremstrahlung and pair production are functions of the energy of the electrons and photons, and also depend on the atomic number of the material through which the cascade develops. The physical length over which each process takes place is called a radiation length. The radiation length in lead is about 6 gms/cm^2 (~ 6mms) while in the case of air it is 9.5 gms/cm^2 and naturally the equivalent length expressed in meters is a function of the height of the atmosphere, since the density falls exponentially. The calculations showed that the number of particles at the cascade maximum could range from a few particles to billions of particles depending on the initial energy. The observed shower phenomenon in cosmic rays at sea level and mountain altitude and the phenomenon of multiplication of particles observed in some experiments found a natural explanation in terms of this cascade development of electrons and photons. Thus the puzzle on the so called 'soft component' got resolved. Of course, the question remained regarding the source of the initial high energy electron or



Development of a shower in matter through successive events of pair production and radiation. Dotted lines represent photons, solid lines electrons.

Fig 2.3

photon. This question we will discuss in a subsequent section.

2.3 The penetrating component - discovery of Mu-meson (Muon)

Even from the first series of underwater experiments in lakes by Millikan and Regener carried out from 1923 to 1928, the existence of a penetrating component of cosmic radiation was suspected. More definitive evidence came from the G.M. counter telescope experiments with varying amount of lead in between the counters (Fig 2.4). The maximum amount of matter used was as much as one meter of lead and according to the cascade theory we have discussed above, no electron or photon could traverse this amount of lead without multiplication. The experiments clearly established the existence of a charged particle that could penetrate a meter of lead or more. In a brilliant paper published in the proceedings of the Royal Society, Homi Bhabha, after analysing the theoretical aspects of 'passage of charged particles though matter and the experimental results came to the conclusion that

either 1. Quantum Electrodynamics which was the theory on which the cascade development was based breaks down at high energy.

Or, 2. There exists in cosmic radiation yet another particle with a mass intermediate between the electron and the proton.

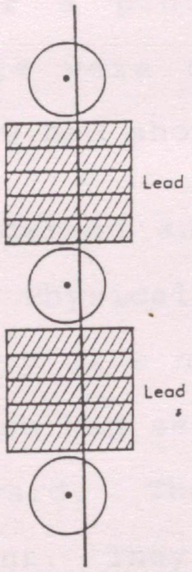
Anderson of the positron discovery fame and Seth Neddermeyer were operating a cloud chamber in a magnetic field with a 3-5 mm thick lead plate in the middle of the chamber. From the curvature of the tracks they found that most of the particles had a rigidity between 10^5 and 10^6 gauss. cm. The anomaly was that if the tracks were due to protons they should ionize more heavily than observed. To get more definitive evidence regarding the nature of these particles they replaced the 3.5 mm lead plate by a 1 cm thick platinum plate (equivalent to 2 cms lead as far as radiation losses are concerned). Since this was equivalent to 4 radiation lengths, electrons could be definitely ruled out since they would multiply into cascades or get absorbed. They summarized their results (1937) as follows:

1. There exist a group of particles which lose a small fraction of their energy in passing through the platinum plate.

2. There exist another group which lose their energy significantly and can be identified with the electrons.

3. The energy loss of the first group, the penetrating particles seems to be only due to ionization. The other electromagnets processes are not important.

4. The particles of the same curvature show both the characteristics. Some of them lose energy fast, the others don't. Therefore they cannot all be the same



Experimental arrangement used to demonstrate penetrating power of cosmic-ray particles. The number of lead bricks between counters can be varied to form an absorber as much as 1 meter thick. Only charged particles capable of traversing the absorber produce coincidences.

Fig 2.4

particles and the explanation that quantum electrodynamics breaks down at high energies is ruled out.

On the basis of all this analysis, Anderson and Neddermeyer concluded, "there exist particles of unit charge, but with a mass (the mass may not have a unique value) larger than that of electron and smaller than that of a proton". The characteristics of this particle were not different from the one Bhabha's analysis had shown.

Anderson and Neddermeyer published their results in the Physical Review, without firmly claiming the discovery of a new particle at that stage. Street and Stevenson had set up a similar cloud chamber experiment at Harvard. The triggering of the cloud chamber was different. They triggered it for penetrating particles that stopped in the cloud chamber by a coincidence and - anticoincidence arrangement above and below the chamber. With this arrangement they could measure, for stopping particles, the ionization by the technique of delayed expansion which caused the ions to separate out considerably before droplets condensed on them. From the ionization and curvature they obtained a very clear case of a stopping particle which had a mass 200 times that of the electron. Brode and his collaborators used a multiple cloud chamber with 15 lead plates each 0.63 cms thick, below a magnetic could chamber. This arrangement enabled the measurement of curvature in the top chamber and the range in the bottom chamber of stopping particles. With this they were able to arrive at a mass of 200 ±2 electron masses. This particle was first given the name mesoton and then changed to mesotron by Anderson's Professor, Robert Millikan in 1937. Bhabha in a paper in Nature (Feb 1939) argued in favour of "meson" which has stuck on.

2.4 <u>The</u> <u>Yukawa</u> <u>Particle</u> (Yukon)

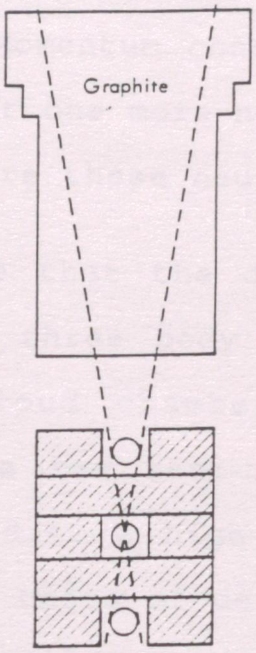
In the period just before the Second World War and during the war period some very interesting and important developments took place in Japan which was a country quite isolated from the rest of the scientific world of Europe and U.S.A. The nuclear physics experiments in these countries had established very interesting aspects of the nuclear forces especially after the discovery of the neutron by Chadwick in 1932. Apart from the very short range of the nuclear forces, what was most intriguing at that time was the forces were the same between proton and proton, between proton and neutron and neutron and neutron. The lack of electric charge on the neutron did not affect the nuclear force. The Japanese theoretical physicist Yukawa had come up with the idea in 1935 that this nuclear force is due to the exchange of a heavy mass particle, on the analogy that the electrical forces between protons and electrons for example, are due to the exchange of photons according to the ideas of quantum electrodynamics. The heavy mass was required to ensure that the forces are short range. Yukawa had come to the conclusion that the mass of this particle is about 200 m_e since the range of nuclear force was ~ 10^{-13} cms. When he was working on this theory he came across the paper of Anderson and Neddermeyer indicating the possibility in cosmic rays of a particle of mass between electron and proton. Yukawa persuaded his Japanese colleague Nishina to carry out an experiment, to look for this intermediate mass particle. Despite being war period and suffering from acute shortage of electrical power for his magnet, Nishina did set up a cloud chamber experiment and did record the existence of particles of mass around 200 m_e. By this time the discovery paper of the American scientists had been published. Yukawa predicted that his particle which he called Yukon would be unstable and would spontaneously decay into other particles with a mean lifetime of about 10^{-8} Sec.

2.5 <u>The Lifetime of the Meson</u>

It was clear that the Meson discovered by Anderson and Neddermayer was the penetrating particle that Cosmic ray scientists had been looking for. However, there was a serious problem. The experiments of the different groups indicated that the absorption of these penetrating particles was less effective in a solid or liquid medium like lead or water than in the atmosphere itself. For the same amount of matter, somehow an extended medium absorbed more particles than a condensed medium. This was established on the basis of intensity measurements at different altitudes and with different amounts of lead in the telescope (Fig 2.5). The explanation for this anomaly was given by the German physicist Kuhlenkampff. He pointed out that a layer of lead of 10 cms thickness corresponds to 8000 cms of air near sea level, and to 16,000 cms at an altitude of 5100 meters. If the mesons are unstable and decay with a mean life of a microsecond (10^{-6} sc), and are travelling close to the velocity of light ($3X10^{10}$ cms/sc), they will not decay appreciably in 10 cms of lead (travel time 0.00033 µs) while quite a few will decay in 8000 cms of (travel time 0.265 µs). Therefore in an extended medium, there will be loss of mesons due to spontaneous decay in addition to absorption.

The meson decay opened up several new lines of investigations. What is the exact mean lifetime? What are the decay products of the meson? Do positive and negative mesons decay with the same lifetime? Very many ingenious experiments were done to find answers to these questions.

Very fortunately, the very very rare kind of events in which the Meson slowed down in passing through the mid plate of a cloud chamber and became so



Experimental arrangement for the comparison of the meson absorption in air and graphite.

Fig 2.5

slow that it started ionizing very heavily and a secondary particle identified as an electron emerging at an angle from the primary were recorded. One such picture is shown in Fig (2.6) These pictures established that the charged secondary in meson decay was the electron. Momentum conservation required that there must be atleast one more neutral particle, if not two or more. What are these neutral particles?

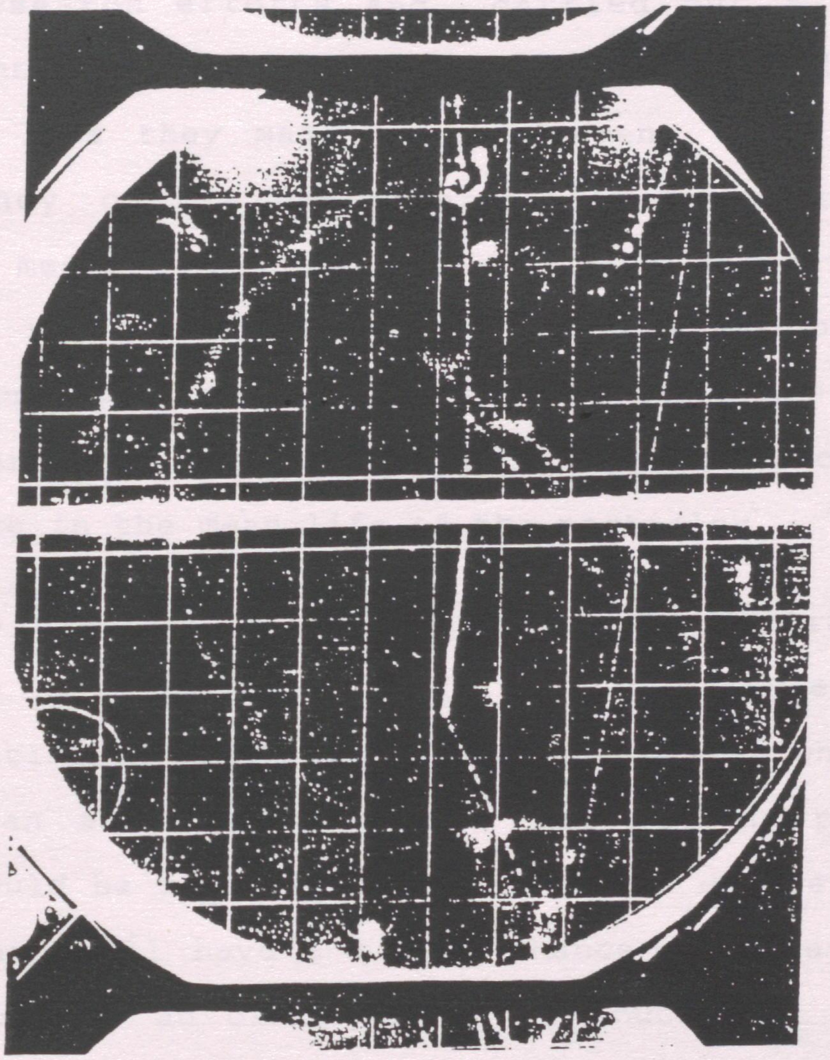
The first clue that the decay of the meson was more likely to be a three body decay than a two body one came from a cloud chamber experiment of Carl Anderson in which he had sent a small cloud chamber with a magnetic field to a high altitude in a balloon and had recorded two cases of decay of mesons. In one case the energy of the electron was 50 mev and in the other case 25 mev. If the decay had been a two body one, then momentum conservation would have required the electron to have the same energy in both cases. More detailed experiments carried out later by bringing the mesons to rest and measuring the energy spectrum of the electrons established the decay to be a three particles decay - one charged and two neutrals.

To save the principles of conservation of energy and momentum in the emission of Beta-particles from radioactive substances, Wolfgang Pauli had postulated in 1931 the emission of a neutral particle with about zero mass in these decays along with the electron.

This neutral particle was given the name 'neutrino' by the famous Italian physicist Enrico Femni who later became the architect of nuclear reactor physics and constructed the first nuclear reactor at Chicago. With the discovery of the neutron in 1932 and its decay into a proton and electron and with the observation that the spectrum required a three body decay, the third particle was identified as the neutrino that Pauli had postulated. The same thing happened with the discovery of the three body decay of the meson. It was immediately attributed to the emission of two neutrinos in the decay of the meson the charged secondary being either an electron or a positron. Later experiments at accelerators established two very interesting results on neutrinos - that there are both neutrinos and antineutrinos and there are three different types of neutrinos with corresponding antineutrinos.

2.6 <u>Complications due to the hasty identification of the Meson with the Yakuwa particle Yukon</u>:

As we have already discussed, Yukawa had postulated the existence of a particle of mass between the electron and positron as the mediator of the nuclear force between proton-proton, proton-neutron and neutron-neutron. With the experimental discovery of the meson by Anderson, the natural assumption was made that the two are the same. This gave rise to a lot of confusion and complication which was resolved by another major discovery.



Decay of a μ meson. The meson enters the cloud chamber from above. It traverses an aluminum plate 0.63 cm thick, where it loses most of its energy. The meson, which leaves the plate as a slow and therefore heavily ionizing particle, comes to rest in the gas. The track of an electron originates from the end of the μ-meson track. The electron, traveling at nearly the speed of light, produces a track approximating that of a minimum-ionizing particle. The tracks of the meson and the electron are slightly bent by a magnetic field, and the direction of the deflection shows that both particles are positively charged. (From R. W. Thompson, *The Physical Review*, vol. 74, p. 490, 1948.)

Fig 2.6

In spite of the second World War bringing to a halt all basic research in Europe, the Italian physicists Conversi Panchini and Piccioni persisted in their research efforts and carried out a crucial experiment with cosmic ray mesons. With a solid iron magnetic lens they made an arrangement (Fig 2.7) by which they could concentrate either positive or negative mesons in an absorber at the bottom of the lens and record the decay time on an event by event basis adopting a delayed coincidence technique. They could change the absorber at the bottom and record any difference in the mean life of the particles.

Two Japanese scientists Tomanaga and Araki had argued in 1940 that there would be a difference in the mean lifetime of positive and negative mesons when they stop in an absorber and decay, because the positive mesons would be repelled by the positive charge on the nucleus and will have a better chance to decay while going round in an orbit around the nucleus. In the case of negative mesons, most would enter the nucleus and get totally absorbed and only a few of them will have a chance to decay.

The results showed that in the case of iron as the absorber all positive mesons brought to rest decayed while none of the negative mesons did. But when the absorber was made of light nuclei like carbon negative mesons also decayed. In fact, by doing experiment with magnesium also as the absorber they came to the conclusion that there was a Z (atomic number) dependence on the capture by nuclei, and consequent Z dependence of the life time.

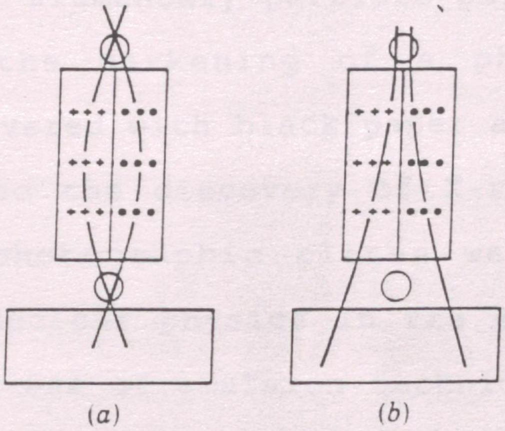
The real anomaly revealed by these experiments was that if the meson was the Yukawa particle, then the nuclear attraction should be quite high even in the case of light nuclei and negative mesons should have been captured by nuclei and not allowed to decay. Such a weak interaction was puzzling and it meant that the meson seen in cosmic rays may not be the Yukawa particle.

Another anomaly was the value of the mean life time itself. It was 100 times longer than what Yukawa had calculated for his particle.

This anomaly was the focus of discussion at a meeting held in Shelter Island in U.S.A. immediately after the war. One of the possibilities proposed by the theoretical physicist Marshak of Rochester was that probably there are two types of mesons in cosmic rays - a heavier one that decayed into the lighter meson. It was the lighter meson that had probably been discovered. The heavier one may be the Yukawa meson.

2.7 Discovery of the Pi-meson, the parent of Mu-meson:

We have seen that the discovery of the Geiger counters for registering charged particles and of the Cloud Chamber for recording tracks of charged particles had been responsible for major advances in cosmic ray



Magnetic lens consisting of two iron bars magnetized in opposite directions. (*a*) The magnetic field points away from the observer (that is, into the page) in the bar at left and toward the observer (that is, out of the page) in the bar to the right. *Positive* particles passing through the upper G-M counter are deflected by the magnetic field toward the lower counter. (*b*) The magnetization of the bars is reversed. Positive particles passing through the upper G-M counter are deflected away from the lower counter. The lens in (*a*) will deflect *negative* particles away from the lower counter; the lens in (*b*) will deflect them toward the counter.

Fig 2.7

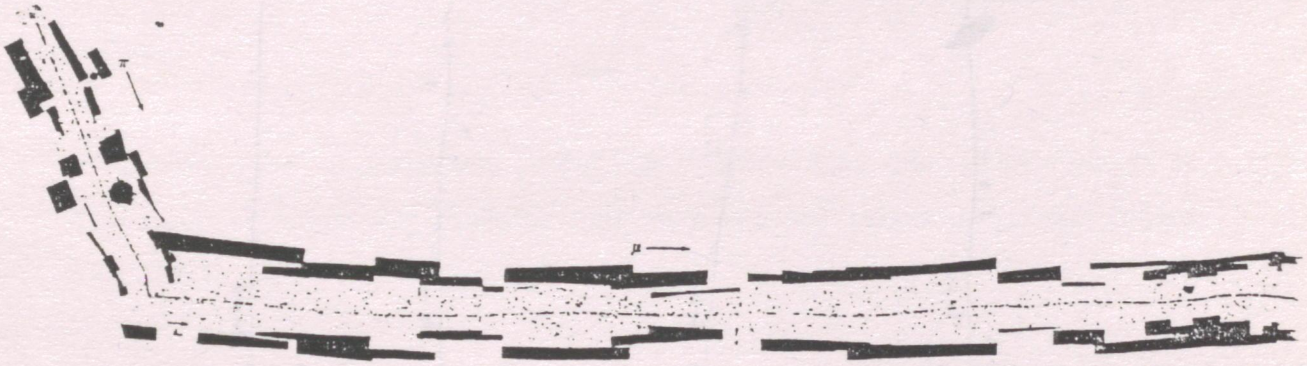
research and played crucial role in the discovery of the positron and the muon. In the mid 40's the introduction of yet another new technique - the photographic emulsion technique, played an important role in further startling discoveries which opened up new vistas of elementary particle physics. It is well known that the darkening of a photographic plate completely covered with black paper and kept in a table drawer, led to the discovery of X-rays by Rontgen in 1895. The photographic plates were used later in research in nuclear physics in the early part of this century. The use of emulsion technique for cosmic ray research was initiated by Powell of the University of Bristol in England in the mid 40's. In collaboration with the famous company Ilford, Powell and Occhialini developed photographic plates which had much higher concentration of Silver Bromide than in the normal plates. This resulted in higher sensitivity to the recording of the charged particles in the emulsion.

Following this, the Eastman Kodak Company in the United States also developed highly sensitive strips of nuclear emulsions that could be used even without any glass backing. Scientists developed techniques like grain counting, scattering of tracks, which enabled quantitative determination of the properties of the charged particles that produced the tracks in the emulsions, properties like the mass, charge, momentum, etc.

In 1947, a Brazilian student who had come to work at Bristol, Lattes and his Professors occhialini and Powell exposed some of the newly developed highly sensitive emulsion plates to cosmic rays at Pic du Midi mountains in the Pyranese. The photomicrograph of a typical interesting event recorded is shown in Fig (2.8)

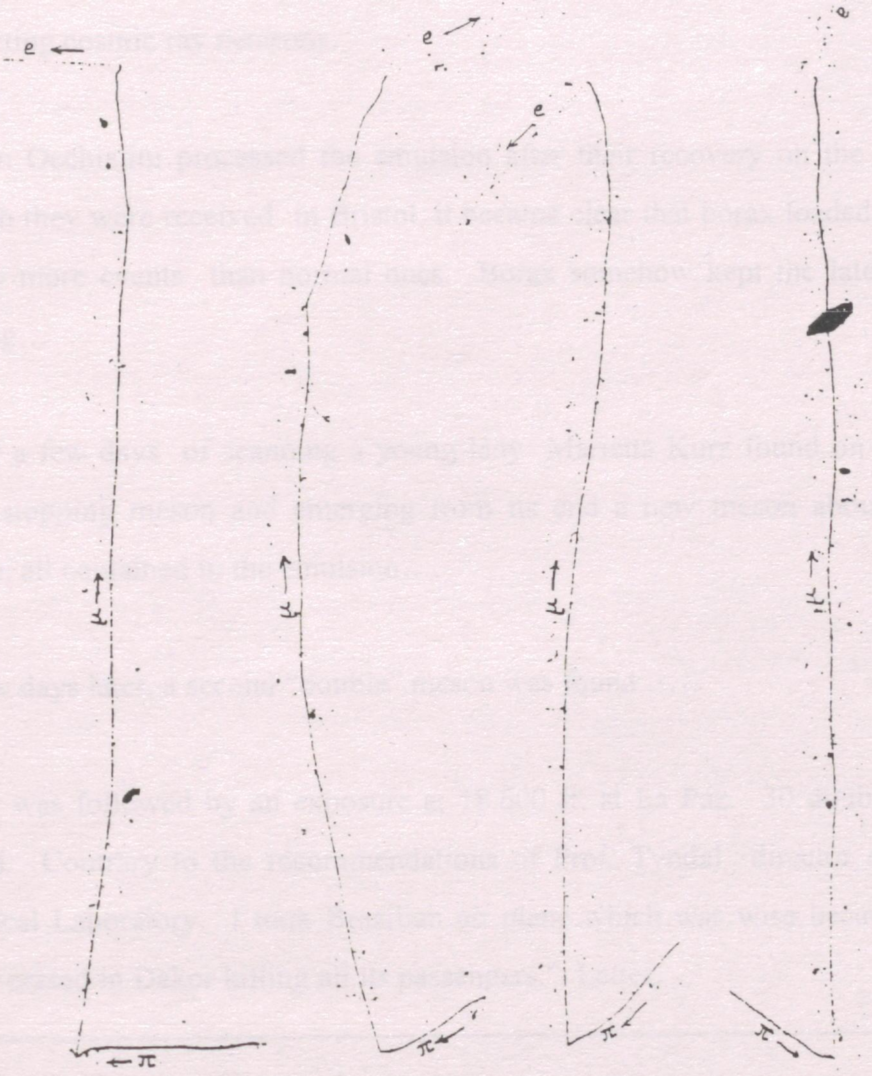
It is seen from the Fig 2.8 that a particle comes to rest in the nuclear emulsion as evidenced by the increased ionization at the end of its range and a second particle starts off with a much lower ionization making a large angle with respect to the stopping particle, loses energy and shows increased ionization before it also comes to rest in the emulsion. From the residual range and ionization measurements on the tracks, Lattes, Occhialini and Powell came to the conclusion that the event corresponded to the decay of a heavier meson to a lighter one. Since the decay of the first particle is not into an electron, but to another lighter meson, the first particle does not correspond to the dominant cosmic ray meson identified with the penetrating component of cosmic radiation. They inferred that the second meson may be the penetrating component.

The second Fig (2.9) clears up the issue further. It shows four cases where a particle comes to rest and a second particle with a range identical to the second particle in the earlier figure, (the lighter meson) comes to rest. From the end of the second particle a



Photomicrograph showing a π meson (π) coming to rest in a nuclear emulsion and a μ meson (μ) arising from the end of the π-meson track. (From C. M. G. Lattes, H. Muirhead, G. Occhialini, and C. F. Powell, *Nature*, vol. 160, p. 453, 1947.)

Fig 2.8



Four examples of the successive decay $\pi \rightarrow \mu \rightarrow e$. The photo-micrographs display the increase in the grain-density of the tracks of the μ-mesons as the particles approach the end of their range. The sparseness of the grains in the tracks of the electrons may be clearly seen.

Fig 2.9

"Occhialini and I decided that we should take some plates to the Pic du Midi in the pyran~~s~~ese for an exposure of about one month. Some were loaded with borax and some were normal plates (without borax). All were made of new concentrated B_1-type emulsion for which a range energy relation already existed. The normal plates were to be used for the study of low energy cosmic rays as a control to see if we were detecting cosmic ray neutrons.

When Occhialini processed the emulsion after their recovery on the same night on which they were received in Bristol, it became clear that borax loaded emulsions had many more events than normal ones. Borax somehow kept the latent image from fading…

After a few days of scanning a young lady Marietta Kurz found on unusual event: One stopping meson and emerging from its end a new meson about 600 microns range, all contained in the emulsion….

A few days later, a second "double" meson was found….

This was followed by an exposure at 18,600 ft. at La Paz. 30 double events were found. Contrary to the recommendations of Prof. Tyndal director of H.H. Will's Physical Laboratory. I took Brazilian air plane which was wise because the British plane crased in Dakor killing all its passengers." Lattes.

third one which has all the characteristics of an electron emerges. Thus the whole scheme of what is happening becomes apparent. The first particle given the name Pi-meson, decays in to a lighter meson given the name Mu-meson which further decays into an electron. The fact that the second meson had the same range in many cases, made it certain that the decay of the Pi-meson was a two body process. The decay scheme came out to be:

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu$$

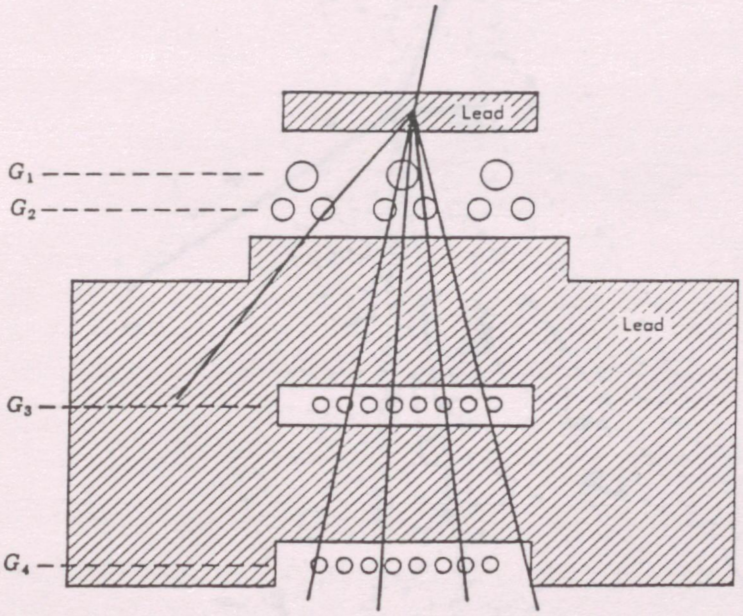
$$\mu^{\pm} \longrightarrow e^{\pm} + \nu + \nu$$

According to this scheme, the Pi-meson was more likely to be the Yukawa particle. Further, experiments confirmed this by establishing that the Pi-meson is a nuclear active particle that interacts strongly with nuclei and its decay life time is about 2.5 X 10^{-8} seconds, more close to what Yukawa had predicted. The mass of the Pi-meson was found to be 273 electron masses compared to 207 electron masses for the Mu-meson.

2.8 <u>Meson</u> <u>Production</u>

We have discussed the evidence for the presence of a variety of particles as part of the cosmic ray beam at various altitudes in the atmosphere. These were sorted out in the first instance into soft and penetrating components. The soft component was identified as comprising electrons positrons and gamma rays and the penetrating component as the mesons. We also saw that the Mu-mesons are from the decay of Pi-mesons. The questions that we have not dealt with so far are (i) What are the sources of the Pi-mesons and gamma-rays? (ii) Do all electrons come only from the decay of Mu-mesons? (iii) What is the relation between the primary cosmic rays and these secondaries that we have dealt with so far. (iv) Are there other types of secondaries too?

All these questions and the generic relations between the various components got answered in the post war period by the experiments carried out at many different laboratories in the world. The evidence for the production of several penetrating particles in nuclear collisions of high energy particles (several Gev) in the cosmic ray beam came from the pioneering experiments of the Hungarian scientist Janossy and collaborators working at Manchester with specially designed shielded Geiger counter telescopes (Fig 2.10), and the multiplate cloud chamber experiments of the Massachusetts Institute of Technology group at Boston and nuclear emulsions exposed at Balloon altitudes (Fig 2.11 and 2.12) Two questions arise in this context. What is the identity of the particles produced in these collisions? and, what is the identity of the particle that collides?

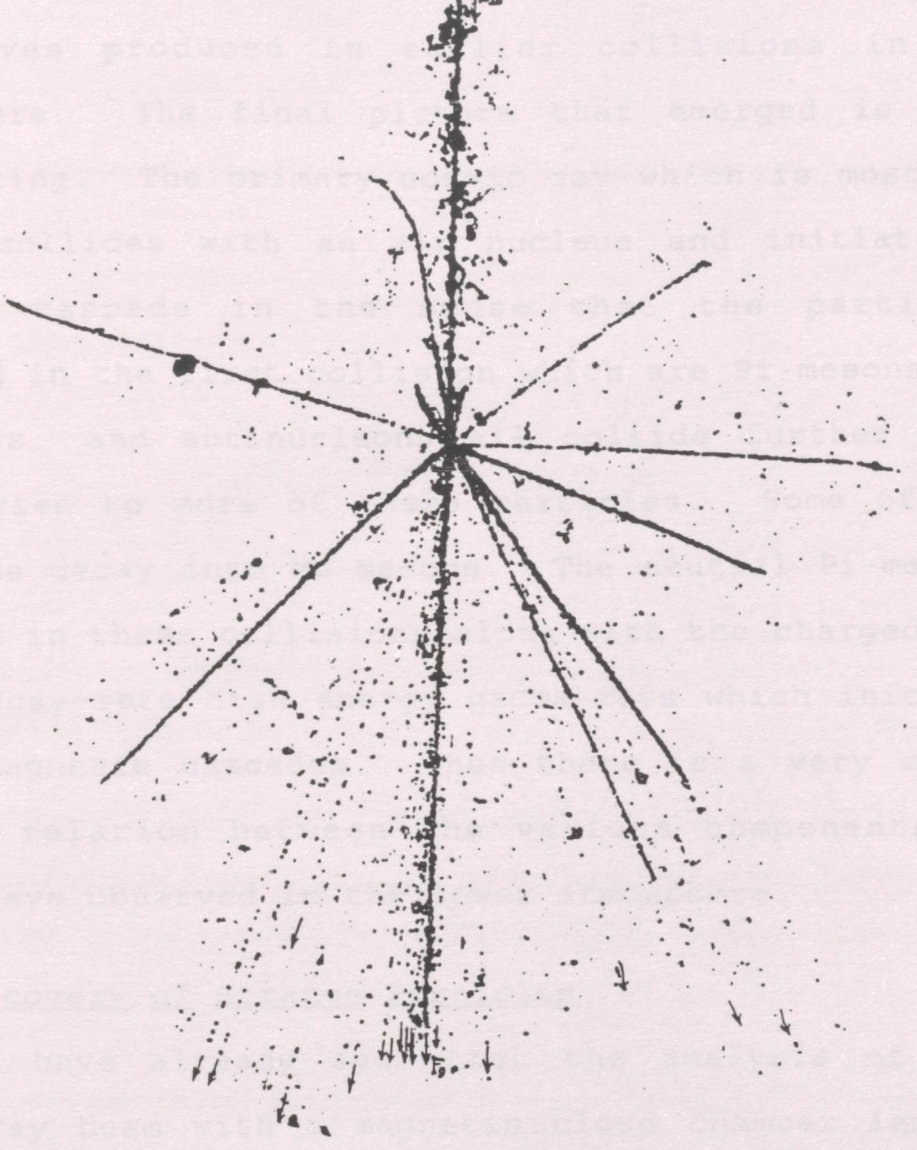


Penetrating-shower detector used by Jánossy in his early experiments. Electronic circuits select simultaneous discharges of at least one counter in group G_1 and two counters each in groups G_2 to G_4. Such coincidences can be produced only by showers containing penetrating particles capable of traversing large thicknesses of lead.

Fig 2.10

A Proton or a Pi-meson collides with a Silver or Bromine nucleus of the emulsion and produces 6 high energy secondaries and 3 heavy fragments.

Fig. 2.11



A sulphur nucleus ($Z=16\pm1$) collides with one of silver or bromide in the emulsion. As a result of the encounter a fluorine nucleus and twenty-five 'shower' particles—protons and π-mesons—emerge.

Fig 2.12

1.3.2

It was established by further experiments that the secondary particles were predominantly the Pi-mesons and the nuclear active particles that produced these collisions were protons, neutrons or Pi-mesons themselves produced in earlier collisions in the atmosphere. The final picture that emerged is very interesting. The primary cosmic ray which is mostly a proton collides with an air nucleus and initiates a nuclear cascade in the sense that the particles produced in the first collision which are Pi-mesons and nucleaons and antinucleons all collide further down giving rise to more of these particles. Some of the Pi-mesons decay into Mu-mesons. The neutral Pi-mesons produced in these collisions along with the charged pi-mesons dcay into high energy gamma-rays which initiate electromagnetic cascades. Thus there is a very close generic relation between the various components of cosmic rays observed in the lower atmosphere.

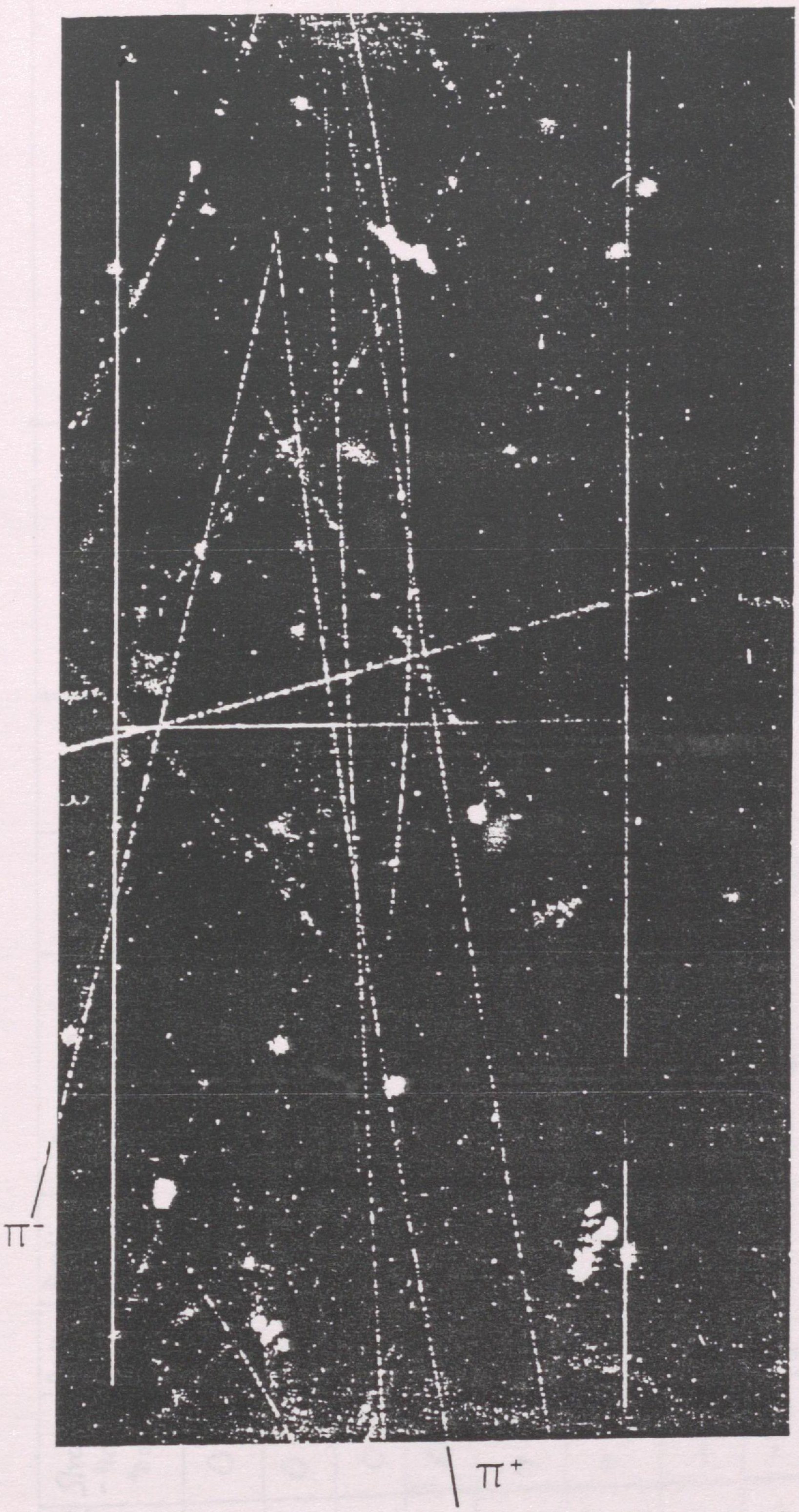
2.9 <u>Discovery of Strange Particles</u>

We have already seen that the analysis of the cosmic ray beam with a magnetic cloud chamber led to the discovery of two new particles, the positron in 1932 and the mu-meson in 1937. This was followed by the discovery of the Pi-meson in 1947 in nuclear emulsions exposed to cosmic rays at high mountains and also to the discovery of V-particles later identified as K-mensons and hyperons. A typical V-particle decaying into two Pi-mesons is shown in Fig. (2.13)

This trend for discovery of new particles continued for the next seven years as well, mostly in nuclear emulsions exposed at balloon altitudes considerably helped in the interpretation by the experiments with large magnetic and multiple cloud chambers operated at high mountains. The list of cosmic ray particles with some of their important properties is given in the table.2·1

The particles discovered range in their mass from one electron mass to 2586 electron masses and the lifetimes of the unstable particles (all except the positron which annihilates when it comes in contact with an electron) range from 2 X 10^{-6} seconds to 8 X 10^{-17} seconds. They are all singly charged and have spin 0 or 1/2. When the K-mesons were discovered, one of the very exciting but at the same time intriguing feature noted was that the K-meson was always produced in association with another Hyperon (particle of mass higher than the nucleon) or another K-meson. This feature came to be known as 'Associated Production' and led Gell Mann and Pais to propose a new quantum number - "strangeness quantum number" - which they postulated should be conserved in strong interactions and not in decay or weak interactions.

It is seen in the table that each particle has an assigned strangeness quantum number and those that have values 1,2, -1, -2 have been called strange particles. Gell Mann predicted on the basis of his



- Example of θ^0-decay (film #R-151) by THOMPSON *et al.* [1953b]. The momenta of the positive and negative fragments are (0.90 ± 0.02) and (1.9 ± 0.1)GeV/c, respectively. Both tracks are at minimum ionization. The angle between the tracks is $(17.5 \pm 0.1)^\circ$ and the $Q(\pi, \pi)$-value is (219 ± 12) MeV.

Fig 2.13

TABLE 2·1

Properties of elementary particles discovered in Cosmic Rays 1930-1955.
(Some of the properties listed - Spin, life time, anti-particle, decay modes were determined later in accelerator experiments)

Name of Particle	Symbol	Strange-ness no	Anti Particle Symbol	Anti Particle Strangeness no	Mass in terms of me	Spin	Charge	Life time in Seconds	Decay Modes
Positron	e^+	0	e^-	0	1	1/2	1	–	–
Muon	μ^-	0	μ^+	0	207	1/2	1	2.2×10^{-6}	$(e^- \nu_\mu \nu_e)$
Pion	π^-	0	π^+	0	273	0	-1	2.6×10^{-8}	$(\mu^- \nu_\mu)$
	π^0	0	π^0	0	264	0	0	8.0×10^{-17}	$(\gamma \gamma)$
Kaon	K^+	+1	K^-	-1	966	0	+1	1.2×10^{-8}	$(\pi^+ \pi^0), (\mu^+ \nu_\mu), (e^+ \pi^0 \nu_e)$
	K^0	+1	$\bar{K}_0$	-1	974	0	0	K_S : 9×10^{-11} K_L : 5.4×10^{-8}	$(\pi^+ \pi^-), (\pi^0 \pi^0)$ $(\pi^0 \pi^0 \pi^0), (\pi^0 \pi^+ \pi^-), (\pi^- e^+ \nu_e)$
Lambda Hyperon	Λ^0	-1	$\bar{\Lambda}_0$	+1	2183	1/2	0	2.5×10^{-10}	$(p \pi^-), (n \pi^0)$
Sigma Hyperon	Σ^+	-1	$\bar{\Sigma}^+$	+1	2328	1/2	+1	8.0×10^{-11}	$(p \pi^0), (n \pi^+)$
	Σ^0	-1	$\bar{\Sigma}^0$	+1	2334	1/2	0	10^{-14}	$(\Lambda^0 \gamma)$
	Σ^-	-1	$\bar{\Sigma}^-$	+1	2343	1/2	-1	1.5×10^{-10}	$(n \pi^-)$
Cascade Hyperon	Ξ^0	-2	$\bar{\Xi}^0$	+2	2573	1/2	0	3.0×10^{-10}	$(\Lambda^0_0 \pi^0)$
	Ξ^-	-2	$\bar{\Xi}^-$	+2	2586	1/2	-1	1.7×10^{-10}	$(\Lambda^0 \pi^-)$

phenomenological theory SU(3) that there should be a particle with a strangeness quantum number (-3) and the particle should have a mass of 1685 Mev. It was a great triumph for the theory that this particle was indeed discovered at accelerators.

We also see from the Table, another interesting feature. The K^0 meson with a mass of 974 m_e decays in two distinctly different modes - sometimes into two pions $(\pi^+\pi^-)$, $(\pi^0\pi^0)$ and at other times into three pions $(\pi^0\pi^0\pi^0)$, $(\pi^0\pi^+\pi^-)$, $(\pi^-e^+\nu_e)$ with quite different life times. These decay schemes posed a serious problems for the theorists. The two body and three body decays for the same particles meant that an important symmetry known as 'parity' was not conserved in these decays. In the cosmic ray work the particle that decayed into two pions was known as the θ-particle and the one that decayed into three pions was known as the τ-meson and the puzzle was called τ-θ puzzle. It took quite an effort to convince everyone that the decaying particles τ and Θ had the same mass. It is this τ-Θ puzzle that led the two chinese physicists Lee and Yang to propose that in Weak interactions parity is not conserved (Mirror Reflection Symmetry is broken) and suggested the famous Beta-decay experiment of oriented cobalt^{60} which was carried out by another Chinese experimental physicist Madame Wu and their prediction confirmed. Lee and Yang were awarded the Nobel Prize for this work.

Chapter 3

Primary Spectrum and Composition

Overview

In this chapter we discuss the nature and properties of the primary radiation. It was only towards the early 40's that it became clear that the primary radiation consists predominaently of protons. A surprising discovery that occurred in 1948 was that the primary radiation has also a heavy component comprising alpha particles and heavy nuclei which together is about 10% of the total. All the primaries are nuclear interacting particles and produce in the atmosphere through collisions with the air nuclei the various types of mesons and also nucleons and anti-nucleons which along with their decay and annihilation products form the secondary component. What came as a great surprise was that the primary particles had energies over a very wide range far in excess of what had been considered to be the case immediately after the discovery of cosmic rays. It turned out the primary spectrum. (Intensity vs Energy) extended over a range of a few hundred Mev to 10^{20}ev and the fall in intensity with energy was characterized by a power law $E^{-\gamma}$ with γ being $\sim$ 1.5 for the integral spectrum. A variety of methods were used for determining the spectra of the different components of the primary radiation. In the first instance upto an energy of 10^{11}ev it became feasible to determine the spectrum and composition using nuclear emulsion stacks flown to stratosphetic altitudes by balloons. At higher energies because of the steep fall in intensity indirect methods had to be used. In the energy range 10^{11}-10^{13}ev, the spectrum could be derived from the measurement of the mu-meson intensities at various underground depths. Beyond 10^{13} ev, the method of Extensive Air Showers had to be used.

In recent years, using large size emulsion stacks flown on balloons for hundreds of hours by repeated flights and long duration flights, it has been possible to extend the spectrum by direct methods upto 10^{14} ev. This has also enabled the composition to be determined upto similar energies.

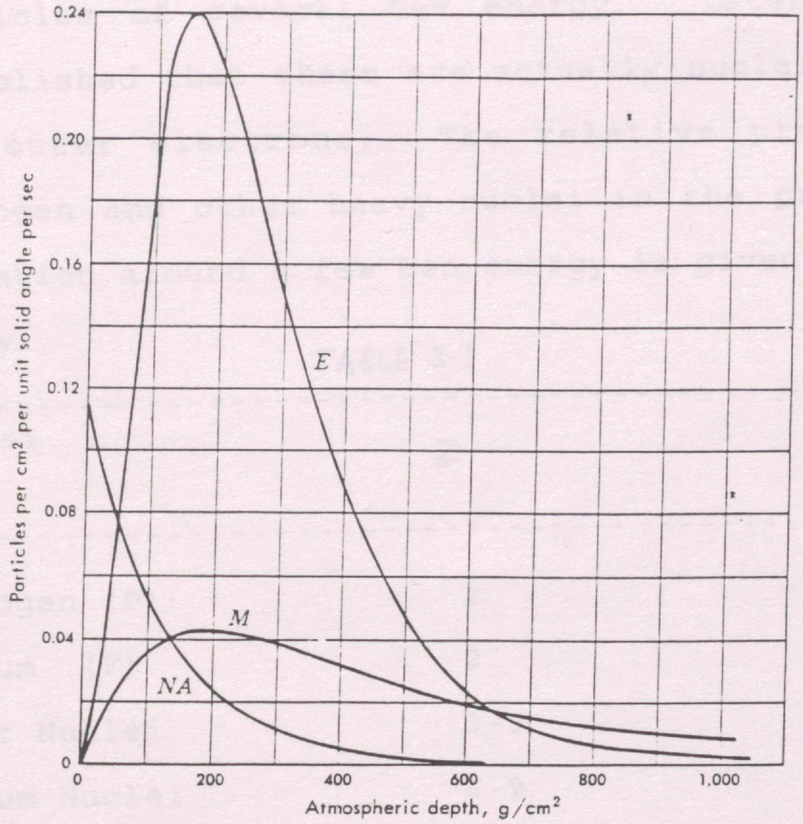
With the air shower method, which is the only method available beyond 10^{14}ev, it has been possible to extend the spectrum upto 10^{20}ev. At these energies high resolution of the primary mass spectrum is not feasible but with the help of montecarlo simulations some crude idea of the primary composition has been obtained. The details of the air shower methodology are elaborated in this chapter. Also the exciting features of some of the highest energy showers recorded beyond 10^{20}ev and the implications regarding the location of the source of such high energy particles are discussed.

3.1 The Composition of the Primary Cosmic Rays

As we have already observed, the altitude effect of cosmic rays and the East-West effect gave clear indication that the primary component of cosmic rays consists predominantly of charged particles. The balloon experiments of Marcel Schein and his collaborators conducted in the early 40's upto altitudes of about 70,000 ft. showed that the charged particles encountered by their telescopes did not give rise to showers, thus clearly ruling out, the primaries to be electrons. The intensity versus atmospheric depth profiles of the three components electrons, muons and the Nuclear Active Component are given in the Fig 3.1. It is evident that the two components muons and electrons are secondary where as the nuclear active component is the one that enters the atmosphere from outside and its intensity gradually decreases as the atmospheric depth increases. The other two reveal their secondary nature by showing peaks further down around 200 gms/cm^2. Among the nuclear active particles known in the late 40's, the proton was the only stable one and the other two the neutron and the Pi-meson were both unstable. Also, the neutron did not have any electric charge. Based on all these considerations the consensus was that the primaries are protons.

3.2 Discovery of Heavy Primaries

In the balloon flights carried out in 1948 by the university of Minnesota and University of Rochester



Vertical intensity of three components of local cosmic radiation as a function of atmospheric depth, in grams per square centimeter. Curve *NA* represents nuclear-active particles with energies greater than about 1 BeV. Curve *E* represents electrons with energies greater than about 100 MeV. Curve *M* represents μ mesons with energies greater than about 200 MeV.

Fig 3.1

p38

groups with piles of nuclear emulsion plates reaching an altitude of 94,000 ft. it became clear that the some of ionizing tracks corresponded to multiply charged particles of several Gev energy. Later experiments established that these are actually nuclei stripped of the outer electrons. The relative proportions of hydrogen and other heavy nuclei in the primary cosmic radiation around a few Gen energy is given in the table below:

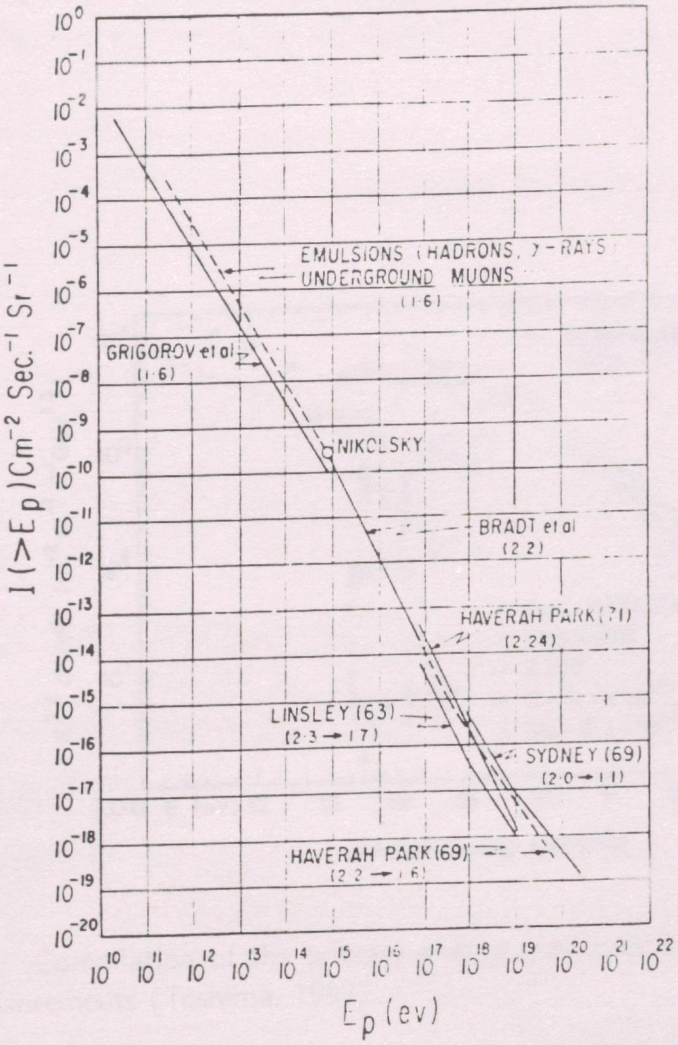
TABLE 3.1

Nuclei	Z	Relative number (E>2.5 Gev)
Hydrogen (P)	1	100,000
Helium (F)	2	6,770
Light Nuclei	3-5	146
Medium Nuclei	6-9	430
Heavy Nuclei	>/10	246

Though there is a general similarity in the abundance of the different elements in the universe and in cosmic rays, there are some significant differences also. The iron group is much more dominant in cosmic rays. These have implication on the types of cosmic ray sources and also on the amount of matter traversed by the particles in their long winding paths from the source to the top of the atmosphere of the earth. Also as will be seen later, the relative abundances do drastically change at high energies. This brings us to another important aspect of the primary radiation - the energy spectrum of protons and of the different components.

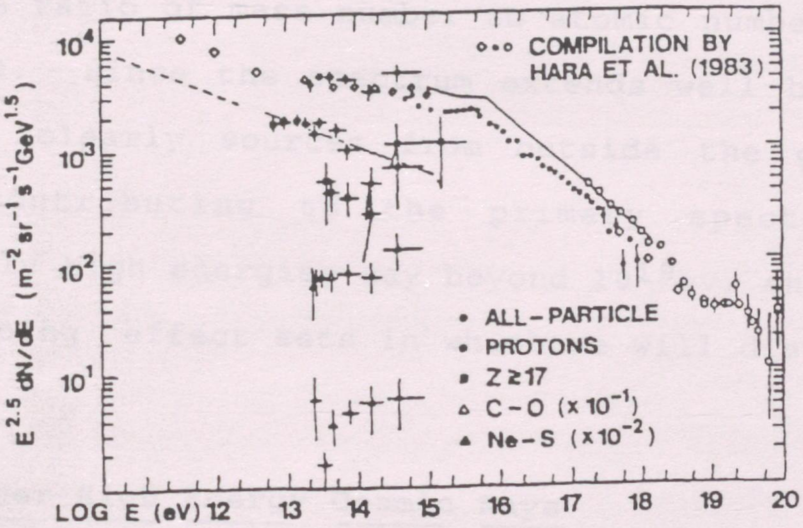
3.3 **The Primary Spectrum**

The primary cosmic ray particles have energies extending from about a Gev (10^9 ev) to greater than 10^{21} ev. Over this energy range the intensity drops from about 1000 particles/cm^2.sc to about 1 particle/1000 km^2. yr. In 12 decades of energy increase the intensity mercifully falls by 22 decades. (Fig. 3.2) But for this steep spectrum, the earth would not have been a safe place for life to evolve and survive. This exponential fall of intensity is characteristic of all the components though the rate of fall may be slightly different (Fig 3.3). At the lower end, the spectrum is dependent on the energy and the latitude of the place because of the earth's magnetic field which bends away particles. For example, at the earth's equator only protons above 15 Gev can enter the earth's atmosphere in the vertical direction. The cut off energy can be as high as 60 Gev at an angle of 60° with respect to the vertical in the Eastern direction and as low as few Gev in the West at the same inclination.



A composite energy spectrum of primary cosmic rays.

Fig 3.2 (a)



JACEE Energy spectrum

Compilation of the primary energy spectrum from direct as well as air shower measurements (Teshima, 1993).

The ordinate is multiplied by $E^{2.5}$ to compress the Vertical Scale

Fig 3.2 (b)

Coming to the high energy end of the spectrum, one would have expected a steep cut off around 10^{15} ev if the particles were produced only by sources within the Galaxy.

The higher energy particles cannot be contained by the magnetic field of the Galaxy and will escape out. The cut off will of course depend on the nature of the primary. If it is a heavy nucleus than the cut off energy per nucleon would be lower by a factor of about 2 since ratio of mass number to atomic number (A/Z) is about 2. Since the spectrum extends well beyond this energy, clearly sources from outside the galaxy are also contributing to the primary spectrum. At extremely high energies say beyond 10^{19}ev, another very interesting effect sets in which we will discuss later on.

3.4 Super High Energy Cosmic Rays

The thoroughly unexpected discovery of a host of fundamental particles in cosmic rays (TABLE) during the period 1947-1955 literally woke up the accelerator community of the world which started building higher and higher energy particle accelerators (The Cosmotron, the Bevatron, etc) with high intensity beams equipped with a host of new types of powerful detectors-bubble chambers, spark chambers, cerenkov detectors, multiwire position sensitive proportional counters etc., that the new field of elementary particle physics was snatched away from the cosmic ray physicists. The accelerators could produce beams that had large numbers of these particles and their properties could be studied with much greater detail and accuracy. These accelerator centres also started attracting theoretical physicists and the closer interactions between the experimentalists and the theorists led to planning and execution of more critical and result-oriented experiments in contrast to the 'open blue sky' approach pursued earlier with cosmic rays. All this changed the very methodology of experimental design and execution.

Though the advent of accelerators was in some respects a set-back for cosmic ray physicists for the pursuit of particle physics, they had many other aspects of cosmic radiation to focuss their attention on. Also, the primary cosmic ray beam contained particles of energy much higher than available at accelerators and also the primary cosmic rays contained high energy alpha-particles and other nuclei so that nucleus-nucleus interactions could be studied at high energy with advantage. So the attention in cosmic rays shifted to the study of higher energy interactions. Essentially there were two methods available. To catch the individual high energy particle either at high balloon altitudes or at high mountain altitudes in nuclear emulsion stacks or in cloud chambers and study the characteristics of interactions like elasticity, cross-section, multiplicity of secondaries, nature of secondaries and so on. The first method was essentially an extension of the nuclear and multiplate cloud chamber methods that we have discussed already.

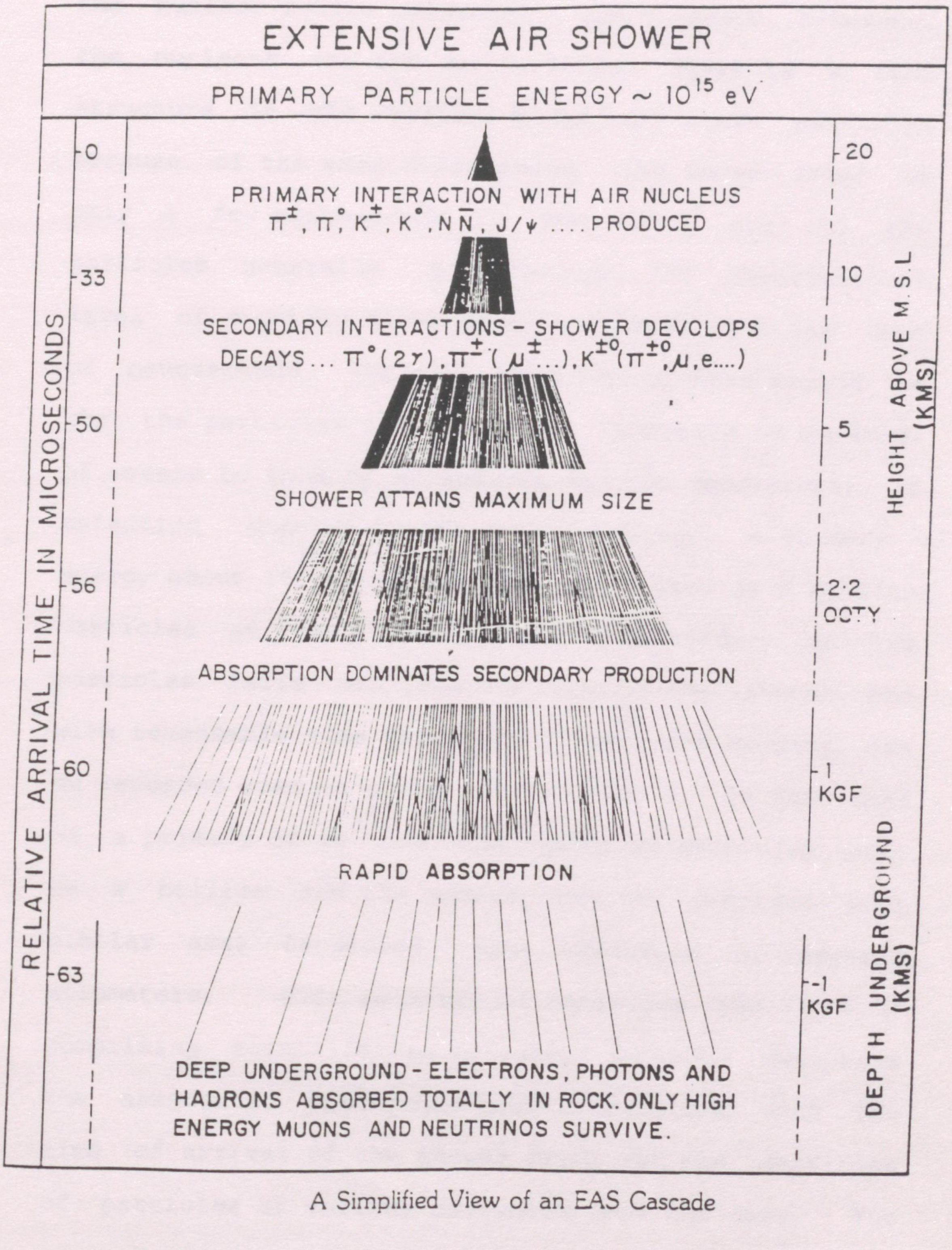
3.5 The Method of Extensive Air Showers

The second method available for cosmic ray physicists is the method of extensive air showers. This method becomes feasible only at energies above 10^{13}ev and has been exploited right up to the highest energies of about 10^{21}ev. Though the method is indirect, it has become powerful and quantitative with the development of the monte carlo simulation techniques made feasible with the advent of large computers.

Thanks to the exponential nature of the fall of atmospheric density as a function of height, a very grandiose and unique and spectacular three dimensional phenomenon takes place whenever a super high energy cosmic ray particle enters the top of the atmosphere. The super high energy particle collides with an air nucleus and produces a large number of secondary particles - mesons, nucleons, antinucleons and a variety of baryons; these include the strange and non-strange particles given in the Table. Most of the secondaries excepting the nucleons are unstable and decay into secondaries (See Table 2·1)However, they are also hadrons or interacting particles and given an opportunity will collide and produce more particles.

Two important effects come into play in deciding whether these particles will decay or collide. One effect is the relativistic elongation of time. Since the secondaries are of high energy their life time will be elongated by a factor (E/mc^2) where E is the energy of the particle and M is the rest mass. For example a secondary Pi-meson of 100 Gev $(10^{11}ev)$ produced in a collision of say $10^{15}ev$, will live for as long as $2.5 \times 10^{-8} \times 10^{11} / (1.38 \times 10^8) = 2 \times 10^{-5}$ seconds and therefore can travel a distance of $3 \times 10^{10} \times 2 \times 10^{-5} = 6 \times 10^5$ cms or 6 kms before decaying. Similar is the case with other unstable particles. This extension of decay length provides an opportunity for such high energy particle to collide in the atmosphere. The secondaries in such high energy collision are extremely collimated. The large distance before collision or decay helps them to spread out laterally.

All this results in the development of a nuclear cascade in the atmosphere. Fig (3.3) The neutral Pi-mesons which have a very short lifetime $(10^{-16}$Secs) decay away soon despite the relativistic elongation into a pair of γ-rays and the γ-rays initiate electromagnetic cascades having their origin close to the various collision points in the nuclear cascade. The most dominant component of this mixed cascade is of-course the electromagnetic component comprising electrons, positrons and gamma rays. The next in



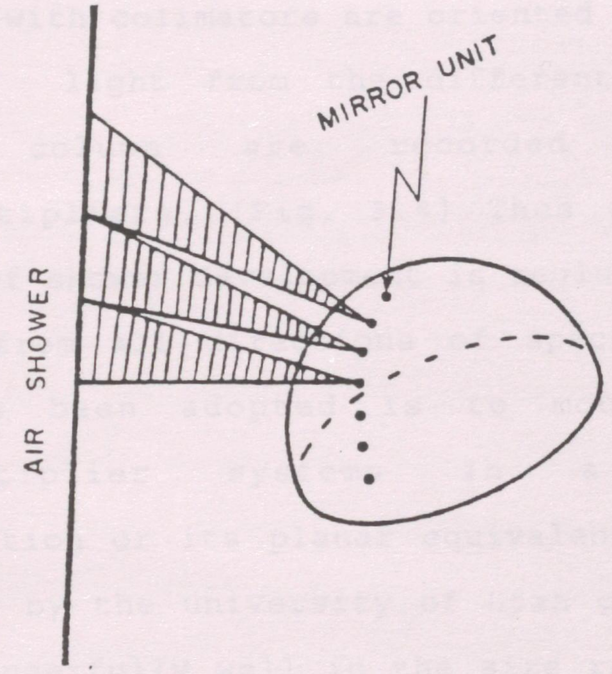
A Simplified View of an EAS Cascade

Fig 3.3

abundance are the mu-mesons which are the decay products of the Pimesons and the K-mesons followed by the nuclear-active component - the Pi-meson, K-mesons, the nucleons and the antinucleons. There is a time structure in the arrival times of these particles because of the mass differences. The shower front is only a few nanoseconds (10^{-9} Sec) thick and all the particles generally pass through the observational level of mountain altitude or sea level in a few tens of nanoseconds. The main advantage of this method is that the particles are spread out laterally to hundreds of meters to tens of kilometers and the sensitivity of detection depends on the primary energy. A primary of energy about 10^{15} ev, gives rise to as many as a million particles at mountain altitude. The density of the particles falls off from the core of the shower and with reasonable size detectors ($\sim 1m^2$) the density can be recorded even at a distance of ~100 m. In the case of a primary of 10^{18} ev, the number of particles will be a billion and the density can be recorded with similar area detectors upto distances of several kilometers. With an array of detectors (see Fig.5.7) comprising scintillators or water cerenkov detectors the associated electronic system registers with the time of arrival of the shower front and the densities of particles at various distances from the core. The arrival times enable the determination of the direction of the incident particle at the top of the atmosphere to an accuracy of about 1^{o} and the densities enable through monte carlo simulations of the cascade, based on nuclear interaction characteristics, the determination of the energy of the primary particle. The main advantage of the extensive air shower method is the large effective area it provides by the technique of sampling of densities by the array of detectors. The primary intensity of cosmic rays falls off steeply (see fig 3.1) and around 10^{15}ev for example, the intensity is a few particles per square meter per year. Large effective areas are required for recording such low intensify phenomena which is provided by the air shower method, which has been exploited right up to 10^{20}ev.

A variety of specially designed detectors - (see next chapter for details) are operated for registering the other components like the muons, N-particles, energy flow, etc. On the basis of this information, the nature of the primary spectrum, the arrival angle anisotropies, the broad identity of primary - whether it is a proton, a light nucleus, heavy nucleus, are all deduced using monte carlo simulations.

A new method of study of very large extensive air showers with energies in the range of 10^{18}ev and above was developed about 20 years ago. This is called the Fly's Eye method. As a large shower develops, in the core region of the shower there will be an intense



. The Fly's Eye air shower detector. Each dot on the geodesic-like dome represents a mirror

Fig 3.4

column of ionization due to the large number of electrons ionizing the nitrogen nuclei of the air. This results in the emission of fluorescent radiation in the optical region. The emission is isotropic. On moonless nights, the fluorescent light from the core is recorded by sensitive photomultipliers even from distances of several tens of kilometers. A set of photomultipliers at the foci of parabolic mirrors provided with colimators are oriented in such a fashion that the light from the different regions of the shower column are recorded by different photomultipliers. (Fig. 3.4) Thus the longitudinal profile of shower development is registered. To record showers from all directions of space, the technique that has been adopted is to mount the mirror-photomultiplier systems in a hemispherical configuration or its planar equivalent. This method pioneered by the university of Utah group in USA, has worked wonderfully well in the size range 10^{18}-10^{20}ev. The longitudinal development profile contains information not only on the size of the shower but also on the nature of the primary initiating the shower.

A large number of air shower arrays have been operated in the past four decades with a variety of detector arrangements. The main results may be summarized as follows:

1. The spectrum extends upto a few times 10^{20}ev.
2. There is no pronounced anisotropy in the arrival

directions of the primary radiation that has led to the identification of specific sources in any of the energy ranges investigated.

3. The spectrum which is characterized by a power law of the form I(E) = Const. $E^{-\gamma}$ shows a steeping around an energy of 10^{15} ev and a flattering around 10^{17} ev. These two have been called for obvious reasons the `Knee' and the `Ankle' regions, in the cosmic ray spectrum.(Fig. 3.5)

4. The composition of the primary radiation does not remain the same at all energies. It has been possible to measure the composition upto $\sim 10^{14}$ ev by flying large area emulsion stacks. The Table 3.1 summarizes the composition status in the energy rage $<10^{13}$ to 10^{15} ev. The composition in the energy range above 10^{14} ev is from air shower simulations of the data on multiplicity distributions of muons, arrival times of different components etc., and is indirect. What is to be noticed is that there is clear indication of the dominant component at lower energy namely protons dropping at energies above 10^{14} ev - a tendency for the composition to become heavier at higher energies.

5. Immediately after the discovery of the universal microwave radiation (the so called 3^{o}K radiation) it was pointed out by Greisen in the United States and Zatsepin and Kuzmin in Russia that this should have a pronounced effect on the primary spectrum at the extreme end. Cosmic rays of energy $>10^{19}$ ev will

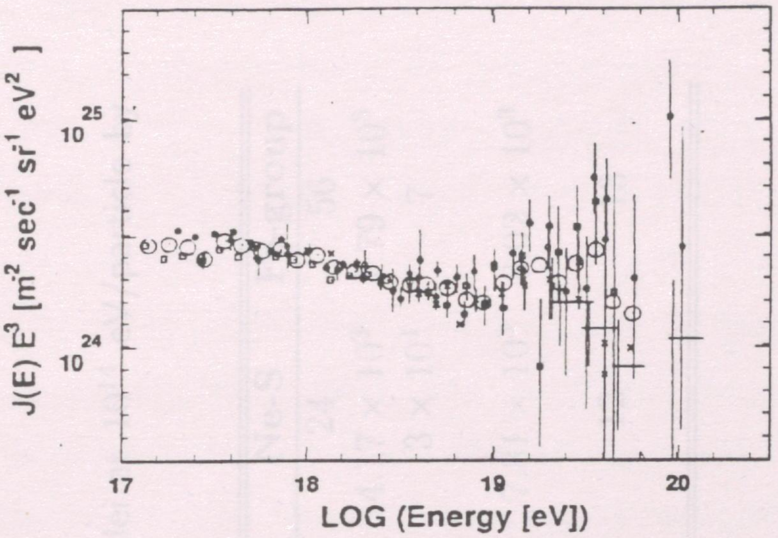


Figure 8.12 Primary energy spectrum at $E_0 > 10^{17}$ eV from the Haverah Park (o), the Yakutsk (×), the stereo Fly's Eye (•), the AGASA (□) experiment and the geometrical average of the four experiments (◯).

Fig 3.5

Table 3.1 An estimate of the composition of primary nuclei at 10^{14} eV/particle by Swordy (1993).

Group of nuclei	p	He	CNO	Ne-S	Fe-group
A	1	4	14	24	56
E (GeV/n)	10^5	2.5×10^4	7.14×10^3	4.17×10^3	1.79×10^3
Flux estimate (GeV/n)	1.3×10^4	2×10^3	1.2×10^2	3×10^1	7
Flux calculated (GeV/particle)	1.3×10^4	2.26×10^4	1.22×10^4	7.81×10^3	8.02×10^3
Relative abundance (%)	20	36	19	12	13

extreme end. Cosmic rays of energy $>10^{19}$ ev will collide with the 3^{o}K photons and will be lost since they give all their energies to secondaries. This should result in a steeping of the spectrum. If heavy primaries are present at these energies they would be disintegrated at a still lower energy. The present experimental results though not conclusive seem to show the effect of this 3^{0} radiation. If the steepening was not seen it would mean that the highest energy cosmic rays are produced in sources within our galaxy or at best within local the super cluster of galaxies. The contributions from extragalactic sources would be ruled out.

3.6 The Highest Energy Cosmic Rays

The most unique and most exciting aspect of cosmic ray studies in recent years has been the recording of showers of energy greater than 10^{20} ev.in an operation period of about 20 years. This has been achieved by three different groups in three different countries - Russia, Japan and USA. The Russian air shower array in Yakutsk in Siberia has been operating with large area water cerenkov detectors for several decades. The Japanese array is called AGASA and is located in the AKENO prefecture not far from Tokyo and has also been operating for two decades with continuous upgradation in the number and distance separation of the scintillation counters. The third is the Fly's Eye array in Utah in the United States.

The details of the three events - the energies and arrival direction are given in the Table (3.2). There are some puzzling features of these events which make them very interesting, in fact, challenging from the point of view of interpretation. There are absolutely no objects in the Galaxy in the directions of these three largest showers which have the minimum features necessary to be sources of such high energy particles. The fact that the primaries have to be either nuclei, or protons or gamma rays limits the maximum distance to 50 mpc. Even among the extragalactic objects within this distance there are no candidate sources at all if the particles have to come straight from the source. The direction of the Fly's Eye event is 88° away from M87 and 134° above from Cyg A which may be categorized among possible sources. Another interesting observation that follows from the Table (3.2) is that two of the events the Yakutsk and the Fly's Eye, are within errors, from the same direction!

TABLE 3.2

Details of the three hghest energy events recorded by the Yakutsk, Fly's Eye and AGASA groups.

Group	**Yakutsk**	**Fly's Eye**	**AGASA**
Date of Observation	May 7, 1989	Oct 15, 1991	Dec 3, 1993
Energy (eV)	2.3×10^{20}	3.2×10^{20}	$(1.7 \sim 2.6) \times 10^{20}$
α (°)	75 ± 10	86 ± 1	18.9
δ (°)	45 ± 4	$44 \pm (10 \sim 20)$	21.1
b (°)	3	8	−41
l (°)	162	167	131

CHAPTER 4

Primary Electrons and Tev and Pev Gamma ray Astronomies

Overview

The primary component of cosmic rays consists essentially of protons and heavy nuclei. However these particles being hadrons collide with interstellar matter and produce charged and neutral Pi-mesons. The neutral Pi-mesons decay into gamma-rays which give rise to cascade showers. Also the charged Pi and K-mesons decay in the interstellar space and give rise to Mu-mesons which in turn decay into electrons and neutrinos. There may be other sources of electrons also. The cloud chamber experiment of James Earl at balloon altitude established in 1961 that in the primaries there are electrons in the Mev-Gev range at the level of about 1% of the other primary particles. Later experiments with nuclear emulsion stacks established the spectrum of electrons right up to several hundred Gev. These electrons spiralling round the magnetic fields give rise to the non-thermal radio background. At higher energies the electrons interact with the ambient radiation fields - the 3° Microwave radiation and the background diffuse gamma radiation. This influences the spectral characteristics of the primary electron component.

The presence of a background gamma radiation in the range of about 50 Mev at the level of about 0.1% of the total primary radiation was also established in 1962.

The observation of highly polarized optical radiation from the Crab Nebula led to the suggestion by the Russian astrophysicist Shlovsky that this intense polarization could be due to synchrotron emission from high energy electrons in the Crab. From the fact that the filamentary magnetic fields were of the order 10^{-3} guass, he deduced that the electrons would have energies of 10^{12}ev. If there were processes in the Crab that could accelerate electrons to this energy, then the same would accelerate protons too and some of these would interact and give rise to, through Pi-zero decay, gamma rays of similar energy. This provided a great motivation for the cosmic ray physicists to look for high energy gamma rays from supernova remnants like Crab in the early 60's. However only upper limits could be set.

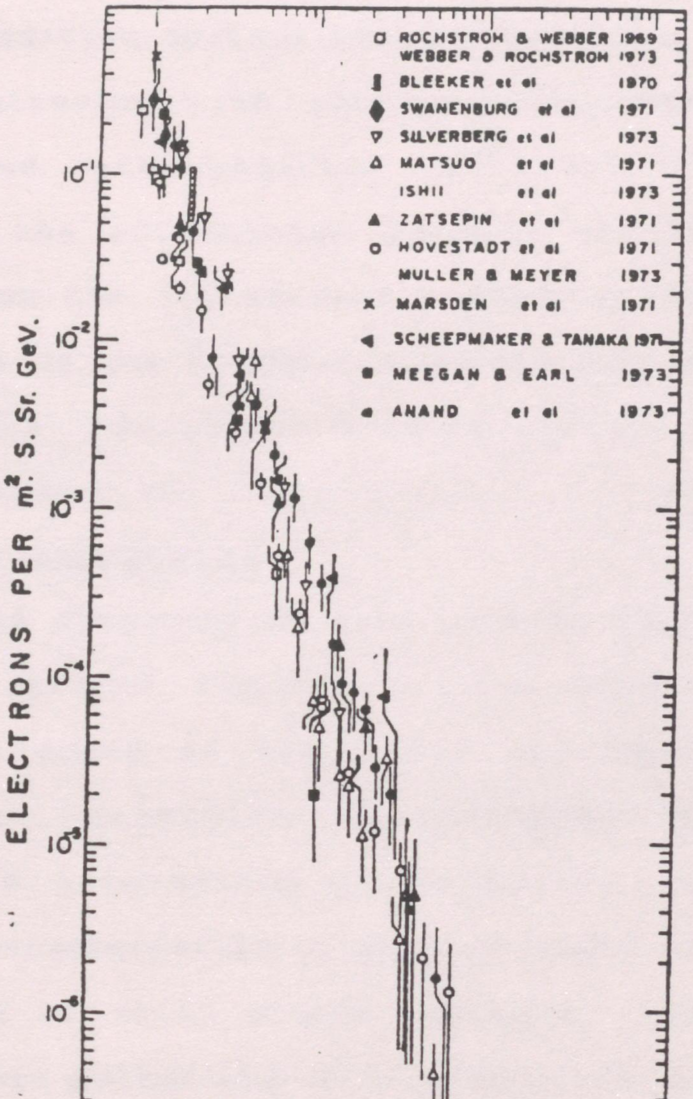
With the discovery of Pulsors in 1967 and their association with spinning neutron stars with high magnetic fields, the interest in Tev gama rays was revived specially since the pulsed emission would provide a unique signature for analysis of the data.

4.1 Electrons in the Primary Radiation

Immediately after the discovery of cosmic rays as an extraterrestrial radiation, it was believed by even eminent scientists of the time, like Millikan that this radiation comprised Gamma Rays produced in the "birth cries" of nuclei synthesized in the interstellar space. Later experiments proved that both these ideas were wrong. The primary radiation was essentially hadronic in nature. It was realised however that these hadrons should give rise to photons and electrons as secondaries, as decay products of unstable particles produced in the collisions with interstellar matter. Electrons at the level of a few percent of the protons were detected in a balloon borne cloud chamber by Jim Earl at the University of Minnesota in 1961. In the same year, Kraushaar and Clark of the Massachusetts Institute of Technology found evidence in a satellite experiments for Gamma rays of energy greater than 50 Mev at the level of 1-2 particles per 1000 of the incident particles. Later experiments by a number of groups extended the observation of the electrons upto several hundred Gev. (fig 4.1)

At energies below 10 Gev, the primary electron spectrum is influenced considerably by solar modulation and is subject to wide fluctuations in intensity. The best results on the electron spectrum are in the range

In this chapter we summarise the results on the electron spectrum and the current status of Tev and the still higher energy Pev astronomies.



World data on the energy spectrum of primary electrons.

Fig 4.1

10-300 Gev. The importance of accurate measurement of the electron spectrum stems from the fact that the non-thermal background radio emission arises from the synchrotron emission of the relativistic electrons spiralling around the magnetic fields. The electrons suffer in addition serious energy losses due to inverse compton scattering with photons associated with the galactic and extra-galactic radiation fields. In particular the interaction between the high energy electrons and the $3^{o}k$ microwave photons has important consequences on the electron spectrum and lifetime and also on the resulting diffuse x-ray, gamma-ray background radiation.

4.2 Tev-Pev Astronomies

With the discovery in late 60's of Pulsars in the radio and optical regions of the electromagnetic spectrum extended to the X-ray and Gamma-rays by balloon and satellite experiments, there was considerable interesting in examining whether the pulsation characteristics of some of these objects were evident even at still higher energies. Soon it was confirmed that pulsations were present at energies of hundreds of Gev in objects like the Crab pulsar. For cosmic ray physicists this was a revival of interest in supernovae as possible sources of high energy cosmic rays. The pulsars with their high magnetic field ($>10^{12}$ gases) and high gradient electric fields, provided the right kind of scenario for the acceleration of charged particles which in turn could give rise to high energy photons.

For the detection of these very high energy photons in the hundreds to thousands of Gev range, a novel variant of the extensive air shower method described earlier was used. The high energy photons from the direction of the pulsar arrive at the top of the atmosphere and give rise to pure electromagnetic cascades. The high energy electrons of the shower travel faster than the photons in the medium of the rarefied atmosphere and give rise to cerenkov radiation mostly in the optical and ultra-violet regions of the spectrum. The Cerenkov Light is collected by a set of mirrors with their axes parallel to each other mounted on an orientation platforms as shown in the figure. 41 The associated electronically operated gear system tracks the source for several hours. A set of photomultipliers are mounted at the foci of the parabolic mirrors. Coincidence arrangement between the photomultipliers ensures that all spurious signals are minimised. The background that remains is due to the air showers themselves produced by the protons and heavy nuclei of cosmic rays. Very ingenious methods have been developed to distinguish these background showers from the photon showers. The number of mu-mesons in pure electromagnetic showers is more than an order of magnitude less than in proton showers. This field which has come to be known as Tev Astronomy (Tev=10^{12}ev) has become a major field of activity in many laboratories in the world.

An aerial view of the array of gamma-ray telescopes at Pachmarhi.

Fig 4.2

A new technique called the 'imaging technique' has been developed by the Whipple observatory group in the USA which has now been adopted by most of the other groups in the world. This technique makes use of the fact that the shape of the pool of Cerenkov light that is sampled at the observational level is distinctly different for showers which are pure electromagnetic showers and those induced by protons and heavy nuclei. The lateral distribution of cerenkov light is also different in the two types of showers and this difference is also exploited by some groups.

Among the radio pulsars those that have shown pulsed emission in the Tev range are the Crab Pulsar, PSR 1509-58, Geminga, Vela and the binary radio Pulsars PSR 1855+09 and PSR 1957+21. Among the x-ray binaries Vela X-1 and Cen x-3 have been identified as possible Tev pulsed sources. Among the cataclysmic variables AM-Hercules, AE Aqr have been identified as Tev pulsed sources. The most surprising among the Tev sources, are the Active Galactic Nuclei Mrk-421 and Mrk-501 detected first by the Whipple group. These are extragalasic sources and the emission is unpulsed or D.C. They were detected by the imaging technique. One anomaly that has persisted is that the imaging technique has not been able to detect any pulsed source so far. The pulsed component even in the Crab pulsar has not been seen though claimed by other groups which do not use imaging technique. Variability in the intensity of the sources is also established. The table gives a list of Tev sources detected so far by the imaging technique.

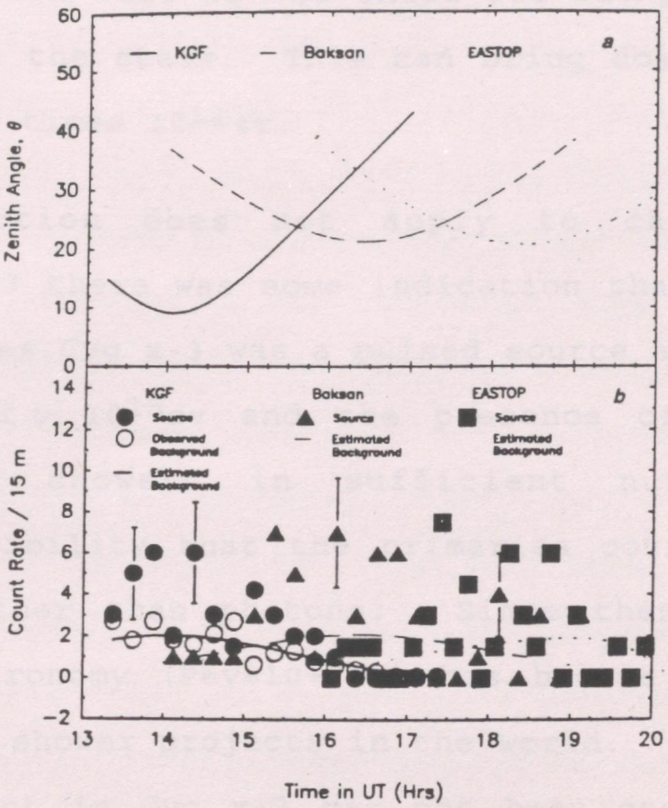
TABLE 4.1

Name	Source type	Chacteristic Emission
Crab	SNR	DC, Steady
PSR 1706-44	SNR	DC, Steady
Vela	SNR	DC, Steady
Mrk 421	AGN	DC, Episodic
Mrk 501	AGN	DC (Episodic)
1ES2234 + 514	AGN	DC (Preliminary)
GSR1915 + 105	μ-Quasar	DC (Episodic)
Velax-1	XRB	Periodic, Variable
Cenx-3	XRB	Periodic, Variable
AE-Agr	CV	Periodic, Variable

DC = Not pulsed; Steady = No time variation; Episodic = Emission during Certain Episodes; Periodic = turns up occasionally; AGN = Active Galactic Nuclei; SNR = Supernova Remnant; XRB = X-ray Binary; CV = Cataclysmic Variable; μ-Quasar = Micro-Quasar

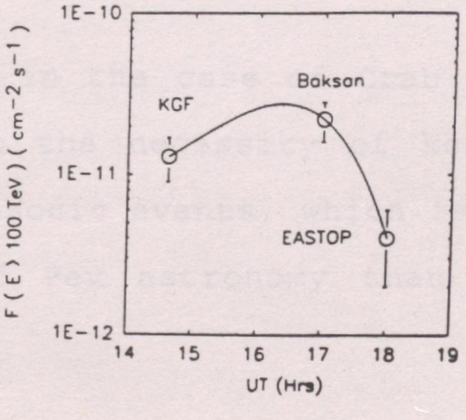
The question naturally arises whether there are photons or particles that are pulsed at still higher energies - at energies above 10^{14}ev. Here nature plays a trick on us. The interaction of photons above this energy with the microwave background photons through the process $\gamma+\gamma$ --> $e^{+}e^{-}$, results in severe attenuation and the extent depends on the distance of the source.

Fig 4.3



Variation of the zenith angle of Crab with time on 23 February 1989 for the KGF, Baksan and EASTOP arrays. *b.* Counting rate in 15-min intervals of events arriving from the Crab direction, plotted against Universal Time for the KGF, Baksan and EASTOP data. The background rates of cosmic rays are estimated assuming an angular distribution of $\mathrm{Cos}^7\theta$ and normalized to the total expected background over the respective periods. The open circles represent the background at KGF obtained from the data itself.

Fig 4.4



Variation of the excess events of energy >100 TeV from Crab with UT during the burst on 23 February 1989 from the KGF, Baksan and EASTOP experiments.

In fact the attenuation is so serious in the case of photons from extragalactic objects like Markarian 421 that there is no hope of seeing any flux beyond about 10^{14}ev at all. There is another, as yet uncertain source of attenuation that is the infra-red background contributed by all the stars. This can bring down the flux even at a few times 10^{12}ev.

This restriction does not apply to charged particles. In 1983 there was some indication that one of the x-ray sources Cyg x-3 was a pulsed source at air shower energies of $\sim 10^{15}$ev and the presence of mu-mesons in these showers in sufficient numbers indicated the possibility that the primaries could be pulsed protons rather than photons. Since then the pursuit of Pev-Astronomy (Pev=10^{15}ev) has become part of most of the air shower projects in the world. While the pulsed component in Cyg x-3 has not been seen at the same level as claimed in 1983, there is still a suspicion that this could be varying in intensity in the Pev range ($>10^{15}$ev). Similar seems to be the case with the Crab pulsar. These are characterized as episodic sources.

There is one episode in the case of Crab that is interesting and points to the necessity of keeping a constant watch on rare episodic events, which is easier to record in the case of Pev astronomy than in Tev astronomy since the acceptance angle of air shower arrays is very wide, though angular resolution can be made small.

On Feb 23rd 1989, the Baksan Air Shower group in Russia reported a Pev burst from the Crab Nebula during the period 14.00-19.00 UT. This observation triggered the KGF group to examine their data on EAS for the same date. The longitude of Baksan is 43°E and of KGF 78.3°E. The KGF data showed that the air shower rate from the direction of Crab was maximum between 13.25-16.0 UT. The Crab Transit at KGF on that date was 14.1 UT. The Gran Sasso collaboration in Italy longitude 42.5°N, also recorded an excess from Crab. The Figure(4.3) shows the observations at the three stations as a function of time. The intensities at the meridian transit of the Crab at the three stations are shown in fig (4.4).

In an experiment like this when the counting rates are low the significance at individual stations may not be high. But the combined probability for such a sequential observation at three different stations with the appropriate phase maxima gives a high significance and focusses attention on the need for continuous monitoring with air shower arrays.

* * *

Chapter 5

Indian Contribution to Cosmic Ray Research

Overview

India started research in the field of cosmic rays though on a low key in the early 40's. However thanks to the foresight of a few individuals, research in this area picked up at a rapid rate and a high level of activity has been maintained right up to the present time. It is interesting that the first ever international Conference on "Elementary Particles" was held in Bombay as early as December 1950. The pace and volume of activity in the different areas of Cosmic ray research in India was such that the 7th International Conference on cosmic rays under the auspices of IUPAP was held in Jaipur in 1963 and the 18th in Bangalore in 1983. In this chapter an account is given in a historical perspective of the development of cosmic ray research in India beginning with some early work in Bengal and Bangalore. This area of research became a major activity at the Tata Institute of Fundamental Research from the time of its inception in 1945 and the activity has continued to this day. The geographic and the logistic advantages that India has for this area of research has been fully exploited. Another important aspect of this area of research, is that it required indiginous development of some of the state of the art technologies - development of stratospheric balloons, varieties of particle detectors like Geiger counters, cloud chambers, scintillation and cerenkov counters, neon flash tubes, spark counters, fast pulsed electronics and display and recording systems, telemetry and telecommand systems - all contemporaneously with advances in other countries.

The chapter describes the results obtained on a variety of aspects of cosmic rays by instruments flown on balloons at different latitudes, through the operation of large cloud chambers at the mountain station Ooty and with large scale installations at various depths underground in the Kolar Gold Mines. The composite and in some respects unique air shower arrays at Ooty and KGF are described and the results obtained on the primaries at very high energies and on the characteristics of interactions deduced are briefly mentioned. An account is given of the first detection of a cosmic ray neutrino interaction with a large scale installation at a depth of 8000 ft. in the Kolar Mines. The results from the Indian experiment Anuradha on NASA Space Shuttle specially designed to uncover some of the intriguing aspects of the low energy anomalous cosmic ray component is also presented. Cosmic rays during their passage through the atmosphere of the earth produce radionuclides like $^{10}\mathrm{Be}$ and $^{32}\mathrm{S}$, which have important applications in geophysics and in determining the mean intensity of cosmic rays over long intervals of time like millions of years. Some of the pioneering work done at TIFR in this field is also dealth with in this chapter. Some of the work on the high energy electron component and in the field of Tev-Pev astronomies currently pursued at Pachmarhi and Mount Abu by Indian scientists have been covered earlier in Chapter 4. Some of the early work on cosmic ray time variation and its correlation with solar activity and atmospheric effects carried out at the Physical Resarch Laboratory, Ahmedabad and at the Gulmarg Cosmic ray laboratory has also been included.

Cosmic Ray Research in India

5.1 Cosmic Ray Research in Bengal

Like in many other areas of science, cosmic ray research in India too, had its beginnings in the Calcutta area. The first Indian cosmic ray physicist is certainly D M Bose who had the unique privilege of working with CTR Wilson, the discoverer of the cloud chamber and also with E Regener in Berlin who did some of the earliest cosmic ray experiments under water. Bose worked with Wilson during 1910-12 and with Regener during the war years 1914-18 and returned to India in 1919. Bose and S K Ghosh built the first cloud chamber during 1920-23 at the Ripon College Calcutta and studied alpha particle collisions with Helium and Nitrogen nuclei. Hariprasad De and M S Sinha used this chamber for cosmic ray work in 1937-38 under the guidance of D M Bose. With the help of S D Chatterjee this was converted into a counter controlled cloud chamber and with the arrival of Sen Gupta, who had worked in Blackett's group at Manchester for 4 years, a 30 cms diameter cloud chamber was designed and constructed at the Bose Institute. Many scientists from Calcutta had the opportunity of working at Manchester in Blackett's group. In fact, one of the earliest review articles to appear on cloud chamber technique in the Reviews of Modern Physics was by Das Gupta and Ghosh. Most of the cloud chamber work during the 40's was on the study of Mu-mesons. M.S. Sinha and his collaborators have done extensive work in this field. In the mid 60's Sinha and his collaborators set up a large scale magnetic spectrograph at Durgapur and measured the momentum spectrum and charge ratio (μ^+/μ^-) upto 800 Gev. Below the spectrograph a cloud chamber was set up and triggered by a delayed expansion mode so that the ionization of tracks could be measured by droplet counting. The variation of ionization loss with momentum was measured in the momentum range 3-200 Gev/c.

As early as 1939, D M Bose and Bibha Chaudhury exposed several batches of glass backed Ilford nuclear emulsion plates to cosmic radiation at Sandakphu (12,000 ft.) and Pharijong (15,000 ft.) in the Himalayas. They found peculiar curved tracks in the emulsion plates unlike the straight alpha particle tracks from Polonium. The curvature was attributed to multiple Coulomb scattering. From the scattering and mean grain spacing they deduced the tracks recorded at 12,000 ft. gave a mean mass of 221 m_e and those at 15,000 ft. a mean mass of 278 m_e. It is interesting that these results were obtained with ordinary emulsions which were not sensitive to minimum ionizing particles. It is the development of higher sensitivity emulsions that enabled Powell and his collaborators to record $\pi\mu$ and $\pi\mu e$ decays in 1947, as explained in Chapter 2.

5.2 Cosmic Ray Research at the Indian Institute of Science (1939-1945)

The Indian Institute of Science, founded by J N Tata in 1909 at Bangalore played an important role in initiating and fostering cosmic ray research though for a brief span of six years 1939-45, essentially the second world war years. This venture proved to be just the beginning of a major research effort in cosmic rays in India, sustained at a very high level for more than 50 years but at other institutions.

In a strange way India should thank the second world war for this. Homi Bhabha, who along with Heitler had developed the cascade theory that had resolved some of the outstanding problems in the field of cosmic rays, had come back to India in 1939 to spend his holiday with his family in Bombay. The world war broke out in September 39 and prevented Bhabha from going back to England where he had been offered a faculty position in Cambridge itself. He also had offers from other countries. As a temporary measure Bhabha joined the Physics Department of the Indian Institute of Science which was headed by C.V. Raman. Under the aegis of the Physics Department, Bhabha set up a "Cosmic Ray Research Unit" and managed to obtain a special grant from the Sir Dorabji Tata Trust. Apart from pursuing his theoretical work and guiding several students for their Ph.D. in theoretical particle physics, Dr Bhabha started experimental investigations in the field of cosmic rays. With the help of S.V.C. Iya of the Electrical Communications Department he built a G.M. Counter telescope for the study of the penetrating component of cosmic rays and measured the intensity at altitudes of 5,000, 10,000, 15,000, 20,000, 25,000 and 30,000 ft. carrying the telescope in a B-29 bomber air craft that belonged to the U.S. air force still stationed in Bangalore. Comparison of these measurements with those of Schein, Jesse and Wolan in the U.S.A. showed that no marked increase in intensity occurred between 3.30^{O}N and 52^{O}N even at an altitude of 30,000 ft. This was in contrast to the behaviour of the total intensity that exhibited pronounced latitude effect at such altitudes. Bhabha also built a 12" diameter circular cloud chamber with the help of R.L. Sengupta who had returned from Manchester after spending several years with Blackett. M.S. Sinha joined Bhabha and used this chamber for investigations on the scattering properties of the penetrating particle - namely the meson.

5.3 Cosmic Ray Research at the Tata Institute of Fundamental Research

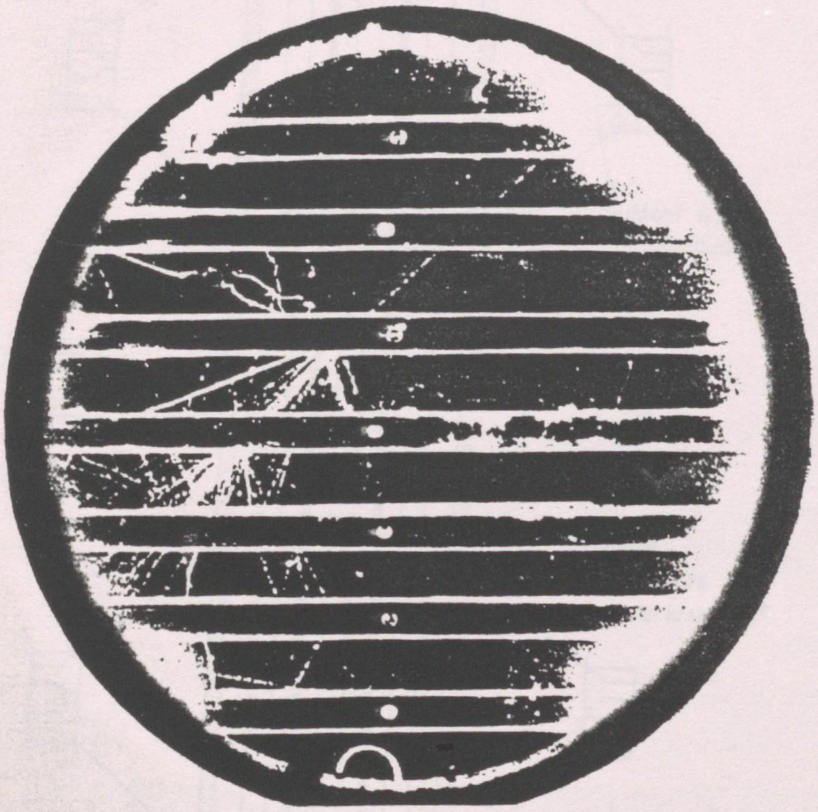
The Cosmic Ray Research Unit at the Indian Institute of Science essentially served as a spring board for launching a more ambitious and more broad based activity in this field at the Tata Institute of

Fundamental Research in Bombay, which Dr Bhabha founded in June 1945 with the help of the Sir Dorabji Tata Trust and the Government of Maharashtra. The new Institute started operating in a small bungalow belonging to the Bhabha family in Pedder Road, Cumbala Hills. P.S. Gill who had worked in the field of cosmic rays at the University of Chicago spent a short time at TIFR and did an experiment on the EAST-WEST effect in one of the open terraces of the building. The cloud chamber that was operating at Bangalore was shifted to Bombay and A B Sahiar set up the chamber for a systematic study of the scattering of mu-mesons. R R Daniel started the nuclear emulsion group under the guidance of H J Taylor, Professor of Physics at the Wilson College. The author of this book (Sreekantan) started building electronic circuits for the study of the decay of mesons.

Under the overall guidance of Bhabha, a major programme was undertaken by A S Rao, R P Thatte, G S Gokhale, V K Balasubramanyan and A W Pereira on the measurement of the penetrating component as a function of altitude at different latitudes. The GM telescope specially designed by Bhabha was flown on clusters of rubber balloons from a number of stations, from Madras in the South to Gulmarg in the North with Bangalore, Puna, Bombay, Ahmadebad and Delhi as intermediate latitude stations.

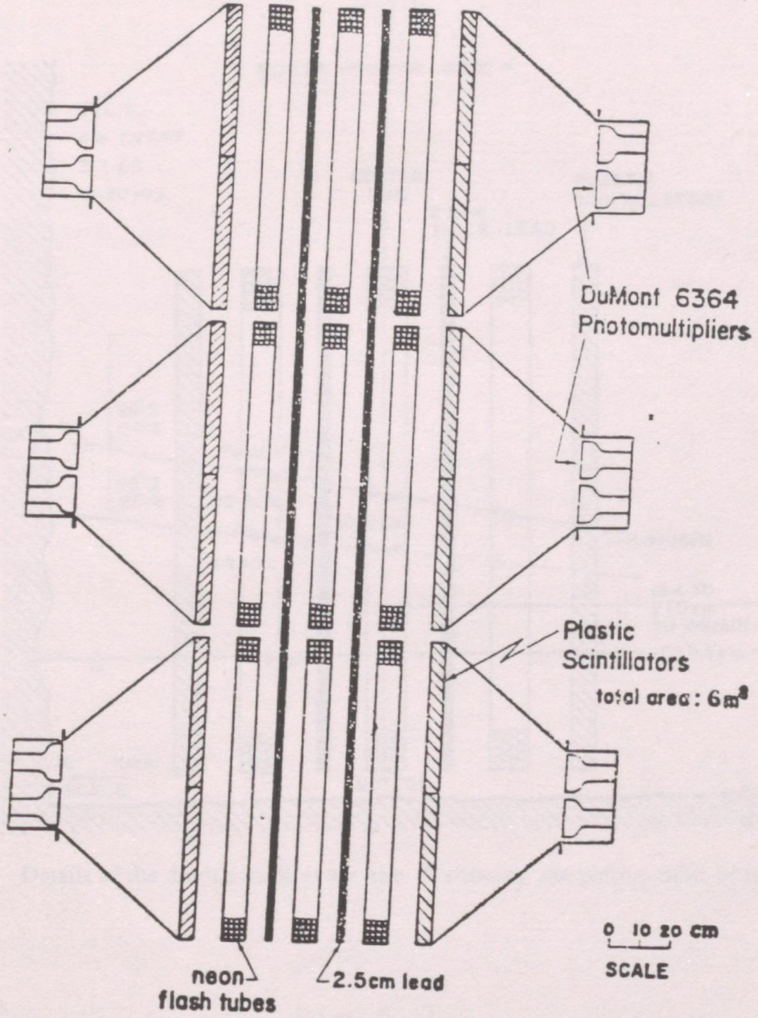
In December 1950, Dr Bhabha organised the first ever International Conference on "Elementary Particles" at the yacht club premises of the institute, the new location of TIFR from 1949 to 1962. This conference was attended by leading theoretical physicists like Wentzel, Rosenfeld, Peierls, Möller, Seligman, and cosmic ray experts like Blackett, Leprince Ringuet, Amaldi, Peters, Feather and Fowler. A major part of the conference was naturally devoted to a discussion of the nuclear interactions of cosmic rays resulting in meson production and on the just discovered V-particles. It served as a wonderful occasion for the young scientists of TIFR to interact with these stalwarts and have fruitful discussions on the future directions of research in cosmic rays and related areas. The nuclear emulsion group of TIFR, Daniel, Lal, Yashpal and Peters made an early impact in the area of strange particle production by presenting significant results at the International Conference on Cosmic rays held at Bagneres de Bigore in France in 1953. Another area in which the group Biswas, Durgaprasad and Peters made important contributions was on the relative abundance of Lithium, Beryllium and Boron in relation to cosmic abundance of these elements. This measurement was essential to estimate the residence time of Cosmic rays in the galaxy, the amount of matter traversed in the interstellar space where these were produced in nuclear collisions of primary Cosmic rays.

It was during the time before the Bombay conference in 1950 when Dr Bhabha was drawing up the programme, that it occurred to him that a very worthwhile field of investigation would be the study of the nature of particles deep underground. Bhabha was curious whether one would find in addition to Mu-mesons other types of penetrating particles. He called me late one evening and suggested that I should plan first to make a systematic measurement of the intensity of penetrating particles at various depths in the Kolar Gold Fields near Bangalore and then design experiments to determine the nature and identity of these particles underground. Accordingly the first set of underground vertical intensity measurements at various depths upto 1000 ft. below ground and the angular distribution of the particles were carried out during 1951 by Sreekantan, Naranan and Ramana Murthy. A multiplate cloud chamber experiment too was carried out at a depth of 100 ft below ground to study interactions of mu-mesons. Later the chamber was shifted to a tunnel at Khandala with an overburden of 190 m.w.e. A typical muon interaction recorded at Khandala is shown in Fig 5.1. A variety of experiments have been undertaken in the Kolar Gold Fields upto a depth of about 9000 ft below ground over the extended period 1951 to 1992. In many of these, there have been large scale international collaborations with scientists from U.K.



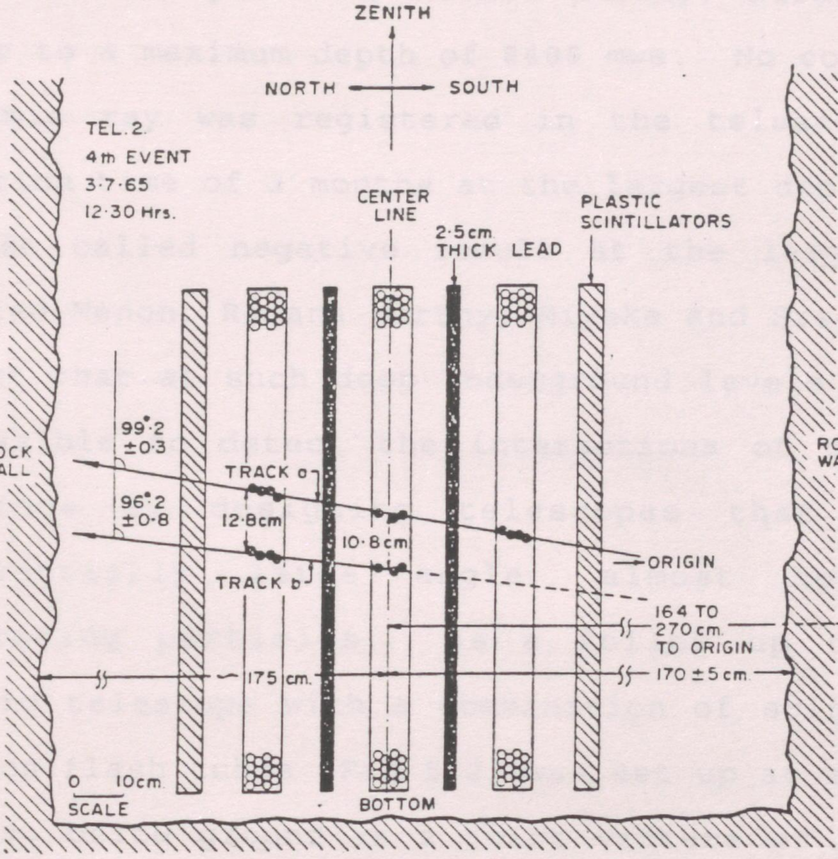
Photograph of a nuclear interaction produced by a penetrating particle underground (190 m w.e.). The heavily ionizing particle coming out of the third plate and going to the left edge of the photograph may be a heavy unstable particle which has stopped and decayed in the fourth plate. The secondary particle probably stops in the last plate after penetrating two plates. Local gas turbulence has distorted the other heavily ionizing track in the third compartment.

Fig 5.1



The first KGF Neutrino Telescope — comprising of vertical walls of plastic scintillators and neon flash tubes assemblies.

Fig 5.2



Details of the double track event (no. 4) showing the bottom third of telescope no. 2.

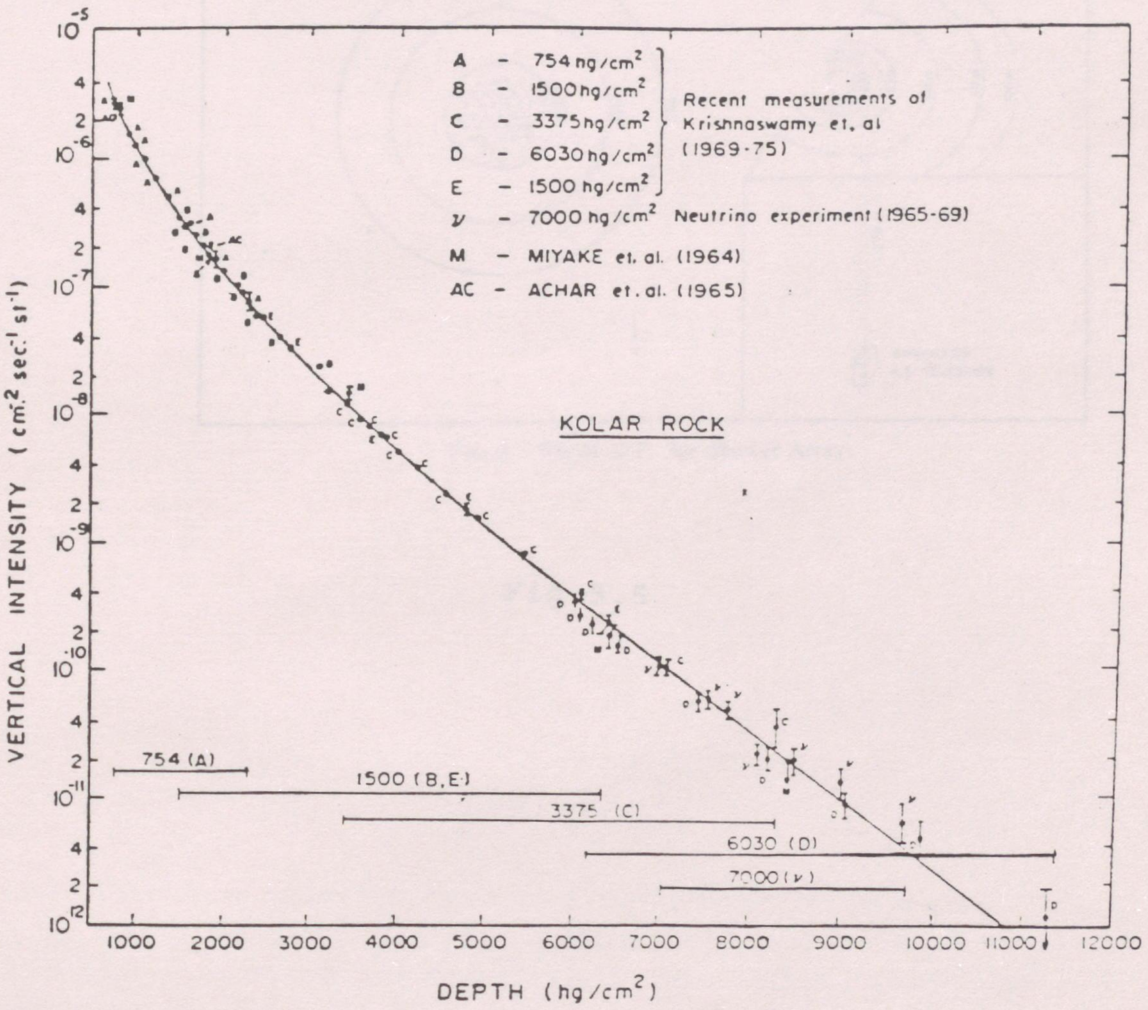
Fig 5.3

and Japan. Let me summarise the highlights of the long series of experiments carried out in the mines in the four decades:

The intensity depth measurements carried out in the first phase upto a depth of 1000 ft. were extended in the second phase by Ramana Murthy, Narasimham and Miyake to a maximum depth of 8400 mwe. No count due to a cosmic ray was registered in the telescope in an operation time of 3 months at the largest depth. It is this so called negative result at the largest depth that led Menon, Ramana Murthy, Miyake and Sreekantan to suggest that at such deep underground levels it should be feasible to detect the interactions of cosmic ray neutrinos by designing telescopes that recorded preferentially large angle, almost horizontal, penetrating particles. As a follow up the first neutrino telescope with a combination of scintillators and neon flash tubes (Fig 5.2) was set up at a depth of 8000 ft. below ground as a joint venture of TIFR, the University of Durham U.K. and the Osaka City University Japan in 1964. Within a few months several clear examples of neutrino interactions were recorded Fig (5.3) and the exciting results reported at the 1965 international conference on cosmic rays held at London. The series of KGF experiments led to the most accurate determination of the intensity as a function of depth upto a maximum equivalent depth of 11,000 m.w.e. based on vertical intensity and angular distributions at various depths.

Another unique installation that was set up in 1960 at KGF by Sivaprasad, Viswanath, Rao, Naranan and Sreekantan was the KGF Air Shower array at the surface with muon detectors at various depths underground Fig (5.5). The highest energy associated masons recorded at a depth of 1972 m.w.e. had a threshold energy 1800 Gev. This was the first experiment to record muons of such high energy in air showers. The surface array of 70 scintillators recorded showers in the energy range 10^{14}-10^{16} ev. The large area Neon Flash tube detector at a depth of 270 m.w.e. enabled the determination of the points of entry of muons of energy greater than 220 Gev at the surface and hence the lateral distribution of muons and the variation of the total number of muons of such high energy as a function of the size of the shower. The very interesting experimental result is shown in the Fig. (5.6). The behaviour of this curve has important implications on the composition of the primaries in the energy range 10^{14}-10^{16} ev.

A second much larger air shower array comprising 127 plastic scintillators each of area 1 m^2 and 7 muon detectors each of area is $20m^2$ (threshold 1 Gov) were operated in KGF for several years. (Fig 5.7) Here the



The variation of intensity of penetrating particles as a function of depth—based on a variety of experiments at the Kolar Gold Fields.

Fig 5.4

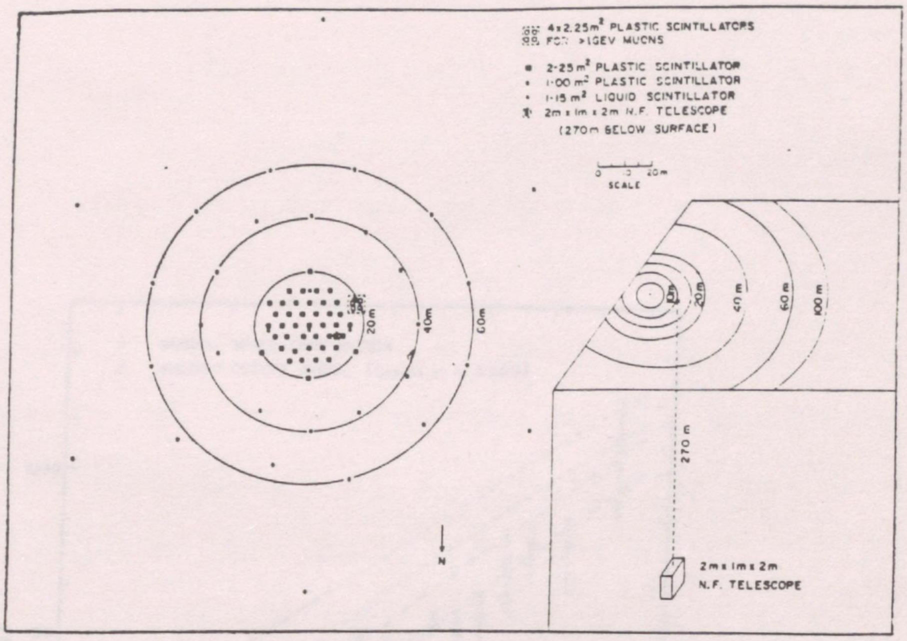


FIG. 8. The K.G.F. Air Shower Array

Fig 5.5

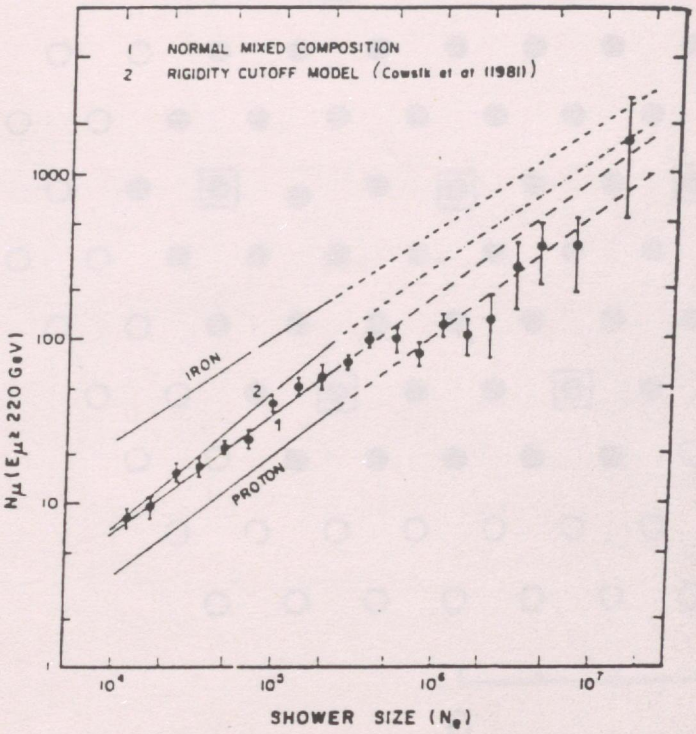
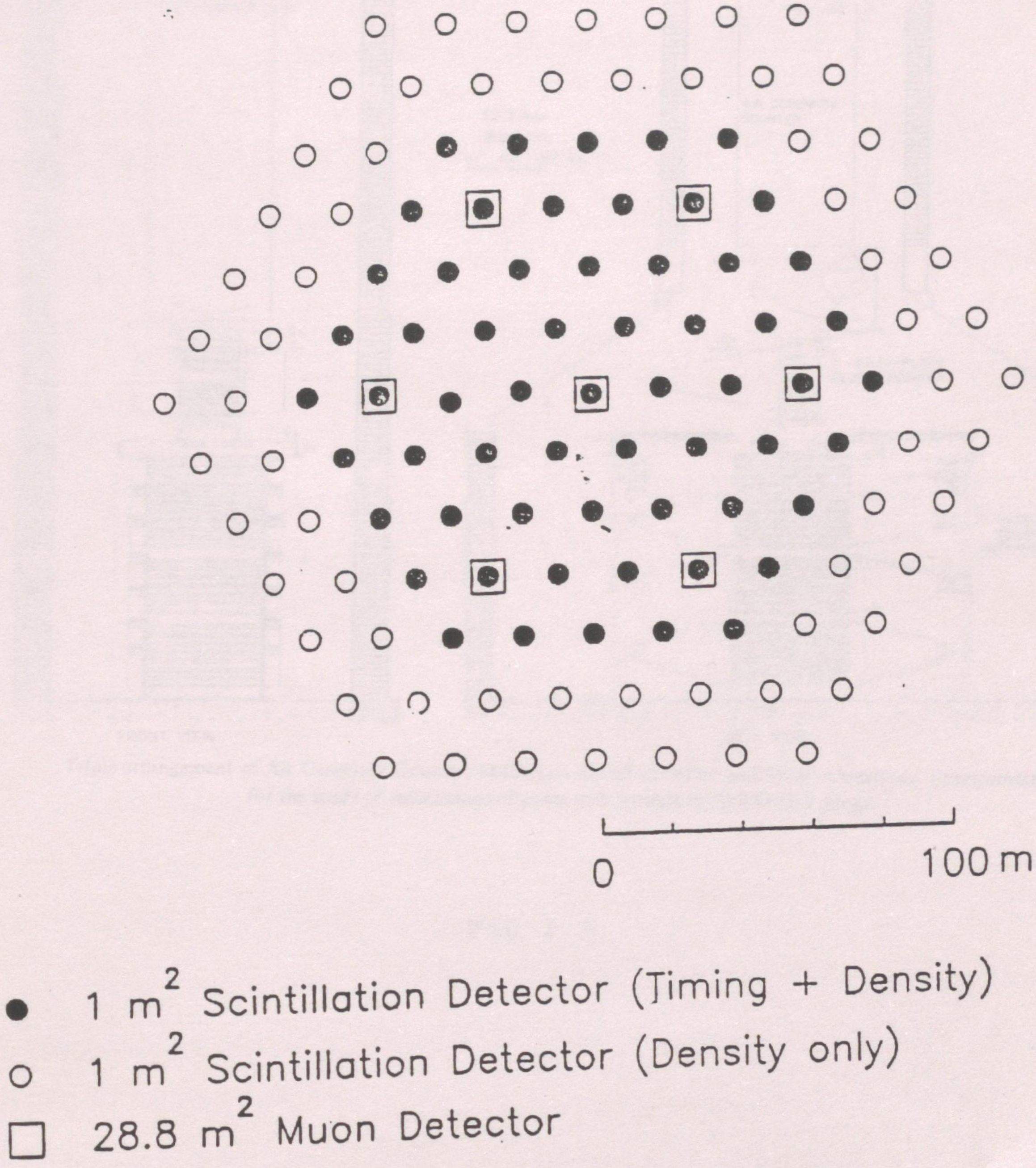


Figure 6.16 Variation of the number of muons of energy > 220 GeV with shower size at 920 g cm^{-2}, compared with Monte Carlo calculations for various models of primary composition using an interaction model with inelastic cross sections increasing with energy (Acharya et al., 1983).

Fig 5.6



A Schematic View of the Kolar Gold Fields EAS Array

Fig 5.7