A Century of Cosmic Ray Research

In 1785, the famous french Scientist Coulomb had published a paper in which he had reported the observation that an electrically charged metal sphere suspended by an insulating silk thread leaked away its charge in a short time. The reason was unknown. The mystery was solved only in the year 1912 by Victor Hess who established through a series of manned balloon flights that the leakage of charge was due to bursts of ionization of the air surrounding the metal sphere by highly penetrating charged particles of extraterrestrial, indeed of extrasolar origin. The name 'Cosmic radiation' was given to this mysterious radiation by Millikan in 1925.

The radiation had several unique and intriguing features. The radiation was present all over the globe. It was pouring in both during day and night and from all directions. It took more than a few decades to figure out the various complexities of the radiation. Studies on the variation of intensity of the radiation as a function of latitude and longitude established the influence of the earth's magnetic field on the radiation and the charged nature of the radiation. (Fig.1 (~~1.3~~)) This led to the discovery of the socalled knee effect of the radiation. (Fig 2 (~~1.4~~)) A very puzzling feature ~~of~~ was the discovery of very anamalous properties of the radiation at both sealevel and at mountain altitudes.

There was clear indication of two components with widely different characteristics. – a soft component that was easily absorbed by a few centimeters of lead and a penetrating component that could penetrate meters of lead. The soft component was observed to arrive not as single particles, but mostly as bursts of ~~almost~~ simultaneous multiple particles. It was also observed that this radiation multiplied into several particles in passing through an absorber like lead. The penetrating particle on the otherhand arrived mostly as a single particle and did not multiply in passing through large thicknesses of lead absorber. However, the absorption characteristics of the penetrating radiation showed a very anomalous feature – ~~that~~ the extent of absorption was different in equal grammage of a condensed medium like lead and an extended medium like the atmosphere. More penetrating particles were lost in the atmosphere compared to the loss in lead. This gave the first clue that the penetrating particle may be undergoing spontaneous decay like a radioactive nucleus. These observational features of cosmic ray experiments were progressing at the sametime as the heady days of the developments in relativity and quantum mechanics and naturally provided crucial confirmations of the theoretical developments in these fields.

The ~~D~~ development of the relativistic quantum equation of the electron by Dirac, led to the prediction of the 'positron' the anti-particle of the electron. Without knowing this theoretical prediction, C.D. Anderson of California Institute of Technology discovered the positron (Fig 3 ~~Fig 2.1~~) while analysing the nature of cosmic ray particles ~~at~~ in a magnetic cloud chamber. This was followed by the development of the cascade theory by Bhabha and Heitler in England and simultaneously by Carlson and Oppenheimer in the U.S. The cascade theory provided a simple and elegant explanation of the features of the soft component of cosmic radiation - the multiplication of particles through a cascade of pair production and γ bremsstrahlung radiation.[5,6] (Figs 4 and 5, ~~2.2~~ 1.5)

From ~~an an~~ a systematic analysis of all the cosmic ray data on the soft and penetrating components, ~~Homi Bhabha~~ ~~in the mid 30's~~ and from a critical assessment of the quantum-electro-dynamics theories, Homi Bhabha, in the mid 30's of the last century came to the conclusion that (i) either quantum electrodynamics breaks down at high ~~energies~~ energies, or (ii) there exists in cosmic radiation a particle with a mass intermediate between that of the electron and proton. Around the same ~~time~~ time, Anderson and Neddermeyer, and also Street and Stevenson were mounting evidence from their cloud chamber experiments on cosmic ray particles for the existence of unit charge particles of intermediate mass. Further experiments established that the mass of this particle, was 200±2 electron masses. While the name 'mesotron' was given to this particle by Millikan, the name 'meson' was suggested by Bhabha in 1939 and the latter name has stuck on.

Soon, the Spontaneous decay of the meson was Recorded in cloud Chamber (~~Fig 6, 2-6~~) and a classic example is shown in Fig 6 (2-6). The half-life of the meson was measured by bringing the meson to rest in an absorber and recording the time of its decay into an electron. It was also established that this meson decay was a three body process involving in addition to the electron, two more neutral particles, the neutrinos. The mean life time of the meson was determined to be 2.2 microseconds.

While the discovery of the meson provided an elegant explanation of the penetrating Component and its decay characteristics ~~exp~~ accounted for the anomalous absorption characteristics discussed earlier, serious problems arose ~~bela~~ because of certain theoretical developments in the field of nuclear physics and also because of the very weak interaction of these particles in nuclear encounters. To explain the strong binding between protons and protons, protons and neutrons and neutrons and neutrons in nuclei, the Japanese physicist Yukawa had postulated the existence of a particle of mass intermediate between the electron and proton, that was continuously exchanged between these nuclear components. With the discovery of the meson, the natural assumption was ~~had~~ made that the Yukawa particle (Yukon) and the experimentally discovered 'meson' were one and the same. This led to lot of confusion and complication and was resolved only through another major discovery.

The experiments of Conversi, Panchini and Piccioni on the mean lifetimes of positive and negative muons coming to rest in absorbers of different atomic numbers showed that while positive mesons decayed in all substances with the same lifetime of 2.2 microseconds, the behavior of negative mesons was distinctly different. While none of the negative mesons decayed in a high atomic number material like iron, some of them did decay in lighter atomic number materials like Carbon and magnesium and a clear dependence on Z could be established. This behaviour was contradictory to the expectation that the meson was the same as the Yukon. In this case the negative mesons also should have decayed in all materials, irrespective of the atomic number. Another discrepancy was that the lifetime of 2 microseconds was a factor of 100 longer than that Yukawa had predicted for the Yukon. Theoreticians like Marshak had been suspecting that there may be two kinds of mesons.

In the mid 40's, Powell and his collaborators at the University of Bristol pioneered the development of the photographic emulsion as a particle detector, even for very high energy particles which had the characteristic of lowest ionization loss in passing through any material. This development was rewarded by.

the discovery of yet another meson (Fig 7, ~~2 8~~). What was remarkable was that this new meson which was given the name Pi-meson, (Pion) decayed spontaneously into the old meson which was now given the Mu-meson (Muon). The Pi-meson had just the characteristics expected of the Yukawa particle - its mass was 273 electron masses and life time 2.6×10^{-8} seconds and it decayed into a Muon and a neutrino.

With the discovery of the Pi-meson, the main features of the different components of cosmic rays encountered at mountain altitude and sea level were satisfactorily explained. The inter-relations between the different components also became clear. The question that remained was - how did these Pi-mesons come into existence at these deep levels of the atmosphere, especially since the Pi-mesons had a mean life of only 2×10^{-8} seconds and despite relativistic elongation of time could not survive for long distances in the atmosphere. What is the connection between these Pi-mesons and whatever is the primary cosmic radiation that is incident at the top of the atmosphere? This takes us to the study of the behaviour of cosmic radiation as a function of altitude to very great heights, started by the pioneer Victor Hess himself. and also

~~The studies on the variation of cosmic ray intensity as a function of altitude revealed that~~ the ~~intensity increased upto a height of corresponding to 200gms/cm² of the atmosphere and then rapidly~~

~~On the Studies on~~ of the penetrating component of cosmic radiation underwater and underground. Though Victor Hess found that the intensity of the ionizing radiation increased as he rose to higher and higher heights upto about 13,000 ft in his manned balloon gondola, later experiments of Regener and others showed that the intensity started slowly levelling of at higher heights corresponding to about 200 gms/cm^2 (Fig 8 Rossi p11). Further experiments revealed that the radiation incident at the top of the atmosphere consisted primarily of protons and it is in the collisions of these primaries with air nuclei that a large number of secondary particles were produced, the most dominant being charged and neutral pi-mesons. The mu-mesons which constituted the penetrating component at lower levels of atmosphere, at mountain altitudes, ~~at~~ underwater and underground were the decay products of the pions. The neutral pions decayed into pairs of γ-rays that gave rise to the soft component of cosmic rays - photons and electrons through cascade development. There was also an indication that the primary cosmic rays extended over a wide energy band, especially from the deep underground experiments. Thus by the late 1940's, the next phase of cosmic ray research got clearly defined:

(i) Study of the characteristics of high energy nuclear interactions.

(ii) Study of the composition and energy range of the primary radiation.

Cosmic Ray Studies on High Energy Interactions :

Era of Particle physics

Around the same time as the discovery of the Pi-meson in nuclear emulsions exposed at mountain altitudes, Rochester and Butler found evidence for yet another new type particles — called by them V-particles in a cloud chamber operated at Sea Level. The photograph of a typical V-particle recorded in a cloud chamber is shown in Fig 9. (~~Fig 15~~). These V-particles were later identified as the K-mesons and Hyperons which actually as "Strange Particles" heralded the new era of fundamental particles and these investigations both with cosmic rays and nuclear accelerators became a major activity of in the area of fundamental research all over the world. The Table 1, (p34) summarises the properties of all the fundamental particles discovered in Cosmic Rays over the decade 1947-1957, the only exceptions being the positron discovered in 1932, the mu-meson in 1937.

These particles, excepting the positron, are all unstable particles and decay away in extremely short intervals of time into other particles. The lifetimes range from 2×10^{-6} seconds to 8×10^{-17} seconds. They are all singly charged and have a spin 0 or 1/2.

When the K-mesons were discovered an intriguing feature that had been noticed ~~in~~ was that the

K-meson was always produced in association with a hyperon or another K-meson. This unique feature which came to be known as 'associated production' led Gellmann and Pais to propose „a 'new quantum number that they called "Strangeness quantum number" to be conserved in strong interactions involving the production of these new particles in addition to the pi-mesons which were treated as non-strange particles. The spontaneous decay behaviour of these strange particles showed that the strangeness quantum number was not conserved in weak interactions. The Table gives also the strangeness quantum numbers that were associated with various particles.

Gellmann predicted on the bases of the phenomenological SU(3) that he developed that there should be a particle with strangeness quantum number (−3) that should be produced in high energy interactions. It was indeed a great triumph for the theory that this particle called Ω^- was discovered later at accelerators.

Yet another important result of great consequence that emerged from a study of these new particles was the first indication of parity non-conservation in weak interactions. It can be seen from the Table that K^0-meson with a mass of 974 me, decays in two distinctly different modes —

→(10)

Sometimes into two pions ($\pi^+\pi^-$, $\pi^0\pi^0$) and at other times into three pions – (π^0, π^0, π^0), ($\pi^0\pi^+\pi^-$) and also ($\pi^- e^+ \nu_e$) with quite different lifetimes for the various decay modes. The occurence of both two body and three body decays for the same particle meant the non-conservation of the symmetry – Parity. In Cosmic Ray Studies the particle that decayed into two pions was called the θ particle and the one that decayed into three was called τ-meson and the puzzle was called τ-θ puzzle. The first reaction was to treat these two as different particles. To resolve the puzzle, Lee and Yang proposed symmetry breaking of the mirror reflection symmetry in weak interactions and suggested the famous β-decay experiment which was successfully carried out by Madame Wu, confirming the parity breakdown.

These discoveries in the area of fundamental particles produced in high energy collisions of cosmic rays and their secondaries provided considerable incentive and justification for the construction of higher and higher energy accelerators. Thus cosmic ray studies on high ~~energy~~ energy interactions gradually shifted to ~~higher and~~

energies beyond the range of accelerators at different points of time. Also the primary cosmic ray beam provided the opportunity for studying the characteristics of collisions involving heavy nuclei, which had been discovered as being present in the primary beam around 1948. Gradually the emphasis in cosmic ray research shifted to a systematic study of the primary spectrum and composition, especially from the point of view of unravelling the sources of cosmic rays and the physical processes responsible for the acceleration of these particles.

Spectrum and Composition of Primary Cosmic Rays

From a variety of ingeniously designed experiments – emulsion stacks flown to balloon altitudes, ~~deep underground~~ measurements of muon intensity upto very great depths underground and the study of extensive air showers, it has become clear that the primary cosmic ray energy spectrum extends from a few hundred MeV to well beyond 10^{20} eV – more than 14 decades of energy the intensity falling by more than 20 decades. The ingenuity required in the design of experiments can be seen from the fact that while the cosmic ray intensity at about one GeV is 1000 particles / cm^2 sec, it falls to 1 particle / 1000 kilometer squared. year.

Though some preliminary ideas on the nature of the primary spectrum were obtained through an analysis of the high energy interactions in nuclear emulsion stacks flown to balloon altitudes, the primary purpose these served was the detection of heavy ~~prim~~ nuclei in the primary radiation. In the balloon flights carried out by the University of Minnesota and University of Rochester groups with piles of nuclear emulsion plates reaching to an altitude of 94,000 ft., ionizing tracks corresponding to multiply charged particles of several Gev energy were recorded and later experiments established that these indeed were due to various types of heavy atoms stripped of their electrons. The Table II shows the relative abundance of these heavy nuclei in the primary radiation (~~Table 3.1 p.34~~). Though there is a general similarity to the universal abundance of elements, the iron group is much more abundant in cosmic rays. A matter of primary interest in cosmic ray studies in more recent years has been the determination of these relative abundances at very high energies. The very special types of ~~em~~ large area emulsion stacks with interspersed X-ray sheets have enabled the determination of the relative abundances of the light, medium and heavy groups of elements upto about an energy per nucleus of 10^{15} eV. (Fig 11 ~~Fig 3 2~~). The shape of the spectra for the different groups beyond this energy range is of great astrophysical interest.

The all particle spectrum in the energy range 10^{11} eV to 10^{15} eV has determined with the help of deep ionization calorimeters on board the Proton Satellite Series by Grigorov et al. This is reproduced in Fig in Fig 12 (~~EAS plot~~).

The all particle primary spectrum over the entire energy range 10^{11} to 10^{20} eV as compiled by ~~Hara et al~~ Teshima in 1983 almost 20 years after Grigorov's experiment is given in Fig 13. It is seen that there is a pronounced change in the slope of the energy spectrum around 10^{15} eV which has come to be known as the "knee" region and again a flattening of the spectrum around 10^{18} eV which has been called the 'Ankle' of the primary spectrum. The factors contributing to these changes are not clear yet. As far as the knee is concerned, for almost fifty years, it has been surmised that this may be connected with the rigidity cut off imposed by the galactic magnetic field; as suggested by Bernard Peters. in the ~~mid~~ ~~early~~ ~~50's~~ mid 1950's. ~~The determination of the composition~~ ~~beyond around and beyond this knee has remained~~

Such a rigidity cut off depends on Z/A which is different by a ~~factor~~ factor 2 between protons and heavy nuclei and since in air shower experiments, what is measured is the total energy of the 'primary,' energy per nucleus, one should expect a steepening of the spectrum over a range of primary energies and also a gradual change in the primary composition moving towards an abundance of heavier and heavier nuclei. An estimate of the relative primary nuclear composition by study in 1993 based on the emulsion track experiments is given in Table 3. (Table 3-1 p48)

At still higher energies the only method available is that of extensive air showers. In this method, the special characteristics of the showers like the delay in the arrival times of the different components of the shower – electrons, muons, nuclear active particles etc, the multiplicity distributions of muons etc. have been used to estimate roughly the primary composition through extensive MonteCarlo simulations of these characteristics. The Table 4 gives ~~A~~ a comparison of the relative composition ~~at~~ in the energy range 10^{13} to 10^{15} ev. One trend that is clear from the table is that at energies beyond 10^{15} there is an increased heavy primary dominance. The question is whether this continued upto very high energies.

~~The possibility of a Steepening of the~~

The flattening of the Spectrum, well beyond the knee region is accounted for in terms of the dominance of a possibility of an extragalactic component of Cosmic Rays which has this ~~characteristic~~ characteristic of the Spectrum and for a long time it was thought that this component has to be necessarily protonic in character since the heavy primaries of ~~etc~~ extragalactic origin would all be disintegrated in nuclear interactions with the extragalactic matter. However, an anomalous situation has developed with the finding of the some of the large air shower experiments in which the longitudinal development and absorption of particles in the cores of showers can be determined and related to the nature of the primary initiating the shower that around an region ~~below~~ of $3 \cdot 10^{17}$ ev there is a dominance of ~~heavi~~ very heavies (iron group) and above this energy the primaries are mostly protons. ~~Immed~~ Immediately after the discovery of the 3° microwave radiation, it was ~~pointed~~ pointed out both by Greisen and Kuzmin that there should be a steepening of the primary cosmic ray spectrum beyond 10^{19} ev., due to the interaction of these particles with the 3° photons. The existence of this effect has been looked for and is perhaps confirmed by the observation that the number of showers of energy greater than 10^{19} ev is an order of magnitude less than that is expected on the basis of a simple extrapolation of the spectrum between 10^{18} and 10^{19} ev. However in the last few years three definite ~~examples~~ cases of showers of energy greater than 10^{20} ev have been recorded. The characteristics of these highest energy showers are given in Table 5. (Table 7-6 p224. EAS Book)

An interesting feature that is to be noted is that all the three showers have come within 50° of the antigalactic centre. These three events have posed a serious challenge in terms of identifying the nature of the primaries of these showers as well as of the possible sources. ~~Neither the protons~~, The absorption characteristics of protons, heavy nuclei and γ-rays show that the distance of the sources has to be less than 50 megaparsecs. There are no interesting active galactic nuclei within this distance and within reasonable direction of arrival of these showers, unless our ideas on the strength of the intergalactic magnetic field of the order of a few microgauss is totally wrong.

Primary Electrons and Gamma Rays

Though the primary radiation is essentially hadronic in nature, the presence of electrons and gamma rays has recognised in balloon borne and satellite experiments as early as 1961.

The primary electron spectrum in the energy range 10 Gev to 1000 Gev is reproduced in the figure 14 (~~Fg 4-1 p54~~)

The special importance of the electron component arises from the fact the background radio emission is due to synchrotron emission of the relativistic electrons spiralling round the magnetic fields. The inverse Compton scattering of the electrons with the photons of the 3° ~~Micr~~ microwave radiation gives rise to the diffuse x-ray and gamma ray background measured in the vicinity of the earth's outer atmosphere.

Tev and Pev γ-ray Astronomies

With the discovery of the Pulsars in the radio and optical and x-ray regions, considerable interest has revived in the search for ~~high~~ very high energy gamma rays especially pulsed γ-rays. The pulsars with magnetic fields of 10^{12} gauss and above in their neighbourhood have considered to be the right kind of environments in which charged particles, ~~effect~~ ~~could be~~ could be accelerated to cosmic ray energies of atleast upto 10^{15} ev. The method of air Cerenkov radiation (Fg 15) has been used effectively upto about (~~Fg 4-2~~ ~~p.55~~) ~~Fg 15~~ to 10Tev.

One of the most prominent sources in the Tev region has been the Crab Nebula. While practically all the groups that have made observations on this source have seen it as steady source there is some dispute still regarding the pulsed component in this energy range. The Table 6 (Table 4.1) gives the list of sources that have been seen in the TeV band and their characteristics. It is seen that there is evidence for atleast two extragalactic sources Markarian 421 and Markarian 501.

In the still higher ~~energy ra~~ energy range greater than 10^{14} ev, the only definitive source is again the Crab nebula, though the famous X-ray source eg. Cyg-X-3 has been claimed to be PeV source occasionally.

Cosmic Ray Muons and Neutrinos

So far we have concerned ourselves with the components of cosmic rays that can easily be detected either at ~~sea~~, sea level or at mountain altitudes ~~and in satellites~~. or at balloon and satellite altitudes. Historically, the study of cosmic rays underwater and underground were started in the 1930's itself to understand the mystery of the penetrating radiation, which later turned out to be the μ-meson component produced in the decays of π and K-mesons. What is most interesting is that cosmic ray muons have been recorded with depths corresponding to 8000 ft below ground in the Kolar Gold Fields and using angular distribution ~~measu~~ measurements, intensities ~~depth~~ corresponding to equivalent depths of 10,000 ft rock have been determined. (Fig 16). ~~(Fig 5.4)~~ ~~p73~~)

The other component of secondary cosmic rays whose investigations have been conducted deep underground is the neutrino component that arises in the decays of K-mesons, π-mesons and μ-mesons in the atmosphere. The fig 17 ~~(Fig 5.3)~~ shows the example of a neutrino interaction in the rock that gives rise to a pair of muons recorded at a depth of 7500 ft in the ~~Kolar mines~~ Kolar mines. The direction of the neutrino is such that it must have originated in the atmosphere somewhere in Australia and travelled almost through the diameter of the earth before interacting in the rock close to the Kolar installation. ~~In recent years~~

~~the determination of the ratio of the electron neutrinos & muon neutrinos in cosmic rays determined in the Superkamiokande set up in Japan with high accuracy has led to the confirmation of the theory of neutrino oscillations.~~

In recent years, through a study of the angular distribution of the neutrino induced upward coming mu-mesons in the underground installation of the Superkamiokande (Okada - HE 4.1.01 - 26ICRC) it has been possible to establish the neutrino oscillations between ν_μ and ν_τ.

The future of Cosmic Ray Research:

Even after a hundred years of Cosmic Ray Research, there remain many outstanding problems ~~both~~ regarding the radiation itself, many astrophysical problems and also problems in the field of elementary particle physics which are engaging the attention of both the experimentalists and the theorists all over the world.

Regarding the radiation itself which extends over 14-15 decades of energy, the sources and mechanisms of accelerations have not been unambiguously established yet though Supernova remnants and Active Galactic Nuclei with condensed objects like Giant ~~Bla~~ blackholes have become increasingly popular as sources and their environments more conducive for high energy acceleration. The composition of the primary ~~Co~~ radiation beyond 10^{15} eV is still not clear. While the change of the shape of the spectrum around the knee region ($\sim 10^{15}$ eV) is well established, the flattening beyond 10^{19} eV and the evidence for a cut off due to 30 radiation is still in dispute. The theoretical work on the acceleration of particles in the neighbourhood of AGN's is throwing open the possibility of detectable fluxes of very high energy neutrinos in the underground and underice installations. The search for high energy quark nuggets and WIMPS or weakly interacting massive particles continues. The sources of the highest energy cosmic rays of energy beyond 10^{21} is also posing serious problems. While accelerator experiments have confirmed by and large many of the characteristics of ultra high energy interactions ~~ye~~ discerned from cosmic ray studies in the earlier years like the rising cross sections, increasing production of nucleons and antinucleons with energy, some anomalies still exist.

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A Century of Cosmic Ray Research

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In 1785, the famous french scientist Coulomb had published a paper in which he had reported the observation that an electrically charged metal sphere suspended by an insulating si~~c~~lk thread leaked away its charge invariably in a short time. The reason was unknown. The mystery was solved only in the year 1912 by Victor Hess (1) who established through a series of manned balloon fights that the leakage of charge was due to bursts of ionization of the air surrounding the metal sphere caused by highly penetrating charged particles of extraterrestrial, indeed of extrasolar, origin. The name `cosmic radiation' was given to this mysterious radiation by Millikan in 1925.

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There was clear indication of two components with widely different characteristics - a soft component that was easily absorbed by a few centimeters of lead and a penetrating component that could penetrate meters of lead. The soft component was observed to arrive not as single particles, but mostly as bursts of simultaneous multiple particles. It was also ~~observed~~ noted that this radiation multiplied into several particles in passing through an absorber like lead. The penetrating particle, on the otherhand, arrived mostly as a single particle and did not multiply in passing through even large thicknesses of a lead absorber. However, the absorption characteristics of the penetrating radiation showed a very anomalous feature - the exten~~d~~t of absorption was different in equal grammage of a condensed ~~medicines~~ ~~matter~~ medium like lead and an extended ~~medicines~~ medium like the atmosphere. ~~More~~ Larger number of penetrating particles were lost in the atmosphere compared to the loss in lead. This gave the first clue that the penetrating particle may be undergoing spontaneous decay like a radioactive nucleus. These ~~observational~~ Special features of cosmic rays ~~experiments~~ were becoming familiar ~~progressing~~ at the sometime as the heady days of ~~the~~ developments in relativity and quantum mechanics and naturally started providing ~~provided~~ crucial confirmations ~~of~~ to the theoretical developments in these fields. The development of the relativistic quantum equation of the electron by Dirac, led to the prediction of the `positron' the anti-particle of the electron. Without ~~knowing~~ being aware of this theoretical prediction, C D Anderson 4 of California Institute of Technology discovered the posit~~ive~~ron (Fig 3) while analyzing the nature of cosmic ray particles in a magnetic cloud chamber. ~~This~~ The positron discovery was followed by the development of the cascade theory by Bhabha and Heitler (6) in England and simultaneously by Carlson and Oppenhiemer (7) in the U.S. The cascade theory provided a simple and elegant explanation of the features of the soft component of cosmic radiation - the multiplication of particles (5) through ~~a cascade of~~ pair production and bremstratlung radiation. ~~(5)~~ **(Fig. 4 and 5)**

From a systematic analysis of all the cosmic ray data on the soft and penetrating components, and from a critical assessment of the quantum-electro-dynamics theories, Homi Bhabha, 8 in the ~~early~~ mid 1930's ~~mid 30's of the last century~~ came to the conclusion that either (i) ~~either~~ quantum electrodynamics breaks down at high energies, or (ii) there exists in cosmic radiation a particle with a mass intermediate between that of the electron and proton. Around the same time, Anderson and Neddermeyer (9), and also Street and Stevenson were mounting evidence, from their cloud chamber experiments, on cosmic ray particles, for the existence of ~~unit charge~~ Singly Charged particles of intermediate mass. Further experiments established that the mass of this particles, was 200 ± 2 electron masses. ~~Which~~ While the name `mesotron' was given to this particle by Millikan, the name `meson' was suggested by Bhabha in 1939 and the latter name has stuck on.

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(ii) Study of the composition and energy ~~range~~ spectrum of the primary radiation

Cosm~~o~~ic ray studies on High energy interactions: Era of Particle Physics

Around the same time as the discovery of the pi-meson in nuclear emulsions exposed at mountain altitudes, Rochster and Bu~~d~~tler (15) found evidence for ~~yet~~ another ~~new~~ type of new particles - called by them V-particles (in a cloud chamber operat~~or~~ed at sea level). The photograph of a typical V-particle (16) recorded in a cloud chamber is shown in **Fig 9.** These V-particles were later ~~identified~~ given the name as the K-mesons and Hyperons ~~which actually~~ the ~~as~~ "~~strong~~ strange particles" that heralded the new era of fundamental particles, ~~whose~~ investigations both with cosmic rays and ~~nuclear~~ accelerators ~~because~~ ~~becme~~ became particles became a major activity of a ~~major activity in the area of~~ on fundamental research all over the world. The Table 1, summarises the properties of all the fundamental particles discovered in cosmic rays over the decade 1947-1957, (the ~~only~~ exceptions being the posit~~i~~ron ~~discussed~~ discovered in 1932, the mu-meson in 1937).

These fundamental particles, excepting the posit~~i~~ron, are all unstable particles and decay away in extremely short intervals of time into other particles. The lifetimes range from 2×10^{-6} seconds to 8×10^{-17} seconds. They are all singly charged and have a spin 0 or 1/2. When the K-Mesons were discovered an intriguing feature that had been noticed was that the K-Meson was always produced in association with a hyperon or another K-meson. This unique feature which came to be known as `associated production' led Gellmann and Pais (17) to propose a new quantum number ~~when~~ which they called "strangeness quantum number" to be conserved in strong interactions involving the production of these new particles ~~in addition to~~ along with the pi-mesons which were treated as non-strange particles. The spontaneous decay behaviour of these strange particles showed that the strangeness quantum number was not conserved in weak interactions. The Table gives also the strangeness quantum numbers that were associated with the various particles. Gellmann predicted, on the basis of the phenomenological SU(3) theory that he developed, that there should be a particle with strangeness quantum number (−3) ~~that should be~~ produced in high energy interactions. It was, indeed, a great triumph for the theory that this particle called Ω^- was discovered later at accelerators.

Yet another important result ~~of great consequency~~ that emerged from a study of these new particles was the first indication of parity non-conservation in weak interactions. It can be seen from the Table that K^0-meson with a mass of 974 me, decays in two distinctly different modes - sometimes into two pions ($\pi^+\pi^-$, $\pi^0\pi^0$) and at other times into three pions - (π^0, π^0, π^0), (π^0, π^+, π^-) and also ($\pi^- e^+ \nu_e$), with quite different lifetimes for the various decay modes. The occurrence of both two body and three body decays for the same particle meant ~~the~~ non-conservation~~s~~ of the symmetry - parity. In cosmic ray studies the particle that decayed into two pions was called the θ particle and the one that decayed into three was called τ-meson and the puzzle was called τ-θ puzzle. The first reaction was ------- to treat these two as different particles. To resolve the puzzle, Lee and ~~y~~Yang (18) proposed symmetry breaking of the mirror reflection symmetry in weak interactions and suggested the famous β-decay experiment, ~~which was~~ successfully carried out by Madame W~~a~~u, confirming ~~the~~ parity breakdown.

These discoveries in the area of fundamental particles produced in high energy collisions of cosmic rays and their secondaries provided considerable incentive and justification for the construction of higher and higher energy accelerators. ~~Thus~~ Advent of high energy accelerators cosmic ray studies on high energy interactions resulted in being gradually shifted to energies beyond the range of accelerators ~~at different parts of time~~. Also the primary cosmic ray beam provided the opportunity for studying the characteristics of collisions involving heave nuclei, which had been discovered ~~as being present~~ in the primary beam around 1948. ~~Gradually~~ Thus the emphasis in cosmic ray research shifted to a systematic study of the primary spectrum and composition, especially from the point of view ------ of unravelling the sources of cosmic rays and the physical processes responsible for the acceleration of these particles.

Spectrum and composition of primary cosimc rays :

From a variety of ingeniously designed experiments - emulsion stacks flows to balloon altitudes, measurements of muon intensity upto ~~very great~~ large depths underground and the study of extensive air showers, it ~~has~~ became clear that the primary cosmic ray energy spectrum extended from a few hundred Mev to well beyond 10^{20} ev - more than 14 decades of energy, the intensity itself falling by more than 20 decades. The ingenuity ~~required~~ demanded in the design of experiments can be seen ~~for~~ from the fact that while the cosmic ray intensity at about one Gev is 1000 particles/cm^{2}sc, it is ~~it falls to 1~~ 1 particle/1000 kilometer squared year.

Though some preliminary ideas on the nature of the primary energy spectrum ~~were obtained~~ came through an analysis ~~------~~ of the high energy interactions in nuclear emulsion stacks flown to balloon altitudes, the ~~primary purpose these served~~ unexpected bonus from these flights was the detection of heavy nuclei in the primary radiation. In the balloon flights carried out in 1948 by the University of Minnesota and University of Rochester groups 1a with piles of nuclear emulsion plates, reaching to an altitude of 94,000 ft., ionizing tracks corresponding to multiply charged particles of several gev energy were recorded. ~~and~~ Later experiments established that these indeed more due to various types of heavy atoms ~~stopped~~ stripped of their electrons. The Table II shows, the relative abundance of these heavy nuclei in the primary radiation. Though there is a general similarity to the universal abundance of elements, the iron group is much more abundant in cosmic rays. A matter of primary interest in cosmic ray studies in more recent years, has been the determination of the relative abundances of various nuclei at very high energies. ~~The very~~ Special types of large area emulsion stacks with interspersed X-ray sheets that have been flown on long duration balloon flights have enabled the determination of the relative abundances of the light, medium ~~midum~~ and heavy groups of elements upto ~~about~~ an energy per nucleus of 10^{15} ev (**Fig 11).** ~~The shape of the spectra for the different groups beyond this energy range is of great astrophysics interest~~. JACEE Ref

The all particle spectrum in the energy range 10^{11}-10^{15} ev was determined with the help of deep ionization calorimeters on board the Proton satellite series by Grigorov *et al*.(20) This is reproduced in **Fig 12**. The all particle primary spectrum over the entire energy range 10^{11}-10^{20} ev as complied by Teshima(21) ~~Hara *et al*~~ in 1993 ~~1983~~ ~~(21)~~ almost 20 ~~10~~ years after Grigorov's experiment is given in **Fig 13**. It is seen that there is a pronounced change in the slope of the energy spectrums around 10^{15} ev which has come to be known as the "knee" region and again a flattening of the spectrum around 10^{18} ev which has been called the `Ankle' of the primary spectrum.* The factors contributing to these ~~thick~~ changes are not clear yet. As far as the knee is concerned, for almost fifty years, it has been surmised that this may be connected with the rigidity cut off imposed by the galactic magnetic field; as ~~Grigorov's~~ suggested by Bernard Peters in the early ~~mid~~ 1950's.

Such a rigidity cut off depends on Z/A which ~~inch~~ is different by a factor 2 for ~~between~~ protons and heavy nuclei and since ~~--------~~ in air shown experiments, ~~what is measured is~~ the total energy of the `primary, energy per nucleus, is measured one should expect a ~~steeparing~~ steepening of the spectrum over ~~on~~ a range of primary energies brought about by ~~and also a gradual change in~~ the primary composition moving ~~moving~~ towards an increased abundance of ~~heavier and~~ heavier nuclei. An estimate of the relative primary nuclear composition around 10^{14} ev, made by S~~h~~wordy (22) in 1993 based on the emulsion stack~~s~~ experiments is given in Table III. At still higher energies the only method available is that of extensive air showers. In this method, the special characteristics of the showers like the delay in the arrival times of the different components of the shower - electrons ~~elements~~, mesons, nuclear active ~~actor~~ particles ~~etc~~, the multiplicity distributions of muons, etc, have been used to estimate roughly the primary composition through extensive montecarlo simulations of these characteristics. ~~The~~ Table IV gives a comparison of the relative composition in the energy range 10^{13}-10^{15} ev.(23) One trend that is clear from ~~for~~ the table is that at energies beyond 10^{15} there is an increased heavy primary dominance. The question is whether this trend ~~continues~~ continues ~~considerable~~ upto very high energies.

The flattening of the spectrum, well beyond the knee region, is accounted for in terms of the setting in ~~of a~~ possibly of ~~dominance of~~ ~~a possibility of~~ an extragalartic component of cosmic rays which has ~~this~~ flatter ~~characteristics of the~~ spectrum. ~~and for~~ For a along time it was thought that this component has to be

* These features became evident from extensive air shower experiments at mountain altitudes and sea level.

necessarily protonic in character since ~~the~~ heavy primar~~y~~ies of extragalarte origin would all be disintegrated in ~~whether interactors~~ nuclear interactions with ~~the~~ extragalatic matter. However, an anomalous situation has developed with ~~the finding~~ of some of the large air shower experiments in which the longitudinal development and absorption of particles in ~~the cases of~~ individual showers ~~can~~ could be determined and related to the nature of the primary, ~~including the shower that around an region of~~ indicating that around 10^{17} ev, there is a dominance of very heavies (iron group) and above this energy the -------- primaries are mostly protons. Immediately after the discovery of the 3^0 microwave radiation, it was pointed out both by Greisen (24) and Zatcepin and Kuzmin (25) that there should be a steepe~~r~~ning of the primary cosmic ray spectron beyond 10^{19} ev, dut to the interaction of th~~o~~ese particles with the 3^0 photons. The existence of this effect has been looked for and is perhaps confirmed by the observations that the necessarily protonic in character since the heavy primary of extragalarte origin would all be disintegrated in whether interactors with the extragalatic matter. However, an anomalous situation has developed with the finding of some of the large air shower experiments in which the longitudinal development and absorption of particles in the cases of showers can be determined and related to the nature of the primary including the shower that around an region of 10^{17} ev, there is a dominance of very heavies (iron group) and above this energy the -------- are mostly protons. Immediately after the discovery of the 3^0 microwave radiation, it was pointed out both by Greisen and Kuzmin that there should be a steepering of the primary cosmic ray spectron beyond 10^{19} ev, due to the interaction of those particles with the 3^0 photons. ~~The existence of this effect has been looked for and is perhaps confirmed by the observations that the~~ number of showers of energy greater than 10^{19} ev is an order of magnitude less than what is expected on the basis of a simple extrapolation of the spectrum between 10^{18} and 10^{19} ev.* ~~have been recorded. The characteristics of these higher energy showers an given in Table V. (Table 7-6 p224 book)~~

*→ An interesting feature that is to be noted is that all the three showers Table V [26, 27, 28] have come within 50^0 of the antigalactic centre. These three events have posed a serious challenge in ~~terms of identifying~~ discerning the nature of the primati~~c~~es of these showers as well ~~a~~ as of identifying the possible sources. The absorption characteristics of protons, heavy nuclei, and γ-rays show that the distance of the sources has to be less than 50 megaparsecs. There are no interesting Active ------ Galactic Nuclei within this distance and within reasonable direction of arrival of these showers, unless our ideas on the strength of the intergalactic magnets field ~~of the~~ of the order of a few micro gauss ------ is totally wrong.

Primary ~~electron~~ electrons and gamma rays

Though the primary Cosmic radiation is essentially hadronic in nature, the presence of electrons and gamma rays was re~~l~~cognised in balloon borne and satellite experiments as early as 1961. The primary electron spectrum in the energy range 10-1000 Gev is reproduced in the **figure 14**. The special importance of the electron component arises for the fact that the background radio emissions is due to synchrotron emission of the relativistic electrons spiralling round ~~the~~ magnetic fields. The inverse Compton scattering of the electrons with the photons of the 3^0 microwave radiation gives rise to the diffuse X-ray and gamma ray background~~s~~ measured in the vicinity of the earth's outer atmosphere. The importance of the study of the high energy electron component is discussed in the Review article of Daniel and Stephens.[29]

~~**Tev and Pev r-ray astronomics**~~

* More recent data on these very high energy showers seems to indicate that this ZKG cut off has not been established ~~unambiguous~~ unambiguously. Also three showers of energy greater than 10^{20} ev have been recorded. *→

Tev and Pev Astronomies:

With the discovery of ~~the~~ Pulsars in the radio and optical and X-ray regions, consider-----able interest was revived in the search for very high energy gamma rays, especially pulsed γ-rays. The pulsars with magnetic fields of 10^{12} gauss and above in their neighborhood were considered to be the right ~~rigor~~ kind of environments in which charged particles could be accelerated to ~~and~~ cosmic ray energies atleast upto 10^{15} ev. For investigations in this domain, the method of air cerenkov radiation (30) ~~(fig 15)~~ has been used effectively upto about 10 Tev. One of the most prominent sources in the Tev region has been the Crab Nebula (Fig 15). While practically all the groups that have made observations on this source have seen it as a steady source ~~there is~~ some have claimed a ~~dispute still regarding the~~ pulsed component in this energy range. The Table 6 gives the characteristics ~~list~~ of sources that have been seen ~~sean~~ in the Tev band ~~and their characteristics~~. It is seen that there ~~those~~ is evidence for atleast two extragalactic sources Mark~~on~~arian 421 and Mark~~on~~arian 501.(29)

In ~~If~~ the still higher energy range Pev (>10^{15} ev) ~~greater than 10^{14} ev~~, the only ~~definite~~ source that has been seen definitely is again the crab nebula, though the famous x-ray source ~~cyg x-3~~ ~~Cyggx-3~~ Cyg-X3 has been claimed to be Pev source, with varying intensity over years ~~occasionally~~.

Cosmic ray muons and neutrinos

So for we have concerned ourselves with the components of cosmic rays that can easily be detected either at sea level or at mountain altitudes or at balloon and satellite altitudes. Historically, the study of cosmic rays underwater and underground were started immediately after the disovery of cosmic rays ~~in the 1930's itself~~ to understand the mystery of the penetrating radiation, which later turned out to be the μ-meson component produced in the decays of π and k-mesons. What is most interesting is that cosmic ray muons have been recorded (down to ~~upto depths~~ very great depths underground. In the kolar Mines in India ~~corresponding to 8000 ft below ground in the kolar and ------ and bring~~ intensity measurements have been carried out upto vertical depths of 8000 ft, and angular distribution measurements, ~~[illegible]~~ upto corresponding ~~and equivalent~~ depths of 10,000 ft rock (32) ~~have been determined~~. **(fig.16)**. The muons produced in the atmosphere have to have energies in the tens of Tev range to penetrate to such depths.

The other component of secondary cosmic rays whose investigations have been conducted deep underground is the neutrino comport that arises in the decays of k-mesons, π-meson and μ-meson in the atmosphere. The **fig 17** shows the example of a neutrino interaction in the rock that gives rise to a pair of muons recorded ~~reloaded~~ at a depth of 8000 ft in the Kolar mines.(33) The direction of the neutrino is such that it must have originated ~~in the atmosphere~~ somewhere in the atmosphere of Australia and travelled

~~--νμ~~ through the di~~o~~ameter of the earth before interacting in the rock close to the ~~k~~Kolar installation.

In recent years, through a study of the angular distribution of the cosmic ray neutrino induced upward ~~uprard coming mu-meons~~ muons in the underground installation, of the Super Kamiokande, ~~33~~(34) ~~super----miollande (okada- HE 4.1.~~01-1~~6ICR~~C) it has been possible to establish the phenomenon of ~~the~~ neutrino oscillations ~~between ν_μ and ν_τ~~. ($\nu_\mu \leftrightarrow \nu_\tau$).

The future of cosmic ray research

Even after a hundred years of cosmic ray research, there remain many outstanding problems regarding the radiation itself, and also on many related ~~many~~ astrophysical problems and ~~also~~ problems in the field of elementary particle physics beyond the range of even the current accelerators. These ~~which~~ are engaging the attention of both the experimentalists and the theorists all over the world.

Regarding the radiation itself Which ~~where~~ extends over 14-15 decades of energy, the sources and mechanisms of accelerations have nor been unambiguously established yet though supernova remnants and Active ~~Actre~~ Galactic Nuclei with ---- ~~both~~ condensed objects like giant blackholes in their Cores have become increasingly popular as source and their environments most condensive for high energy acceleration. The composition of the primary radiation beyond 10^{15} ev is still not clear. While the change of the shape of the spectrum around the knee region ($\sim 10^{15}$ ev) is well established, the flattering beyond 10^{19} ev and the evidence for a cut off due to 30 radiation is still indispute. The theoretical work on the acceleration of particles in the neighborhood of AGN's is throwing open the possibility of recordable fluxes of very high energy neutrinos in the underground and undevice installations. The search for high energy quark nuggets and WIMPS or weakly interacting massive particles continues. The sources of the highest energy cosmic rays of energy beyond 10^{21} is also posing serious problems while accelerator experiments have confirmed by and large many of the characteristics of ultra high energy interactions discerned from cosmic ray studied in the earlier years like the riffing cross sections, increasing production of nucleon and antinucleons with energy, some anomalies still exist.

Earlier

A Century of Cosmic Ray Research*

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In 1785, the famous french scientist Coulomb had published a paper in which he had reported the observation that an electrically charged metal sphere suspended by an insulating silk thread leaked away its charge invariably in a short time. The reason was unknown. The mystery was solved only in the year 1912 by Victor Hess [1] who established through a series of manned balloon fights that the leakage of charge was due to bursts of ionization of the air surrounding the metal sphere caused by highly penetrating charged particles of extraterrestrial, indeed of extrasolar, origin. The name `cosmic radiation' was given to this mysterious radiation by Millikan in 1925.

The radiation had several unique, at the same time intriguing features. The radiation was present all over the globe. It was pouring in both during day and night and from all directions. It took more than a few decades to figure out the various complexities of the radiation. Studies on the variation of the intensity of the radiation as a function of latitude and longitude established the influence of the earth's magnetic field [2] on the radiation and its charged nature (**Fig 1**). This led to the discovery of the so called "knee" [3] of the radiation **(Fig 2).**

There was clear indication of two components with widely different characteristics - a soft component that was easily absorbed by a few centimeters of lead and a penetrating component that could penetrate meters of lead. The soft component was observed to arrive not as single particles, but mostly as bursts of simultaneous multiple particles. It was also noted that this radiation multiplied into several particles in passing through an absorber like lead. The penetrating particle on the otherhand, arrived mostly as a single particle and did not multiply in passing through even large thicknesses of a lead absorber. However, the absorption characteristics of the penetrating radiation showed a very anomalous feature - the extent of absorption was different in equal grammages of a condensed medium like lead and an extended medium like the atmosphere. Larger number of penetrating particles were lost in the atmosphere compared to the loss in lead. This gave the first clue that the penetrating particle may be undergoing spontaneous decay like a radioactive nucleus. These special

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* To appear in the 125th Anniversary Celebratory Volume of the Indian Association for the Cultivation of Science, Calcutta. (2001)

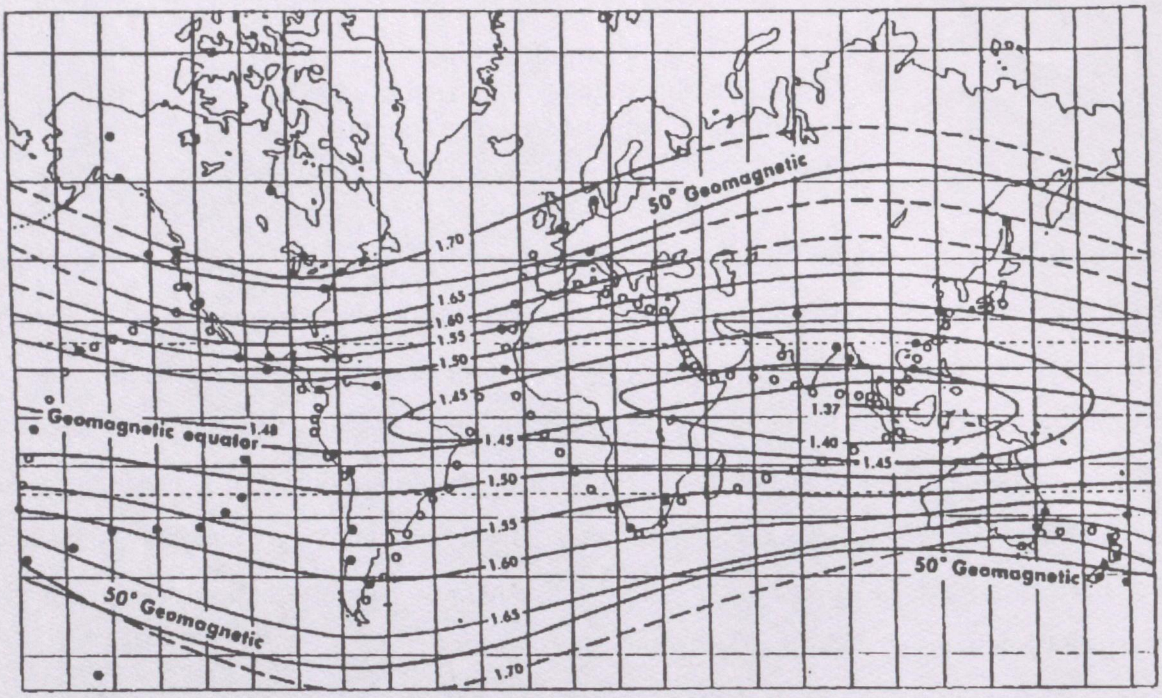


Figure 1. Isocosms, or curves of equal cosmic-ray intensity, according to A.H. Compton. The numbers on the curves give the intensity of the cosmic radiation level, as measured by the number of ion pairs they produce in 1 cm^2 of air at standard temperature and pressure. Dots show locations where measurements were made. The graph also shows the geomagnetic equator and two geomagnetic parallel (50°N and S). (From a paper in *Review of Scientific Instruments*, vol. 7, p. 70, 1936).

features of cosmic rays were becoming familiar at the sometime as the heady days of developments in relativity and quantum mechanics and naturally started providing crucial confirmations to the theoretical developments in these fields. The development of the relativistic quantum equation of the electron by Dirac, led to the prediction of the `positron' the anti-particle of the electron. Without being aware of this theoretical prediction, C D Anderson [4] of California Institute of Technology discovered the positron (Fig 3) while analyzing the nature of cosmic ray particles in a magnetic cloud chamber. The positron discovery was followed by the development of the cascade theory by Bhabha and Heitler [6] in England and simultaneously by Carlson and Oppenhiemer [7] in the U.S. The cascade theory provided a simple and elegant explanation of the features of the soft component of cosmic radiation - the multiplication of particles [5] through pair production and bremstratlung radiation. **(Fig 4 and 5)**

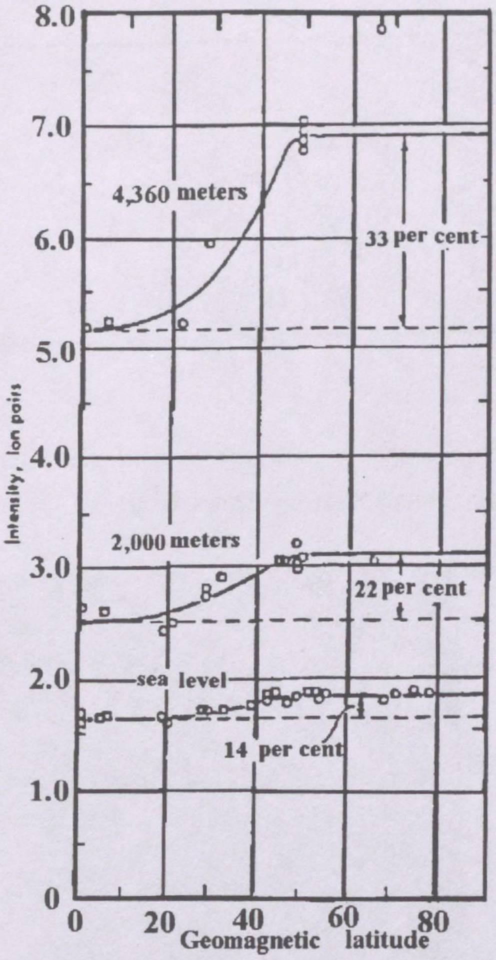


Figure 2. Cosmic-ray intensity as a function of geomagnetic latitude at three different altitudes. The intensity is measured by the number of ion pairs produced by cosmic rays in 1 cm^3 of air at normal temperature and pressure. (From A.H. Compton, *The Physical Review*, vol. 43, p.387, 1933).

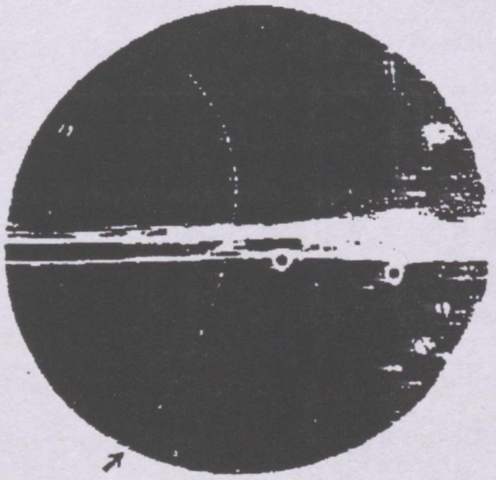


Figure 3. The positron, or positive electron, was identified as the particle that entered the cloud chamber from below and produced the track curving sharply to the left after traversing the lead plate. The photograph, taken by Anderson in 1932, definitely established the existence of positrons. (From a paper in *The Physical Review*, vol. 43, p. 491, 1933.)

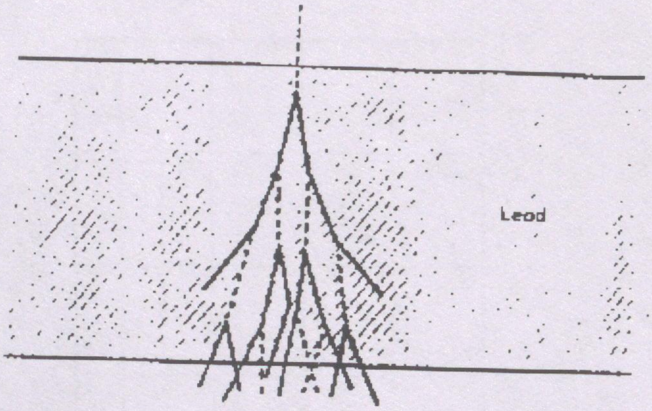


Figure 4. Development of a shower in matter through successive events of pair production and radiation. Dotted lines represent photons, solid lines electrons.

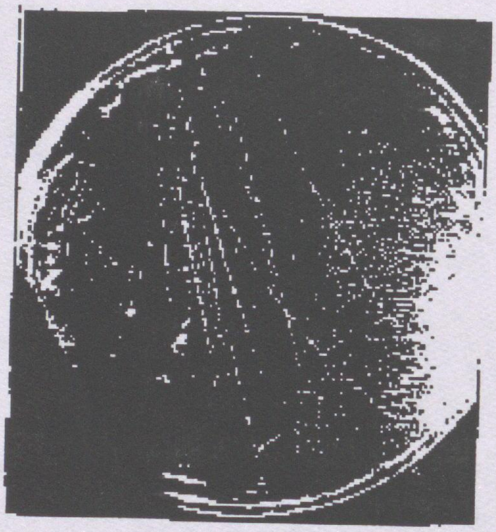


Figure 5. Photograph obtained by Blackett and Occhialini with their counter-controlled cloud chamber. The chamber is situated between the poles of an electromagnet. Sixteen separate tracks of secondary particles enter the chamber simultaneously; they originate above the chamber, being produced, apparently, 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 Occhialine [5], *Proceedings of the Royal Society* (London), vol. A139, p. 699, 1933)

From a systematic analysis of all the cosmic ray data on the soft and penetrating components, and from a critical assessment of the quantum-electro-dynamics theories, Homi Bhabha [8], in the mid 1930's, came to the conclusion that either (i) quantum electrodynamics breaks down at high energies, or (ii) there exists in cosmic radiation a particle with a mass intermediate between that of the electron and the proton. Around the same time, Anderson and Neddermeyer [9], and also Street and Stevenson [10] were mounting evidence, from their cloud chamber experiments on cosmic ray particles, for the existence of singly charged particles of intermediate mass. Further experiments established that the mass of this particle, was 200 ± 2 electron masses. While the name `mesotron' was given to this particle by Millikan, the name `meson' was suggested by Bhabha in 1939 and the latter name has stuck on.

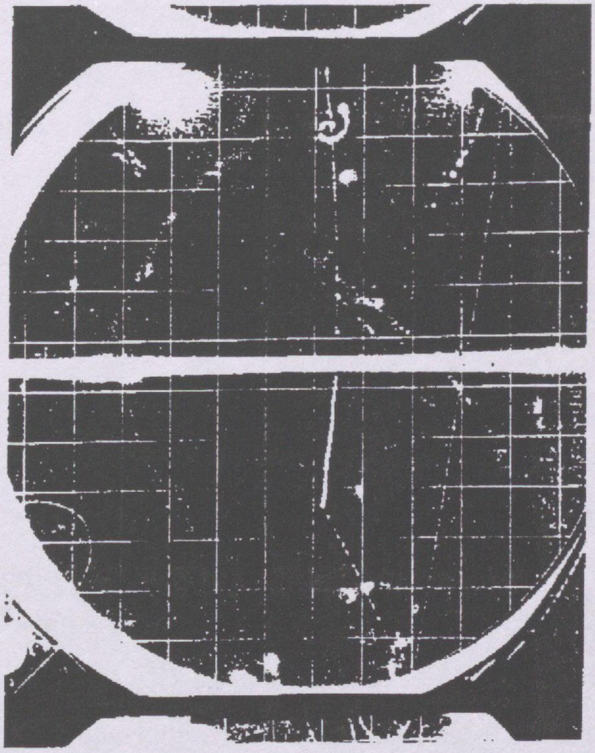


Figure 6. Decay of a μ meson. The meson enters the cloud chamber from above. It traverses an aluminum plate 0.63 cm thick, where it loses most of its energy. The meson, which leaves the plate as a slow and therefore heavily ionizing particle, comes to rest in the gas. The track of an electron originates 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.)

Soon, the spontaneous decay of the meson was recorded in cloud chamber and a classic example of the decay [11] is shown in **(Fig. 6)**. The half-life of the meson was measured by bringing it to rest in an absorber and recording the time of emission of the charged decay product, the electron. It was also established that this meson decay was a three body process involving in addition to the electron, two more neutral particles, namely the neutrinos. The mean life time of the meson was determined to be 2.2 microseconds.

While the discovery of the meson provided an elegant explanation of the penetrating component, its decay characteristics and accounted for the anomalous absorption characteristics discussed earlier, serious problems arose because of certain theoretical developments in the field of nuclear physics and also because of the very weak interaction of these particles in nuclear encounters. To explain the strong binding between protons and protons, protons and neutrons and neutrons and neutrons in nuclei, the Japanese physicist Yukawa [12] had postulated the existence of a particle of mass intermediate between the electron and proton, that was continuously exchanged between these nuclear components. With the discovery of the meson, the natural assumption was made that the Yukawa particle (Yukon) and the experimentally discovered `meson' were one and the same. This led to a lot of confusion and complication and was resolved only when another major discovery followed.

The experiments of Conversi, Panchini and Piccioni [13] on the mean lifetimes of positive and negative mesons brought to rest in absorbers of different atomic numbers showed that while positive mesons decayed in all substances with the same lifetime of 2.2 microseconds, the behaviour of negative mesons was distinctly different. While none of the negative mesons decayed when stopped in a high atomic number material like iron, some of them did decay in lighter atomic number materials like carbon or magnesium and a clear dependence on Z could be established. This behaviour was contradictory to the expectation

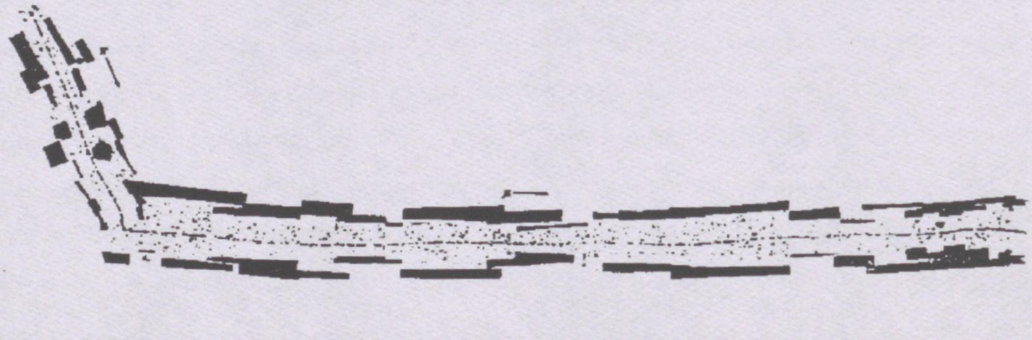


Figure 7. Photomicrograph showing a π meson (π) coming to rest in a nuclear emulsion and a μ meson (μ) arising from the end of the π-meson track. (From C.M.G. Lattes, H. Muirhead, G. Occhialini, and C.F. Powell, *Nature*, vol. 160, p. 453, 1947.)

that the meson was the same as the Yukon. In this case the negative mesons should not have decayed in any of the materials, irrespective of their atomic number. Another discrepancy was that the lifetime of 2 microseconds was a hundred times longer than what Yukawa had predicted for the Yukon. Theoreticians like Marshak had been suspecting that there may be two kinds of mesons.

In the mid 40's Powell and his collaborators at the University of Bristol pioneered the development of the photographic emulsion as a particle detector, even for very high energy particles which had the characteristic of lowest ionization loss in passing through materials. This development was rewarded by the discovery of yet another meson [14] **(Fig 7)**. What was remarkable was that this new meson which was given the name Pi-meson, (Pion) decayed spontaneously into the old meson which was now called the Mu-Meson (Muon). The Pi-meson had just the characteristics expected of the Yukawa particle - its mass was 273 electron masses and lifetime 2.6×10^{-8} seconds and it decayed into a muon and a neutrino.

With the discovery of the Pi-meson, the main features of the different components of cosmic rays encountered at mountain altitudes and sea level were satisfactorily explained. The inter-relations between the different components also become clear. The question that remained was – how do these Pi-mesons come into existence at these deep levels of the atmosphere, especially since the Pi-mesons have a mean life of only 2×10^{-8} seconds and despite relativistic elongation of time, cannot not survive for long distances in the atmosphere? What is the connection between these Pi-mesons and whatever is the primary cosmic radiation that is incident at the top of the atmosphere?

Such issues takes us to the studies that had been carried out on the behaviour of cosmic radiation at very great heights, started by the pioneer Victor Hess himself. Victor Hess had found that the intensity of the ionizing radiation increased as he rose to higher and higher heights upto about 13,00 ft in his manned balloon gondola. Later experiments of Regener and others showed that the intensity started slowly levelling off at still higher heights **(Fig 8)**. Further experiments revealed that the radiation incident at the top of the atmosphere consisted primarily of protons and it is in the collisions of these primaries with air nuclei that a large number of secondary particles were produced, the most dominant being charged and neutral pions. The muons which constituted the penetrating component at lower levels of atmosphere, at mountain altitudes, underwater and underground, were the decay products of the pions. The neutral pions decayed into pairs of gamma rays that gave rise to the soft component of cosmic rays - photons and electrons through cascade development. There was also an indication especially from the deep underground experiments that the primary cosmic rays extended over a wide energy band. Thus by the late 1940's, the new phase of cosmic ray research got clearly defined:

(i) Study of the characteristics of high energy nuclear interactions.

(ii) Study of the composition and energy spectrum of the primary radiation

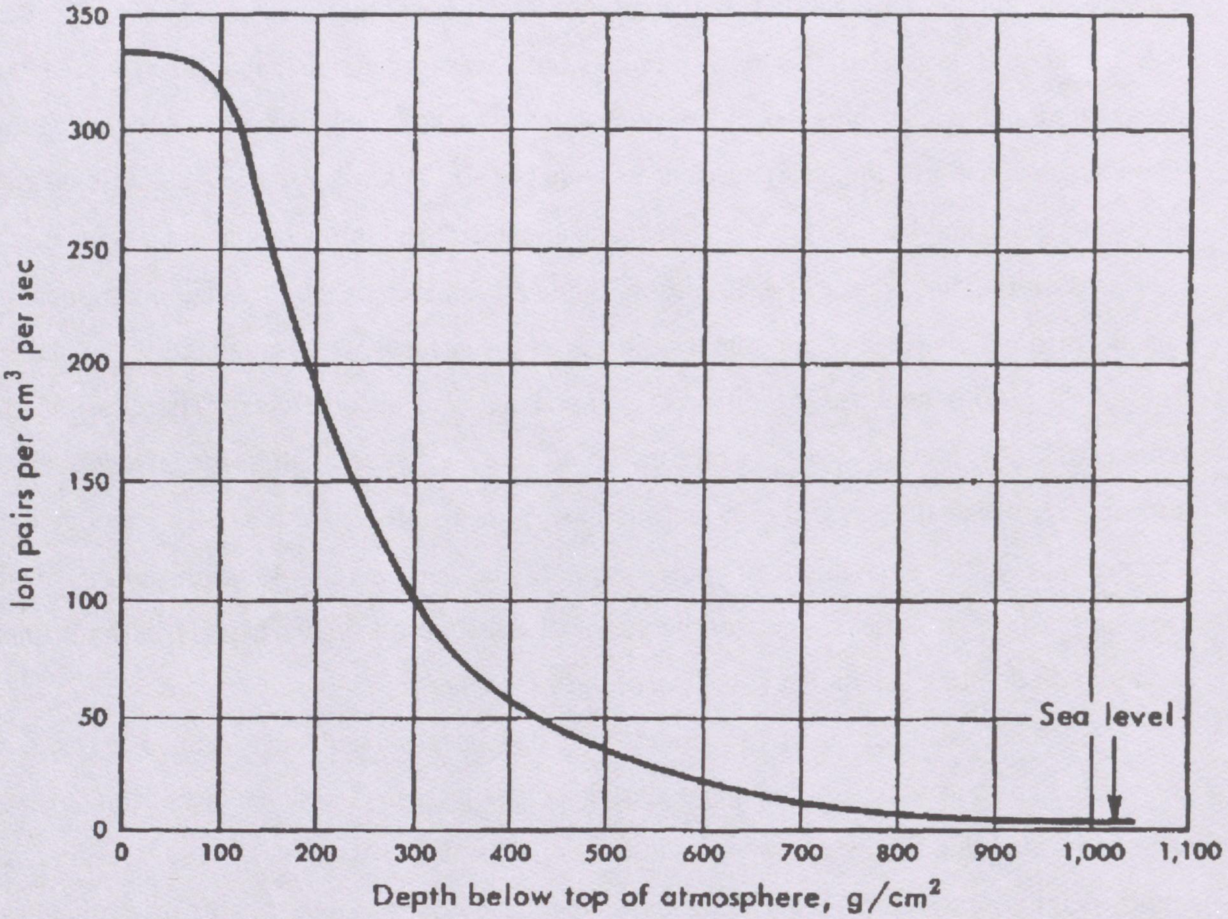


Figure 8. Intensity of cosmic rays as a function of atmospheric depth, as measured by Regener and his group with balloon-borne electroscopes. The atmospheric depth plotted on the horizontal axis is the mass per unit area of the air layer above the electroscope. The vertical scale gives the number of ion pairs produced per second by cosmic rays in 1 cm^3 of air at standard temperature and pressure. In these units, the cosmic-ray intensity at sea level is about 2.

Cosmic ray studies on High energy interactions: Era of Particle Physics

Around the same time as the discovery of the pi-meson in nuclear emulsions exposed at mountain altitudes, Rochester and Butler [15] found evidence in a cloud chamber operated at sea level for another type of new particle - called by them `V-particle'. The photograph of a typical V-particle [16] recorded in a cloud chamber is shown in **Fig 9.** These V-particles were later given the names the K-mesons and Hyperons, the "strange particles" that heralded the new era of fundamental particles. Investigations both with cosmic rays and accelerators on fundamental particles became a major activity of research all over the world. The **Table 1**, summarises the properties of all the fundamental particles discovered in cosmic rays over the decade 1947-1957, (the exceptions being the positron discovered in 1932, the mu-meson in 1937).

These fundamental particles, excepting the positron, are all unstable particles and decay away in extremely short intervals of time into other particles. The lifetimes range from 2×10^{-6} seconds to 8×10^{-17} seconds. They are all singly charged and have a spin 0 or 1/2. When the K-mesons were discovered an intriguing feature that had been noticed was that the K-meson was always produced in association with a hyperon or another K-meson. This unique feature which came to be known as `associated production' led Gellmann and Pais [17] to propose a new quantum number which they called "*strangeness quantum number*" to be conserved in strong interactions involving the production of these new particles along with the pi-mesons which were treated as non-strange particles. The spontaneous decay behaviour of these strange particles showed that the strangeness quantum number was not conserved in weak interactions. The Table gives also the strangeness quantum numbers that were associated with the various particles. Gellmann predicted, on the basis of the phenomenological SU(3) theory that he developed, that there should be a particle with strangeness quantum number (–3) produced in high energy interactions. It was, indeed, a great triumph for the theory that this particle called Ω^- was discovered later at accelerators.

Yet another important result that emerged from a study of these new particles was the first indication of *parity non-conservation* in weak interactions. It can be seen from the Table that 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 – (π^0, π^0, π^0), (π^0, π^+, π^-) and also ($\pi^- e^+ \nu_e$), with quite different lifetimes for the various decay modes. The

Table 1. Properties of elementary particles discovered in cosmic rays 1930-1955 [53]

(some of the properties listed - spin, lifetime, antiparticle, decay modes were determined later in accelerator experiments)

Name of particle	symbol	Strangeness No.	Anti particle symbol	Anti particle strange mass No.	Mass in terms of M_c	Spin	Charge	Lifetime 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}	$(e^- \nu_\mu \nu_c)$
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}	$(\pi^+\pi^0)$, $(\mu^+\nu_\mu)$, $(e^+ \pi^0 \nu_c)$
	K^0	+1	$\overline{K}_0$	−1	974	0	0	K_s: 9×10^{-11} K_L: 5.4×10^{-8}	$(\pi^+\pi^-)$, $(\pi^0\pi^0)$, $(\pi^0\pi^0\pi^0)$, $(\pi^0\pi^+\pi^-)$, $(\pi^- e^+\nu_c)$
Lambda Hyperon	λ^0	−1	$\overline{\Lambda}_0$	+1	2183	1/2	0	2.5×10^{-10}	$(p\pi^-)$, $(n\pi^0)$
Sigma Hyperon	Σ^+	−1	$\overline{\Sigma}^+$	+1	2328	1/2	+1	8.0×10^{-11}	$(p\pi^0)$, $(n\pi^+)$
	Σ^0	−1	$\overline{\Sigma}^0$	+1	2334	1/2	0	$\times10^{-14}$	$(\Lambda^0\gamma)$
	Σ^-	−1	$\overline{\Sigma}^-$	+1	2343	1/2	−1	1.5×10^{-10}	$(n\pi^-)$
Cascade Hyperon	Ξ^0	−2	$\overline{\Xi}^0$	+2	2573	1/2	0	3.0×10^{-10}	$(\Lambda^0{}_0 \pi^0)$
	Ξ^-	−2	$\overline{\Xi}^-$	+2	2586	1/2	−1	1.7×10^{-10}	$(\lambda^0\pi^-)$

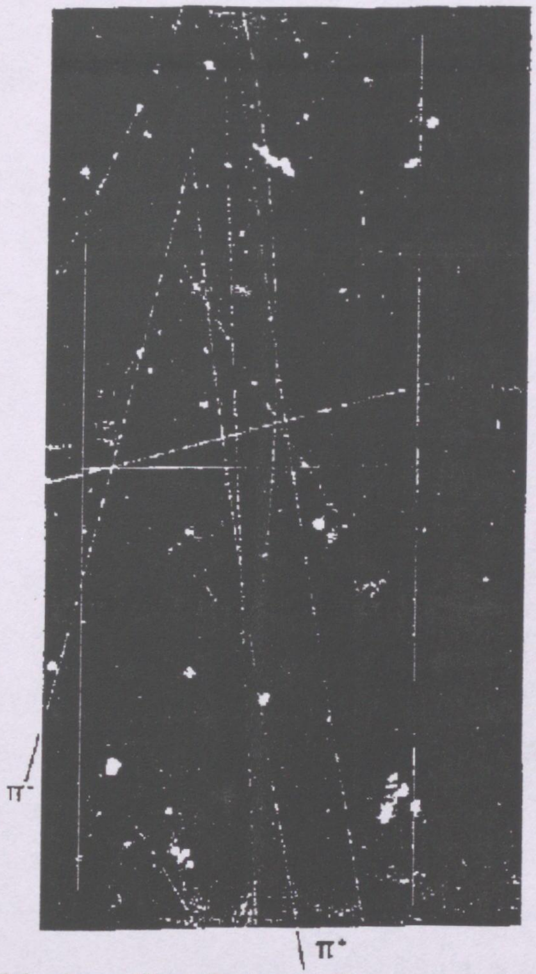


Figure 9. Example of θo-decay (film #R-151) by Thompson *et al.* (1953b). The momenta of the positive and negative fragments are (0.90 = 0.02) and (1.9 = 0.1) GeV/e, respectively. Both tracks are at minimum ionization. The angle between the tracks is (17.5 = 0.1) and the Q(π, π)-value is (219 = 12) MeV.

occurrence of both two body and three body decays for the same particle meant non-conservation of the symmetry – parity. In cosmic ray studies the particle that decayed into two pions was called the θ particle and the one that decayed into three was called τ-meson and the puzzle was called τ–θ puzzle. The first reaction was to treat these two as different particles. To resolve the puzzle, Lee and Yang [18] proposed symmetry breaking of the mirror reflection symmetry in weak interactions and suggested the famous β-decay experiment, successfully carried out by Madame Wu, confirming parity breakdown.

These discoveries in the area of fundamental particles produced in high energy collisions of cosmic rays and their secondaries provided considerable incentive and justification for the construction of higher and higher energy accelerators. Advent of high energy accelerators resulted in cosmic ray studies on high energy interactions being gradually shifted to energies beyond the range of accelerators. Also the primary cosmic ray beam provided the opportunity for studying the characteristics of collisions involving heavy nuclei, which had been discovered in the primary beam around 1948. Thus the emphasis in cosmic ray research shifted to a systematic study of the primary spectrum and composition, especially from the point of view of unravelling the sources of cosmic rays and the physical processes responsible for the acceleration of these particles.

Spectrum and composition of primary cosmic rays:

From a variety of ingeniously designed experiments – emulsion stacks flown to balloon altitudes, measurements of muon intensity upto large depths underground and the study of extensive air showers, it became clear that the primary cosmic ray energy spectrum extended from a few hundred Mev to well beyond 10^{20} ev – more than 14 decades of energy, the intensity itself falling by more than 20 decades. The ingenuity demanded in the design of experiments can be seen from the fact that while the cosmic ray intensity at about one Gev is 1000 particles/cm^2sc, it is 1 particle/1000 kilometer squared year at 10^{20} ev.

Though some preliminary ideas on the nature of the primary energy spectrum came through an analysis of the high energy interactions in nuclear emulsion stacks flown to balloon altitudes, the unexpected bonus from these flights was the detection of *heavy nuclei* in the primary radiation. In the balloon flights carried out in 1948 by the University of Minnesota and University of Rochester groups [19] with piles of nuclear emulsion plates, reaching to an altitude of 94,000 ft., ionizing tracks corresponding to multiply charged particles of several Gev energy were recorded. Later experiments established that these indeed were due to various types of heavy atoms stripped of their electrons. The **Table 2** shows the relative abundance of these heavy nuclei in the primary radiation. Though there is a general similarity to universal abundance of elements, the iron group is much more abundant in cosmic rays. A matter of primary interest in cosmic ray studies in more recent years has been the determination of the relative abundances of various nuclei at very high energies. Special types of large area emulsion stacks with interspersed X-ray sheets that have been flown on long duration balloon flights, have enabled the determination of the relative abundances of the light, medium and heavy groups of elements upto an energy per nucleus of 10^{15} ev (**Fig 10).**

The all particle spectrum in the energy range 10^{11}–10^{15} ev was determined with the help of deep ionization calorimeters on board the Proton satellite series by Grigorov *et al*

Table 2. …..

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

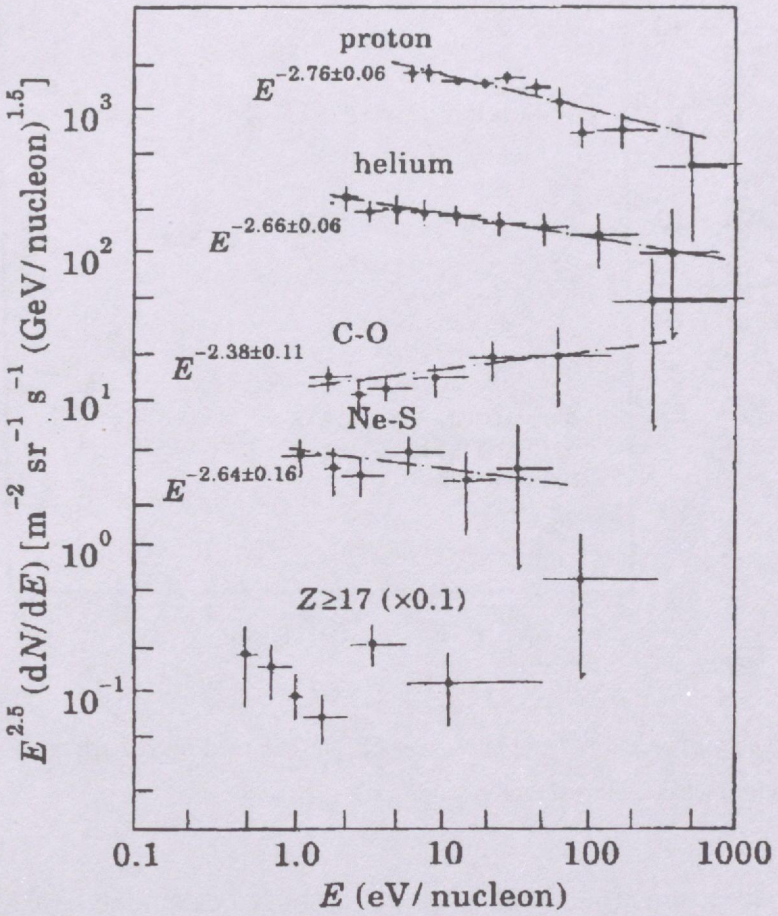


Figure 10. Combined fluxes of JACEE 1-12 for individual elements.

[20]. This is reproduced in **Fig 11**. The all particle primary spectrum over the entire energy range 10^{11}–10^{20} ev as compiled by Teshima [21] in 1993, almost 20 years after Grigorov's experiment is given in **(Fig 12)**. It is seen that there is a pronounced change in the slope of the energy spectrums around 10^{15} ev which has come to be known as the "knee" region and again

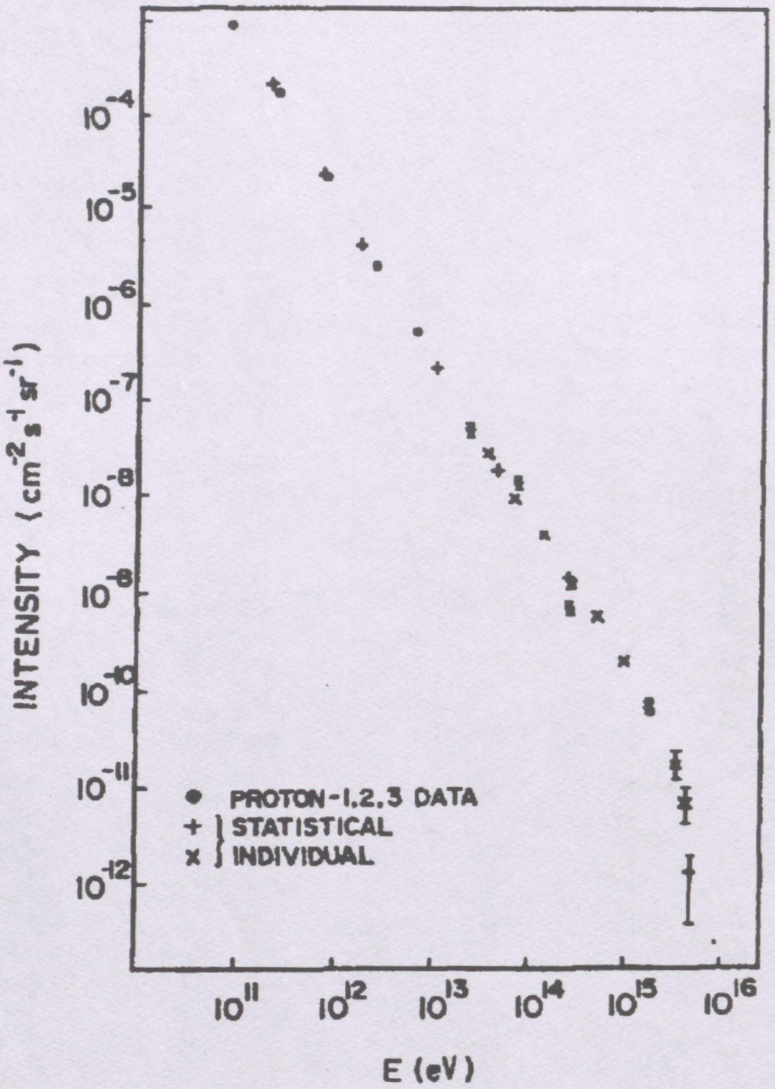
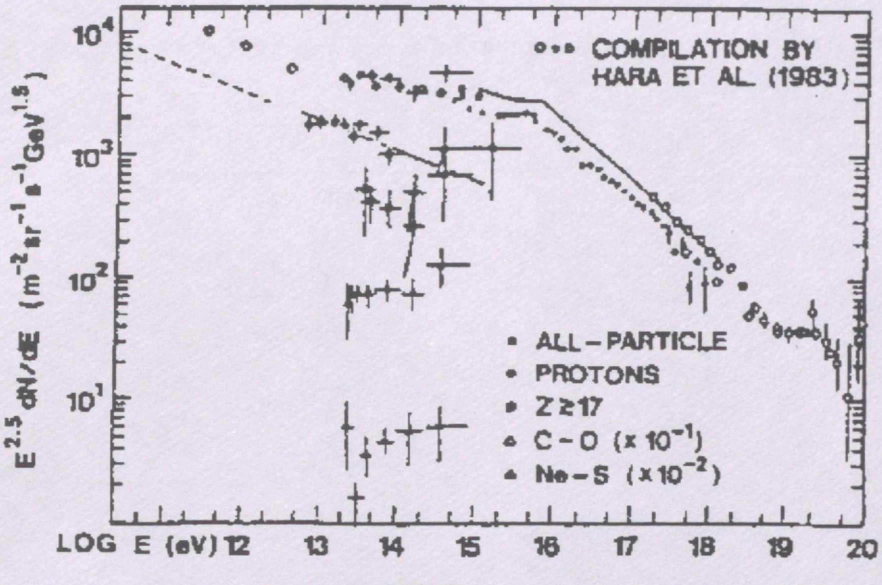


Figure 11. The all particle integral energy spectrum obtained by Grigorv *et al.* (1971) using total absorption calorimeters on board Proton satellites.

a flattening of the spectrum around 10^{18} ev which has been called the `Ankle' of the primary spectrum. These features became evident from extensive air shower experiments at mountain altitudes and sea level. The factors contributing to these changes are not clear yet. As far as the knee is concerned, for almost fifty years, it has been surmised that this may be connected with the rigidity cut off imposed by the galactic magnetic field; as suggested by Bernard Peters in the early 1950's.

Such a rigidity cut off depends on Z/A which is different by a factor 2 for protons and heavy nuclei and since in air shown experiments, the total energy of the `primary, energy per nucleus, is measured one should expect a steepening of the spectrum over a range of primary energies brought about by the primary composition moving towards increased abundance of



JACEE Energy spectrum

Figure 12. Compiltion of the primary energy spectrum from direct as well as air shower measurements (Teshima, 1993).

heavy nuclei. An estimate of the relative primary nuclear composition around 10^{14} ev, made by Swordy [22] in 1993 based on the emulsion stack experiments is given in **Table 3**. At still higher energies the only method available is that of extensive air showers. In this method, the special characteristics of the showers like the delay in the arrival times of the different components of the shower – electrons, mesons, nuclear active particles, the multiplicity distributions of muons, etc, have been used to estimate roughly the primary composition through extensive montecarlo simulations of these characteristics. **Table 4** gives a comparison of the relative composition in the energy range 10^{13}–10^{15} ev [23]. One trend that is clear from the table is that at energies beyond 10^{15} there is an increased heavy primary dominance. The question is whether this trend continues upto very high energies.

The flattening of the spectrum, well beyond the knee region, is accounted for in terms of the setting in, possibly of an extragalartic component of cosmic rays which has flatter spectrum. For a long time it was thought that this component has to be necessarily protonic in character since heavy primaries of extragalarte origin would all be disintegrated in nuclear interactions with extragalatic matter. However, an anomalous situation has developed with of some of the large air shower experiments in which the longitudinal development and absorption of particles in individual showers could be determined and related to the nature of the primary, indicating that around 10^{17} ev, there is a dominance of very heavies (iron group) and above this energy the primaries are mostly protons. Immediately after the discovery of

Table 3. 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

Table 4. Composition of primary cosmic rays

Energy	Protons	Alpha-particles	CNO	Si	Fe
$<10^{13}$ ev	42	24	13	10	11
$\sim10^{14}$ ev	20	36	19	12	13
$\sim10^{15}$ ev (a)	6	4	16	32	42
$\sim10^{15}$ ev (b)	11	14	15	17	43

the 3^0 microwave radiation, it was pointed out both by Greisen [24] and Zatcepin and Kuzmin [25] that there should be a steepening of the primary cosmic ray spectron beyond 10^{19} ev, due to the interaction of these particles with the 3^0 photons. The existence of this effect has been looked for and was thought to be confirmed by the observation that the number of showers of energy greater than 10^{19} ev is an order of magnitude less than what is expected on the basis of a simple extrapolation of the spectrum between 10^{18} and 10^{19} ev. More recent data on these very high energy showers, however, seems to indicate that this ZKG cut off has not been established unambiguously. Also three showers of energy greater than 10^{20} ev have been recorded. An interesting feature that is to be noted is that all the three showers **Table 5** [26–28] have come within 50^0 of the antigalactic centre. These three events have posed a serious challenge in discerning the nature of the primaries of these showers as well as of identifying the possible sources. The absorption characteristics of protons, heavy nuclei, and γ-rays show that the distance of the sources has to be less than 50 megaparsecs. There are no interesting Active Galactic Nuclei within this distance and within reasonable directions of arrival of these showers, unless our ideas on the strength of the intergalactic magnetic field, of the order of a few microgauss, is totally wrong.

Table 5.

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}	$(1.7 \sim 2.6) \times 10^{20}$
$\alpha(^\circ)$	75 ± 10	86 ± 1	18.9
$\delta(^\circ)$	45 ± 4	$44 \pm (10 \sim 20)$	21.1
b(°)	3	8	-41
1(°)	162	167	131

Primary electrons and gamma rays

Though the primary cosmic radiation is essentially hadronic in nature, the presence of electrons and gamma rays was recognized in balloon borne and satellite experiments as early as 1961. The primary electron spectrum in the energy range 10–1000 Gev is reproduced in the **(Fig 13)**. The special importance of the electron component arises from the fact that the background radio emissions is due to synchrotron emission of the relativistic electrons spiralling round magnetic fields. The inverse Compton scattering of the electrons with the photons of the 3^0 microwave radiation gives rise to the diffuse X-ray and gamma ray backgrounds measured in the vicinity of the earth's outer atmosphere. The importance of the study of the high energy electron component is discussed in the review article of Daniel and Stephens [29].

Tev and Pev γ-ray astronomies

With the discovery of Pulsars in the radio, optical and X-ray regions, considerable interest was revived in the search for very high energy gamma rays, especially pulsed γ-rays. The pulsars, with magnetic fields of 10^{12} gauss and above in their neighborhood were considered to be the right kind of environments in which charged particles could be accelerated to cosmic ray energies atleast upto 10^{15} ev. For investigations in this domain the

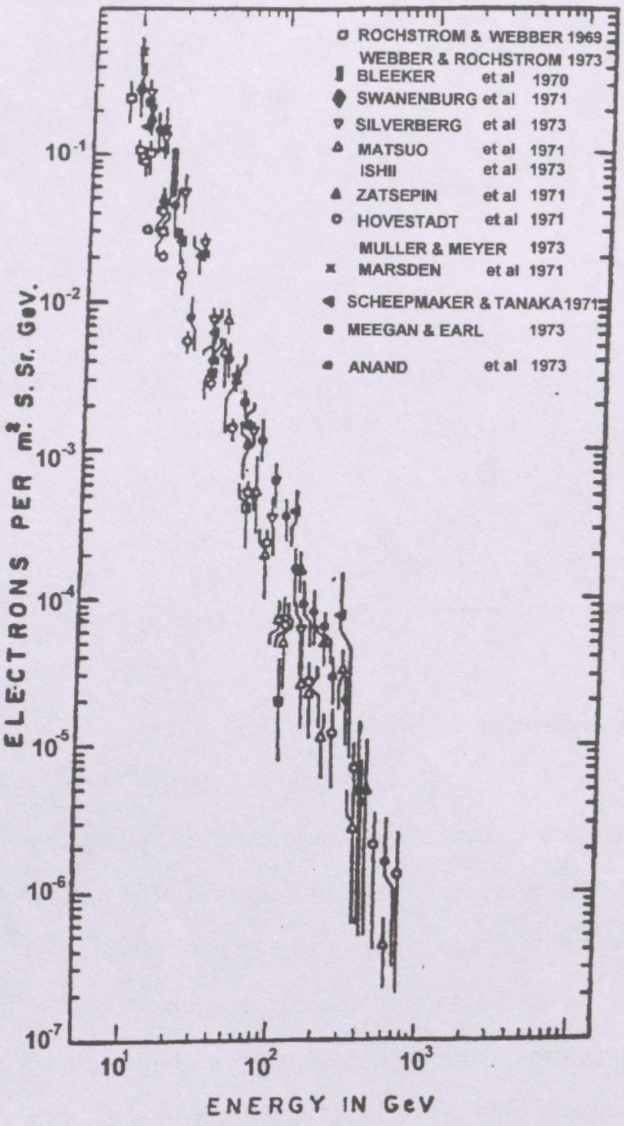


Figure 13. World data on the energy spectrum of primary electrons.

method of *air cerenkov radiation* [30] has been used effectively upto about 10 Tev. One of the most prominent sources in the Tev region has been the Crab Nebula **(Fig 14)**. While practically all the groups that have made observations on this source have seen it as a steady source, some have claimed a pulsed component in this energy range. The Table 6 gives the characteristics of sources that have been observed in the Tev band. It is seen that there is evidence for atleast two extragalactic sources Markarian 421 and Markarian 501.

In the still higher energy range of Pev (> 10^{15} ev), the only source that has been seen definitely is again the crab nebula, though the famous x-ray source Cyg-X3 has been claimed to be a Pev source, with varying intensity over years.

Table 6. Source List

Name	**Source type**	**Independent detections**	**Characteristic emission**
Crab	SNR	8, regular	DC, steady
PSR 1706-44	SNR	1	DC, steady
Vela	SNR	1	DC, steady
Mrk 421	AGN	5	DC, episodic
Mrk 501	AGN	2	DC, episodic
1ES2234+514	AGN	1, preliminary	DC
GRS1915+105	μ-quasar	1, preliminary	DC, episodic
Vela X-1	XRB	5	Periodic, variable
Cen X-3	XRB	2	Periodic, variable
AE Aqr	CV	5	Periodic, variable

[B. Christo Raubenheimer, *High Energy Astronomy and Astrophysics*, Universities Press, 193 (1998)]

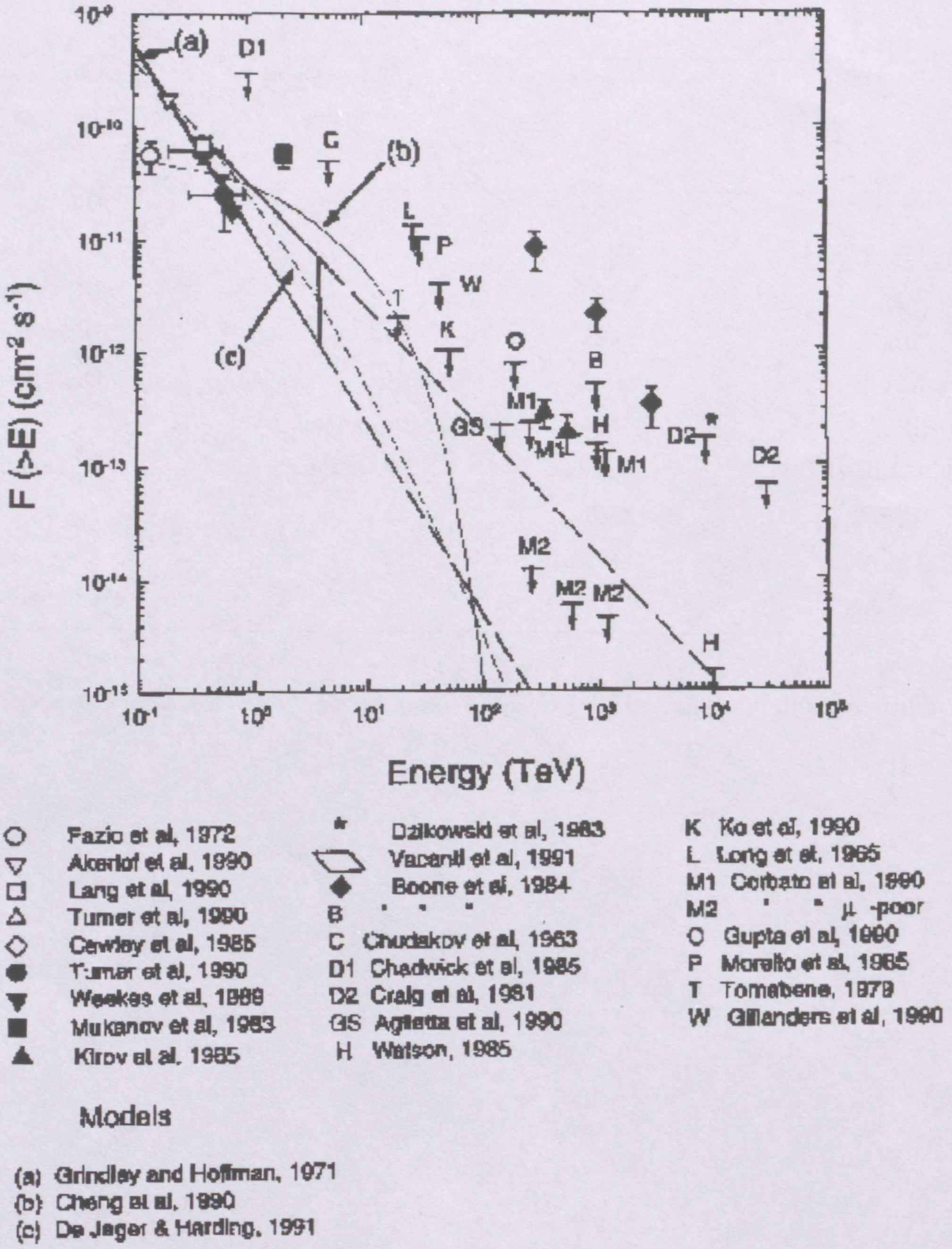


Figure 14. Energy spectrum of gamma rays from Crab Nebula obtained from various observations compared with model predictions. For references see Rao and Sreekantan (1992) [31].

Cosmic ray muons and neutrinos

So for we have concerned ourselves with the components of cosmic rays that can easily be detected either at sea level or at mountain altitudes or at balloon and satellite altitudes. Historically, the study of cosmic rays underwater and underground were started immediately after the discovery of cosmic rays to understand the mystery of the penetrating radiation, which later turned out to be the μ-meson component produced in the decays of π and k-mesons. What is most interesting is that cosmic ray muons have been recorded down to very great depths underground. In the Kolar mines in India, intensity measurements have been carried out upto vertical depths of 8000 ft., and angular distribution measurements, corresponding to depths of 10,000 ft rock [32] **(Fig 15)** . The muons produced in the atmosphere have to have energies in the tens of Tev range to penetrate to such depths.

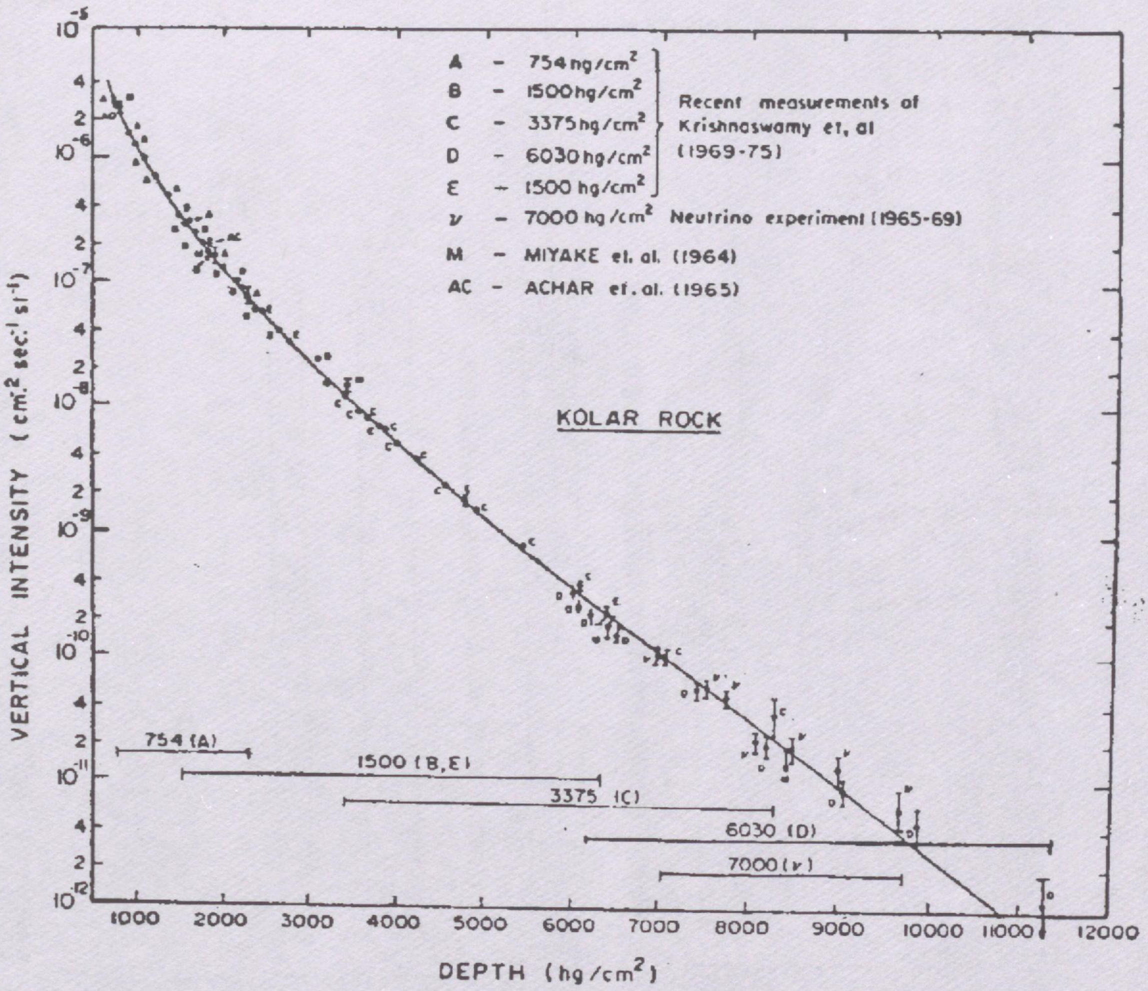


Figure 15. The variation of intensity of penetrating particles as a function of depth—based on a variety of experiments at the Kolar Gold Fields. (M.R. Krishnaswamy *et al.*, *Proc. ICOBAN*, Bombay (1982) p. 115.)

The other component of secondary cosmic rays whose investigations have been conducted deep underground is the neutrino comport that arises in the decays of k-mesons, π-meson and μ-meson in the atmosphere. The **(Fig. 16)** shows the example of a neutrino interaction in the rock that gave rise to a pair of muons recorded at a depth of 8000 ft in the Kolar mines [33]. The direction of the neutrino is such that it must have originated somewhere in the atmosphere of Australia and travelled through the diameter of the earth before interacting in the rock close to the Kolar installation.

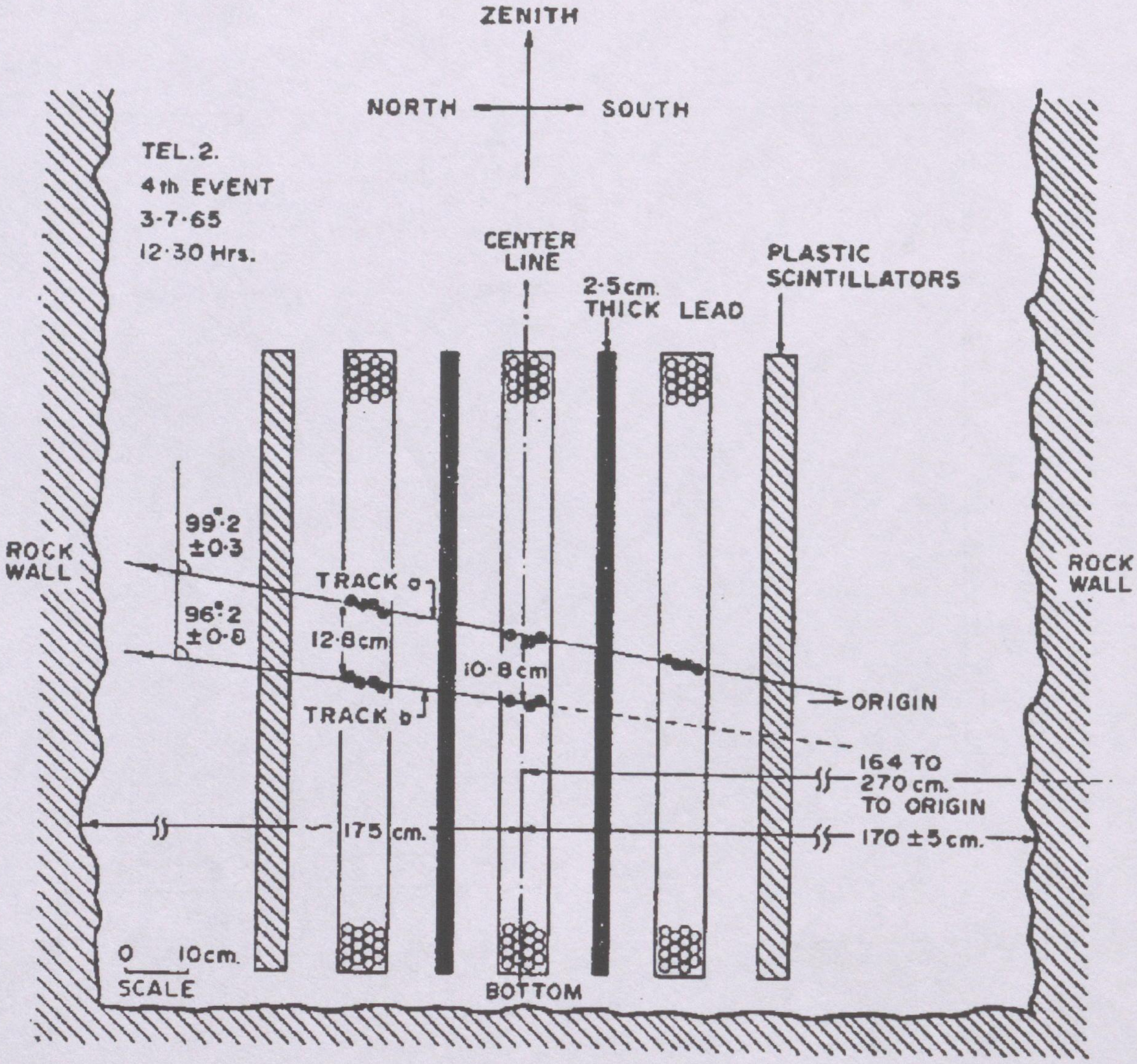


Figure 16. One of the early cosmic ray neutrino interactions recorded at K.G.F. The two penetrating tracks meet below the horizon at a depth of 7500 hg/em2 about a meter inside the rock. [C.V. Achar *et al.*, *Phys. Lett.*, vol. 19, p. 78, (1965).]

cm^2

Several underground experiments had indicted an anomaly in the ratio of ν_μ to ν_e flux among the neutrinos produced by the decay of μ, π and k-mesons in the earth's atmosphere. The Super Kamiokande installation in Japan set up essentially for resolving the solar neutrino problem, has given a clear indication that there might be flavour oscillations in the atmospheric neutrinos produced by cosmic rays. From an analysis of the angular distribution of upward going muons in the Super Kamiokande [34], they find evidence for $\nu_\mu \leftrightarrow \nu_\tau$ oscillation.

The future of cosmic ray research

Even after a hundred years of cosmic ray research, there remain many outstanding and very challenging problems regarding the radiation itself and also on related astrophysical and elementary particle physics problems. It is now well established that the primary cosmic radiation extends well over 14–15 decades of energy with rapidly falling intensity, the highest energy particles being $\sim 10^{21}$ ev. Neither the mechanism of acceleration nor the identity of the sources have been unambiguously established yet. The neutron star environments with magnetic fields exceeding 10^{12} gauss for energizing particles up to about 10^{15} ev and the Active Galactic Nuclei with giant black holes in their cores for accelerating particles to energies beyond 10^{15} ev have been the most popular, though some have evoked the possibility of the annihilation or collapse of Topological Defects of Big Bang Origin [35]. It is interesting that the characteristics of the highest energy showers and their arrival directions are not consistent with the primaries of the showers being either nuclei, protons, neutrons or gamma rays.

The evidence for flattening of the spectrum beyond 10^{17} ev and the slight tendency for an upward trend in the spectrum beyond 10^{19} ev and the possible absence of the ZKG cut off are again problems that need considerable clarification. While the arrays like the FLY'S EYE [36], AGASA [37] YAKUTSK [38] which provided the crucial results on these very large air showers over the last few decades, will continue to gather more data in the future, the new arrays like the {Hi ReS} [39], AUGER [40] which are designed to have very much larger effective areas, might help in cleaning up many of these issues. Several new arrays with special design to clinch the composition problem in the knee region, HEGRA [41], CASCADE [42], GRAPES [43], TIBET [44] etc., have come into operation. The Whipple telescope [45] gave a breakthrough in the field of Tev astronomy by developing the Cerenkov Imaging technique and proving its effectiveness by detecting even extragalactic sources. The new installations at Pachmari [46] and Mount Abu [47]in India which have many new design features for investigations in this area of astronomy have also started operating. The installation MILAGRO [48] that has been set up in Los Alamos is expected to bridge the crucial gap between the Tev and Pev astronomies. The recent book of Rao and Sreekantan [49] gives a full account of the current status of cosmic ray research at these high energies and the future direction in which experimental effort is progressing.

With the possibility of large scale cosmic ray installations coming in to operation on the Space Stations, it is expected that many of the problems connected with primary composition at low energies, the flux of primary antiprotons and positrons, the relative fluxes of isotopes and of very heavy nuclei, the discrepancies regarding the characteristics of interactions as discerned from the large area emulsion chamber experiments and the accelerator experiments in the hundreds of Tev region, will all get resolved. Prospects on ultra high energy neutrino astronomy with deep underwater SADACO [50], NESTOR [51] and under ice installation AMANDA [52] seems very bright.

Acknowledgement

I have made extensive use of Bruno Rossi's book "Cosmic Rays" [53] while dealing with historical aspects of cosmic ray research.

References

1. Hess Victor, *Physica Zeits* **13,** Nos 21/22 , 1090, (1912)
2. A.H. Compton, *Reviews of Scientific Instruments* **7**, 70, (1936)
3. A.H. Compton, *Phys. Rev.* **43**, 382, (1933)
4. C.D. Anderson, *Phys. Rev.* **43,** 491, (1933)
5. P.M.S. Blackett and G. Occhialini, *P.R.S.* **A139**, 699, (1933)
6. H.J. Bhabha and W. Heitler, *P.R.S.* **A159**, 432, (1937)
7. J.F. Carlson and J.R. Oppenheimer, *Phys. Rev.* **51**, 220, (1937)
8. H.J. Bhabha, *P.R.S.* **164**, 257, (1938)
9. S.H. Neddermeyer and C.D. Anderson, *Phys. Rev.* **51**, 884, (1937)

10. J.C. Street and E.C. Stevenson, *Phys. Rev.* **51**, 1005, (1937)
11. R.W. Thomson, *Phys. Rev.* 74, 490, (1948)
12. H. Yukawa, *Proc. Phys. Math. Soc. Japan* **17**, 48, (1935)
13. M. Conversi, E. Pancini and O. Piccioni, *Phys. Rev.* **68**, 232, (1945)
14. C.M.G. Lattes, H. Muirhead, G.P.S. Occhialini and C.F. Powell, *Nature* **159**, No. 4047, 694, (1947)
15. G.D. Rochester and C.C. Butter, *Nature* **160**, 855, (1947)
16. R.W. Thomson, A.V. Buskirk, L.R. Fretter, C.J. Karzmark and R.H. Rediker, *Phys. Rev.* **90**, 1122, (1953)
17. M. Gellmann and A. Pais, Proc. 1954 *Glasgow Conference on Nuclear and Meson Physics* **342**, (1955)
18. T.D. Lee and C.N. Yang, *Phys. Rev.* **104**, 254, (1956)
19. H.L. Bradt and B. Peters, *Phys. Rev.* **74**, 1828, (1948)
20. N.L. Grigorov et al, Proc. 12th International Conference on Cosmic Rays, Hobart, **5** (1971)
21. M. Teshima, *Proc. 23rd ICRC, Calgary, Invited Rapporteur and Highlights Papers*, 257 (1993)
22. S. Swordy, *Proc. 23 rd ICRC, Invited Rapporteur and Highlights Papers*, 243 (1993)
23. R. Srivatsan, Ph.D. Thesis, Bombay University (1994)
24. K. Greisen, *Phys. Rev. Lett.* **16**, 748, (1966)
25. G.T. Zatcepin and V.A. Kuzmin, *Soviet. Phys. JETP* **4**, 114, (1966)
26. B.N. Afanasiev *et al*, Proc. *Tokyo Workshop for the study of Extremely High Energy Cosmic Rays*, Tokyo, 23, (1993)
27. P. Somers, *Ibid* (1993)
28. N. Hayashida, *ICCR Report*-324-94-19, (1994)
29. R.R. Daniel and S.A. Stephens, *Space Sci. Rev.* **10**, 599, (1970)
30. T.C. Weekes, *Space Sci. Rev.* **59**, 319, (1992)
31. M.V.S. Rao and B.V. Sreekantan, *Current Sci.* **62**, 617, (1992)
32. M.R. Krishnaswamy *et al*, *Proc. ICOBAN*, Bombay, 115, (1982)
33. C.V. Achar *et al*, *Phys. Lett.* **19**, 78, (1965)
34. A. Okada, *Proc. 26th ICRC*, Utah, HE 4.1.01 (1999)
35. P. Bhattacharjee, *Current Sci.* **71**, No.7, 532, (1996)
36. D.J. Bird *et al*, *Astrophys. J.* **424**, 491, (1994)

37. S. Yoshida *et al*, *Astroparticle Phys.* **3**, 105, (1996)
38. B.N. Afansiev *et al*, *Proc. 24th ICRC*, Rome, **2**, 756, (1995)
39. T. Abu-Zayyad *et al*, *Proc. 25th ICRC*, Rome, **5**, 321, (1997)
40. M. Boratav, *Proc. 25th ICRC*, Durban, **5**, 205 (1997)
41. R. Plaga *et al*, *Proc. 24th ICRC*, Rome, **2**, 693, (1995)
42. H.O. Klages, *Proc. 25th ICRC*, Durban, **8**, 297, (1997)
43. S.K. Gupta *et al*, *Proc. 25th ICRC*, Durban, **4**, 153 (1997)
44. M. Amenomori *et al*, *Proc. 22nd ICRC*, Durban, **2**, 704, (1995)
45. T.C. Weekes, *Space Sci. Rev.* **75**, 1, (1996)
46. P.N. Bhat, *High Energy Astronomy and Astrophysics*, University Press, 370 (1997)
47. C.L. Bhat, *Proc. ICRC*, Durban, **8**, 211 (1997)
48. G.B. Yodh, *High Energy Astronomy and Astrophysics*, University Press, 216 (1997)
49. M.V.S. Rao and B.V. Sreekantan, "*Extensive Air Showers*", World Scientific (1998)
50. L.G. Dedenko *et al*, *Proc. 25th ICRC*, Durban, **7**, 89, (1997)
51. A. Capone, *Proc. 25th ICRC*, Durban, **7**, 49, (1997)
52. S.W. Barwick *et al*, *Proc. 25th ICRC*, Durban, **7**, 1, (1997)
53. Bruno Rossi, "*Cosmic Rays*" Mc-Graw-High Book Co. (1964)