

## COSMIC RAYS

### 1. Early History:

The mysterious leakage of electric charge from a charged metal sphere suspended by an insulating silk thread had puzzled ~~Henri~~ Coulomb as early as 1785. The mystery remained till the early part of this century when C.T.R Wilson<sup>(1)</sup> connected the leakage with the phenomenon of 'ionization' of the surrounding air. With the discovery of radioactivity in 1896 and the realisation that traces of radioactive material were present all over the earth it was presumed that the ionizing radiations were the radioactive emanations from the earth. In a classic endeavour Wulf<sup>(2)</sup> who had designed a novel version of the electroscope for measuring the intensity of the ionisation climbed the Eiffel Tower in Paris with his instrument and noticed that the ionization did decrease with height. Gockel<sup>(3)</sup> reached still higher heights with his instrument carried on balloons and his results cast some doubt on the hypothesis that the radioactivity of the earth was responsible for the ionization of the air. A series of manned balloon flights by Victor Hess<sup>(4)</sup> in particular the one on August 7, 1912 when he and his assistants carried three electroscopes and floated for several hours at altitudes between 13,000 and 16,000 ft. clinched the issue. Victor Hess announced that the radiation responsible for the mysterious ionization was coming from "above" and was possibly of extra-terrestrial origin. Further experiments by a variety of investigators all over

the world established that the radiation was not only extra-terrestrial, but extra-solar as well. The name cosmic radiation was given to this radiation by Millikan in 1925.

Even as late as 1929, the precise nature of this cosmic radiation had not been established. Millikan had made been pursuing the idea that they are gamma rays produced in the nucleo-synthesis that may be going on in the inter-stellar space. The variation of cosmic ray intensity with geomagnetic latitude first recorded by Clay<sup>(5)</sup> gave the indication that the radiation may have a charged component influenced by the geomagnetic field. The world wide survey of the latitude effect organised by Compton<sup>(6)</sup> and the discovery of the East-West effect by Johnson<sup>(7)</sup> left no doubt that the radiation was definitely influenced by the geomagnetic field and therefore, comprised mostly charged particles.

Subsequent analysis of the cosmic ray beam at sea level and mountain altitude by geiger counter telescopes and cloud chamber experiments showed that the radiation had two components; a "soft component" that was easily absorbed in a few millimeters of lead and most frequently was in the form of a shower of several particles. The second component which was called the "penetrating component" could pass through several meters of lead and even upto great depths in water and underground. The absorption characteristics of the penetrating component<sup>(8)</sup> were truly baffling. The absorption as measured by the disappearance of particles was

more in a rarefied medium like air than in an equal amount of condensed matter like water or lead. A major breakthrough in the understanding of the nature of the 'soft component' came through developments that had taken place in the field of quantum-electro-dynamics (QED) and more importantly with the discovery of the 'positron'. The discovery of the 'positron' was made in 1932 by Carl Anderson<sup>(9)</sup> while analysing the charged Cosmic ray particles with a magnetic cloud chamber. The positron fitted very well the anti-particle in the quantum mechanical formulation of the relativistic electron theory by Dirac. Blacket and Occhialini<sup>(10)</sup> who were also at the Cavendish Laboratory in Cambridge where Dirac held the theoretical physics chair, had recorded in their cloud chamber instances of multiple charged particles that showed non-ionizing links between pairs of them with a common vertex. These events displayed beautifully the phenomenon of the creation of electron-positron pairs predicted by Dirac's theory.

The mystery of the nature of the penetrating component remained for a few more years. The cascade theory of electron shower development developed by Bhabha and Heitler<sup>(11)</sup> and Carlson and Oppenheimer<sup>(12)</sup> ruled out the penetrating particle to be an electron. The experimental observation with magnetic cloud chambers that there were as many positively charged penetrating particles as negatively charged ruled out the possibility of these being the Protons, the only positively charged particles known at that time

other than the positrons. Bhabha<sup>(13)</sup> in a paper in the proceedings of the Royal Society, London through a detailed analysis of the Cosmic Ray experiments till then, had come to the conclusion that either quantum electrodynamics must break down at high energies or there must be present in cosmic rays, particles of mass intermediate between the electron and the proton and this would constitute the penetrating component.

The evidence for the existence of a particle of intermediate mass came in 1937 from the Cloud Chamber experiments of Anderson and Neddermeyer<sup>(14)</sup>, Street and Stevenson<sup>(15)</sup> and the name "meson" was given by Millikan. The meson was soon found to be an unstable particle decaying (see fig. 1) with a half life of about 2 microseconds into electrons and neutral particles identified later as neutrinos. The anomalies that had been noticed in the altitude variation of the penetrating component by Rossi and collaborators got resolved by the relativistic elongation in the decay time of muons at high energies.

Around the time of the discovery of the meson, Hideki, Yukawa<sup>(16)</sup> was developing the theory of nuclear forces through the exchange of a heavy mass particle between the nucleons. The hasty identification of the meson with the Yukawa exchange particle caused some confusion. The experiments of Conversi, Pancini and Piccioni<sup>(17)</sup> had shown that the meson was not a strongly interacting particle with the nucleons. They had found that negative mesons did not

get captured by Carbon nuclei, but decayed like positive mesons.

The anomaly was resolved in 1947 by the discovery of Powell & collaborators<sup>(18)</sup> of another meson heavier than the one that had been recorded till then. The heavier meson was given the name "Pi-meson" (pion) and the lighter one the "Mu-meson" (muon). It was established that the Pi-meson decayed into mu-meson (see fig. 2 & 3) with a half-life of  $10^{-8}$  seconds and fitted very well all the characteristics of the Yukawa particle. Negative pi-meson when brought to rest resulted in the explosion of the nucleus giving rise to a larger number of fragments.

## 2. Cosmic Rays and the Era of Particle Physics

We have seen in the previous section that the analysis of the cosmic ray beam at sea level and mountain altitudes with cloud chambers and nuclear emulsions led to the discovery of the positron, the mu-meson and the pi-meson. This was the beginning of a new era in the history of high energy physics. Further experiments with magnetic and multiplate cloud chambers at sea level and mountain altitudes and with nuclear emulsion stacks flown to balloon altitudes led to the discovery of a range of new particles produced along with Pi-mesons in high energy collisions of the primary cosmic rays with matter. The Table-I gives a list of all the particles discovered in cosmic ray studies along with their characteristic properties. The particles that had

a mass between that of the Pi-meson and the Nucleon were called "K-mesons" and those that had a mass greater than the nucleon were called "hyperons." A very important feature that was noticed early and which had very significant consequences was that the K-mesons were produced either with other K-mesons or with hyperons and were never produced singly. This "associated production" led to the postulation of the conservation of a new quantum number called "strangeness" and each K-meson and hyperon had an associated strangeness quantum number. While this conservation law was strictly obeyed in the production process, in the decay process they violated the conservation law. A strange particle decayed freely into non-strange particles as can be seen from the decay schemes given in the table. Yet another interesting aspect of decay was that the same particle (defined in terms of mass) decayed sometimes into two secondary particles and sometimes into three secondary particles  $K^+ \rightarrow \pi^+ + \pi^0$ ,  $K^+ \rightarrow \pi^+ + \pi^- + \pi^+$ . The K-mesons that decayed into two pions were called the  $\theta$ -mesons and those that decayed into three  $\tau$ -mesons. This  $\tau$ - $\theta$  puzzle led to the postulation of the breakdown of parity which was another milestone in the history of physics.

The empirical classification of the particles according to different schemes led to the recognition of the role of "symmetry" in particle physics and to the prediction of new sets of particles that had not been discovered in cosmic rays, which however, were later discovered at accelerator

experiments and laid the foundation for the Standard Model of Particle Physics.

### 3. Deep Underground Experiments on Cosmic Radiation - Muons and Neutrinos.

While a larger number of experiments were carried out at shallow depths underground and underwater to measure the intensity of the penetrating component right from the time of discovery of cosmic rays, the most systematic deep underground experiments on the intensity and angular distribution of muons were carried out in the Kolar Gold Mines in India from 1951 to 1970, with crossed neon-hodoscope - telescopes and scintillators. The intensity vs depth based on these experiments which extend upto an equivalent vertical depth of 11,000 hg/cm<sup>2</sup> is given in the fig.4. It is seen that the intensity falls by more than a factor of a million in going from 1000 hg/cm<sup>2</sup> (sea level) to the largest depth. These intensity - depth measurements served the important purpose of defining the nature of the primary spectrum of cosmic rays in an energy range that was not accessible by direct experiments till recently. The frequency of multiple muons and their lateral separation provided important clues to the composition of the primaries in the Tev energy range.

The observation that no count was registered in a large area muon telescope over a period of 3 months at a depth of 8000 hg/cm<sup>2</sup> led the KGF group (19) to point out the feasibility of detecting cosmic ray produced neutrinos with

suitably designed telescopes operated at such large depths. The first neutrino telescope was set up in the mines as a collaboration between the Tata Institute of Fundamental Research, Bombay, the University of Osaka City, Japan, and the University of Durham, U.K. The fig.5 shows one of the very early neutrino events recorded with this telescope. The important feature to note from the figure is that two penetrating tracks meet at a point below the horizon at a depth of 7500 m.w.e. and the event is clearly due to an interaction of a neutrino that had passed through the earth and interacted in the rock at a distance of a few meters from the telescope. A similar experiment for cosmic ray neutrino detection was set up by Reines and his collaborators <sup>(20)</sup> in the Gold Mines in South Africa. The low background deep underground sites became the ideal location for setting up large area detectors designed for the detection of possible decay of the proton which was one of the requirements of the theories on unification of strong, electromagnetic and weak interactions. The proton decay telescopes in turn have provided large amount of data on cosmic ray muons and neutrinos and have proved valuable in the analysis of the direct production of muons or in the decay of extremely short lived heavy particles produced in high energy collisions and in looking for possible celestial sources of high energy neutrinos.

#### 4. Extensive Air Showers:

A very grandiose phenomenon that takes place in the earth's atmosphere is the development of an extensive air shower whenever a very high energy cosmic ray particle is incident at the top of the atmosphere. In the nuclear interactions with the air nuclei the primary particle produces a large number of charged and neutral  $\text{Pi}$  and  $\text{K}$ -mesons and also nucleon-antinucleon pairs. The charged secondaries either interact further down or decay into other particles, thus leading to the development of a nuclear cascade. The neutral pions decay immediately into a pair of gamma rays and they give rise to electromagnetic cascades. Thus by the time the shower of particles reach mountain altitude or sea level, there would be hundreds to billions of particles depending on the energy of the primary that entered the atmosphere. While the shower particles would be spread over several hundreds to several tens of square kilometers areas the particles mostly keep the direction of the primary. By measuring the arrival time of the particles in the shower front it is possible to determine the direction of the shower to an accuracy of a few degrees. From a study of the different components of the air shower particles, in particular electrons, muons and hadrons, it has been possible to deduce the nature of the primary - proton or heavy nucleus at energies where direct measurements of the nature of the primaries with nuclear emulsion stacks or electronic detectors is not feasible due to the extremely low flux. The

main advantage of the extensive air shower method is that the effective area of recording increases with energy.

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At energies beyond  $10^{17}$  ev, it has been feasible to study the longitudinal development of the shower in the atmosphere through a registration of the fluorescent photons emitted by nitrogen nuclei excited by the large density of ionizing electrons and positrons in the core regions of the developing shower. The special detector that has been developed by the University of Utah group<sup>(21)</sup> for this purpose is known as the "Fly's Eye" detector and has proved to be extremely valuable in extending the studies on cosmic rays upto the highest energies ( $\sim 10^{20}$  ev).

In contrast to a hadron which initiates a nuclear-cum-electromagnetic cascade, whenever a very high energy gamma ray arrives at the top of the atmosphere it initiates a pure electromagnetic cascade resulting in the production of a large number of relativistic electrons and positrons. When these fast particles traverse the atmosphere, they give rise to Cerenkov emission in the visible range. These Cerenkov photons are collected by large parabolic mirrors mounted on orientation platforms and focussed on to photomultipliers at their foci. Coincidence techniques are used to discriminate background noise. This technique has become powerful in what has come to be known as Tev Astronomy, in the energy range  $10^{11}$  -  $10^{13}$  ev, just below the threshold for recording normal extensive air showers with arrays of particle detectors. The Tev astronomy has so far established three sources of very

high energy gamma rays - the Crab Nebula within our galaxy and two extragalactic objects Markarian 421 and Markarian 501.

##### 5. Primary Cosmic Rays: Spectrum and Composition

Studies on the effects of the earth's magnetic field on the intensity of cosmic ray particles by a measurement of the latitude effect at various altitudes had shown that the primary cosmic ray particles are mostly positively charged particles and in the early 1940's Marcel Schein and his collaborators<sup>(22)</sup> established that the primary particles are mostly protons. It is in the collisions of these protons with air nuclei that most of the secondaries are produced. A new dimension was added to the study of primary cosmic rays when Bradt and Peters<sup>(23)</sup> discovered that in addition to protons, there are a small fraction of alpha-particles and other completely stripped heavy nuclei. In 1952 James Earl<sup>(24)</sup> discovered a small fraction of electrons also in the primary radiation.

The energy spectrum - the flux of particles as a function of energy of primary cosmic rays extends over  $10^8$  ev to about  $10^{20}$  ev. The decrease of flux with energy is represented by a power law of the form  $N(E).dE = \text{Cont.} \cdot E^{-\gamma} dE$  where the exponent  $\gamma$  changes in different energy ranges. Different types of experiments with different experimental techniques had to be deployed to determine the spectrum - the all particle spectrum, over such a wide energy range. In the

<sup>8</sup> <sup>12</sup>  
 range  $10^8 - 10^{12}$  ev, the flux was determined by emulsion stacks flown to balloon altitudes and by transforming the intensity-depth relation of muons to the primary spectral characteristics using properties of high energy nuclear interactions like inelasticity, multiplicity, transverse momentum distribution etc. and the decay characteristics of the pions and K-mesons into muons. In the energy range  $10^{12} - 10^{14}$  ev, electronic detectors flown on balloons to stratospheric altitudes and on satellites as well as large size nuclear emulsion stacks interspersed with x-ray sensitive sheets flown on long duration balloons have been used. In the energy range  $10^{14} - 10^{17}$  ev the size spectrum of extensive air showers measured at mountain altitudes have been related to the primary spectrum. At energies greater than  $10^{17}$  ev, the large air shower arrays and the Fly's Eye array have given the information on the nature of the primary spectrum.

It is seen from the composite Figures (6 and 7) that there is a pronounced change of slope around  $10^{15}$  ev - "the knee" of the cosmic ray spectrum, which flattens around  $10^{18}$  ev - "the ankle" of the primary spectrum. With the discovery of the universal 3 K microwave radiation, it was pointed out by Greisen <sup>(25)</sup> and independently by Zatcepin and Kuzmin <sup>(26)</sup> that there should be a steepening of the primary spectrum due to the interaction of primaries with the  $3 \times 10^{19}$  photons at energies beyond  $10^{19}$  ev. The existence of this effect has been confirmed by the observation that the number

of showers of energy greater than  $10^{19}$  ev is an order of magnitude lower than what is expected on the basis of an extrapolation of the spectrum in the energy range  $10^{18}$  -  $10^{19}$  ev. However, it is important to point out that in the last few years three very definite cases of showers of energy greater than  $10^{20}$  ev have been recorded.

The composition of the primary radiation does not remain the same at all energies. The variation of composition at different energies is given in the Table-II, as a relative percentage of the total.

**TABLE-II: Composition of Primary Cosmic Rays:**

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

While at energies below  $10^{14}$  ev, it has been possible to determine the composition by direct measurements of the charge of the incoming nuclei by nuclear emulsion stacks and estimate the energy by interaction characteristics, at higher energies the only method available is the method of extensive air showers. Here the characteristics of the shower like the delay in arrival times of the different components <sup>(27)</sup> or the multiplicity distribution of muons <sup>(28)</sup> etc have been used to arrive at the primary composition through the use of extensive montecarlo simulations.

## 6. Sources of Cosmic Rays and Acceleration Mechanisms:

Even 86 years after the discovery of cosmic rays, it has not been possible to identify any definite source of high energy ( $>20\text{Gev}$ ) cosmic rays. Occasionally, solar flares do give rise to particles upto 15 Gev or so. The problem of identifying the sources is connected with the fact that the galactic magnetic field isotropises the arrival directions of charged primaries upto  $\sim 10^{17}$  ev. The flux of primaries falls steeply beyond this energy. To be able to collect even a few thousand showers it takes years of efforts even with large extensive air shower arrays. So far, the efforts of the last 20 years have not revealed any pronounced anisotropy at energies beyond  $10^{17}$  ev. Of the three sources that have been recognised as Tev Gamma ray sources, only one the Crab Nebula is galactic and the other two Mrk 421 and Mrk 501 are extragalactic AGN's and the mechanism of production of the Tev gamma rays are most likely electromagnetic processes rather than nuclear. There are some indications that on occasions the Crab Nebula does produce particles in the Pev ( $10^{15}$  ev) energy range. A similar claim has been made regarding the X-ray source Cyg X-3.

There are many mechanisms available for accelerating charged particles - mass motions, electric field gradients, magnetic field irregularities, particles riding on electromagnetic waves etc. Fermi suggested in 1949 that charged particles could be accelerated through repeated

collisions with moving magnetized clouds, the kinetic energy of the clouds being transformed to energy of particles. Nowadays there are many variants of this idea and the most favoured sites for acceleration are the shock waves generated in the supernovae explosions, in active galactic nuclei (AGN's) and radiogalaxies. Drury <sup>(29)</sup> has reviewed the various mechanisms and their relative merits. In the shock wave acceleration mechanisms, the magnetic fields play the role of confining the particles and there exists therefore an important relation between the dimensions of the astronomical objects and the strength of the magnetic field as shown in the fig.8. effective for acceleration process.

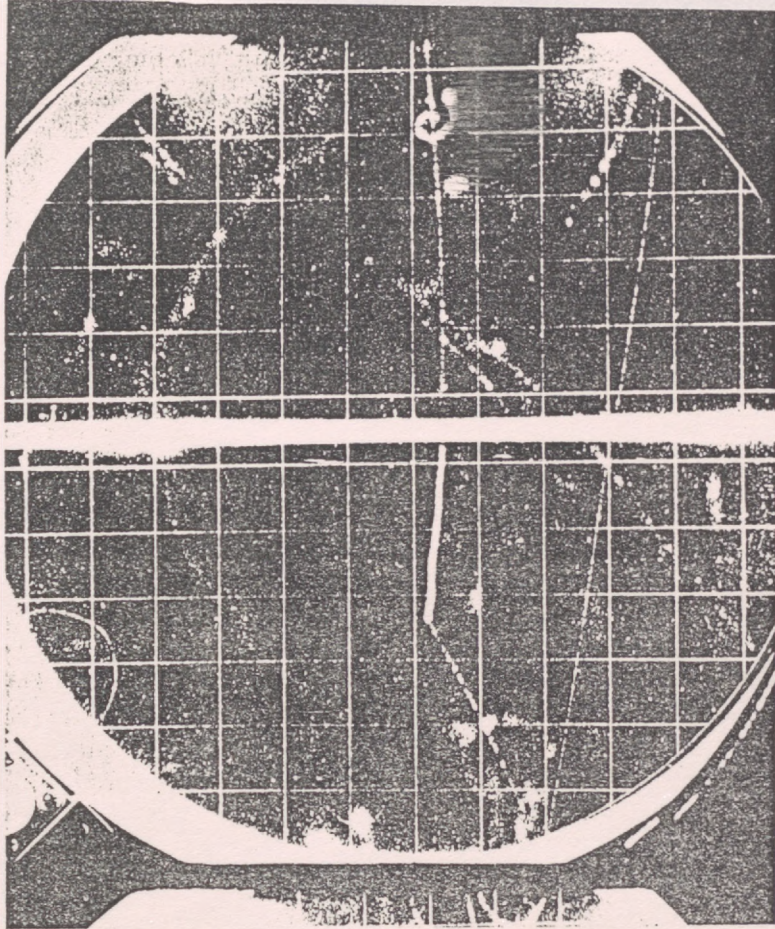
Apart from Fermi acceleration which has the advantage of giving the power law spectral characteristic of the cosmic ray spectrum, the acceleration of particles by the very strong gradients of electric fields generated by rotating magnetic fields around pulsars have also been considered. In this mechanism, power law is not a favoured spectrum and also the particles have to pass through a dense plasma cloud before escaping. With these types of mechanisms, acceleration upto  $\sim 10^{15}$  ev is thought to be possible in shocks associated with supernovae remnants in the galaxy itself. At higher energies where the spectrum steepens and composition changes to heavy dominance, acceleration upto  $10^{18}$  ev could still be from a second galactic source, but beyond  $10^{18}$  ev where the particles cannot be retained within the galaxy, the source or sources have to be extragalactic. However, because of the  $3 \times 10^6$  microwave radiation, there is a

constraint on the maximum distance which for example is of the order of  $\sim 60$  mega parsecs in the case of particles of energy  $\sim 3 \times 10^{20}$  ev. In the case of three highest energy cosmic rays recorded, so far no potential sources within this distance have been identified eventhough the directions of arrival of the showers are known to better than  $10^\circ$ . The possibility of such very high energy particles arising out of the spontaneous decay of cosmic strings and other topological defects that could have been produced in the early phases of the Big Bang Creation of the universe has been pointed out by P. Bhattacharjee <sup>(30)</sup> among others. In such a case the primaries will have to be necessarily fundamental particles like protons, neutrons  $\gamma$ -rays, neutrinos etc. and not heavy nuclei.

TABLE I

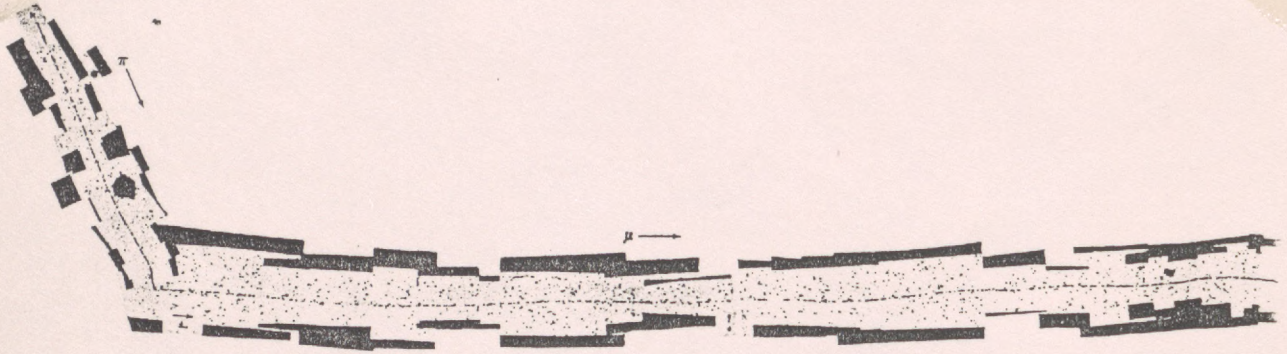
Properties of elementary particles discovered in Cosmic Rays 1930-1955.  
 (Some of the properties listed - Spin, life time, anti-particle, decay modes  
 were determined later in accelerator experiments)

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



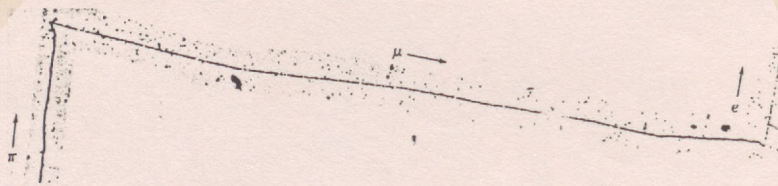
Decay of a  $\mu$  meson. The meson enters the cloud chamber from above. It traverses an aluminum plate 0.63 cm thick, where it loses most of its energy. The meson, which leaves the plate as a slow and therefore heavily ionizing particle, comes to rest in the gas. The track of an electron originates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

Fig. 1



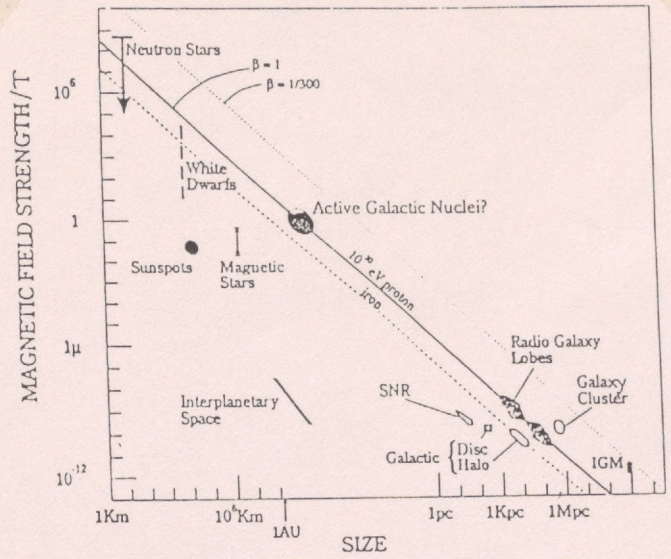
Photomicrograph showing a  $\pi$  meson ( $\pi$ ) coming to rest in a nuclear emulsion and a  $\mu$  meson ( $\mu$ ) arising from the end of the  $\pi$ -meson track. (From C. M. G. Lattes, H. Muirhead, G. Occhialini, and C. F. Powell, *Nature*, vol. 160, p. 453, 1947.)

Fig 2.



Photomicrograph of tracks in a nuclear emulsion, showing a  $\pi$  meson ( $\pi$ ) that comes to rest and decays into a  $\mu$  meson ( $\mu$ ). The  $\mu$  meson in turn comes to rest and decays into an electron ( $e$ ). (From R. H. Brown, U. Camerini, P. Fowler, H. Muirhead, C. F. Powell, and D. M. Ritson, *Nature*, vol. 163, p. 47, 1949.)

Fig 3.



Magnetic field strengths and typical linear dimensions for various astronomical objects, some of which are potential sites for acceleration of cosmic rays. For illustration, the restrictions on the possible astronomical objects that can in principle accelerate protons to  $10^{20} \text{ eV}$  are indicated. Only objects on, or to the right of, the solid diagonal line can accelerate protons to  $10^{20} \text{ eV}$  for relativistic characteristic shock velocities ( $\beta = 1$ ). The dotted line marked  $\beta = 1/300$  indicates the limit if the shock velocities are only  $\sim 1000 \text{ km s}^{-1}$ . The applicable restrictions on the possible astronomical objects that can accelerate iron nuclei to  $10^{20} \text{ eV}$  are also indicated (from Drury).

Drury L. o'c Contemp Phys. 35 (1994), 231

Fig. 8

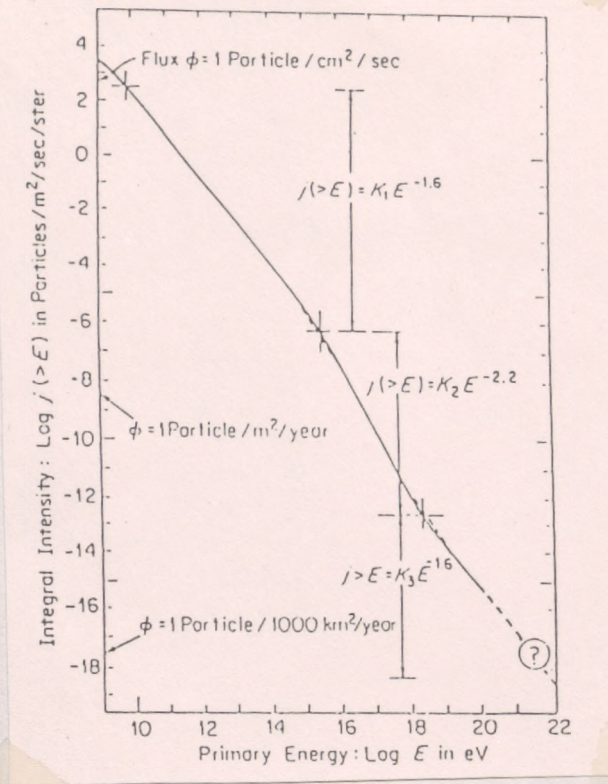


Fig. 6 Integral Primary Energy Spectrum of all particles as it stood in 1971.  
 (Pomerantz, M.A, Cosmic Rays, Von Nostrand Reinhold, New York, 1971)

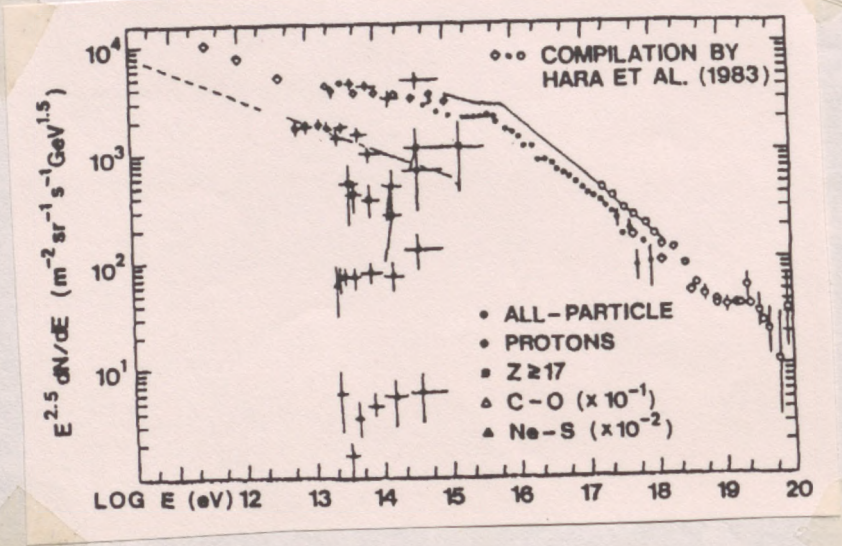


Fig 7. The Differential Spectrum of all particles and of different components in 1993  
 (Teshima M. Proc. XXIII ICRC, Calgary 1993, 257  
 Editors. D.A. Leaty, R.B. Hicks & D. Venkatesan, World Scientific)  
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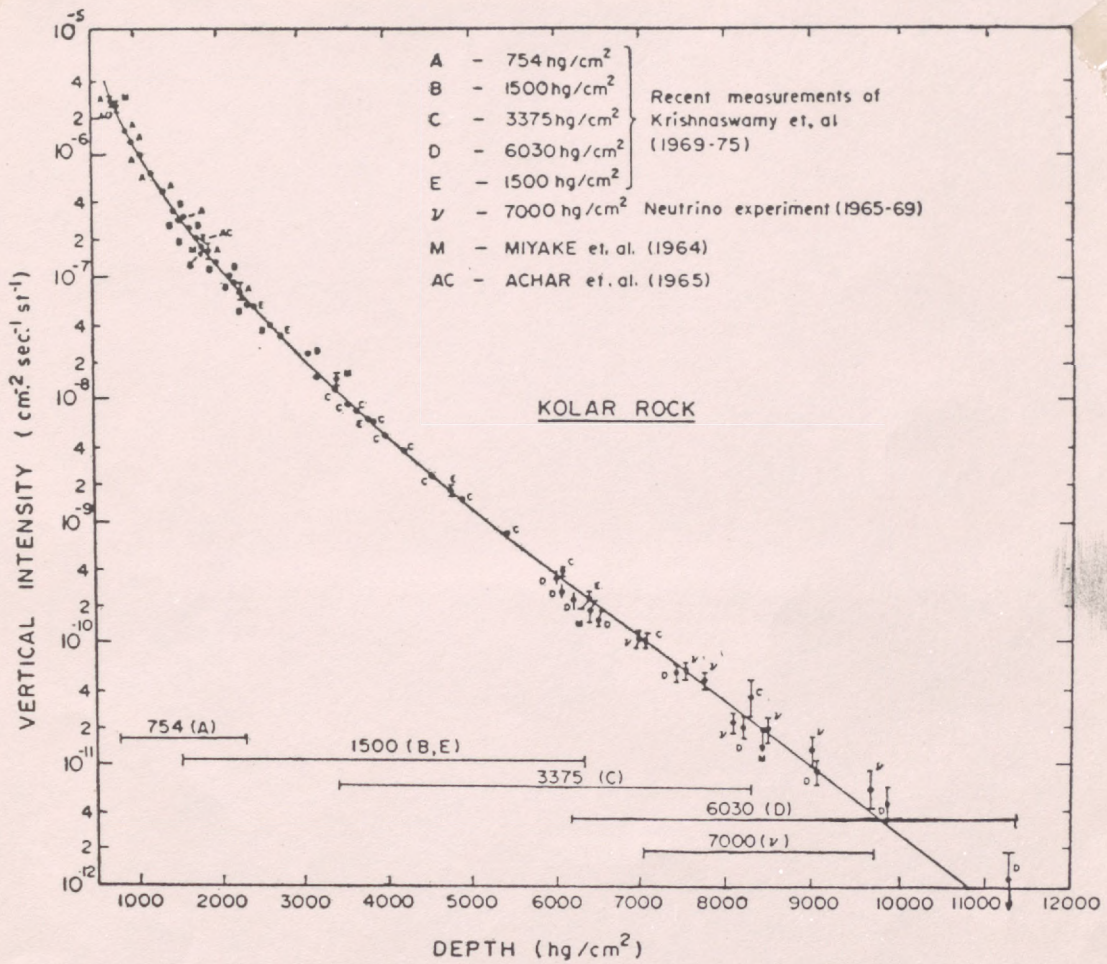


Fig. 4 The variation of intensity of penetrating particles as a function of depth—based on a variety of experiments at the Kolar Gold Fields. (Krishnaswamy et al)

(Krishnaswamy, M.R et al, Proc. ICOBAN, Bombay (1982) 115.)

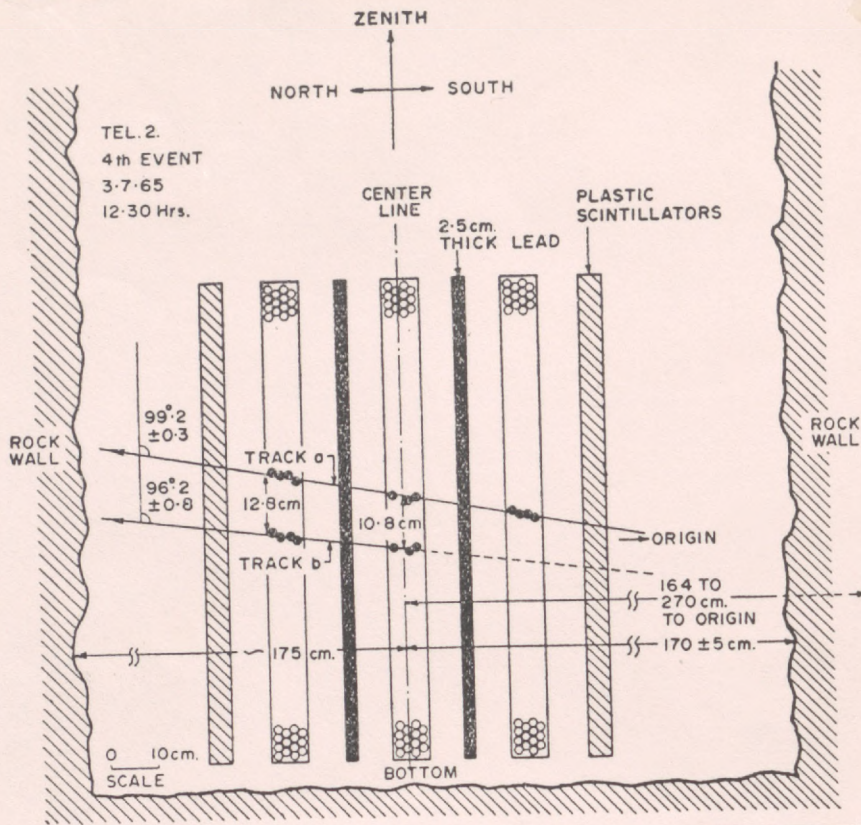


Fig. 5. One of the early Cosmic Ray neutrino interactions recorded at K.G.F. The two penetrating tracks meet below the horizon at a depth of  $7500 \text{ hg/cm}^2$  about a meter inside the rock.  
 [ Achar c.v. et al *Phy. Lett.* 19 (1965) 78

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