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PERSPECTIVES OF COSMIC RAY RESEARCH

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Physicists at the beginning of the century were baffled by the presence of an ionising radiation that seemed to be present almost every where on the sufrace of the earth. A new dimension was added to this mystery in 1912 when Victor Hess on the basis of a series of manned balloon flights in which he himself went up to altitudes of 13000 ft. in the atmosphere, established that the radiation responsible for the mysterious ionization was extraterrestrial in origin. The name"Cosmic Rays" was given to this extraterrestrial radiation by Millikan around 1925 even though at that time it was not absolutely clear that the radiation was not of solar origin. In the intervening period 1912-76 Cosmic Ray research has been a continously expanding field of activity which has contributed on the fundamental side to the unravelling of many physical and astrophysical processes and phenomena and on the technological side to the development of a variety of particle detectors, ingenious electronic circuits and data registration systems and methods of analysis and also to the development of stratospheric ballooning of very heavy payloads for long hours. As investigation progressed in the last sixty years the very many facets of cosmic radiation began to unfold. It became clear that there is a primary radiation that is incident on the top of the earth's atmosphere which is distinctly different in nature from the secondary radiation observed lower down in the atmosphere and at mountain altitudes, sea level and underground. The primary rediation extends over the energy range $\backsim 10^6$ to 10^{20} eV and consists of protons, alpha particles and heavy nuclei and also electrons, gamma-rays and neutrinos. The secondary radiation which results from the nuclear encounters of the hadrons (protons and heavy nuclei) consist of pions, kaons, nucleons and anti-nucleons and in much smaller measure hyperons and other strange particles. A very important and predominant secondary component is the muon which was recognised as the penetrating component of cosmic radiation arising in the decay of pions and kaons. Yet another secondary component which is of special importance in cosmic ray research is the neutrino which arises from the decay of pions, kaons and muons. The very high energy hadrons (energy greater than 10^{13} eV) give rise to the spectacular phenomenon of extensive air showers. The primary hadron entering the atmosphere collides with an air nucleus, loses a fraction of its energy and travels further down. The energy that is lost by the primary particle goes into production of a large number of secondaries—pions, nucleons, anti-nucleons, kaons and other strange particles. The neutral pions decay immediately into gamma-rays which initiate electromagnetic cascades in the atmosphere. Some of the charged pions and kaons and the nucleons and anti-nucleons interact further in the atmosphere and give rise to secondary cascades. The pions and kaons that do not interact, decay into muons and neutrions. The surviving primary collides repeatedly and transfers its energy to nuclear and electromagnetic cascades. Because of the exponential nature of the atmosphere the secondaries produced in the various collisions, decays and multiplication processes spread out considerably from the initial direction of the primary, as a consequence by the time the resulting air shower, reaches mountain altitude or sea level, it is spread out to several hundreds of metres to several kilometers depending upon the energy of the primary particle. But for this unique phenomenon of extensive air showers cosmic ray research beyond 10^{15} eV where the intensity of the primary radiation falls below a particle per m^2 per year would not have been possible. By adopting very special and ingenious methods it has been possible to take advantage of the very large spread of extensive air showers and thus get large effective areas of detection and obtain valuable information on the primary radiation and also on the characteristics of high energy interactions up to energies of $\backsim 10^{20}$ eV.

In the next section we will summarise the main results that have been obtained on the cosmic radiation itself both the primary and secondary components and outline the outstanding problems that remain unanswered and require further investigation. In the third section we will summarise the main results that have been obtained on the characteristics of ultra high energy nuclear interactions from cosmic ray studies and indicate what type of problems remain for further investigation-

In the last section we will consider a few typical and illustrative ingenious approaches that are in an advanced stage of planning or execution and which give some idea of the type of future research endeavours in this area of cosmic ray research.

In this article we will not be considering at all certain important aspects of cosmic ray research like cosmic ray pre-history, modulation of cosmic rays, solar particles, since these require even to do minimal justice special full length articles on each of them. For the same reason we will also not consider the newly emerging field of X-ray, gamma-ray astronomy even though it falls well within the purview of cosmic ray research.

2. Properties of Cosmic Radiation

(a) The spectrum, composition and anisotropy of the primary nuclear radiation :

The present status of the primary spectrum[1] over the energy range 10^{10} eV to 10^{20} eV is shown in Fig. 1. It is seen that for a change in 10 orders of magnitude in energy, the intensity drops by about 17 orders of magnitude. The primary spectrum in the energy range 10^{10} to 10^{15} eV has recently been determined by a series of Soviet satellite experiments[2] making observations directly on the primaries. There is a discrepancy by a factor of about two in intensity between these direct results and those deduced from indirect methods— from the spectra of high energy muons at sea level and of hadrons and gamma-rays in the atmosphere. The cause of this discrepancy is still not understood. There is an indication of a steepening of the spectrum beyond about a few times 10^{14} eV, and this may be related to either the transformation of the primary component from predominantly galactic to extragalactic or due to changes in the primary composition or characteristics of interactions. Early results[3] had indicated a flattening of the primary spectrum beyond 10^{17} eV which however is not borne out by recent experiments.[1] It is possible to fit all the data beyond 10^{15} eV to a single power law spectrum with an exponent of about 2.1. Very recently he Havera Park group[4] have some evidence for a flattening of the spectrum beyond 10^{19} eV. The shape of the spectrum beyond 10^{17} eV and the existence or absence of a steepening beyond 10^{19} eV are extremely important from an astrophysical point of view, particularly for understanding the origin of the primary radiation. Because of the onset of photo-nuclear interaction between the 3° K microwave photons and cosmic ray primaries at energies beyond 10^{19} eV, a steepening of the spectrum is expected if the cosmic radiation is of extragalactic origin.[1] The absence of a steepening at this energy would mean that cosmic rays arise essentially from within the super cluster of galaxies.

The primary composition is well established in the energy range few hundred MeV to a few tens of GeV, the two predominant components being protons and helium nuclei. Nuclei of charge greater than or equal to 3 account for only about 1% of the total number of primary particles. The relative abundance of L-group nuclei lithium, beryllium and boron, of the M-group carbon, nitrogen and oxygen and fluoridne, and the H or heavy group neon and heavier nuclei, is fairly well determined in this energy range. There have been some surprises in the relative abundances in the energy range 10-100 GeV per nucleon that have been determined very recently.[5] Li, Be, B which arise as a result of fragmentation of heavier nuclei in the matter traversed between the source and the earth becomes less abundant at higher energies (Fig. 2). The ratio of carbon to oxygen decreases with energy (Fig. 3) and the relative abundance of the iron group (Mn+Fe+Ni) increases compared to (C+O). These new results imply energy dependence of (i) the cross section for the production of secondaries and or (ii) the amount of matter traversed between the source and the earth and or (iii) the amount of matter traversed in the source itself.

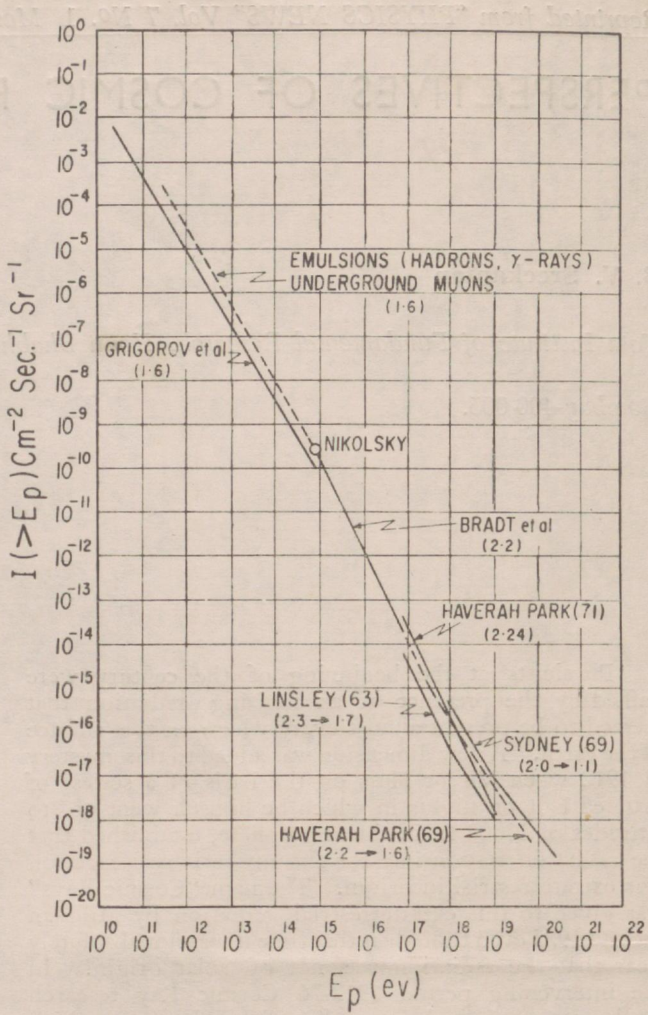

Fig. 1. A composite energy spectrum of primary cosmic rays.

There is no positive evidence yet so far of the presence of transuranic elements in the primary radiation.

The primary composition beyond 10^{12} eV is still in a very uncertain stage. The only statement that can be made on the basis of the measured ratio of positive

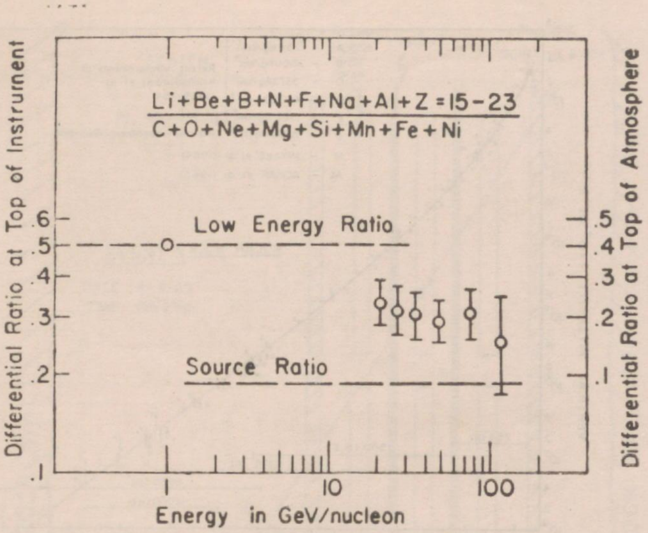

Fig. 2. The energy dependence of light to medium nuclei at high energies.

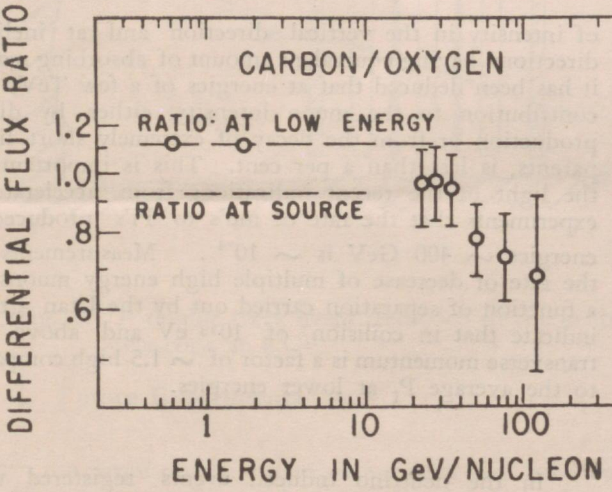

Fig. 3. The energy dependence of the rate C/O.

to negative muons of energy greater than 10^{11} eV is that the composition cannot be predominantly heavy.

While it is fairly well established that there are no pronounced anisotropies (less than 1%) upto energies of 10^{17} eV, the situation at higher energies is not clear, particularly at energies beyond 10^{19} eV where isotropising of arrival directions by the galactic magnetic field becomes ineffective and one should observe anisotropies if they are present. There have been some claims recently[6] about a time dependant and energy dependent anisotropy at these energies. Further experiments with considerable statistics to enable classification in finer energy intervals are necessary to settle this question.

(b) Primary Elections :

The primary electrons constitute less than a percent of the charged primary flux. The primary electron spectrum has been measured over the energy range 0.1 MeV to about 800 GeV and the spectrum above 10 GeV is shown in figure 4. At energies below 10 GeV the primary electron spectrum is influenced considerably by solar modulation and is subject to wide fluctuations in intensity. The best results on the electron spectrum are in the range 10—300 GeV[7] . It is still not clear whether there is a break in the electron spectrum in this energy range and if so precisely at what energy. The importance of the measurement of the electron spectrum stems from the fact that the non-thermal background radio emission arises from the synchrotron emission of the relativistic electrons spiraling round the magnetic fields. The electrons suffer in addition serious energy losses due to inverse Compton scattering with the photons associated with galactic and extragalactic radiation fields. In particular the interaction between the high energy electrons and the 3°K microwave photons has important consequences on the electron spectrum and life time and also on the resulting diffuse X-ray, gamma-ray background radiation.

3. Cosmic Ray Studies on High Energy Interactions

The primary and secondary hadrons, and the muons and neutrinos in cosmic rays have been used for the study of the interaction characteristics of these particles upto very high energies. The important results that emerged from cosmic ray studies and that preceded the results from the high energy accelerators are the following :

(i) The increase of the total inelastic cross-section with energy[8] .

(ii) Increase in the cross-section for the production of nucleon, anti-nucleon pairs with energy[9].

(iii) Increase of secondary multiplicity at a rate faster than log E.

(iv) Evidence for the production of fire balls and the possible increase in the mass of the quantized fireballs with energy.

(v) Frequent occurrence of secondaries having large transverse momenta and possible increase of average P_t with energy.

There are strong indications from some experiments[1] of drastic changes in the collision characteristics of hadrons at energies greater than ∽ 10^{13} eV. These imply (i) increase of average inelasticity, (ii) faster rise of multiplicity $E^{\frac{1}{2}}$, (iii) further increase in the production of nucleons and anti-nucleons (vi) production of super heavy fireballs and (v) transfer of large fraction of the primary energy into soft component—What has been called 'gammaisation". There are also indications of the production of massive (few GeV) long lived ($\gtrsim 10^{-12}$ sc) particles in high energy collisions[10]. There are also peculiar instances in which there seems to be evidence for the production of large number of nucleon—anti

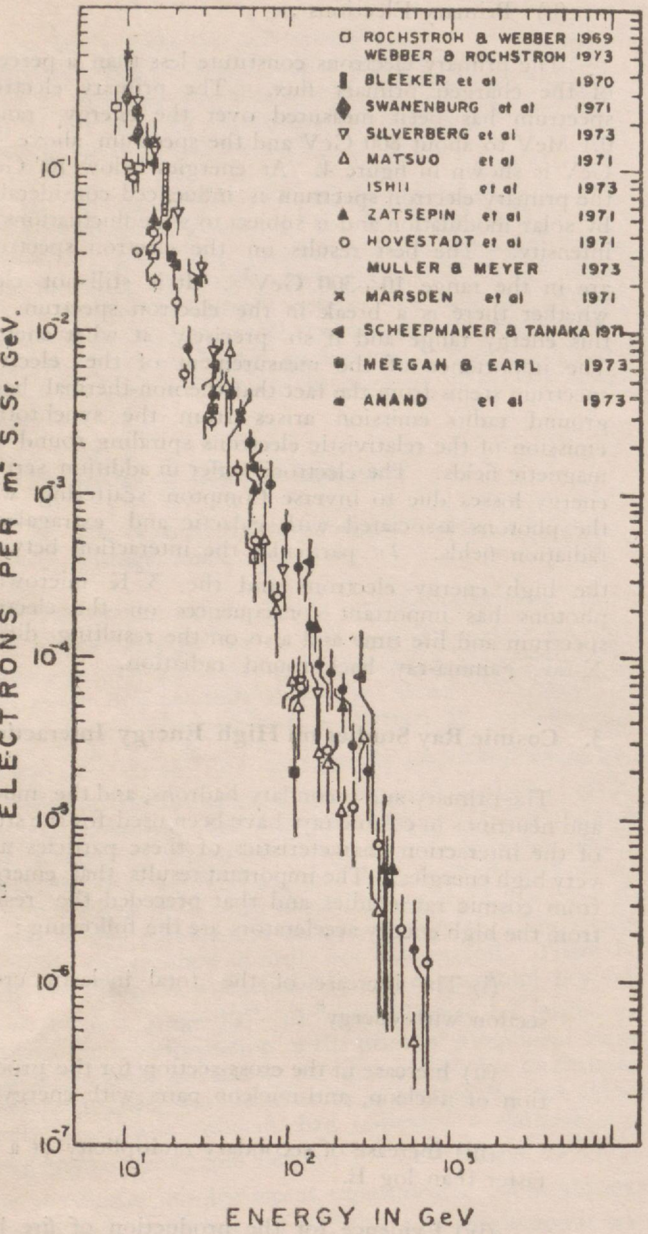

Fig. 4. World data on the energy spectrum of primary electrons.

nucleon pairs without the production of large number of pions[11].

These results are in an energy range just above the energy presently available at the Intersecting Storage Rings (ISR) at CERN and only further cosmic ray studies can lead to more definite conclusions.

The study of high energy muons at sea level and deep underground have led to important results on certain aspects of high energy interactions both of hadrons and leptons. Fig. 5 shows the intensity depth relation of muons deduced from vertical intensity and angular distribution measurements carried out in the Kolar Gold Fields in India. On the basis of detailed comparison of intensity in the vertical direction and at inclined directions having equivalent amount of absorbing matter it has been deduced that at energies of a few TeV, the contribution to the muon intensity either by direct production or from the decay of extremely short lived parents, is less than a per cent. This is important in the light of the recent indications from accelerator, experiments that the rate of mu's to Pi's produced at energies $\backsim$ 400 GeV is $\backsim 10^{-4}$. Measurements on the rate of decrease of multiple high energy muons as a function of separation carried out by the Utan group indicate that in collision of 10^{13} eV and above the transverse momentum is a factor of $\backsim$ 1.5 high compared to the average P_t at lower energies.

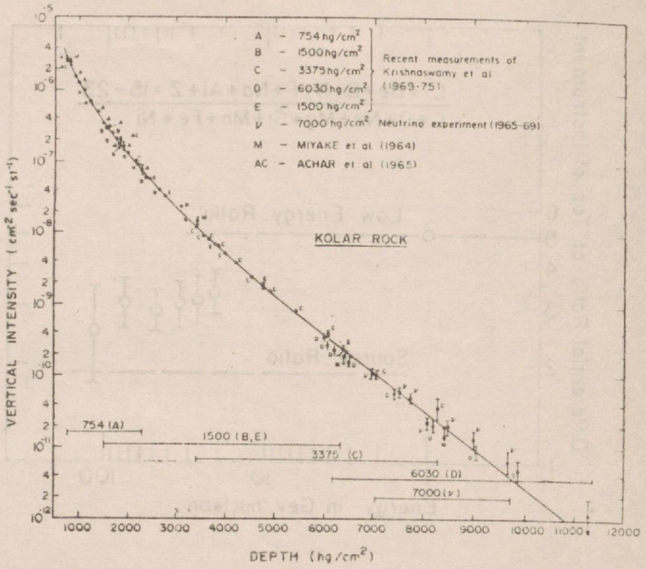

Fig. 5. Vertical intensity of muons as a function of depth underground measured at Kolar Gold Fields.

In the neutrino induced events registered with visual detectors in the KGF experiment[12] an anomaly has persisted right from the early days. The fraction of events in which multiple tracks are seen is high compared to single muon events. In some of the multiple events there is an indication that the charged secondaries converge to a point and in some cases the point convergence is in air suggesting the possible decay of a heavy particle produced in the interaction of a neutrino in the rock (Fig. 6). If these events are interpreted as decays of new heavy mass particles (of mass a few GeV) one runs into serious difficulties, regarding the cross section for their production which will have to be comparable to or higher than the cross section for interaction of the type $\nu + n \rightarrow \bar{\mu} + p$ or $\nu + p \rightarrow \mu^+ + n$ in which only single muons are produced. Another difficulty is that these heavy mass particles will have to have life time greater than 10^{-9} seconds to be able to traverse a few metres before decaying. Further experiments are essential to understand this very puzzling phenomenon particularly since accelerator experiments have not so far found any evidence for this type of events.

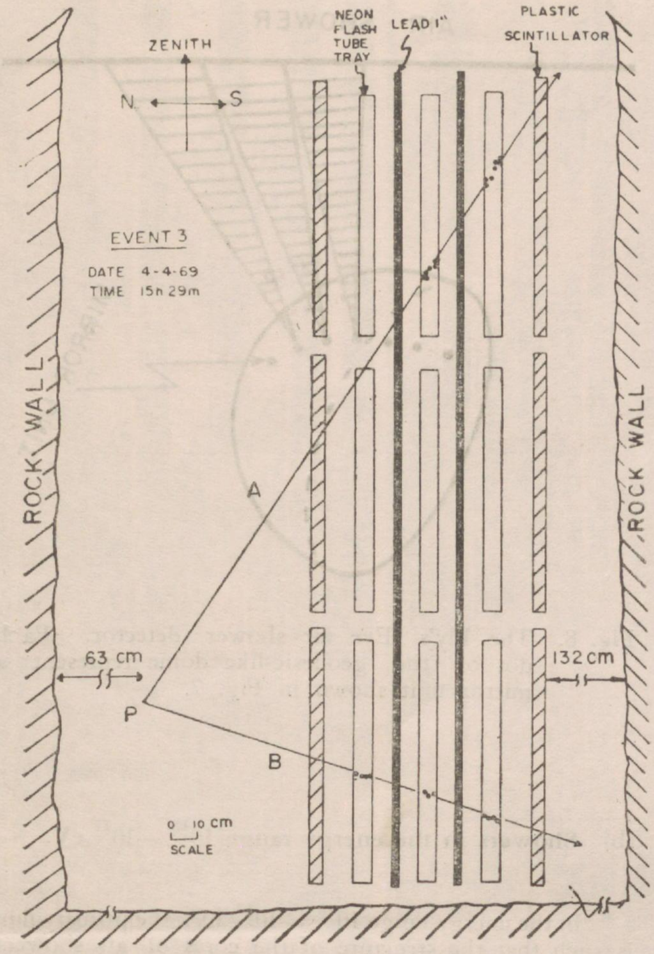

Fig. 6. A double track event recorded in the neutrino telescope at KGF.

4. Future Experiments

A large number of experiments are in progress at several mountain stations to elicit information on the characteristics of interaction in the energy range 10^{12} —10^{15} eV using deep ionization calorimeters, combinations of transition radiation detectors and calorimeters, emulsion chambers of hundreds of square metre area and large volume cloud chambers. Some of these form part of air shower installations. Soon one can expect that similar installations will begin to operate in the space shuttles which will also carry specialized experiments for the determination of the primary composition including isotopic composition, the electron energy spectrum etc. Therefore there is a good possibility that many of the outstanding problems upto 10^{15} eV in cosmic rays and high energy interactions will be solved within the next decade or so. At energies higher than 10^{15} eV satellite experiments will not be of much consequence since the flux at these energies is as low as a particle per square metre per year. One has to necessarily depend on air shower experiments. The conventional type of air shower arrays may not add much to our knowledge in this field. Several new approaches have emerged which hold promise of a better understanding of both the primary radiation and interaction characteristics at these super high energies.

(a) The Fly's Eye: Study of Showers $>10^{17}$ eV.

A novel and new type of air shower detector called the Fly's Eye has veen designed by the Utah group[13] which if successful will lead to the solution of many of the problems on cosmic rays at energies greater than 10^{17} eV. The main principle of the detector is the same as the one that was proposed and attempted by Greison more than a decade ago—detection of air showers through the atmospheric fluorescence given off after the excitation by relativistic electrons in the shower. The Utah proposal, however, is a coniderably modified and improved version which has many new ideas incorporated in it.

The Fly's Eye will consist of a mosaic of 948, photomultipliers clustered in groups of 12 in the focal plane of 79 large mirrors each 60″ in diameter with F/1.0 Fig. (7). The mirrors and the photomultiplier clusters

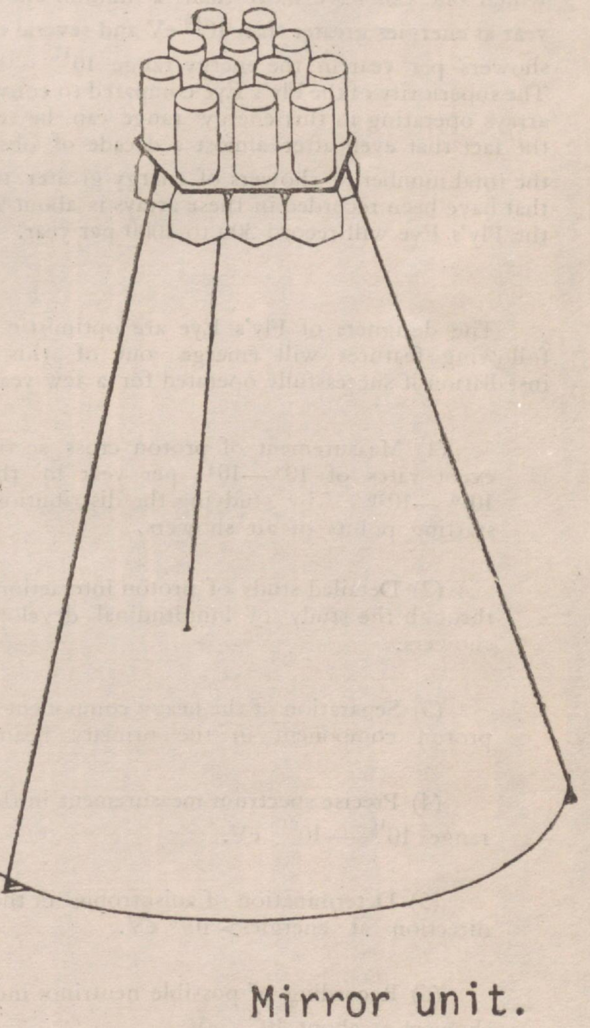

Fig. 7. The mirror unit in the Fly's Eye air shower detector.

will be mounted on a geodesic-like structure Fig. (8) and exposed to the night sky on clear moonless nights. Each of the 948 photo tubes will have field of view of 5.5 degrees. The data acquisition and processing will naturally be performed on an on-line computer system.

The principle of the Fly's Eye detector is as follows :

When an air shower passes by the side of the Fly's Eye different photo tubes will record the light intensity emerging from different longitudinal segments of the shower. The recording system registers the pulse heights and the time of arrival of the light at each of the photomultiplier tubes. The azimuth and elevation of each segment are known from the position of the different photo tubes that respond. From these parameters it is possible to compute the direction of the shower distance to the axis and the size of the shower. Unlike in conventional arrays in this method use is made of the longitudinal development and absorption of the shower in the lower atmosphere. The chief merit of this technique is that at an energy of 10^{16} eV one can hope to have an effective area of detection of 1.5 Km^2 and at 10^{19} eV, an area of 2×10^3 to 10^4 Km^2 as a consequence of which one can have more than a million showers per year at energies greater than 10^{16} eV and several thousand showers per year in the energy range 10^{17} —10^{19} eV. The superiority of the Fly's Eye compared to conventional arrays operating in this energy range can be seen from the fact that even after almost a decade of observation the total number of showers of energy greater than 10^{19} that have been recorded in these arrays is about 92 while the Fly's Eye will record 300 to 1000 per year.

The designers of Fly's Eye are optimistic that the following features will emerge out of this unique installation if successfully operated for a few years. :

(1) Measurement of proton cross section with event rates of 10^3 —10^4 per year in the range 10^{16} —10^{19} eV by studying the distribution of the starting points of air showers.

(2) Detailed study of proton interaction models through the study of longitudinal development of showers.

(3) Separation of the heavy component from the proton component in the primary beam.

(4) Precise spectrum measurement in the energy range 10^{16} —10^{21} eV.

(5) Determination of anisotropies in the arrival direction at energies $> 10^{16}$ eV.

(6) Recording of possible neutrino induced air showers at about 10^{20} eV.

(7) Recording of anomalous gamma-ray bursts of the type detected in the Vela satellites.

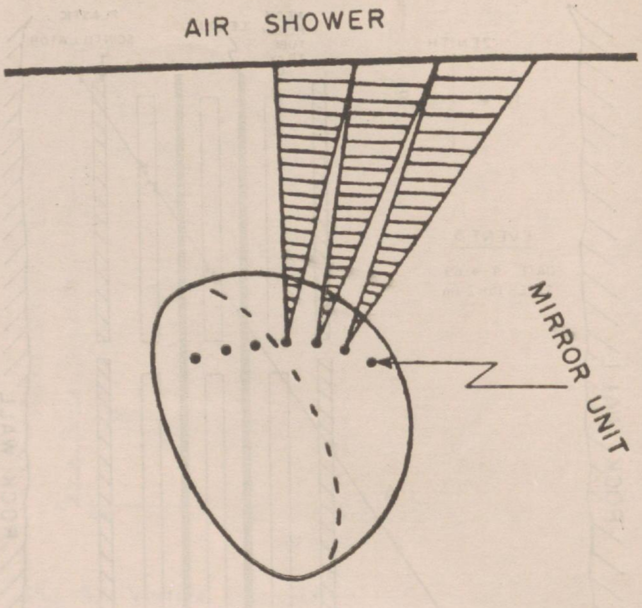

Fig. 8. The Fly's Eye air shower detector. Each dot on the geodesic-like dome represents a mirror unit shown in Fig. 7.

(b) Showers in the energy range 10^{13} —10^{17} eV.

In the energy range 10^{13} —10^{17} eV., the primary flux is such that the structure of the cores of air showers (Fig. 9) induced by the primary protons and nuclei can be studied by arrays of effective area a few hundred square metres. The study of the lateral distribution of the different components electrons, muons, hadrons, energy flow and Cerenkov radiation etc. and the correlation between different components enable to discern with the help of Monte Carlo simulations, the effects of composition and change in the characteristics of interactions. Several new complex arrays have come up in the last few years with this specific objective :

(i) The new KGF Air Shower Array

The new array has 73 scintillators at the surface of the Kolar Gold Mines for measurement of densities of charged particles, and 3 large area muon detectors at underground depths of 270, 600 and 1072 metres. A two square metre crossed neon flash tube telescope at the depth of 270 metres records the direction of associated muons of energy greater than 220 GeV to an accuracy of quarter degree. This enables the determination of the point of entry of the muon at the suface to an accuracy better than a square metre. The surface array determines the core position to an equivalent accuracy. The experiment therefore determines accurately the lateral distribution of very high energy muons produced in the atmosphere in collisions of energy greater than 10^{13} eV. The, average transverse momentum and the fraction of very large transverse momentum cases can be determined without ambiguity, from the lateral distribution measurements.

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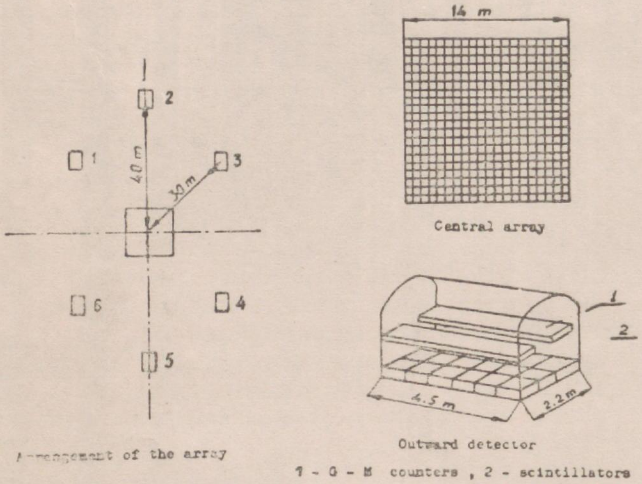
Fig. 9. Typical multicore structure of an air shower—recorded with the 2 sq. m multiplate cloud chamber in the Ooty air shower array.

(ii) The New Caucasus Array

The Moscow University group[14] have set up a new air shower array (Fig. 10) at Caucassus with a mosaic of 400 liquid scintillators covering an area of 200 sq. metres with four outward detectors each having 18 scintillators of effective area 9 sq. metres at a distance of 30 m and two similar detectors at a distance of 40 m. The high resolution and large area is particularly suitable for the study of multiple cores in air showers.



F ig. 10. The new Caucasus air shower array. The central array has 400 liquid scintillators each of 0-5m² area.

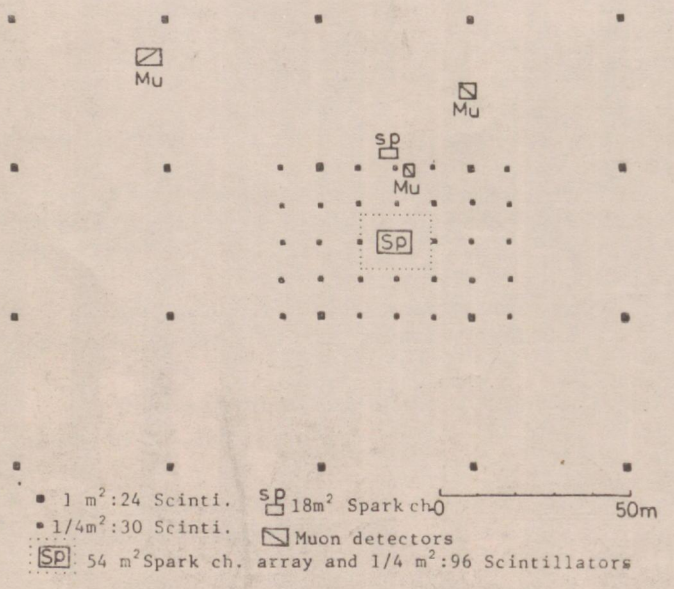


Fig. 11. The Plan View of the new Mount Norikura array.

(iii) The Mount Norikura Array.

The new array at Mount Norrikura[15] in Japan shown in Fig 11, and Fig 12 is composed of 150 scintillation counters and two spark chamber arrays one of area 54 sq. m and the other 18 sq. m and three muon detectors of total area 30 sq. m using proportional counters under concrete and lead.

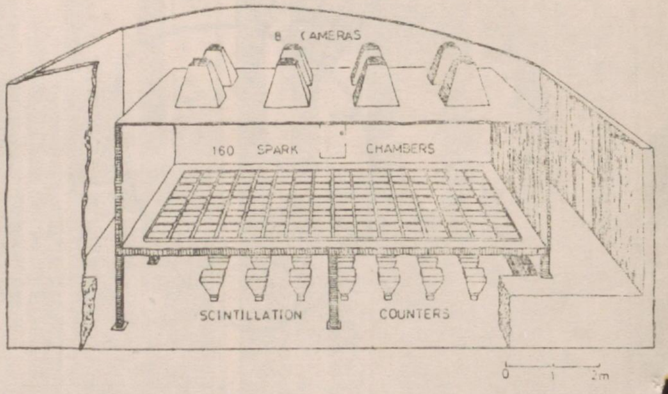


Fig. 12. The central part of the Norikura array.

The scale and complexity of the new installations some of which have been briefly described above are such that single large groups even, find it difficult to cope with the demands on resources, technical and scientific personnel and management problems and it has become customary for several small groups in the departments of physics and astronomy in different universities to combine and put in a concerted effort taking individual responsibility on different aspects. This is happening in U. K., U.S.S.R., U.S.A., and Japan. It is perhaps time that a similar approach is adopted in India too especially since cosmic ray research provides excellent opportunities for training and education in a variety of disciplines—nuclear physics, high energy physics, elementary particle physics, astronomy and astrophysics, and on the technology and applications side familiarity is gained in particle detectors, electronics, telemetry, on-line computer systems, software development, Monte Carlo simulation techniques, fabrication of payload instruments for balloons, rocks and satellites.

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