

B. V. Sreekantan

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HOMI JEHANGIR BHABHA
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Edited by

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PREFACE

Ever since the death of Dr. Homi Jehangir Bhabha in a tragic air crash on the 24th of January 1966, it has been the common wish of many of us, his students and associates at TIFR, to bring out a collection of his scientific papers which would undoubtedly be of special value to those who enter into research careers in theoretical physics, cosmic radiation and elementary particles, as well as to the historians of science. This long-felt wish has now materialised on the occasion of the 75th birth anniversary of Dr. Bhabha which fell on 30th October 1984. Dr. Bhabha's most active period of research, 1930-54, coincided with the period of spectacular developments in many areas of physics, both on the experimental and theoretical sides—especially in the areas of nuclear physics, cosmic ray physics and elementary particle physics. To serve as an introduction to Homi Bhabha's life in science, the environment in which he worked in the early years and the environment he created very successfully in later years, we have, in three articles that follow, outlined the historical perspective in which he made his contributions. The first article which has been written by me deals with the particular circumstances in which Dr. Bhabha got interested in the field of cosmic radiation and did pioneering work on both theoretical and experimental aspects and also the way he grew at the Tata Institute of Fundamental Research, one of the largest schools of cosmic ray research in the world, a school which has continued to make over the last four decades notable contributions to practically every aspect of this radiation. In the second article Prof. Virendra Singh has elucidated the background in which the contributions of Dr. Bhabha were made on several aspects of theoretical physics, elementary particles physics, in particular mathematical physics. These include Bhabha scattering, Bhabha-Heitler cascade theory, Bhabha-Corben theory of relativistic spinning point particles and relativistic Bhabha equations. Bhabha was among the earliest major workers on meson theory. The nomenclature 'meson' itself is due to Bhabha, Kemmer and Pryce.

Apart from having been a theoretical physicist of international distinction, Dr. Bhabha was also a great builder of scientific institutions in India. He founded the TIFR in 1945 and as its Director for 21 years, was responsible for growing this institution into an internationally recognised centre of fundamental research. He was also the founder of the Atomic Energy programme of the country and at the time of his tragic death, held the concurrent positions of Director of the Tata Institute of Fundamental Research, Chairman of the Atomic Energy Commission, and Secretary to the Department of Atomic Energy, Government of India. He was the President of the first UN Conference on Peaceful Uses of Atomic Energy, held in Geneva in 1955. He was the President of IUPAP during 1960-63. While it has not been possible to include the many writings and speeches of Dr. Bhabha on aspects of public policy in science in this volume, Prof. Udgaonkar, in the third article, has strung together extracts from Dr. Bhabha's speeches and writings to give a general idea of his philosophy and methodology in the growth of science in the country. It is hoped that,

at a later date, it would be possible to bring out a collection of his important speeches and other writings as well.

In order to give a full flavour of the life and work of Dr. Bhabha and do justice to his many-sided personality, we have included in the appendices the commemoration lectures on Dr. Bhabha by Sir John Cockcroft and Prof. M.G.K. Menon, delivered at the Royal Institution of Great Britain and published by the Royal Institution in 1967. This book also contains a short tribute to Dr. Bhabha by our late Prime Minister Smt. Indira Gandhi. We have also included as an appendix the article by Prof. Penney in the *Memoirs of the Royal Society*, London, of which Dr. Bhabha was elected Fellow in 1941. We would like to mention that the book 'Homi Bhabha as Artist' published by Marg in 1968 portrays beautifully the artistic aspect of Dr. Bhabha's personality—paintings, architecture, music and literature.

We would like to thank the Council of Tata Institute of Fundamental Research for encouraging us to bring out this volume and the Department of Atomic Energy for making available the necessary funds. The existence of a bound volume that contained most of the papers of Dr. Bhabha which had been compiled by the TIFR Library staff in 1962 was a great help in undertaking this venture. Mr. M.G. Railkar has helped us in obtaining permission from the various agencies to reproduce papers published in their respective journals. The list of institutions that have cooperated in this regard is given at the end of the book. We are indebted to Mrs. Mani Vajifdar who has very enthusiastically handled all aspects relating to the interaction with the press in bringing out this volume. We would like to thank the Tata Press for the great care and professionalism shown in the printing of this volume.

B.V. Sreekantan

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INTRODUCTORY ARTICLES

H. J. Bhabha:
His Contributions to Cosmic Ray Physics

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3. Cosmic Ray Research at the Tata Institute of Fundamental Research, Bombay.

1. *Dr. Bhabha at the Cambridge University, U.K.*

After completing with distinction at the age of 21, a tripos in mechanical sciences at the University of Cambridge, propelled by an inner urge to pursue a career in mathematics and physics, Homi Bhabha entered into research in theoretical physics at the same University in 1930. Bhabha's early scientific work and his later phenomenal success as a builder of institutions are so intimately related to the course of developments that took place world over in the task of unfolding the mysteries of Cosmic Radiation, and the emergence of the new field of elementary particle physics, that it is necessary to review briefly the status of cosmic ray research around 1930 when he began his research and trace the rapid advances in this field in the years that followed.

Even though the historic manned balloon flight of Victor Hess¹ on August 7, 1912 in which Hess himself climbed to an altitude of 16,000 feet, clearly established the extraterrestrial nature of the penetrating ionising radiation, even as late as 1929 the precise identity of this radiation had not been understood. The hypothesis that Millikan had made, based upon the absorption features known upto that time, that the radiation consists of high energy gamma rays presumably arising in the nucleosynthesis processes in interstellar space, held sway still. The variation of cosmic ray intensity with geomagnetic latitude recorded by Clay² gave the first indication that the radiation may have a charged component that was influenced by the geomagnetic field. The coincidence experiments of Bothe and Kolhorster³ revealed for the first time that a large fraction of the ionising radiation observed deep down in the atmosphere indeed consisted of charged particles. The world wide survey of the latitude effect organised by Compton⁴ and the discovery of the East-West effect by Johnson⁵ left no doubt that the radiation coming from outside was definitely influenced by the earth's magnetic field and therefore comprised of charged particles.

The absorption measurements carried out with coincidence telescopes by Rossi⁶ revealed that a sizeable fraction of cosmic ray particles that penetrated 25 cms of lead were also capable of penetrating a meter of lead. In another classic experiment in which counters were arranged in a triangular configuration in a horizontal plane, below a lead absorber, Rossi⁷ obtained evidence for the production of secondary particles by the passage of cosmic rays through the lead absorber. Also Cloud Chamber experiments of Skobelzyn⁸ and of Blackett and Occhialini⁹ had revealed instances of the passage of several simultaneous particles through the chambers which apparently were generically related arising perhaps in a common complex physical process.

Two exceedingly interesting and significant developments took place in the year 1932—one was the discovery of the neutron by Chadwick¹⁰ which helped to remove many of the puzzling features of the nuclei of atoms and the other was the discovery of the positron, the antiparticle of the electron by Carl Anderson¹¹ in an

analysis of cosmic ray particles with a magnetic cloud chamber. The discovery of the positron was a great triumph to the relativistic quantum mechanical formulation of the theory of the electron achieved by Dirac¹². Blackett and Occhialini⁹ who were also in the Cavendish Laboratory at Cambridge where Dirac was a professor in Theoretical Physics, had recorded instances of multiple charged particle events in their cloud chamber which appeared to have non-ionising links between pairs of charged particles emanating from a common vertex. These events fitted beautifully the phenomenon of pair production or materialisation of photons into electron-positron pairs, predicted by Dirac's theory. GM counter experiments under very large thickness of lead by Rossi¹³ soon revealed some interesting properties of the showers. The number of coincidences as a function of the thickness of lead absorber showed a maximum at about 1.5 cm of lead. Further the experiment of Rossi with different absorbers showed that showers were produced more abundantly in heavy elements than in light elements. On the theoretical side a major development was the quantitative calculation on the basis of relativistic quantum mechanics, of the energy loss of fast electrons and photons in passage through matter. These calculations revealed several surprising features: (i) the radiation losses were enormously greater for light particles such as electrons compared to heavy particles like protons; (ii) radiation process in elements of high atomic number were appreciably higher compared to losses in elements of low atomic number; (iii) radiation loss for all particles increased rapidly with energy. Equally surprising was the calculated behaviour of the pair production cross-section. This increased sharply with the atomic number of the medium and at energies greater than 1 MeV, the loss due to pair production was much higher than that due to Compton effect, and at still higher energies the Compton effect could be ignored in comparison to pair production.

The very first paper of Dr. Bhabha¹⁴ entitled "Zur Absorption der Höhenstrahlung" published in 1933 in *Zeitschrift Für Physik*, was concerned with an explanation of the experimental observations of the absorption features and shower production of cosmic rays in terms of the then prevailing theoretical ideas. This was followed by several papers^{15,16,17,18,19} on the physical processes connected with the passage of fast electrons and protons through matter. In the most celebrated paper which appeared as a note in *Nature* in 1936, Bhabha and Heitler²⁰ formulated for the first time the cascade theory of the electron according to which a high energy electron in passing through matter gave rise to a high energy photon by bremsstrahlung process and the photon in turn produced a pair of positive and negative electrons; these in turn led to further production of photons and the cascade process continued until the energy of the particles fell below a critical threshold value. (Simultaneously Carlson and Oppenheimer²¹ also developed a similar theory.) Thus a single electron multiplied in passing through matter into several electrons. This was precisely the type of phenomenon that was required to explain the showers observed in cosmic rays by Rossi, Blackett and others. Using the cross-section given by Bethe and Heitler²² for pair production and bremsstrahlung radiation, Bhabha and Heitler made quantitative estimates of the number of electrons that formed part of the cascade at different depths (expressed in a new unit defined by them as "the radiation length") for

different energy electrons and showed that the general features of the cascade agreed with the experimental findings of Rossi. It was obvious that a similar cascade would also be initiated by a high energy photon. A detailed paper entitled "the Passage of Fast Electrons and the Theory of Cosmic Showers" by Bhabha and Heitler²³ appeared in the Proceedings of the Royal Society, the same year (1933). In this paper Bhabha and Heitler clarified the anomaly regarding the penetrating power of the electron which had been deduced somewhat differently by Bethe and Heitler. In their original calculations Bethe and Heitler had shown that an electron of $\sim 10^{10}$ eV would have a range of only 1.5 km of air. This was in clear contradiction to the observation of high energy electrons deep down in the atmosphere and had therefore cast doubts on the validity of quantum electrodynamics at high energies. Bhabha and Heitler pointed out that while the earlier calculation by Bethe and Heitler was quite correct in deducing the mean range of electrons, the feature that had been missed by them was that the electron would result in a cascade multiplication in passing through the atmosphere, with the consequence that there would be a large probability for one of the secondaries to reach the bottom of the atmosphere. Thus the cascade shower theory in a way restored the validity of quantum electrodynamics, even upto very high energies.

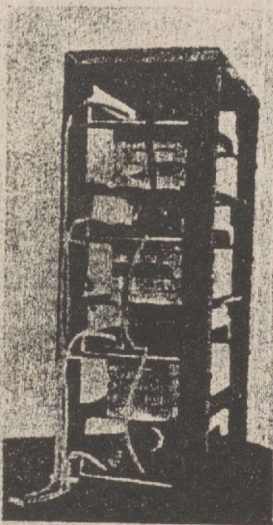
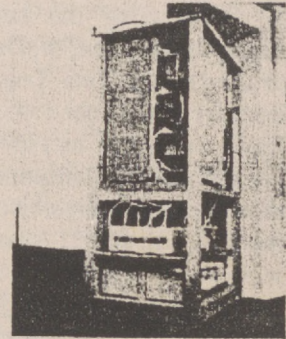
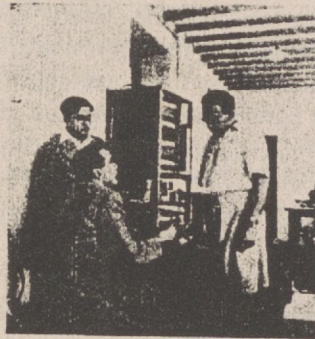
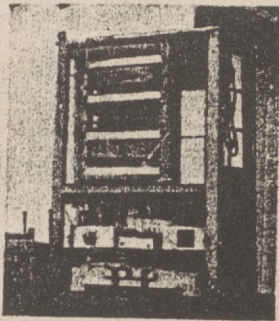
Further, Bhabha²⁴ in a classic paper entitled "On the Penetrating Component of Cosmic Radiation" communicated to the proceedings of the Royal Society in July 1937, critically analysed the experimental data existing upto that time on the soft and penetrating components and concluded that a 'breakdown' of the quantum mechanical theory of radiation as was envisaged by some, would not explain the latitude effect of cosmic rays, and the shape of the transition curve of large cosmic ray bursts. He pointed out that these features find a natural explanation if the radiation consisted also of new particles with mass between those of electrons and protons, something of the order of 100 electron masses. Some of the cloud chamber experiments which were designed to identify the nature of the penetrating particles through a measurement of ionisation and energy loss, were leading to similar conclusions. The experiment of Neddermeyer and Anderson²⁵ with a 1 cm thick platinum plate across the middle of the magnetic chamber clinched the issue. The meson as the penetrating particle of cosmic radiation was discovered. Street and Stevenson²⁶ soon established that the mass of the meson was about 200 electron masses. In the flush of the discovery of the meson, it was natural to identify it straightaway with the heavy mass particle that had been postulated by Yukawa²⁷ to explain the behaviour of nuclear forces. Very soon however it became apparent that there were serious problems with this identification. Bhabha²⁸ was the first to predict that the meson would be unstable and would spontaneously decay into electron and neutrino. The lifetime of the meson as deduced from the absorption rate in the atmosphere was a hundred times too long—in the region of microseconds, even after taking into account the relativistic time elongation effect. Also the nuclear absorption effects of negative mesons when stopped in a light substance like carbon did not conform to the expectation of the interacting nature of the Yukawa particle.

2. Dr. Bhabha at the Indian Institute of Science, Bangalore

The status of cosmic ray and elementary particle physics (the latter had just come on the scene) was as stated in the previous section when Dr. Bhabha returned to India and over the next few years set up the Cosmic Ray Research Unit at the Indian Institute of Science, Bangalore, as part of the Department of Physics, headed by the Nobel Laureate Sir C.V. Raman. The tremendous scope for both theoretical and experimental research that this field had opened up was abundantly clear to him. He was also aware of the special advantages that India offered for cosmic ray work because of the availability of a wide range of latitudes from magnetic equator in the south to 25° north magnetic latitude in Kashmir, within the boundaries of a single country, and a wide range of high mountain stations easily accessible for carrying out experiments. In fact Prof. Millikan came all the way from the USA to carry out balloon flights from different stations in India to study the latitude effect of cosmic rays. While continuing his theoretical studies along with a band of young physicists and mathematicians he had collected around him, on elementary particles, cascade theory, meson production etc. (discussed by Prof. Singh in the next article), Dr. Bhabha embarked also on a programme of experimental studies of the penetrating component of cosmic radiation. He designed, based on his first hand familiarity with cascade theory, a unique Geiger counter telescope that preferentially selected the penetrating component without requiring too much lead absorber. This telescope had 5.25 cm thick lead absorber in between the counters split into two layers of 1.25 and 4 cm thickness and had two anti-coincidence counters on either side of the middle counter. A second instrument he had designed consisted of a quadrupole coincidence GM telescope with 20 cms lead split into four layers between the GM counters. The telescopes were flown in an aircraft from Bangalore (3.3° N) on December 26 and 28, 1944 and had half hour exposures at altitudes of 5000, 10000, 15000, 20000, 25000, and 30000 ft. These constituted the first measurements²⁹ of the high altitude intensities of mesons at equatorial latitude. A subsequent flight was made a few months later. The comparison of results with those of Schein, Jesse and Wollan³⁰ showed that there was no marked increase of the latitude effect of mesons between 3.3° N and 52° N even to altitudes of 30,000 ft. (275mb) in striking contrast to the total intensity which exhibited a very pronounced latitude effect at such high altitudes.

The photograph on page XVII shows Dr. Bhabha with his cosmic ray telescopes engaged in a discussion with his colleagues.

At the Indian Institute of Science he also got constructed a 12" diameter circular cloud chamber identical to the one operating at that time in Prof. P.M.S. Blackett's laboratory at Manchester University and initiated a systematic study of the scattering properties of the penetrating component. He had recognised that such a study was crucial to resolve the riddle about the interaction characteristics of the meson that had been identified as the penetrating component.

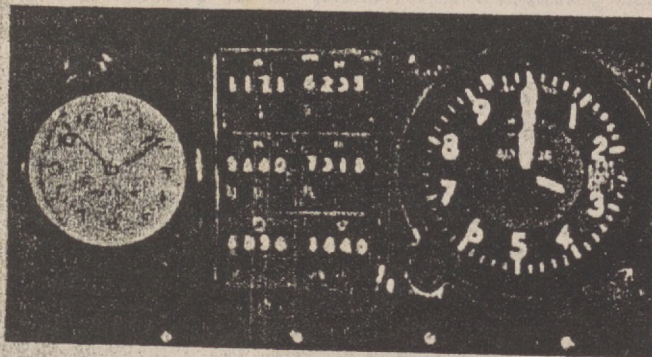


Top: Views of one of the units sent up to 32,000 feet with its sides removed. The top of the unit contains two cosmic ray telescopes. The electrical amplifiers are on the lower shelf. The dry batteries are at the bottom.

Left: A cosmic ray telescope with four counters. The three thick lead blocks traversed by the cosmic rays are seen between the counters.

Bottom right: The new anti-coincidence method for excluding the soft component.

Bottom left: A photographic record taken during the high altitude experiment. The six cosmic ray readings are shown in the middle. The altitude indicated by the altimeter on the right is 30,000 feet.



3. *Dr. Bhabha and Cosmic Ray Research at the Tata Institute of Fundamental Research*

Recognising the need for an institute solely devoted to the pursuit of fundamental research, Dr. Bhabha, with the enthusiastic support of Mr. J.R.D. Tata of the Dorabji Tata Trust, founded the Tata Institute of Fundamental Research in Bombay in the year 1945. The commemoration lecture given by Prof. Menon at the Royal Institution in 1967 which is reproduced in the appendix describes in a vivid manner the circumstances in which the TIFR was founded, its objectives and the extent to which the objectives were realised in Bhabha's own lifetime as Director of the Institute for 21 years.

The Institute naturally started with a major experimental programme in cosmic rays. The 12" diameter Cloud Chamber that was operating at the Indian Institute of Science was moved to Bombay and further systematic work on the scattering characteristics of the mesons was continued. A High Altitude Studies group was constituted and a programme of balloon flights (with clusters of rubber balloons) to measure the intensity of the penetrating component at different latitudes and altitudes was taken up. Balloon flights were made from Madras, Bangalore, Bombay, Pune, Ahmedabad, Delhi and Srinagar. These led to most interesting results on the intensity variation with altitude of the penetrating components at low latitudes. The first results of the TIFR group were presented by Dr. Bhabha³¹ at the International Conference on Theoretical Physics held at Kyoto and Tokyo in 1953.

As early as 1947 itself Dr. Bhabha who had close contact with Prof. Powell of Bristol University, the pioneer in the development and use of nuclear emulsions for cosmic ray research, started a group at TIFR to work with nuclear emulsions. The discovery of the pi-meson by Powell and his collaborators³² using this new technique had not only solved the riddle of the meson but also led to the adoption of this technique for a variety of experiments. The TIFR group started exposing emulsions at balloon altitudes to determine the nature of the primary composition and study the characteristics of very high energy interactions induced by primaries. It so happened that Prof. Bernard Peters of University of Rochester, USA, who was involved in the discovery of the presence of heavy nuclei³³ in the primary cosmic radiation, came as a delegate to the Elementary Particle Conference organised by Dr. Bhabha at Bombay in December 1950. At the invitation of Dr. Bhabha, Prof. Peters joined TIFR in 1951 and stayed on at the Institute for 8 years. This gave a boost to the cosmic ray programme of the Institute in general, and to the nuclear emulsion programme in particular. In 1956 Prof. M.G.K. Menon, who had spent 8 years at the University of Bristol in Prof. Powell's laboratory and had made pioneering contributions in the field of elementary particles through cosmic ray studies, also joined TIFR. The balloon flight programme gained momentum. The development of large volume plastic balloons was undertaken for a variety of experiments on cosmic rays. Over the years this activity grew to such an extent that a permanent Balloon Facility for fabrication of plastic balloons and launching them

was set up at Hyderabad. Today the Facility has the capability to manufacture balloons upto 10 million cft. volume and launch payloads upto 1000 kg. So far 112 flights have been made by the TIFR group for cosmic ray experiments and 96 for X-ray, Gamma Ray Astronomy experiments. The Balloon Facility is used both as a national and international facility.

In the paper entitled "Investigation of Heavy Mesons by Means of a Solid Emulsion Block" Dr. Bhabha³⁴ presented at the International Conference on Theoretical Physics at Kyoto and Tokyo in 1953 some of the important early results from the nuclear emulsion group of the Institute. In later years the nuclear emulsion group made very significant contributions on the electron component of primary radiation³⁵ and on the isotopic composition³⁶ of the primary radiation.

Another line of activity initiated by Bhabha as early as 1950 which over the years developed into a major thrust area of research at TIFR was the utilisation of the deep underground levels in the Kolar Gold Mines near Bangalore for experiments in the field of cosmic radiation. These were initiated at a time when the role of k -mesons which had just been discovered as another important source of muons through spontaneous decay, had not been clearly recognised. In fact one of Dr. Bhabha's ideas to initiate experiments underground was to examine critically whether the muon was the only penetrating charged particle underground or whether there were other particles of different masses that were also penetrating. The first series of experiments³⁷ on the measurements of the intensity and angular distribution of penetrating particles began in October 1951 and were followed by several others³⁸ which led to the most accurate measurement of the intensity right down to depths of 9000 feet below ground. These experiments also led to the realisation that at depths greater than 8000 feet it should be possible by suitable design of detector systems to record interactions of cosmic ray neutrinos³⁹. In fact through an international collaborative venture a large scale neon hodoscope system was installed in the KGF Mines and the first clear evidence for natural neutrino interaction with visual detectors was reported at the Cosmic Ray Conference⁴⁰ in London in 1965. Taking advantage of the flat terrain at the surface of the mines and the existence of various deep underground levels, a unique extensive air shower array was also set up at KGF⁴¹. While the surface array recorded the various properties of the air showers (size, core position, angle of arrival etc.), visual detector assemblies deep underground detected the associated ultra high energy muons. In December 1964 Dr. Bhabha inaugurated this air shower installation at KGF. While investigations of muons, neutrinos and air showers have continued with various types of installations at KGF, since 1981 a large area detector specifically designed for recording nucleon decay is operating in the mines at the same underground level at 8000 ft. where the first neutrino interaction was recorded. In the first three years of operation several candidate events⁴² for nucleon decay have been recorded.

As stated earlier, the small cloud chamber that Bhabha got built while at Bangalore, was one of the first instruments of cosmic ray research at TIFR. The

Cloud Chamber group of the Institute started building larger and larger chambers. In December 1954 a double cloud chamber set-up was installed in the mountain station at Ooty in South India for the study of strange particles. This was followed by a unique set-up of a triple arrangement of a total absorption spectrometer, a multiplate cloud chamber and an air Cerenkov counter one above the other for the investigation of the differences in the interaction characteristics of pions and protons⁴³. This was achieved before the advent of the CERN 30 GeV accelerator. In December 1964 when Dr. Bhabha was on a holiday at Ooty, he was thrilled to see the world's largest multiplate cloud chamber operating there as part of the extensive air shower array. The Ooty Air Shower Array led to several important results on the characteristics of very high energy interactions⁴⁴ through a systematic study of hadron component of the air showers and one of the most important results was the discovery relating to an increase in the cross-section for the production of nucleon-antinucleon pairs at high energies⁴⁵.

Thus while Dr. Bhabha's personal involvement in experimental research tapered off in the early 50s with his increasing administrative responsibilities as the Director of TIFR which was fast growing and as Chairman of the Atomic Energy Commission, and Secretary, Department of Atomic Energy, the cosmic ray programmes that he initiated at the Institute gained strength. Over the last four decades more than five hundred papers have been published in the field of cosmic rays alone and several scores of scientists have obtained their Ph.D. degree on work carried out in the field of cosmic radiation. Research has been conducted at the Institute on practically all aspects of cosmic radiation, primary composition, high energy interaction of hadrons, muons, neutrinos, extensive air showers, cosmic ray produced radio activity etc.

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