Bhabha Centenary Year (2008-2009)

Remembering Dr. Homi Bhabha, the Physicist

Bhabha Atomic Research Centre
Mumbai 400 085

Homi Bhabha Birth Centenary Year
30 October 2008-30 October 2009

I am burning with a desire to do physics. I will and must do it some time. It is my only ambition. I have no desire to be a 'successful' man or the head of a big firm. There are intelligent people who like that and let them do it. I hear you saying 'But you are not Socrates or Einstein'. No – and that is what Berlioz's father said to Berlioz. He called him a useless musician when he was young – Hector Berlioz who is now accepted as one of the world's greatest geniuses and France's greatest musician. How can anybody else know at what time what one will do, if there is nothing to show. ... It is no use saying to Beethoven 'You must be a scientist for it is a great thing', when he did not care two hoots for science; or to Socrates 'Be an engineer; it is the work of an intelligent man'. It is not in the nature of things. I therefore earnestly implore you to let me do physics.

- Homi Bhabha
Letter to his father
Cambridge 1928

Homi Bhabha Birth Centenary Year
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Remembering
Dr. Homi Bhabha, the Physicist

सत्यमेव जयते

Government of India
Bhabha Atomic Research Centre
Mumbai 400 085
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Homi Bhabha Birth Centenary Year
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भारत सरकार
Government of India

डॉ. श्रीकुमार बॅनर्जी
निदेशक,भाभा परमाणु अनुसंधान केंद्र
सदस्य,परमाणु ऊर्जा आयोग

Dr. Srikumar Banerjee
Director, Bhabha Atomic Research Centre
Member, Atomic Energy Commission

FOREWORD

Bhabha Centenary Year (2008-2009) is a celebration of the intellectual and artistic pursuits of a towering personality, who Lord Redcliffe-Maud aptly described as *'a world citizen qualified in all three subjects- education, science and culture'*.

The year-long celebrations in the DAE include organization of several symposia and conferences on specialized subjects. We shall also have two major international events – the first in New Delhi during September 29-October 1, 2009 on Peaceful Uses of Atomic Energy to commemorate the 1955 Conference on the same title which was presided over by Dr. Homi Bhabha and the second one in TIFR, Mumbai to be organized jointly by all institutions of our Department along with Academies of Science (INSA, IASc, NASc and the Royal Society, London) which will highlight various creative pursuits – both scientific and artistic – of Dr. Bhabha.

The seminar at BARC, *'Remembering Dr. Homi Bhabha, the Physicist'* is a part of this celebration, but with a difference. This seminar attempts to simulate the golden era of quantum physics and Bhabha's well deserved place in it. Imagine the young Bhabha joins Cambridge in 1927 for a degree in engineering, gets influenced by the stalwarts like Rutherford and Dirac and realizes that *'I am burning with a desire to do physics. I will and must do it some time. It is my only passion.'* The rest is then a history- Bhabha comes up with his original works, notably on electron-positron scattering, cosmic ray showers and the existence of mu-meson. In the seminar at BARC we attempt to re-create this epoch by two young scientists of our center. In a way, they impersonate the young Bhabha and describe to the audience his fundamental discoveries in a pedagogic manner. The audience consists of the young and the old, amateurs and experts as Dr. Bhabha might have had at his time. I believe that this effort will certainly be helpful in strengthening in our research center the spirit of inquiry, the passion for basic research and vibrancy of thoughts- the qualities epitomized by Dr. Bhabha. In addition to the young scientists' presentations, we have with us Prof. B.V.Sreekantan, formerly Director, TIFR, who worked with Dr. Bhabha in his formative years, and he will narrate his scientific interactions with Dr. Bhabha for the benefit of the young audience.

I would like to appreciate here the efforts of the organizing committee, and especially of Dr. B.N. Jagatap, Dr. V.M. Datar, Dr. S. Kailas and Dr. Ramesh Koul in making this function a reality.

I sincerely believe that the seminar *'Remembering Dr. Homi Bhabha - The Physicist'*, is an apt tribute to the intellectual giant of our times, and will help us to remind the great responsibility of fostering science and technology in this country that we have on us.

Srikumar Banerjee
30.3.09
(S. Banerjee)

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Preface

It gives us great pleasure in bringing this volume to you on the occasion of the celebration of the Bhabha centenary year, 2008-09. Dr. Homi Bhabha was a multifaceted personality-a physicist, an artist, a visionary and a builder of institutions. In this volume, we focus on one aspect of his towering personality, as one of the leading physicists of his time.

Homi Bhabha studied at Cambridge, first getting a degree in Mechanical Engineering as his father wished, but then taking to his passion viz. Physics. He was deeply influenced by Dirac who was at Cambridge during the same period. It was also here, at the Cavendish Laboratory, that Rutherford was leading a team of scientists who were making path breaking and fundamental discoveries. He completed his Ph.D. in 1935 under the guidance of Fowler, who was also the thesis advisor of the Nobel laureate and renowned astrophysicist, S. Chandrasekhar. During the period 1932-33 he spent some time with Pauli at Zurich, Fermi at Rome and Bohr at Copenhagen. Bhabha returned to India in 1939 intending to return to Europe and take up a position in a good University there. The war made this difficult and he joined the Indian Institute of Science, Bangalore instead. He was elected Fellow of the Royal Society at the age of 32 on the basis of a recommendation by C.V. Raman, which was seconded by Dirac. As a Professor at I.I.Sc. at the age of 33, he began a pursuit of cosmic ray research using aircraft to carry radiation measuring equipment and make measurements on meson intensities at near equatorial latitudes. In 1945 he started the TIFR with a grant from the Dorabji Tata trust. In a rather short period he gathered a team of young scientists around whom new programmes were built. Leading scientists from all parts of the globe such as John Cockcroft, P.M.S. Blackett, Cecil Powell, Wolfgang Pauli, Paul Dirac, Niels Bohr, S. Chandrasekhar, T.D. Lee, Murray Gell Mann, Bruno Rossi, George Gamow and Hans Bethe visited the TIFR and interacted with the young scientists there. He also started the Wednesday Colloquium, which he used to attend when at Bombay. The Atomic Energy Establishment at Trombay, (renamed the Bhabha Atomic Research Centre after his untimely death in 1966) was inaugurated in 1957. He initiated the atomic energy programme in India very early and was also responsible for starting the three stage approach based on natural uranium and heavy water, a second phase based on plutonium, uranium and thorium and finally on uranium-233, which was bred in phase 2, and thorium.

In physical sciences, Bhabha is well known for two pieces of his work, viz., relativistic electron-positron scattering including exchange, better known as the 'Bhabha Scattering', and the theory of electromagnetic cosmic ray showers. Less well known is the fact that he was the first to propose the existence of a heavier cousin of the electron, now known as the mu-meson, to explain the penetrating component of cosmic ray secondary particles and suggest using this to test relativistic time dilatation. This proposal was the first to enlarge the family of electron and its associated neutrino and is probably the first paper suggesting what is now known as the second generation of leptons. He also coined (along with M. Price and N. Kemmer) the word *meson* for the particle proposed by Yukawa for mediating the strong nuclear force between nucleons (neutrons and protons).

The idea behind the seminar 'Remembering Dr. Homi Bhabha, the Physicist' is to present to a multidisciplinary audience these great scientific contributions of Bhabha in a pedagogic manner. The idea of organizing a commemoration in this format is that of Dr. S. Banerjee, Director, BARC. Two young physicists from our centre have been chosen to talk on Bhabha scattering and the theory of cosmic ray showers. In order to introduce Bhabha as a physicist to the younger colleagues, we have a talk by Prof. B.V. Sreekantan, former Director, TIFR, who joined TIFR in the early years and worked closely with Dr. Bhabha. Articles based on these three talks together with a foreword by Dr. S. Banerjee are included in this commemorative volume. We thank Prof. Sreekantan for his kind consent to reproduce here his article that appeared in 'Resonance'. We have included in this volume, a list of publications of Dr. Bhabha, his famous quotations on the role of science and technology in the development of the country, and also a photo album that shows Dr. Bhabha with the leading physicists of his time. In addition, the volume contains an article that provides an analysis of the impact of the scientific papers of Dr. Bhabha. We sincerely hope that this volume brings to you the essence of the scientific pursuit of Bhabha.

We would like to acknowledge help from various quarters, which made this volume a reality. We sincerely thank TIFR Archives, and the American Institute of Physics for permission to reproduce some rare photographs. Thanks are also due to Indian Physics Association and the Indian Academy of Sciences for permitting us to reprint Prof. Sreekantan's article. We acknowledge help from Prof. Dipan Ghosh (IIT, Mumbai), Prof. A.K. Grover (TIFR), Shri P. R. Vijayaraghavan and Dr. Suresh Kumar for the help they rendered during the compilation of this volume. Special thanks are due to Shri A.G. Apte and his colleagues in Computer Division of BARC for making possible the electronic announcement and on-line registration of the seminar. The task of publication of this book in a shortest possible time was possible entirely due to the efforts of Scientific Information and Resource Division of BARC and we thank Dr. Vijai Kumar and his colleagues for the same. We place on record our sincere appreciation for the support rendered by Shri R.K. Sharma, MRPA of SIRD and Shri P. Aranjo, PRO, BARC.

V.M. Datar
B.N. Jagatap
S. Kailas
R. Koul

BARC, Mumbai
March 30, 2009

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Homi Bhabha and Cosmic Ray Research in India

B. V. Sreekantan

B V Sreekantan is currently the Sir S Radhakrishnan Visiting Professor at the National Institute of Advanced Studies, Bangalore. He was Director of Tata Institute of Fundamental Research, Mumbai during the period 75-87. He obtained his PhD from Bombay University in 1954 for his work on 'underground cosmic rays' under the guidance of Homi Bhabha.

Cosmic rays are very high energy particles arriving from the depths of space and incident on the earth's atmosphere at all places and at all times. The energy of these particles extends over 12 decades from around 10^9 ev to 10^{21} ev and mercifully for the survival of life, the intensity falls by at least 22 decades from about 100 particles/cm^2/s to 1 particle/1000 km^2 /year. Cosmic ray research led to the discovery of many of the fundamental particles of nature in the 30's, 40's and 50's of this century and ushered in the era of 'elementary particle physics' at man-made accelerators. Even 86 years after the discovery, the sources of these particles and the mechanism of acceleration continue to remain a mystery.

Homi Bhabha who became famous for his 'cascade theory of the electron' in the 30's did pioneering theoretical and experimental research in this field during his post doctoral fellowship in Cambridge and later at the Indian Institute of Science in Bangalore. The Tata Institute of Fundamental Research, which he founded in 1945, became under his leadership, a major centre of cosmic ray research covering practically all aspects of the radiation and continues to be active in this field.

In 1934, Bhabha was awarded the Isaac Newton Studentship at Cambridge which enabled him to complete his PhD under R H Fowler.

Homi Bhabha is well known among the scientists of India and the public at large as the 'Father of India's Atomic Energy Programme'. What is not so well known however, particularly among the younger generation, is the fact that he made outstanding contributions in the field of theoretical physics and played a very important role in initiating and fostering cosmic ray research in India. Thanks to the unique start given by him in the 40's, cosmic ray research in India grew into one of the largest activities in the world covering all aspects of the radiation in the 50's and 60's. In recognition of this, the Cosmic Ray Commission of the IUPAP held its 7th International Conference on Cosmic Rays, one of the earliest in the series, at Jaipur in India in 1963. It is most interesting and instructive to know how all this was achieved and what exactly motivated a young man in his thirties to initiate work in a highly sophisticated and highly technology dependent field so early in India. Let us look at the background of Bhabha and the times in which he began his research.

Homi Bhabha at Cambridge

Homi Bhabha was born on 30th October 1909 and had his school education at the Cathedral and John Connon High School in Bombay and his college education at the Elphinstone College and the Royal Institute of Science. At the age of 18, he left for England to pursue further studies at Cambridge. As desired by his parents, he completed his Mechanical Tripos with distinction and persuaded them to let him do a Mathematical Tripos since his own interests were in physics. Immediately after his second Tripos, he got a travelling fellowship and had the wonderful opportunity of working for short periods with Wolfgang Pauli at Zurich and with Enrico Fermi at Rome. In 1934, he was awarded the Isaac Newton Studentship at Cambridge which enabled him to complete his PhD under R H Fowler. He continued his research at Cambridge till 1939. The research that he did during this period had a direct bearing on the resolution of several important issues of cosmic ray phenomena and the interactions of particles especially electrons, protons and photons at high energies, in the context of the developments in the field of quantum mechanics and relativity. To appreciate these contributions of Bhabha it is necessary to become familiar with the status of cosmic ray studies in the early 30's.

Fig. 1: Victor Hess in the Gondola in which he went up to an altitude of 16,000 ft for measurement of cosmic ray intensity in 1912.

Cosmic Rays in the Atmosphere: The 'Soft' and 'Penetrating' Components

The presence of a penetrating ionising radiation of extraterrestrial origin was established in 1912 by Victor Hess through a series of manned balloon experiments (Figure 1). The name 'Cosmic Rays' was given to this radiation by Millikan in 1925. Analysis of the radiation at sea level and mountain altitude by a series of experiments with Geiger–

Muller telescopes and magnetic cloud chambers, revealed that the radiation contained two components with distinctly different properties. One component, called the 'soft component', was easily absorbed in a few centimetres of lead, quite frequently multipled in number in passing through thin sheets of lead and also arrived at the observational level in multiples – as a shower of particles separated by several tens of centimetres. The second component, called 'penetrating component' could penetrate large thicknesses of matter, even a metre of lead, without multiplying. The only fundamental particles that were known at that time were the electrons, the photons, the protons and the α-particles. To this small list two more were added in 1932, the neutron and the positron. The positron was discovered by Anderson in a cloud chamber that had been set up to analyse the cosmic ray beam and its discovery was a great triumph to the relativistic quantum mechanical formulation of the theory of the electron developed by Dirac at Cambridge. Around the same time in the early 30's, Blackett and Occhialini who were also working at Cambridge had recorded several instances of multiple charged particles which had obvious non-ionising links between pairs of them. These events fitted beautifully the phenomenon of pair production or conversion of quanta into electron-positron pairs according to Dirac's theory. The calculations on the energy losses of charged particles by Bethe and Heitler revealed several surprising features – higher losses for lighter particles, (more for electrons than for protons of the same energy), higher losses in passing through matter of higher atomic number, and higher losses at higher energies.

Bhabha and Heitler made quantitative estimates of the number of electrons in the cascade at different depths, for different initiating energy of the electrons.

All these features came in very handy in the explanation of cosmic ray anomalies. Clearly, Bhabha was at the right place at the right time. The very first paper of Bhabha entitled 'Zur Absorption der Hohenstrahlung' published in 1933 in Zeitschrift Fur physik was concerned with the explanation of the absorption features and shower production in cosmic rays. In 1936, Bhabha in collaboration with Heitler formulated the 'cascade theory of the electron' according to which a high energy electron passing through matter gave rise to a high energy photon by bremstrahlung 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 value. Carlson and Oppenheimer also developed a similar theory simultaneously in the USA. Based on Bethe– Heitler cross sections, Bhabha and Heitler made quantitative estimates of the number of electrons in the cascade at different depths, for different initiating energy of the electrons. These calculations agreed with the experimental findings of Bruno Rossi in cosmic ray showers. The problem of the 'soft' component was thus totally resolved. In a classic paper entitled 'On the penetrating component of cosmic radiation' communicated to the Proceedings of the Royal Society in July 1937, Bhabha made a careful analysis of the experimental data on the soft and penetrating components and concluded that a 'breakdown' of the quantum mechanical theory of radiation at higher energies as proposed by some theorists would not explain the experimental results on the latitude effect of cosmic rays and the shape of the transition curve of large cosmic ray bursts. He emphasised that these features would find a natural explanation if cosmic radiation contained charged particles of mass intermediate between electron and proton and set the mass as ~100 electron masses.

Around the same time, Neddermeyer and Anderson, and Street and Stevenson discovered in their cloud chamber experiments, charged particles of intermediate mass whose mass was set at ~ 200 electron masses. The name 'meson' was given to this new particle. Bhabha predicted (in a paper in Nature, 1938) that the meson would be unstable and would probably decay into an electron and neutrino. The phenomenon of meson decay was helpful in resolving anomalous absorption of the penetrating component in the atmosphere. The relativistic elongation of time as predicted by the special theory of relativity was confirmed through meson decay experiments.

Bhabha and Cosmic Ray Research at the Indian Institute of Science, Bangalore

Bhabha came on a brief holiday to India in 1939. He could not go back to England as planned, since the second world war broke out in September 1939, and there was the prospect of heavy bombing over England by the Germans. Bhabha decided to stay back in India for a while. This decision turned out to be a turning point, a landmark not only in the academic career of Bhabha, but also in the advancement of Indian science and technology in the post independent era.

Bhabha predicted (in a paper in Nature, 1938) that the meson would be unstable and would probably decay into an electron and neutrino.

Bhabha joined the Physics Department of the Indian Institute of Science, headed by C V Raman. He got a special grant from the Sir Dorab Tata Trust. He gathered some students to work with him in theoretical particle physics and one of them was Harish-Chandra, who later held a professorial chair in mathematics at the Princeton Institute of Advanced Studies.

In parallel, Bhabha also started experimental work in cosmic rays. He was cognisant of the unique advantages of India to work in this field – wide range of latitudes from equator in the south to 25° N in Kashmir within the boundaries of a single country; mountain stations in the south and north and the deepest mines in the world. Millikan had come all the way from the USA to do experiments at several stations in India in the mid 30's.

With a uniquely designed GM telescope, which Bhabha built with the help of S V C Iya, the penetrating particle intensities were measured at altitudes of 5000, 10,000, 15,000, 20,000, 25,000 and 30,000 ft, using a B-29 bomber aircraft belonging to the US Air Force. These constituted the first measurements at such high altitudes in an equatorial latitude. Comparison with the measurements of Schein, Jesse and Wollan in the USA, established that no marked increase of intensity occurred between 3.3°N and 52°N even at an altitude of 30,000ft., in contrast to the total intensity which exhibited very pronounced latitude effect at such altitudes.

At the Indian Institute of Science, Bhabha also got constructed a 12" diameter cloud chamber identical to the one operating in Manchester. R L Sengupta, who had worked in Blackett's Laboratory helped Bhabha in the design and construction of this chamber, which was used by M S Sinha to study the scattering characteristics of mesons. Vikram Sarabhai set up a telescope to study the time variation of cosmic ray intensity.

With financial support from the Sir Dorabji Tata Trust and the Government of Maharashtra, Bhabha established the Tata Institute of Fundamental Research in Bombay in June 1945.

Bhabha and Cosmic Ray Research at the Tata Institute of Fundamental Research

While at the Indian Institute of Science, Bhabha recognized the need for setting up in the country an institute solely devoted to the pursuit of fundamental research especially in the area of nuclear science that was emerging as a virgin area of fundamental science. The developments in the field of cosmic ray studies and in the area of nuclear physics with accelerators had convinced Bhabha that the future lay in these areas. With financial support from the Sir Dorab Tata Trust and the Government of Maharashtra, Bhabha established the Tata Institute of Fundamental Research in Bombay in June 1945. The formal inauguration of TIFR was at IISc, Bangalore. The TIFR became an aided institution under the Department of Atomic Energy later and was recognised as the National Centre for Nuclear Science and Mathematics by the Government of India. Bhabha himself used to say that TIFR was the 'cradle of the Atomic Energy Programme' of the country. Bhabha was the Director of TIFR from 1945 to January 1966 – till his untimely death in a tragic air crash on the Alps.

The TIFR naturally started with a major experimental programme in cosmic rays, taking cognisance of the fact that cosmic ray research had entered its second phase the world over. The π-meson as the parent of the μ-meson was discovered in 1947 by Powell and his collaborators at the University of Bristol exposing the newly developed high sensitivity nuclear emulsions in the Jungfraujoch mountains in Switzerland. Rochester and Butler discovered the same year the V^0 particles, which were later identified as the K-mesons and hyperons through nuclear emulsion experiments by several groups. Bradt and Peters discovered around the same time the presence of α-particles and other stripped heavy nuclei in the primary cosmic radiation which consisted predominantly of protons. Also, most importantly, the act of meson production had been caught both in nuclear emulsions and in multiplate cloud chambers.

Fig. 2: Bhabha and A S Rao with a typical cosmic ray telescope – of the type that was being launched from the Central College grounds, Bangalore in the late forties, on clusters of rubber balloons.

With these developments, the new directions of cosmic ray research had become clear. To enter the international arena in this field, the emphasis had to be on: (i) the investigations on the primary component – spectrum, composition, anisotropy of arrival directions; relative proportions of rare nuclei, electrons, γ-rays; (ii) the detailed study of the characteristics of nuclear collisions of the primaries as well as of the secondaries produced in these collisions; (iii) the studies on the penetrating components – muons and neutrinos in deep underground installations; (iv) studies on the extensive air showers initiated in the atmosphere through the nuclear and electromagnetic cascades by the primaries; (v) study of the radio isotopes produced by cosmic rays; (vi) time variation studies on cosmic ray intensity and correlations with solar activity (Fig. 2).

These multidimensional studies to be carried out in a variety of locations with specially designed detector systems, required the inhouse development of a variety of technologies – to name a few – plastic balloon fabrication technology, fabrication of GM counters, plastic scintillators, multiplate cloud chambers, pulsed electronic circuits and even a digital computer. Thanks to the organisational genius of Bhabha, all this was done in a record time in TIFR itself. The Indian industry was very backward in the 40's and 50's and importing then was just not thinkable because of shortage of foreign exchange and the enormous delays of transportation. The cosmic ray programme did get a fillip in the 50's by Bernard Peters, the co-discoverer of heavy primaries and M G K Menon who worked for 8 years in Powell's laboratory, joining the Nuclear Emulsion Group of TIFR.

At the International Conference on Cosmic Rays held at Bagneres in 1953, TIFR made its first impact by presenting very significant results on K-mesons and hyperons obtained from the analysis of emulsion stacks exposed at Hyderabad. The emulsion group kept a high profile of original contributions in the field of high energy interaction studies, the relative abundances of Li, Be and B in the primaries, hyperfragments and on the spectrum of primary electrons. The deep underground experiments in the Kolar Gold Fields initiated at the instance of Bhabha as early as 1950, and which continued for more than four

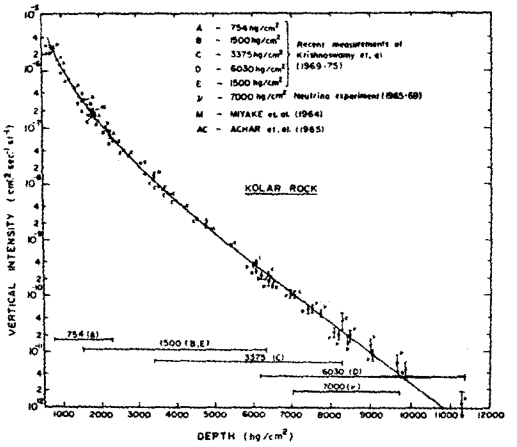

Fig. 3: The variation of intensity of penetrating particles as a function of depth, based on a variety of experiments at the Kolar Gold Fields.

decades, till 1994, was another line of activity in which pioneering contributions were made – most accurate μ-meson intensity and angular distribution measurements upto very high energies (Fig. 3), detection of neutrino induced interactions with a visual detector, limits on the lifetime of protons etc. These involved very large scale installations and also international collaborations. Extensive air shower array with a variety of detectors for different components – scintillators, Cerenkov counters, total absorption spectrometer, multiplate cloud chamber started operating in the late 50's in a the mountain station at Ooty. The time structure measurements of hadrons with the total absorption spectrometer, led to the first recognition of increased cross section for the production of nucleons and antinucleons at high energies. Bhabha, when he visited the Ooty Laboratory in 1964, was thrilled to see the world's largest multiplate cloud chamber operating there. This cloud chamber gave unique information on the highest energy jets produced by the incidence of several parallel hadrons (Fig. 4). At the Kolar Gold Fields, a second air shower array was set up at the surface of the mines with large area detectors at several depths underground that recorded the associated very high energy muons. This set-up gave very valuable information on the composition of the primaries in the crucial knee region 10^{14} –10^{16} ev.

In a short article like this it is difficult to do full justice and bring out the full flavour and ramification of all the work in cosmic rays that got initiated at the instance of Bhabha. Bhabha's was a multidimensional, many splendoured personality that influenced not only cosmic ray research, but many other fields too. But cosmic rays were very dear to him, all through his life, may be because his very first paper was on cosmic rays.

Even 86 years after the discovery of cosmic rays, 50 years after entering the second phase, despite colossal efforts by groups all over the world, not a single source of cosmic rays of high energy (> 20 Gev) has been identified even though it is firmly established that the spectrum extends beyond 10^{20} ev. The mechanism by which particles are accelerated to such high energies is also not known. The high rotating magnetic field environments of the neutron stars in pulsars in the galaxy and the extragalactic AGN (active galactic nuclei) with suspected giant black holes in their centres are thought to be

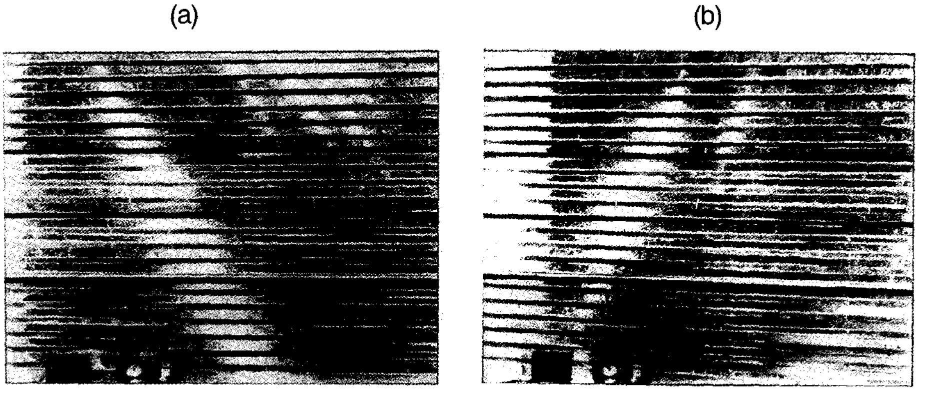

Fig. 4: Development of cascade in a multiplate cloud chamber at Ooty.
(a) A cascade having an elongated tube-like structure which is not completely absorbed even after 20 radiation lengths, the estimated energy is 2.4 TeV.
(b) A cascade which develops from the first plate of the chamber and shows a rapid absorption after the maxima. The method of cascade widths has been used for energy estimation which is 750 GeV.

the strongest candidates. Gigantic multiplex installations are coming up to settle this question. What other exotic particles there are among the primaries and what new particles are produced in super high energy collisions are other aspects which are receiving special attention in the design of next generation cosmic ray experiments.

Suggested Reading

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Bhabha Scattering

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1. Introduction

Bhabha scattering refers to his original work on electron-positron scattering which was published in the Proceedings of the Royal Society, London in 1936 [1]. Earlier, Bhabha had published several other papers on positron interaction using Dirac's hole theory. Positron is the anti-particle of electron. However, the paper titled "The Scattering of Positrons by Electrons with Exchange on Dirac's Theory of Positron" was his crowning achievement and the process now well known as Bhabha scattering. In the classical picture, electrons are considered as individual particles distinguishable from each other. However, in the quantum mechanical description, this distinguishability is lost and the effect of particle exchange on scattering needs to be considered. Mott was the first to study this exchange effect in electron-electron scattering in 1929 [2]. He showed that exchange effects play an important role in the collision process and the expression he derived is now known as Mott scattering formula. His original work was non-relativistic and there the exchange effect vanishes when the two electrons have their spins pointing in opposite directions. Later on, Moller extended Mott's work to the case of a relativistic electron and the scattering process is known as Moller scattering [3]. Moller found that the exchange effects are non-vanishing even when electron spins are anti-parallel except in the non-relativistic limit.

At that time it was not at all clear whether the exchange effect needs to be included in the case of electron-positron scattering. If a positron is regarded as an independent particle which obeys the Dirac equation, positron-electron scattering should not have any exchange effects. On the other hand, if the positron is regarded as the absence of an electron in the negative energy Dirac sea (hole), exchange effects can not be neglected. Both these approaches lead to completely different results except in the non-relativistic limit. Comparison of experimental measurements with theoretical calculations would have been best way to resolve this ambiguity. Since experimental data was not available at that time, the applicability of exchange phenomena in the case of electron-positron scattering was debatable as the result could be an artifact of an incorrect interpretation of Dirac's hole theory. Bhabha however pointed out that another way of looking at the extra exchange contribution was to regard it as due to annihilation of an electron-positron pair followed by simultaneous creation of a new electron-positron pair. Being encouraged by a recent theory of Pauli and Weisskopf [4], Bhabha proposed that the exchange term should be present in the scattering of any two particles which can annihilate each other and be created in pairs. Thus, like Moller, Bhabha obtained an expression for electron-positron scattering that contains three terms, one due to the direct process, a second one due to pair production following annihilation and third one being an interference term. Figure 1 shows the experimental measurements which became available in 1954 almost 18 years after Bhabha's theoretical predictions. Positrons from radioactive sources were directed onto thin films of mylar and differential cross sections were measured as a function of incident energy. Thus, Bhabha's theory was beautifully confirmed by experiment [5].

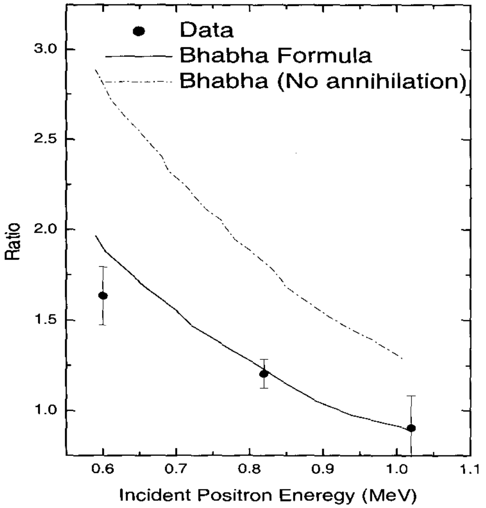

Fig.1: Experimental data for electron-positron scattering at $\theta = 90°$ as a function of the incident positron energy. The Y-axis shows the ratio of the cross section scaled down by the factor $2\pi r_0^2$ when $r_0 = e^2/mc^2$. The solid line shows the prediction of the Bhabha formula whereas the dashed line is the result one expects without any annihilation effect.

In the following sections, we will discuss Bhabha scattering in some detail. We will give a very brief introduction to the Dirac equation including Dirac's hole theory and will discuss exchange effects on both electron-electron and electron-positron scattering. Finally, we will write down the expression for both Moller and Bhabha scattering. In this article, quite often, results will be quoted avoiding derivations as far as possible while giving more emphasis on the interpretation of the physical processes.

2. Cross Section

Figure 2 shows an example of electron positron scattering in the centre of mass frame. It is simply the process in which the electron-positron approach each other and fly apart (generally in some other direction). Like any other reaction, the comparison between experiment and theory centres on the cross section. As an

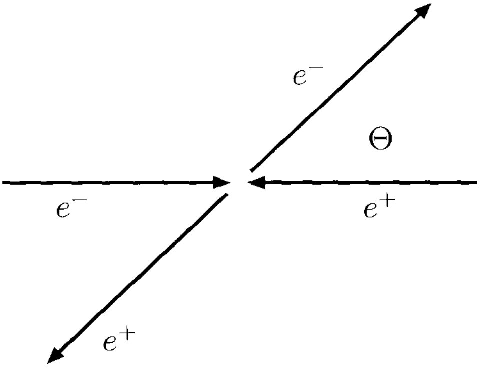

Fig.2: An electron-positron (e^- e^+) scattering reaction, viewed in the centre of mass frame of reference. Note that the z axis is conventionally taken to point along the electron's initial direction of motion so that scattering angle θ is the same as the usual polar angle in spherical coordinates.

example, we consider the reaction of the form

$$a+b \rightarrow c+d \tag{1}$$

with two particles in the initial state *i* and two in the final state *f*. If we regard a as the projectile and *b* as the target particle, then the cross section for the above reaction is defined as,

$$\sigma(\Omega)d\Omega = \frac{W}{\Phi} \tag{2}$$

where W is the number of projectile particles (electrons) scattered into the solid angle $d\Omega$ per unit time and ϕ is the incident flux or intensity. If n_a is the density of particles in the incident beam and v_i is the relative velocity of *a* and *b*, then the flux of particles per unit time through unit area normal to the beam is

$$\phi = n_a v_i \tag{3}$$

If there are n_b particles in the target per unit area, each of effective cross section σ, the probability that any incident particle will hit a target is σn_b and the number of interactions per unit area per unit second will be $v_i \rightarrow n_a n_b \sigma v_i$. The interaction rate (hence, the transition rate) per target particle is therefore,

$$W = \sigma\phi = \sigma n_a v_i \tag{4}$$

Assuming azimuthal symmetry, the solid angle $d\Omega$ can be written as

$$d\Omega = 2\pi sin\theta d\theta \tag{5}$$

where θ is the angle between the scattered and incident direction, known as the scattering angle. It will be noted here that the term cross section originates for the fact that σ has the dimension of area which is expressed in units of barn (1 $barn = 10^{-24}\ cm^2$). In case of collider experiments, both particles *a* and *b* (electron and positron for example) move in opposite directions and are made to cross each other at fixed interaction points. An useful measure of the collider performance is the luminosity *L*. The reaction rate *R* (same as *W*) is given in terms of *L* by

$$R = L\sigma \tag{6}$$

where the luminosity has the same dimension as that of the flux. If the two bunches of *N* particles are circulating in the machine with frequency *f*, the luminosity at the interaction point is

$$L = \frac{N^2 f}{A} \tag{7}$$

where *A* is the effective cross sectional area of the beam overlap. The correct determination of luminosity is an important aspect of any collider experiments as the production cross section of any new particle depends on the luminosity *L*. Therefore, the theoretical estimate of σ of the reaction which has been well understood like the Bhabha scattering is used to calculate *L* by measuring the reaction rate.

A classical example of Coulomb scattering is the famous Rutherford scattering which was derived by Rutherford in connection with the scattering of alpha particles by the atomic nuclei. Since this topic can be found in many text books, we just quote the final result,

$$\sigma(\theta) = \frac{1}{4}\left(\frac{Z_1 Z_2 \alpha}{2E}\right)^2 \frac{1}{\sin^4\theta/2} \tag{8}$$

where Z_1 and Z_2 are the atomic number of projectile and target respectively and the repulsive Coulomb force is given by

$$F = \frac{Z_1 Z_2 e^2}{4\pi r^2} = \frac{Z_1 Z_2 \alpha}{r^2} \tag{9}$$

The total cross section can be obtained by integrating the above equation over all the angles θ. However, such an attempt will result in a divergent integral. The reason for this divergence is the long range nature of the Coulomb interaction. The small deflections occur for particles with large impact parameters. Only if the force field is cut-off beyond a certain distance, the scattering cross section will be finite. Physically, such a cut-off occurs for the Coulomb field of a nucleus as the result of the presence of atomic electrons which screen the nucleus. Thus the divergence can be avoided by using a screened Coulomb potential.

The above result was derived classically. The same result can be obtained by using non-relativistic quantum mechanics. However, in quantum mechanics, it is convenient to use the formula for *W* in terms of transition amplitude given by

$$W = \frac{2\pi}{\hbar}\left|M_{if}\right|^2 \rho_f \tag{10}$$

where M_{if} is the transition amplitude from the state *i* to state *f* and ρ is related to the density of final state *f*. The above relation is also known as Fermi's Golden Rule and can be found in many text books on quantum mechanics.

3. Basic Features of Dirac Equation

The Schrodinger equation can be derived by starting with the classical energy-momentum relation,

$$\frac{p^2}{2m}+V=E \tag{11}$$

and applying the quantum prescription

$$p \rightarrow -i\hbar\nabla, \quad E \rightarrow i\hbar\frac{\partial}{\partial t} \tag{12}$$

and letting the resulting operator act on the wave function ψ, we get the famous Schrodinger equation

$$-\frac{\hbar^2}{2m}\nabla^2\Psi+V\Psi=i\hbar\frac{\partial\Psi}{dt} \tag{13}$$

For a free particle, the stationary solution,

$$\Psi=Ae^{-\frac{i}{\hbar}\boldsymbol{p}.\boldsymbol{r}} \tag{14}$$

satisfies the above equation. Note that (14) represents a plane wave solution and **p** = ħ**k** is the momentum vector of propagation. In quantum mechanics, the modulus of the amplitude $|\psi|^2 = |A|^2$ is interpreted as the probability of finding the particle at the point (x, y, z).

The Schrodinger equation being non-relativistic cannot describe the properties of elementary particles when their velocity is large. Dirac proposed a relativistic wave equation in 1928 consistent with the energy momentum relation $E^2 = p^2c^2 + m^2c^4$. The original argument of Dirac in search of a relativistic equation was it must be a first order differential equation both in time and space coordinates as in relativity both time and space are treated symmetrically as the components of the position four vector. He wrote down a wave equation,

$$i\hbar\frac{\partial\Psi}{\partial t}=\frac{c\hbar}{i}(k.\nabla)+k_0mc^2\Psi \tag{15}$$

where **k** and k_0 are four dimensional square matrices (The Dirac γ matrices are related to **k** and k_0). It follows that the wave equation ψ should also have four components $\psi = (\psi_1, \psi_2, \psi_3, \psi_4)$ to be consistent with the above equation which now describes the particle with additional degrees of freedom (intrinsic spin of the particle). The plane wave solution of Dirac equation has the form

$$\Psi(r,t) = Ae^{-\frac{i}{\hbar}(Et-\boldsymbol{p}.\boldsymbol{r})}u(E,\boldsymbol{p}) \tag{16}$$

The above solution has a space-time part, which is same as the free particle solution of Schrodinger wave equation (13) and a four component wave function u (E, **p**) = (u_1, u_2, u_3, u_4) where u_i's are known as Dirac spinors. The above Dirac equation (15) admits two solutions for energy (proof not given)

$$E = \pm\sqrt{m^2c^4 + p^2c^2} \tag{17}$$

The positive root is associated with particle state and the negative root with anti-particle state. Thus if u_1 and u_2 are the spinors for electrons with energy *E* and momentum **p**, u_3 and u_4 are the spinors for positrons with energy -*E* and momentum -**p**. Alternatively, if we assign positive energy and momentum to positron (say v_1 and v_2), they will also satisfy the Dirac equation.

The Dirac equation had remarkable success in explaining the spin and magnetic moment of electron in natural way. However, the puzzling feature of the Dirac equation was the prediction of negative energy states for electrons. Later on in 1930, Dirac proposed that all the negative energy states are filled in accordance with the Pauli exclusion principle. He postulated that all the negative energy states are occupied and regarded the vacuum as an infinite sea of $E < 0$ electrons. Now, the positive energy electrons cannot collapse into the lower (negative) energy levels as this is prevented by the exclusion principle. One can however create a hole in the sea by excitation of an electron from a negative energy ($E < 0$) state to a positive energy state ($E>0$). The absence of an electron of charge -*e* and energy -*E* is interpreted as the presence of an antiparticle (positron) of charge e and energy +*E*. Thus, the net effect of this excitation is the production of a pair of particles $e^- + e^+$ which clearly requires energy $E \geq 2mc^2$. Later on in 1932, C. D. Anderson discovered a positively charged particle with the same mass as the electron which is now referred to as the positron. Until 1934, the Dirac equation was considered to be the only acceptable relativistic wave equation. In 1934, Pauli and Weisskopf revived the Klein-Gordon equation by inserting the charge -*e* into j^μ and interpreting it as the charge current density of the electron. Now that $\rho = j^0$ represents the charge density and not a probability density, having negative value was no longer objectionable and the $E < 0$ solution was regarded as an $E > 0$ solution of particles of opposite charge (antiparticles). Unlike hole theory, this interpretation is applicable to bosons as well as to fermions.

4. Coulomb Scattering of Electron by Nuclei

We have written down the Schrodinger and Dirac equations and the nature of the plane wave solutions. Let us now proceed to estimate the scattering cross section of an electron (positron) from an atomic nucleus. Since the nucleus is heavy, there will not be any recoil effect. Therefore,

$$E_i = E_f \quad |p_i| = |p_f| = p \tag{18}$$

The transition probability from the initial state i to the final state *f* can be written as [6]

$$M_{if} = C\int d^3r \Psi^*_f V(r) \Psi_i \tag{19}$$

where ψ_i and ψ_f describe the initial and final wave functions of the scattered electron and C is a constant given by $C = -m/(2\pi\hbar^2)$. In the plane wave approximation for both ψ_i and ψ_f

$$\Psi^*_f \quad \Psi_i = e^{-\frac{i}{\hbar}(\boldsymbol{p}_f - \boldsymbol{p}_i).r} = e^{-\frac{i}{\hbar}q.r} \tag{20}$$

where $\boldsymbol{q} = (\boldsymbol{p}_f - \boldsymbol{p}_i)$ is the momentum transfer. Substituting the above equation in (19) and using V(r) = ($Z\alpha$ /r), the transition probability can be written as

$$M_{if} = \frac{mZ\alpha}{|q|^2\hbar^2} \tag{21}$$

where we have used

$$\int \frac{e^{\frac{-i}{\hbar}(q.r)}}{r} d^3r = \frac{4\pi}{|q|^2} \tag{22}$$

as the Fourier transform of the potential V(r) in momentum space. Since the recoil energy of the nucleus can be neglected.

$$|q|^2 = 2p^2(1-\cos\theta) = 4p^2\sin^2\theta/2 \tag{23}$$

Finally, we can write

$$\frac{d\sigma}{d\Omega} = |M_{if}|^2 = \left(\frac{Zm\alpha}{|q|^2}\right)^2 = \left(\frac{Zm\alpha}{4p^2\sin^2\theta/2}\right)^2 \tag{24}$$

Using $p^2 = 2mE$, we get

$$\frac{d\sigma}{d\Omega} = \frac{1}{16} \frac{Z^2\alpha^2}{E^2 \sin^4\theta / 2} \tag{25}$$

which is the same as the classical formula for Rutherford scattering. Note that in the above derivation we have used ψ as the solution of Schrodinger equation (14). Now we will follow the similar procedure to derive $d\sigma/d\Omega$ for the relativistic electron using Dirac wave functions. Accordingly, the transition matrix is given by [7]

$$M_{if} = -ie\int d^4x \Psi(x_f)\gamma^{\mu} A_{\mu} \Psi_i(x) \tag{26}$$

Note that (19) and (26) look similar except for the fact that it is written in the covariant form. Instead of d^3r, now the integration is carried out over four dimensional volume d^4x ($d^4x = dt\, dx\, dy\, dz$). The interaction potential $V(r)$ has been replaced with a covariant field $\gamma^{\mu}A_{\mu}$ [8] whose zero[th] component is $-\gamma^0 Ze/(4\pi r)$. Similarly, instead of the Schrodinger wave function, we now have the Dirac wave function given by,

$$\Psi(r,t) = Ae^{-\frac{i}{\hbar}(Et - \boldsymbol{p}.\boldsymbol{r})} u(E, \boldsymbol{p}) \tag{27}$$

where the normalisation factor $A = \sqrt{(m/E)}$.

The scattering cross section will be obtained from the relation

$$\int |M_{if}|^2 \frac{d^3 p_f}{(2\pi)^3} \tag{28}$$

where the integration is carried out over the final state phase space volume $d^3p_f/(2\pi)^3$. The details of the integration will be omitted here and the final expression is

$$\frac{d\sigma}{d\Omega} = \frac{4Z^2\alpha^2 m^2}{|q|^4} |\bar{u}(p_f)\gamma^0 u(p_i)|^2 \tag{29}$$

We will now make a comparison between (24) and (29). Notice that both the equations have a term proportional to $|q|^{-4}$ due to the integral of the type

$$\int \frac{e^{\frac{-i}{\hbar}(q.r)}}{r} d^3r = \frac{4\pi}{|q|^2} \tag{30}$$

However, (29) has an extra factor $|F|^2=|u^{\cdot}(p_f)\gamma^0 u(p_i)|^2$ of Dirac spinors which is absent in (24). The matrix element $|F|^2$ is purely algebraic and needs to be evaluated taking an average over all spin orientations. This is a lengthy calculation involving matrix algebra which can be carried out using Casimir's trick and the trace theorem. The details of the calculation are not illuminating for the present purpose. We again quote the final result for $|F|^2$ as

$$\frac{1}{m^2}(1-\beta^2\sin^2\theta/2) \quad (31)$$

which gives the relativistic expression for the scattering cross section,

$$\frac{d\sigma}{d\Omega}=\frac{Z^2\alpha^2}{4p^2\beta^2\sin^4\theta/2}(1-\beta^2\sin^2\theta/2) \quad (32)$$

where $\beta = \mathbf{v}/c$. The above expression reduces to the Rutherford cross section for $\beta \to 0$ ($p^2\beta^2 = 2mE\mathbf{v}^2 = 4E^2$),

$$\frac{d\sigma}{d\Omega}=\frac{Z^2\alpha^2}{16E^2\sin^4\theta/2} \quad (33)$$

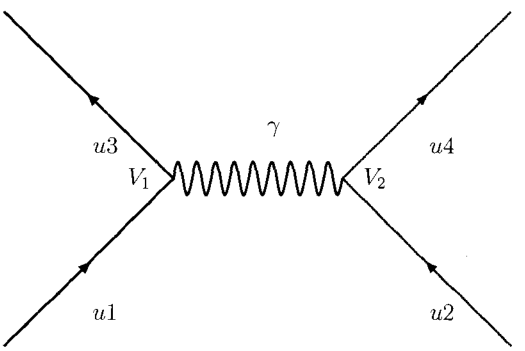

Fig. 3: The Feynman diagram for electron-electron scattering. A direct process.

5. Moller Scattering

So far we have considered the scattering of an electron by a heavy target so the target recoil energy can be neglected. Therefore the matrix element $|F|^2$ contains only the electron spinors (only for projectile) corresponding to the initial and final state scattering. If we need to extend the calculations to the case of electron-electron scattering, we need to consider the recoil of target electron as well. So, $|F|^2$ will now have the contributions from the target electron as well (see Figure 2). As a generalization of (29), we can now write down an expression for electron-electron scattering [7]

$$\frac{d\sigma}{d\Omega} = \frac{m^2 e^2}{4E^2(2\pi)^2} |F_1|^2 \tag{34}$$

where

$$F_1 = \frac{\left[\bar{u}_3 \gamma^{\mu} u_1\right]\left[\bar{u}_4 \gamma_{\mu} u_2\right]}{(p_1 - p_3)^2} \tag{35}$$

Figure 3 shows the pictorial representation of electron-positron scattering invented by Richard Feynman in the late 1940s. Each straight line in the diagram represents an electron (particle) if the arrow points up or positron (antiparticle) if the arrow points down. Also the diagram at the bottom represents electrons (positrons) in the initial states while the top portion of the diagrams corresponds to the final state. The wavy line represents a photon which, in this case, is a virtual particle since it appears as an intermediate quantum mechanical state but is not observed. Electron u_1 emits a photon that is absorbed by electron u_2. Emission by electron u_2 and absorption by electron u_1 is equally likely as demanded by symmetry. Since the photon cannot be observed, it is virtual. Virtual processes are allowed by the Heisenberg uncertainty principle which states that an observation to measure the energy of a system to within ΔE requires at least a time $\Delta t \geq \hbar / \Delta E$. Hence if a particle with total energy E lives only for a time t, we will not be able to observe it if $tE \leq \hbar$. This relation can also be used to estimate the range R of an interaction produced by field quanta of mass m. The quanta propagate up to a distance $R = ct$. If the minimum energy required to produce a particle of mass m is $E \approx mc^2$, the range R is given by $R \approx \hbar /(mc)$, the Compton wavelength of the particle of mass m.

With the help of above diagram (Figure 3), it is now easier to understand the matrix element as given above. The spinors u_1 and u_2 correspond to the electrons in the initial states with momentum four vector p_1 and p_2 respectively. After scattering (due to absorption or emission of photon) their energy and momentum change. The final state is represented by the spinors u_3 and u_4 with momentum four vectors p_3 and p_4 respectively. Therefore, the matrix element F_1 contains term like $\left[\bar{u}_3 \gamma^{\mu} u_1\right]$ for first vertex (V_1) and $\left[\bar{u}_4 \gamma_{\mu} u_2\right]$ for second vertex (V_2) . The denominator contains the term $(p_1 - p_3)^2$ which is the square of the four momentum transfer of one of the electron due to scattering. It may be mentioned here that Figure 3 represents a scenario which is known as direct process. There is a diagram of second type as shown in Figure 4 which also contributes to the electron-electron scattering process. This we will term as exchange process which arises due to the indistinguishable nature of the electrons. Putting it in another way, if we are detecting a scattered electron at an angle $d\Omega$, it is imposible to say which of the two electrons enter the detector. This indistinguishability leads to an important effect which is best discussed by examining what happens to the wave function of an assembly of identical quantum particles. Consider a set of N identical particles. Denote their position coordinates by q_1, q_2, ...q_N and spin coordinates by σ_1, σ_2, ...σ_N.

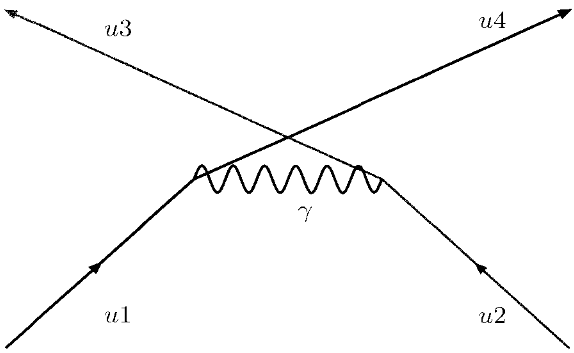

Fig. 4: The Feynman diagram for electron-electron scattering. An exchange process.

Let $\psi\,(q_1, q_2, q_i, ...q_N, \sigma_1, \sigma_2, \sigma_j, ...\sigma_N)$ denotes the N particles wave function. Now let us swap both the position and spin coordinates between any two particles and call the wave function $\psi'(q_1, q_2, q_j, ...q_N, \sigma_1, \sigma_2, \sigma_i, ...\sigma_N)$. The question is how these two wave functions are related under two particle exchange. If the particles are Bosons (have integral spins), the wave functions are said to be symmetric and we have $\psi = \psi'$. In case of Fermions (having half integral spin), the wave functions are said to be anti-symmetric for which $\psi = -\psi'$. Aapplying this principle to electron-electron scattering, we will now require a second term with a negative amplitude F_2 given by

$$F_2 = -\frac{\left[\bar{u}_4\gamma^{\mu}u_1\right]\left[\bar{u}_3\gamma_{\mu}u_2\right]}{(p_1 - p_4)^2} \qquad (36)$$

The total scattering cross section should now be expressed as

$$\frac{d\sigma}{d\Omega} = \frac{m^2e^2}{4E^2(2\pi)^2}\left|F_1 + F_2\right|^2 \qquad (37)$$

which for ultra-relativistic particle *(m/E*$\rightarrow$ 0) becomes

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2}\left(\frac{1}{\sin^4\theta/2} + \frac{1}{\cos^4\theta/2} - 1\right) \qquad (38)$$

This is known as Moller scattering. Notice that the first term is due to a direct process, the second term is due to the exchange process and the third one is the interference term.

6. Bhabha Scattering

Bhabha studied the electron-positron scattering using Dirac's interpretation of positron which is an unoccupied electron in the negative energy Dirac sea. Bhabha gave the beautiful explanation, which we quote here, "The physical process we are considering is the following. Initially we have an electron in a state a_+^0 of positive energy and a positron of b_+^0, also of positive energy. After the scattering process the electron is to be found in a state a_+' and the positron in a state b_+'. On the Dirac theory of the positron the process is considered in the following way. The two states of the positron b_+^0 and b_+' correspond to two unoccupied states of negative energy which we call a_-' and a_-^0 respectively. We then have, initially, an electron, which we shall denote by the suffix 1, in the state a_+^0, another electron, which we shall denote by the suffix 2, in the state of negative energy a_-^0 and an unoccupied state of negative energy a_-' representing the positron. After the scattering, the electron 1 goes to the final state a_+' and the electron 2 jumps into the unoccupied state a_-' leaving the state a_-^0 unoccupied which then appears as the scattered positron. This is the normal scattering process. The effect of exchange arises in this, that we should get into the same physically observable final state if the electron 1 jumped into the unoccupied state a_-' and the electron 2 jumped into the final state a_+'. But we may clearly consider this process as one in which the original electron and the positron have annihilated one another with the simultaneous creation of a new pair. It appears then that we should expect extra term in the mutual scattering of any two particles that can be an annihilated and created in pairs."

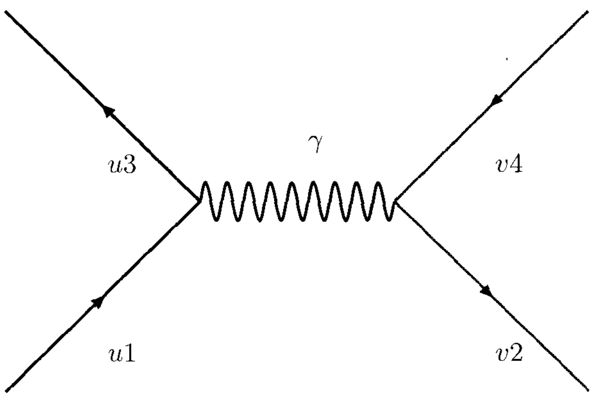

Fig. 5: The Feynman diagram for electron-positron scattering. u and v are the spinors for electron and positron respectively. This corresponds to a direct process.

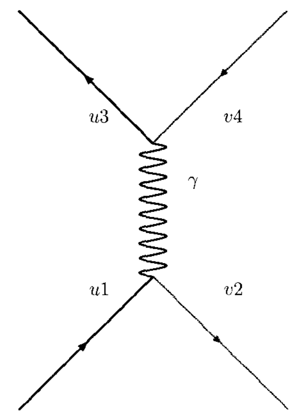

Fig. 6: The Feynman diagram for electron-positron annihilation.

The above process is now easier to understand using Feynman diagrams. Figure 5 shows the Feynman diagram of an electron-positron scattering what is known as the direct process. Note that the up arrow represents an electron where as the down arrow represents a positron. This diagram is very much similar to the diagram of Figure 3 except that u_2

and u_4 need to be replaced by v_2 and v_4 which are the spinors for positrons. Accordingly, the matrix element F_1 can be written as

$$F_1 = \frac{\left[\bar{u}_3\gamma^{\mu}u_1\right]\left[\bar{v}_2\gamma_{\mu}v_4\right]}{(p_1 - p_3)^2} \qquad (39)$$

Now the question arises: as in the case of the electron, should there also be an exchange term for the case of positron scattering. The positron is different from the electron, after all, as it has positive electric charge. Therefore, there should not be any exchange effect in case of electron-positron scattering. On the other hand, if one invokes Dirac's interpretation i.e. positron is a negative energy state of an electron, then the exchange effect cannot be ignored. To resolve this anomaly, Bhabha looked at this process in a different way by arguing that electron and positron can annihilate giving rise to a virtual photon which undergoes pair production. Thus, the electron and positron re-appear as a pair of newly created electron and positron. This process is shown in Figure 6. Therefore, as in electron-electron scattering, there should also be an anti-symmetric exchange term which will look like

$$F_2 = -\frac{\left[\bar{u}_3\gamma^{\mu}v_4\right]\left[\bar{v}_2\gamma_{\mu}u_1\right]}{(p_1 + p_2)^2} \qquad (40)$$

As before, the cross section needs to be evaluated by adding the amplitudes $|F_1 + F_2|^2$. The final result will be (under ultra-relativistic assumption $m/E \to 0$).

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8E^2}\left(\frac{1+\cos^4\theta/2}{\sin^4\theta/2} + \frac{1+\cos^2\theta/2}{2} - \frac{2\cos^4\theta/2}{\sin^4\theta/2}\right) \qquad (41)$$

In the above, the first term is the ordinary scattering term. We would have got this term if we had considered the positron as an independent positively charged particle in the state of positive energy. The other two terms represent the effect of exchange. More precisely, the second term is due to annihilation and the third term is due to the interference of these two processes.

7. Summary

The exchange effect in Moller scattering was easy to interpret as the electrons are indistinguishable from each other. However, in case of electron-positron scattering, interpretation of exchange effects on the basis of Dirac's hole theory was somewhat ambiguous as electrons and positrons are non-identical particles. Now we know, any particle-antiparticle pair will contribute to the extra effect irrespective of whether the particles are fermions or bosons. Therefore, Bhabha's way of looking at the exchange effect through the annihilation and simultaneous pair production was indeed remarkable. In modern field theoretical terminology, Bhabha carried out calculations to the lowest order of perturbation theory and deliberatively ignored the radiative corrections. His primary motivation was to bring out the important role of the exchange effect on electron-positron scattering. In recent times, the work of Bhabha has been extended to include the radiative corrections. These calculations agree very well with experimental data obtained from electron-positron collider experiments. In fact, Bhabha scattering is used to measure, routinely, the luminosity in electron-positron collider beam experiments.

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[8] γ^μ stands for the Dirac matrices , the index μ has four values $\mu = 0, 1, 2, 3$. Similarly the field A_μ also has four components.

Bhabha-Heitler Theory of Cosmic Ray Air Shower

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1. Introduction

Cosmic ray air shower or extensive air shower is a very important phenomenon in cosmic ray physics and γ-ray astronomy. It is the backbone of ground based detection of cosmic rays and γ-rays. It is necessary to study the properties of cosmic ray shower to identify cosmic ray particles and γ-photons coming from the outer space using ground based detectors. It was Homi Bhabha and W. Heitler who first introduced the concept of cosmic ray air shower and studied the properties of air shower theoretically in their paper in 1937 [1]. After a brief introduction to cosmic rays and cosmic ray air shower, the work of Bhabha and Heitler will be discussed.

2. Cosmic ray

Discovery

Cosmic rays are the energetic charged particles and electromagnetic radiation of cosmic origin. In the year 1900, Henri Becquerel discovered radioactivity in France. He observed that certain elements transform into other elements by emitting "particles" which he called "radiation". Immediately after his discovery physicists noticed that the electroscopes discharge in presence of radioactive material and the rate of discharge was a measure of the intensity of radiation from the radioactive material. Later it was observed that electroscopes discharge even in absence of any radioactive material and it can not be accounted for just by the leakage of charge. This essentially led to the idea that some background radiation was responsible for the discharge of the electroscope. In 1912, Victor F Hess carried out manned balloon experiments to measure the background radiation levels at different altitudes in the Earth's atmosphere with the expectation that the background radiation should decrease if it were due to the earth. He went up to an altitude of 16500 feet with his instrument and found that the radiation level increased with the altitude. This led to the conclusion that the background radiation is coming from the outer space and the background radiation was named as *cosmic radiation* by Robert Millikan. In 1928 Clay observed the *latitude effect* of cosmic rays. The cosmic ray intensity on the

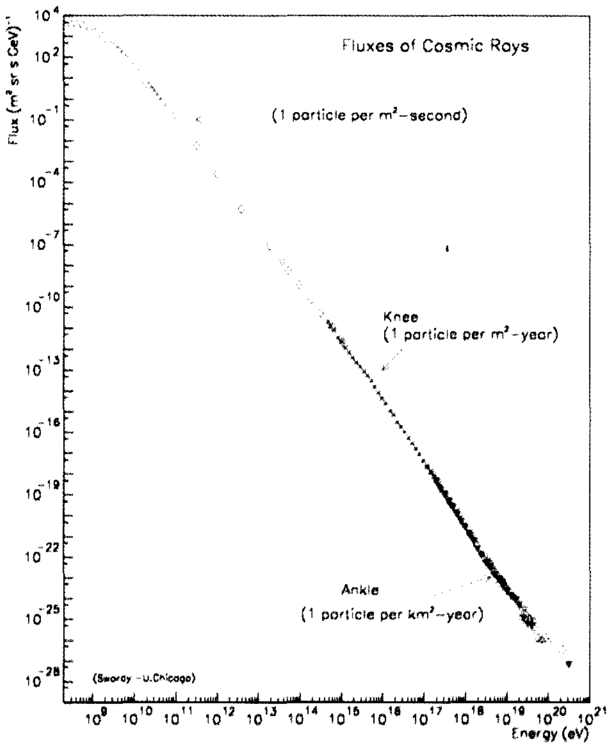

Fig. 1: Observed cosmic ray spectrum. The green line indicates the power-law spectrum with spectral index 2.7. Reproduced from http://astroparticle. uchicago.edu/cosmic_ray_ spectrum_ picture.htm

earth depends on the geomagnetic latitude. This can be understood if the cosmic particles are *charged.*

Victor Hess was awarded the Nobel Prize in 1936. Since its discovery in 1912 physicists made several attempts to understand the nature and properties of cosmic radiation through different balloon, satellite and ground-based experiments. In the following we will discuss the experimentally observed properties of cosmic rays.

Cosmic ray spectrum

Cosmic rays have two main components - *(i) primary cosmic rays* and *(ii) secondary cosmic rays.* Primary cosmic rays which are produced in astrophysical sources, consist of protons, alpha particles, heavy nuclei, electrons and gamma-rays. The fractional contributions of alpha particles, heavy nuclei, electrons and photons are very low compared to the protons.

The secondary component of cosmic rays is produced by the interaction of primary cosmic rays with the interstellar matter as well as the Earth's atmosphere. It consists of pions, kaons, muons, electrons, positrons and neutrinos. It also contains UV-optical photons produced in Cherenkov and fluorescence processes, and radio emission by electrons and positrons in the geomagnetic field. The secondary component produced in the Earth's atmosphere can be measured at mountain altitude or at sea level.

The all-particle (excluding the photons and neutrino) spectrum for primary cosmic rays is shown in Figure 1. The spectrum can be represented by a power-law, i.e. the number of particles within the energy E and $E + dE$ is given by

$$N(E)dE = N_0\, E^{-\alpha}\, dE \qquad (1)$$

where N_0 and α are the normalization and spectral index respectively. The observed spectrum extends over the energy range 10^6 eV to 3 $\times 10^{20}$ eV. Due to the solar modulation the cosmic ray spectrum shows a turn over below 10^8 eV. Below the particle energy 5 $\times 10^{15}$ eV, the spectral index is 2.7. At 5 $\times 10^{15}$ eV spectrum shows a break with a change in spectral index from 2.7 to 3.1. This is known as the *knee*. The spectral slope changes again from 3.1 to 2.7 at 3 $\times 10^{18}$ eV and the spectrum turns up. The second spectral break at 3 $\times 10^{18}$ eV is known as the *ankle*.

It is generally believed that the cosmic rays up to the ankle originate in our galaxy whereas the particles above the ankle energy are of extragalactic origin. But the origin of the spectral breaks at the knee and ankle are unclear. For particles above the ankle energy the argument is as follows. The Larmor radius of a charged particle of charge Ze and energy E (>3 $\times 10^{18}$ eV) in the galactic magnetic field (~ 1μG) is given by

$$R_L = 300\left(\frac{1\mu G}{B}\right)\left(\frac{E}{10^{18}\, Z\, eV}\right) pc \qquad (2)$$

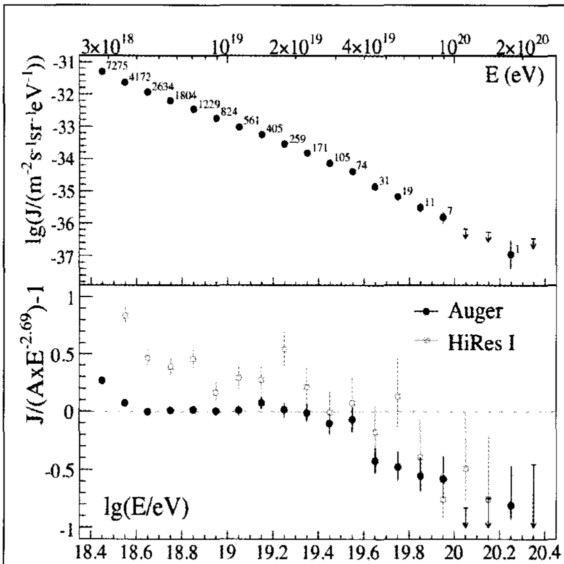

Fig. 2: The observed cosmic ray spectrum with ground based arrays HiRes and Auger in the energy range 10^{18}-10^{20} eV. The spectrum shows the spectral steepening above 2×10^{19} eV indicating GZK cut-off. Reproduced from [6]

where *pc* is the astronomical unit of distance and equals 3.26 light years which is 3 $\times 10^{18}$ cm. Therefore for protons ( ) with energy higher than 3 $\times 10^{18}$ eV, the Larmor radius is higher than the galactic dimension (~ 300 pc). This makes it difficult to confine energetic protons within the galaxy and the particles will leak through our galaxy. This makes it natural for particles above the ankle energy to be of extragalactic origin.

Another important feature of cosmic ray spectrum is the Greisen-Zatsepin-Kuzmin (GZK) cut-off. Immediately after the discovery of 2.7K cosmic microwave background (CMB) radiation in 1960s, Greisen [2] and Zatsepin and Kuzmin [3] independently pointed out that the cosmic ray particles above 5 $\times 10^{19}$ eV, if they are protons, would interact with the CMB photons and produce pions. By this process protons will lose most of their energy and the cosmic ray spectrum is expected to have an exponential cut-off around 5 $\times 10^{19}$ eV and it is known as GZK cut-off. Recent observations by HiRes [4] and Pierre Auger observatory [5] confirm the presence of the GZK cut-off (Figure 2).

3. Origin of cosmic rays

The possible sources of cosmic rays, where charge particles are produced and accelerated, are still not known. It has already been mentioned that cosmic rays are produced both in galactic and extragalactic sources. Some possible sources are discussed in the literature.

The most prominent candidates as sources of cosmic rays in our galaxy are supernova remnants. Stars with mass higher than $10M_{\odot}$ (mass of the sun, $M_{\odot} \sim 10^{33} gm$) explode at the end of their evolutionary phase throwing matter at very high speed into the interstellar medium. Such an explosion releases energy $\sim 10^{51}$ *erg* and most of the energy is available in the shock waves produced in the interstellar medium. Using the following order-of-magnitude estimates one can conclude that the energy available in a supernova explosion is sufficient to energies galactic component of cosmic rays.

The observed energy density of the cosmic rays in the galaxy is

$$\rho_{CR} \approx 1 \ eV/cm^3 \tag{3}$$

Approximating the galactic disc to a cylinder of radius *R=15 kpc* and height *h=300 pc*, we obtain an estimate of the volume of the galaxy,

$$V_D = \pi R^2 h = 4 \times 10^{66} \ cm^3 \tag{4}$$

Therefore, the luminosity of cosmic rays is

$$L_{CR} \approx \frac{\rho_{CR} V_D}{\tau_{esc}} \approx 5 \times 10^{40} \ ergs/s \tag{5}$$

where it is assumed that the escape time scale for cosmic rays from the galactic disc is $\tau_{esc} \sim 10^6 \ yr$. Rate of supernova explosions in a typical galaxy as ours is approximately once in 30 yrs. Therefore the luminosity of the available kinetic energy in the supernova explosion $L_{SN,KIN} \sim 3 \times 10^{42} \ erg/s$. Comparing this value with L_{CR} , it is very clear that if one percent of the luminosity of the supernova goes into cosmic rays, then one can explain the cosmic ray luminosity. This energy estimate makes the supernova remnants a powerful source of cosmic rays.

Among other galactic sources, pulsars and galactic micro-quasars may also act as possible sites for cosmic ray production and acceleration. Active galaxies with powerful radio jets and gamma-ray bursts are the possible extragalactic sources of high energy cosmic rays above the ankle in the cosmic ray spectrum.

4. Cosmic ray air shower

When cosmic rays hit the earth's atmosphere, they interact with the atmospheric nuclei. The nature of the first interaction depends on the kind of cosmic ray particle interacting. This interaction produces secondary particles which, in turn, interact with the atmosphere and produce more particles and photons and thereby produce a cascade known as cosmic ray air shower. If the first interaction between the cosmic ray and the atmospheric nuclei is electromagnetic, the cascade generated is known as *electromagnetic cascade*. If the incident cosmic ray interacts with the atmospheric nuclei through strong interactions then the cascade is known as a *hadronic cascade*.

Electromagnetic cascade

If a very high energy (~ 10^{12} eV) γ-ray hits the atmosphere, the first interaction that takes place with the atmospheric nuclei is pair production. This produces an electron-positron pair. Electron and positron both interact with the atmosphere to produce bremsstrahlung radiation. If the bremsstrahlung photons are sufficiently energetic (> 1.022 MeV) then they again produce electron-positron pairs which in turn will produce bremsstrahlung radiation and so on. Thus a cascade of electrons, positrons and photons will be produced in the atmosphere. This process will continue till the radiative losses of electrons and positrons dominate over ionization losses and the photons continue to produce electron-positron pairs. Thus the shower reaches its maximum development at a depth X_{max} (say) from where the ionization loss of electrons and positrons start dominating. It can be shown that

$$X_{max} \propto \ln E_0 \tag{6}$$

where E_0 is the energy of the initial γ-ray. It can also be shown that the number of electrons and positrons produced in the shower at the shower maximum is

$$N(X_{max}) \propto E_0 \tag{7}$$

The γ-ray induced shower is schematically shown in Figure 3(a). It is to be noted that the electrons and positrons in the cascade also produce Cherenkov photons in the air shower which is of immense importance in γ-ray astronomy. Similar electromagnetic showers will develop if the initial particle is an electron, positron or muon. The only difference is that in such cases the first interaction will take place through the bremsstrahlung process.

Hadronic cascade

When hadrons, which are mostly protons in cosmic rays, hit the atmosphere and undergo nuclear interactions, the interaction produces further hadrons and other nuclei. These new particles interact again with the atmospheric nuclei and so on. These processes produce a cascade of hadrons and fragments of atmospheric nuclei. Among hadrons in the cascade there will be neutral and charged pions ($\pi^0, \pi^\pm$). Each neutral pion decays into two γ-photons ($\pi^0 \rightarrow 2\gamma$) and these γ-photons initiates electromagnetic showers in the atmosphere. On the other hand charged pions and muons ($\mu^\pm$) undergo the following decay processes,

$$\begin{aligned} \pi^\pm &\longrightarrow \mu^\pm + \nu_\mu \\ \mu^\pm &\longrightarrow e^\pm + \nu_e + \nu_\mu \end{aligned} \tag{8}$$

where ν_μ and ν_e are muon and electron neutrinos respectively. The γ-photons produced in the decay of neutral pions, lectrons and positrons initiate electro-magnetic showers in the atmosphere. Thus a hadronic cascade becomes a combination of many mini electromagnetic cascade, fragmented nuclei and neutrinos. The hadronic cascade is schematically shown in Figure 3(b). Due to the large transverse momentum of the particles produced in strong interactions the lateral spread of particles in the hadron initiated shower is much higher than that in the electromagnetic shower.

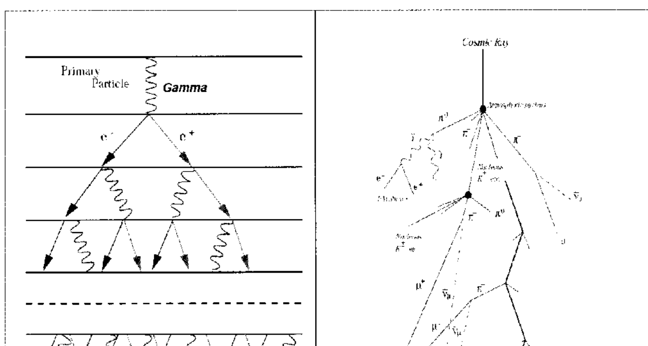

Fig. 3: Cosmic ray air shower: (a) Electromagnetic cascade, (b) Hadronic cascade.

Air showers are fundamentally very important in the context of ground based observation of cosmic rays and very high energy gamma-ray astronomy. Apparently it looks like that the primary particle is completely lost in the air shower. But each shower actually carries the signature of the primary particle which interacted with the atmosphere. The photon and particle yield in the air shower and their energy distribution depend entirely on the energy of the primary particle and the nature of the first interaction taking place in the atmosphere. Even the lateral distribution of particles in the shower depends on the progenitor type. Another important feature is the location of the shower maximum X_{max}. For the same energy of the progenitor particle, the location of the shower maximum depends on the mass of the particle. For example, for the same initial energy E_O, the shower maximum for the proton will have a much higher value compared to the shower maximum for a nuclei of mass number A, although the total number of particle produced at the shower maximum in both cases are the same. Therefore, if one has the estimates of different physical quantities of the air shower, then from the measurements of secondary particles and photons produced in the air shower one can trace back the progenitor particle.

Cosmic ray air showers were first observed independently by Bruno Rossi [7] and Pierre Auger [8] in 1934 and 1938 respectively. It was Bhabha and Heitler [1] who first gave the theory of cosmic showers for electromagnetic cascade in the atmosphere in 1937. They first analytically estimated the average number particles produced in the electromagnetic cascade, the fluctuations and the angular spread of air shower. In the following section we discuss the Bhabha-Heitler theory very briefly.

5. Bhabha-Heitler Theory

According to the relativistic quantum mechanics, as it was shown by Bethe and Heitler [9], relativistic electrons or positrons with energy much higher than their rest mass energy would lose a large fraction of their energy in the field of a nucleus. This is due to the large cross-section estimated for this process. Therefore, if a highly energetic electron with energy greater than $10^{12}\ eV$ enters the atmosphere then according to the theoretical estimates, the electron would lose all its energy very quickly and would have a range 2 km in the atmosphere. But the experiments by Regener [10] on cosmic rays in 1934 showed the presence of high energy electrons with energy higher than at the sea-level. This implies that the electron travelled a path of approximately 8 km through the atmosphere. This result led to a doubt on the theoretical estimates of the cross-section using relativistic quantum mechanics and it was thought that the quantum electrodynamics breaks down at very high particle energy.

Bhabha and Heitler [1] argued that the fast electron indeed lose all its energy in the very first collisions as it was predicted by theoretical estimates of quantum electrodynamics. But the energy goes into a very high energy photons with energy comparable to that of the initial electron. This high energy photon then produces electron-positron pair in the medium where each particle has half the energy of the photon. These particles further produce high energy photons by interacting with the atmospheric nuclei which in turn will produce electron-positron pair and so on. This essentially produces a shower of electrons, positrons and photons in the atmosphere. These particles indeed were detected at the sea-level. In each step of photon and pair production in the air shower the products will be almost aligned to the direction of initial electron due to the Lorentz boosting.

Thus Bhabha and Heitler introduced the idea of air shower and gave a formal analytical structure to calculate the number of electrons/positrons with certain energy produced at a depth l in the atmosphere. The results of the Bhabha and Heitler theory successfully explained the observations of Regener and Rossi. In the following we discuss how Bhabha and Heitler derived the physical quantities relevant to the electromagnetic cascade.

The problem addressed by them is the following : *Given an electron/positron which enters a thick layer of matter with energy E_0 what is the number of electrons/positrons with energy greater than E found at any given point below the top layer?*

To obtain the answer to the above question Bhabha and Heitler started with the following assumptions – (a) Ionization loss of electrons and positrons is completely neglected. If the ionization loss of electron/positron becomes equal to the radiation loss then the particle would be considered as 'stopped', (b) All particles and photons considered here have energy above $10^7\ eV$ and (c) Shower development is one dimensional. There are certain assumptions regarding the cross-sections of the processes involved here and those are as follows.

The differential cross-section for the emission of a photon with energy between ϵ and $\epsilon + d\epsilon$ by an electron with energy E_0 can be written as

$$\Phi_\epsilon\, d\epsilon = \bar{\Phi} F\left(\frac{\epsilon}{E_0}\right)\frac{d\epsilon}{\epsilon} \qquad (9)$$

Here $\bar{\Phi}$ is a constant depending on the material in question and it is given by

$$\bar{\Phi} = \frac{Z^2}{137}\left(\frac{e^2}{mc^2}\right)^2 \qquad (10)$$

where Z is the atomic number of the material. It was shown by Bhabha and Heitler that $F\left(\frac{\epsilon}{E_0}\right)$ can be approximated as

$$F\left(\frac{\epsilon}{E_0}\right) = a\ \ln 2 \qquad (11)$$

where is a constant and in air $a = 23$.

The differential cross-section for the creation of a pair by a photon of energy ϵ when a positron has energy between E_+ and $E_+ + dE_+$

$$\Phi_{E_+} dE_+ = \bar{\Phi} G(E_+, \epsilon) dE_+ \tag{12}$$

It was shown by Heitler [11] that $G(E_+, \epsilon)$ is a slowly varying function of ϵ only. Therefore, it can be assumed that

$$G(E_+, \epsilon) = G(\epsilon) = G \tag{13}$$

With the above assumptions and cross-sections for the physical processes Bhabha and Heitler considered a homogeneous beam of positrons of energy E_0 incident on the top layer of a medium. Let $f_+ (l,E)$ be the number of positrons with energy greater than E, $f_- (l,E)$ be the number of electrons with energy greater than E and $h(l,\epsilon)\, d\epsilon$ be the number of photons with energy between ϵ and $\epsilon + d\epsilon$ at a scaled depth l below the surface. l is a dimensionless quantity with $l = b\lambda$ where λ is physical thickness of the medium and $b = a\phi\sigma$, σ be the number density of the medium. The number of photons in the energy range ϵ and $d\epsilon$ emitted by positrons with energy greater than in travelling a distance $dl = b\, d\lambda$ is given by

$$\delta h_+ = \Phi_\epsilon\, d\epsilon\, \sigma\, f_+(l,\epsilon)\, d\lambda = \ln 2\, f_+(l,\epsilon) \frac{d\epsilon}{\epsilon} dl \tag{14}$$

Similarly for electrons one can have

$$\delta h_- = \Phi_\epsilon\, d\epsilon\, \sigma\, f_-(l,\epsilon)\, d\lambda = \ln 2\, f_-(l,\epsilon) \frac{d\epsilon}{\epsilon} dl \tag{15}$$

The number of photons in the energy range ϵ and $\epsilon + d\epsilon$ lost in creating electron-positron pairs in the same length dl is given by

$$\bar{\Phi}\, G\, \sigma\, h(l,\epsilon)\, d\epsilon\, d\lambda = \alpha h(l,\epsilon)\, d\epsilon\, dl \tag{16}$$

where $\alpha = G/a$ and it is equal to 0.6 for air. Therefore the net change in the photon number over the length dl is $\delta h = (\delta h_+ + \delta h_-) - \alpha h(l,\epsilon)\, d\epsilon\, dl$, which leads to the equation of continuity for photons given by

$$\frac{\partial h(l,\epsilon)}{\partial l} = \frac{\ln 2}{\epsilon}\left(f_+(l,\epsilon) + f_-(l,\epsilon)\right) - \alpha h(l,\epsilon) \tag{17}$$

Equation (17) is a first order inhomogeneous differential equation. Its solution is given by

$$h(l,\epsilon) = \frac{\ln 2}{\epsilon} e^{-\alpha l} \int_0^l dl' \left(f_+(l,\epsilon) + f_-(l,\epsilon)\right) + h(0,\epsilon)\, e^{-\alpha l} \tag{18}$$

where $h(0,\epsilon)$ is the integration constant. Physically it implies the number photons falling at the top layer of the medium. In this particular case, $h(0, \epsilon) = 0$.

Just like the photon distribution, the electron and positron distribution can also be estimated at a depth l inside the matter. The electrons are produced only in pair creation process while the positron contribution comes from those created in pair production process as well as the primary positrons which survive up to the depth l. Bhabha and Heitler showed that the total number of positron with energy greater than E at a depth can be given by

$$f_+(l,E) = W\left(l, \ln\frac{E_0}{E}\right) + \int_0^l dl' \int_0^E dE' \int_0^{E'} d\epsilon\, \frac{h(l',\epsilon)}{\epsilon}\, W\left(l - l', \ln\frac{E'}{E}\right) \tag{19}$$

In equation (19) first term represents the probability that a primary positron with initial energy survives up to the depth l and has energy E. It gives the primary photon contribution at a depth l. The term $W\left(l-l', \ln\frac{E'}{E}\right)$ gives the probability that a positron produced at a depth l with energy E reaches a depth l with energy E. So the second term gives the total contribution of positrons produced in pair creation process at different depth $l'(<l)$, but survive up to the depth l. The probability distribution $W(l,\eta)$ is defined by (see Appendix of [1])

$$W(l,\eta) = \int_0^\eta d\xi\, \frac{e^{-\xi}\xi^{l-1}}{\Gamma(l)} \tag{20}$$

where $\Gamma(l)$is the gamma-function.

In case of electrons, for obvious reasons, the only contribution comes from the pair process and the number of electrons produced should be equal to the number of positrons produced in pair creation. Therefore

$$f_-(l,E) = f_+(l,E) - W\left(l, \ln\frac{E_0}{E}\right) \tag{21}$$

Using equations (18), (19) and (21), and changing the variable from E to $y = ln\ (E_0 / E)$, $f\_(l,E)$ can be written as

$$f\_(l,y) = \alpha \ln 2\, e^{-\alpha l} \int_0^l dl' \int_0^{l-l'} dl''\ e^{-\alpha(l'+l'')} \int_0^y dy'\ W(l'+1, y-y')\,[W(l'',y') + 2f\_(l'',y')] \quad (22)$$

Thus the number of electrons at a depth with energy higher than E can be obtained by solving the integral equation (22). Bhabha and Heitler solved it by expanding $f\_(l,y)$ in the form of a series

$$f\_(l,y) = \sum_{n=1}^{\infty} f_n(l,y) \quad (23)$$

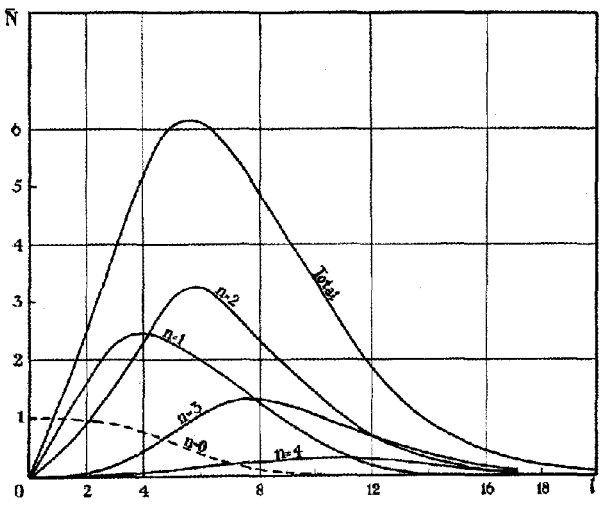

Fig. 4: Variation of average number of particles with the depth in the medium for y = 5. Reproduced from [1].

Each term in the series of equation (18) has a physical meaning. The n-th term in the series $f_n(l,y)$ represents the electrons produced in the n-th step due to the pair production of the n intermediary photon. $n = 0$ represents the primary particle which does not exist for electrons in this case. The n-th term can be written as

$$f_n(l,y) = \frac{(2\alpha \ln 2)^n}{2} e^{-\alpha l} \int_0^l dl' \int_0^y dy'\ e^{-\alpha l'} \frac{l'^n\,(l-l')^{n-1}(y-y')^{n-1}}{n!\,(n-1)!\,(n-1)!} W(l'+n, y') \quad (24)$$

These results are very general and can be used for both positron as well as electron initiated showers. Figure 4 shows the variation of particle number with the depth l for $y=5$. The average number $\overline{N}$ is identical to $f\_(l,y)$ given by the integral equation (22). Curves for different values of n signify the contribution of different term in the series (23). $n=0$ curve gives the contribution of the primary at different depths. The total curve peaks for a value of l between 5 and 6. When applied to the actual data Bhabha-Heitler theory could explain the results obtained by Regener [10] and Rossi [7].

Although Bhabha and Heitler started with the assumption that the shower is one dimensional, they also estimated the mean angular spread of the shower. If E be the energy of an electron or positron produced at a depth then the mean angle which the direction of the particle makes with the direction of the photon producing it is $\sim \frac{mc^2}{E}$. Now if this particle is generated at the 2n-th stage of the shower development then the maximum total deflection will be of order $2n\frac{mc^2}{E}$. If it is considered that the individual deflections are random, then the mean deflection suffered by the particle will be of order $\sqrt{2n}\frac{mc^2}{E}$.

6. Concluding remarks

In this article, with a brief introduction cosmic ray and cosmic ray air shower, the Bhabha-Heitler theory of cosmic ray air shower is discussed. Bhabha-Heitler theory is of fundamental importance because, for the first time it introduced and gave a formal theoretical structure to the concept of cosmic ray air shower. Bhabha and Heitler analytically estimated the physical quantities, such as, average number of electrons and positrons in an electromagnetic cascade, the fluctuation developed in a cascade and the angular spread of the cascade. It satisfactorily explained the results of observations by Rossi and Regener. Thereby, Bhabha and Heitler initiated a new era in cosmic ray physics.

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Homi Jehangir Bhabha : A Scientometric Perspective

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1. Introduction

Homi Jehangir Bhabha, the architect of Indian Nuclear Science and Technology was born on 30^{th} October 1909 in Mumbai. He had his early education at Cathedral and John Connon Schools, Elphinston College and Institute of Science, Mumbai up to the age of seventeen. Bhabha joined Caius College, Cambridge, in 1927 and was a scholar of the college during 1929-1930. He obtained Mechanical Sciences Tripos in First Class in June 1930 and thereafter went on to work as a research student in theoretical physics. When the Second World War broke out in 1939, Bhabha came to India on a holiday and remained in India thereafter. He spent nearly five years at Indian Institute of Science, Bangalore, where he came in contact with the Nobel Laureate Sir C.V. Raman.

He was chiefly responsible for the establishment of Tata Institute of Fundamental Research (TIFR) and Bhabha Atomic Research Centre (BARC) (Formerly Atomic Energy Establishment Trombay (AEET) and other DAE establishments. He held many positions in different capacities and received many awards/ honours including Padma Bhushan (1954) in recognition of his outstanding contribution in the field of Nuclear Science and Technology. Bhabha was also an institution builder, painter, musician, educationist and administrator. He died in a tragic air-crash on Mont Blanc on 24^{th} January 1966. Very few may be aware of the fact that he was nominated for the Nobel Prize in the second half of the twentieth century by J. Hadamard, a mathematician from the Institut de France (Singh, 2009).

This paper attempts to highlight quantitatively the scientific contributions of Homi Jehangir Bhabha. H. J. Bhabha published 66 scientific papers during 1933-1966. This paper brings out interesting aspects of Bhabha's papers such as synchronous self-citations, citation image- makers, highly cited papers, and eponymous citations. It also discusses the growth and development of literature on 'Bhabha scattering'.

2. Publication Productivity

H. J. Bhabha published his first paper at the age of 24 in 1933 in *Zeitschrift Fuer Physik* for which he won the Isaac Newton studentship. He subsequently published 65 papers, his last paper was published in 1966, the same year as his untimely demise at the age of 56. His 66 papers could be categorized into nine fields: Cosmic ray physics (18 papers); Elementary particle physics, and Field theory (14 papers each); Quantum electrodynamics (6 papers); Nuclear physics (4 papers); General, and Interaction of radiation with matter (3 papers each); Mathematical physics, and General physics (2 papers each). His most productive publishing years were 1938 to 1942, during which time he published 20 papers. His most preferred channel of communication was journals: *Proceedings of the Indian Academy of sciences A: Physical Sciences* (14 papers); *Proceedings of the Royal Society of London A: Mathematical and Physical Sciences* (14 papers); and *Nature* (8 papers).

The striking feature of his papers is that he is single author in 48 (80%) of his papers and he is the first author of all his papers except one (Taylor et al 1950). His collaborators are indicated in Table 1.

Table 1: Co-authors of H. J. Bhabha

Authors	Authorships
Bhabha, H.J.	66
Harish-Chandra	3
Saxena, R.C.	2
Hoteko, H.E.	2
Heitler, W.	2
Daniel, R.R.	2
Chandrashekhar Aiya, S.V.	2
Chakrabarty, S.K.	2
Taylor, H.J.	1
Swami, M.S.	1
Shrikantia, G.S.	1
Ramakrishnan, A.	1
Madhava Rao, B.S.	1
Hulme, H.R.	1
Heeramaneck, J.R.	1
Corben, H.C.	1
Chou, C.N.	1
Carmichael, H.	1
Prasad, N.B.	1

3. Citation Identity

The citation identity of an author are the authors cited by him/her. Analysis of 635 references in the 66 papers, indicated that his citation identity comprised of 212 authors (Swarna et al 2008). The most frequently cited authors by H. J. Bhabha are indicated in Table 2.

Table 2: The most frequently occurring names in Bhabha's citation identity

Author	No. of times referenced
Heitler, W.	48
*Dirac, P.A.M.	29
*Pauli, W.	22
*Heisenberg, W.	22
Kemmer, N.	21
*Rossi, B.	20
*Blackett, P.M.S.	17
*Bethe, H.A.	13
Wilson, A.H.	12
Fierz, M.	12
Harish-Chandra	10
Auger, P.	10

**Nobel Prize winners*

4. Self-citations

H. J. Bhabha cited his own works 133 times. According to Kragh (1990) scientists who follow an independent research program outside the mainstream of a research field will tend to cite themselves frequently. Study of his synchronous self-citations as a knowledge generating system was made by Swarna et al (2006). High rate of self-referencing indicates the extent of self-consistency in the research of the author during the period. This also indicates that the focus of the researcher was in micro-domain that had proportionately few scientists working at the global level and very few were associated with him. Confidentiality of the research endeavour was the prime consideration at that time. He had referred to his paper 'Classical theory of mesons' (Bhabha, 1939) maximum 16 times. So it is considered as classic paper. This shows his consistency in pursuing research in the domain of mesons.

5. Citation Image Makers

In addition to these self-references analyses, it is contextual to note that H.J. Bhabha is being cited by others even now, which is a direct indicator of the relevance of his research. Authors citing his works are his citation image makers. A study by Swarna et al (2008) indicates that out of 66 papers, he received 331 citations to 31 papers from 1982 to 2006 according to Science Citation Index (SCI). On an average he received 10.7 citations per cited paper (citation rate) and 5 citations per publication (cited and uncited). According to Gusman (2003) citation rate gives measure of productivity or relative importance for the cited papers, especially within the concerned field. It is possible he would have received many more citations earlier to 1982 period and an appreciable number of papers would have been cited. The five most cited papers during 1982 to 2006 are documented in Table 3.

Table 3: Five most cited papers of H.J. Bhabha during 1982 – 2006

Subject	Cited works	Times cited
Quantum electrodynamics	'The scattering of positrons by electrons with exchange on Dirac's theory of the positron', *Proc. Royal Soc. A*, V.154, 1936: pp. 195-206	54
Elementary particle physics	'Relativistic wave equations for the elementary particles', *Rev. Mod. Phys.*, V.17, 1945: pp. 200-216	38
Elementary particle physics	General classical theory of spinning particles in a Maxwell field', *Proc. Royal Soc. A*, V.178, 1941: pp. 273-314	32
Cosmic ray physics	The passage of fast electrons and the theory of cosmic showers', *Proc. Royal Soc. A*, V.159, 1937: pp. 432-458	31
Quantum electrodynamics	The creation of electron pairs by fast charged particles', *Proc. Royal Soc. A*, V.152, 1935: pp. 559-586	23

Bhabha's most cited paper (54 times) according to Singh (1985) is considered the crowning achievement. This paper titled 'The scattering of positrons by electrons with exchange on Dirac's theory of positron' earned him the eponym 'Bhabha scattering'. 'The passage of fast electrons and the theory of cosmic showers' earned him another eponym 'Bhabha equations'. His paper titled 'The creation of electron pairs by charged particles' (23 times) was published when he was holding a Isaac Newton studentship (1934-1936). According to Sen (1969) scientists whose works are cited by Nobel laureates can be considered as the 'richest' members of the scientific community. In this sense Bhabha has the distinction of being cited by P.M.S. Blackett (1948) and H. Yukawa (1949) in their respective Nobel Lectures (Frangsmyr, 1998): "Nuclear forces, heavy electrons and the beta-decay" (Bhabha, 1938a) and "On the theory of heavy electrons and nuclear forces" (Bhabha, 1938b).

6. Eponymous Citations

Epoch-making research by H.J. Bhabha has gained eponymous status synonymous with his name and international fame. Study by Swarna et al (2004) have identified fifty-nine distinct eponyms for Bhabha. The seven most frequently occurring eponymal phraseology for H. J. Bhabha along with the number of records retrieved in SCI were: Bhabha scattering (290), angle Bhabha scattering (42), small angle Bhabha scattering (21), radiative Bhabha scattering (17), large-angle Bhabha scattering (16), resonant Bhabha scattering (12), and low angle Bhabha scattering (process) in 10 records. 'Bhabha scattering' is the broad term for the phenomenon.

7. Bhabha Scattering

Further study was carried out on *Bhabha scattering* by Kademani et al (2009). This study attempts to highlight quantitatively the growth and development of world literature on Bhabha scattering in terms of publication output as per International Nuclear Information System (INIS) (1970-2008), Science Citation Index (1982-2008) and INSPEC (1969-2008) databases. A total of 1305 papers were published by the scientists on Bhabha scattering. Figure 1 gives year-wise papers published and collaboration pattern. Solo research activity prevailed during 1969-1993, whereas group (five or more authors) collaborative research activity was high during 1994-2008.

7.1 Country-wise Distribution of Research Output

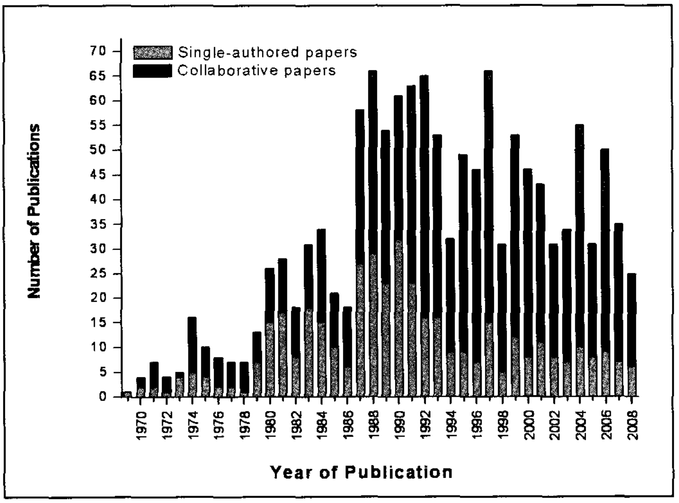

Fig: 1: Year-wise publication productivity on Bhabha scattering

Forty-seven countries were involved in research carried out in the field of Bhabha scattering. Germany had 421 papers, while USA had 420 papers; Italy with 293 papers, Switzerland with 263 papers, France with 178 papers, England with 155 papers and Russia with 150 papers were the other countries doing significant research in the field. India is in 15th position with 82 papers (Table 4).

7.2 Most Prolific Authors in Bhabha Scattering

There were 6655 authors contributing to this field. The most prolific authors were Martin-JP (90 papers); Alexander-G, Gary-GW and Hawkes-CM (67 each), Becker-U (64 papers) (Table 5).

Table 4: Country-wise distribution of papers on Bhabha scattering (≥ 50 papers)

Sl. No.	Country	No. of Papers	Sl. No.	Country	No. of Papers
1	Germany	421	12	Peoples-R-China	109
2	USA	420	13	Hungary	93
3	Italy	293	14	Canada	90
4	Switzerland	263	15	India	82
5	France	178	16	Israel	71
6	England	155	17	South-Korea	58
7	Russia	150	18	Finland	57
8	Poland	141	19	Norway	53
9	Japan	132	20	Bulgaria	50
10	Netherlands	127	21	Greece	50
11	Spain	116			

Table 5: List of authors with ≥ 50 papers on Bhabha scattering

Author Name	No. of Papers	Author Name	No. of Papers
Martin-JP	90	Mikenberg-G	60
Alexander-G	67	Bella-G	59
Gary-JW	67	Karlen-D	59
Hawkes-CM	67	Barlow-RJ	58
Becker-U	64	Bell-KW	58
Dittmar-M	63	Bethke-S	58
Branson-JG	61	Chang-CY	58
Allison-J	60	Duchovni-E	58
Kawamoto-T	60	Kellogg-RG	58
Lloyd-SL	60	Kobayashi-T	58
		Loebinger-FK	58

Chen-A	57
Komamiya-S	57
Orito-S	57
Ward-BFL	57
Heuer-RD	56
Mattig-P	56
Miller-DJ	56
Carter-AA	55
Charlton-DG	55
Chen-HS	55
Clare-R	55
Duerdoth-IP	55
Mori-T	55
Biebel-O	54
Bourilkov-D	54
Burger-JD	54
Carter-JR	54
Chiefari-G	54
Field-JH	54
Hauschild-M	54
Hemingway-RJ	54
Herten-G	54
Hill-JC	54
Jovanovic-P	54
Lellouch-D	54
Martin-AJ	54
Meijers-F	54

Oreglia-MJ	54
Roney-JM	54
Adriani-O	53
Arcelli-S	53
Axen-D	53
Banerjee-S	53
Behnke-T	53
Bock-P	53
Burckhart-HJ	53
Cuffiani-M	53
Dado-S	53
Duckeck-G	53
Engler-A	53
Fabbri-F	53
Giacomelli-G	53
Goldberg-J	53
Hanson-GG	53
Keeler-RK	53
Kraemer-RW	53
Lafferty-GD	53
Layter-JG	53
Ludwig-J	53
Marcellini-S	53
Mckenna-J	53
Merritt-FS	53
Mes-H	53
Michelini-A	53

Mohr-W	53
Oneale-SW	53
Pilcher-JE	53
Plane-DE	53
Runge-K	53
Vonkrogh-J	53
Anderson-KJ	52
Bobbink-GJ	52
Bohm-A	52
Brown-RM	52
Capell-M	52
Carnegie-RK	52
Chen-GM	52
Coignet-G	52
Geichgimbel-C	52
Gentile-S	52
Igokemenes-P	52
Jeremie-H	52
Kawagoe-K	52
Kennedy-BW	52
LeCoultre-P	52
Levinson-L	52
Mashimo-T	52
Anderhub-H	51
Azemoon-T	51
Azuelos-G	51
Bay-A	51

Filthaut-F	51
Ganguli-SN	51
Gurtu-A	51
Hofer-H	51
Hou-SR	51
Jadach-S	51
Landi-G	51
Letts-J	51
Alcaraz-J	50
Alviggi-MG	50
Andreev-VP	50
Arefiev-A	50
Bagnaia-P	50
Battiston-R	50
Berges-P	50
Bertucci-B	50
Betev-BL	50
Biland-A	50
Chemarin-M	50
Chen-HF	50
Clare-I	50
Colino-N	50
Deiters-K	50
Denes-P	50
Diemoz-M	50
Dionisi-C	50
Doria-A	50

Berdugo-J	51
Borgia-B	51
Cerrada-M	51
Ferguson-T	51
Fesefeldt-H	51
Duchesneau-D	50
Eppling-FJ	50
Extermann-P	50
Falciano-S	50
Fay-J	50
Fisher-PH	50
Forconi-G	50
Freudenreich-K	50
Gutay-LJ	50

Hebbeker-T	50
Herve-A	50
Jin-BN	50
Jones-LW	50
Kaur-M	50
Kittel-W	50
Konig-AC	50
Kunin-A	50
Lebrun-P	50
Lecoq-P	50
Leiste-R	50
Linde-FL	50
Lohmann-W	50

7.3 Organisation-wise Distribution of Papers

In all, 655 organisations were involved in the research activity in the field of Bhabha scattering. Istituto Nazionale di Fisica Nucleare, Italy (INFN) topped the list with 256 papers; University of Bologna, Italy (144 papers); Deutsches Elektronen Synchrotron, Germany (DESY) with 138 papers, and University of Hamburg, Germany (124 papers). In India, Tata Institute of Fundamental Research is the most productive Institute with 54 papers (Table 6).

7.4 Preference of Channels of Communication by Scientists

Scientists communicated their papers through variety of communications channels. Journal articles constituted 66.44% of the total papers, followed by reports (18.47%), conference papers (5.67%) and books (5.52%). The distribution of papers were spread over 106 journals. The leading journals preferred by the scientists were *Physics Letters-B* with 188 papers followed by *Nuclear Physics-B* with 91 papers and *Physical Review-D* with 90 papers. Table 7 provides scattering of papers in top 21 highly preferred journals. Out of 910 journal articles, about 82 percent of the papers were published in the journals with impact factors ranging from 0.17 to 38.40. This indicates the publication behaviour of scientists who preferred to publish their papers in high impact journals. Remaining 18 percent of the papers were published in the journals not covered by SCI database.

Table 6: Distribution of institutes as per number of papers on Bhabha scattering

Sl. No.	Institute	Country	No. of Papers
1	Istituto Nazionale di Fisica Nucleare (INFN)	Italy	256
2	European Organisation for Nuclear Research (CERN)	Switzerland	243
3	University of Bologna	Italy	144
4	Deutsches Elektronen Synchrotron (DESY)	Germany	138
5	University of Hamburg	Germany	124
6	Rutherford Appleton Laboratory	England	116
7	University of Heidelberg	Germany	89
8	University of California Riverside	USA	84
9	Rhein Westfal Th Aachen	Germany	82
10	Massachusetts Institute of Technology	USA	79
11	University of Lyon 1	France	77
12	University of Roma La Sapienza	Italy	77
13	Stanford University	USA	76
14	University of Maryland	USA	75
15	University of Birmingham	England	71
16	University of Manchester	England	71
17	University of Florence	Italy	68
18	University of Montreal	Canada	68
19	University of Oregon	USA	68
20	Institute of High Energy Physics	PRC	67
21	Princeton University	USA	67
22	Joint Institute of Nuclear Research	Russia	66
23	University of British Columbia	Canada	66
24	University of Tokyo	Japan	66
25	Institute of Nuclear Physics	Poland	65
26	California Institute of Technology (CALTECH)	USA	64
27	Tel Aviv University	Israel	64
28	University of Turin	Italy	64
29	University of California	USA	63
30	University of Freiburg	Germany	63

31	University of Perugia	Italy	63
32	University of Victoria	Canada	63
33	University of Michigan	USA	62
34	University of Trieste	Italy	62
35	Indiana University	USA	61
36	University of Chicago	USA	60
37	Carleton University	Canada	59
38	Max Planck Institute Physics and Astrophysics	Germany	59
39	University of Bonn	Germany	59
40	University of Tennessee	USA	59
41	Weizmann Institute Science	Israel	59
42	Purdue University	USA	58
43	University of Karlsruhe	Germany	58
44	Kobe University	Japan	56
45	Carnegie Mellon University	USA	55
46	University of Paris 11	France	55
47	National Institute Nuclear and High Energy Physics	Netherlands	54
48	Tata Institute Fundamental Research	India	54
49	Technion Israel Institute of Technology	Israel	54
50	University of Alberta	Canada	54
51	Commissariat à l'Énergie Atomique (CEA)	France	53
52	Nationaal Instituut Voor Subatomaire Fysica (NIKHEF)	Netherlands	53
53	Paul Scherrer Institute	Switzerland	53
54	University of Geneva	Switzerland	53
55	University of Milan	Italy	53
56	Hungarian Academy of Science	Hungary	52
57	Institute of Theoretical & Experimental Physics	Russia	51
58	Louisiana State University	USA	51
59	University of Naples	Italy	51
60	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT)	Spain	50
61	Northeastern University	USA	50

Table 7: Journals preferred for publishing articles on Bhabha scattering

Sl. No.	Journal	No. of Papers	IF-2007
1	Physics Letters-B	188	4.189
2	Nuclear Physics-B	91	4.645
3	Physical Review-D	90	4.696
4	European Physical Journal-C	61	3.255
5	Nuclear Instruments and Methods in Physics Research-A	54	1.114
6	Zeitschrift fur Physik-C	45	-
7	Physical Review Letters	38	6.944
8	Acta Physica Polonica-B	32	0.664
9	Verhandlungen der Deutschen Physikalischen Gesellschaft	30	-
10	Computer Physics Communications	24	1.842
11	AIP Conference Proceedings	18	-
12	High Energy Physics and Nuclear Physics	13	0.171
13	Zeitschrift fur Physik-A	11	-
14	International Journal of Modern Physics-A	9	0.764
15	Nuclear Instruments and Methods in Physics Research B	9	-
16	Physical Review-C	9	3.302
17	Physics Reports	9	20.263
18	Progress of Theoretical Physics	8	1.936
19	Journal of High Energy Physics	7	5.659
20	Pramana Journal of Physics	7	0.383
21	Journal of Physics-A	6	1.68
22	Physics of Atomic Nuclei	6	0.515
23	Journal of Experimental and Theoretical Physics	5	1.075
24	Nuovo Cimento-A	5	-

8. Conclusion

H. J. Bhabha contributed to nine main domains: Cosmic ray physics (18 papers); Elementary particle physics, and Field theory (14 papers each); Quantum electrodynamics (6 papers); Nuclear physics (4 papers); General, and Interaction of radiation with matter (3 papers each); and Mathematical physics, and General physics (2 papers each). His research has earned him eponymous status synonymous with his name and international fame. Citations to his works is an indication of the relevance of his research even today.

Bhabha communicated his paper 'The scattering of Positrons by Electrons with exchange on Dirac's theory of the Positron' to *Proceedings of the Royal Society of London* on 20^{th} October 1935, which was subsequently published in 1936 to calculate cross section for electron – positron scattering which later became an eponym as 'Bhabha Scattering'. Research on this theory is still being carried out by scientists across the world. The 1305 papers published during 1969-2008 shows the relevance of Bhabha's theory even after 75 years of his work.

Bhabha is one of the greatest scientists that India has ever produced. Bhabha once said "*I know quite clearly what I want out of my life. Life and my emotions are the only things I am conscious of. I love the consciouness of life and I want as much of it as I can get. But the span of one's life is limited. What comes after death no one knows. Nor do I care. Since therefore, I cannot increase the content of life by increasing its duration, I will increase it by increasing its intensity. Art, music, poetry and everything else that consciousness I do have this one purpose-increase the intensity of my consciousness of life*". True to his statement, he lived his life very creatively as a scientist, painter, musician, institution builder and a great human being. He is a '*Role Model*' scientist for the younger generation to emulate.

A scientist, as an individual can make a great contributions to science, but when he creates and nurtures group of people, capable of carrying out high quality research work during the following generations is still a greater achievement. Added to this development of indigenous resources, setting practically attainable guidelines, taking up projects and seeing through their logical conclusions leading to fruitful results is the hall-mark of a great scientist as well as a great scientific leader. All these aspects amply demonstrated in the case of illustrious research career of Bhabha.

He undoubtedly remains in the science and technology map of the world, both at national and international level for years and ages to follow.

Acknowledgements

Authors are highly indebted to Dr. S. Kailas, Associate Director, Physics Group, BARC and Dr. B. N. Jagatap, Head, Atomic Physics & Quantum Optics Section, BARC for their encouragement and valuable suggestions to improve this paper.

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Homi Bhabha on Science, Technology & Education

On long term basic research

No country which wishes to play a leading part in the world can afford to neglect pure or long term research.

Importance of fundamental physics

It is absolutely in the interest of India to have a vigorous school of research in fundamental physics, for such a school forms the spearhead of research not only in less advanced branches of physics but also in problems of immediate practical applications in industry

Role of science for technology.

I believe that ...the problem of establishing science as a live and vital force in society is an inseparable part of the problem of transforming an industrially underdeveloped to a developed country.

Synergy between university and national lab

An important difference between the TIFR and most of the labs of CSIR, namely that the TIFR has been a constituent recognized institution of the Bombay university from the very beginning and has had close relations with many other universities in India, so that students of many of them have done work for the Ph.Ds of their universities in the institute(TIFR)

Centres of excellence around outstanding men

The philosophy underlying the foundation of the institute (TIFR) was the same as that underlying the Max Planck Institutes in Germany, namely the Kaiser Wilhem society shall not first build an institute for research and then seek out the suitable man but shall first pick up an outstanding man, and then build an institute for him.

Importance of indigenous science and technology

The relative roles of indigenous science and technology and foreign collaboration can be highlighted through an analogy. Indigenous science and technology plays the part of an engine in an aircraft, while foreign collaboration can play the part of a booster. ....If Indian industry is to take-off and be capable of independent flight, it must be powered by science and technology based in the country

Science administration

The type of administration required for the growth of science and technology is quite different form the type of administration required for the operation of industrial enterprises.....The administration of scientific research and development ...must necessarily be done by scientists and technologists themselves.

Importance of doing research in one's own country

I had the idea after the war I would accept a job in a good university in Europe or America because universities like Cambridge or Princeton provide an atmosphere which no other place in India provides at the moment. But in the later two years I have come more and more to the view that provided proper appreciation and financial support are forthcoming, it is one's duty to stay in one's own country and build up schools comparable to that other countries are fortunate in possessing.

Scientists on Homi Bhabha

In the summer of 1933 Niels Bohr invited me to his usual summer conference in Copenhagen.... I remember traveling north in the train from Berlin, opposite to a dark-skinned young man whom I took to be an Italian. After a while I pulled out a crime novel by Edgar Wallace in order to refresh my scanty knowledge of English, which I had learnt when I was twelve but never used since. The moment I did that the man opposite me said 'You are a physicist?' Surprised I asked 'Why should you think so?' He said 'You read Edgar Wallace.' Now surely it is quite wrong to assume that only physicists read Edgar Wallace, but he was right. I was a physicist. This confirmed my view that a really good scientist is one who knows how to draw correct conclusions from incorrect assumptions.

The man was Homi Bhabha, a handsome Indian from a wealthy Parsee family; he had studied in Cambridge and spoke impeccable English. When I later came to live in Copenhagen we became friends; he introduced me to Beethoven's late quartets...Bhabha was also a very competent painter, and a first rate theoretical physicist. But I was amused when one day when he casually asked for instruction on how to use a Geiger counter; he was to travel to India by boat next week and wanted to measure the variation of cosmic rays with latitude. I told him the story of the boy who wanted to be a baker and was told he would have to serve a three years' apprenticeship: one year to run errands of the baker's wife; one to clean out the oven, and last to learn how to bake the bread. He smiled and got my point.

- Otto Frisch
What Little I remember
Cambridge University Press, 1979

In November (1932) Homi Bhabha arrived. He came from Cambridge (England) with a recommendation from R.H. Fowler- that is to say a recommendation of a kind. Fowler realized Bhabha was very gifted, but he also thought him opinionated and unruly, so he felt Bhabha needed a strong hand. 'You can be as brutal as you like' he wrote. This Pauli enjoyed immensely; he showed me the letter and repeated over and over again, 'I can be as brutal as I like'. I wonder whether Fowler was subtle enough to understand that this letter was the best way to make Pauli well disposed towards Bhabha. But it did work out the other way and they became good friends, although it must be admitted that Bhabha sometimes turned to Wentzel rather than Pauli when he wanted to discuss an entirely new idea. Bhabha who came from a wealthy Parsee family in Bombay, was a man of many parts. He was not only a gifted physicist but also a painter; he was widely read and knew much about music. Also he had a knack of becoming befriended by interesting *people. My wife liked to refer to him as the fairy-tale prince......Bhabha and I became good friends and often had our meals together.*

- Hendrik Casimir
Haphazard Reality: Half a Century of Science
Harper & Row Publishers, New York, 1983

Affectionate and sensitive, elegant and humorous, dynamic, one of the very few people who enhance life whatever the content of their living - fantastically talented but so fastidious about standards that he was never a dilettante. Whatever he set himself to do, he did as a professional - but one who worked for love; restlessly creative, enhancing life because he loved all forms of it. So he became a living proof that scientific excellence can go with excellence in art, and racial differences need be no bar to friendship. He stood out as a world citizen qualified in all three subjects- education, science and culture.

- Lord Redcliffe-Maud

It [the idea for the cascade process] must have been 'in air' and I am sure several physicists thought about it. We soon found ourselves, Bhabha and I, calculating what should, according to the theory, happen step-by-step when a fast electron passes through matter; the emission of several gamma-quanta, each of which would subsequently create a pair, which in turn would emit gamma-quanta, which again create pairs and so on till the energy was exhausted. This was the theory of showers.

- W. Heitler

The decision to use the word meson (for the Yukawa particles) was made in a certain private house in Cambridge (that of Egon Bretscher) by Maurice Price, Homi Bhabha and myself.

- N. Kemmer

Homi was surely, in a sense, a man out of his own time. He had the wide breadth of interests, the penetrating intellect, the abounding personal confidence in the ability of the human understanding, by observation and excitement, to unravel the secrets of nature, which are characteristic of the great figures of the Renaissance. But perhaps such figures have an essential creative role to play in all ages.

- Cecil Frank Powell

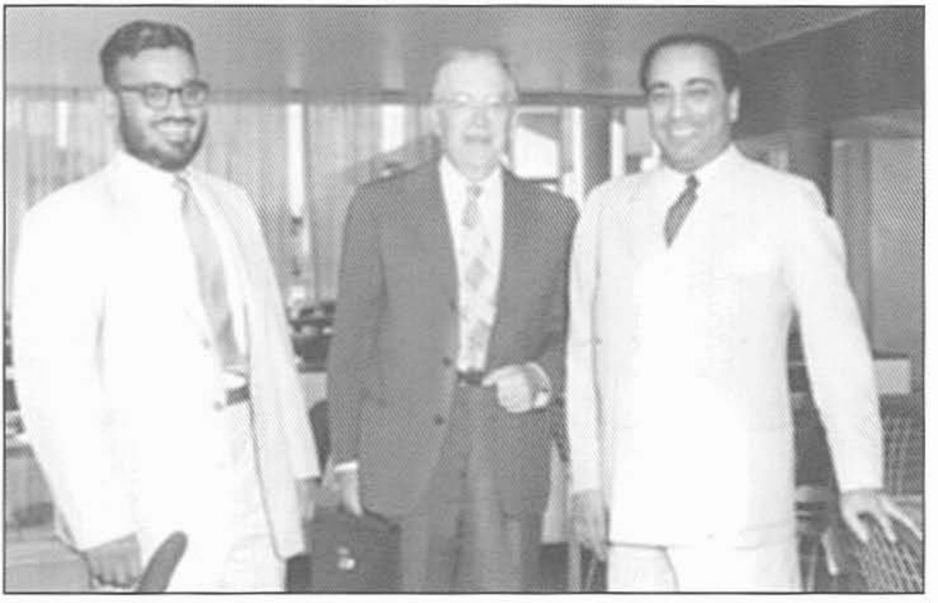
Human progress has always depended on the achievements of a few individuals of outstanding ability and creativeness. Homi Bhabha was one of them.

- Sir John Cockcroft

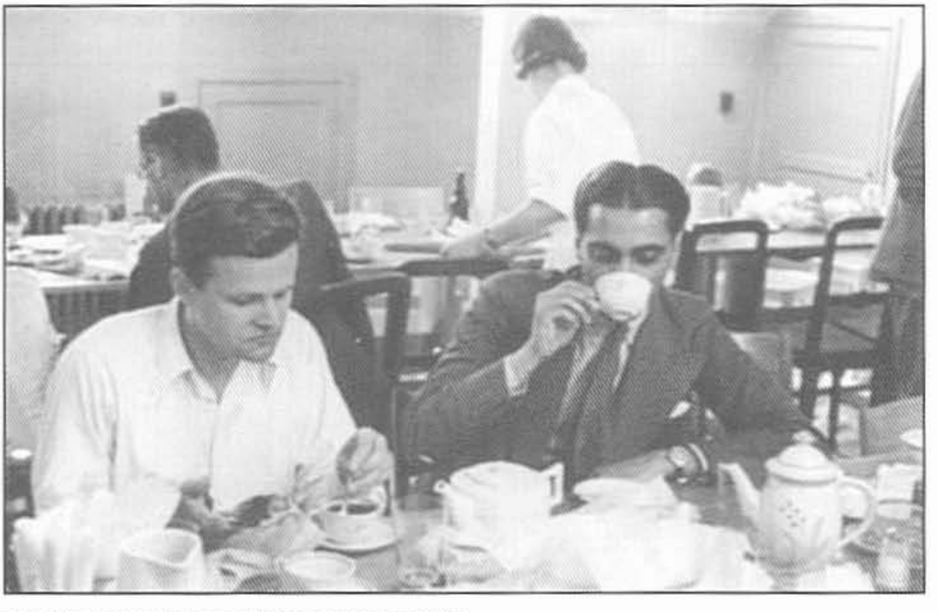
Photo Gallery : Homi Bhabha with Scientists

With Albert Einstein, Hideki Yukawa, John Archibald Wheeler
Credit line: Princeton University, Courtesy AIP Emilio Segre Visual Archives, Yukawa Collection

With Robert Marshak and Robert Oppenheimer
Credit line: Princeton University, Courtesy AIP Emilio Segre Visual Archives

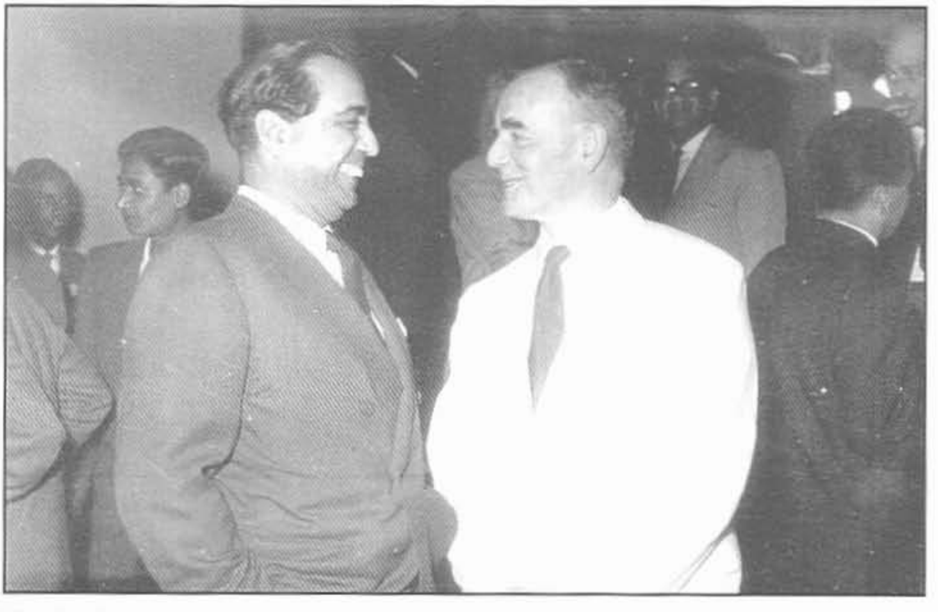


With M.G.K. Menon and Emilio Segre
Credit line: AIP Emilio Segre Visual Archives



With Carl Friedrich von Weizasacker in 1936
Credit line: Photograph by Paul Ehrenfest, AIP Emilio Segre Visual Archives

With John Cockcroft and Mrs. Cockcroft
Courtesy: TIFR Archives



With Cecil Powell
Courtesy: TIFR Archives

With C.F. Powell, Vikram Sarabhai and Patrick M.S. Blackett
Courtesy: TIFR Archives

With C.V. Raman at I.I.Sc., Bangalore
Courtesy: TIFR Archives

With Niels Bohr
Courtesy: TIFR Archives

A group photo in 1933 (from L): Niels Henrik David Bohr; Paul Adrien Maurice Dirac, Werner Heisenberg, Paul Ehrenfest, Max Delbruck, Lise Meitner, Carl Friedrich von Weizsacker, Edward Teller, Homer Jensen, Walter Heitler, Otto Robert Frisch, Milton S. Plesset, Sir Rudolf Ernst Peierls, Eugene I. Rabinowitch, Nordheim, Lothar Wolfgang, Hendrik Brugt Gerhard Casimir, Christian Moller, Felix Bloch, Hans Kopfermann, Harald August Bohr, Fritz Kalckar, Arnold Rosenblum, Charles Lambert Manneback, George Placzek, Victor Frederick Weisskopf, Niels Arley, Chanchal Kumar Majumdar, Oskar Benjamin Klein, Homi Jehangir Bhabha, Leon Rosenfeld, Jacob Christian Jacobsen, Egil Andersen Hylleraas
Credit line: Nordisk Pressefoto, courtesy AIP Emilio Segre Visual Archives, Magrethe Bohr Collection

Sketches of Scientists by Homi Bhabha

29/6/1949

C.V. Raman

Prof. Engelhardt

Prof. P. M. S. Blackett

Prof. Niels Bohr

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OFFICE COPY

Ref:CII/Per-XT/[illegible]   August 12, 1952.

My dear Fermi,

I would appreciate it if you would send me reprints of your two papers on High Energy Nuclear Events, one in the Progress of Theoretical Physics (Vol. 5, No. 4, July-August 1950, pp. 570 - 583) and the other in the Physical Review (Phy. Rev. Vol. 81, pp. 683 - 687).

I would also be glad if you would put me on your regular mailing list and send me reprints of your future papers as they appear.

I hope to be in Chicago between the 7th and the 15th of September for three or four days and look forward to seeing you then. Please convey my regards to the Wentzels, the Allisons, and other friends in Chicago.

With my regards to you and Mrs. Fermi,

Yours sincerely,

H.J.B.

Professor E. Fermi,
Institute for Nuclear Studies,
University of Chicago,
Chicago 37, Illinois,
U. S. A.

Ideas are some of the most important things in life, and men are prepared to suffer and die for them.

- Homi Bhabha

AIR MAIL

Ref:TFR/Per-PAMD/183 March 10, 1949.

My dear Dirac,

I have been invited to attend and be one of the principal lecturers at the Mathematical Congress to be held at Vancouver in August/September this year. They have informed me that you too are one of the principal lecturers. Before I finally accept the invitation, I would like to know whether you have attended such a congress before and the sort of audience that one might expect so that one may plan one's lectures accordingly. Will you stay in Vancouver during the whole period from the 16th August to the 10th September? I would like to know how many lectures you propose to give and on what subjects. I should be grateful if you could send me an immediate reply. It will be rather difficult for me to spend such a long period in Canada just at that time.

I have found recently that for particles of spin 1 there are other irreducible relativistic equations besides the Klein-Gordon and the Proca equations. We have also been able to give a proper treatment of fluctuations in showers.

With best wishes to you and Mrs.Dirac,

Yours sincerely,

HJB

Prof.P.A.M.Dirac,F.R.S.,
St.John's College,
Cambridge,ENGLAND.

HJB:asr.