Bhabha's Contributions to Elementary Particle Physics and Cosmic Rays Research

Virendra Singh

Tata Institute of Fundamental Research
Homi Bhabha Road, Mumbai 400 005, India

* email: vsingh1937@gmail.com

1. Introduction

Homi Jehangir Bhabha (1909-66) started his career as a theoretical physicist at Cambridge in the nineteen-thirties and distinguished himself in the emerging areas of elementary particles, or high energy physics, and cosmic rays. He worked actively in these areas for a period of about two decades (1933-1954) and made many significant contributions. His name is commemorated in these fields through the electron-positron scattering process being called Bhabha Scattering[1]. Bhabha-Heilter cascade theory of cosmic ray showers[2] was a signal contribution to the cosmic ray studies. His name is also associated to Bhabha-Corben theory of relativistic spinning classical particles[3]. The Bhabha equations[4] investigated possible relativistically invariant linear wave equations for elementary particles. Bhabha was also responsible for the nomenclature 'meson' for the bosonic elementary particles of 'intermediate' mass, along with N. Kemmer and M.H.L. Pryce[5]. The terminology 'orthochronous' for those Lorentz transformations, which do not change the sign of time-coordinate, also originated with him in his work on Bhabha equations[6]. Bhabha also initiated experimental work on cosmic rays, when he was at the Indian Institute of Science, Bangalore and continued it further at Tata Institute of Fundamental Research, Bombay (now Mumbai).

We propose to discuss here his various scientific contributions.

2. Cambridge Period

Bhabha went to Cambridge in 1927 and joined Gonville and Caius College as a student of mechanical engineering. Around the time the excitment was rather high there in the theory of elementary particles and radiation especially in quantum electrodynamics.

Dirac, at Cambridge, had proposed his quantum theory of emission and absorption of radiation in 1927. This was followed by his Dirac equation. This described relativistically the electron in the same sense as Maxwell equation describe the radiation. Dirac equation was seen to incorporate the phenomenon of electron spin and magnetic moment quite naturally and was shown to lead to experimentally correct Sommerfeld formula for the energy levels of the Hydrogen atom. The main new feature of the Dirac equation was the existence of negative energy states for electrons and this was rather puzzling as electrons in these states were predicted to move in a direction opposite to that of the external applied electromagnetic force. To get out of this quandary, Dirac proposed, in 1930, that all the negative energy states are filled with one electron each in accordance with Pauli principle. An unoccupied negative energy state, i.e. 'a hole', would behave as a charged particle with an electric charge opposite to that of an electron. This 'hole' theory of Dirac was the first introduction of the concept of 'antiparticles' in physics. These particles, now called positrons, were observed experimentally by C.D. Anderson in 1932 and have the same mass as electron.

Bhabha was swept was all this intellectual excitement in quantum electrodynamaics. He wrote to his father asking his permission to change to theoretical physics. As he wrote, 'I seriously say to you that business or a job as an engineer is not the thing for me. It is totally

foreign to my nature and radically opposed to my temperament and opinions. Physics is my line, I know I shall do great things here'. His father was agreeable to let him pursue theoretical phyiscs, and get a mathematics tripos, provided Bhabha devoted himself first to his mechanical tripos, and obtained a first class. Bhabha did that in June 1930 was free to devote himself to his interest in theoretical physics thereafter. His initial interests were mainly in the positron theory and cosmic rays physics. We shall describe some of his main work in these areas before going on to describe his later work in meson theory.

2.1 <u>Positron theory: Bhabha Scattering</u>

Bhabha investigated positron interactions in a number of his papers using Dirac's hole theory. The first of these dealt with "Annihilation of Fast Positrons by Electrons in the K-shell" which was received by Royal Society on May 4, 1934.[7] The work on this paper was begun at Cambridge with H.R. Hulme, and finished by Bhabha at Institute of Physics in Rome where he was visiting Enrico Fermi on his Rouse Ball Travelling studentship in Mathematics which he held for 1932-1934. The next electrodynamic process he considered was the creation of electron-positron pairs by fast charged particles[8]. He was holding an Isaac Newton studentship (1934-1936) at this time.

The crowning achievement of this group of papers on positron interactions was Bhabha's investigation of electron-positron scattering, a process now known as "Bhabha Scattering". The paper is titled 'The Scattering of Positrons by Electrons with Exchange on Dirac's Theory of Positron'[1] and was received by the Royal Society on Oct. 20, 1935.

Mott had earlier considered exchange effects in non-relativistic electron-electron scattering. He had found that exchange effects are considerable except that the effect vanishes when the 'two electrons have antiparallel spins'[9]. Möller had generalised these results to the relativistic electron-electron scattering, now called Möller Scattering[10], and found that the exchange effects are non-vanishing even when electron spins are antiparallel except in the non-relativistic limit.

Now if a positron is regarded as an independent particle, which also obeys Dirac equation, then the positron-electron scattering should show no exchange effects. If on the other hand, positron is regarded as an electron in an unoccupied negative energy state then we should expect exchange effects. These two hypotheses would lead to different results. To quote Bhabha, "The difference would be due to the effect of exchange between the electron we observe initially and the virtual electrons in states of negative energy"[11]. Except in the non-relativistic limit, the effect of the exchange was found considerable. It was not completely clear at this time whether such an exchange effect is simply not an incorrect prediction of the Dirac theory as the exchange was between an observable electron of positive energy and another virtual one of negative energy.

Bhabha however pointed out that another way of looking at this 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 and that such terms should be present in the scattering of any two particles which can annihilate each other and be created in pairs. He noted that such terms were present in a recent theory of Pauli and Weisskopf[12] having particles which obey not the exclusion principle but rather obey Einstein-Bose statistics.

A consequence of this calculation was an expected considerable increase in the number of fast secondaries for positrons of high energies. Bhabha's theory was beautifully confirmed by experiments. Our faith in the correctness of Bhabha scattering formulas is such that they are now routinely used to calibrate the beams at large accelerators using positron or other antiparticle beams.

It should be noted that the discovery of substitution law or crossing symmetry property of local quantum field theory allows us to get the matrix elements for Bhabha Scattering from those of the Möller scattering and vice versa[13]. Of course the discovery of the substitution law itself owes much to these earlier calculations of the related processes.

2.2 <u>Cosmic Ray</u>

In 1936, Bhabha was awarded a Senior Studentship of the Exhibition of 1851. This was also the year in which he and W. Heitler, from Bristol, met together. They had common interest in high energies. Indeed the very first publication of Bhabha in 1933, written from Zurich where he was visiting W. Pauli from Cambridge, was 'On the Absorption of the Cosmic Rays[14] and he had discussed the role of electron showers in it. Since that time he had devoted himself to positron processes in quantum electrodynamics. W. Heitler had also been working on similar subjects. Bethe and Heitler had worked on bremstrahlung radiation from charged particles and on high energy photon induced pair production. Heitler had published the first edition of his book "Quantum Theory of Radiation" in 1936. The result of this collaboration between Bhabha and Heitler was their celebrated cascade theory of electron showers[2].

2.2.1 <u>Bhabha-Heitler Theory</u>

The Bethe-Heitler theory predicted large crosssections for energy loss of electrons or positrons passing through the field of a nucleus by bremstrahlung in a *single* encounter. These hard quanta also have a large probability for materialising as electron-positron pairs. The theoretical "range" of an electron of 10^{12} eV was found to be only about 2 km of air, 2 m of water or 4 cm of lead. It, however, seemed to disagree with the observation of fast electrons at sea level which have traversed 8 km of atmosphere. The common belief was that these observations signify a breakdown of Quantum Electrodynamics. Bhabha and Heitler however went on to show, through their cascade theory, that quantum electrodynamics was quite consistent with the observed phenomenon.

What happens is as follows: A fast electron does loose all its energy after a short distance of travelling through matter just as predicted by Bethe-Heitler formula. This energy however

reappears in the form of radiation quanta which, for large initial electron velocities, have a large probability of moving in the direction of the original fast electron. There is reasonably high probability that these radiation quanta are hard. Again, in accordance with quantum electrodynamics, these radiation quanta materialise, after traversing a short distance through matter, into electron-positron pairs. Again there is a reasonably high probability that the resulting pair consists of a fast electron and a fast positron moving in the direction of the disappearing hard quanta. This process of conversion into photons and reconversion into electron-positron pairs can take place many times. The total effect is thus as if the original electron was losing its energy much more slowly than implied by the theoretical "range" mentioned earlier.

These ideas of Bhabha and Heitler provided a natural explanation of the cosmic ray showers. The calculated curves for the expected number of electrons n $(E, h; E_0)$, above a certain energy E and at distance h below the top of the atmosphere when an electron with energy E_0 is incident at the top of the atmosphere, agreed well with the observed curves by Rossi[15] and the ionisation curves of Regener[16].

The idea that cosmic ray showers could be explained this way was 'in the air'. L. Nordheim, in a conversation with Heitler in 1934, and Carmichael in a conversation with Bhabha had already considered the possibility but "owing to the ill-founded suspicion in which the theory was then held, it did not seem worthwhile carrying out any calculations"[17]. The cascade theory was also given at about the same time by J.F. Carlson and J.R. Oppenheimer[18].

2.2.2 <u>Penetrating Component of Cosmic Radiation</u>

It was very suggestive from the work on absorption of cosmic rays in lead by Rossi and others that cosmic rays consist of two components: a soft component and a penetrating component[19]. The intensity of the soft component is reduced by about 30 percent in passage through about 10 cm of lead. There are, however, also single charged particles, belonging to the penetrating component, which can traverse one meter of lead. The properties of the soft component could be completely accounted for, by Bhabha-Heitler theory, if it consisted of electrons. The penetrating component was, however, still an enigma. It was not possible for quantum electrodynamics to account for the penetrating component if these particles were electrons. There was therefore a breakdown of quantum electrodynamics for higher energies and/or the penetrating components was not composed of electrons.

Bhabha, in a remarkable paper submitted to the Royal Society on Oct. 4, 1937, carried out a powerful analysis of both the theoretical and the observational situation about the penetrating component of cosmic radiation[20].

He first showed that a "breakdown" of quantum electrodynamics for the energy loss of electrons was not a viable alternative for the observed phenomenology of cosmic radiation. He showed that if the breakdown energy is around 10 GeV or higher for electrons then no

latitude effect would be there at sea level. The shape of the transition curve for large showers also led to a similar conclusion.

It therefore seemed that a viable alternative is to regard the penetrating component of cosmic radiation as consisting of particles other than electrons. Could they be protons? Initially Bhabha and Heitler had inclined to this view while Blackett was of the view that they are electrons. It, however, gradually became clear that these particles could not be protons either in view of Blackett's arguments against the proton hypothesis[21].

Bhabha therefore investigated in this paper the hypothesis that "There are in the penetrating component of Cosmic radiation new particles of electronic charge of both signs, and mass intermediate between those of the electron and proton"[22]. He called them heavy electrons. The illustrative mass values considered were 10 and 100 times the electron mass. We quote "A comparison with the measurements of Auger and others therefore allows one to conclude that if the hypothesis of new particles is right, *the majority of the penetrating particles must have masses nearer to a hundred times the electron mass rather than ten times the same*"[23]. Thus Bhabha had, in a brilliant piece of cosmic ray phenomenology, essentially predicted the existence of a new particle. Similar conclusions had also been reached by Neddermyer and Anderson, and by Street and Stevenson[24]. These particles are now called muons and the first clear case of their track was observed in Cosmic rays in 1938 by Anderson and Neddermyer[25]. Their mass is about two hundred electron masses.

2.3 Meson Theory

Bhabha, when he predicted the "meson" in October 1937, was not aware of Yukawa's meson theory[26], which was brought to his attention by Heitler in a discussion about cosmic radiation presumably some time between October 4, 1937 and Dec. 13, 1937 when he sent his first note on meson theory for publication[27]. It was natural for Bhabha to identify Yukawa's mesons with those indicated by cosmic ray phenomenology.

2.3.1 A Test of Relativistic Time-dilation

It was first pointed out by Bhabha, in his note to Nature[27] that positive (negative) mesons should sponteneously decay into a positron (electron). In this note he also pointed out "This distintegration being spontaneous, the U-particle may be described as a 'clock', and hence it follows merely from considerations of relativity that the time of distintegration is longer when the particle is in motion". The U-particles referred to the mesons. Thus the lifetime of a particle T, moving with a velocity v, should be given by

$$T = T_0 / \sqrt{|1 - (v/c)^2|}$$

where T_0 is the lifetime of the particle at rest and c is the velocity of light. This was nicely confirmed by experiments and constitutes one of the most beautiful tests of the special theory of relativity.

2.3.2 <u>Vector-Meson Theory</u>

The identification of Yukawa's mesons with those required by cosmic ray phenomenology allows one to couple the problem of nuclear forces with that of the cosmic rays. It may be noted that the particles required by cosmic ray phenomenology are now identified with muons, while the Yukawa mesons are identified with the pions which were only discovered in 1948 by C.F. Powell. However this confusion of the Yukawa mesons with muons was very fruitful as it gave a great impetus to the development of the meson theory which had not received much attention till that time. The earliest major workers on Meson Theory, apart from those in Yukawa's group i.e. S. Sakata and Taketani, were Bhabha at Cambridge, N. Kemmer in London, H. Fröhlich and W. Heitler at Bristol.

The original Yukawa theory had considered the mesons to be scalar particles, i.e. having no spin and with positive parity. This assignment does not give rise to a satisfactory nuclear force between nucleons i.e. protons and neutrons. Mesons, further, have to have integral spin and must obey Bose-Einstein statistics. Bhabha therefore considered the generalisation that the mesons are vector particles i.e. having spin one and odd parity. He used Proca's wave equation to describe the meson field. The coupled nucleon-meson field system was then quantised and nucleon-nucleon interaction calculated using second order perturbation theory. Bhabha was gratified that "The interaction is therefore just of the required form consisting of Heisenberg and Majorana forces of the right sign so as to allow one to make the triplet state of the deuteron the lowest stable state. We would emphasize the fact that since only the squares of g_1 and g_2 enter into this expression, the sign of the Majorana force is beyond our control, and it is to be looked upon as a strong argument in favour of this theory that it allows only that sign of the force which actually occurs in nature"[28]. Bhabha also calculated meson-nucleon scattering crosssections in the lowest order. There were at that time no data for this process. Related investigations were also carried out by other workers.

2.3.3 <u>Classical Meson Theory</u>

The vector nature of the meson fields gave rise to large probabilities at high energies for multiple processes. Also the theory had more severe divergence problems compared to quantum electrodynamics. There were apprehensions that these imply the breakdown of either quantum mechanics or meson theory even for lower energies comparable to meson mass. All of these were essentially based on second order perturbative calculations in meson-nucleon coupling constants. It is to be remembered that these coupling constants are rather large as the meson-nucleon interaction is strong. As such these calculations are not necessarily reliable.

In order to escape the limitations of the perturbation theory in coupling constant, in dealing with quantum meson-field theory, Bhabha decided to investigate the classical meson field theory in interaction with a fermion[29]. The meson field was described, as earlier, by the Proca wave equation, except that now the meson field components were taken as commuting

variables. The fermion was taken as a point classical particle having spin and moving along classical world-lines. This entailed a generalisation of the method of Dirac used in treating the behaviour of a classical point electron in the field of electromagnetic radiation[30].

The meson-fermion scattering crosssections were calculated. These are analogous to Thomson scattering for zero mass photons and were found to smoothly go to that limit as meson mass went to zero. Indeed it was found that at high energies, i.e. energies much larger than meson mass, the behaviour was essentially the same as that in Dirac's case. Before the advent of the Chew-Low theory, these were among the best theoretical attempts to deal with the meson-nucleon scattering problem.

3. Bangalore Period

Bhabha was in India, in 1939, on a holiday when the second world war broke out. The subsequent war conditions made it impossible for him to return to England. His earliest communications to the Proceedings of the Indian Academy of Sciences are from this period and were received by them in October 1939. The second of these two papers deals with the classical theory of the electron and is still bylined as Gonville and Caius College. In early 1940 Bhabha joined Indian Institute of Science, Bangalore as special Reader incharge of a Cosmic Ray Unit.

3.1 <u>Classical Relativistic Spinning Point Particle Theory: Bhabha-Corben equations</u>

Bhabha was originally drawn to the classical theory of relativistic point particles as a way to take into account the reaction of the emitted or scattered radiation, whether of electromagnetic quanta or of mesons i.e. radiation reaction, on the motion of fermions. The quantum treatment of the interaction of point particles with fields, which depended on the perturbation theory in the coupling constant, was not very satisfactory. It was even more so when the explicit spin dependant interaction, e.g. Pauli anomalous moment term for interaction with electromagnetic field or similar for vector meson fields, were taken into account. The interactions tend to increase with energy. It was pointed out by Bhabha that these effects are due to neglect of the radiation reaction and that the quantum treatment can be trusted only in the region of energy where this neglect of radiation reaction is justified. Faced with this situation it was natural to go back to the classical limit where it is, in principle, possible to take radiation reaction into account either exactly or with controlled approximations. For spinless charged particles it was possible to do this by using Dirac's work on the point electron theory[30]. The electron theories had been in existence since Lorentz's work in 1892 but Dirac's work of 1938 was the first logically correct relativistic classical point electron theory.

In Dirac's work the spin of the electron was not taken into account. It was therefore necessary to generalise Dirac's work to the case of spinning point particles. Bhabha had already begun some work on this problem with H.C. Corben before leaving Cambridge and

it was continued at Bangalore. A preliminary note on this work was sent to Nature on March 17, 1940 and was his first research note from Indian Institute of Science, Bangalore. The definitive paper on this work, giving Bhabha-Corben equations, was titled "General Classical Theory of Spinning Particles in a Maxwell field"[3]. The case of a meson field was treated in a sequal which followed immediately after this paper[3].

The point electron theories previous to the work of Dirac, and related work of Pryce, had approached the problem of a point electron as the limit of a finite-size electron. This procedure is not very satisfactory in view of the conflict between the concept of a rigid-body and relativity. In the procedure of Dirac and Pryce one assumes the validity of field equations right upto the point particle world-line but one modifies the definition of the field energy in the presence of singularities. This is also the procedure adopted by Bhabha and Corben.

The effect of radiation reactions was, as expected by Bhabha, to reduce the scattering crosssection. Indeed for large energies it was found to decrease inversely as the square of the incident photon frequency for the compton-process.

Bhabha was elected a Fellow of the Royal Society, London in 1941.

3.2 <u>Meson Theory and Nucleon Isobars</u>

Before the discovery of the pion in 1947 the muon was confused with Yukawa's meson. The meson theorists had the unenviable task of explaining as to why the meson-nucleon scattering is weak – since muons do not scatter much on the nucleons – and yet at the same time the nuclear forces arising from the exchange of the same mesons is strong.

It was noted by Bhabha that the scattering of the longitudinally polarised *neutral* vector mesons on nucleons shows a decrease as E^{-2}, E being the meson energy, for large energies in contrst to the scattering of longitudinally polarised *charged* mesons whose scattering on nucleons increases as E^2. This difference was traced by Bhabha to what we would refer in modern terminology as being due to the cancellation between direct channel nucleon pole and the crossed channel nucleon pole in case of neutral mesons and a lack of such a cancellation for charged mesons. For charged mesons we do not have both direct and crossed channel exchanges possible if only Nucleons of charge +1 and 0 exist. In order to have the cancellation mechanism available, Bhabha therefore suggested that the nucleon may exist in charge states +2 and -1 also. The contribution from these charged states was needed to provide the cancellation. In general nucleon isobars may have any charge and neutron and proton are only the lightest ones occuring in nature[31]. This was the first suggestion of the existence of the nucleon isobars.

Bhabha communicated the idea to Heitler and he also pursued it. This mechanism, referred to as Bhabha-Heitler mechanism, for reducing the mesons crosssections, was one of the major reasons for a study of the strong coupling theory of nucleon isobars. The first nucleon isobar $N^\star$ (1240 MeV) was discovered by Fermi et al in the pion-nucleon scattering experiments in 1952.

3.3 <u>Cosmic Rays</u>

In his capacity as special reader in charge of cosmic ray unit at Indian Institute of Science, Bangalore, Bhabha planned to pursue both theoretical and experimental work in the area of cosmic rays. The unit was set up as part of the department of Physics which was headed by Nobel Laureate Sir C.V. Raman. Given his pioneering work on cosmic ray showers with Heilter, and the scope offered by the experimental work on Cosmic to study high energy interaction, involving particle production, it was a natural choice. India also offered a tremendous geographical advantage of comprising magnetic latitudes ranging extensively from equator to 25° North within its' confines for studying high energy cosmic rays.

3.3.1 <u>Cascade theory</u>

The initial cosmic ray work in the cosmic rays concerned itself with refinements of the classic Bhabha-Heitler theory. They had made a number of simplifying assumptions. In particular it was assumed that one can ignore collision loss below a certain critical energy i.e. the energy at which collision loss is equal to radiation loss. Further if the energy is above this critical energy it was assumed that it would lead to an absorption of the cascade. In view of the improvement in the quality of the observational data it had become necessary to improve the theoretical treatment.

There had been previous attempts, notably by Snyder and Serber, to give an improved treatment taking collision loss into account[32], but there were some doubts about the convergence of their series solutions. Bhabha and Chakrabarty gave a solution of this problem in the form of a rapidly converging series[33].

In all these treatments the lateral spread of the shower is neglected. The collision loss is taken as a constant β independent of the energy of the charged particle. Actually it is not strictly constant but in the whole relevant energy range of 5 to 150 MeV it increases less than by a factor of 1.5 and it is thus reasonable to treat it is a constant. For radiation loss and pair creation one can use the exact expressions of Bethe and Heitler. An exact solution of the Landau-Rumer equations[34], describing the longitudinal evolution of the shower, for the number of charged particles and radiation quanta was given by K.S.K. Iyengar[35]. His solution was, however, not easily amenable to extracting numerical results. Bhabha and Chakrabarty, used the asymptotic form of the Bethe-Heitler expressions, in their solution. Using Mellin transform techniques it was then possible to obtain a series solution which was rapidly convergent. It is possible to regard the Bhabha-Chakrabarty solution as an analytic continuation of the results of Snyder and Serber.

3.3.2 <u>Experimental cosmic ray work</u>

The first problem which Bhabha decided to tackle experimentally in cosmic rays was to study latitude effect for mesons. The soft component of the cosmic rays, consisting of electrons, positrons and gamma rays, was described quite correctly by the cosmic ray shower

theory. The hard component of the cosmic rays, consisting mainly of mesons, was much less understood theoretically and needed experimental observations. The hard component would also include high energy protons.

In order to devise experimental set up to study the hard component of the cosmic rays, containing mesons, it was necessary to devise procedures to discriminate between the soft and the hard components experimentally. Bhabha studied this problem in 1943. He came to the conclusion, using recent detailed work of Bhabha and Chakrabarty[33] on the cosmic ray showers, that the usual method of separating the two components of cosmic rays by interposing absorbers, such as lead, of different thickness, and measuring the cosmic ray absorption, is not sufficiently reliable.

Bhabha devised a new method (Bhabha method) for this purpose. The absorper of total thickness t is divided into two of thickness t_1 and $t-t_1$. Between the two parts of the absorbers are interposed a set of counters C and D in anticoincidence. The whole sandwich is then placed between the set of counters A on one side and counters B on the other side. The set of counters A, B and C (or D) are in coincidence. Bhabha showed that such an arrangement would be able to take better advantage of shower multiplication by soft component to better discriminate the soft and the hard component[36].

The experimental measurements of the vertical intensity of mesons were carried out in two aeroplane flights at Bangalore with magnetic lattide of 3.3° N.[37] The first flight carried two sets of counter telescopes viz (i) with total thickness of lead absorber equal to 5.25 cms and divided into two absorber one of 1.25 cm and other of 4.0 cm. The arrangement here used Bhabha method and (ii) a quadruple coincidence counter telescope with 3.0 cm of lead absorber. The measurements were taken upto 15000 ft. The second flight carried a quadrupole coincidence counter with 20 cm of lead and carried out measurements upto 30,000 ft. A comparison of the experimental measurements by Bhabha and his group in these flights with those of Schein, Jesse and Wollan[38] carried out at Chicago, magnetic latitude 52.5° N, showed that for meson intensity there was "no marked increase even to attitudes corresponding to 275 milli bars pressure". This was quite in contrast to the total cosmic ray intensity which showed a marked increase of latitude effect upto these heights.

Another flight making such measurement later extended the results upto an attitude of 40,000 ft above Bangalore with similar results.

4. Bombay Period

During the five year period in Bangalore "he found his mission in life"[39] as an institution builder. As a result of correspondence with J.R.D. Tata and Sir Sorab Saklatvala, he founded the Tata Institute of Fundamental Research at Bombay in 1945. The institute started functioning in June 1945 with H.J. Bhabha as its Director and was formally inaugurated on 19 December 1945. Initially the work at the Institute was carried out in the areas of mathematics, theoretical physics and a continuation of the experimental work in cosmic

rays. He was appointed as the first chairman of the Atomic Energy Commission when it was founded in 1948 and became Secretary to the Department of Atomic Energy of the Government of India in 1954.

4.1 Bhabha Equations

The first research paper from Tata Institute dealt with "Relativistic Wave Equations for the Elementary Particles" and appeared in an issue of Reviews of Modern Physics to commemorate the Sixtieth birthday of Prof. Niels Bohr[4].

Dirac, as mentioned earlier, had given his relativistic wave equation in 1928 which described the behaviour of electrons with spin one half and had successfully predicted the existence of positrons. Dirac equation was a first order equation and its success encouraged similar attempts to find wave equations describing particles with a spin having a value other than one half. Duffin, Kemmer and Petiau had given similar first order wave equations describing particles with spin-0 and spin-1. The spin-1 equations were Proca equations. Dirac, and Fierz and Pauli had proposed relativistic wave equations for particles having any integral or half-odd integral spin. An unsatisfactory feature of the equations proposed by Dirac, and Fierz and Pauli for spin greater than one, was the presence of subsidiary conditions. These subsidiary conditions created difficulties when one considered these particles in interaction with electromagnetic fields. The difficulty was connected to the fact that these could not be derived from a variational principle. Bhabha therefore proposed to investigate general first-order relativistic wave equations, without any subsidiary conditions i.e. equations for wave field ψ of the form

$$(\alpha^k p_k + \chi)\psi = 0$$

where $p_k = i\partial/\partial x^k$, α^k s are four matrices ($k = 0, 1, 2, 3$) and χ is an arbitrary constant. Such equations have come to be known as Bhabha equations. Sometimes the nomenclature "Bhabha equations" is used to refer to a restricted subclass of equations where six Lorentz generators, together with four α^k s, form an $SO(5)$ algebra. This restricted subclass was investigated by Bhabha in detail and from now on in this section we shall mean this subclass when we refer to Bhabha equations.

As Bhabha equations involve an $SO(5)$ algebra they can be completely classified by using the representation theory of the $SO(5)$ algebra. Bhabha was among those few physicists of his time who were at home with group theory. His essay "The Theory of the Elementary Physical Particles and their Interactions", for which he was awarded Adams Prize in 1942, had contained a fair amount of the theory of orthogonal groups. Bhabha equations were found to contain Dirac equation for spin one-half and Duffin-Kemmer-Petiau equations for spin-0 and spin-1 as special cases. These equations were special cases for Dirac-Fierz-Pauli equations also. Bhabha equations, for spin greater than one, were however from Dirac-Pauli equations, and led to multiple mass states.

4.2 Cosmic Rays

4.2.1 Cascade Theory and Stochastic Processes

Bhabha and Chakrabarty extended their calculations of the number of charged particles and quanta, in 1948, to cover the case of showers in thin layers. They brought to completion this part of their work on cascade theory which deals only with mean numbers of shower particles at various depths.

The study of the fluctuations of the number of shower particles is also of great importance in the study of cosmic ray showers. One of the conceptual difficulties in attacking the problem was that it involved a system whose state space was continuous and not discrete. The electrons and photons do have a continuous variation in energy. Bhabha therefore derived the product density function method for the continuous parametric systems and applied it to derive the equations for the cosmic ray cascade theory which determine the mean numbers (i.e. Landau-Rumer equations) and the mean square deviations of the numbers[40]. These equations were solved in a subsequent paper with Ramakrishnan[41].

4.2.2 Experimental work in Cosmic rays

The program of measuring the hard component of the cosmic ray intensity, at various Indian latitudes and it's variation with altitudes was continued at Bombay. Towards this objective Bhabha organised a High Attitude Studies group whose main program was to organise Balloon flights for these studies. The balloon flights were initially made at from Bangalore and Delhi. Bhabha reported these results at a conference at Kyoto-Tokyo in 1953.[42] Later flights were also made from many other locations as well.

Bhabha made a preliminary begining for nuclear emulsion work with cosmic rays by flying in an airplane a Ilford C2 plates loaded with Boron at an average altitude of 8000 ft for 72 hours in 1948. An example of "meson" scattering with nuclear excitation was recorded and published with his student Roy Daniel[43]. Later Bhabha induced Bernard Peters, of Rochester University, to take over the Nuclear emulsion group at Bombay in Dec. 1950. Peters was well known for his discovery of heavy nuclei in primary cosmic rays.

A 12″ diameter cloud chamber, similar in design to one at Blackett's laboratory at Manchester, which Bhabha had got built at Bangalore was also moved to Bombay and work on meson scattering continued. Prof. Sreekantan took over the further developments here[44].

Bhabha also started thinking about Kolar Gold Fields as a facility for deep underground experiments on cosmic rays around 1950. Prof. M.G.K. Menon joined the Cosmic ray group from Prof. Powell's group in 1956.

4.3 <u>Multiple Meson Production</u>

This is essentially Bhabha's last piece of theoretical research work[45]. His work in Bangalore and Bombay had been decidedly more mathematical as compared with his work at Cambridge which had been on the whole, phenomenological. In his work on multiple meson production he again displays a phenomenological strain.

In the center of mass system the two colliding nucleons suffer relativistic contraction in the direction of motion and appear as colliding discs. Different mechanisms were invoked by Fermi and Heisenberg as to how the nucleon energy is converted into mesons. Bhabha suggested the hypothesis that the strong interactions get localised both due to relativistic contraction as well as due to the time of interaction being very small. On this picture the energy available for meson production is much less than the total available c.m. energy.

The real surge of interest in multiple meson production had to wait till early nineteen seventies when sufficient high energy data became available. In Bhabha's picture it is somewhat natural to assume that not only the strong interaction gets localised but the production of mesons also gets localised, leading to a damping of transverse momenta[46]. Bhabha's model thus can be regarded as a oprecursor of the parton model.

5. Concluding Remarks

Bhabha's work in theoretical physics was carried out in a wide variety of styles. His work, with Heitler, on cascade theory, is of a kind which would now be described as phenomenology. Some of his work had speculative components e.g. his work on penetrating component of cosmic rays where he suggested the existence of "muon" like particles and his work on meson-nucleon scattering where he suggested the existence of "nucleon isobars" especially those having electric charge of +2 and -1 in the units of proton charge. His work on the theory of relativistic spinning particles in classical physics was originally motivated by the problem of radiation reaction. One cannot, however, help feeling that this motivation was strongly reinforced by the aesthetic appeal of this investigation. Here one has a well defined "complete" theory in a world described by classical physics. The finer aspects of this theory cannot be tested in the real world as there are important quantum corrections which vitiate any testing. His work on relativistically invariant wave equations, though motivated by a possible application to "nucleons", could be regarded as almost pure mathematical group theory. In fact work on these equations provided the backgorund for the later important work on the theory of noncompact groups by his collaborator Harish-Chandra.

Though Bhabha's main scientific work and achievements were in theoretical physics. He was sensitive to the importance of experimental work as well. His cosmic ray experiments were not carried out by using techniques used in similar work elsewhere but used a noval method devised by himself.

We have restricted ourselves in this paper to the research contributions of Bhabha in physics. This hardly exhausts Bhabha's contribution to science. He played an important

role as a developer of scientific institutions in India. He was also an excellent science administrator with an innovative style of management. More than any other person, Bhabha was responsible for introducing and nurturing modern nuclear science and technology in India. His role in the emergence of Bombay school of modern Indian painting has also been taken note of. But, in a sense, all these later achievements of Bhabha have their origins in the excellence he achieved in his scientific research.

Bibiliographical Notes:

This paper overlaps in some places with author's earlier related writings:

(1) H.J. Bhabha: His Contributions to Theoretical Physics, in Homi Jehangir Bhabha: Collected Scientific Papers, Editors: B.V. Sreekantan, Virendra Singh and B.M. Udgaonkar, p.xxii-xlvii, TIFR, Mumbai (1985).

(2) H.J. Bhabha in The Scientist in Society, p. 181-193, Thema, Calcutta (2000).

References

1. H.J. Bhabha, Proc. Roy. Soc. (London) 154A, 195 (1936).

2. H.J. Bhabha and W. Heitler, Proc. Roy. Soc. (London), 159A, 432 (1937).

3. H.J. Bhabha and H.C. Corben, Proc. Roy. Soc. (London), 178A, 273 (1941) and
H.J. Bhabha, Proc. Roy. Soc. (London), 178A, 314 (1941).

4. H.J. Bhabha, Rev. Mod. Phys. 17, 200 (1945).

5. N. Kemmer, Suppl. Progr. Theor. Phys., 30th Anniversary of Meson theory issue, p. 602-608 (1965).

6. H.J. Bhabha, Rev. Mod. Phys. 21, 451 (1949).

7. H.J. Bhabha and H.R. Hulme, Proc. Roy. Soc. (London) 146A, 723 (1934).

8. H.J. Bhabha, Proc. Roy. Soc. (London) 152A, 559 (1935), and
H.J. Bhabha, Proc. Camb. Phil. Soc. 31, 394 (1934).

9. N.F. Mott, Proc. Roy. Soc. (London) 126A, 259 (1930).

10. C. Möller, Ann. Physik 14, 531 (1932).

11. Ref. 1 p. 196.

12. W. Pauli and W. Weisskopf, Helv. Phys. Acta, 7, 709 (1934).

13. K. Baumann, Acta Physica Austriaca $\underline{7}$, 96 (1953).

14. H.J. Bhabha, Zeits. f. Physik $\underline{86}$, 120 (1933).

15. B. Rossi, Int. Conf. on Nucl. Phys., London (1934).

16. G. Pfotzer and E. Regener, Nature (London) $\underline{136}$, 718 (1935).

17. Ref. 2 p. 434.

18. J.F. Carlson and J.R. Oppenheimer, Phys. Rev. $\underline{51}$, 220 (1937).

19. B. Rossi, Ric. Scient. $\underline{1}$, vi.559 (1934);
    P. Auger and L. Leprince-Ringuet, C.R. Acad. Sci. Paris $\underline{199}$, 785 (1934).

20. H.J. Bhabha, Proc. Roy. Soc. (London) $\underline{164A}$, 257 (1938).

21. P.M.S. Blackett, Proc. Roy. Soc. (London) $\underline{159A}$, 1 (1937).

22. Ref. 20 p. 258.

23. Ref. 20 p. 281.

24. S.H. Neddermeyer and C.D. Anderson, Phys. Rev. $\underline{51}$, 884 (1937);
    J.C. Street and E.C. Stevenson, Phys. Rev. $\underline{51}$, 1004 (1937).

25. S.H. Neddermeyer and C.D. Anderson, Phys. Rev. $\underline{54}$, 88 (1938).

26. H. Yukawa, Proc. Phys-Math. Soc. Japan $\underline{17}$, 48 (1935).

27. H.J. Bhabha, Nature (London) $\underline{141}$, 117 (1938).

28. H.J. Bhabha, Proc. Roy. Soc. (London), $\underline{166A}$, 501 (1938). See p. 524.

29. H.J. Bhabha, Proc. Roy. Soc. (London) $\underline{172A}$, 384 (1939).

30. P.A.M. Dirac, Proc. Roy. Soc. (London) $\underline{167A}$, 148 (1938).

31. H.J. Bhabha, Proc. Ind. Acad. Sci. $\underline{11A}$, 347, 468 (1940);
    H.J. Bhabha, Phys. Rev. $\underline{59}$, 100 (1940).

32. H. Snyder, Phys. Rev. $\underline{53}$, 960 (1938);
    R. Serber, Phys. Rev. $\underline{54}$, 317 (1938).

33. H.J. Bhabha and S.K. Chakrabarty, Proc. Roy. Soc. (London) $\underline{181A}$, 267 (1943) and
    Proc. Ind. Acad. Sci. $\underline{15A}$, 464 (1942).

34. L. Landau and G. Rumer, Proc. Roy. Soc. (London) $\underline{166A}$, 213 (1938).

35. K.S.K. Iyengar, Proc. Ind. Acad. Sc. $\underline{15A}$, 195 (1942).

36. H.J. Bhabha, Proc. Ind. Acad. Sc. <u>19A</u>, 530 (1944).

37. H.J. Bhabha, S.V. Chandrasekhar Aiya, H.E. Hoteko and R.C. Saxena, Current Science <u>14</u>, 98 (1945); Phys. Rev. 68, 147 (1945); and Proc. Nat. Inst. Sci. India <u>12</u>, 219 (1946).

38. M. Schein, W.P. Jesse and E.O. Wollan, Phys. Rev. <u>47</u>, 207 (1935) and <u>57</u>, 840 (1940).

39. M.G.K. Menon, in "Homi Jehangir Bhabha" 1909-1966, The Royal Institution of Great Britain, London (1967) p. 17.

40. H.J. Bhabha, Proc. Roy. Soc. (London) <u>202A</u>, 301 (1950).

41. H.J. Bhabha and A. Ramakrishnan, Proc. Ind. Acad. Sc. <u>32A</u>, 141 (1950).

42. H.J. Bhabha, Proc. Intl. Conf. on "Theoretical Physics", Kyoto-Tokyo (1953), (Sc. Council of Japan) p. 95 (1954).

43. H.J. Bhabha and R.R. Daniel, Nature (London) <u>161</u>, 883 (1948).

44. B.V. Sreekantan in "Homi Jahanger Bhabha: Collected Scientific Papers".

45. H.J. Bhabha, Proc. Roy. Soc. (London), <u>219A</u>, 293 (1953).

46. D.S. Narayan, Nucl. Phys. <u>B34</u>, 386 (1971).