Historical Note

Bibha Chowdhuri – Her Cosmic Ray Studies in Manchester

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Abstract

The name Biva/Bibha Chowdhuri/Chaudhury (1913-1991) appears in literature whenever there is a talk of the experimental discovery of mesotrons/mesons and there are enough reasons for it. She can be seen as the first Indian woman in the field of high energy particle physics. She obtained her Ph.D. degree from the University of Manchester on cosmic rays, in the laboratory of the Nobel Laureate PMS Blackett. However, very little is known about her Ph.D. work at Manchester. The present article focuses on her work at Manchester leading to her Ph.D. degree and discusses the acceptance of her work by the international scientific community.

Key words: Bibha Chowdhuri, Bose Institute, D M Bose, Extensive air showers, Mesons.

1. INTRODUCTION

We found a variation in the spelling of her name: Biva Chaudhuri, Bibha Chowdhuri, B Chaudhury. We have followed the spelling Bibha Chowdhuri (abbreviated as BC) in this article as we found the same on the title page of her Ph.D. thesis (Fig. 1), which can therefore be considered as her authentic spelling.

Bibha Chowdhuri was born at a time when higher studies in science in India was at its beginning. BC did her M.Sc. in physics from the Calcutta University in the year 1936 and joined Calcutta University immediately after under Professor D M Bose for her Ph.D. degree. When D M Bose joined Bose Institute as its Director after the death of Sir J C Bose in 1937, his students including BC, followed him to join Bose Institute. At that time very few women ventured to undertake postgraduate studies in physics and this was more true in India. Seen in Indian context,

Fig. 1. Cover page of Bibha Chowdhuri's Ph.D. thesis submitted in 1949 at Manchester University, UK. Note that the thesis was typed in a manual typewriter. (Courtesy: Manchester University, UK)

the courage exhibited by BC to undertake physics research for a Ph.D. degree is legendary. An extensive study by R M Godbole and R Ramaswamy shows that until 2012 only 3.3% of INSA Fellows in physics were women whereas in

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Chemistry this number is 0.08%. The total number for all subjects together is 5%. “The percentage of women in the fellowship for the IASc is 7%, for INSA it is 5%, the numbers being fairly similar in other academies. In TWAS as well, the percentage of women Fellows is around 7%.” (Godbole and Ramaswamy, 2015, pp. 67-84).

History is replete with many instances where achievements made by women in science and other fields had, in general, been underestimated and marginalised and due credit had been denied. Therefore, it is not surprising that very little has been written on Indian women scientists.¹ Rohini M Godbole, Centre for High Energy Physics, Indian Institute of Science (IISc), Bangalore, in a conference said that

‘there was no such thing as women’s science. The participation of women in science in India is meagre. I will look forward to a day when people don’t say, ‘I’m a woman scientist, instead they say I’m a scientist’ (Basu, 2016).’

Not long ago, the Indian Academy of Sciences, Bangalore brought out ‘*Lilavati’s Daughters: The Women Scientists of India*’ (Godbole and Ramaswamy, 2009, pp. 68-69). The book deals with 100 women scientists from Victorian era to present-day. S Raychaudhuri, TIFR, in his writing on ‘The early days of particle physics in India’ states: ‘Even the landmark volume on Indian women scientists, *Lilavati’s Daughters* ..., does not feature her [B. Chowdhuri’s] name (Raychaudhuri, 2016, pp. 148-172).’ None of the three Science Academies of India elected her to be a Fellow.² Recently, in ‘*Scientifically Yours - Selected Indian Women Scientists*’, life history of 13 Indian women scientists has been explored (Bhattacharya, 2017,

pp.351-352). This also does not include the name of BC.

To the best of our knowledge almost nothing has been written on Bibha Chowdhuri who was the first Indian woman to work on cosmic rays or rather high energy particle physics. Her life and scientific work will be explored by the present authors in a book to be published soon (Singh and Roy, 2018). The present article focuses on her scientific work done in the U.K. and the reception of her work by the western scientific community. We have also tried to explore the reasons for her courageous choice of profession.

2. BIBHA CHOWDHURI – EARLY LIFE

Almost nothing is known or available about Bibha Chowdhuri’s life, except a brief life sketch published in a Bengali magazine by Ranatosh Chakrabarti (2005, pp.159-161), Roy and Singh (2018, pp. 159-164). Most of the information about Bibha Chowdhuri and her family presented in this article has been obtained from Ms. Rita Sarkar (*nee* Palit), wife of my (Roy’s) physicist friend Dipak Sarkar. Rita Sarkar had been in close association with the family of Bibha Chowdhuri for a long time. The Palit family and Chowdhuri family lived in two adjacent houses on Upper Circular Road (now Acharya Prafulla Chandra Road) and then lived in the same premises on Broad Street, Kolkata (erstwhile Calcutta). Bibha Chowdhuri died in her Broad Street residence on 2nd June, 1991.

Bibha Chowdhuri was born in 1913. Her father Banku Behari Chowdhuri was a doctor by profession. They were zamindars of Bhandarhati in the district of Hooghly in Bengal. Her mother

¹ For the study of three Indian women physicists, who worked in C.V. Raman’s laboratory and Raman’s reaction to them, see, Sur A., *Dispersed Radiance: caste, gender and modern science in India*, Navayana Publishing, New Delhi 2011. Sur A. *Dispersed Radiance - Women Scientists in C. V. Raman’s Laboratory*, Meridians 1, 95-127, 2001. Other worth reading book is by Krishna S., Chadha G., Eds., *Feminists and Science: Critiques and Changing Perspectives in India*, Sage Publications India Pvt. Ltd., New Delhi 2017.

² We are thankful to Professor Arnab Rai Chaudhuri, Indian Institute of Sciences, Bangalore, for this information.

was Urmila Devi, daughter of Girish Chandra Mazumdar. Urmila's sister Nirmala was married to Sir Nilratan Sircar, a famous doctor, after whose name the Campbell Medical School at Sealdah, Kolkata was renamed. Urmila Devi's family was Brahmo (who followed the doctrines of Brahmo Samaj). Brahmo Samaj discarded the multi-god Hindu beliefs, idolatory and rituals and focussed on education especially among women. Her upbringing, as we understand, was influenced by the doctrines and attitudes of Brahmo Samaj.

In order to marry Urmila, Banku Behari had to convert to the Brahmo doctrine and became a member of Brahmo Samaj. This change of religious following costed him badly and he had to lose the right to the property of his parents.

Banku Behari had five daughters and one son. Eldest daughter Roma Chowdhuri was a teacher at Brahmo Balika Vidyalaya (Brahmo Girls' School) in Kolkata. After retirement she started a nursery school "Southern Nursery and Infant School" on Ritchie Road (now known as Pankaj Mallik Sarani) in Kolkata. The school is still running. His second daughter died at an early age. His third daughter was Bibha Chowdhuri born in 1913. The fourth daughter of Banku Behari was Leela Chowdhuri who worked in Tea Board in Kolkata for a while. Later she went to England to be trained in the Montessori system of education. She retired as Principal of Jadavpur Vidyapith (Junior Section) in Kolkata. The youngest daughter of Banku Behari was Uma Chowdhuri who did post-graduation in psychology from Calcutta University and did her Ph.D. in social psychology from the USA. After her return from the USA, she took a job in the Health Department of West Bengal Government. She worked on the social aspects of aborigines (like *jarwās* in Andaman), *santhāls* etc. Ranjit Chowdhuri was the only son and youngest of all, who obtained his engineering degree from Jadavpur University in Kolkata. He was Sales Manager in English Electrics.

All her siblings and she herself remained un-married. One probable reason, as we feel, is that Brahmos were a small community and they preferred to make matches within their own community. As because they were alienated from the main stream Hindu society, getting a proper match within the Brahmo community was difficult. In general, "The proportion of women scientists who never married (14%) is higher than that of similar male scientists (2.5%), ..." ³

3. BIBHA CHOWDHURI IN BOSE INSTITUTE

Immediately after obtaining her M.Sc. degree in physics from Calcutta University in 1936, Bibha Chowdhuri started working under D M Bose, Palit Professor of Physics, at Calcutta University. When D M Bose joined Bose Institute as its Director in late 1937, all his research students, including BC, also joined Bose Institute. According to M S Sinha, her colleague at Bose Institute and batch-mate of M.Sc. class, she worked at Bose Institute during the period 1939-42 (Sinha, 1986, pp.359-367). However, we find a report titled 'Studies in nuclear disintegration by cosmic rays using photographic plate method' published in the Annual Report of Bose Institute for the year 1938-39 which indicates that she was in Bose Institute before 1939.

She made a significant contribution towards the discovery of mesons using photographic plates while in Bose Institute and published three papers consecutively in *Nature* (Bose and Chowdhuri, 1941, pp. 240-241; 259-260; 1942, 302). She was involved in a work in which several batches of Ilford half-tone plate were exposed to cosmic rays at two stations located at different altitudes: Sandakphu (12000 ft.) and Pharijong (15000 ft). After developing and processing these plates, BC scanned them under the microscope and found that many of the recorded tracks were curved. Such curvature was not observed in α -tracks from Po or proton tracks obtained from elastic scattering of neutrons from

³http://www.ias.ac.in/public/Resources/Initiatives/Women_in_Science/AASSA_India.pdf, Feb. 16, 2018.

a radium-beryllium radioactive source recorded in the same emulsion. The curvature in these tracks was due to multiple Coulomb scattering of these particles of various momenta by nuclei present in the emulsion and the variable grain spacing along the tracks was due to variable velocity of the charged particle as it slows down in the emulsion. A careful analysis of the mean Coulomb scattering and mean grain spacing of measured track lengths in the emulsion led to a division of the tracks into two groups having the same mean grain spacing ($5 - 6 \mu$ (same velocity) but different mean angles of scattering. These estimates finally gave the average mass of the first group (almost all recorded at Sandakphu) as $221 m_e$ and the average mass of the other group (all recorded at Pharijong) as $278 m_e$ (m_e is mass of electron). Furthermore, the particles of higher mass were recorded at a higher altitude leading to a tentative conclusion that those recorded at lower altitude (Sandakphu) were the decay products of those recorded at the higher altitude (Pharijong). These investigations could not be continued due to the non-availability of more sensitive emulsion plates during the war years. Seven years after this discovery of mesons by D M Bose and Bibha Chowdhuri, C F Powell made the same discovery of pions and muons and further decay of muons to electrons using C2 and G5 electron sensitive plates using the same technique as was used by D M Bose and Bibha Chowdhuri and won the Nobel Prize.

Bibha Chowdhuri left Bose Institute and joined the cosmic ray research laboratory of P M S Blackett at the University of Manchester in 1945. It is unclear why BC, in spite of her significant work, did not go for a Ph.D. degree from the University of Calcutta. BC started working on the extensive air showers in cosmic rays at Manchester.

4. COSMIC RAYS AND EXTENSIVE AIR SHOWERS – A SHORT REVIEW

Before describing Bibha Chowdhuri's work on extensive air showers in cosmic rays at

Manchester, it is imperative to understand the extensive air showers phenomenon and its importance in particle physics at that time. Cosmic rays are high-speed energetic particles accelerated outside the solar system. These possess the highest known energy of individual particles in the universe. The energy spectrum of primary cosmic rays extends from 1 GeV (10^9 eV) to above 10^{20} eV. At energies above 1 GeV most of the cosmic rays are accelerated in our galaxy. In this energy range the cosmic ray flux is dominated by H nuclei, i.e. protons. The best way to study cosmic rays is to detect them outside the atmosphere. This is the reason why cosmic ray studies are made at high altitudes. This is not, however, always possible since the flux of cosmic rays is proportional to $E^{-2.7}$. At energies above 100 TeV their flux is so small that no precise measurement is possible even in a detector size that fits in a balloon or a space craft. However, at this energy sufficient particles are produced in the atmosphere as secondary to the incoming primary cosmic rays. Some of the secondaries reach mountain altitudes and as the energy of the primary increases, they can even be found at sea level. The transverse momentum acquired by secondary particles at production and the scattering which the shower particles, in particular, undergo through interactions with the material of the atmosphere are such that the secondaries are spread over significant areas at the observational level. The phenomenon of the almost simultaneous arrival of many particles over a large area is called an Extensive Air Shower (EAS). At energies around 10^{15} eV about 106 particles cover approximately 104 m^2 while at 10^{20} eV some 1011 particles are spread over about 10 km^2 (Kampert and Watson, 2012).

In order to understand the nature of primary particles it is important to study the nature of air shower. Till the discovery of extensive air showers, the maximum energy of primary particles was conceived to be 10 GeV. The discovery of extensive air showers in 1938, however, radically

changed this situation with the highest energy being pushed up by about 5 orders of magnitude, probably the single largest advance to our knowledge of energy scales ever made. It is now known that the energy spectrum extends to beyond 10^{20} eV but it has taken over 60 years to consolidate this picture (Kampert and Watson, 2012).

It is worth mentioning that when the shower phenomenon was initially observed, only the muon was known, in addition to the proton, neutron, electron and positron, so that a realistic understanding of shower development had to wait until the discovery of the charged pion and its decay chain in 1947 and of the neutral pion in 1950. Initially it was thought that showers were initiated by electrons and/or photons. Once it was recognised that the initiating particle was almost always a proton or a nucleus, the first steps in understanding the nuclear cascade focussed on such matters as whether a proton would lose all or only part of its energy in a nuclear collision or how many pions were radiated in such a collision. A combination of observations in air showers made using Geiger counters and cloud chambers from studies in nuclear emulsions and of early accelerator information was used to resolve the debate.

The technical development of significant importance in the study of EAS in cosmic rays was the invention of coincidence technique by Walter Bothe in late 1920s for which he was awarded the Nobel Prize in 1954 (Bothe, 1929, pp. 1-5). In 1929, W Bothe and W Kolhörster, Berlin, observed that when two Geiger-Müller counters are placed above each other, a part of the counts/pulses was observed in both the instruments which (counters) were due to the same particles. They concluded that the cosmic rays have a particle nature. They also observed the decrease of coincidences because of absorption by materials (Bothe and Kolhörster, 1929, pp.751-777).

In 1931, J N Hummel, Germany, developed a circuit which enabled registering coincidence-impulse in more than one Geiger-Müller-counters simultaneously (Hummel, 1931, pp. 765-781). Bruno Rossi from Italy, who worked with German physicists observed that with increase of thickness the rate of coincidence of such particles first increases in lead with the increase of thickness, and then starts decreasing with increase of the thickness of the absorber (Rossi, 1933, pp.151-178). This led to the famous Rossi curve. In 1934, M Ackemann, Germany, observed a second maximum in Rossi-curve. He attributed this effect to the hard component of the radiation (Ackemman, 1934, pp.169-170).

In 1937, K Schmeiser and W Bothe observed a small number of coincidences in an unshielded counter array, which were separated by a few metres (Schmeiser and Bothe, 1938, pp.61-177). A year later, i.e. in 1938, H Euler and Werner Heisenberg published on the absorption of the components of the cosmic rays. They gave a theory on the behaviour and the secondary effects of the fast protons and neutrons, and the heavy electrons. The theoretical results were then compared with the experimental results in which, first the spectra of the individual particles and their transformation in the atmosphere, and then its secondary effects like smaller showers, bigger showers, collisions and nuclear transformation were compared (Euler and Heisenberg, 1938, pp. 1-69).

5. BIBHA CHOWDHURI IN MANCHESTER

Bibha Chowdhuri joined the cosmic ray laboratory of would-be Nobel Laureate P M S Blackett in 1945 (Blackett was awarded Nobel Prize in 1948) at a time when studies on extensive air showers in cosmic rays were one of the most important investigations in particle physics.

For instance, a local newspaper (Fig. 2) *The Manchester Herald* reported her work under

Fig. 2. Bibha Chowdhuri's interview and her work at Manchester, UK was reported in the *The Manchester Herald* by Bright Maxwell. (Courtesy: Prof. A K Ganguli)

the title: 'Meet India's New Woman Scientist – She has an eye for cosmic rays.' The article was written by Birgit Maxwell based on an interview taken on her. BC said:

Women are terrified of physics - that is the trouble. It is a tragedy that we have so few women physicists today. In this age when science, and physics particularly, is more important than ever, women should study atomic power; if they don't understand how it works, how can they help decide how it should be used? I can count the women physicists I know, both in India and England, on the fingers of one hand. At school scientifically-inclined girls choose Chemistry; perhaps because a really sound grasp of Higher Mathematics is one essential of any Physicist's equipment.

The reporter wrote:

Mathematics presented no problem to Miss Chowdhuri; she took to the study 'like a duck to water'. ... If you ask her why she chose to specialise in Physics, she says simply: 'I followed my inclination.'

About her research work, it was noted:

'Bibha Chowdhuri's particular programme is the study of extensive air showers caused when cosmic rays enter the earth's atmosphere from the

interstellar spaces. A cosmic ray touching a nuclear particle produces a shower, which extends itself by scattering in lower altitudes." **"Miss Chowdhuri is trying to discover the how, why and wherefore of this process; ultimately she hopes to estimate the exact extent of scattering and the number of particles involved. ...The extensive air showers Miss Chowdhuri is investigating, contain both kinds, though mainly soft ones; she hopes to find out in exactly what proportions."** (emphasis in original).

The journalist said that cosmic ray research is closely related to atomic physics; and is an abstruse subject to understand, but under Miss Chowdhuri's expert guidance "I began to understand something of the question."

BC was asked how many pictures were taken by her during the last three years. 'Literally thousands', she replied. As far as her future plan was concerned, we read: 'As soon as her thesis on 'Extensive Air Showers' is completed, some time in the next few months, Miss Chowdhuri will take her Degree of Philosophy. She then intends to return to Calcutta and continue her research there.'

The journalist was of the opinion: 'I am certain that she will undertake another task too when she gets home; she will try to persuade more Indian girls to follow in her own distinguished footsteps.' As we shall see later, her dream never turned to reality.

She submitted her PhD thesis in early 1949. She 'was examined by Lajos Janossy (external) and J G Wilson (internal) in March 1949. The minutes of the General Board of Faculties confirm that she successfully defended her thesis.' What puzzled us is the long gap of about three years between the submission of her thesis and obtaining her Ph.D. degree. When enquired about this we got the following reply from the University of Manchester: 'It is clear that she successfully completed her thesis in March 1949. The gap between this and the actual graduation on 3 December 1952 is not obviously

explicable but may have been due to demands of “employment/ residence. There is nothing to suggest this was due to problems with the thesis (Peters, 2017).”

6. RETURN TO INDIA

While Homi J Bhabha was looking for young scientists for the newly established TIFR (Tata Institute of Fundamental Research, Bombay), he asked J H Wilson, who was one of BC’s Ph.D. examiners, about his opinion of Bibha Chowdhuri. It seems that his opinion was positive, as BC was offered a job at the TIFR.

B V Sreekantan of National Institute of Advanced Studies, Bangalore, who worked at the TIFR, wrote to us that BC joined the Institute in 1949 and was there till 1957 or so. After leaving TIFR she spent a year abroad and then spent several years at Physical Research Laboratory, Ahmedabad before going back to Kolkata⁴. In an article he mentioned that B Peters, M G K Menon, S Biswas, (Miss) Bibha Chowdhuri, Appa Rao, Gaurang Yodh joined TIFR at about the same time and gave a big boost to its cosmic ray activity.⁵

To find out more about her stay abroad, we contacted the University of Michigan where she worked with Prof. J G Wilson. Miss Caroline Barraco - Reference Assistant, Bentley Historical Library, communicated to us:

I am responding to your reference request regarding Bibha Chowdhuri. I wasn’t able to find much more on her time at the university. There’s one other note about her in the Regents Proceedings, from the March 1957 meeting. It says she was given a stipend of \$2,500 in her role as a Physics Department Visiting Lecturer”.⁶

India’s renowned Plasma Physics scientist, Yogesh C Saxena, Sr. Prof. (Retired), Institute for Plasma Research, Gandhinagar, Gujarat, who did his Ph. D. under the guidance of BC (technically he did his Ph.D. under Vikram Sarabhai because BC was not a registered guide at that time) recalled:

My first meeting with Bibha Chowdhuri was during the course work, which I was taking as a Research Scholar, at Physical Research Laboratory (PRL), Ahmedabad in year 1964. She gave us a course on Interaction of High Energy Particle and Matter and I was highly impressed by the way she taught.⁷

Saxena recalls:

I was more inclined to do experimental work and I learnt that Bibha Chowdhuri was planning a new experiment on ‘Detection of High Energy Muons Associated with Extensive Air Showers of Cosmic Rays’ and I decided to join her as a student, to the surprise of many of my colleagues and seniors. At that time there was a feeling in the Research Scholars at PRL that she was a tough person to work with, which turned out to be totally misplaced as I discovered during my work with her for next several years.

As far as her teaching qualities are concerned, Saxena writes:

She was a very good teacher and took care that I kept up with the required studies while doing the experiment and collecting data and she provided the books and papers for that. She had a very good understanding of the subject and was of great help in analyzing and interpretation of the experimental data. In addition to the Cosmic Rays and High energy Physics, she taught me French language, which was part of the Ph.D. Curriculum at Gujarat University at that time.

Unfortunately, she did not care much about publishing her work in international journals. One

⁴ Prof. B.V. Sreekantan, Private communication, Jan. 2, 2018.

⁵ Sreekantan B.V., Sixty Years of the Tata Institute of Fundamental Research 1945-2005; The role of young men in the creation and development of this institute, Lecture delivered on 18th August 2005 at the Tata Institute of Fundamentals Research as one of JRD Tata Birth Centenary Events organized by TIFR Alumni Association.

⁶ Caroline Barraco - Reference Assistant, Bentley Historical Library, 150 Beal Avenue Ann Arbor, Michigan, U.S.A. Private communication, Oct. 23, 2017.

⁷ Yogesh Chandra Saxena, Sr. Prof. (Retired), Institute for Plasma Research, Gandhinagar, Gujarat. Private communication, Dec. 28, 2017

of her students recalled: ‘While the research work she carried out was of high quality, she was a bit conservative in her approach to publication and she submitted most of her papers from this work to Indian Academy Journal for publication.’

She was intensely involved with the Kolar Gold mine experiment using an indigenously developed detector to be placed at a depth of 700 ft. and to be operated in conjunction with the Extensive Air Shower array of TIFR on the ground. She worked out the modalities of the experiment with TIFR group and arranged the site underground as well as rented a bungalow for her and her assistants.

After the Kolar Gold Mine experiment, she had a plan to set up a new experiment at Mount Abu on radio frequency emissions associated with Extensive Air Showers. She had discussed these plans in detail with Vikram Sarabhai before his untimely demise. ‘Changes at PRL afterwards results in change of directions and the program and PRL did not permit her to take up that experiment. She took a voluntary retirement from PRL and moved to Kolkata to continue her pursuit of High Energy Physics.’

She continued to be associated with physics research at Saha Institute of Nuclear Physics in Kolkata till her death and also participated in seminars and conferences. She published several papers during this time jointly with other scientists of different institutes of Kolkata.

7. BIBHA CHOWDHURI’S PhD THESIS – A SUMMARY

Bibha Chowdhuri started her thesis with the historical survey of extensive air showers, a short review on ‘General structure of extensive showers’, ‘Spread of showers’, ‘Origin of showers’ and ‘Penetrating components in extensive showers.’ The experimental set up used for the study of density spectrum of air showers is shown in Fig. 3. About the recording technique she wrote:

A coincidence is recorded between the shielded counter tray and the four other counters, if an air shower selected by the four-fold array is accompanied by a penetrating particle. These penetrating counts were recorded on the cloud chamber photographs by means of an indicator lamp.

Fig. 3. A, B, C and D are four counters to select samples of Extensive Air Showers. The three counters are placed on the three sides of an equilateral triangle, whereas the 4th between the two side counters. The area of each counter was 200 cm². Cc' is the position of the cloud chamber, which has an effective area approximately 70 cm². P- counter is shielded by lead

To study the distribution of particle densities a large number of photographs by triggering arrangement were taken. The number of tracks on each photograph and effective collecting area of cloud chamber enabled her to calculate the densities of extensive showers. Out of thousands of photographs, she selected 1460 photographs, which fulfilled particular conditions such as, they did not contain tracks which were either too old (too broad photographic lines) or too new (too thin). The photographs were classified into group A and B. In group ‘A’ ‘The particle densities in these showers were observed to have no definite relationship to the density of penetrating events.’ (Fig. 4).

In group ‘B’, ‘all the photographs showing tracks which do not meet in any local point were included.’ For this group she produced a table on ‘total number of shower photos with a particular number of tracks and number of photos accompanied by penetrating events. From her

Fig. 4. A large shower produced in the material of cloud chamber, which is not accompanied by a penetrating event. (Credit: University of Manchester).

results she concluded that ‘the distribution of particle densities in Extensive Showers obeys a power law.’ She determined the exponent of the integral density spectrum (Fig. 5) (Chowdhuri, 1948, pp. 21-25).

Further, she studied the three-fold, four-fold and five-fold coincidences with iron and lead plates as absorbers. In one series, coincidences of the penetrating set with the four-fold counters were recorded with the shielded counters under a 15 cm. lead shield. In the second series, the top 5 cm of lead was exchanged for 16 cm. of iron. She

found that the density spectrum as well as the counting rates under the two different conditions were the same (Chowdhuri, 1948, pp. 25-26). She was of the opinion that according to the cascade theory:

At lower altitude, due to the effect of cascade multiplication the density of particles in a shower will be increased, so the probability of recording the dense part of a shower will increase with decreasing altitude. Thus the whole spectrum will be slightly biased towards large showers at lower altitudes and thus the value of the exponent will be slightly reduced (Chowdhuri, 1948, pp. 40-41).

She stated that even if all these results and her experimental results are taken into account: ‘we find no clear evidence whether this variation in exponent from 1.7 – 1.5 is due to the effective altitude or is a mere fluctuation in the experimental results (Chowdhuri, 1948, pp. 40-41).’ She proposed – before definite conclusion can be reached, more experiments at different altitudes should be performed.

As far as the density spectrum of penetrating Extensive Showers was concerned she stated that due to particular experimental

Fig. 5. Left: Density distribution of all observed Showers. The broken line represents the curve B on the right side. Right: Density distribution of Showers with penetrating events (right). (Credit: University of Manchester)

conditions: (i) 'The exponent of extensively penetrating Showers was found to be of the same order as for all particle extensive Showers. However, due to the effect of shielding, the values of the counting rates of the penetrating extensive Showers should be relatively lower than those of all particle Showers.' (ii) 'It was observed that penetrating extensive Showers were 300 times less frequent than all particle extensive Showers of the same density (Chowdhuri, 1948, p. 45).'

BC also studied 'the probability of a Shower particle being accompanied by a penetrating event, its dependence on the density of the shower particles and on the atomic number of the local absorber.' For finding 'the probability of a Shower particle being accompanied by a penetrating event' she calculated the ratio C_p/C_s , that is, the ratio of the penetrating shower counting rates to the total shower counting rate; which were determined by her experimentally. With this ratio it was possible to find the probability (k) of a soft particle being accompanied by a penetrating event. The values for five-fold and four-fold coincidences vs. ϵ (which is the product of probability k and

area of shielded counters) determined by her are shown in Fig. 6.

BC determined the 'dependence of ' k ' on the particle densities of an Extensive Shower.' From her experimental arrangement and results, she concluded that 'the probability of a shower particle being accompanied by a penetrating event is approximately constant for the whole range of particle densities of the shower recorded (Chowdhuri, 1948, p 50).' She emphasized the importance of her results as follows:

It shows that the density of penetrating events is approximately proportional to the density of shower particles. The most probable conclusion from this is that they are created locally. If this is not the case, it is difficult to understand how the penetrating particles, like mesons or nucleons, coming along with other soft particles of the shower obey the same law of scattering as the soft particles. One could expect the penetrating particles to be distributed differently from the general shower particles. Thus, the penetrating particles in Extensive Showers are mostly locally produced by the electronic component of the Extensive Showers (Chowdhuri, 1948, pp. 51-52).

Fig. 6. Left - Ratio of C_{p5}/C_{s4} vs. ks , where s is the area of shielded counter. From the intersection of the two curves the value of k can be determined. Right - The ratio of the four-fold penetrating shower counting ratio to the three-fold shower ratio. From the point of intersection of the observed and calculated curves, the k comes out to be 0.025 ± 0.003 . This value found by BC was in agreement with the results of the other investigators. (Credit: University of Manchester)

She also studied the 'dependence of 'k' on 'Z', that is, the atomic number of the local absorber.' She was of the opinion that if penetrating particles are produced by electrons and photons, then the production cross-section should be strongly dependent on the atomic number of the local absorber (Chowdhuri, 1948, p. 56). However, before her, W B Fretter had suggested that the cross-section is proportional to Z^2 (Fretter, 1948, pp.41-46). He studied the penetrating showers in lead plates with cloud chamber technique. He found various examples of mesons accompanying air showers. He wrote:

but no production of penetrating particles in lead by electronic radiation was observed. The pictures taken give general support to recent theoretical speculation that the primary radiation produces penetrating particles and electronic radiation in the same event (Fretter, 1948, pp.41-46).

For the study of 'Production of the penetrating particles in groups', BC, took photographs under two different conditions. In the first case the experimental arrangement was the same as before, the only difference was that instead of a single indicator lamp for all the six counters joined together, a separate neon indicator lamp was used for each counter. She wrote:

Thus, if any one of the six shielded counters was discharged simultaneously with the main shower set then it was recorded on the Cloud Chamber' photograph by means of an indicator lamp. So by this procedure one is able to find whether a single counter or more than one was discharged simultaneously with the main shower set. Thus, it indicates whether a penetrating event contains a single particle or a group of particles (Chowdhuri, 1948, p. 26).

The above procedure was intended to find out, whether penetrating events are of a simple or complex nature, that is, whether they are produced singly or in groups. The experiments were performed without- and with absorber. It was shown that 'penetrating particles are mostly created in the local absorber, not coming from air along with other soft shower particles (Chowdhuri,

1948, p. 61).' Her conclusion was supported by Italian physicists G Salvini and G Tagliaferri, University of Milan (Salvini and Tagliaferri, 1948, pp. 261-262).

At the University of Cornell, Ithaca, U.S.A., G Cocconi and K Greisen were working on the penetrating showers. They were of the opinion that 'In the accompanied showers the penetrating particles are very likely to pre-exist in the air; in the unaccompanied showers they are created in the absorbers surrounding the counters by a nucleonic component of the cosmic radiation (Cocconi and Greisen, 1948, pp. 62-65).' BC while discussing their results stated that her experiments show that the 'penetrating events mostly consist of groups of particles and must be produced locally (Chowdhuri 1948, p. 64).' She discussed the differences between the two experimental set ups and showed that Cocconi-Greisen experimental setup 'is such that it cannot record particles of the same group, unless they have spread out at a very wide angle and escaped absorption in lead. This also indicates that these particles are not very penetrating (Chowdhuri, 1948, p. 68).' Further she stated that J Daudin's experiment supports her view, whose result is intermediate between her and Cocconi's. He (Daudin) showed that 40% of the particles are absorbed in 0.8 cm. lead.

In the foregoing, she argued in favour of production of penetrating particles in absorbers. Under the section 'On the investigations with a thin roof at a certain height above the penetrating set' she gave the following three possibilities of their production:

- (1) groups of mesons may be produced in local absorber by nucleons present in the air shower, by some nuclear interaction as in the production of local penetrating showers. (2) Penetrating particle groups may consist of protons or other heavy nuclear particles due to some sort of star-like nuclear process generated in local absorber either by nucleon or by other fast shower particles. (3) Penetrating particles can be produced in the local absorber by soft particles, i.e., electrons and

photons present in the Air Shower (Chowdhuri, 1948, pp. 70-79).

With her own experiments and that of L Janossy and G D Rochester⁸; and D Broadbent and L Janossy (1948, pp.364-385), she came to the conclusion: ‘we are justified in rejecting the suggestion that the nucleons are responsible for the production of penetrating particles in Extensive Showers (Chowdhuri, 1948, pp. 73-74).’ A paper of L Janossy and D Broadbent is of interest as it gives the analysis of the experimental work done by them and other scientists on the causes of the ‘production of penetrating particles in extensive air showers’, but more importantly ‘**use is also made of unpublished experimental material obtained by Miss B Chowdhuri**’ (emphasis added). The authors wrote in abstract, and they acknowledge: ‘We are ... indebted to Miss B Chowdhuri for communicating unpublished results (Broadbent and Janossy, 1948, pp.364-385).’

About the angular distribution of particles her view was:

The Italian workers – Salvini and others (Salvini and Tagliaferri, 1948, pp.261-262) (...) observed that the frequency of two close counters discharging simultaneously is much higher than that of two distant ones. The differences that they observed is quite significant, so considering our lack of material in this case, we think we are not justified in drawing any definite conclusions on the angular distribution of these particles (Chowdhuri, 1948, pp. 77-76).

Also, she observed the ‘Absorption of penetrating particles in lead.’ About the experimental set up she described that:

Six shielded counters were spit up into two groups of three counters. The two groups were separated vertically by 10 cm. of lead. The top trays of counter were shielded by 15 cm. lead. Both top and bottom trays of counters were surrounded by

8 cm. lead on all sides. In order to allow for the geometry of the arrangement, a series of photographs was first taken with only 10 cm. air space [and then with 10 cm. lead absorber] between the two counter trays (Chowdhuri, 1948, p.30).

Her experimental results are shown in Fig. 7 and Fig. 8.

No. of lamps on		No. of Tracks.		No. of Photos.
Upper	Lower			
3	3	0 - 2		2
3	3	> 10		1
3	2	0 - 2		1
3	1	0 - 2		1
3	0	0 - 2		2
2	3	6 - 10		1
2	2	0 - 2		1
2	1	0 - 2		1
2	0	0 - 2		2
1	3	0 - 2		1
1	2	> 10		1
1	1	0 - 2		1
1	1	0 - 2		6
1	0	0 - 2		11
		3 - 5		1
		6 - 10		1
0	3	0 - 2		1
		3 - 5		1
0	2	0 - 2		1
0	1	0 - 2		13
		3 - 5		1
		6 - 10		2
		> 10		1
0	0	0 - 2		273
0	0	3 - 5		8
		6 - 10		3
		> 10		2

Fig. 7. Results with 10 cm. air space between two counter trays. (Credit: University of Manchester)

No. of lamps on		No. of Tracks.	No. of Photos
Upper	Lower		
3	3	0 - 2	1
3	2	6 - 10	1
3	1	0 - 2	1
3	0	0 - 2	2
2	3	6 - 10	1
2	2	0 - 2	0
2	1	0 - 2	1
2	0		0
1	3	0 - 2	1
1	2	0 - 2	1
1	1	0 - 2	4
1	0	0 - 2	12
1	0	3 - 5	1
1	0	6 - 10	1
0	3		0
0	2	0 - 2	1
0	1	0 - 2	7
		3 - 5	1
0	0	0 - 2	266
		3 - 5	11
		6 - 10	5
		> 10	2

She observed: 'the nature of the distribution of tracks with corresponding number of indicator lamps on is the same as we observed previously (Chowdhuri, 1948, p.33).'

Other part of her Ph.D. thesis deals with 'The distribution of the Angular deviations of Shower particles from the vertical direction.' She measured the projected angles of tracks in each shower from the vertical direction. For showers with two or more tracks, she took average direction of all tracks from the vertical. The showers were grouped in four classes; and plotted in intervals of 10 degrees. She produced tables with 'Single track showers', '2-4 track showers', '5-15 track showers' and '>15 track showers.' For each table the values for 'Angles from the vertical', 'Total number of photos' and 'Number of photos accompanied by penetrating events' were given. An example of such table is shown in Fig. 9 (Chowdhuri, 1948, pp. 33-36).

Angles from the vertical	Total No. of Photos.	No. of Photos. accompanied by penetrating events
0 - 10°	97	32
10 - 20°	84	27
20 - 30°	60	20
30 - 40°	19	5
40 - 50°	10	4
50 - 60°	2	0
60 - 70°	3	1
70 - 80°	2	1
80 - 90°	0	0

Fig. 9. Experimental result –Distribution of the angular deviations of tracks in vertical direction. (Credit: University of Manchester)

Her measurement showed that the shower particles in single tracks as well as showers with large number of particles were concentrated within 30 degree of the vertical. In every group there was a small percentage making an angle greater than 30 degree with the vertical. For instance, single track, 2-4 track and 5 track were 16.8%, 13% and 8.7% respectively. This percentage showed a

decrease with increasing density of shower particles. From that she concluded: 'It is possible that sometimes the low density parts of showers contain some very low energy particles which are scattered at large angles from the vertical direction (Chowdhuri, 1948, p. 81).'

She observed a prominent maximum for single track showers at 0-10° angles; which was not the case in other groups. She had no explanation for it. She stated that M Deutschmann made similar experiment and found similar results, however, he recorded only 100 number of showers, thus his statistics is poor. Here she refers to Martin Deutschmann, University of Freiburg, Germany. He wrote an article, which was based on his Ph.D. thesis. With a big cloud chamber, he studied 200 extensive showers. He also studied the frequency distribution of the radiation densities; and found that heavy particles were detectable only in very small numbers. He also measured the directions of incidence of the showers (Deutschmann, 1947, pp.61-69).

In 1943, G Cocconi *et al.* in a series of experiments studied the particle density of the extensive showers in air. They found a correlation between the average density of the extensive showers and the total recording surface area (Cocconi, Loverdo and Tongiorgi, 1943, pp.314-324). A year before, that is, in 1942, P Auger and J Daudin from France observed:

The production of multiple secondary particles by cosmic rays under thick layers of lead has been studied with coincidence counters and with a cloud chamber. Part of the coincidences obtained under 15 cm of lead is attributed to groups of particles of atmospheric origin associated with extensive showers. The other part is due to a local effect produced in the lead by single penetrating particles. Among the particles emitted in these processes, some have the penetrating power of low energy mesons (Auger and Daudin, 1942, pp.549-556).

BC's study of the number of showers accompanied by penetrating events showed that the distribution of these showers was similar to the general distribution. It confirmed that the extensive showers are 'generally of an electronic nature, the electronic part of the showers can give rise to penetrating events locally (Chowdhuri, 1948, p. 82).' She concluded: 'Extensive showers, accompanied by penetrating events are of the same type as the all particle extensive showers. This was also confirmed by Cocconi's *et al.* (Cocconi, Loverdo and Tongiorgi, 1943, pp.314-324) and Daudin's experiments. They had observed that the exponent of the density spectrum of extensive penetrating shower is the same as that for all particle showers.

From the summary of BC's PhD thesis we see that she showed (Chowdhuri, 1948, pp. 82-87) that the penetrating particles are mainly produced in the local absorbers. They do not come from air along with other soft shower particles.

With various arguments she ruled out:

They are groups of mesons produced by nucleons present in Air Showers, in approximately the same way as in local penetrating showers.' The experimental results cannot be accounted for 'some sort of nuclear explosion or star-like process taking place in the local absorber and produced by the fast soft particles of Air Showers.

Her final conclusion was:

The soft particles in Air Showers are the origin of the penetrating events. These events, however, are not due to meson showers produced by soft particles, because the large production cross-section – which means a strong interaction between electrons and mesons – would also require a reverse process, such a process has not been observed experimentally. And also the Z^2 [where Z is atomic number] dependence of cross-section of production cannot be explained by such process (Chowdhuri, 1948, pp. 82-87).

And further:

We are led to the conclusion that the majority of penetrating events are due to soft particles of Air

Showers, and that they are not mesons or other heavy ionising particles but may be some ionizing particle having a lighter mass than mesons, produced in thin layers of local absorber. In order to fit the cross-section of production their mass may be 5 – 7 times the electron mass, as suggested by Auger and Janossy and others (Chowdhuri, 1948, pp. 82-87).

She continued:

"..., from the evidence of the roof experiment we can further conclude that these particles are unstable and their life period may be of the order of 10^{-9} sec (Chowdhuri, 1948, pp. 82-87)."

In general, scientists were not sure about the nature and production of particles. For instance, A. Mura *et al.* wrote:

The existence of a penetrating component in extensive atmospheric showers has been investigated by several workers, using different methods. Results obtained with cloud-chambers do not seem to justify a final conclusion. Cocconi and co-workers, using counters, decided in favour of the presence of meson showers simultaneous with extensive showers; more recently, Rogozinski, using counters driving neon lamps, concludes that mesons are probably associated with extensive showers (Mura, Salvini and Tafliaferri, 1947, pp.367-369).

How far work of BC and other associates played role in winning the Physics Nobel Prize for P M S Blackett in 1948 is unknown. The fact is, in 1932, he and 'Giuseppe Occhialini connected the cloud chamber to a Geiger counter, which detects the passage of a particle. In this way a picture could be captured precisely when a particle passed by. Patrick Blackett showed, among other things, that with the application of high energy, pairs of electrons and positrons could be formed out of light particles, photons.'⁹ In 1948, he was awarded the Nobel Prize in Physics 'for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation.'

⁹ https://www.nobelprize.org/nobel_prizes/physics/laureates/1948/blackett-facts.html, Dec. 31, 2017.

Evidently BC was a privileged physicist to work in the laboratory of the future Nobel Prize laureate. BC acknowledged the following in her thesis:

'I wish to record my sincere thanks to Professor Blackett for the encouragement; and facilities he has given for conducting experiment this experiment. I am also greatly indebted to Professor L Janossy [Hungarian born physicist] and Dr J G Wilson [U.S.A.] for many helpful suggestions and discussions during the progress of the work (Chowdhuri, 1948, p. 96).'

8. RECEPTION OF BIBHA CHOWDHURI'S WORK BY THE INTERNATIONAL SCIENTIFIC COMMUNITY

As far as we know, BC published two papers in British journals based on her Ph.D. thesis. In her article in *Nature* she showed that (1) The density of penetrating events associated with extensive showers is proportional to the total particle density in the region of the shower. (2) The average probability of a single ionising shower particle associated with a subsequent penetrating count is 0.020 ± 0.002 , and almost independent of shower density over the whole range of densities. (3) No significant change in the rate for penetrating events took place when part of the shielding lead plate was replaced by iron of equal thickness in the units of cascade theory (Chowdhuri, 1948 p.680; 1950, pp.165-172). In her publication in *Proceedings of Physical Society*, London, she wrote that she extended her experiments in such a way that the discharge of individual counters in the shielding layer were distinguished and recorded on cloud chamber photographs. This was meant to get information concerning the nature of the events arising under 15 cm. of lead absorber when extensive showers fall upon the apparatus. Her experimental set-up is shown in Fig. 10.

One of her conclusions was:

It seems, ..., plausible to regard the penetrating particles in extensive showers as single particles

Fig. 10. Above: The six counters kept horizontally in a single cavity in the lead shield, with 15 cm. lead above the counter and 8 cm. lead at the sides and below the counters. Below: The counters are placed in two layers, with three counters spaced 1 cm. apart in each layer and 'the layers spaced vertically about 15 cm. lead' and are 'shielded on the remaining side by 8 cm. lead. Measurements were made with and without 10 cm. lead in the cavity between the two counter layers. When the lead was not in position the total material between the two counter layers were two thin iron sheets of thickness 1.5 cm. each.' (Credit: *Proc. Phys. Soc.*).

capable of producing large numbers of secondaries in the local shielding material, which are the immediate agency for discharging the shielded counters. This conclusion ... agrees well with the 'hypothesis ...' suggested by Broadbent and Janossy (1948, pp.364-385), where penetrating particles are supposed to come from the air above capable of discharging the shielded counter set by means of a triple knock-on showers. But it has been shown from all existing measurements that the probability of production of knock-on secondaries by i-mesons is too small to account for our result (Chowdhuri, 1950, pp.165-172).

And further:

'..., if the above conclusion is valid, it is not easy to associate the required behaviour of the penetrating particles carrying energy into the shielded cavity with the known behaviour of ordinary i-mesons. We have not distinguished, however, between the operation of known mechanisms for new particles of appropriate

properties and the occurrence of some hitherto unexplored process taking place for familiar particles (Chowdhuri, 1950, pp.165-172) .’

Shortly after her publication, S M Mitra and W G V Rosser, who were also working in the same laboratory as BC, wrote on the ‘Momentum spectrum of the particles in extensive air showers.’ While discussing density distribution of the particles in showers they stated that due to the work of various authors such as B Chowdhuri it is known that the distribution of shower densities follow a power law of particular form. They wrote:

Following Chowdhuri (...), the density distribution obtained in the present experiment can be compared with the results of Cocconi, Loverdo and Tongiorgi by comparing the observed rate of the occurrence of showers showing n track above the lead plate with the rate calculated according to the formula ... (Mitra and Rosser, 1949, pp.364-369).

G Cocconi and K Greisen, Cornell University, New York, while writing on ‘ λ -Mesons in air showers’ wrote that L Janossy and C B A McCusker who studied the penetrating particles in lead did not mention the thickness of lead plates, ‘but we conclude from their sketch of the apparatus and from their statement that the experiment was a repetition of a similar one by Miss Chowdhuri, that the thickness was 15 cm. or less.’ They were of the opinion that ‘at least 20 cm. of lead is required to reduce the soft component of the showers to a level of intensity that is small compared with that of the penetrating particles (Cocconi and Greisen, 1949, p. 810).’

While discussing the nature of penetrating particles in air showers, L Janossy and C B A McCusker stated that air showers mainly contains electrons and photon, but in addition a small percentage of particles which penetrate more than electrons. The work of various scientists shows that they cannot be mesons. A group of physicists call them λ -mesons, having mass about 3 times the mass of electron. Other group (that is Broadbent and Janossy) suggested them to be ‘heavy electrons’ of the mass about $10 m_e$. The

recent experimental results presented in a symposium held at Bristol in September 1948 give additional support to these hypothesis. He reported about Miss Chowdhuri’s experimental work, which was presented in the symposium, who showed that a considerable change of the rate of fourfold coincidences in the presence of the roof was noticed. For four-fold the actual rate observed by her was as follows:

With roof	0.263 ± 0.037
No roof	0.474 ± 0.053
Difference	0.211 ± 0.064

The authors stated that her experiment was repeated and confirmed by them in Dublin. They also performed experiment with bricks. Their conclusion was that the two experiments show that thin lead roof reduces the number of penetrating extensive showers recorded, while a mass-equivalent brick roof show no considerable effect (Janossy and McCusker, 1949, pp. 181-183).

K Greisen *et al.*, while referring to BC’s article (Chowdhuri, 1950, pp.165-172) opined:

The high energy N-component, capable of producing penetrating showers, has been found to have an intensity near the cores of air showers about 60 percent as great as that of the non-interacting penetrating particles, and about $\frac{1}{2}$ percent as great as that of the electrons. It is suggested that all of the N-component in the lower atmosphere belongs to extensive showers and contributes to the shower development. Near the core, the lateral density distribution of the N-component is found to be as strong as that of the electrons (Greisen, Walker and Walker, 1950, p.545).

‘Reports on Progress in Physics’ while writing review on ‘The nuclear interactions of cosmic rays’ stated:

Counter work by Chowdhuri (1950), Sitte (1950b) and McCusker (1950) shows that below 20 cm. of lead the penetrating component of extensive showers consists of some 80% mesons and 20% of nuclear-interacting particles. It is thus abundantly clear that there exists a very close connection between the soft and hard components

of showers (Rochester and Rosser, 1951, pp.227-287)."

What we see from the foregoing is that B Chowdhuri was an integral part of the western scientific community and her work had received a glowing acceptance in the scientific community.

CONCLUSION

It is an enigma why a scientist of Bibha Chowdhuri's calibre, who did such significant research on contemporary modern physics at a time when very few women ventured to take physics research as a profession, did not attract any attention from her country of origin. Surprisingly enough her involvement and contribution to the Kolar Gold mine experiment had been underplayed and remained practically unmentioned in any literature. That she was a victim of gender discrimination in the male dominated scientific society may not be ruled out.

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BIBLIOGRAPHY

Ackemann, M. Komponentenerlegung der kosmischen Ultrastrahlung mit Hilfe von Zweifachkoinz-

idenmessungen, *Naturwissenschaften* 11(1934):169-170.

Auger, P and Daudin J. Multiple secondary effects of the penetrating cosmic radiation at sea level, *Phys. Rev.* 61(1942):549-556.

Barraco Caroline - Reference Assistant, Bentley Historical Library, 150 Beal Avenue Ann Arbor, Michigan, U.S.A. Private Communication, Oct. 23, 2017.

Basu, M. Women's Science Congress seeks raison d'être, *Bangalore Mirror*, Jan. 5, 2016.

Bhattacharya, K. Book review, Raza Gauhar, Gopichandran R, Venkateswaran TV and Misra Kinkini Dasgupta (Eds). Scientifically Yours - Selected Indian Women Scientists, CSIR-NISCAIR, and Vigyan Prasar, DST, 2016, *Indian Journal of History of Science* 52(2017):351-352.

Bose, D M and Chaudhuri B. Origin and nature of heavy ionization particles detected on photographic plates exposed to cosmic rays, *Nature* 147(1941):240-241.

Bothe, W. Zur Vereinfachung von Koinzidenzzählungen, *Zeitschrift für Physik* 59(1929):1-5.

Bothe, W and Kolhörster W. Das Wesen der Höhenstrahlung, *Zeitschrift für Physik* 56(1929):751-777.

Broadbent, D and Janossy L. Production of penetrating particles in extensive air showers, *Proc. R. Soc. Lond.* 192(1948):364-385.

Chakrabarti, Ranatosh. *Jnan O Bijnan*. (February 2005):159-161.

Chowdhuri, B. A photographic method of estimating the mass of the mesotrons, *Nature* 148(1941):259-260; 149(1942):302

Chowdhuri, B. Extensive penetrating showers, *Nature* 161(1948):680.

Chowdhuri, B. Extensive air showers associated with penetrating particles, PhD thesis, University of Manchester, Manchester (1948):21-25; 25-26; 26; 30; 33; 33-36; 40-41; 45; 50; 51-52; 56; 61; 64; 68; 70-79; 73-74; 75-76; 81; 82; 82-87; 96.

Chowdhuri, B. Experiments on the nature of penetrating events in extensive air showers, *Proc. Phys. Soc.* 63(1950):165-172.

Cocconi, G and Greisen, K. On the penetrating showers of cosmic rays, *Phys. Rev.* 74:(1948)62-65.

Cocconi, G; Loverdo, A and Tongiorgi V. Sugli sciame estesi dell'aria, *Nuovo. Cim.* 1(1943):314-324.

- Cocconi, G and Greisen K. λ -Mesons in air showers, *Nature* 163(1949):810.
- Deutschmann M. Untersuchung der kosmischen Strahlenschauer mit Hilfe einer großen Wilson-Kammer, *Zeitschrift für Naturforschung* 2(1947):61-69.
- Euler, H and Heisenberg, W. Theoretische Gesichtspunkte zur Deutung der kosmischen Strahlung, *Ergebnisse der Exakten Naturwissenschaften* 17(1938):1-69.
- Fretter, W B. Penetrating Showers in Lead, *Phys. Rev.* 73(1948):41-46.
- Godbole, R M and Ramaswamy, R. Women Scientists in India, (http://www.ias.ac.in/public/Resources/Initiatives/Women_in_Science/AASSA_India.pdf). Jan. 15, 2018. (in: Women in Science & Technology in Asia, The Association of Academies and Societies of Sciences in Asia, (2015):67-84. (<http://www.interacademies.org/Publications/28012.aspx>).
- Godbole, R M and Ramaswamy, R. (Eds.). *Lilavati's Daughters: The Women Scientists of India*, Indian Academy of Sciences, Bangalore, 2008.
- Venkataraman, V. Indian Women in Science - Universal tales of women's struggles to attain parity in the world of scientific research, *c & en* 87(2009):68-69.
- Greisen, K and Walker W D and Walker, S P. N-Component in Extensive Air Showers, *Phys. Rev.* 80(1950):535-545.
- http://www.ias.ac.in/public/Resources/Initiatives/Women_in_Science/AASSA_India.pdf, Feb. 16, 2018.
- https://www.nobelprize.org/nobel_prizes/physics/laureates/1948/blackett-facts.html, Dec. 31, 2017.
- Hummel, J N. Eine neue Methode der selbsttätigen Koinzidenzzählung, *Zeitschrift für Physik* 70(1931):765-781.
- Janossy, L and Broadbent, D. Production of penetrating particles in extensive air showers, *Proc. R. Soc. Lond.* 192(1948):364-385.
- Janossy, L and McCusker, C B A. The nature of penetrating particles in air showers, *Nature* 163(1949):181-183.
- Kampert, K H and Watson, A A. Extensive Air Showers and Ultra High-Energy Cosmic Rays: A Historical Review, *European Physics Journal*, arXiv:1207.4827v1 [physics.hist-ph], July 19, 2012.
- Mitra, S M and Rosser, W G V. Momentum spectrum of the particles in extensive air showers, *Proc. Phys. Soc.* 62(1949):364-369.
- Mura, A; Salvini, G and Tafliaferri G. Presence of a Penetrating Component in Extensive Showers in the Atmosphere, *Nature* 159(1947):367-369.
- Peters, James. Library, University of Manchester, Private Communication, Oct. 2, 2017.
- Raychaudhuri, S. The early days of particle physics in India, (in: CU Physics 100 – Department of Physics – University of Calcutta 1916-2015 Gangopadhyay G, Kundu A, (Eds.)), University of Calcutta, Calcutta (2016):148-172.
- Rochester, G D and Rosser, W G V. The nuclear interactions of cosmic rays, *Rep. Prog. Phys.* 14(1951):227-287.
- Rossi B. Über die Eigenschaften der durchdringenden Korpuskularstrahlung im Meeresniveau, *Zeitschrift für Physik* 82(1933):151-178.
- Roy, S C and Singh, Rajinder. Bhibha Chowdhuri: An Unknown Indian Woman Scientist, *Science and Culture* 84 (2018): 159-164.
- Salvini G and Tagliaferri G. On the penetrating component of air showers, *Phys. Rev.* 73(1948):261-262.
- Saxena, Yogesh Chandra. Sr. Prof. (Retired), Institute for Plasma Research, Gandhinagar, Gujarat. Private Communication, Dec. 28, 2017.
- Schmeiser, K and Bothe, W. Die harten Ultrastrahlenschauer. *Ann. Phys.* 424(1938):161-177.
- Singh, Rajinder and Roy, S C. *A Jewel Unearthed: Bibha Chowdhari*, Shaker Publishers, 2018.
- Sinha, M S. Sixth D M. Bose Memorial Lecture delivered on 28.4.1986 under the auspices of ISNA, *Science and Culture* 52(1986):359-367.
- Sreekantan, B V. Private Communication, Jan. 2, 2018