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First hints of electromagnetic showers in Bruno Rossi's notebooks

In 1927 the Russian Physicist Dmitry Skobelzyn published photographs of secondary electron tracks produced by a beam of gamma rays in a Wilson cloud chamber placed in a magnetic field of 1500 gauss[1]. After the discovery of Compton effect, Skobelzyn had begun to investigate the recoil-electron tracks of gamma-rays in late 1923 in the laboratory of his father, a professor of physics at the Leningrad Polytechnical Institute[2]. On two of these photographs the tracks of one or two unusually high-energy particles appeared not connected with the gamma-ray beam coming from radioactive materials. The particle was not deflected by the magnetic field, which led to the conclusion that its energy must have been about 20 MeV, an unprecedented value at the time. At the time experiments concerning the absorption of cosmic rays in mountain lakes were conducted particularly by Robert A. Millikan and G. Harvey Cameron, Werner Kolhörster, Victor F. Hess, Victor Regener. Basing on the results thus obtained, Millikan hypothized that cosmic rays were a very hard «ultra-gamma rays» produced as a product of synthesis of various light nuclei in the interstellar space. At the end of the 1920s the generally accepted view was that primary cosmic rays were high-energy photons (*Ultragammastrahlung* in the German literature) which were thought to be absorbed through Compton collisions alone (at the same time charged particles were supposed to lose energy only through the ionization of matter)[3]. After his first casual observations Skobelzyn published a full report on his researches which was received on February 23 1929 by *Zeitschrift für Physik*. Using the just published Klein-Nishina theory of the Compton effect he concluded that these were to be considered secondary electrons produced by «Hesschen Ultra-γ-Strahlen». In a section specifically dedicated to the observation of small groups of particles he established that «One cannot doubt that the different components of such groups are generated by a single *Strahlungszentrum*». By analyzing his data, Skobelzyn showed that the number of groups of particles that he found greatly exceeded anything that could be expected on statistical grounds[4]. He had already presented these results in course of a discussion at an informal conference on γ- and β-ray problems held at Cambridge in July 1928. When he showed his collection of photographs Geiger announced that Walter Bothe and Werner Kolhörster were using the new Geiger-Müller counter[5] to register cosmic rays by the coincidence of pulses in two wire counters[6]. Actually, they sent a brief note to *Naturwissenschaft* on November 2, referring about measurements of the absorption of the secondary electrons by placing lead plates of increasing thicknesses between the counters. As a result of their coincidence observations they referred having observed ionizing particles penetrating 1 cm of lead[7]. On June 18, 1929, Bothe and Kolhörster's submitted to *Zeitschrift für Physik* their famous article containing detailed researches on the nature of *Hohenstrahlung* which marked a turning point in the history of cosmic ray research[8]. They immediately stated that they had started their famous experiment on the ground that while the different properties of the Höhenstrahlung – intensity, distribution, absorption and diffusion, and even its origin – were object of research and discussion, «die eigentliche Hauptfrage, nämlich die nach dem Wesen der Höhenstrahlung, bisher keine experimentelle Beantwortung gefunden hat»[9]. In recalling the common views about cosmic rays as high-energy gamma rays, due to their extraordinary penetrating power, they mentioned Skobelzyn's fast electrons whose energies appeared to be about 1.5×10^7eV, and agreed with him that these particles should be connected with the *Höhenstrahlung*. The problem was thus the following: «Was this corpuscular radiation to be considered a secundary radiation of a γ-radiation, as up to that moment, or was it to be considered as the Höhenstrahlung proper?»[10]. Gamma rays were known to ionize through the intermediary of secondary charged particles such as electrons ejected from atoms by the Compton effect. Their penetrating power was known to be much smaller thant that of the parent gamma rays. Therefore, it was expected that cosmic gamma rays would be accompanied by a flow of "soft" secondary rays, in equilibrium with the radiation by which they were produced. The conventional cosmic-ray absorption measured by placing an absorber above the detector, would thus reflect the gamma-ray absorption without being affected by the properties of the secondary "soft" radiation. Until Bothe and Kolhörster's experience, it had not been possible to imagine an experiment measuring the absorption of the secondary particles. Their researches were made possible by the new

Geiger-Müller device, an instrument which could *count* single cosmic rays. Electroscopes of the type used in earlier work on cosmic rays could detect only the combined ionizing effects of large numbers of particles. Since many years, individual ionizing particles had been observed in cloud chambers and had been "counted" by observing the scintillation produced on a fluorescent screen. Even the point counter developed by Hans Geiger while working in Ernest Rutherford's laboratory between 1906 and 1912 was not well suited to cosmic-ray studies being not very stable and not sufficiently large to study a radiation whose intensity was as small as that of cosmic rays. With the Geiger-Müller counter cosmic ray research became a branch of physics. Bothe and Kolhörster observed the frequent simultaneous discharge of two counters placed one above the other, and remarked that the coincidences must be due to the passage of individual charged particles through both counters, showing that they could not be the result of a double Compton effect, considering both its quite low probability and the high frequency of such coincidences[11]. This conclusion did not in principle contradict the view that the primary radiation consisted of high-energy photons. Absorption measurements in the atmosphere and under water had shown the cosmic radiation to be more penetrating than any other. From the shape of the absorption curves the energies of such *Ultragammastrahlung* had been calculated, and it had been concluded that cosmic rays were a mixture of photons with energies ranging from 20-30 to several hundred MeV. The ionizing particles causing the simultaneous discharges might have been the recoil electrons arising from Compton collisions of these photons, which would thus have more than enough energy to traverse the counter walls. In this case, only a small fraction of particles should be able to traverse both counters and produce coincidences if a 4.1 cm of gold (high density would grant a high stopping power) was placed between the counters. They found that the rate of coincidences was still 76% of what it had been without the block. This meant that 76% of the charged particles present in the cosmic radiation near sea level could penetrate 4.1 cm of gold. Near sea level the absorption curve of cosmic radiation resembles the absorption curve of photons having a mean free path of about 300g/cm^2 in air or water. Calculation based on Klein-Nishina theory predicted an energy of approximately 60 MeV for such photons. After removing the upper iron and lead shield housing containing the counters, Bothe and Kolhörster observed a reduction of the counting rate by only 24%[12]. This result was very surprising considering that only a small fraction of the recoil electrons of the hypothetical primary photons found at any point of the atmosphere should have had a greater range. In order to generate such penetrating electrons, some of the photons could nevertheless have a greater energy and generate a small fraction of recoil electrons able to pass through the gold block used by Bothe and Kolhörster. Nevertheless, as Rossi remarked much later, the crucial point was: If the rays are photons, an absorber that produces only a minor change in the radiation intensity when placed above an electroscope or a single Geiger-Müller counter produce completely different effects – depending on whether primary cosmic rays are photons or charged particles – when placed between two counters:

> If the rays are photons, the absorber drastically reduces the coincidence rate (even though some of the Compton electrons may have enough energy to traverse the absorber). If the rays are charged particles, the absorber affects the coincidence rate only slightly.[13]

At this point, one could nevertheless object that the largest energies of the recoil electrons had been calculated basing on a range of several hundred MeV for the primary photons. This was an arbitrary extrapolation of the known properties of photons and electrons at low energies according to the Klein-Nishina theory of the Compton effect, which was known to be valid for energies of the order of 1 MeV[14]. Moreover, one must keep in mind that these theoretical computations were based on the assumption that high-energy photons were absorbed predominantly through Compton collisions alone. It was thus possible that the energies of cosmic-ray photons might be much greater than those computed from their mean free path according to the equation of Klein and Nishina. «For this reason – remarked Rossi – it would be misleading to claim that the experiment of Bothe and Kolhörster had proved the corpuscular nature of cosmic rays»[15]. They suggested that the primary cosmic radiation consisted of ionizing particles and that the ionizing particles observed near sea level were those among the primary particles that were capable of traversing the atmosphere, a conclusion which later did not turn out to be correct. Cosmic rays were indeed charged particles, but they behave very differently than people thought at the time. In any case, their coincidence experiment was the first attempt to submit the gamma-ray hypothesis to an objective test, and, Bruno Rossi was rather skeptical about Millikan's theory of *Ultragammastrahlung* as «birth cry» of atoms in interstellar space. A theory which, in his opinion, «lacked of a strong experimental evidence»[16]. He was deeply struck by Bothe and Kohlhörster's startling conclusions, and became convinced that their fundamental experiences had clearly indicated the existence of a very penetrating corpuscular radiation, even if it remained an open question whether this corpuscular radiation was identical with the cosmic rays themselves, or was secondary in its nature, produced by primary rays of an electromagnetic character. When Bruno Rossi left Arcetri in the Summer of 1930 and went to Charlottenburg, at Bothe's laboratory, thanks to a grant of the Italian National Council of Research, he had been abundantly involved in hands-on researches in cosmic ray physics. After devising a new method for recording coincidences based on the use of the Geiger-Müller counter[17] he had begun some experiments with the aim of investigating on the nature of the «radiation from above». The capabilities of the coincidence method were fully developed by Rossy with the application of electronic devices. The circuit that later became known after his name, could accomodate any number of counters and provided a much finer temporal resolution than the original method of Bothe and Kolhörster: «It appears that the triple coincidences method is the only one available for studying the form of the paths of cosmic rays»[18]. With this powerful tool in his hands, which in particular extended considerably the possibility of choosing different geometrical arrangements during the experiments, as became clear very soon, Rossi began a series of preliminary researches which were his first contribution to the cosmic-ray research field[19]. After Bothe and Kolhörster's work, the astrophysical and the physical aspects of the cosmic-ray problem had become well defined: on one side there was an interest in establishing the nature of the primary cosmic rays, as this knowledge could throw some light about their place of origin and their production mechanism; on the other side there was the local radiation, found at the place where measurements were made. Investigations on the local radiation became the object of Rossi's research program, on the ground of the same reason stated by Bothe and Kolhörster: the real question of the day was the nature of the *Höhenstrahlung*, and he was determined to seek an answer to such a question. Rossi spent the whole Summer 1930 in Berlin-Charlottenburg, working on improvement of Bothe and Kolhörster's experiment. He used an experimental arrangement very similar to Bothe and Kolhörster's, but from a conceptual point of view he worked basing on the idea that the penetrating radiation had a corpuscular nature. They had showed that the penetrating power of the ionizing particles which were at the origin of the observed coincidences, was very close to the penetrating power of the cosmic radiation itself (which should have coincided with the penetrating power of the hypothetical gamma rays). In Rossi's opinion, further researches were necessary to establish the *origin* of the corpuscular radiation, which generated the phenomena connected with the penetrating radiation. Where the word *origin* implicitally meant also *nature* of such radiation. The principal novelty of his experiments in Berlin was that he made a direct comparison between the coincidence rates recorded when a 9.7 cm lead absorber was placed *above* the counters with those recorded when the same absorber was placed *between* the counters. The choice of the first configuration would in fact show that «Thus things were not quite as simple as suggested by the assumption of Bothe and Kolhörster»[20]. As Rossi remarked at the beginning of his report of the experiments conducted in Berlin, sent to *Zeitschrift für Physik* on January 5, 1931, the

> [...] so called "absorption of the penetrating radiation" is a measure of the intensity variation of the corpuscular radiation produced by interposing a shield. Such absorption would exactly coincide with the absorption of the corpuscular radiation if *all* the corpuscular radiation would be originated *above* the absorbing shield; if otherwise new corpuscular rays are generated by an ultra-gamma radiation, the absorption of the penetrating radiation will be smaller than the corpuscular radiation's; but in general, it will be also different from the primary ultra-gamma radiation's absorption. Except for the case of perfect balance (saturation) between the latter and its secondary radiation[21].

If the coincidenced were originated by particles of the primary radiation which had crossed the whole Earth atmosphere, the frequency should have been the same in both cases. In the second case he found that the coincidences were reduced by 16%, a result very near to what had already been found with the photographic method of registration used by Bothe and Kolhörster. The main interest of his experience resided in the result found in connection with the first experimental arrangement, which gave an excedence of about 4%. This result had a very strong experimental base because it was obtained using the new electronic methods which gave the possibility of a long series of measures, in order to considerably diminish statistical fluctuations. Each type of experience lasted 149h and 58'[22]. After discussing the existence of such a difference Rossi stated:

> As far as the interpretation of experimental results is concerned, the hypothesis of the existence of a *secondary radiation originated inside the lead* appears to be the most likely explanation of the difference found, even if it

> maybe not the only one. The double tracks observedy by Skobelzyn by the Wilson chamber method allow us to consider the possibility that also the *corpuscular radiation can generate secondary corpuscles with great penetrating power* [my emphasis][23].

In a report with the title *The Problem of the penetrating Radiation* published on *La Ricerca Scientifica*, the Journal published by CNR, Rossi explicitely put the question: «Actually, what is the nature of these secondary rays?»[24]. He immediately pointed out that there was not an alternative explanation to the presence of such softer secundary radiation: the penetrating corpuscular radiation itself must have been its origin. He also mentioned Bothe's hypothesis: «the secundary radiation might have been the same corpuscular radiation observed in Skobelzyn's photographs». He concluded the report pointing out that

> […] the most urgent object of research is that of throwing light on the nature of the penetrating corpuscular radiation, of measuring its energy, of establishing its origin, and, last but not least, of investigating which might be the role of its secundary radiation in the observed phenomena.

In October 1931 a Conference on Nuclear Physics was held in Rome with physicists from all over the world. Fermi asked Rossi tho give an introductory speech on the problem of cosmic rays. It was the occasion to present the corpuscular hypothesis to a scientific community «still strongly attached to the old γ-ray hypothesis». Millikan was furious when his theory of the *Birth cry* of atoms was disputed by a «26 years old», nearly unknown, Bruno Rossi. «[…] by indirect arguments» Rossi had become convinced that «many particles must have much greater ranges» than 10 cm of lead. Such an evidence would «kill once and for all the γ-ray hypothesis»[25]. For this reason he felt that it was crucial to verify experimentally that this was indeed the case. The conference ended on October 17. On October 25 Rossi wrote on his notebook the following title: *Assorbimento in un metro di Pb* (Absorption in 1 m lead)[26]. The full potentialities of the coincidence method could now be achieved with the circuit he had devised, which not only allowed the recording of many-fold coincidences, but also improved the time resolution from 1/100 seconds to something of the order of 10^{-3} seconds. He was the first to use three-fold coincidenced between counters, which he arranged vertically one above the other separating them by a lead absorber of variable thickness (from 25 to 101 cm). The third counter had the purpose of reducing the number of unwanted chance coincidences. He arranged the results of his experiments in a day by day table at the end of the notebook, starting from October 29, until October 7/8. After the first great decrease with 10 cm of lead, he found that about 50% of the particles "filtered" by 10 cm of lead had ranges of at least one meter of lead, that is greater that about the thickness of the whole atmosphere. On December 16 he sent a letter to *Naturwissenschaft*. His conclusions were very sharp: «These results confirm and complete the conclusions to which the author had come in discussing the precedent research». Here he quoted his article on *Zeitschrift für Physik* (1931)[27]. Such a result was really hard to believe at a time when the most penetrating charged particles known were high energy β-rays from radioactive substances, whose ranges were smaller than 1 mm of lead. Much more surprising results were obtained from his investigations on the suspected production of secondary particles by penetrating cosmic rays, which he carried on using a triangular arrangement of Geiger-Müller counters surrounded by lead recorded a large number of three-fold coincidences[28]. When the upper shield was removed, the coincidence rate fell almost to zero, showing that cosmic rays were enormously more effective than any other known rays in producing a secondary radiation[29]. «Most of the coincidences observed were due to associated groups of particles (at least two) arising from interactions of cosmic-ray particles in the shield itself». Qualitatively, this was the effect he had been looking for, recalled Rossi later[30]. These results strongly suggested that, contrary to the tentative opinion of Bothe and Kolhörster, the local radiation must be, at least to a large extent, of secondary origin. Rossi must have written a short letter, probably to *Naturwissenschaft*. He well remembered that the high rate of coincidences was so astounding, that a German magazine refused to publish his paper, which was accepted by *Physikalische Zeitschrift* («after Heisenberg had vouched for my credibility»). Actually, Heisenberg was well aware of Rossi's work, to which he dedicated two whole pages of his "theorethical reflections" on cosmic rays published in 1932 on *Annalen der Physik* (submitted February 13)[31]. Rossi's notebooks show that he continued to work both on the 1 m lead experience and on the secondary radiation research. He used different configuratios of the counters, changing the position and the thickness of the layers of matter where the secondary particles were produced[32], comparing the behavior of different materials[33], placing absorbing shields in different positions. In a very neat notebook marked with the title *Experiences on secundary radiation* Rossi summarized all his data on absorption and diffusion in different tables[34]. In an article published on the *Rendiconti Lincei* (presented at the *Accademia dei Lincei* on May 1, 1932)[35] the figure 2 on page 738 testifies the most significant results of this work, which became known as the Rossi curve. It showed a rapid rise of the triple coincidence rate as the thickness of the lead, iron or aluminum layer above the counters (placed at different positions) was increased to about 1.5 cm, reached a maximum and diminished for greater thicknesses according to the range of the secondary particles. Rossi found that beyond the maximum the curve dropped «much more rapidly than the absorption curve of cosmic rays at sea level»[36]. As previously suspected, Rossi could now clearly state what he had previously suspected: the local cosmic rays consisted of two components, a soft one capable of generating the secondary radiation, having a mean penetration of about one centimeter (and thus rapidly attenuated in lead), and a penetrating primary component capable of traversing great thicknesses of lead and only occasionally giving rise to a shower[37]. Rossi could also conclude that the effect was not due to the production of new secondary corpuscular rays from the «hypothetical ultra-γ radiation», confirming that «the primary radiation could not be of ondulatory character»[38]. In a short time the existence of a locally produced particle *shower* was demonstrated beyond any doubt by Blackett and Occhialini thanks to the cloud chamber triggered by counters (Summer-Autumn1932), a most fruitful cooperation between «Image and logic», the best demonstration of the matter-antimatter connection within the frame of Dirac's theory of the relativistic electron. The electron-photon cascade showers theory, which explained satisfactorily the nature of the soft component of cosmic rays, was independently published by Bhaba and Heitler, Carlson and Oppenheimer in 1937[39].

Reality had surpassed the physicists'dream, as Rossi had guessed two years before:

> The most recent experiments have brought to light such strange facts that we are almost led to ask ourselves whether the penetrating radiation may not be something fundamentally different from all other known radiations, or at least,wheather, in the transition from the energies encountered in the ordinary radioactive processes to the energies encoutered in the ordinary radioactive processes to the energies encountered in the phenomena of the penetrating radiation, the behavior of particles and photons does not change much more deeply than one might have thought until now[40].

Note:

1 Skobeltzyn, D., *Die Intensitätsverteilung in dem Spektrum der γ-Strahlen von RaC*, «Zeitschrift für Physik», 1927, 43, pp. 354-378.

2 *Id., The early stage of cosmic-ray particle research*, in *The Birth of Particle Physics*, a cura di Brown, L.M., Hoddeson, L., Cambridge University Press, Cambridge 1983, pp. 111-119.

3 In the 1910s N. Bohr had published two fundamentals papers on the theory of ionization produced by very fast – particles: Bohr, N., *On the Theory of the Decrease of Velocity of Moving Electrified Particles on Passing through Matter*, «Philosophical Magazine», 1913, 25, pp. 10-31; *Id., On the Decrease of Velocity of Swiftly Moving Electrified Particles in Passing through Matter*, «Philosophical Magazine», 1915, 25, pp. 581-612.

4 Skobeltzyn, D., *Über eine neue Art sehr schneller γ-Strahlen*, «Zeitschrift für Physik», 1929, 54, pp. 686-702.

5 The invention had been just announced on July 7th of that same 1928.

6 Skobeltzyn, D., *The early stage of cosmic-ray particle research*, cit., p. 113.

7 Bothe, W., Kolhörster, W., *Eine neue Methode für Absorptionsmessungen an sekundären Strahlen*, «Naturwissenschaften», 1928, 16, pp. 1045-1045.

8 Bothe, W., Kolhörster, W., *Das Wesen der Höhenstrahlung*, «Zeitschrift für Physik», 1929, 56, pp. 751-777.

9 Ivi, p. 751.

10 «The real question, that is the nature of the radiation from above, has not received any experimental answer up to now». Ivi, p. 752.

11 Ordinary – or – rays must be excluded because the 1 mm thick counter walls of zinc would stop all such particles. The counters were housed in a container made of two layers respectively of 5 cm of iron and 6 cm of lead (about 150 years old) to avoid possible effect of ambient radioactivity.

12 See Bothe, W., Kolhörster, W., *Das Wesen der Höhenstrahlung*, cit., Table 3, p. 759.

13 Rossi, B., *Cosmic Rays*, G. Allen and Unwin Ltd, London 1964, p. 40.

14 It was already clear that the formula was already failing if applied to the most energetic gamma rays from radioactive substances.

15 Rossi, B., *Cosmic Rays*, cit., p. 41.

16 *Id., Momenti nella vita di uno scienziato*, Zanichelli, Bologna 1987, p. 7.

17 *Id., Method of Registering Multiple Simultaneous Impulses of Several Geiger's Counters*, «Nature», 1930, 75, p. 636.

18 He declared that he was going to employ it in experiments on the magnetic deviation of these radiations. With this remark Rossi concluded the description of his method of registering multiple simultaneous impulses of several Geiger's counters. It is well known how deeply Rossi got involved in the study of geomagnetic effects, to which he gave a main contribution. This argument will not be touched in the present work.

[19] These aimed at measuring the efficiency of the counters and their dependence on the voltage applied. He also checked that the penetrating particle came preferentially from the vertical direction («Rendiconti Lincei», 1930, 11, pp. 478-482). Next he tried to investigate on the nature of the corpuscular cosmic radiation as well as on the energy of the corpuscles, undertaking an extensive series of measurements of their deflection, first by means of a strong magnetic field, and later using an arrangement based on two magnetized bars («Physical Review», 1930, 36, p. 606; «Nature», 1931, 128, p. 300).

[20] Rossi, B., *Early days in cosmic rays*, «Physics Today», 1981, 34, pp. 35-41, on p. 37.

[21] *Id., Über den Ursprung der durchdringenden Korpuskularstrahlung der Atmosphäre*, «Zeitschrift für Physik», 1931, 68, pp. 64-84.

[22] Rossi, B., *Über den Ursprung der durchdringenden Korpuskularstrahlung der Atmosphäre*, cit., pp. 71-72.

[23] *Id., Über den Ursprung der durchdringenden Korpuskularstrahlung der Atmosphäre*, cit., p. 73.

[24] *Id., Il problema della radiazione penetrante*, «Ricerca Scientifica», 1931, 2, pp. 307-320.

[25] Id., Early days in cosmic rays, cit., p. 39.

[26] Massachusetts Institute of Technology, Bruno Rossi Papers, MC166, Box 1, Folder 8.

[27] Rossi, B., Absorptionmessungen der durchdringenden Korpuskularstrahlung in einem Meter Blei, «Naturwissenschaften», 1932, 20, pp. 64-65.

[28] See B. Rossi Papers, MC166, Box 1, F. 6 (Notebook 3-12-31 to 1-2-32), and F 7 (Notebook 21-12-31 to 1-2-32).

[29] Rossi, B., Nachweis einer Sekundärstrahlung der durchdringenden Korpuskularstrahlung, «Physikalische Zeitschrift», 1932, 33, pp. 304-305.

[30] Id., Early days in cosmic rays, cit., p. 41.

[31] Heisenberg, W., *Theoretische Überlegungen zur Höhenstrahlung*, «Annalen der Physik», 1932, 13, pp. 430-452.

[32] See both Notebooks in Box 1, F. 9, particularly the one beginning on June 26, 1932, where drawings indicate the use of two aligned counters under what he calls a «scatteratore di Pb» (lead scatterer) divided by a lead shield from a third lower counter.

[33] See Box 1, Folder 10. In the Notebook beginning on April 4, 1932, there is a Table arranging data about different materials on June 14. On May 25 he also carried on «magnetic experiences» on the secondary radiation. A second Notebook reporting analogouse experiences is marked June 7 and ends on July 31.

[34] Box 1 Folder 10, Notebook entitled *Esperienze sulla radiazione secondaria. 1932.*

[35] Rossi, B., *Sugli effetti secondari della radiazione corpuscolare*, «Rendiconti Lincei», 1932, 15, pp. 734-741.

[36] *Id., Early days in cosmic rays*, cit., p. 41.

[37] *Id., Sugli effetti secondari della radiazione corpuscolare*, cit., p. 739.

[38] Rossi, B., Crinò, B., *Le anomalie di assorbimento della radiazione penetrante*, «Rendiconti Lincei», 1932, 15, pp. 741-746.

[39] Carlson, J.F., Oppenheimer, J.R, *On multiplicative showers*, «Physical Review», 1937, 51, pp. 220-231. Bhabha, H. J., Heitler, W., *The Passage of Fast Electrons and the Theory of Cosmic Showers*, «Proceedings of the Royal Society of London», 1937, A159, pp. 432-458.

[40] Rossi, B., Il problema della radiazione penetrante, in Convegno di Fisica Nucleare, Reale Accademia d'Italia, Roma 1932, pp. 51-66.