

## LATTES' CONTRIBUTION TO THE DISCOVERY OF THE $\pi$ MESON IN BRISTOL

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A historical investigation of the discovery of the  $\pi$  meson has been already done both from a global scientific point of view<sup>1</sup>, and from a sociological one<sup>2</sup>. The aim of this contribution is to show Lattes' own specific scientific role in the discovery of the  $\pi$  meson in Bristol by Powell's team. Besides of his own articles, quite interesting material can be found in Brazilian studies of the history of physics<sup>3</sup>.

In 1935, Hideki Yukawa<sup>4</sup> predicted the existence of the  $\pi$  meson as the particle responsible for the strong interaction, that keeps an atomic nucleus together. The potential of interaction is of the form  $V(r) = g e^{-kr}/r$ , where  $k = m_\pi c/\hbar$  is the inverse of the strong interaction range (its experimentally established magnitude is of the order of  $10^{-15}$  m). From the value of  $k$  it was possible to obtain a valuation of the mass of the  $\pi$  meson:  $m_\pi = \hbar k/c = 0,3 \times 10^{-27}$  kg.

In 1937, Carl David Anderson and Seth Henry Neddermeyer were trying to detect the  $\pi$  meson. They actually discovered the mesotron<sup>5</sup>. It is understandable that they confused the two particles, because the mass at rest of the muon (about 105 MeV) is a bit smaller than that of the  $\pi$  meson (about 140 MeV for  $\pi^+$  and  $\pi^-$ , and about 135 MeV for  $\pi^0$ ). Yukawa furthermore predicted a  $\beta$  decay for the  $\pi$  meson:  $\pi \rightarrow e + \nu_e$ . We know today that this decay is forbidden for the  $\pi^0$  meson (because of electric charge

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<sup>1</sup> For a historical introduction and many useful contributions, see, for example: Brown, Hoddeson (1983); Foster (1988); Powell (1950); Rechenberg, Brown (1990); Rossi (1964); Russo (2000); Sekido, Elliot (1985); Wilson (1952).

<sup>2</sup> See: Ribeiro de Andrade (1997a); Ribeiro de Andrade (1997b); Ribeiro de Andrade (1999).

<sup>3</sup> See: Caruso, Marques, Troper (1999); Marques (1999); Modernell (1999); Nussenzweig *et al.* (1995); Schwartzman (1978a); Schwartzman (1987b); Schwartzman (1984).

<sup>4</sup> Yukawa (1935); Yukawa (1949).

<sup>5</sup> Then called, not properly,  $\pi$  meson; today: muon.

conservation), and it has a very small probability to happen for the charged  $\pi$  meson (about  $1,267 \times 10^{-4}$ ), whereas their typical decay is:  $\pi \rightarrow \mu + \nu$ . The weak decay is typical of the muon:  $\mu \rightarrow e + \nu_{\mu} + \nu_e$  with the energy spectrum of the produced electron just like a  $\beta$  decay one.

In 1943, Marcello Conversi, Ettore Pancini, and Oreste Piccioni, in Rome, performed the experiment demonstrating that the muons could not be the mesons theoretically predicted by Yukawa, since they did not interact strongly with atomic nuclei<sup>6</sup>, but they acted as they were a kind of heavy electron. Muons could not be therefore the particles that, colliding against the atmospheric nuclei, originate cosmic rays showers.

Again in 1943, Yasutaka Tanikawa, Shoichi Sakata, and Takeshi Inoue advanced the “two mesons” hypothesis, suggesting that the  $\pi$  meson decay in a muon was followed by the muon decay in an electron  $\mu \rightarrow e + \nu_{\mu} + \nu_e$  with  $\nu_{\mu}$  and  $\nu_e$  having a small mass and 1/2 spin. This hypothesis was also independently put forth, in 1947, by Robert Eugene Marshak and Hans Albrecht Bethe. The discovery of the “double mesons,” on the other hand, happened a little earlier; it was just the research at the H. H. Wills Laboratories then joined by Lattes.

In the H. H. Wills Laboratories, they used nuclear emulsions, experimentally produced by Ilford Ltd., and they exposed them at high altitude to detect the disintegration due to cosmic ray collisions against the atmosphere. They expected the  $\pi$  meson to be among the disintegration products. Cecil Frank Powell was interested in the technique of nuclear emulsions from 1938 on, following a suggestion of Walter Heitler who had informed him that, in 1937, Marietta Blau and Herta Wambacher had obtained the tracks of low energy protons and of nuclear disintegration products in the nuclear emulsions exposed on the Austrian Alps at 2300 m. Heitler and Powell exposed a series of Ilford emulsions on Jungfraujoeh (3500 m) and confirmed Blau and Wambacher’s results.

Powell decided to develop the technology of the Ilford emulsions, preferring them to the cloud chamber because of the superiority of their results, and increasing the concentration of silver bromide, since the emulsions till then used were able to detect only low-energy protons and  $\alpha$  particle tracks. Around the end of WW II, Powell obtained Patrick Maynard Stuart Blackett’s help too, who supported a scheme to develop emulsions, chaired by Joseph Rotblat. Blackett furthermore called Giuseppe Occhialini from Brazil to work with the Allied project to build the atomic bomb, but,

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<sup>6</sup> Conversi, Pancini, Piccioni (1947).

due to his nationality, Occhialini could not take part in that research and decided to join Powell's team.

Cesare Mansueto, Giulio Lattes, Ugo Camerini, and Andréa Wataghin, at the University of São Paulo, had built in the meanwhile a cloud chamber to study slow mesons, and they sent Occhialini some photographs obtained with this apparatus. After having received from Occhialini some photographs of protons and  $\alpha$  particle tracks, Lattes realized that the nuclear emulsion technique could give unquestionably better results. He asked to join Powell's team to study the new Ilford emulsions. In 1946, thanks to Occhialini's and Powell's help, but also thanks to the lack of experimental physicists in minor universities, Lattes obtained a scholarship from the cigar industry that financed Bristol University, and could really go to England.

The first experiment assigned to Lattes<sup>7</sup> consisted of measuring the level of samarium  $\alpha$  decay (discovered by Hevesy and Pahl in 1932). In 1938, Wilkins and Dempster discovered that the  $\alpha$  particles were emitted by the isotope  $^{148}\text{Sm}$ . Subsequent measurements determined the  $\alpha$  particles range as  $1,13 \pm 0,02 \text{ cm}$ <sup>8</sup>, while Taylor and Mäder showed the presence of a proton emissions whose range was determined as 3,5 cm by Taylor and Dabholkar with photographic emulsion techniques.

Lattes used the new high-loaded Ilford emulsions, 40  $\mu\text{m}$  thick, and spread over them a solution of 33,75 mg samarium sulphate at 99,97% in 2  $\text{cm}^3$  of distilled water. With a flow of dry air, the water of the solution evaporated within 2 h leaving a samarium sulphate film on the emulsions. After 20 days, the plates were washed for an hour to remove the sulphate film, after which they were developed and analyzed with a microscope. Lattes could observe a large number of tracks distributed in a peak centered on 7  $\mu\text{m}$ . From the range-energy relation obtained with the studies on protons (from d-p reactions) and on  $\alpha$  particles (from d- $\alpha$  reactions), Lattes could obtain samarium  $\alpha$  particles range as  $1,12 \pm 0,03 \text{ cm}$ , quite similar to preceding observations.

A second, much fainter peak (1,4 %) was centered on 23  $\mu\text{m}$ . A similar (in range and intensity) peak appeared using a neodymium sulphate solution. Lattes deduced that the peak was due neither to samarium nor to neodymium radioactivity<sup>9</sup>. The quality of the emulsions was not such to be able to

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<sup>7</sup> Cuer, Lattes (1946); Lattes, Samuel, Cuer (1947).

<sup>8</sup> The range is in standard air, if not otherwise specified.

<sup>9</sup> See Cuer and Lattes' article for an analysis of the different possibilities about the nature of the source of such  $\alpha$  particles.

establish the nature of the particles causing those tracks. Lattes made the experiment again using a more diluted samarium sulphate solution (3 mg in 2 cm<sup>3</sup> distilled water) and could ascribe the second peak tracks to  $\alpha$  particles with a  $3,90 \pm 0,08$  cm range. Counting the number of tracks in a selected area, and evaluating the number of samarium atoms in such area, Lattes was also able to determine the samarium decay time in  $(1,3 \pm 0,1) \times 10^{11}$  y.

Lattes took some time to study the emulsion technique, hoping to apply in the future the new discoveries about cosmic rays. To obtain the range-energy relation, Lattes<sup>10</sup> calibrated the new emulsions. Working with Waller (Ilford Ltd.), Camerini (from Brazil), and Johnny Williamson (of the chemistry department), Lattes obtained from Ilford Ltd. the production of special borax-loaded plates. He was convinced that the borax would fix the track left in the emulsion due to the interaction between a particle and an emulsion atom. Lattes' new assignment was now to determine the shrinkage rate of the new nuclear emulsions, while Occhialini and Powell, using the old emulsions, worked on 10 MeV n-p scattering. For his research, Lattes could produce, by mean of a 1 MeV deuterium beam produced by the Cockcroft-Walton accelerator in Cambridge, the particles from artificial disintegration of light isotopes to use as probe to determine the shrinkage rate. Considering the time at his disposal, Lattes planned to study the following reactions:  ${}^2\text{H}(d, p){}^3\text{H}$ ;  ${}^6\text{Li}(d, p){}^7\text{Li}$ ;  ${}^7\text{Li}(d, p){}^8\text{Li}$ ;  ${}^9\text{Be}(d, p + 2n){}^8\text{Be}$ ;  ${}^{10}\text{B}(d, p){}^{10}\text{B}$ ;  ${}^{11}\text{B}(d, p){}^{12}\text{B}$ .

From the analysis of the tracks left in the new emulsions, Lattes, Fowler, and Cuer obtained a range-energy relation in the new Ilford plates for  $\alpha$  particles, protons, and deuterons up to 10 MeV, determining the mean range in the emulsion of homogeneous beams of particles ( $\alpha$  particles from natural radioactive sources, and protons from known disintegration reactions). From the masses of the considered nuclei, it was possible to calculate the energy of the beams of particles produced with the different reactions. The above reactions, obtained from the collision of 900 keV deuterons against nuclei of light elements, permitted Lattes to determine the range in emulsions of 12 homogeneous beams of protons with energy between 2 and 13 MeV, so as to be able to draw the range-energy curve.

Lattes, Fowler, and Cuer also found that the relation between the range in air and in the emulsion was not constant. To use the results more easily, they were expressed as a function of the mean stopping power  $S$  of the emulsion, that is, the ratio between the mean range in air (Livingston and Bethe's values, for protons) and the one in the emulsion. From the measure of the

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<sup>10</sup> Lattes, Fowler, Cuer, Peter (1947a).

mean range  $r$  of a beam of protons, from Lattes-Fowler-Cuer's curve, they could obtain the stopping power  $S_r$  and, from this value, the range in air  $R = S_r \times r$  corresponding to the unknown energy of the beam of protons by means of Livingston-Bethe's curve. Analogous results were obtained for beams of  $\alpha$  particles from samarium, heavy elements, and from the reaction  ${}^6\text{Li}(d, \alpha){}^4\text{He}$ .

Lattes' relation was then used to detect single charged particles (in our case, the  $\pi$  meson)<sup>11</sup>. By means of the reaction  ${}^{11}\text{B}(d, n){}^{12}\text{C}$ , they produced a beam of neutrons with an energy distribution peaked at 13.4 MeV. With the borax-loaded plates, Lattes proposed to obtain the neutrons' energy and momentum from the reaction  ${}^{10}\text{B}(n, 2\alpha){}^3\text{H}$ . To reduce fading of the borax-loaded plates, Lattes had to choose between reducing the exposition time or detecting the cosmic rays at high altitude. At this point, Lattes and Occhialini decided to expose the borax-loaded plates at high altitude. Occhialini exposed the first plates, with the help of the French astronomers of the local observatory, on Pic-du-Midi (2800 m), in the French Pyrenées, for six weeks. Other plates were brought by Perkins of the Imperial College at high altitude (9100 m) on an RAF airplane. Only part of the plates was borax-loaded with the new B<sub>1</sub> type emulsion, whose range-energy relation was known. The normal plates, on the other hand, were used to study low-energy cosmic rays and to check if they would detect cosmic neutrons.

It was Occhialini, on the very night of his return to Bristol, who developed the emulsions after having recovered them from Pic-du-Midi. The difference between normal plates and borax-loaded ones was clear at once. Since the borax slows down the fading of the image, the loaded emulsions were able to record or, better, to keep the record of a greater number of tracks, whereas in the normal plates the detection power considerably decreased after about a week<sup>12</sup>. In C<sub>2</sub> emulsions, 40  $\mu\text{m}$  thick, besides the solitary tracks produced by protons with energy up to 30 MeV, there were about 300 disintegration stars (about 3000 stars were predicted in the whole), with a mean value of 2 stars/cm<sup>2</sup>.

Because of both the number and the variety of the tracks impressed in the new emulsions, the measurement of the neutron energy took second place. It was decided to concentrate the whole lab staff on the study of low-energy normal events. Perkins was the first person to observe an event regarding a  $\pi$  meson: the capture of a  $\pi$  meson by a nucleus, causing a nuclear

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<sup>11</sup> Lattes, Fowler, Cuer (1947b).

<sup>12</sup> Occhialini, Powell (1947).

disintegration. Perkins, however, had no borax-loaded emulsions, and he was not able to detect directly the  $\pi$  meson.

Marietta Kurz was the first person to find a result predicted by the “two meson” hypothesis. In a single emulsion, she found the track of a meson (a  $\pi$  meson) up to its stopping point, and a second track, beginning from the end of the first one, of a second meson (actually: a muon), stopping in the same emulsion too, with a 600  $\mu\text{m}$  range. It was a  $\pi$  meson and not a proton because of the different variation of the density of the grains impressed in the emulsion as a function of the range. The multiple scattering, measured as a function of the residual range, permitted her to make a preliminary evaluation of the  $\pi$  meson’s mass (between 50 and 150 MeV). Within a few days, Irene Roberts found a similar case, but the second track did not end in the same emulsion. In this case, it was however possible to determine the value of the range; it was about 610  $\mu\text{m}$ . These results were published in *Nature*<sup>13</sup>, as well the determinations of cosmic ray neutron energy, obtained by means of such emulsions<sup>14</sup>.

The experiments on multiple disintegration produced by cosmic rays gave the result that some of these events were due to high-energy neutrons. The classical method of measuring neutron energy (measure of the recoil of a hydrogen nucleus collided by the neutron) was vain. Lattes and Occhialini began a series of measurements of cosmic neutron energy by using the collision against the boron nuclei of the new emulsions. By means of the 900 keV deuteron beam produced with the Cockcroft-Walton accelerator in Cambridge, Lattes and Occhialini produced neutron beams, with a flux geometry measured with an error of  $\pm 1^\circ$ . They considered only the neutrons ejected in the same direction of the deuteron beam, and with energy of 9,6 MeV and 13,4 MeV. They made them collide against a plate of the new emulsion, orthogonal to the colliding beam direction. Besides the expected reaction  $^{10}\text{B}(n, \alpha)^7\text{Li}$ , they also observed many disintegrations into three particles, that they identified with the reaction  $^{10}\text{B}(n, 2\alpha)^3\text{H}$ , with  $Q = 0,4$  MeV. The energies of the produced particles were:  $E_{\alpha 1} = 7,4 \pm 0,2$  MeV,  $E_{\alpha 2} = 1,4 \pm 0,4$  MeV;  $E_{3\text{H}} = 5,0 \pm 0,1$  MeV. The total energy of the reaction products was then  $13,8 \pm 0,5$  MeV, corresponding to an energy of the colliding neutrons  $13,4 \pm 0,5$  MeV. The error in the energy (and the analogous on the momentum) was due to the uncertainty in the energy of short range  $\alpha$  particles.

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<sup>13</sup> Lattes, Muirhead, Occhialini, Powell (1947).

<sup>14</sup> Lattes, Occhialini (1947).

After these lab results, it was possible to analyze directly the plates exposed to the cosmic rays on Pic-du-Midi. In the emulsions, there were many disintegration stars, similar in shape to those produced by 13,4 MeV neutrons:  $^{10}\text{B} (n, 2\alpha) ^3\text{H}$ . Since all the tracks stopped in the emulsions, it was possible to measure their range and to distinguish the kind of particle from the different type of track. The energy-range relation was known only for energy values up to 50 MeV, so the energy value of the most energetic  $\alpha$  particle could only be deduced in  $E = 26,5 \pm 1,5$  MeV, while for the other  $\alpha$  particles they normally obtained  $E = 2,9 \pm 0,2$  MeV and for  $^3\text{H}$   $E = 7,4 \pm 0,1$  MeV, corresponding to a total energy of the reaction products of  $36,8 \pm 1,8$  MeV and to the energy of the colliding neutron of  $45 \pm 8,5$  MeV. The analysis of the reaction products energy and momentum permitted them in addition to determinate the mass of the colliding particle in  $1,23 \pm 0,30$  uma. Considering the uncertainty in the energy of the first  $\alpha$  particle and in the direction of the second  $\alpha$  particle, the determined mass confirmed that the particle was a fast neutron (it was excluded the hypothesis that the reaction was due to the photo-disintegration of a boron nucleus).

Lattes and Occhialini concluded that the energy and momentum of fast neutrons with energy up to 100 MeV could be measured with the new borax-loaded emulsions, keeping in mind the fact that, at higher energy,  $^3\text{H}$  would be present in the dissociated form  $p + 2n$ . This technique was potentially generalizable to reactions concerning light nuclei different from boron (lithium, beryllium, etc.), particularly in the cases with at least three reaction products.

With the study of the meson tracks by mean of the impressed grain counting, the Bristol team was able to determinate the mass of the single-charge meson whose track stopped in the emulsion. First, they defined the grain density in a track as the grain number in a unitary length track. From the range-energy relation for the emulsion (determined by Lattes, Fowler, and Cuer), the measures of the tracks of fast protons permitted them to obtain a calibration curve that connected the grain density with the energy loss rate of the particle producing the track. Counting the grains along a track left by a meson, and from the calibration curve, they could deduce the total energy loss of the meson in the emulsion. Using the range-energy curve, the values of the (measured) range and of the energy (from the calibration curve), they could obtain a measure of the meson's mass.

This method was tested with protons and gave good results. The greatest source of measurement errors that this method gives when applied to cosmic rays is the fading of the latent images. To obviate the fading, they decided to

establish the calibration curve basing on the tracks of random protons (such as to obtain a mean fading) among those produced by disintegration stars. They obtained good mean values for the protons but with single values comprised between  $1300 m_e$  and  $2400 m_e$ <sup>15</sup>. This error obviously affected the measures of meson mass, even if grain counting permitted them to distinguish mesons from protons. The mesons' tracks could be recognized if they were longer than  $100 \mu\text{m}$  in the emulsion. Both grain density and coulombian scattering had of course to correspond to meson-typical values. It was not possible to exclude that some<sup>16</sup> of these tracks were actually due to protons.

In *Processes Involving Charged Mesons*, the Bristol team reported their results of the analysis of 65 meson tracks stopping in the emulsions, classified as follows: a) 40 tracks due only to one particle; b) 15 tracks due to one or more heavy secondary particles from disintegration; c) 4 tracks whose secondary particle is a hydrogen nucleus or of another element; d) 2 tracks whose secondary particles is a meson; e) 4 tracks whose secondary particles is not determinable for certain. The probability that the tracks of primary and secondary particles (in the d) case) were due to two unrelated events was evaluated in less than  $10^{-9}$ . In one of the two d) cases, grain counting permitted them to evaluate the mass of the two particles: primary particle  $m = 350 \pm 80 m_e$ , secondary particle  $m = 330 \pm 50 m_e$ . The errors are due to the standard deviation of the grain number in the tracks. Considering the mean fading used in the calibration curve, the values obtained should be considered as too high (low) if the track were due to a primary particle that had impressed the emulsions near the end (beginning) of the exposition time. Since the tracks left by, respectively, the primary and the secondary particle were produced within a very short interval of time, their fading was assumed to be the same, permitting them to evaluate as less than  $100 m_e$  the mass difference between the two particles. In the second d) case, the secondary particle left the emulsion just before the end of its range (seen from the grain density), consenting, in this case too, to obtain results similar to the preceding ones.

The two d) cases were first interpreted by the Bristol team as a meson (primary particle) colliding against a nucleus of the emulsion, causing the ejection of another meson (secondary particle) of the same mass as the first

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<sup>15</sup> The accepted value is  $1836 m_e$ .

<sup>16</sup> They were convinced that such a probability was small, even if difficult to evaluate.

one, in two possible ways<sup>17</sup>:  $A(\mathbf{m}^-, \mathbf{m}^+)B$ , or  $A(\mathbf{m}^+, \mathbf{m}^-)C$ , where  $A(N, Z)$  is a stable nucleus of the emulsions, while  $B(N, Z - 2)$  and  $C(N, Z + 2)$  are the nuclei produced by the respective reactions. This interpretation predicted the absorption of energy by the nucleus  $A$ , whereas the experimental observation showed that the secondary meson had an energy of about 2 MeV. A second proposed interpretation was the process  $A_g(\mathbf{m}^-, \mathbf{m}^+ + Y)X$ , where  $X$  and  $Y$  are two nuclei with  $Z_X + Z_Y = 45$ ,  $Z_X \approx Z_Y$ . In this case, the energy conditions are satisfied but the fact that the emulsions did not show the tracks of two recoiling nuclei implied that their energy was of the order of some  $\mu\text{eV}$ ; the probability of this second kind of process was thus very low. The third interpretation considered the possibility that the two mesons were of different mass, and this assumption was compatible with the grain counting. Assuming a reaction such as  $^{12}\text{C}(\mathbf{m}^-, \mathbf{m}^+)^{12}\text{Be}$  (or with other light nuclei), and having an evaluation of the masses of the two nuclei, the difference between the masses of the two mesons had to be of the order of  $60 m_e$ .

The Bristol team stated that the only meson theory they knew that predicted the existence of mesons of different mass was Schwinger's<sup>18</sup>. According to Schwinger, a negative vector meson should have a very short life and should cause the production of a pseudo-scalar meson with the same charge but with a less mass, and of a photon. At that point, it was interesting to try to detect if the pseudo-scalar meson were always produced with the same or lesser energy as the first one. If this is the case, the process would be a fundamental one. The observations of the new decay mode of the mesons, according to the Bristol team, would have furthermore contributed to the solution of a problem exposed in articles by Fermi, Teller, Weisskopf<sup>19</sup>, and Wheeler<sup>20</sup> concerning the order of value of the intensity of the strong interaction as obtained from the coincidence measurements in the interactions between mesons and nuclei<sup>21,22</sup>.

To determine the meson's mass, the Bristol team proposed to observe the total energy released in the nuclear disintegration due to the collision with a meson. They had to consider the type of disintegrated nucleus, and the

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<sup>17</sup> In the original article, the mesons are generally written as  $\mu$ . To avoid confusions with the muon, we will write here the mesons as  $\mathbf{m}$ .

<sup>18</sup> Schwinger (1942).

<sup>19</sup> Fermi, Teller, Weisskopf (1947).

<sup>20</sup> Wheeler (1947).

<sup>21</sup> Conversi, Pancini, Piccioni (1947).

<sup>22</sup> Sigurgeirsson, Yamakawa (1947).

emitted neutrons (not revealed by the photographic emulsion). They found a track that demonstrated such a disintegration, corresponding to the reaction  $^{14}\text{N} + \mathbf{m}^- \rightarrow 2\alpha + 2\text{p} + 4\text{n}$  with the meson beginning energy equal to 15 MeV, corresponding to a mass of  $240 m_e$  (in agreement with the value of  $240 \pm 50 m_e$  obtained with grain counting). This conclusion was proposed very cautiously because of the uncertainty in the number of ejected neutrons.

In 1946, to confirm the discovery of the  $\pi$  meson made on Pic-du-Midi, the Bristol team decided that they had to get other recordings of similar events quickly (so as not to be preceded by Perkins' team of the Imperial College) in order to achieve for their work the necessary scientific validity. Lattes found at the Bristol Department of Geography an indication of a meteorological station at high altitude in the Andes: Chacaltaya station, in Bolivia, founded by Ismael Escobar in 1942. This site, about 20 km from La Paz, was chosen for its extremely advantageous geographical position: it is at high altitude (5500 m); it receives a cosmic ray flux 100.000 times greater than that on Pic-du-Midi; it is situated on the geomagnetic equator, permitting them to study the time variation of cosmic rays, and the cosmic ray sources in both the hemispheres; it points towards the center of the Galaxy. Thanks to its features, the Universidad Mayor de San Andrés transformed in 1951 the Chacaltaya station into the Laboratorio de Física Cósmica, directed by Escobar, where international scientific projects took place, such as the Bolivian Air Shower Joint Experiment (BASJE), and the Saytama – Yamanashi – San Andrés collaboration (SYS).

Lattes proposed to Powell and Occhialini to find funds for him to go as soon as possible to Chacaltaya to expose the new borax-loaded plates for one month. Thanks to the results obtained on Pic-du-Midi, the British government decided to finance Lattes' mission, following the conviction that the development of nuclear physics would have had political-military advantages. The first plates were developed after one month in La Paz, but the liquids employed were not appropriate. Notwithstanding the image was spotted, Lattes observed it with Costa Ribeiro's microscope in Rio de Janeiro, and he found a complete track of the "double meson", with a 600  $\mu\text{m}$  track for the second meson. All the other emulsions were developed and studied in Bristol and gave as a result about 30 tracks of "double mesons". The discovery doubtless represented an important step in the history of the comprehension of the structure of matter.

Back in Bristol, Lattes had to determine the mass ratio between the first and the second meson by means of counting measures on the tracks<sup>23</sup>. Lattes

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<sup>23</sup> Lattes, Occhialini, Powell (1947).

obtained results that convinced him that the observed process was fundamental: 130 MeV for the  $\pi$  meson and 103 MeV for the muon, with a  $\pi$  meson decay time of  $10^{-8}$  s. The first meson (the  $\pi$  meson) was thus identified with Yukawa's meson, and the second meson with Anderson's meson (muon)<sup>24</sup>. It was furthermore postulated the  $\pi$  meson typical decay reaction that, to grant momentum conservation, included a neutral small mass particle (then identified with the muonic neutrino  $\nu_\mu$ ):  $\pi \rightarrow \mu + \nu_\mu$ .

Lattes, Occhialini, and Powell used again the definition of a meson as a particle with mass intermediate between that of the proton and that of the electron, but, in the same time, they stressed the fact that the meson was not necessarily subject to strong interaction with the nucleons, nor it was associated with the forces responsible for nuclei cohesion. The data at their disposal were 644 mesonic tracks ending in the plate emulsions: 451 exposed at 2800 m at the Observatory on Pic-du-Midi and 193 exposed at 5500 m at Chacaltaya. The 451 Pic-du-Midi tracks corresponded to the arrival of about 1,5 mesons per day in  $1 \text{ cm}^3$  of emulsion. Taking into account the fact that no tracks of short range were observed, and the fading, this value was to be considered a lower limit. Since this value agreed with the one obtained from measurements with other techniques, and since it agreed with the value measured at sea level and with the predicted decrease as a function of altitude, they could be sure that the revealed mesons were a common component of cosmic rays.

The table below shows the details of all the events concerning observed secondary mesons:

Event n°	Primary meson ( $\pi$ ) range	Secondary meson ( $\mu$ ) range
1	133 $\mu\text{m}$	613 $\mu\text{m}$
2	84 $\mu\text{m}$	565 $\mu\text{m}$
3	1040 $\mu\text{m}$	621 m
4	133 $\mu\text{m}$	591 $\mu\text{m}$
5	117 $\mu\text{m}$	638 $\mu\text{m}$
6	49 $\mu\text{m}$	595 $\mu\text{m}$
7	460 $\mu\text{m}$	616 $\mu\text{m}$
8	900 $\mu\text{m}$	610 $\mu\text{m}$
9	239 $\mu\text{m}$	666 $\mu\text{m}$
10	256 $\mu\text{m}$	637 $\mu\text{m}$
11	81 $\mu\text{m}$	590 $\mu\text{m}$

<sup>24</sup> Lattes, Occhialini, Powell (1948).

We can get the mean range  $614 \pm 8 \mu\text{m}$  and the straggling coefficient  $(\sum \Delta_i^2/n)^{1/2} = 4,3 \%$  where  $\Delta_i = R_i - R$ , with  $R_i$  the range of the  $i$ -th secondary meson, and  $R$  the mean value for  $n$  particles of the same kind. We can observe that the given values are actually the length of the projections of the true trajectories on a plane parallel to the surface of the emulsion. On the other hand, since the trajectories are inclined at only a small angle with respect to the emulsions, such values are not very different from the true ones. On the basis of these first measures of the mesons, the Bristol team could state two important conclusions:

1) – Since the direction of the secondary meson is oriented at random, it is possible to calculate the probability  $P$  that its trajectory remains entirely (that is, for more than  $500 \mu\text{m}$ ) within a  $50 \mu\text{m}$  thick emulsion. By assuming a rectilinear trajectory, and considering that coulombian scattering increases the possibility of escaping the emulsion, they determined the probability  $P$  to be about 5%. The 6 Pic-du-Midi events, whose track was wholly in the emulsions, correspond to about  $120 \pm 50$  total events. As a first conclusion, the production of a secondary meson was a common mode of decay of a considerable fraction of those mesons, whose trajectory was wholly in the emulsion.

2) – If the secondary mesons were always ejected with the same velocity, the values of the range of the secondary mesons would peak around a mean value, as it actually is. As a second conclusion, the secondary mesons had all the same mass, and they were ejected with the same kinetic energy. The Bristol team confirmed the supposition that it was a fundamental phenomenon, since it was independent from the kind of collided nucleus of the emulsion. It was so called “ $\mu$  decay” and, to distinguish the kinds of mesons, instead of the generic symbol  $\mu^{25}$ , they used  $\pi$  for the primary meson, and  $\mu$  for the secondary meson.

With the known range-energy relation for protons up to 13 MeV, and with an assumed value of the mass of  $\mu$  meson, they could determinate the energy of the meson with an error valued about 10%. Here are the data reported for different mass values:

Mass ( $m_e$ )	100	150	200	250	300
Energy (MeV)	3,0	3,6	4,1	4,5	4,85

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<sup>25</sup> To avoid confusion, we had written it as **m**.

They already noticed that, due to energy conservation,  $\mu$  decay could not be interpreted assuming the same mass for the two kinds of mesons. Notwithstanding the precautions to be kept in mind in deducing mass values from emulsion grain counting measurements, the almost simultaneous production of the two mesons implied that all the conditions were the same for both mesons. This result validated the measurement technique. They measured grain density by counting the number  $N$  of impressed grains in a succession of 50  $\mu\text{m}$  intervals along the trajectory, observed with a  $\times 2000$  optic microscope. In the case of  $\mu$  decay, the curve  $\text{Log}_{10}N - \text{Log}_{10}R$  ( $R$  is the residual range) was different for the two kinds of mesons, that is, there was a difference in the grain density in the tracks of the  $\pi$  and  $\mu$  mesons, corresponding to different masses (as long as both mesons were single-charged, a fact confirmed by the grain density at the end of the tracks).

To obtain a more precise measure of the ratio of the two masses, they had to use  $\pi$  meson tracks on the order of 600  $\mu\text{m}$ . These are rather infrequent cases: in the first table, they are the events 3 and 8. In event 3, they obtained a mass ratio  $m_{\pi}/m_{\mu} = 2,0$ , and in event 8) the value 1,8. In these two events, the errors derived, besides from the standard deviation on the number of grains counted, also from the fact that the emulsions were not perfectly homogeneous. In the other events (with  $\pi$  meson track less than 600  $\mu\text{m}$ ), the mass ratio was lower. They however estimated a lesser limit valued as  $m_{\pi}/m_{\mu} = 1,5$ . The obtained values of  $m_{\pi}/m_{\mu}$  were strictly connected with the interpretation of  $\mu$  decay. With the hypothesis that the  $\pi$  meson decays spontaneously in a  $\mu$  meson and a photon with equal and opposite momenta, assuming a value for the mass of the  $\mu$  meson, they could calculate its energy from the value of measured range and then determinate its momentum. This way, they also obtained the energy and momentum of the photon, and they could calculate the mass of the  $\pi$  meson from the energy conservation  $m_{\pi}c^2 = m_{\mu}c^2 + E_{\mu} + h\nu$ .

Assumed $m_{\mu}$ ( $m_e$ )	$E_{\mu}$ (MeV)	$h\nu$ (MeV)	$m_{\pi}$ ( $m_e$ )	$m_{\pi}/m_{\mu} \pm 3\%$
100	3,0	17	140	1,40
150	3,6	23	203	1,35
200	4,1	29	264	1,32
250	4,5	34	325	1,30
300	4,85	39	387	1,29

Assuming a value for  $m_\mu$  between  $100 m_e$  and  $300 m_e$ , they obtained a value for  $m_\pi/m_\mu$  lower than 1,45, also under the possible hypothesis that a light particle would be ejected, such as an electron or a neutrino. Under the hypothesis that a neutral particles, of mass similar to that of the  $\square$  meson, would be ejected, then they had a ratio  $m_\square/m_\square = 2,1$ . The conclusion obtainable from the measurements was that the  $\mu$  meson ejection could not be considered the product of the  $\pi$  meson spontaneous decay with the production of also a photon or a light particle because of momentum conservation. The experimental results rather agreed with the production of a second particle with mass comparable with that of the  $\square$  meson.

The analysis of 644 primary mesons tracks wholly contained in the emulsion permitted them to identify 145 events of secondary particles production:

- 40 events of a meson production: they were therefore the decay of a  $\pi$  meson, even if it was not always sure the nature of the secondary meson.
- 105 events of heavy particle production: these were nuclear disintegrations produced by the primary meson.

The Bristol team decided, even if they had no evidences to back up this hypothesis, to considerate the 105 disintegration events as due to slow mesons, called  $\sigma$  mesons. Since the meson-nucleus interaction is short range, the nuclear coulombian repulsion against a positive particle implies that only the interaction of a nucleus with a negative particle can cause a disintegration event.  $\sigma$  mesons, cause of the nuclear disintegration, were therefore considered to be negative mesons. Later on, the Bristol team will put in evidence that  $\pi$  mesons, and some of  $\sigma$  mesons, are particles of the same kind, but with opposite electric charge.

To discuss the mesons' origin, the Bristol team had to deal with the problem of determining the production rate of the different kinds of mesons and correcting the values of the numbers of observed tracks. The tracks heavily inclined with respect to the plates plane, and the tracks shorter than<sup>26</sup>  $50 \mu\text{m}$  were hard to find and to interpret. To discriminate among the various tracks, they had to keep in mind also if this operation had or not influenced the numerical ratio among the different kinds of mesons.<sup>27</sup>

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<sup>26</sup> The track length is actually always the projection of the true trajectory on the plates plane.

<sup>27</sup>  $\sigma$  mesons track was actually identified thanks to the disintegration star, while  $\pi$  track mesons was identified thanks to the long  $\mu$  meson track.

In the case of mesons whose track was wholly inside the emulsion, and did not give origin to secondary heavy particles, they plotted the number of mesons in a 20  $\mu\text{m}$  interval as a function of the meson's range in the emulsion. Under the hypothesis of rectilinear and randomly oriented tracks, they could compare the experimental plot with a theoretical distribution  $N(t)\delta t = \sum N_0/d [1 - t/(d^2 + t^2)^{1/2}]\delta t$  where:

- $N(t) \delta t$  is the number of tracks whose projected range lies within the interval  $(t, t + \delta t)$ ;
- $\sum N_0$  is the total number of tracks in the observed area;
- $d$  is the emulsion thickness.

The relation between the number of tracks  $\sum N_t$  whose projected range is greater than  $t$  is given by  $\sum N_t = \sum N_0[(d^2 + t^2)^{1/2} - t]$ . When  $\sum N_t$  was experimentally determined, they could calculate the value  $\sum N_0$  as in the following table (referred to 3,5  $\text{cm}^3$   $\text{C}_2$  emulsion exposed for 40 days on Pic-du-Midi):

$t$ ( $\mu\text{m}$ )	$\sum N_t$	$\sum N_0$
400	42,5	$679 \pm 104$
300	62	$748 \pm 95$
200	96,5	$783 \pm 77$
100	185,5	$795 \pm 58$
80	199,5	$709 \pm 49$
60	212	$569 \pm 41$
40	224	$465 \pm 31$

The experimental plot corresponded to the theoretical value of  $\sum N_0 = 795 \pm 58$  mesons, whose tracks ended wholly in the emulsion, without giving origin to secondary heavy particles<sup>28</sup>. From table 4, we can see that these results were consistent with the assumption that no track with a projected range longer than 100  $\mu\text{m}$  was lost, while it was reasonable to expect more or less important losses for shorter ranges. The Bristol team assumed therefore that the total number of tracks in the emulsion could be determined by counting the tracks with  $t > 100 \mu\text{m}$ , using so the value  $\sum N_0 = 795$  obtained from the value  $\sum N_{100} = 185,5$ . In a similar way, they obtained the

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<sup>28</sup> They are therefore  $\pi$  mesons, with indistinguishable  $\mu$  meson track, and  $\sigma$  mesons, with indistinguishable disintegration products.

results concerning  $\sigma$  mesons (recognizable from the nuclear disintegration products) valued at  $122 \pm 20$ . The total number of slow mesons was therefore valued in  $(795 \pm 58) + (122 \pm 20) = 917 \pm 70$ .

To evaluate the number of  $\pi$  mesons, they worked in two ways. A first estimate of the number of  $\pi$  mesons was obtained with the same method used for  $\sigma$  mesons. From the 6 tracks of  $\pi$  mesons that had produced  $\mu$  mesons with range in emulsion longer than 500  $\mu\text{m}$ , thanks to the equation  $\sum N_t = \sum N_0 [(d^2 + t^2)^{1/2} - t]$ , they determined the real number of events as  $120 \pm 50$ . A second estimate was obtained observing the events whose  $\mu$  meson range in emulsion is limited to a certain interval of values, so determining a number of events as  $115 \pm 20$ . Combining the two results, they obtained the mean value of the number of  $\pi$  mesons:  $117 \pm 20$ . Similar results were obtained from the analysis of the emulsions exposed at Chacaltaya. Table 5 shows the final data of the analysis of Pic-du-Midi (2800 m) emulsions (3,5  $\text{cm}^3$  large, 50  $\mu\text{m}$  thick) and of Chacaltaya (5500 m) emulsions (1,1  $\text{cm}^3$  large, 100  $\mu\text{m}$  thick) exposed for 40 days.

	Pic-du-Midi		Chacaltaya	
	$\sum N_0$	Number/ $\text{cm}^3\text{d}$	$\sum N_0$	Number/ $\text{cm}^3\text{d}$
Mesons	$917 \pm 70$	$6,5 \pm 0,5$	$269 \pm 25$	$6,1 \pm 0,6$
$\pi$ mesons <sup>29</sup>	$117 \pm 20$	$0,8 \pm 0,2$	$40 \pm 20$	$0,9 \pm 0,5$
$\sigma$ mesons	$122 \pm 20$	$0,9 \pm 0,2$	$46 \pm 9$	$1,0 \pm 0,2$
$\mu$ mesons <sup>30</sup>	$117 \pm 20$	$0,8 \pm 0,2$	$40 \pm 20$	$0,9 \pm 0,5$
Unaccounted	$561 \pm 100$	$4,0 \pm 0,7$	$143 \pm 40$	$3,3 \pm 0,9$
Disintegration in at least 5 charged particles		10,5		
$\pi^-$ and $\sigma$ mesons		$1,7 \pm 0,5$		
Slow mesons from disintegration		$0,6 \pm 0,3$		

<sup>29</sup> This line has the same values of “ $\mu$  mesons” line, as they supposed that an equal number of  $\mu$  mesons detected in the plates were due to  $\pi$  mesons stopped not in the emulsion but very close to it.

<sup>30</sup> Due to the decay of  $\pi$  mesons at rest.

The most obvious result of this table is that there were no substantial difference between the numerical values corresponding to the two different altitudes. There were different conditions of exposition, and different times passed between the exposing of the plates and their development, so the distribution ratios among the kinds of mesons were not calculated with absolute certainty.

With the numerical values relative to the slow mesons, the Bristol team went on to analyze a theoretical model that was able to give numerical results compatible with the experimentally obtained values. In the Pic-du-Midi plates there were about 4000 tracks due to high-energy nuclear disintegrations with mesons production. Under the usual assumptions of tracks wholly contained in the emulsion and randomly oriented tracks, they estimated that the energy of a meson able to go through the plates had to be of the order of 50 MeV. This value was becoming an upper limit to the energies to take in account. For energies between 1 MeV and 3 MeV, they observed the tracks of 4 disintegrations corresponding to 12 theoretical disintegrations<sup>31</sup>. Assuming that the values of energy up to 50 MeV (upper limit) are equally likely, the value of 12 disintegrations (for energies between 1 MeV and 3 MeV) corresponded to  $0,6 \pm 0,3$  mesons/cm<sup>3</sup>d that, even if cautiously, fully agreed with the obtained numbers of  $\pi^-$  and  $\sigma$  mesons<sup>32</sup>. This result confirmed the hypothesis that a considerable (but not yet determinable) fraction of the observed  $\pi^-$  and  $\sigma$  mesons were originated from nuclear disintegration phenomena.

Let now see the final theoretical interpretation of the measurements conducted by the Bristol team, based on the interpretation the simplest among those taken in account, consisting in the following points<sup>33</sup>:

- $\pi$  mesons and most of  $\sigma$  mesons are particles of the same kind but opposite charged, produced by nuclear disintegration processes.
- $\pi^+$  mesons undergo  $\mu$  decay giving origin to a  $\mu$  on whose decay no hypothesis is made.
- $\pi^-$  are caught by nuclei giving origin to nuclear disintegrations with the emission of heavy particles.
- Unaccounted mesons are to be considered  $\mu$  mesons from  $\pi$  mesons decay outside the emulsion.

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<sup>31</sup> The true number of tracks of a certain kind is always greater than the experimentally determined one.

<sup>32</sup> See table 5, line "slow mesons from disintegrations".

<sup>33</sup> Lattes, Occhialini, Powell (1947).

- Fly time of  $\pi$  and  $\mu$  mesons in the emulsions is  $10^{-11}$ s.

These hypotheses permitted them to interpret the following experimental facts:

- The number of  $\pi^-$  and  $\sigma$  mesons is the same within the limit of experimental error.
- The relative frequency of the different kinds of mesons does not significantly vary with the altitude.
- The products of  $\pi^+$  mesons decay are positively charged and do not interact with nuclei such as to cause a nuclear disintegration with the emission of heavy particles.
- The cosmic rays penetrating component at sea level consists of (positive and negative)  $\mu$  mesons due to the decay in flight of the  $\pi$  mesons formed in high atmosphere.  $\mu^-$  mesons are to be caught by a nucleus of the silver halide of the plates or undergo a  $\beta$  decay in the emulsion<sup>34</sup>, while  $\mu^+$  mesons interact with the atomic electrons.
- The interaction of  $\mu$  mesons with nuclei is much fainter than that of  $\pi$  mesons.
- The sum of the mean-life of  $\pi$  and  $\mu$  mesons is  $2 \times 10^{-6}$  s, with the  $\mu$  meson with longer mean-life<sup>35</sup>.

The positive result of this research was of course due to the contributions of various scientists (Lattes, Occhialini, Powell, Camerini, Fowler, Cier, Escobar, etc.), and of the co-operation of various institutions: H. H. Wills Laboratory, Ilford Ltd. Cavendish Laboratory, Cambridge High Tension, Getúlio Vargas Foundation, France Embassy in London, Pic-du-Midi Observatory, Department of Geography of the University of Bristol, Bolivian Meteorological Service, etc. The official communication, apart from the published articles, was at the Conference on Cosmic Rays and Nuclear Physics held at the Institute of Advanced Studies in Dublin (July 5-12, 1947). Powell, spokesman of the Bristol team, presented their conclusions strengthening their scientific character, but the skepticism in a physicists circles, more engaged in the analysis of Pancini-Piccioni-Conversi's experiment, required further open discussions of the argument and close examinations of the calculations to confirm their validity. Lattes

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<sup>34</sup> With probability valued, respectively, in 1/3 and 2/3.

<sup>35</sup> The values accepted today are  $2,197134 \times 10^{-6}$  s for  $\mu$  meson and  $2,6030 \times 10^{-8}$  s for  $\pi^+$  meson.

too took part in some of these conferences, in particular at those in Scandinavia (Copenhagen and Lund) where he was invited by Bohr, enthusiastic about the discovery.

Thanks to a Rockefeller scholarship, at the end of 1947, Lattes went to Berkeley to do research with Gardner. They wanted to detect the  $\pi$  mesons artificially produced with the new 184-in (about 4,67 m) cyclotron operating with beam of 380 MeV  $\alpha$  particles (95 MeV per nucleon) colliding against a 1/16 in thick carbon target and with  $C_2$  and  $C_3$  Ilford plates and Eastman NTB plates with 100  $\mu$  thick emulsions. This energy is not sufficient to produce  $\pi$  mesons, so Lattes tried the favorable collisions, those in which the internal momentum of a nucleon in a single  $\alpha$  particle adds (in the vector sense) to the momentum of the beam of the  $\alpha$  particles thus giving sufficient energy in the center of mass frame of reference. Lattes was actually able to produce  $\pi$  mesons, both negatively<sup>36</sup> and positively<sup>37</sup> charged. Measuring the range and the curvature radius of the orbits in an assigned magnetic field, he was able to estimate the mass of  $\pi$  mesons as about 153 MeV. A last kind of research was shortly conducted by Lattes in Berkeley before his return to Brazil: the analysis of the plates that McMillan had exposed to the  $\gamma$  rays produced by a 300 MeV electrosynchrotron. Lattes obtained 12 tracks of  $\pi$  mesons, of both charges. It was the first detection of artificially photoproduced  $\pi$  mesons.

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<sup>36</sup> Gardner, Lattes (1948).

<sup>37</sup> Bishop, Gardner, Lattes (1948); Burfening, Gardner, Lattes (1949).

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