The Indirect Observation of the Decay of Mesotrons.

Italian Experiments on Cosmic Radiation, 1937-1943

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ABSTRACT

Following the discovery of mesotrons (intermediate-mass particles) in cosmic radiation, a group of physicists in Rome participated in a program of experiments designed to achieve the first observation of the spontaneous decay of elementary particles. The experimental results were classified as "indirect observations" of the microphysical process of decay, and the development of experimental methods was regarded as a progression toward increasing observational directness. This paper traces the activities of the Rome cosmic-ray experimenters, viewing them as a stream in the international current of interest and research on the "natural β-radioactivity" of the mesotrons, and paying attention to the aspects of their experimental practices that the researchers associated with observational directness. It shows that the attribution of degrees of directness depended on the elimination of intrusive "additional assumptions" in the phenomenological models of the experiments.

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1. INTRODUCTION

If a tourist chanced to visit the Basilica of Maxentius in Rome in the ominous summer of 1939, she could have observed four men busy around a cable-rigged aluminium box, which they carted in and out the building, evidently convinced that they were observing something from the sky. The imperial ruins became briefly a cosmic-ray observatory for a team of physicists who gathered in Rome on the eve of WWII, after the emigrations of their leaders Enrico Fermi and Bruno Rossi, in an effort to keep alive the work that had just recently propelled Italian physics to the frontiers of modern research. If asked about their undertakings, the physicists would have explained that the composition of cosmic radiation inside the high-vaulted basilica was the same as a few meters under water; that they were looking for the most elementary form of β radioactivity, the decay of the particles then called *mesotrons* or *mesons*; that, in case of success, they would be the first to observe the spontaneous disintegration of an elementary particle, an event happening on a time scale of the order of a microsecond; and that their observation would strongly support an explanatory hypothesis known as *Yukawa's theory*, which unified nuclear and cosmic-ray physics.[1] The tourist would have had to take their word for it.

Observing cosmic rays is different from observing ancient monuments, people around us, or the stars. It is a branch of microphysical research, conducted through practices that stemmed from late nineteenth-century experiments with electrical discharges and early twentieth-century studies of radioactivity, and developed conjointly with traditions of specialized instruments and annexed techniques. A philosophical current that has been characterized as "austere empiricism" has long cautioned against the assimilation of such practices to ordinary observation.[2] To the austere empiricist, microphysical entities and processes are unobservable. Science begins and ends in sensorial experience, and particles like the mesons should be regarded as theoretical constructs, which have the function of helping predict, from past observations, the observable output of laboratory instruments. A different current of thought, closer to scientists' lexicon and practices, recognizes the tendency of physical research to move away from immediate experience. Science has taught us that the human senses are narrow-range receptors of a limited set of signals from the physical world. In this light, research begins in perception only in the sense that scientific observation is an extension of ordinary observation, not only based on the best knowledge available but actually required by it. Moreover, as Pierre Duhem pointed out, the result of a physics experiment is not a sensorial fact, but an abstract and symbolic representation that is connected to the fact by the theories held by the experimenter.[3] The term "observation", Ian Hacking noted, has always been associated with the use of instruments, for example in astronomy, and the instruments were for measuring things before they began extending observation beyond the senses.[4] In this perspective, scientific observation is a reasoned extension of ordinary observation and, at the same time, an abstraction from it. Relativity theory and

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[1] The particles studied by the Rome physicists are today called *muons*; their decay and radioactive β-decay are now regarded as two distinct phenomena produced by the same fundamental force.

[2] The phrase "austere empiricism" is from Grover Maxwell, "The ontological status of theoretical entities", in H. Feigl and G. Maxwell, eds., *Scientific explanation , space, and time* (Minneapolis, 1962), 3-27, on 8.

[3] Pierre Duhem, *The aim and structure of physical theory* (Princeton, NJ, 1991), on 144-147.

[4] Ian Hacking, *Representing and intervening. Introductory topics in the philosophy of natural science* (Cambridge, 1983), on 168.

quantum mechanics reinforced physicists' profession of empiricism by alleging a deep distinction between observable and unobservable variables, and claiming a ban on the unobservable. Nonetheless, their notion of observability was based on idealized extensions of the observation of classical variables, not on the austere empiricists' idea of observation.

The Italian cosmic-ray physicists, of the school of Fermi and Rossi, were noted for their avoidance of questions that made no practical difference.[5] Whatever epistemic value they might have privately granted the objects of microphysics, to any practical and public effect they equated their experimental observations to observations *tout court*. For example, instruments like the one used in the Maxentius Basilica were called, in a carefree optical analogy, "cosmic-ray telescopes". Still, not all the observations made with them were regarded as equal. The experiment of which the measurements in the basilica were part was an acknowledged case of *indirect* observation, while other experiments, aiming at same microphysical process, were classified as *direct* observations. Furthermore, Rossi and the Rome cosmic-ray experimenters were conducting a series of investigations, and presented the new experiments in the sequence as being "more direct" than the previous ones. It is of course possible that they were gesturing to an ideal scientific canon in order to uphold their work at a time of professional uncertainty. Nonetheless, their recurrent uses of the terminology of directness were consistent, they were consistent with similar uses by some of their colleagues, and they consistently corresponded to practical choices and acts. The qualification of indirectness was operative in their practice, whereas the distinction between perception and instrumental detection was not. But what is the meaning of directness when the only form of observation possible is theory-imbued instrumental detection?

Analyses of directness in scientific observation have been carried out from a perspective in which observation is regarded as transfer of information from an object to the observer. Accordingly, they have been concerned with the inferential structure of the end result of the experimental process, the observational claim, which is seen to descend from an "observation-situation".[6] Experimental observations, however, are not reducible to the passive reception of information from a static situation. They are active interventions of the researchers in the material world and, at the same time, dialogical constructions of persuasive arguments within the norms of a professional community.[7] From this angle, a series of early particle experiments self-described as a progression in directness is an open invitation to examine the co-shaping of an observational claim and its observation-situation (object, information, *and* transmission channel) in the history of microphysics. Directness constitutes one of the two "axes" along which, according to

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[5] Roberto Maiocchi, *Non solo Fermi. I fondamenti della meccanica quantistica nella cultura italiana tra le due guerre* (Firenze, 1991).

[6] Peter Kosso, "Dimensions of observability," *British journal for the philosophy of science 39* (1988), 449-467; Peter Kosso, *Observability and observation in physical science* (Dordrecht, 1989); Dudley Shapere, "The concept of observation in science and philosophy," *Philosophy of science, 49* (1982), 485-525.

[7] Peter L. Galison, *How experiments end* (Chicago, 1987); Benoît Godin and Yves Gingras, "The experimenters' regress: From skepticism to argumentation," *Studies in history and philosophy of science 33* (2002), 137-152; Hacking, *Representing and intervening*; Andy Pickering, "Living in the material world: On realism and experimental practice", in D. Gooding, T. Pinch, and S. Schaffer, eds., *The uses of experiment. Studies in the natural sciences* (Cambridge, 1989), 257-297.

Peter Galison, the solidity of experimental results is formed, the other axis being stability. Galison characterizes directness as an attribute that is increased by "moves that bring experimental reasoning another rung up the causal ladder". He also admits in the same breath that "no experiment is ever 'direct' in the strict logical sense."[8] What does it mean, then, to improve the directness of an experiment? What moves do experimenters make in order to achieve this effect?

My essay attempts to answer these questions in a historical case. It reconstructs the steps through which cosmic-ray physicists developed an observational technique when, riding the early successes of quantum field theory, they set themselves the challenge of studying a new and ephemeral kind of particles. As it happens with experiments, the drive to directness eventually produced a clash with a conspicuous element of the web of presuppositions from which the prediction of decays had sprung. In 1947, three members of the Rome group, Oreste Piccioni, Marcello Conversi, and Ettore Pancini, who were carrying forth the program initiated at the Basilica of Maxentius in the direction of direct observations, obtained an unexpected result. Their work is today celebrated as the experimental discovery that terminated the prolonged misidentification of the cosmic-ray mesotrons with the quanta of Yukawa's theory.[9] But the outcome of these events was not only the rectification of a memorable mistake; it was also the acquisition of a body of experimental methods that constituted the first observations of the spontaneous instability of elementary particles. Therefore, I hope that my work will contribute to a historical understanding of the experimental underpinnings of high-energy physics, and in particular of the translation of particle decay from a theoretical idea into an empirical notion.

I shall first introduce the instruments and techniques used by the Italian cosmic-ray physicists, recall the connection between cosmic radiation and Yukawa's theory, and outline the beginning of mesotron studies in Italy. I shall then trace the stream of mesotron experiments conducted by the Rome physicists under the leadership of Gilberto Bernardini, connecting them also to similar experiments by Bruno Rossi and by other experimental groups abroad, up to the beginning of the direct observation of mesotron decay by Piccioni and Conversi.

2. COSMIC RAYS AND PARTICLE OBSERVATIONS

The 1930s were the happy years of nuclear physics. They opened with the discovery of the neutron and closed with the possibility of fission chain reactions, meanwhile advancing (though not in a linear way) the understanding of β-radioactivity and artificial radioactivity. The Rome physics department was on the forefront of these

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[8] Galison, *How experiments end*, on 259-260 (ref. 7).

[9] See, for example, Robert N. Cahn and Gerson Goldhaber, *The experimental foundations of particle physics* (Cambridge, 1989), on 18-37. Historical treatments of this episode can be found in L. M. Brown and L. Hoddeson, eds., *The birth of particle physics. Based on a Fermilab symposium* (Cambridge, 1983), on 17-19 and 155-250; Allan Franklin, *Are there really neutrinos? An evidential history* (Cambridge, Mass., 2001), on 100-104; Galison, *How experiments end*, on 124-126 (ref. 7); Peter L. Galison, *Image and logic: A material culture of microphysics* (Chicago, 1997), on 202-210; Daniela Monaldi, "Life of μ : The observation of the spontaneous decay of mesotrons and its consequences, 1938-1947," *Annals of science, 62* (2005), 1-37; Abraham Pais, *Inward bound: Of matter and forces in the physical world* (Oxford 1986), on 426-433 and 452-455; Helmut Rechenberg and Laurie M. Brown, "Yukawa's heavy quantum and the mesotron (1935-1937)," *Centaurus, 33* (1990), 214-252.

developments with Enrico Fermi's formulation of a theory of β-decay, and with Fermi and his associates' experiments on neutron-induced radioactivity.[10] In the second half of the decade, however, Fermi and his close collaborator, Franco Rasetti understood that if they wanted to remain on the vanguard of the field they needed to upgrade their material and institutional resources. In 1937, they submitted a request to the *Consiglio Nazionale delle Ricerche* (CNR) for the foundation of a national institute of radioactivity having an organization and a budget adequate to keep up with equivalent organizations in Europe and America. Their main aspiration was to construct a cyclotron to provide high-energy artificial radioactive sources, now necessary for cutting-edge nuclear studies. After consulting with Ernest O. Lawrence over the summer, they estimated that the machine would cost one million lire. They received 150000 lire, and neither the radioactivity institute nor the Italian cyclotron became reality.[11] Thus Fermi and Rasetti turned their attention to another area of microphysical research, cosmic radiation. There, high-energy radiation was free, and the latest advances promised a fundamental connection with the innermost workings of the nucleus.

Until then, in Italy cosmic-ray research had been practiced by handful of young physicists who had begun their careers at the University of Florence. The most prominent among them were Bruno Rossi, a recognized world authority in cosmic rays, Giuseppe Occhialini, co-discoverer of electron-positron pairs, and Gilberto Bernardini, today remembered as one of the pillars of European post-war physics.[12] The Rome and the Florence schools—known as the Via Panisperna school and the Arcetri school, after the places in which the respective physics laboratories were located—are today regarded as the driving forces of a brief scientific *rinascimento* that retrieved Italian physics from long-standing backwardness and stagnation.[13] While the Rome group had concentrated heretofore on the nucleus under the conviction that it was the last frontier of the unknown, the Florence researchers had found their matter in the application of a new and affordable experimental technique to the study of cosmic rays. The technique consisted of using electronic counters according to the so-called method of coincidences.

Cosmic-ray physics as well had been marked by a rapid evolution since 1930. More precisely, it had advanced in unexpected directions thanks to the application of two novel kinds of instruments, cloud chambers and electronic counters, and to the development of observational techniques that connected the outputs of the instruments to the newest microphysical theories. Radioactivity and cosmic radiation shared a large part of their observational histories because they manifested themselves in the same way, by ionizing surrounding matter, and were therefore observed through the same instruments.

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[10] Gerald Holton, "Fermi's group and the recapture of Italy's place in physics", *The scientific imagination* (Cambridge, MA, 1998), 155-198; E. Segrè, *Enrico Fermi physicist* (Chicago, 1972). Francesco Cordella, Alberto De Gregorio, and Fabio Sebastiani, *Enrico Fermi. Gli anni italiani* (Roma, 2001).

[11] G. Battimelli and M. De Maria, "Prefazione. Da Via Panisperna a Los Alamos", in Edoardo Amaldi, Giovanni Battimelli, and Michelangelo De Maria, *Da via Panisperna all'America. I fisici italiani e la seconda guerra mondiale* (Roma, 1997).

[12] Occhialini observed electron-positron pairs in collaboration with P. M. S. Blackett in Cambridge in 1932-33. He also collaborated to the discovery of the π-mesons with C. F. Powell in Bristol in 1947.

[13] M. De Maria, G. Malizia, and A. Russo, "La nascita della fisica dei raggi cosmici in italia e la scoperta dell'effetto est-ovest", *LXXVI Congresso nazionale della SIF* (Trento, 1990); Bruno Benedetto Rossi, *Moments in the life of a scientist* (Cambridge, 1990); Arturo Russo, "Bruno Rossi e la scuola di Firenze", in A. Casella et al., eds., *Una difficile modernità. Tradizioni di ricerca e comunità scientifiche in italia, 1890-1940* (Pavia, 2000), 287-298.

They remained, however, two separate fields of research (cosmic rays being in some cases background noise to terrestrial radioactivity and vice versa) until 1937, when a freshly discovered class of particles in cosmic radiation was linked to a recently formulated quantum-field theory of nuclear phenomena.

The electronic counter, also known as electron tube or Geiger-Müller counter, is a device capable of revealing the passage of a single fast charged particle, by the amplification of its ionization effects, in the form of a sharp electrical pulse.[14] The method of coincidences consists of registering the concomitant signals of two or more counters, and interpreting the excess of such signals over the number expected to occur by chance ("chance coincidences") as causally related events ("true coincidences"). The method of coincidences was established as a general means of investigation for cosmic rays in conjunction with the overthrow of the then current view about the nature of the rays, and with a consequent shift in the motivation of cosmic-ray studies. The penetrating rays from outer space were initially thought to be bursts of electromagnetic radiation of extremely high energies, called "ultra-gamma rays" or *Ultrastrahlen*, and their interest lay mainly in their unknown extra-terrestrial origin. The ionizing effects of the ultra-gamma rays were explained by their capability to eject electrons when colliding with atoms, according to the mechanism known as Compton effect. In 1929, Walther Bothe and Werner Kolhörster at the *Physikalisch-Technischen Reichsanstalt* in Berlin had observed a high rate of coincidences from two electron tubes having their axes horizontal and on the same vertical plane, and had interpreted them as caused by the passage of single cosmic rays through the two tubes. They had also showed that the interposition of four centimetres of gold between the two counters, which would have absorbed any Compton electron, suppressed only a small fraction of the coincidences. These signals, they concluded, could not be secondary effects of *Ultrastrahlen* but had to be produced by highly penetrating charged corpuscles in the cosmic radiation itself.[15] If Bothe and Kolhörtser were right, the cosmic rays were no longer only a cosmological phenomenon, but could afford a testing ground for the application of the new microphysical theories, the relativistic extension of quantum mechanics and quantum electrodynamics (QED), to the interactions of charged particles in matter.[16]

Upon reading Bothe and Kolhörster's paper, Rossi realized that their technique could be advanced if the coincidences were registered by an electronic circuit rather than by a photographic setup, as it was initially done. He immediately started manufacturing Geiger-Müller tubes according to the German recipe, and connected them to a circuit of his own design, which can be described as a physical realization of the logical operator AND. Rossi's invention was a modular circuit that could record coincidences from an arbitrary number of counters with a high, and highly improvable, time resolution. It made

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[14] Thaddeus J. Trenn, "The Geiger-Müller counter of 1928," *Annals of science, 43* (1986), 111-135.
[15] W. Bothe and W. Kolhörster, "Das Wesen der Höhenstrahlung," *Zeitschrift für Physik, 56* (1929), 751-777.
[16] Laurie M. Brown and Lillian Hoddeson, "The birth of elementary particle physics: 1930-1950", in Brown and Hoddeson, eds., *The birth of particle physics,* 3-36 (ref. 9); David C. Cassidy, "Cosmic ray showers, high energy physics, and quantum field theories: Programmatic interactions in the 1930's.," *Historical studies in the physical sciences, 12* (1981), 1-39; Peter Galison, "The discovery of the muon and the failed revolution against quantum electrodynamics," *Centaurus, 26* (1983), 262-316; Galison, *How experiments end*, on 75-133 (ref. 7). For the history of QED, see S. S. Schweber, *QED and the men who made it: Dyson, Feynman, Schwinger, and Tomonaga* (Princeton, NJ, 1994).

the coincidence method a powerful and versatile technique, for it could accommodate any number of detectors in varied arrangements. It also lent itself to modification in order to register a signal from a counter concurrent with the absence of signal from another counter, a combination that in physics is known as "anticoincidence" and in logic as NOT. Rossi's circuit was to become the basis not only of a new class of particle detection methods, but also of the whole field of electronic logic.[17]

Suitable arrangements of counters, absorbers, and recording circuits could now be used to select and count rays according to their penetration power and their direction of incidence. Setups of this kind, which could be rigidly inclined at various angles to observe spatially defined "beams" of radiation from above, became standard in experimental studies of cosmic radiation during the 1930s, and came to be referred to as "counter telescopes" or "cosmic-ray telescopes". The structures and the electronics recording systems became increasingly sophisticated—with the implementation of various arrays of counters in coincidence, anticoincidence, and delayed coincidence, and with gradually higher efficiency, stability, and time resolutions—and capable of probing in ever finer detail into the nature and behaviour of the cosmic particles.

Peter Galison has identified two grand genealogies of particle detectors: the "image tradition", centered on visualizing devices such as cloud chambers, nuclear emulsions, and bubble chambers, and the "logic tradition", which used electronic counters like Geiger-Müller tubes, scintillators, and spark chambers. Material apparatus was propagated within each tradition together with corresponding experimental styles and strategies of demonstration. The image tradition pursued the ideal of mimetic representation and relied on the persuasive power of visual impact, sometimes attributing conclusive force to individual "golden event" pictures. In contrast, the logic tradition depended entirely on statistical arguments and on the strength of large numbers.[18] But, of course, just as the power of images was often bolstered by statistical reasoning, the logic of signal selection in a coincidence experiment relied on the formation of mental images of the microphysical processes under study. The two traditions also have a common root, for it is ionization that gives rise to trails of droplets in a cloud chamber and to electrical discharges in a counter. Particle detection depends essentially on ionization. The French cosmic-ray specialist Pierre Auger wrote, "It is not an exaggeration to say that we have acquired a sixth sense – the sense of ionization."[19] Although cloud-chamber images were sometimes hailed as the most direct way to observe particles, in both traditions learning how to use the acquired sense was a sedimentary process, in which the modeling of observational procedures was interdependent with the modeling of the phenomena observed, and volatile interpretations of instrumental data gradually consolidated to form the basis of further interpretations.

3. NEW PARTICLES, THE DECAY HYPOTHESIS AND FERMI'S THEORY OF β-DECAY

Fermi and Rasetti started experimenting on cosmic rays in the fall of 1937 in collaboration with Bernardini, who had recently been appointed to the University of

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[17] Bruno Rossi, "Method of registering multiple simultaneous impulses of several Geiger's counters," *Nature, 125* (1930), 636. Galison, *Image and logic*, on 453-454 (ref. 9).
[18] Galison, *Image and logic* (ref. 9).
[19] Pierre Auger, *What are cosmic rays?* (Chicago, 1945), on 8.

Bologna but worked part-time in Rome because his institution lacked the necessary research facilities.[20] The experiments were motivated by the prospect of detecting a new phenomenon, the spontaneous decay of a newly discovered kind of particles. In order to understand how and why Fermi, Rasetti, and Bernardini addressed this problem, let us first take a glance at the status of cosmic-ray physics at the time, as it was summarized by Rossi for the *Società Italiana di Fisica* (SIF), and by Bernardini for the *Società Italiana per il Progresso delle Scienze* (SIPS).[21] During the first half of the 1930s, surveys of geomagnetic effects had confirmed that the rays arriving from outer space, the "primary rays", were for the most part high-energy corpuscles of predominantly positive charge. Observations with cloud chambers in magnetic fields had shown that the cosmic radiation at sea level contained corpuscles of positive and negative charge in approximately equal proportions, having energies from a few millions up to at least tens of billions electron-volts. Observations with cosmic-ray telescopes, of which Rossi had become a leading exponent, had revealed two kinds of rays distinguished by their different powers of penetration. While one kind was easily absorbed in matter and was no longer detectable, for example, beneath a few centimetres of lead, the other kind was barely affected, and decreased by less than fifty percent even across a meter of lead. The two kinds were called the "soft" and the "hard" components of cosmic radiation.

A fundamental link between quantum-relativistic theory and cosmic radiation had been established at the Cavendish Laboratory in 1932, when P. M. S. Blackett and Giuseppe Occhialini had built the first counter-controlled cloud chamber. Blackett and Occhialini confirmed the discovery of positive electrons just made by Carl D. Anderson at Caltech, observed the creation of electron-positron pairs, and identified the new particles with the "anti-electrons" of P. A. M. Dirac's theory.[22] Furthermore, cloud-chamber pictures and non-linear arrays of counters displayed sprays of particles of variable number and extension, which were called "showers".[23] Shower particles were soft rays generated within the atmosphere. As investigations with metal plates in cloud chambers explored the structure of showers, it appeared that at least some of these occurrences could be QED cascades, generated by succession and multiplication of the two quantum processes of pair production and *Bremsstrahlung* (photon radiation). QED, however, was affected by an apparently incurable problem of divergent calculations, which seemed to disqualify it from describing the emission of radiation above a hundred million electron-volts, and hence from being a truly fundamental theory.

It had become clear that the primary rays interacted with terrestrial matter and produced secondary rays, but the relation between the hard and soft components, and

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[20] With them was also briefly Giuseppe Cocconi, a young recruit from Milan. In the summer of 1938 Cocconi went back to Milan, where he conducted experimental studies of the new particles in collaboration with Vanna Tongiorgi. E. Amaldi, "Gli anni della ricostruzione. Parte I," *Scientia, 114* (1979), 29-50, on 31. Edoardo Amaldi, Giovanni Battimelli, and Michelangelo De Maria, *Da via Panisperna all'America: I fisici italiani e la seconda guerra mondiale* (Roma, 1997), on 66.

[21] Gilberto Bernardini, "Vedute moderne sui raggi cosmici. Con particolare riguardo alla natura delle particelle che li costituiscono e al fenomeno degli sciami," *Il nuovo cimento, 14* (1937), 383-388; Bruno Rossi, "Le attuali conoscenze sperimentali sulla radiazione cosmica," *Il nuovo cimento, 15* (1938), 43-65.

[22] M. De Maria and A. Russo, "The discovery of the positron," *Rivista di storia della scienza, 2* (1985), 237-286; Xavier Roqué, "The manufacture of the positron," *Studies in history and philosophy of modern physics, 28* (1997), 73-129.

[23] The Italians called them "*sciami*", which means swarms.

their relations to the primary rays remained unclear. It seemed possible that the primary radiation was composed only of hard rays, and that some of these generated the soft rays as secondary particles upon entering the atmosphere. Another hypothesis, which according to Rossi was better supported by experimental evidence, was that the primary radiation included both soft and hard rays, and that they were independent of one another. Rossi summed up the composition of cosmic radiation in the low atmosphere as follows. There were two kinds of charged corpuscles: the hard ones, which rarely generated showers and were absorbed by matter in proportion to the amount of mass traversed; and the soft ones, of much lower penetration power, which generated a large number of showers and were absorbed more easily by elements of high atomic number.

Compounded with the problem of elucidating the interactions of the cosmic rays was the question of what particles they were. The only charged particles known at the time were electrons and positrons, which have the same mass and opposite charge, and protons, which have the same charge as positive electrons and mass approximately two thousand times larger. It was possible to estimate roughly the mass of a slow particle from its momentum or energy, and the density of ionization along its track in a cloud-chamber picture. From these measurements, almost all the particles in the low-energy end of the cosmic-ray spectrum appeared to have electron masses. But this method of identification was inapplicable to most rays, because particles moving at relativistic speeds are indistinguishable in terms of ionization. Crucial progress had been made in 1936, when it was established that the QED cascade model successfully explained the observed features of showers even in the high-energy range in which QED was allegedly inapplicable. The part of soft rays constituted by shower particles could now be readily identified with the positive and negative electrons of a QED cascade. If, however, QED was accepted as valid at any energy, there arose the problem of explaining the hard rays, which ionized less than protons of the same momentum and had positive and negative charges, yet did not radiate enough to be high-energy electrons and positrons as described by QED. For these reasons, Carl D. Anderson and Seth H. Neddermeyer, and Jabez C. Steet and Edward C. Stevenson had recently put forward experimental arguments to claim that the hard rays were hitherto unknown particles, having masses larger than the mass of the electron and smaller than that of the proton.[24] Rossi and Bernardini closed their lectures stating that further studies were necessary to assess the hypothesis of intermediate-mass particles put forward by the Americans.

The earliest phase of cosmic-ray activities in Rome is documented by a series of working notes by Fermi.[25] Between June and November 1937, Fermi examined several cosmic-ray experiments concerning the production and the absorption of showers in the atmosphere and in water. He jotted down scattered remarks such as, "How does it happen that there is electronic radiation at sea level? […] Showers produced everywhere with

[24] Seth H. Neddermeyer and Carl D. Anderson, "Note on the nature of cosmic ray particles," *Physical review, 51* (1937), 884-886. J. C. Street and E. C. Stevenson, "New evidence for the existence of a particle of mass intermediate between the proton and the electron," *Physical review, 52* (1937), 1003-1004; J. C. Street and E. C. Stevenson, "Penetrating corpuscular component of the cosmic radiation," *Physical review, 51* (1937), 1005. Galison, "The discovery of the muon" (ref. 16); Galison, *How experiments end*, on 75-133 (ref. 7).

[25] Enrico Fermi, Notebook 22, 1937, Report A, 1937, and Report E, 1938, *Fermi Manuscripts*, Domus Galilaeana, Pisa. See also Matteo Leone, Nadia Robotti, and Carlo Alberto Segnini, "Fermi archives at the Domus Galilaeana in Pisa," *Physis, 37* (2000), 501-533.

strong penetration."[26] From the production of showers, Fermi went on to examine Anderson and Neddermeyer's and Street and Stevenson's experiments on the nature of the hard rays. This transition suggests that Fermi was pursuing the conjecture that the production of showers "everywhere with strong penetration" might be explained by a direct relation between the soft component and the hard, and hoped that such relation might be specified if the hard rays were particles of intermediate mass.

Anderson and Neddermeyer, in fact, understood the intermediate particles to be "higher mass states of ordinary electrons", called them "heavy electrons", and believed them to have a spectrum of different mass states. They supposed that, in analogy with the transitions between the excited states of an atom, transitions occurred between mass states, turning eventually the heavy electrons into their ground state of ordinary (positive and negative) electrons. The mass-state transitions could account for the evident absence of intermediate particles from ordinary matter as well as for the relation of intermediate particles to the electron component of cosmic radiation. Nonetheless, while the name "heavy electrons" remained in use for a time to refer to the new particles, Anderson and Neddermeyer's idea of electronic mass states was immediately eclipsed by a different picture, which derived from a hitherto unnoticed theory formulated by Hideki Yukawa in 1934.

Yukawa had postulated the existence of a new fundamental field to account for the interactions between protons and neutrons in a nucleus, including the mechanism of β-decay according to Fermi's theory. Fermi had represented β-decay as the transition of a nuclear particle from its neutron state into its proton state, with the concurrent creation of an electron-neutrino pair.[27] According to Yukawa, the transformation happened via an intermediate step: the neutron transformed into a proton emitting a field quantum, and the field quantum transformed into an electron-antineutrino pair (Table 1). In order to reproduce the observed range of the nuclear binding force, the field quanta would have to have a mass inversely proportional to the range. Yukawa estimated that the mass would be about 200 times the mass of an electron, and surmised that the new particles should be observable in cosmic radiation.[28]

β-decay in Fermi's theory	**β-decay in Yukawa's theory**
$n \rightarrow p + e + \nu$	$n \rightarrow p + \mu$ $\mu \rightarrow e + \bar{\nu}$

Table 1 The process of β-decay in Fermi's and Yukawa's theories

Yukawa's work was initially neglected, but the international physics community was alerted to its potentialities when Anderson and Neddermeyer claimed the observation

[26] "*Come accade che c'è radiazione elettronica a livello del mare?* […] *Sciami prodotti ovunque con forte penetrazione*", Fermi, Notebook 22, on 182 (ref. 25).

[27] Enrico Fermi, "Tentativo di una teoria dei raggi beta," *Nuovo Cimento, 2* (1934), 1-19.

[28] Hideki Yukawa, "On the interaction of elementary particles. I," *Proceedings of the Physico-Mathematical Society of Japan, 17* (1935), 48-57. Laurie M. Brown and Helmut Rechenberg, *The origin of the concept of nuclear forces* (Bristol, 1996); Rechenberg and Brown, "Yukawa's heavy quantum and the mesotron" (ref. 9).

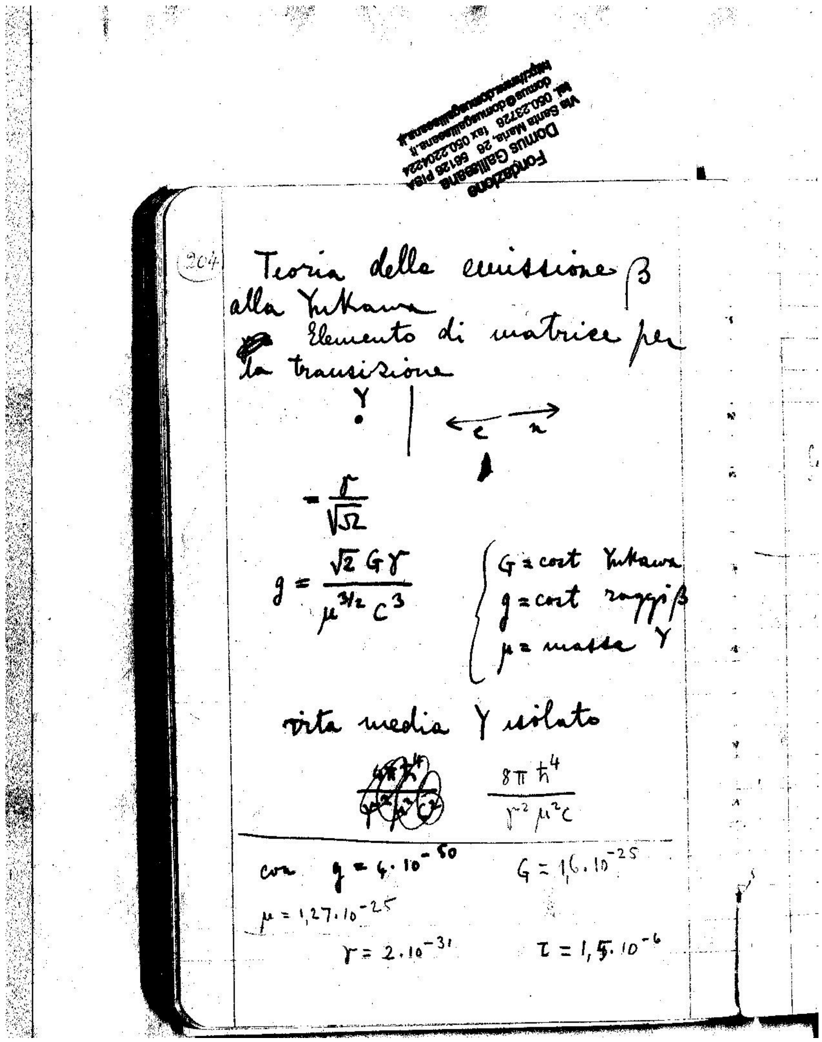

Fig. 1 Fermi's calculation of the mean lifetime of the "*yukone*". Enrico Fermi, 1937, Notebook 22, *Fermi Manuscripts*, Domus Galilaeana, Pisa.

of intermediate particles. Despite reservations about the formal structure of the theory, which was affected by more severe mathematical difficulties than QED, European theorists adopted Yukawa's idea of a fundamental nuclear field and began improving and developing it. The development most relevant for our purposes was the expression of an immediate consequence of Yukawa's β-decay, namely, that a free nuclear quantum would spontaneously decay into an electron (of the appropriate charge) and a neutrino, at a rate that could be calculated from the theory, once the values for mass and coupling constant were given. Yukawa had strangely overlooked the instability of the free nuclear quantum, but it followed so plainly from his theory that most physicists hardly noticed the omission and treated the prediction of spontaneous decay as an integral part of Yukawa's theory.

Fermi went straight from the review of intermediate-particle experiments to a systematic study of Yukawa's theory. He examined first the proton-neutron attraction according to Yukawa, referring to the nuclear quantum by the symbol "Y" and calling it "*yukone*". Then, he opened a page with the title, "Theory of β emission à la Yukawa". Yet, he did not deal with β radioactivity but immediately calculated the mean lifetime of an "isolated Y", which he found to be 1.5×10^{-6} seconds (Fig. 1).

Fermi, Rasetti, and Bernardini began working on the detection of β-decay in cosmic radiation in November 1937, presumably soon after Fermi's estimate of the mean lifetime. They designed a cosmic-ray telescope which included sets of counters in coincidence as well as in anticoincidence, and performed many runs of measurements to test the apparatus.[29] This early attempt was interrupted in March 1938, and nothing about it was published.

By this time, Homi J. Bhabha, an Indian theorist then working in Cambridge, had published the suggestion that cosmic-ray phenomena could be accounted for if it was admitted that the new particles were not higher-mass electrons but Yukawa's nuclear quanta, that they originated from the primary rays in the high atmosphere, and that they spontaneously transformed into electrons and (unobservable) neutrinos, as was required by their role in the mechanism of β-decay. Bhabha also pointed out that in order to apply the concepts of radioactive decay to cosmic rays it was necessary to take into account the transformation of time according to the theory of relativity. All the particles of the same species would have the same mean lifetime at rest, but a moving particle would be like a timer in motion, and its time of decay would become longer proportionally to its energy. Bhabha's considerations started a tide of interest in the disintegration of intermediate particles in cosmic rays. In May 1938, Europe's leading cosmic-ray specialist, P. M. S. Blackett introduced a discussion meeting at the Royal Society of London stating that the "birth, life, and death" of the new particles was the main problem now to be solved.[30]

The first work on intermediate particles from Rome was published by Bruno Ferretti, a graduate from Bologna who came to Rome as Fermi's assistant at around this time. Ferretti was assigned to analyze the theoretical consequences of the decay of hard rays into electrons and positrons. The purpose was to inquire whether the soft radiation observed at sea level could be generated by the hard component through disintegrations. Ferretti focused on Yukawa's "theory of β-radioactivity" without differentiating it from the decay of an isolated quantum, which he actually called "the YUKAWA process". He chose to work with a lifetime of 10^{-6} s, close to Fermi's estimate, although he was clear that this value was not "a priori more reliable than others" and that the theory left "an indetermination of various orders of magnitude" on this quantity. One microsecond was only a workable compromise between the range allowed by the theory and the applicability to cosmic ray phenomena.[31]

If the hard rays were β-radioactive, they could not be primary rays but would have to be generated in the upper atmosphere. Moreover, at least part of the soft radiation observed in the lower atmosphere had to be produced by their disintegrations. Ferretti calculated the disintegration probability of an intermediate particle of a given energy and

[29] Fermi, Report A, sect. b, and Report E (ref. 25).
[30] E. J. Williams, "Cosmic rays," *Nature, 141* (1938), 1085-1087, on 1086.
[31] "*il [detto] processo di YUKAWA*" and "*benché [questo valore] non sia a priori piú attendibile di altri anche molto diversi*" and "*[sussiste] una indeterminazione di vari ordini di grandezza*". Bruno Ferretti, "Su una possibile origine della radiazione cosmica molle a livello del mare," *Il nuovo cimento, 15* (1938), 421-424, on 422.

the number of electrons produced in a given layer of air by multiplication according to the QED cascade model. This analysis was the starting point of the following phase of cosmic-ray activities in Rome, but Ferretti's circumspection regarding the lifetime value was soon forgotten.

The Rome physicists were not alone in regarding the spontaneous decay of the hard rays the prime empirical test of the theory that, to everyone's understanding, had predicted it. Many experimenters and theoreticians, in Europe, America, and Japan, were spellbound by the unified answers to nuclear and cosmic-ray questions promised by the application of Yukawa's theory of β-decay to cosmic-ray phenomena. At a meeting of the British Association in August, Blackett sketched an estimate of the mean lifetime from cosmic-ray data, which he declared to be in "most satisfactory" agreement with Yukawa's calculations, and Niels Bohr proposed to name the new particles "yukons".[32]

Bernardini presented his group's program of research at a joint meeting of the SIPS and the SIF in September 1938. He explained the essentials of Yukawa's theory and stated that the existence of intermediate particles was now confirmed by various experiments. Of the many names that had been given to the new particle, "*mesotrone, barytrone, jukone*," Bernardini favoured *mesotrone*, even as he endorsed the identification of the new particles with the heavy quanta of Yukawa's theory.[33] His preferences were fully in line with those of the majority of cosmic-ray specialists abroad. It is ironic that "mesotron" prevailed just as the connection with Yukawa's quanta did, for this neologism was advocated by Anderson, Neddermeyer, and Millikan precisely as a theory-neutral designation for a class of particles which they insisted was premature to associate with nuclear theory. The variant "meson" became equally common, and the articulations of Yukawa's ideas became known as "meson theory". Hereafter, for brevity I shall refer to the hopeful identification of the mesotrons with Yukawa's quanta as the "nuclear connection".

Bernardini introduced then the decay hypothesis and its consequences for the cosmic radiation:

> In order to explain β-radioactivity, YUKAWA had to admit that the new particle disintegrated spontaneously in an electron and a neutrino with a mean lifetime of about 10^{-6} sec. Recently, EULER and HEISENBERG ("Erg. Exak. Naturwis." 17, 1, 1938) held the hypothesis that the hard component of cosmic rays is constituted of mesotrons, produced in the first layers of the atmosphere probably by *photons*, and then disintegrating with a mean life of the order of 10^{-6} sec, according to the Yukawa theory.[34]

Werner Heisenberg and his assistant, Hans Euler had just published an extensive review of cosmic rays experiments and theory, which immediately became the reference of

[32] P. M. S. Blackett, "High altitude cosmic radiation," *Nature, 142* (1938), 692-693; Robert A. Millikan, "Mesotron as the name of the new particle," *Physical review, 55* (1939), 105.

[33] Gilberto Bernardini, "L'elettrone pesante e i raggi cosmici (relazione redatta dal prof. Giulio dalla Noce)," *Il nuovo cimento, 16* (1939), on 266. Emphasis in the original. The oddly spelled *jukone* was presumably the autarkic version of Fermi's *yukone* and Bohr's yukon.

[34] "*Per spiegare la radioattività β, YUKAWA doveva ammettere che la nuova particella si disintegrasse spontaneamente in un elettrone e in un neutrino con una vita media di circa 10^{-6} sec. Recentemente EULER e HEISENBERG ("Erg. exak. Naturwis",* 17*, 1, 1938) hanno sostenuto l'ipotesi che la componente dura dei raggi cosmici consista di mesotroni, prodotti nei primi strati dell'atmosfera probabilmente da* fotoni*, e poi disintegrantisi con una vita media dell'ordine di 10^{-6} sec, secondo la teoria di YUKAWA.*" Ibid., on 267.

choice for most experimentalists in the field. Apparently, the assertiveness of this work had already had the effect of calcifying Fermi's early (and presumably tentative) estimate of the lifetime, obscuring the caution expressed by Ferretti. The notion that a microsecond lifetime derived from Yukawa's theory would be then persistently propagated into all the experimental studies of the Rome group until 1946.[35]

Bernardini's talk was followed by an animated discussion, the topic of which was unfortunately not recorded. We only know that the SIF president, Antonio Carrelli closed the discussion pointing out that the current trend in mesotron studies derived from Fermi's theory of β-decay, which had shown the possibility of particles transforming into one another. This was an understatement of the seminal role of Fermi's work. Not only was Yukawa's idea of the nuclear mediator an outgrowth of the Fermi-field concept, which stemmed from Fermi's theory, but also Yukawa's β-decay was a direct development of Fermi's. The credibility of the new theory rested on its capacity to reproduce the empirical success of Fermi's formulae while clarifying their relation to its own formulae. Since the intervention of the mediating quantum did not change the calculated rates of β-decay and could be understood as a refinement of Fermi's process, Yukawa himself had made his case stating that his theory did not "differ essentially from Fermi's theory."[36] But, as the SIF audience could not have failed to notice, Yukawa's ideas were poised to displace Fermi's theory as a fundamental theory, demoting it to an effective model, an approximation serviceable as a computational tool. Yukawa's theory is now celebrated in physics textbooks as the first theory of the strong nuclear force. Its original inclusion of β-decay, prototypical manifestation of the weak force, is either unmentioned or dismissed as an irrelevant misstep. Yet, Fermi's entourage received Yukawa's theory first of all as a theory of β-decay, to be put to test with cosmic ray observations. As Bernardini reported at the end of his lecture, experiments concerning the generation of electrons from the decay of mesotrons were already in progress in Rome.

4. THE 1939 CRISIS AND THE FIRST CERVINIA EXPEDITION

Just as the mesotrons were being officially introduced to the Italian physics community, Mussolini's government began issuing a series of anti-Semitic decrees, the infamous "racial laws", which triggered a catastrophic brain-drain and terminated the physics *rinascimento*. Rossi, among many other Italians of Jewish origin, lost his citizenship and the right to public employment. He and his wife repaired to Bohr's institute in Copenhagen. Fermi, whose wife was Jewish and whose appreciation of the scientific policies of the regime had already worn thin, left for the USA straight from Stockholm, where he went in December to receive the Nobel Prize. Rasetti also, though not personally affected, decided to put some distance between himself and his homeland, and made contacts with the University of Laval in Quebec through the *Accademia Pontificia delle Scienze*. He would cross the ocean at the beginning of summer, 1939,

[35] Most experimenters subscribed to the nuclear connection unquestioningly, even after the theoreticians made it clear that no variety of Yukawa's theory could be brought into quantitative agreement with the experimental results from the hard component of cosmic rays. Anderson and Neddermeyer were notable exceptions. See, for example, Seth H. Neddermeyer and Carl D. Anderson, "Nature of cosmic-ray particles," *Reviews of modern physics, 11* (1939), 191-207, on 206 and 207.
[36] Yukawa, "On the interaction of elementary particles. I," on 216 (ref. 28).

together with Amaldi, who was going to collect technical information at cyclotron sites.[37] The cyclotron project, in fact, was briefly (and vainly) revived by the possibility of obtaining funds for a national science showpiece at the *Esposizione Universale* that was due to take place in Rome in 1942. Amaldi also intended to test the ground for his own emigration, but the outbreak of war in Europe forced him to abandon the plan.

Amaldi and Bernardini found themselves the elder children of an orphaned scientific family. The situation has been characterized by Amaldi as the "collapse", or the "disaster of physics in Italy."

> Here and there, scattered in the Italian universities, some fragments were left of the valid research groups that had been decapitated just in their infancy. In order to survive scientifically it was clearly necessary to do everything possible to join the efforts and thus start collecting "the survivors" in a small number of places. This idea, thoroughly discussed with Bernardini, Ferretti, and Wick, constituted a line of action that we tried to follow for years. [38]

Gian Carlo Wick, young professor of theoretical physics in Padua and already well known internationally, had recently authored a generalization of Yukawa's mass-range relation that was based only on the principles of indetermination and of conservation of energy, and was therefore independent of any specific form of the quantum field interactions.[39] Rasetti, Amaldi, and Bernardini agreed that he was the most suitable replacement for Fermi, and they obtained his transfer to Rome in the fall of 1939. Amaldi worked at the completion of a project initiated by Fermi and Rasetti, a Cockroft-Walton accelerator, which was built at the *Istituto Superiore della Sanità* (ISS, the institute of public health) for potential medical applications. With the ISS machine, Amaldi was able to lead a series of studies of neutron-induced nuclear reactions, which represented the continuation of the Via Panisperna's school specialty studies. Mesotron studies could also be continued, thanks to the inclusion of cosmic radiation among the topics of the *Istituto Nazionale di Geofisica* (National Institute of Geophysics), which was founded in 1938 and received funding from the *Comitato Nazionale per la Geofisica e la Meteorologia* of the CNR. A group of young collaborators gathered around Bernardini. Rossi's assistant, Ettore Pancini, initially commuted from Padua and in 1940 moved to Rome as a researcher of the ISS. Bernardo Nestore Cacciapuoti came as an assistant to the chair of experimental physics from Palermo. Ferretti and Wick provided theoretical support, and Ferretti helped with experimental work. Bernardini recruited Oreste Piccioni, who had been the last Italian student to graduate with Fermi. Mario Ageno, another of Fermi's students, also took part in the first mesotron activities.

Bernardini's team trod two paths to the experimental detection of mesotron decay. One was the analysis of the ratio of hard and soft rays under the hypothesis examined theoretically by Ferretti, that the soft rays were generated by the hard rays via spontaneous disintegrations. The other was the study of an effect that came to be known

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[37] Bernardini to Amaldi, 10-9-1939, in Amaldi, Battimelli, and De Maria, *Da via Panisperna all'America*, on 119 (ref. 11).

[38] "*Qua e là, sparsi per le università italiane, erano rimasti alcuni brandelli dei gruppi di ricercatori validi che erano stati decapitati proprio sul nascere. Per poter sopravvivere scientificamente bisognava chiaramente far di tutto per congiungere gli sforzi e quindi cominciare a riunire 'i superstiti' in un numero ristretto di sedi. Questa idea, ampiamente discussa con Bernardini, Ferretti e Wick costituí una linea di azione a cui cercammo di attenerci per anni.*" Amaldi, Battimelli, and De Maria, *Da via Panisperna all'America*, on 65 (ref. 11). See also Amaldi, "Ricostruzione," on 33 (ref. 20).

[39] Gian Carlo Wick, "Range of nuclear forces in Yukawa's theory," *Nature, 142* (1938), 993-994.

as “anomalous absorption”. In both experiments, the Bernardini team aimed at obtaining “more direct” results than the ones already available, and their plan involved the collection of data at widely different altitudes above sea level. A first attempt at the anomalous absorption measurement was made by Ageno and Ferretti in May 1939 at Campo Imperatore, a ski resort on the Gran Sasso d’Italia, in the Appennini Mountains not far from Rome. As Ferretti “disclosed strong doubts about the reliability of the measurements carried out at Campo Imperatore,” Bernardini and the others decided to repeat the experiment in the Alps, near the Matterhorn, where they could count on “spectacular cable lifts and great possibilities for taking advantage of height differences.”[40] They organized a multi-purpose expedition and spent the months of August and September taking data in Chatillon (500 m), Cervinia-Breuil (2050 m), and at Pian Rosà (3460 m), to be used together with data collected in Rome (55 m).

In order to see why the planned experiments were billed as “more direct” observations of decay, I shall follow mainly the trail of anomalous absorption measurements. For the official record, the spontaneous decay of an elementary particle was observed for the first time by that method, although in a manner that was qualified as indirect. First, however, I shall briefly consider the measurements of the soft and hard components, which appeared at the beginning equally amenable to higher directness, and which included the excursion to the Basilica of Maxentius.

5. THE RATIO OF SOFT AND HARD RAYS

The first quantitative comparisons between the theoretical prediction of decay and the experimental evidence from cosmic rays were made in the spring and summer of 1938. The theoretical term of these comparisons was the value $\tau = 0.5\times10^{-6}$ s, which Yukawa had calculated from his theory (somewhat hastily, it turned out) after Bhabha’s publication of the decay hypothesis. The role of empirical term was initially played by another estimate of the same quantity, produced by Euler from the measured ratio of soft and hard rays. Euler’s value was calculated on the basis of a model of the generation of soft rays from the hard rays, which consisted of the application of Yukawa’s explanation of β-decay to the hard rays plus the theory of QED cascades, and did not depend on the formal expression of Yukawa’s field. Euler judged his number, $\tau = (2\pm1)\times10^{-6}$ s, to agree with Yukawa’s.[41]

Although Euler’s calculation was an empirical estimate, it fell short of being a direct observation. Bernardini and his collaborators maintained that any evidence of decay electrons hitherto obtained was “indirect” because it was “based on detailed calculations of certain delicate effects with the cascade theory of showers.” They planned “to follow a more direct line of attack,” which meant replacing the fastidious calculations with the practical troubles of measuring cosmic-ray intensities in different experimental conditions at different atmospheric depths. The interpretation of the data, however, turned out to be less straightforward than they had hoped.

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[40] “*[Ferretti] ha palesato forti dubbi sull’attendibilità delle misure effettuate a Campo Imperatore*” and “*funivie spettacolose e di grandi possibilità per quanto riguarda [lo] sfruttamento di dislivelli*.” Bernardini to Amaldi, September 10, 1939, in Amaldi, Battimelli, and De Maria, *Da via Panisperna all'America*, on 117 (ref. 11). This letter is headed “G. Bernardini (Rome) to E. Amaldi (USA),” but it was probably written from Cervinia. Ageno was unable to take part in the final part of the experiment because he was drafted in early September.

[41] Brown and Rechenberg, *The origin of the concept of nuclear forces*, on 178-183 (ref. 28).

Bernardini and his team assumed that all the soft radiation present in the low atmosphere originated from the hard rays, both through the interactions of hard rays with matter and, if the decay hypothesis was correct, through QED cascades initiated by decays. Any residual soft component was presumed to derive from primary rays, and was therefore expected to be prevalent in the high atmosphere and reduced to zero near sea level. Ferretti's calculations entailed that the soft rays generated by decays would be copious in air and negligible in a medium of density comparable to that of water. Ideally, then, the difference between the ratio of soft rays to hard rays in open air at sea level, and the same ratio under water would afford an estimate of the percentage of soft rays imputable to decays. The measurements at the Basilica of Maxentius served this purpose. The large vaults of the building, in fact, offered favourable experimental conditions because they provided absorbing material "arranged in a rather symmetrical way relatively to the system of counters," and positioned sufficiently away from the counters to prevent "any effect due to the coherence of the secondaries."[42] The roof would screen any soft rays coming from outside without affecting the spectrum of hard rays, and was equivalent to four or five meters of water in terms of interactions. Measurements inside the basilica were therefore equivalent to measurements under water.

The physicists found that the ratio of electrons to mesotrons was 25 percent outside the basilica and 5 percent inside. They could not, however, conclude that the 20 percent difference came from decays. In a series of control measurements, Cacciapuoti had found that the soft rays decreased with altitude less rapidly than expected, suggesting that a residual component might still be present in the low atmosphere. In the hope of dispelling this suspicion, Bernardini and his collaborators took the experiment to the Alps. They piled a meter of soil on the concrete roof of a garage in Cervinia, and then measured the soft radiation inside the garage. Since soil and concrete formed an absorber roughly equivalent to the air layer between Rome and Cervinia, finding less soft radiation in the garage than in Rome would have meant that at least some of the soft rays of Rome were originated from mesotron decays during the flight through the atmosphere. Unfortunately, in the garage Bernardini and collaborators measured a ratio very close to the Rome value. They observed,

> The rather large number of electrons found in case (a) [i.e., at Cervinia under the layer of soil and concrete] is puzzling; it must be largely due to electrons which are *not* secondaries of the mesotron, and which are able to make themselves felt through the thick layer.[43]

Supplementary tests of the variation of the soft component with altitude were carried out in Rome, Antey (1050 m), Cervinia, and Pian Rosà, and indicated the existence of a large

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[42] "*Il materiale assorbente era disposto in modo piuttosto simmetrico rispetto al sistema dei contatori*". G. Bernardini et al., "Sulle condizioni di equilibrio delle componenti elettronica e mesotronica intorno al livello del mare," *Il nuovo cimento, 17* (1940), 317-344, on 320. G. Bernardini et al., "The genetic relation between the electronic and mesotronic components of cosmic rays near and above sea level," *Physical review, 58* (1940), 1017-1026, on 1020. The initial motivation of the measurements in the basilica was to clarify an apparent inconsistency between the first results on anomalous absorption and some existing results on the ratio of soft and hard rays. G. Bernardini, B. N. Cacciapuoti, and B. Ferretti, "Misura del rapporto fra l'intensità della componente molle e della componente dura della radiazione penetrante sotto uno strato equivalente a 4 metri d'acqua al livello del mare," *La ricerca scientifica, 10* (1939), 731-733; G. Bernardini and B. Ferretti, "Alcune osservazioni sulla natura della componente penetrante dei raggi cosmici," *La ricerca scientifica, 9* (1938), 732-734.

[43] Bernardini et al., "Genetic relation," on 1021 (ref. 42). Emphasis in the original.

residual component, indeed sufficient to comprise the whole difference between the soft-to-hard ratios outside and inside the Basilica of Maxentius. Hence, the experiment failed to give any certain sign of decay electrons. The only conclusion that could be drawn was a lower limit on the mean lifetime, which would have to be at least 4.4×10^{-6} s to account for the negative result. The generation of soft radiation, the Rome physicists concluded, was still little understood, and the lower limit on the lifetime should be taken with reserve. Such skepticism was especially justified in the light of the results from the measurements of anomalous absorption, which were meanwhile finding lifetime values below the supposed lower limit.

6. THE ANOMALOUS ABSORPTION OF MESOTRONS IN AIR

The possibility of using absorption rates to detect decays was first suggested in June 1938 by Helmuth Kulenkampff, a physicist from Jena who reported to the German Physical Society about a comparison of the penetration of hard rays in air and in solids.[44] Kulenkampff confirmed that the intensity of the rays decreased in metals as expected, but noted that in air the decrease was considerably stronger. The difference contradicted a long-standing rule called the "mass absorption law", according to which the rate of absorption was roughly proportional to the amount of mass traversed, independently of the material traversed. Different absorbers were thus considered to have the same absorbing power if their depths were inversely proportional to their densities, and were accordingly measured in g/cm^2. The only known deviation from the mass absorption law was by *Bremsstrahlung*, which depended on the square of the atomic number of the medium and would thus contribute lower absorption in air than in the metal sheets. As the hard rays were distinguished from ordinary electrons precisely by their much lower propensity to radiate, they were expected to follow the mass absorption law in any medium. The phenomenon reported by Kulenkampff, to which also previously unnamed irregularities in other experiments were soon imputed, became known as "the anomalous absorption of air", or simply "anomalous absorption". Kulenkampff explained it as the result of spontaneous decays. If the heavy electrons were spontaneously unstable, more of them would decay while crossing a long distance in the air than a short distance in metal, and the recorded intensity of radiation would correspondingly decrease.

Euler and Heisenberg elaborated on Kulenkampff's idea in their review article on cosmic radiation. The experiments, Euler and Heisenberg admitted, did not give any answer yet as to whether all the intermediate particles had the same mass or different masses, but the data "could be reconciled" with a unique value of 160 m_e. If no assumption on the mass value was made, there was no theoretical standpoint from which the particles could be studied. The hypothesis of a single mass, instead, would allow the connection of the intermediate particles with Yukawa's theory. Although it was premature to talk of a definitive confirmation of the theory, it was nevertheless sensible to explore what consequences the nuclear connection would have on the analysis of experimental results. Hence, Euler and Heisenberg discussed the hypothesis that the Yukawa particle possessed "a natural β-radioactivity," for which Yukawa had calculated the mean lifetime to be $\tau = 0.5\times10^{-6}$ s. Euler and Heisenberg combined Bhabha's

[44] H. Kulenkampff, "Bemerkungen über die durchdringenden Komponente der Ultrastrahlung. (zum Teil nach Messungen von H. Kappler und H. Martin.)," *Verhandlungen der Deutschen Physicalischen Gesellschaft, 2* (1938), 92.

relativistic considerations with Kulenkampff's explanation of anomalous absorption, and developed the argument quantitatively. In particular, they wrote the probability of decay per unit of distance, *w*, as dependent on the motion of the particle according to the formula $w = \mu/\tau P$, where μ represents the mass, P the momentum, and τ the mean lifetime of the particle at rest. Euler and Heisenberg showed that the decay explanation could account for the anomalous absorption results obtained by Alfred Ehmert as well as those by Pierre Auger. From Ehmert's absorption curves, they derived the value $\tau = 2.7\times10^{-6}$ s, a value that they judged to be in "quite satisfactory" agreement with Yukawa's.[45]

Studies of absorption of cosmic rays in air, water, and solids had been the stock in trade of cosmic-ray experiments. Workers in the field jumped at the anomalous absorption argument, and many were able to retrieve instances of deviations from the mass-absorption law from their own or their colleagues' records. Blackett, for example, was "delighted" by Euler and Heisenberg's explanation.[46] In an address to the British Association delivered in August 1938, he cited domestic measurements that Follet and Crawshaw had conducted "in the 'tube' station at Holborn," Ehmert's comparison of absorption in air and water, and detailed investigations by Auger and his collaborators, which seemed to indicate that air at low pressure absorbed more than air at normal pressure. Blackett used these data to calculated a rough estimate of the lifetime, $\tau = 2\times10^{-6}$ s.[47]

In October, Bohr convened a meeting of cosmic-ray experts in Copenhagen, which Fermi also attended. It was in this occasion that the participants, obliging the letter but not the spirit of Millikan's campaign, agreed to call the new particles mesotrons.[48] After the conference, Blackett and Rossi promptly published twin notes on *Nature* under the same title, "Further Evidence for the Radioactive Decay of the Mesotron." Rossi went back to a set of data that he and his assistant Sergio De Benedetti had recorded five years earlier near Asmara, the capital of the Italian colony of Eritrea in East Africa. Besides the geomagnetic effect that they were looking for, Rossi and De Benedetti had also noted an inexplicable decrease in intensity of cosmic radiation with the inclination from the vertical direction, which they called the "zenith effect". Now, Rossi was able to interpret the effect as caused by spontaneous decays, and to calculate from the Eritrean data a mean lifetime of $\tau \sim 2\times10^{-6}$ s, with an uncertainty of fifty percent due chiefly to arbitrariness in the average energy of the mesotrons.[49] Blackett produced another estimate, $\tau = 1.7\times10^{-6}$ s, of the mesotron lifetime from absorption measurements by various experimenters, emphasizing this time the explicit use of the relativistic time transformation in his calculation.[50]

[45] H. Euler and W. Heisenberg, "Theoretische Gesichtspunkte zur Deutung der kosmischen Strahlung," *Ergebnisse der exakten Naturwissenschaften, XVII* (1938), 1-69, on 26-27 and 42-43.
[46] Blackett, quoted in Brown and Rechenberg, *The origin of the concept of nuclear forces*, on 183 (ref. 28).
[47] Blackett, "High altitude cosmic radiation," on 693 (ref. 32).
[48] Millikan, "Mesotron as the name of the new particle" (ref. 32).
[49] Sergio De Benedetti, "Absorption measurements on the cosmic rays at 11º 30' geomagnetic latitude and 2370 meters elevation," *Physical review, 45* (1934), 214-215; Bruno Rossi, "Further evidence for the radioactive decay of mesotrons," *Nature, 142* (1938), 993; Bruno Rossi, "Directional measurements on the cosmic rays near the geomagnetic equator," *Physical Review, 45* (1934), 212-214.
[50] P. M. S. Blackett, "Further evidence for the radioactive decay of the mesotrons," *Nature, 142* (1938), 992. I shall discuss this paper in more detail in sect. 10.

Thus, a handful of retrospective examinations supported Bhabha's web of hypotheses. In the enthusiasm of his first lifetime estimate, Blackett commented,

> Though this value is about four times that predicted by Yukawa, the agreement must be considered as most satisfactory in view of the early stages of the theory and of the crudeness of the deductions from experiments.
> There seems, therefore, to exist definite experimental evidence for the spontaneous decay of the new particle. The accurate determination of this time of decay and of the mass of the particle is now one of the outstanding problems of cosmic ray research. [51]

Upon reconsideration, however, other experts decided that the evidence was not definitive yet, and that the case should not be closed on re-interpretations of old data. After all, no one had detected a general phenomenon in the scattered absorption irregularities before Bhabha's extension of Yukawa's theory.[52] Before claiming the observation of decay, the physicists deemed necessary to conduct new experiments designed for the purpose.

In the course of their work, the mesotron researchers would come to refine their goal and redefine the proper means to achieve it, thus recognizing that their pursuit was composite. The observation can be seen in retrospect to have consisted of three parts: to test whether anomalous absorption was a phenomenon, to ascertain whether this phenomenon was a manifestation of spontaneous decays, and to verify if the decay of mesotrons was the process described by Yukawa's theory. The distinction between the first two was made early on, but separating the third part took longer. It took time to fully realize that the simple observation of decays was insufficient to support any specific theoretical scheme unless it was accompanied by a definite quantitative agreement between experimental and theoretical lifetimes. In fact, while a theoretical calculation of the lifetime required a mathematical formulation of the decay interaction, the expectation of spontaneous instability for a particle of intermediate mass could be justified from the general standpoint of quantum-field theory. This distinction, as obvious as it appears now, was not immediate for experimenters confronted for the first time with unstable particles. Still unequipped with a general experimental framework for the disintegration of isolated particles, they overestimated the dependence of their experimental models on the theory formulated by Yukawa, and settled for a slipshod quantitative match. The detection of mesotrons' decays continued to be regarded as a confirmation of Yukawa's theory until 1946, despite the growing discrepancy between theoretical and experimental lifetimes.

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[51] Blackett, "High altitude cosmic radiation," on 693. .

[52] On the contrary, the mass-absorption rule had until then been invoked to identify the hard rays in contrast to the Z^2-dependent absorption of electrons. Bhabha himself, before his adoption of Yukawa's theory, repeatedly stated that the hard component obeyed the mass-absorption law, even as he was looking for a mechanism to transmute heavy electrons into ordinary electrons. At that time, he had actually dismissed the possibility of spontaneous decay. H. J. Bhabha, "On the penetrating component of cosmic radiation," *Proceedings of the Royal Society of London, A164* (1938), 257-294, on 258 and 260.

The first to expressly arrange an experiment to observe anomalous absorption and to measure the lifetime were two members of Auger's group, Paul Ehrenfest Jr. and André Fréon. Prompted by a private exchange with Heisenberg, Ehrenfest and Fréon used a cosmic-ray telescope set up in a station on the Jungfraujoch to confirm the "*paradoxe d'absorption*" and measure the mean lifetime, which they found to be twice as large as Blackett's estimate.[53] By the time they published their results, at the end of 1938, Yukawa had made it known that his first calculation was wrong, and had published a value two times smaller. This amounted to a disagreement of a factor ten to twenty between theoretical and experimental lifetimes. Ehrenfest and Fréon offered five possible reasons for the discrepancy, ranging from large errors in their measurement to an error in the theoretical calculation. Notably absent from their list was the possibility that the

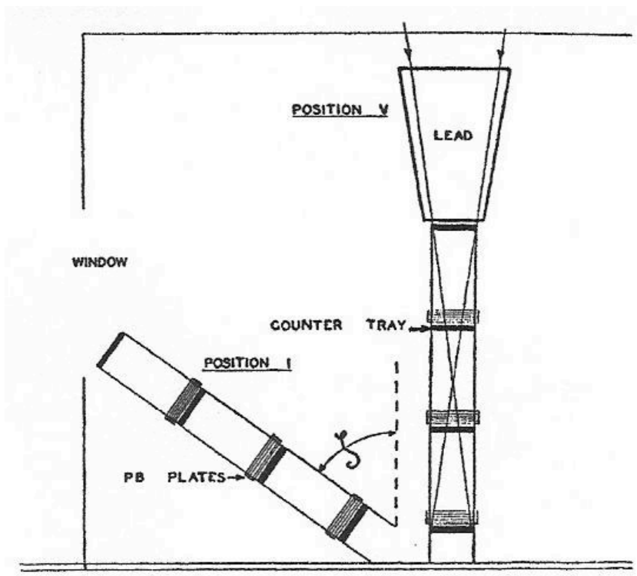

Fig. 2 An example of the "inclination method". From M. A. Pomerantz, "The instability of the mesotron", *Physical review 57* (1940), 3-12, on 7. Experiments of this kind compared the coincidence counts obtained with the counter telescope inclined at an angle and with the counter telescope vertical and surmounted by a solid absorber. Interpreting the data as evidence of mesotron disintegrations required assumptions about the directional distribution, the height of production, the energy spectrum, and the mass of the mesotrons.

nuclear connection was mistaken. A similar result was reported by Thomas H. Johnson and Martin A. Pomerantz of the Franklin Institute in Philadelphia shortly thereafter. Johnson and Pomerantz measured the different absorption rates in water and in air taking advantage of a nine-meter water tower built on top of their laboratory room. By two different methods of analysis, they produced the intervals $(2-4)\times10^{-6}$ s and $(2.4-2.6)\times10^{-6}$ s for the mean life. Both calculations, the authors emphasized, "involve

[53] Paul Jr. Ehrenfest and André Fréon, "Désintégration spontanée des mésotons, particules composant le rayonnement cosmique pénétrant," *Comptes rendus de l'Academie des Sciences de Paris, 207* (1938), 853-855.

assumptions that must be regarded as more or less arbitrary in the present state of our knowledge."[54]

Kulenkampff's and Ehmert's measurements, Rossi's zenith effect, Johnson and Pomerantz's, and Ehrenfest and Fréon's experiments relied on the comparison of hard-ray intensities in air at different inclinations from the vertical to evaluate the different rates of disappearance across different distances. The validity of all these comparisons depended evidently on the assumption that the distribution of hard rays was the same in every direction (Fig. 2). There were, however, reasons to suspect that the distribution of primary rays at the top of the atmosphere was distorted by the earth's magnetism. Bernardini and his collaborators realized that the assumption of an isotropic distribution would become unnecessary if the comparison was made between air and dense materials at different atmospheric depths in the same direction. As we have seen, Ageno and Ferretti first attempted measurements of this kind at Campo Imperatore in May 1939. Bernardini and the others took then the experiment to the Alps, where they recorded hard-ray intensities alternatively in Chatillon and Pian Rosà. Their first paper on these measurements appeared in *La ricerca scientifica* in November. It reported that the difference between the number of mesotron counts at Chatillon in air and the number at Pian Rosà under 39 cm of lead established the existence of anomalous absorption independently of the isotropy hypothesis. From these data, the authors evaluated a lifetime of five microseconds, which they judged to be affected by large uncertainties, for the measurements were arduous and the absorption differences relatively small. As they prepared an article in English for *Physical review*, they learned that Rossi and Fermi, now both in the USA, had carried out closely related work, which they needed to reckon with.

7. "DIRECT" AND "INDIRECT" TESTS OF DECAY

Rossi had left Copenhagen at the end of 1938 to work for six months in Blackett's laboratory in Manchester with a fellowship of the Society for the Protection of Science and Learning. He had moved then to the United States, where he was offered prospects of a stable position. Reviewing the evidence for mesotron decay for a symposium on cosmic rays at the University of Chicago in the summer of 1939, Rossi had classified the relevant experiments up to date into "direct tests" and "indirect tests" of the decay hypothesis. He grouped as direct tests all the experiments that aimed at the observation of electrons ejected from mesotrons. In other terms, he considered as a direct test both the visualization of an electron track starting at the end of a mesotron track in a cloud chamber picture, and the detection of meson-electron sequences by means of a coincidence setup. The class of indirect test was instead constituted by studies of anomalous absorption and of ratios of soft to hard rays. Rossi did not provide an explicit definition of directness and indirectness, but offered an implicit definition when introducing the indirect tests:

> Several consequences of the decay hypothesis can be investigated experimentally, thus allowing an indirect test of this hypothesis. [55]

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[54] T. H. Johnson and M. A. Pomerantz, "The difference in the absorption of cosmic rays in air and water and the instability of the barytron," *Physical review, 55* (1939), 104-105.

[55] Bruno Rossi, "The disintegration of mesotrons," *Reviews of modern physics, 11* (1939), 296-303, on 296.

If the indirect tests were those that looked for the consequences of decay, the direct ones must have been those able to reveal decay itself. Rossi's laconic unconcern in drawing this distinction suggests either an already current usage or the feeling that the usage would be unproblematic. In any case, the classification was unproblematically adopted by other mesotron experimenters.

Rossi was evidently not applying the dichotomy of philosophical empiricism, according to which some scientific propositions ("observation statements") can be tested directly while others ("theoretical statements") can be tested only through their observable consequences, for according to that dichotomy mesotrons and their decays would be irremediably unobservable and the decay hypothesis could not be tested directly.[56] What distinction was he applying, then? It is not self-evident why anomalous absorption (that is, the disappearance of mesotrons that could not be explained by interactions) should be regarded as a *consequence* of spontaneous disintegrations, while the detection of the disintegration debris should not.

It is not surprising that the cloud-chamber pictures would be counted as direct observations. Peter Galison has amply illustrated the historical force of the "homomorphic form of evidence" produced by the cloud chamber and other detectors of the image tradition. He gives examples of philosophers and physicists to whom "the importance of the Wilson chamber lay in its ability to display individual processes, directly and not through a long, complicated, and indirect chain of inference." For many, cloud-chamber pictures came to define what the "direct observation" of a microphysical event was.[57] Nevertheless, the grouping of visual and non-visual tests indicates that in our case the perception of observational directness bypassed the apparent immediacy of visualization. If Rossi and his colleagues' harboured the impression that the chain of inferences was null or minimal in the tests they called direct, their impression must have rested on other basis than the sensorial impact of the final form of evidence.

In his analysis of the "direct" observation of the solar core, Shapere has noted that physicists' sorting of observations from inferences relies on pragmatic and contextual distinctions rather than logical ones.[58] Recognizing the application of a weak sense of inference in experimental reasoning is a crucial step toward explaining Rossi's classification. It is nevertheless only a first step, for all the tests of decay were at that point equally provisional and affected by uncertainties.

A more complete answer may be found examining how the experimenters built the chain of inferences necessary to relate their manipulations and the responses of the apparatus to the entities and processes under study. Rather than conforming to a predefined protocol of implications, this construction unfolded as an adaptable process of modeling, which was organized into two areas. One area was dedicated to understanding and controlling the operations of the instruments, the other to establishing relations, both mathematical and causal, between the output of the instruments and the microphysical

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[56] For an explication and critique of the observable-theoretical dichotomy, see Mary Hesse, "Theories, dictionaries, and observation," *The British journal of the philosophy of science, 9* (1958), 12-28.

[57] Galison, *Image and logic*, on 66-70 (ref. 9). It must be noted that to some analysts, who adhered more reflectively to the purported empiricism of modern physical methodology, the imaging of particles by cloud-chamber pictures exemplified precisely what a direct observation was not. See, for instance, Henry Margenau, "Methodology of modern physics," *Philosophy of science, 2* (1935), 48-71 and 164-187, on 58. Also, Hesse, "Theories, dictionaries, and observation," on 26-27 (ref. 56).

[58] Shapere, "The concept of observation," on 517 (ref. 6).

process in question.[59] Rossi's classification becomes intelligible when this differentiation is brought into focus. In the case of the tests of decay, the modeling of the instrument, however complex and inferential it was, did not affect the assignment of an experiment to the class of direct or indirect tests. The attribution of directness depended on the amount of background information and inferential reasoning that was judged to be necessary to connect the output of the instruments to the objects under study.

The appearance of particle tracks in cloud-chamber photographs allowed the mechanisms of track formation to be confined within the "instrumental" compartment of the production of evidence. Similarly, in the coincidence experiments that aimed at detecting decay electrons, the occurrence of signals interpretable as mesotron-electron sequences allowed the interactions that produced the signals to be left out of the field of view when the focus was on mesons-to-electrons transformations. In this way, inspecting an ionization pattern in the expanding gas of a cloud chamber or counting suitably selected signals from a counter telescope could create the impression of capturing the micro-process under study without material interferences, and also without the need of calculations and interpretation. (More accurately, at this stage the direct experiments created the impression of capturing the *absence* of decays, because all attempts had hitherto achieved negative results.) In contrast, comparing absorption rates in air and solids for an anomalous absorption experiment demanded the explicit consideration of the interactions of mesotrons with matter, and the appropriate quantification of their effects, within the part of experimental modeling that constituted the analysis of the instrumental output, in the phenomenological model of the experiment.

Rossi's classification of directness was also aided by the contrast between the histories of the two classes of tests. The indirect tests called for a new interpretation of features of cosmic radiation that had already been studied for other reasons, whereas the search for electrons ejected from the end-point of a mesotron trajectory had no prior purpose. In the one case, the instrumental records had to be fitted into a pre-existing pattern of expectations and were thereby interpreted as a phenomenon, the anomalous absorption of air, of which decay was offered as the putative cause. Other causes could be, and indeed were, imagined. In the second case, the pattern of expectations was still undeveloped; the instrumental displays were matched only to a mental picture of either decay or absence of decay, with no intermediate phenomenon to be explained. This sense

[59] My analysis follows Pickering's discussion of the "interactive stabilization" of plastic resources in experimental practice. Pickering calls the two areas of experimental modeling "instrumental model" and "phenomenal model". I will focus on the second, and, following the physicists and Galison, shall call it the "phenomenological model". The term "phenomenology" is used in physics with different meanings and nuances, but it broadly refers to an intermediate level of conceptualization, ranging from mere description to causal interpretation, of the data of experiments, whenever a more general and abstract level of theory is assumed. Further insight into the structure of the phenomenological model is provided by Hacking's "taxonomy" of the elements of laboratory experiments. Pickering, "Living in the material world", on 276-277 (ref. 7); Galison, How Experiments End, on 253 (ref. 7); Ian Hacking, "On the stability of laboratory science", *The Journal of Philosophy*, 85 (1988), 507-514, and "The self-vindication of the laboratory sciences", in A. Pickering, ed., *Science as practice and culture* (1992), 29-64. What counts as instrumental output in an experiment is not defined in advance; separating the two areas of experimental modeling is part of the modeling process. The production of reliable instrumental outputs, and the roles played in it by practical know-how, and by interactions between the laboratory and the larger technological context, deserve in-depth study for an understanding of experimentation. They are, however, beyond the scope of this paper.

of directness was a function of the historical route to the observation, because it derived from the accidental lack of alternative interpretations of the data. In an otherwise similar case that occurred eight years later, a team from Bristol examined two-track images in the course of investigating the nuclear interactions of mesons in matter. In that event, what the experimenters saw in the pictures was the capture of a meson by a nucleus of the photographic emulsion, followed by the ejection of another meson. Only after theoretical considerations did they set forth a spontaneous-decay interpretation of the pattern detected in the images.[60]

As decay consolidated as a fact, the experiments lost the function of qualitative tests, while their role as measurements of the lifetime intensified. Cloud-chamber experiments, unhelpful with this task, left center stage to the counter experiments, which were instead well suited to the determination of a statistical parameter like the mean time of decay. The "direct" and "indirect" classification among the counter experiments remained, even though it shifted in meaning and came to qualify the different lifetime measurements. It became apparent that any measurement of the lifetime from anomalous absorption would unavoidably require an input for the mass value, whereas electronic counts of decay electrons would enable the calculation of the mean lifetime independently of the mass. Hence, a "direct observation" of the lifetime came to be understood as a measurement free of the "additional assumption" of a mass value. Furthermore, as the methods for observing decay by means of counter telescopes diversified, finer degrees of directness were attributed to the different experiments regardless of where they belonged in the gross "direct" and "indirect" classification. Albeit unsystematic, these various senses of directness were congruous because, as we will see, they all referred to the presence or absence of what the experimenters regarded as "additional assumptions", or "supplementary hypotheses", in the phenomenological models of the experiments.

8. ROSSI'S FIRST OBSERVATION OF DECAY AND FERMI'S POLARIZATION EFFECT

Rossi had concluded his review stating that the direct tests were against the decay hypothesis because no decay electrons had been detected, and the indirect tests were still inconclusive. He had therefore set stronger basis for a research program than the one initially outlined by Blackett. Thanks to Arthur H. Compton's support, Rossi could start to actualize his plan immediately, and concentrated on anomalous absorption measurements, the main example of indirect tests. His work advanced in parallel to the analogous operations of his colleagues in Rome, for he also had become convinced that the directness of anomalous absorption tests could be increased by means of measurements at different altitudes:

> New experiments were therefore necessary and the most direct way to test the disintegration hypothesis appeared to us to be an exact comparison between the "absorption" of the vertical mesotrons in air and in some dense material.[61]

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[60] The episode to which I am referring was the discovery of the π-meson via meson-to-meson decays. In that case, the pictures were not taken from a cloud chamber but by means of nuclear emulsions. C. M. G. Lattes et al., "Processes involving charged mesons," *Nature, 159* (1947), 694-697.
[61] Bruno Rossi, Norman Hilberry, and J. Barton Hoag, "The variation of the hard component of cosmic rays with height and the disintegration of mesotrons," *Physical review, 57* (1940), 461-467, on 461.

With the collaboration of Norman Hilberry and J. Barton Hoag, Rossi assembled a coincidence-counter apparatus, loaded it into an old bus, and drove it to Denver (1600 m), Echo Lake (2300 m), and the top of Mt. Evans (4300 m) in the Colorado Rocky Mountains. The intensity of hard rays was recorded at every station, and the decrease in atmospheric depth at the higher stations was compensated by means of mass-equivalent blocks of graphite. In this way, Rossi could compare the attenuation in air with that in carbon without having to assume an isotropic distribution of mesotrons (Fig. 3).

Rossi wrote in his autobiography,

> We [Rossi, Hilberry, and Hoag] had thus achieved the first unambiguous demonstration of the anomalous absorption of mesotrons in the atmosphere, therefore proving their radioactive decay in flight. […]
> This was the first time that the radioactive instability of a subnuclear particle had been experimentally demonstrated.[62]

Although at least three published reports of similar experiments preceded his, Rossi's claim is backed by his careful design, transparent analysis, and persuasive discussion, and most importantly by the long-run validation of his lifetime measurement by subsequent measurements. Interpreting the data according to the decay hypothesis, Rossi calculated the average ranges of mesotrons before decay at the different altitudes. From the calculated range, assuming a mass of 160 m_e and an average momentum derived from Blackett's energy measurements, he obtained the lifetime value $\tau = 2\times10^{-6}$s.

[62] Rossi, *Moments in the life of a scientist*, on 51 (ref. 13). See also Bruno Rossi, "The decay of "Mesotrons" (1939-1943): Experimental particle physics in the age of innocence", in Brown and Hoddeson, eds., *The birth of particle physics* (1983), 183-205 (ref. 9).

The "therefore proving" in Rossi's autobiographical narration is a retrospective

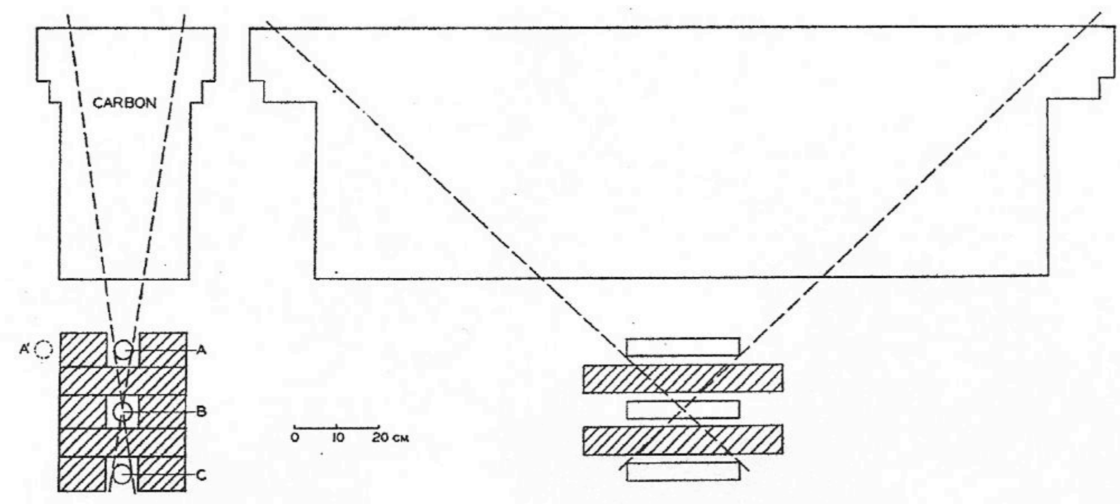

Fig. 3 Rossi's first Colorado experiment, an example of the method of different altitudes. From Rossi, Hilberry, and Hoag, "The variation of the hard component of cosmic rays with height and the disintegration of mesotrons", *Physical review 57* (1940), 461-467, on 462. Data were taken with this apparatus in Chicago (180 m), Denver (1600 m), Echo Lake (3200 m), and Mt. Evans (4300 m). Experiments of this kind compared the coincidence counts obtained with the counter telescope in the vertical direction under a solid absorber (in this experiment, 87 g/cm^2 carbon) and at a lower altitude without the solid absorber. The data could be interpreted as evidence of mesotron disintegrations without any assumption about the angular distribution, the height of production, and the energy or momentum spectrum of the mesotrons. Calculating the average lifetime, however, still required an assumption about the average momentum (or the energy spectrum) of the mesotrons.

shortcut that contrasts with the awareness, subtly expressed in the experimental report at the time, that demonstrating anomalous absorption did not automatically mean demonstrating decay:

> The counting rate observed under a given mass of air-plus-carbon was found to be considerably larger than the rate observed under the same mass of air alone. We interpret the difference as due to the spontaneous decay of the mesotrons which form the hard component of cosmic rays.[63]

It is interesting to compare this conclusion with Blackett's and Rossi's previous pronouncements on the matter. Here, Rossi no longer relied on an alleged agreement between his measurement and the theoretical prediction, but assembled an argument from smaller parts, each independent of the hypothesis under test and thus experimental by default. First, he dispelled potential anxieties about technical faults and preventable systematic errors by describing his setup, his data-taking procedure, and his efficiency and calibration checks. Then, he disposed of the possibility that his data displayed some behaviour particular to his experimental arrangement and accountable for by articulations of conventional (non-decay) theory. He did so by means of eclectic reasoning, combining a common-sense appeal to the implausibility of unknown absorption mechanisms peculiar to air alone of all the materials investigated, theoretical reasons (formulae

[63] Rossi, Hilberry, and Hoag, "The variation of hard cosmic rays with height," on 461 (ref. 61).

showed that the known absorption mechanism, ionization, was not exactly proportional to the mass traversed but increased weakly with the atomic number Z), experimental design (carbon was chosen because its Z was close to the average of the air components), and empirical tests (a test run in carbon and lead, two elements of widely different Z, confirmed that the measured absorption followed roughly the mass-absorption law anyway). Next, Rossi considered the possibility, suggested to him by Fermi, that a fraction of the mesotrons signals were in fact simulated by showers initiated in the graphite. This local soft radiation could give rise to spurious counts, thus producing experimental noise to the mesotron signals. Test runs were performed to estimate the incidence of local showers, and they turned out to be of minor importance. Rossi could therefore trust that his data showed a genuine "physical" effect, a general phenomenon related to the hypothesis under study. Finally, Rossi confronted (in a classical footnote) one further objection raised by Fermi.

Fermi had become immediately involved in fission research upon arriving at Columbia University, yet he had not forgotten the mesotrons. To him, the whole web of conjectures that linked anomalous absorption to β decay was still to be demonstrated. He spent the summer of 1939 teaching theoretical physics at the University of Michigan in Ann Arbor, and lectured on the new cosmic ray particles. During this time, he developed his own interpretation of anomalous absorption. He wrote,

> The great theoretical importance of this conclusion [i.e., that the anomalous absorption of mesotrons is evidence of their spontaneous decays] justifies careful investigation of possible alternative explanations of the observed difference in absorption. I have therefore considered the following effect which seems to explain the observations, at least to some extent, without assuming the decay of the mesotron.[64]

The current understanding of anomalous absorption assumed that mesotrons were absorbed predominantly by ionization and that, at parity of mass traversed, ionization was independent of the density of the absorber. Fermi reasoned that the electric polarization of the surrounding medium, which did depend on density, ought to affect the electromagnetic field of the ionizing particle. The effect of polarization would be negligible for slow particles or in gases, but it would decrease considerably the ionization of fast mesotrons in dense materials, resulting in a difference in apparent absorption of the same sign as that resulting from spontaneous decays.

> Indeed, if it were possible to prove that [the polarization effect] accounts for all the differences observed experimentally, this would eliminate the strongest argument in favor of the decay of the mesotron.[65]

Fermi communicated personally his alternative explanation to Rossi before publishing a preliminary note on it. Rossi applied Fermi's reasoning to the conditions of his experiment and found that the polarization effect had indeed to be taken into account, but that it could only be responsible for less than half of the observed absorption difference. In a second, more extended paper that expounded the general aspects of the polarization effect on the interactions of particle in matter and then applied it to some specific cases, Fermi agreed that the effect had only a minimal influence on Rossi, Hilberry, and Hoag's results. Having thus circumscribed the only alternative explanation of the observed

[64] Enrico Fermi, "The absorption of mesotrons in air and in condensed materials," *Physical review, 56* (1939), 1242.
[65] Enrico Fermi, "The ionization loss of energy in gases and in condensed materials," *Physical review, 57* (1940), 485-493, on 492.

phenomenon that had occurred to anyone, Fermi and Rossi concluded the observed phenomenon was indeed evidence of mesotron decays.

While on his cyclotron tour in the summer 1939, Amaldi visited Fermi in Ann Arbor and Rossi at Echo Lake. He returned to Rome at the beginning of October and rejoined Cacciapuoti and Bernardini, who were back from Cervinia and were about to publish their results. Although Amaldi wrote in his memoir that Fermi told him about the polarization effect at Ann Arbor, and he would presumably have passed the information to his friends, the paper on anomalous absorption that Ageno, Bernardini, Cacciapuoti, Ferretti, and Wick published in November made no reference to either Fermi's or Rossi's work.[66] Only their second article, submitted several months later, contained a discussion of Fermi's effect and of Rossi, Hilberry, and Hoag's results. Bernardini and his collaborators reached the conclusion that Fermi's correction would be small for mesotrons in the energy range detected by their apparatus, but that it would have to be retroactively applied to Euler and Heisenberg's estimate, increasing it by a factor two and thus bringing it in agreement with their current measurement. They also noted the agreement between their experiment and a similar one recently conducted by Pomerantz. The discrepancy between their lifetime value, which they had now settled at four microseconds, and Rossi, Hilberry and Hoag's value of two microseconds, gave them pause, but they were unable to identify a cause for it.[67] By this time, Fermi had written to Amaldi,

> I convinced myself that my hopes of explaining all the decay of the mesotron as an effect of the dielectric constant were largely optimistic. In reality, one can explain a considerable percentage of it in some experiments, but in many others the effect is practically negligible. On the other hand, the picture published by Williams in Nature seems to definitely establish the decay process. It is a pity that the mean life turns out to be a hundred times too long to explain à la Yukawa also the β rays.[68]

E. J. Williams and G. E. Roberts at the University College of Wales had published the first "direct" evidence of decay, a cloud-chamber photograph showing mesotron-to-electron tracks, in January 1940.[69] Following Williams' lead, cosmic-ray experimenters received this result not only as the ultimate proof of decay, but also as the demonstration that mesotron decay was a indeed a form of β-radioactivity, and thereby as a further reinforcement of the nuclear connection. The Rome physicists had developed a blind spot even for Fermi's warnings; like most of their colleagues, they continued to identify mesotron decay with Yukawa's β-decay.

Another experiment of the different-altitude kind was conducted almost at the same time by a team from Duke University. W. M. Nielsen, C. M. Ryerson, L. W.

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[66] M. Ageno et al., "Sulla instabilità del mesotrone," *La ricerca scientifica, 10* (1939), 1073-1081; Amaldi, Battimelli, and De Maria, *Da via Panisperna all'America*, on 72 (ref. 11).

[67] M. Ageno et al., "The anomalous absorption of the hard component of cosmic rays in air," *Physical Review, 57* (1940), 945-950.

[68] "*Mi sono convinto che le mie speranze di spiegare tutto il decadimento del mesotrone come effetto della costante dielettrica erano largamente ottimistiche. In realtà in alcuni esperimenti se ne spiega una percentuale considerevole ma in moti altri l'effetto è praticamente trascurabile. Del resto la fotografia pubblicata da Williams in Nature sembra stabilire definitivamente il processo del decadimento. Peccato che la vita media risulti cento volte troppo lunga per spiegare alla Yukawa anche i raggi β.*" Fermi to Amaldi, 14 March 1940, *Fermi Manuscripts*, Domus Galilaeana, Pisa.

[69] E. J. Williams and G. E. Roberts, "Evidence for transformation of mesotrons into electrons," *Nature, 145* (1940), 102-103, on 102. See also E. J. Williams and G. R. Evans, "Transformation of mesotrons into electrons," *Nature, 145* (1940), 818-819.

Nordheim, and K. Z. Morgan took measurements of mesotron absorption in air and graphite in Durham and atop Mt. Mitchell (2040 m) in North Carolina. They also confirmed that the anomalous absorption of the hard component was "real" and that their measurements gave "strong support to the mesotron decay hypothesis."[70] Focusing on the dependence of the lifetime measurements on the energy of the particles, the Duke University group selected hard rays in two different energy ranges and calculated the respective lifetime values 1.2×10^{6}s and 2.4×10^{-6}s. At this point, all the mesotron experimenters had become concerned with comparing their numerical results with other experiments. This growing preoccupation seemed to override any interest in the theoretical estimates.

Bernardini and his collaborators continued their mesotron studies and planned a new expedition to Cervinia for the summer 1940. In June, however, Mussolini drove Italy into the war. The Rome physicists' plans were delayed, and would be carried out only during the winter 1940-41.

9. THE SECOND CERVINIA EXPEDITION AND THE DIFFERENTIAL METHOD

The 1939 experiments had achieved the direct observation of anomalous absorption thanks to the method of different altitudes. Since no competing explanation of the phenomenon was offered besides the now defused polarization effect, the experiments were also accepted as indirect observations of mesotron decays. But if the experimenters were unanimous in their qualitative conclusion, their quantitative results were not in good agreement with one another. They concentrated therefore on finding and eliminating the causes of discordance between the different measurements. Much effort was devoted to comparative examinations of the different-altitude experiments in order to learn how to correct instrumental errors such as variations in the efficiency of the coincidence sets, scattering of mesotrons in the absorbers, and interference of showers. These corrections included modifications of the apparatus (improvements in the manufacture of the counters and technical advancements in the electronic recording system) as well as numerical adjustments of the data based on control and calibration measurements.[71]

Another area of critical scrutiny concerned the interpretation of the (corrected) instrumental outputs. To measure the lifetime, the experimenters needed a mathematical expression that represented it as a function of the recorded attenuation rates. Writing an expression of this sort meant modeling, in a form that was mathematically convenient, empirically adequate, and causally plausible, how the mesotrons varied in number while descending from their point of generation through material media. Physicists call this kind of modeling "phenomenology". Besides being embedded in a taken-for-granted body of knowledge about the behaviour of particles and the structure of the atmosphere, each phenomenological model was built out of a core hypothesis (the question under study, the Yukawa-Bhabha hypothesis of decay), plus a set of additional explicit assumptions. Additional assumptions are common ingredients of the phenomenological

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[70] W. M. Nielsen et al., "A measurement of mesotron lifetime," *Physical review, 57* (1940), 158.

[71] Operations of this sort are a pervasive feature of experimentation. Pickering describes them as the mutual shaping of the "material procedure" and of the "instrumental model", two elements of the threefold "interactive stabilization" that constitutes the production of experimental results. Galison emphasizes the isolation of a signal from the "background noise" as central to the assembly of an experimental demonstration. Pickering, "Living in the material world"; Galison, *How experiments end*, on 2 and 255-257 (ref. 7).

model of an experiment. They have the function of connecting the core hypothesis, which usually belongs in a fundamental level of theory, to the phenomena elicited under specific experimental conditions.[72]

Johnson and Pomerantz had described the assumptions of their model as "more or less arbitrary in the present state of our knowledge." The Italians wrote that the additional assumptions of the anomalous absorption model were "somewhat reliable hypotheses", but added that about them one could have "the greatest reservations."[73] As the precariousness of these assumptions prevented them from blending into the background of taken-for-granted knowledge, they were perceived to be causes of indirectness in the measurements. The progression of experimental work on mesotron decay was guided by the aim of reducing the perceived indirectness, which could be achieved through the elimination of the additional assumptions, or through their consolidation.

First of all, as we have seen, calculating the lifetime from absorption rates required necessarily a value for the mesotrons mass.[74] Mass estimations could be obtained from end-range cloud-chamber tracks, but the uncertainty of these measurements was still high and the spread of results remained large. Most experimental observations indicated the range of 130-250 m_e, and values as low as 50 m_e and higher than 500 m_e had been reported. Rossi and the Italians adopted for their calculations the value $\mu=160\ m_e$, while Pomerantz chose $\mu=200\ m_e$. Nielsen *et al*. preferred to leave the mass dependence explicit and presented their results in the form "$\tau = \gamma(\mu c^2/10^8$ ev)", providing an experimental value for the factor γ. Thus, one point had become evident: the experimental quantity that one could hope to determine "directly" from anomalous absorption was not the average lifetime but the ratio of the lifetime to the rest energy of the mesotrons, $\tau/\mu c^2$. Even with this proviso, however, the experimental results were discordant and motivated the physicists to seek further improvements.

Some of the questionable assumptions could be discarded altogether by changing the experimental conditions. The method of different altitudes had served precisely this purpose for the hypothesis of isotropic distribution. Each time they implemented a new experimental design to get rid of an unwanted assumption, Bernardini and Rossi described the step as an increment of directness. For example, Bernardini and his team summed up their experiments as follows:

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[72] Hacking, "The self-vindication of the laboratory sciences" (ref. 59); Galison, *How experiments end*, on 252-253 (ref. 7). For the argument that fundamental laws are only true of ideal models, while "phenomenological laws" describe reality, see Nancy Cartwright, *How the laws of physics lie* (Oxford, 1983). Cartwright focuses on theoretical issues, and uses the term "law" for models that have wider applicability than any specific experimental setup. Hacking, who is concerned with experiments, coins the expression "topical hypotheses", to signal the readiness to revision of phenomenological models, and their local and skin-deep character. Like "phenomenology", the term "model" is widely and diversely used because of its versatility, and does not lend itself to one encompassing definition.

[73] "[…] *ipotesi sotto certi aspetti attendibili, ma intorno alle quali si possono fare le più ampie riserve.*" G. Bernardini et al., "Sulla vita media del mesotrone," *Il nuovo cimento, 19* (1942), 69-99, on 69.

[74] The difference of attenuation rates was mathematically related to the probability of decay per unit path, which, according to the basic law of radioactive decay and to elementary considerations of relativistic mechanics, was directly proportional to the ratio between the rest energy and the average lifetime of the particle, $\mu c^2/\tau$.

> Recently we have tried to eliminate the introduction of these supplementary hypotheses, and to determine the ratio $\tau/\mu c^2$ from the phenomenon of anomalous absorption as directly as possible.[75]

The model applied by Bernardini and his group in their first anomalous absorption experiment, as well as that used by Pomerantz, made explicit assumptions concerning the height of production of the mesotrons and their spectrum of energy.[76] Rossi, Hilberry, and Hoag, and Nielsen *et al.* had devised derivations of $\tau/\mu c^2$ that did not require guessing at what altitude the mesotrons were produced in the atmosphere. Now, the only explicit assumption that still affected the anomalous absorption method was the hypothesis relative to the energy (or momentum) distribution of the observed particles. The next round of decay experiments was therefore marked by the intent to free the lifetime measurements of "this last arbitrariness."[77]

Bernardini and his associates had planned a second Cervinia campaign for the summer 1940 but "[d]ifficulties [that have] arisen in consequence of the current international situation"[78] caused the plan to be postponed to the following winter. Like the 1939 operations, the 1940-41 expedition served several experiments on mesotron decay. Two of these were continuations of the previous year's efforts: further work on the ratio of soft and hard components, and new observations of anomalous absorption. In addition, Bernardini also opened a new line of research, for which he revived a kind of equipment that Rossi had tried and discontinued in 1930 and was known as "magnetic lenses". These objects were magnetized iron blocks used in place of the ordinary absorbers in a counter-coincidence setup in order to determine the charge sign of the hard rays by means of their magnetic deflection. To work with them, Bernardini enrolled two neo-graduates, Marcello Conversi and Eolo Scrocco. A series of measurements were conducted by means of magnetic lenses by Bernardini, Conversi, Pancini, and Scrocco, and were interpreted through a model of the deflection of charged particles in magnetized iron developed by Wick, which they called "theory of the instrument". They confirmed the existence of an excess of about 20 percent of positive charges in the hard rays. In addition, magnetic lenses were deployed to provide supplementary information about the energy spectrum and the lifetime of the mesotrons at different elevations, which would be welcome when the main line of lifetime measurements, the anomalous absorption trail, failed to reach a satisfactory convergence of outcomes.[79]

Concerning the soft and hard components, Bernardini, Cacciapuoti, and Piccioni investigated the production of secondary electrons by mesotrons, the multiplication of electrons and photons according to QED cascade theory, and the absorption of secondary electrons in various settings, for example, in a rock tunnel in Tivoli (near Rome), and

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[75] "*Recentemente si è perciò cercato di eliminare l'introduzione di queste ipotesi supplementari e di determinare il rapporto $\tau/\mu c^2$, dal fenomeno dell'assorbimento anomalo, il più direttamente possibile.*" Bernardini et al., "Sulla vita media del mesotrone," on 69-70 (ref. 73).

[76] The energy distribution was assumed to be a power law of the form $(\text{Energy})^{-\gamma}$ with $2<\gamma<3$, and the height of production was assumed to be 9/10 of the height of the atmosphere.

[77] "*quest'ultima arbitrarietà.*" Bernardini et al., "Sulla vita media del mesotrone," on 69 (ref. 73).

[78] "*Difficoltà sorte in seguito alla attuale situazione internazionale*[.]" Ibid., on 70.

[79] G. Bernardini and M. Conversi, "Sulla deflessione dei corpuscoli cosmici in un nucleo di ferro magnetizzato," *La ricerca scientifica, 11* (1940), 840-848; G. Bernardini et al., "Sull'eccesso positivo della radiazione cosmica," *La ricerca scientifica, 12* (1941), 1227-1243; M. Conversi and E. Scrocco, "Ricerche sulla componente dura della radiazione penetrante eseguite per mezzo di nuclei di ferro magnetizzati," *Il nuovo cimento, Ser. 9, 1* (1943), 372-413.

under lead and aluminium plates at Pian Rosà. Again, these measurements only allowed the frustrating conclusion that either residual secondary electrons were generated by some unknown non-ionizing radiation, or the interaction of mesotrons in matter were more complex than currently admitted.[80]

For the new studies of anomalous absorption, the Italians assembled a counter telescope that, besides correcting the known instrumental imperfections of the previous one, would allow observations independent of assumptions about the energy distribution (Fig. 4). They followed a method that had been first used by Pomerantz in combination with the inclination method in a single location. The same method was then applied by Nielsen *et al.* and by Rossi in their second different-altitude experiments, which they carried out in the summer of 1940.[81] Previous observations of anomalous absorption had accepted all the particles capable of traversing the apparatus. As the hard rays were known to have penetration ranges univocally determined by their initial energies, these experiments were interpreted as counting all mesotrons having energies above a minimum. The new method consisted of counting the number of particles that traversed the apparatus, subtracting the number of those that were able to traverse and additional absorber, and interpreting the remainder as the number of mesotrons within a minimum and a maximum of energy. If the absorbers were chosen as to correspond to suitable penetration ranges, the counts obtained in this way could be interpreted as numbers of mesotrons having energies within a narrow band, which could thus be treated as having approximately the same energy. Following Pomerantz, the experimenters called the first procedure the "integral method" and the second one the "differential method."

The pursuit of directness was not limited to the elimination of the few explicit assumptions. Another way of improving the phenomenological model did not involve changes in the layout of the experiment, but refinements and consolidations of the supporting background knowledge. In addition to the explicit assumptions, in fact, the model implicitly rested on other presuppositions, which were not enunciated at the beginning but would be as the experimental work progressed, singled out as it were from the underlying body of tacit knowledge, with a view to reducing the residual uncertainty that they entailed.

One such source of uncertainty was identified in the absorption law on which the comparison of attenuation rates in different media depended. As we have seen, the standard had been to regard equal masses of different materials as equivalent in terms of absorption according to the mass-absorption rule. It was now recognized as necessary to replace this approximate rule with a more accurate criterion, more rigorously derived from the theory of energy losses. The differential method added one further reason to seek a better law of absorption, for it relied on an exact relation between the initial energy of a mesotron and its penetration range in a given medium. Thus, Pomerantz applied the quantum-mechanical equation for ionization energy losses that had been developed by

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[80] G. Bernardini and B. N. Cacciapuoti, "Sulla componente elettronica della radiazione cosmica e la teoria dei processi moltiplicativi," *La ricerca scientifica, 12* (1941), 981-983; G. Bernardini et al., "Sulla produzione della radiazione secondaria elettronica da parte dei mesotroni," *La ricerca scientifica, 12* (1941), 321-340; B. N. Cacciapuoti and O. Piccioni, "Sull'assorbimento della componente elettronica della radiazione cosmica," *Il nuovo cimento, Ser. 9, 1* (1943), 3-11. The origins of the soft component would be clarified with the discovery of the neutral pions in 1950.

[81] W. M. Nielsen et al., "Differential measurement of the meson lifetime," *Physical review, 59* (1941), 547-553; M. A. Pomerantz, "The instability of the meson," *Physical review, 57* (1940), 3-12.

Hans Bethe and by Felix Bloch in order to evaluate the amount of lead equivalent to the additional depth of air for the comparison of attenuation rates in his experiment, and to calculate the limits of the energy band corresponding to the selected penetration ranges for the differential method. At the same time, he checked the theoretical equation by subsidiary measurements in lead and in water in order to be reassured of its applicability. Rossi and Nielsen *et al*. upgraded to the same formula for their new experiments; in addition, they augmented its empirical adequacy by applying to it corrections due to Fermi's polarization effect, with the corrections adapted to the respective experimental arrangements.

In Rome, Wick took charge of the formulation of a model of the energy dissipation of fast mesotrons in dense substances, starting from the quantum-mechanical theory of energy losses developed by Bethe, Bloch, and Bhabha, and integrating Fermi's effect with it. He used his model to calculate the energy-range relations in air, water, and lead, and presented them in an easy-to-use graphical form.[82] Bernardini and his collaborators used Wick's chart for two purposes in the new anomalous absorption experiment: to determine the amounts of lead needed at the higher elevations (Cervinia and Pian Rosà) to compensate for the atmosphere at the lower elevations (Roma and Cervinia), and to calculate the energy intervals defined by the penetration ranges in their apparatus for the differential method.

Bernardini and his team recorded the threefold and fourfold coincidences in a cosmic-ray telescope, in which the first three sets of counters (ABC) corresponded to a penetration range of 15 cm of lead, and the four sets (ABCD) to 35 cm (Fig. 4). The differences between threefold and fourfold coincidences recorded at each station were then used to calculate the attenuation rates of approximately mono-energetic mesotrons between Rome and Cervinia, Cervinia and Pian Rosà, and Rome and Pian Rosà. From the attenuation rates, $\tau/\mu c^2$ was calculated for each pair of stations. Two different $\tau/\mu c^2$ values could be computed from the Cervinia-Pian Rosà difference because data relative to two energy bands were collected there. Furthermore, the data also allowed new applications of the integral method, which were carried out for comparison purposes. The values found by means of the differential method were 2.97×10^{-8} s/Mev from the comparison between Rome and Cervinia, 2.48×10^{-8} s/Mev and 1.84×10^{-8} s/Mev between Cervinia and Pian Rosà, and 2.48×10^{-8} s/Mev between Rome and Pian Rosà. After a painstaking discussion of possible sources of error and a detailed comparison with other experiments, Bernardini and his collaborators offered $\tau/\mu c^2=2.5\times10^{-8}$ s/Mev as the most reliable value, with an uncertainty of about 25 percent. They remarked, with some exasperation, that the precision of experimental outcomes was so far "*molto mediocre* [very mediocre]," and added,

[82] Gian Carlo Wick, "Sull'assorbimento dei mesoni veloci," *La ricerca scientifica*, *12* (1941), 859-873. Wick also made a re-evaluation of the mesotron energy spectrum at different elevations, which Bernardini and the others employed to apply the integral method to the new data for comparison purposes. Later, Wick extended his calculations to iron and graphite. G. C. Wick, "Sul frenamento delle particelle veloci," *Il nuovo cimento, Ser. 9, 1* (1943), 302-313.

It must be noted, however, that this is a purely experimental value and it is calculated on the hypothesis that the penetrating component of the cosmic radiation is constituted by a single type of particles. [83]

This baffling comment (given the intense employment of Wick's theoretical work in the analysis that precedes it) was probably intended to recall that the differential method had cleared the measurement of the last unwanted explicit assumption, the form of the energy spectrum. At the same time, it pointed self-contradictorily to another assumption, hitherto implicit, which the experimenters had now isolated as a potential cause of the persisting dispersion of the various "purely experimental" results.

The assumption that the hard rays were constituted by particles of a "single type" was not, as yet, supported by experimental evidence. For example, John A. Wheeler and Rudolf Ladenburg compiled the existing observations and concluded that they did not "allow a decision of the very important question whether the mass of the meson is unique."[84] The credit enjoyed by the single-mass assumption derived, as we have seen, from the nuclear connection, which was initially propped by the alleged agreement between the theoretical prediction of decay and the empirical evidence. But then, the match of theory and observation had become ambivalent. On the one hand, direct and indirect experiments had verified the instability of mesotrons, and the direct experiments had confirmed that mesotrons decayed into electrons plus some other undetected particle

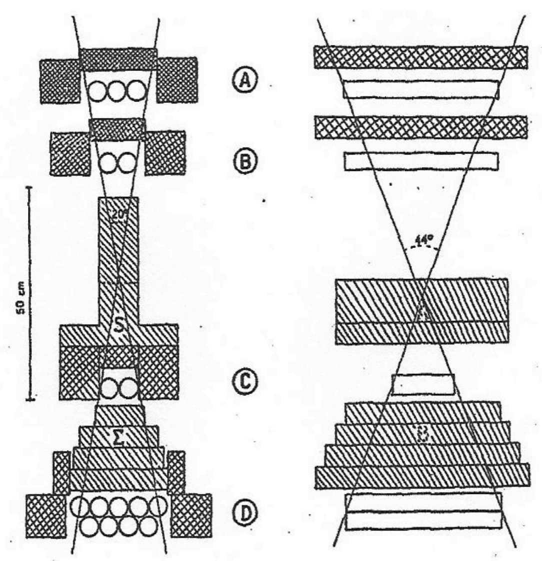

Fig. 4 The second anomalous-absorption experiment by Bernardini and his group, an example of the "differential method", which maximized the directness of indirect observations of mesotron decay. From Bernardini et al., "Sulla vita media del mesotrone", *Il nuovo cimento*, *19* (1942), 69-99, on 71. The difference between the number of threefold coincidences (ABC) and the number of fourfold coincidences (ABCD) measured the number of mesotrons having sufficient energy to cross the upper part of the apparatus but insufficient to cross the lowest absorber (Σ). A setup of this kind eliminated the need of assumptions about the energy distribution for the calculation of $\tau/\mu c^2$.

[83] "*Però si deve notare che questo è un valore puramente sperimentale e che è calcolato nell'ipotesi che la componente penetrante della radiazione cosmica sia costituita da un unico tipo di particelle.*" Bernardini et al., "Sulla vita media del mesotrone," on 98 (ref. 73).

[84] John A. Wheeler and Rudolf Ladenburg, "Mass of the meson by the method of momentum loss," *Physical review, 60* (1941), 754-761, on 760.

(or particles), as the theory predicted. On the other hand, the quantitative difference between the measured lifetime values and those from Yukawa's theory (which improved calculations placed between 10^{-9} and 10^{-8} s) had grown and, for the theorists at least, had become incurable.[85]

No mesotron experimenter acknowledged a theory-observation conflict in his published works. Some did, however, question the single-mass hypothesis on the basis of the discrepancies among observational results, which must have felt more pressing than the wider gap from a still unsettled theory. Pomerantz, for example, listed the "existence of a variable mass" among the possible causes of the spread of lifetime values measured with the integral and the differential methods. The theorist Paul Weisz performed a comparative analysis of available anomalous absorption data and found that the diverse mesotron lifetimes could be brought into agreement if a spectrum of mass was assumed.[86] Bernardini and his team opined that their $\tau/\mu c^2$ values displayed an apparent increase with increasing altitude and increasing average energy, but that further studies were necessary to assess the plausibility of an actual spread of values. Accordingly, they planned an independent check of this suggestion by means of measurements with the magnetic lenses.

The same setup could also be used to derive information about the probability of decay and the energy distribution of the incoming mesotrons, according to a rather complex phenomenological model that included Wick's calculation of the magnetic deflection of mesotrons (the "theory of the instrument") as well as assumptions about the height of production of mesotrons and their initial energies, a series of approximations, and a window of uncertainty over the distortions caused by the scattering of the mesotrons in iron. The model might have been unwieldy, but the experimenters noted that the apparatus and its electronics were simple and suited to rugged conditions.

[85] See, for example, H. A. Bethe and L. W. Nordheim, "On the theory of meson decay," *Physical review, 57* (1940), 998-1006, on 1004.

[86] Pomerantz, "The instability of the meson" (ref. 81); Paul Weisz, "The rest mass of the mesotron," *Physical review, 59* (1941), 845-849.

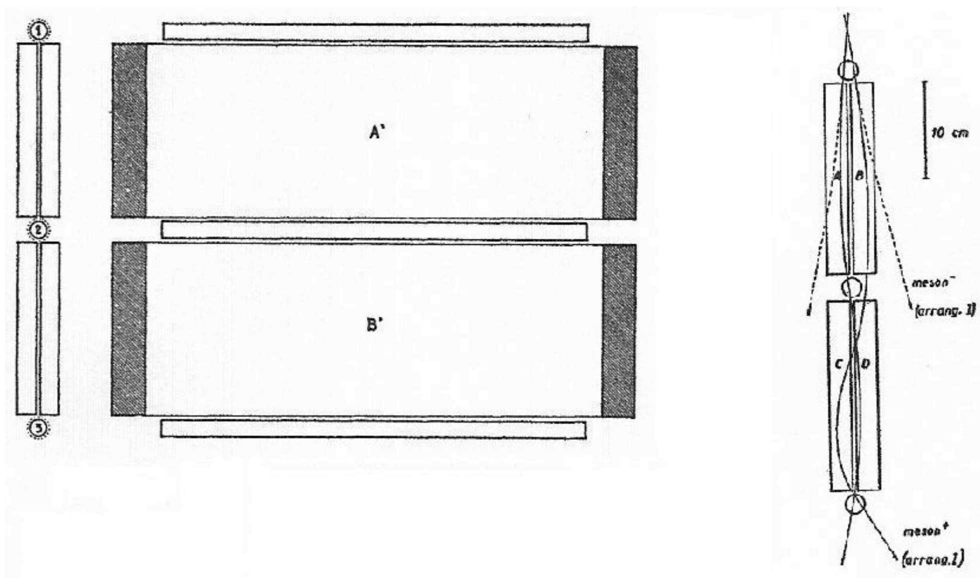

Fig. 5 The magnetic deflection experiment carried out by Bernardini, Conversi, Pancini, and Wick in Rome and at Pian Rosà in 1940-41. The leftmost diagram shows a front view of the setup, in which the three circles represent the counters, and the rectangles represent the iron blocks. The diagram in the middle shows a side view. The rightmost picture shows examples of particle trajectories when the two magnetic lenses operated with "parallel" magnetization. From Bernardini et al., "Positive excess in mesotron spectrum", *Physical review, 60* (1941), 535-536, on 535, and "Researches on the magnetic deflection of the hard component of cosmic rays", *Physical review*, *68* (1945), 109-120, on 109.

Bernardini hoped to test in this way the postulated variation of the ratio $\tau/\mu c^2$ over a large range of elevations. He and Scrocco installed the magnetic-lens system on an aeroplane and began taking data at high altitude. Unfortunately, an accident in flight damaged the apparatus, and the wartime circumstances prevented the effort from being pursued any further. Useful results, however, could be obtained with magnetic lenses at Pian Rosà and in Rome. In 1943, Conversi and Scrocco published a detailed report of measurements taken in the shack at Pian Rosà, and on a terrace of the physics department in Rome, in open air and with a brick wall build around the apparatus. Their $\tau/\mu c^2$ results, which had the merit of being "substantially different from the usual ones, all based on the anomalous absorption of mesotrons", are remarkably close to the present value, but they were not in good agreement with the then current value from anomalous absorption.[87] Bernardini, in fact, had just written a review article on anomalous absorption and had reached the conclusion that the most reliable value was $\tau/\mu c^2 = 3\times10^{-8}$ s/MeV.[88] Mistrusting their assumptions, Conversi and Scrocco resorted to inverting the experimental reasoning. They fixed $\tau/\mu c^2$ at 3×10^{-8} s/MeV, and then calculated the energy spectrum, which resulted to be more energetic than was generally assumed. In any case, the data were unambiguously consistent between low and high altitude. They demonstrated that one value of the $\tau/\mu c^2$ ratio was adequate to describe the entire meson

[87] "*sostanzialmente diverso dai soliti, basati tutti sull'assorbimento anomalo dei mesoni.*" Conversi and Scrocco, "Ricerche sulla componente dura", on 374 (ref. 79).

[88] G. Bernardini, "Über die anomale Absorption in Luft und die Lebensdauer des Mesons," *Zeitschrift für Physik, 120* (1942), 413-436, on 432.

population between Rome and the Alps, thus discrediting the existence of different types of mesons.[89]

10. THE DECAY HYPOTHESIS AND THE RELATIVISTIC DILATION OF TIME

The differential method offered the opportunity to push further the transparency of the measurement by articulating yet another assumption that was previously only partially explicit in the phenomenological models, namely, the relativistic transformation of time. As we have seen, Bhabha had pointed out that in order to apply the concept of spontaneous decay to cosmic rays one had to take into account the relativity of time. The time parameter governing the rate of decays, the mean lifetime of the particle at rest, would be transformed in proportion to the energy of the particle relatively to a reference frame in which the particle was in motion. Time relativity was incorporated into the decay interpretation of anomalous absorption, but Blackett had focused expressly on it in the note on mesotron decays that he published after the 1938 meeting in Copenhagen. Instead of taking the relativistic time transformation as a premise, he took decay as a premise, that is, he assumed that absorption differences under equivalent masses were due to spontaneous disintegrations. He then proceeded to estimate the mean ranges of hard rays before decay from various sets of data, corresponding to different mean energies of the hard rays, in order to check whether the mean ranges were proportional to mean energies. He concluded with the following reasoning:

> If τ and τ_0 are the decay times of a particle of mass μ when at rest and when moving with energy $E \gg \mu c^2$, we have, from relativistic considerations,
>
> $$L = c\tau = \tau_0 E/\mu c$$
>
> whence $L/E = \tau_0/\mu c$ = constant. This is seen to be approximately the case, thus verifying approximately the change of time-scale of a moving particle.[90]

It is hardly plausible that Blackett might have thought relativistic time dilation—predicted by Einstein in 1905 and built into Dirac's theory of the electron and quantum field theory—in need of verification. In any case, since no independent evidence of decay existed at that point, and since time dilation was a necessary premise for the quantity L to be interpretable as "mean range before decay", Blackett's argument was circular and could not be seriously considered as an empirical verification of time dilation in the hypothetic-deductive sense.[91] What Blackett had shown was that data from various sources displayed approximate consistency when they were cursorily arranged into an interpretive scheme that included both spontaneous decay and time dilation. It must

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[89] Conversi and Scrocco mentioned that a hypothesis had been set forth, concerning the existence of two mesons, one of which had a much lower mean life and was present prevalently in the higher layers of the atmosphere. Unfortunately, the reference for this hypothesis is missing. Conversi and Scrocco, "Ricerche con nuclei di ferro magnetizzati," on 405 (ref. 79).

[90] Blackett, "Further evidence," on 992 (ref. 50).

[91] Blackett demonstrated that, if the absorption differences under equal masses were assumed to depend exponentially on the differences of distance traversed, i.e. if the attenuation not due to mass absorption were assumed to follow the law $I = I_0 \exp(-l/L)$, then the exponential parameter L for each group of particles of mean energy E turned out to be roughly proportional to the E. Since disintegrations are "spontaneous" when their rate is constant for the particle species, without relativistic time dilation Blackett's calculation would have amounted to a refutation of spontaneous decay.

simply have been satisfactory for him to point out that the consistency demanded the explicit intervention of a principle otherwise hidden within the theoretical background.

The differential method suggested to Rossi the possibility of displaying the dependence of mean range before decay on momentum (Rossi used momentum rather than energy) in a single experiment. Rossi and his new collaborator, David B. Hall performed differential absorption measurements for two groups of mesotrons having different penetration ranges at two different altitudes, Denver and Echo Lake, in the summer of 1940. They reported that the difference in attenuation rates between air and iron was larger for the group of lower penetration. If interpreted according to the decay hypothesis, this result was qualitatively consistent with the variation expected from relativity. Rossi's discussion made it clear that the decay interpretation hung on the time dilation principle, and that the experiment would not be able to test one hypothesis independently of the other. In Rossi's words,

> The experiment described in the present paper were primarily designed to test the dependence of the disintegration probability on momentum expressed by [the equation $L = p\tau_0/\mu$]. The purpose was to provide an additional check of the disintegration hypothesis and simultaneously to verify the relativistic transformation formula for time intervals.[92]

Rossi continued the experiment the following summer and was able to establish the relativistic relation in a quantitative way. Unlike the absorption law, the assumption of time dilation had not been put on the spot because of its perceived imprecision and instability. The motivation in this case seems to have been simply the pragmatic realization of an opportunity offered by the experimental method. Time dilation could be expressed as a separate mathematical relation between quantities that could now be made to correspond to instrumental readings solely through the theory of energy losses. In other terms, a previously hidden assumption could be tested singularly, rather than through the overall outcome, because it could be matched in detail to the data without introducing any further assumption. Once more, Rossi described this experimental move as an increment of directness:

> The dependence of L on p expressed by [the equation $L = p\tau_0/\mu$] implies that the interpretation of the experimental results is most direct and unambiguous when mesotrons belonging to a narrow momentum interval are recorded.[93]

In fact, the physicists reckoned that with the experimental treatment of relativistic time dilation the indirect experiments had reached the maximum directness to which they could aspire. Rossi, and Piccioni and Conversi from Bernardini's group switched then to experiments of the "direct" class, with which they hoped to win some more degrees of directness.

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[92] Bruno Rossi and David B. Hall, "Variation of the rate of decay of mesotrons with momentum," *Physical Review, 59* (1941), 223-228, on 224. An important improvement to the differential method introduced by Rossi and Hall was the use of a circuit for the registration of anticoincidences. This circuit recorded events in which a signal from a set of counters (or a coincidence of more sets) was concomitant with the absence of a signal from another set. In this way, Rossi and Hall were able to record the numbers of hard rays traversing the upper part of the apparatus and stopping in the bottom absorber (that is, the numbers of mesotrons within a minimum and a maximum of energy), whereas their colleagues estimated the numbers statistically by subtraction.

[93] Bruno Rossi et al., "Further measurements of the mesotron lifetime," *Physical Review, 61* (1942), 675-679, on 675.

11. THE "DIRECT" EXPERIMENTS

An experiment of the direct class was carried out by Franco Rasetti at Laval University during the first half of 1941. It followed an unsuccessful effort to detect decay electrons from stopped mesotrons with a coincidence setup that was made in 1939 by C. G. Montgomery, W. E. Ramsey, D. B. Cowie, and D. D. Montgomery at the Franklin Institute. Rasetti amended that first attempt by importing the anticoincidence technique that Rossi had used for the differential method. Montgomery *et al.* and Rasetti presented their work as "more direct" than the anomalous absorption experiments because it was independent from assumptions about the height of production and the mass of mesotrons. Montgomery *et al* had introduced their work as follows:

> Notwithstanding the short lifetime, some mesons should come to rest before disintegration, and it should be possible to determine, in a more direct manner, the time until decay.[94]

Similarly, Rasetti remarked on the directness of his first estimation of the lifetime:

> So far the accuracy of the present measurement is rather poor; its interest lies rather in affording a determination of the mean life that is more direct and less dependent upon accessory hypotheses than the one deduced from the atmospheric absorption effect.[95]

The task of experiments of the direct type was to record events in which a mesotron entered an absorber, slowed down, disintegrated according to the statistical law of radioactive decay, and emitted a detectable electron and an undetectable neutrino. Accordingly, the experimental setups aimed at registering the particles that were emitted with delay from an absorber placed below a counter telescope, with the telescope arranged to select hard rays. When a coincidence in the telescope was followed, after a suitable interval of time, by a discharge in a set of counters adjacent to the bottom absorber, the "delayed coincidence" was interpreted as a decay event. Montgomery *et al.* had been unable to discern any signal above the expected experimental noise. Rasetti succeeded because he improved drastically the ratio of signal over noise by placing anticoincidence counters below the absorber to suppress the number of go-through mesotrons, and using a thin absorber with side counters to detect the outgoing electrons. Therefore, his phenomenological model did rely on the absorption law for mesotrons, even though less quantitatively than the differential method of the anomalous absorption experiments. Rasetti also realized that interpreting the side coincidences as outgoing electrons required approximate knowledge of the distribution of initial energies for the electrons, and hence at least a rough estimate of the mesotron mass and the number of decay products per each mesotron. For these reasons, his final report was more circumspect about directness than the preliminary ones.[96]

Rasetti estimated statistically the numbers of decay events within fixed windows of time by using three coincidence circuits with different time resolutions, and subtracting the numbers recorded with the higher resolutions from the number recorded with the lowest resolution. He wrote an equation that allowed him to calculate the mean

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[94] C. G. Montgomery et al., "Slow mesons in cosmic radiation," *Physical review, 56* (1939), 635-639, on 635.

[95] Franco Rasetti, "Mean life of slow mesotrons," *Physical review, 59* (1941), 613.

[96] Franco Rasetti, "Disintegration of slow mesotrons," *Physical review, 60* (1941), 198-204; Franco Rasetti, "Evidence for the radioactivity of slow mesotrons," *Physical review, 59* (1941), 706-708.

lifetime simply from the ratio of these two differences. The only presupposition formally required to write the equation was the exponential law of radioactive decay. All the decay experiments had hitherto tacitly assumed that the decay rates of mesotrons followed an exponential law. As the differential method had done for the principle of time relativity, Rasetti's procedure made the assumption of an exponential law at the same time manifest and unnecessary.

Other experimenters, enticed by Rasetti's success, realized that technical refinements of the electronics systems would enable the registration of decay rates in connection with precise time intervals for more than two time intervals, thereby making possible a point-by-point verification of the time dependence of decay rates. Rossi designed a "time circuit" capable of measuring the interval between the arrival of a mesotron and the subsequent emission of an electron. He could thus plot an experimental decay curve. The curve fitted an exponential curve with remarkable precision, and the mean lifetime calculated from it was $\tau = (2.3 \pm 0.2) \times 10^{-6}$ s.[97] Piccioni and Conversi also were inspired by Rasetti—whose experiment they judged "beautiful" but "somewhat acrobatic"[98]—to undertake the direct observation of mesotron decay with a more advanced electronics system. In 1943, in the face of considerable difficulties due to the state of war and the German occupation, Piccioni and Conversi were able to complete their measurements, to determine four points of the decay curve and thus verify the exponential law, and to measure a mean lifetime of $\tau = 2.3 \times 10^{-6}$ s with a precision of 7.5 percent.[99]

Achieving the direct observation of decays created the conditions to investigate the behaviour of mesotrons at the end of their range in matter. Measuring the ratio of number of decays to the number of stopped mesotrons provided the means to observe the rates of capture of mesotrons by the atomic nuclei of the medium, and to compare these quantities to theoretical expectations. The nuclear capture of mesons became of paramount interest at the end of the war for the physicists in America. They were returning to fundamental research from their engagement in weapon development with a new mission and a new experimental horizon: the mission of gaining full control of the nuclear forces, and the vast new range of possibilities offered by a state-funded accelerator program.[100] The experimental investigation of the nuclear capture of mesons by means of the direct observation of cosmic-ray decays was a pivotal element of this historical juncture, which can be regarded as the beginning of high-energy physics.

12. CONCLUSION

Several factors played a role in the quest for increasingly direct observations of mesotron decay. In the first place, the experimenters had to decide when an observation had been achieved at all. Euler and Heisenberg's starting optimism and Blackett's early

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[97] Bruno Rossi and Norris Nereson, "Experimental determination of the disintegration curve of mesotrons," *Physical Review, 62* (1942), 417-422.

[98] "*… la tecnica usata da Rasetti nella sua bella esperienza era, per così dire, un po' acrobatica…*", Bernardini et al., "Sulla vita media del mesotrone," on 98 (ref. 73).

[99] M. Conversi and O. Piccioni, "Misura diretta della vita media dei mesoni frenati," *Il nuovo cimento, 2* (1944), 40-70. See also M. Conversi and O. Piccioni, "On the mean life of slow mesons," *Physical review, 70* (1946), 859-873.

[100] Monaldi, "Life of μ" (ref. 9). See also D. Monaldi, "Mesons in 1946", in *Atti del XXV Congresso Nazionale di Storia della Fisica e dell'Astronomia* (Milano, 2005).

claim of "definite experimental evidence for the spontaneous decay of the new particles" rested heavily on the assessment of would-be agreement between lifetime calculations from experimental models and the lifetime calculated from Yukawa's formulae. This allegation, however, was not regarded as conclusive. New experiments were designed and carried out expressly to observe decay; they left the stage of mutual support between hypothesis and evidence and moved toward ways of testing the hypothesis upon independent evidence.

Of course, whatever evidence the cosmic-ray experimenters could obtain was conditional upon the system of assumptions that they took for granted or were prepared to accept. As Duhem argued long ago, the statement of an experimental result in physics implies "an act of faith in a whole group of theories."[101] Microphysical experiments, not only the statement of their results, would be inconceivable outside their specific theoretical frameworks, which normally consist of several layers of background knowledge and theory. Nevertheless, the conceptual framework of an experiment is neither a single theory nor a Duhemian organism but a loosely connected patchwork of different theories of varying levels of generality, more or less improvised models, practical rules, and common-sense assumptions, parts of which can be doubted, revised, or even discarded without compromising the rest. For this reason it is possible to test a hypothesis while making use of many other assumptions without incurring in logical circularity. The danger of circularity was never severe in the mesotron case because the hypothesis under study was only distantly related to the theories deployed to constitute the evidence, and the initial collusion of hypothesis and evidence was limited to reciprocal validation. The question of epistemic independence is nevertheless relevant to an inquiry about the directness of observation. Several authors have identified the disengagement of the theories constituting the evidence from the theories pertaining to the object of investigation as the foremost requirement for an experimental conclusion to be an observation rather than an inference.[102] In this view, if one also maintains with Shapere that the "direct" in scientists' "direct observations" is just an emphatic mark of the contrast between observations and inferences, rather than a further attribute of observations, epistemic independence becomes a major determinant of directness.[103]

The mesotron experimenters did not simply distinguish between what was an observation and what was not; they also identified gradations in directness among observations. In the first place, they divided the experiments into "direct tests" and "indirect tests" of the decay hypothesis. The imaging of decay in the cloud chamber was generally considered a direct observation of the micro-process regardless of the interactions occurring within the instrument to generate the image. This outlook may testify to the suggestion of visualizations. Still, in the case of mesotron decay it was extended also to the counter experiments that, without producing images, had an analogous conceptual structure. The analogy points to the tendency of experimenters to compartmentalize their understanding of an experiment, to adapt it to an ideal organization in which the instrument performs no other function than that of providing access to the micro-process under study. The complexities involved in the operations of

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[101] Duhem, *The aim and structure of physical theory*, on 183 (ref. 3).
[102] Hacking, *Representing and intervening*, on 183-185 (ref. 4); Kosso, "Dimensions of observability," on 456-457 (ref. 6); Kosso, *Observability*, on 43-50 (ref. 6).
[103] Shapere, "The concept of observation," on 511-512 (ref. 6).

the instrument and in their interpretation, although absorbing a large portion of the experimental work, are ideally corralled into the instrumental part of the experiment, as to interfere as little as possible with the so-called "physical" part. The attribution of directness to the "direct" tests depended on the interpretive steps between the instrumental output and the hypothesis under study, no matter how much interpretation went into the production of the instrumental output. Only the minimization of calculations and additional assumptions necessary to connect the instrumental output to the hypothesis under study, and the perceived absence of alternative explanations of the instrumental output (which was contingent on the history of the experiments) entered the physicists' considerations of directness.

Along with from the coarse classification of experiments into direct and indirect, other factors determined degrees of directness within both classes. One factor was the possibility of measuring many values of two related quantities in order to display in detail a functional relation that had previously just been assumed to hold. For example, the mesotron experimenters attributed a higher degree of directness to the anomalous absorption experiments in which energies and decay rates could be measured separately by means of the differential method, so that the dependence of decay probability on momentum entailed by the relativity of time could be exhibited. Similarly, in the class of direct experiments, directness was maximized by the possibility of plotting more than two points of the decay curve in order to test the law of exponential decay.

Most importantly, the progression in directness of the mesotron decay experiments highlights the role of the phenomenological models. With this expression I referred to the models that, in each experiment, connected the theoretical process under study to the instrumental output under the conditions of the experiment. They were structured into a core of hypotheses relative to the process under study, a set of "additional assumptions" or "supplementary hypotheses", and a body of tacit background knowledge. The goal of eliminating the additional assumptions, either by implementing new experimental conditions that made them unnecessary, or by reducing their uncertainty and thus absorbing them into the background knowledge, was the most prominent gauge by which the cosmic-ray experimenters defined their progress toward the first direct observation of the spontaneous disintegration of an elementary particle.