

# Chapter 3

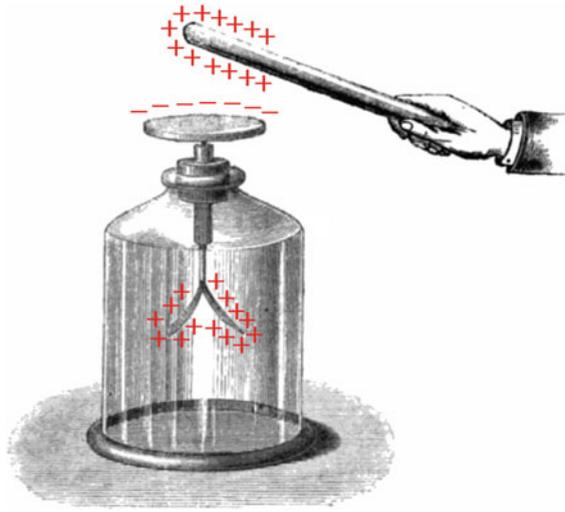
## Cosmic Rays and the Development of Particle Physics



*This chapter illustrates the path which led to the discovery that particles of extremely high energy, up to a few joule, come from extraterrestrial sources and collide with Earth's atmosphere. The history of this discovery started in the beginning of the twentieth century, but many of the techniques then introduced are still in use. A relevant part of the progress happened in recent years and has a large impact on the physics of elementary particles and fundamental interactions.*

By 1785, Coulomb found that electroscopes (Fig. 3.1) can discharge spontaneously, and not simply due to defective insulation. The British physicist Crookes, in 1879, observed that the speed of discharge decreased when the pressure of the air inside the electroscope itself was reduced. The discharge was then likely due to the ionization of the atmosphere. But what was the cause of atmospheric ionization?

The explanation came in the early twentieth century and led to the revolutionary discovery of cosmic rays. We know today that cosmic rays are particles of extraterrestrial origin which can reach high energy (much larger than we shall ever be able to produce). They were the only source of high-energy beams till the 1940s. World War II and the Cold War provided new technical and political resources for the study of elementary particles; technical resources included advances in microelectronics and the capability to produce high-energy particles in human-made particle accelerators. By 1955, particle physics experiments would be largely dominated by accelerators, at least until the beginning of the 1990s, when explorations possible with the energies one can produce on Earth started showing signs of saturation, so that nowadays cosmic rays are again at the edge of physics.



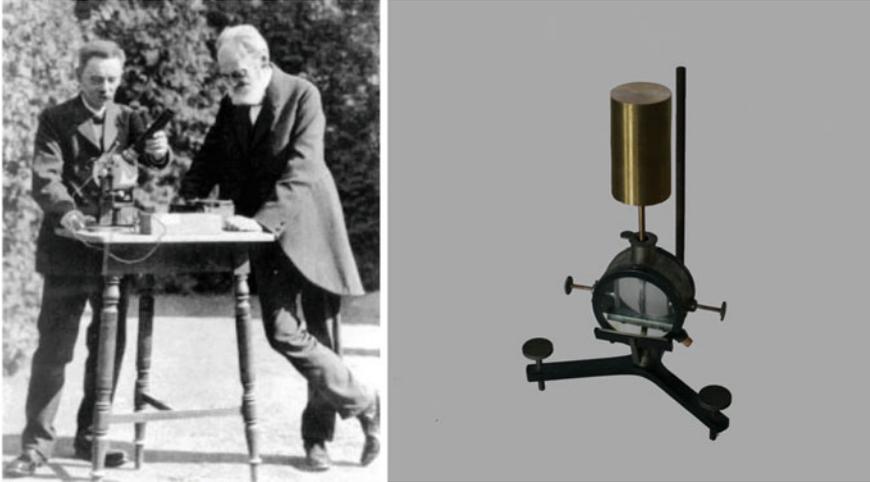
**Fig. 3.1** The electrostatic demonstrator is a device for detecting electric charge. A typical electrostatic demonstrator (the configuration in the figure was invented at the end of the eighteenth century) consists of a vertical metal rod from the end of which two gold leaves hang. A disk or ball is attached to the top of the rod. The leaves are enclosed in a glass vessel, for protection against air movements. The test charge is applied to the top, charging the rod, and the gold leaves repel and diverge. By Sylvanus P. Thompson [public domain], via Wikimedia Commons

### 3.1 The Puzzle of Atmospheric Ionization and the Discovery of Cosmic Rays

Spontaneous radioactivity (i.e., the emission of particles from nuclei as a result of nuclear instability) was discovered in 1896 by Becquerel. A few years later, Marie and Pierre Curie discovered that Polonium and Radium (the names Radium A, Radium B, ..., several isotopes of the element today called radon and also some different elements) underwent transmutations by which they generated radioactivity; these processes were called “radioactive decays.” A charged electrostatic demonstrator promptly discharges in the presence of radioactive materials. It was concluded that the discharge was due to the emission of charged particles, which induce the formation of ions in the air, causing the discharge of electrostatic demonstrators. The discharge rate of electrostatic demonstrators was used to gauge the radioactivity level. During the first decade of the twentieth century, several researchers in Europe and in the New World presented progress on the study of ionization phenomena.

Around 1900, C.T.R. Wilson<sup>1</sup> in Britain and Elster and Geitel in Germany improved the sensitivity of the electrostatic demonstrator, by improving the technique for its insulation in a closed vessel (Fig. 3.2). This improvement allowed the quantitative

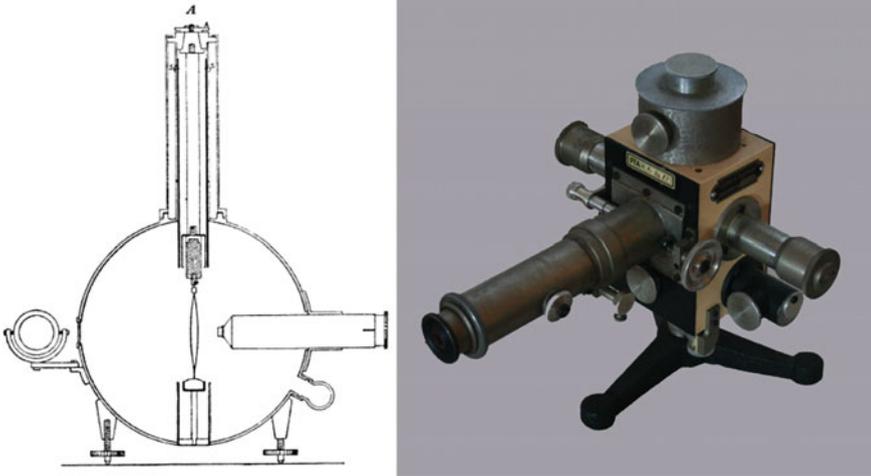
<sup>1</sup>Charles Thomson Rees Wilson, (1869–1959), a Scottish physicist and meteorologist, received the Nobel Prize in Physics for his invention of the cloud chamber; see the next chapter.



**Fig. 3.2** Left: The two friends Julius Elster and Hans Geitel, gymnasium teachers in Wolfenbüttel, around 1900. Credit <http://www.elster-geitel.de>. Right: an electroscopes developed by Elster and Geitel in the same period (private collection R. Fricke; photograph by A. De Angelis)

measurement of the spontaneous discharge rate and led to the conclusion that the radiation causing this discharge came from outside the vessel. Concerning the origin of such radiation, the simplest hypothesis was that it was related to radioactive material in the surroundings of the apparatus. Terrestrial origin was thus a commonplace assumption, although experimental confirmation could not be achieved. Wilson did suggest that atmospheric ionization could be caused by a very penetrating radiation of extraterrestrial origin. His investigations in tunnels, with solid rock for shielding overhead, however, could not support the idea, as no reduction in ionization was observed. The hypothesis of an extraterrestrial origin, though now and then discussed, was dropped for many years.

By 1909, measurements on the spontaneous discharge had proved that the discharging background radiation was also present in insulated environments and could penetrate metal shields. It was thus difficult to explain it in terms of  $\alpha$  (He nuclei) or  $\beta$  (electrons) radiation; it was thus assumed to be  $\gamma$  radiation, i.e., made of photons, which was the most penetrating among the three kinds of radiation known at the time. Three possible sources were then hypothesized for this radiation: it could be extraterrestrial (possibly from the Sun); it could be due to radioactivity from the Earth crust or to radioactivity in the atmosphere. It was generally assumed that there had to be large contribution from radioactive materials in the crust, and calculations of its expected decrease with height were performed.

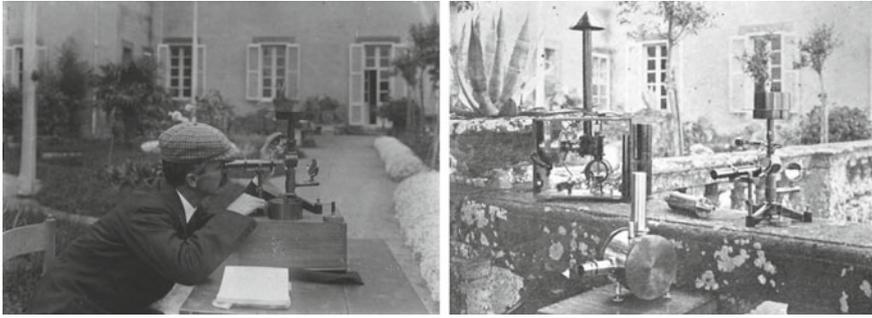


**Fig. 3.3** Left: Scheme of the Wulf electroscope (drawn by Wulf himself; reprinted from *Z. Phys.* [public domain]). The main cylinder was made of zinc, 17 cm in diameter and 13 cm deep. The distance between the two silicon glass wires (at the center) was measured using the microscope to the right. The wires were illuminated using the mirror to the left. According to Wulf, the sensitivity of the instrument was 1 V, as measured by the decrease of the interwire distance. Right: an electroscope used by Wulf (private collection R. Fricke; photograph by A. De Angelis)

### 3.1.1 *Underwater Experiments and Experiments Carried Out at Altitude*

Father Theodor Wulf, a German scientist and a Jesuit priest, thought of checking the variation of ionization with height to test its origin. In 1909, using an improved electroscope in which the two leaves had been replaced by metal-coated silicon glass wires, making it easier to transport than previous instruments (Fig. 3.3), he measured the ionization rate at the top of the Eiffel Tower in Paris, about 300 m high. Under the hypothesis that most of the radiation was of terrestrial origin, he expected the ionization rate to be significantly smaller than the value on the ground. The measured decrease was, however, too small to confirm the hypothesis: he observed that the radiation intensity “decrease at nearly 300 m [altitude] was not even to half of its ground value,” while “just a few percent of the radiation” should remain if it did emerge from ground. Wulf’s data, coming from experiments performed for many days at the same location and at different hours of the day, were of great value and for a long time were considered the most reliable source of information on the altitude variation of the ionization rate. However, his conclusion was that the most likely explanation for this unexpected result was still emission from ground.

The conclusion that atmospheric ionization was mostly due to radioactivity from the Earth’s crust was challenged by the Italian physicist Domenico Pacini. Pacini developed a technique for underwater measurements and conducted experiments in



**Fig. 3.4** Left: Pacini making a measurement in 1910. Courtesy of the Pacini family, edited by A. De Angelis [public domain, via Wikimedia Commons]. Right: the instruments used by Pacini for the measurement of ionization. By D. Pacini (Ufficio Centrale di Meteorologia e Geodinamica), edited by A. De Angelis [public domain, via Wikimedia Commons]

the sea of the Gulf of Genova and in the Lake of Bracciano (Fig. 3.4). He found a significant decrease in the discharge rate in electroscopes placed three meters underwater. He wrote: “Observations carried out on the sea during the year 1910 led me to conclude that a significant proportion of the pervasive radiation that is found in air has an origin that is independent of direct action of the active substances in the upper layers of the Earth’s surface. [...] [To prove this conclusion] the apparatus [...] was enclosed in a copper box so that it could immerse in depth. [...] Observations were performed with the instrument at the surface, and with the instrument immersed in water, at a depth of 3 m.” Pacini measured the discharge of the electroscope for 3 h and repeated the measurement seven times. At the surface, the average ionization rate was 11.0 ions per cubic centimeter per second, while he measured 8.9 ions per cubic centimeter per second at a depth of 3 m in the 7 m deep sea (the depth of the water guaranteed that radioactivity from the soil was negligible). He concluded that the decrease of about 20% was due to a radiation not coming from the Earth.

After Wulf’s observations on the altitude effect, the need for balloon experiments (widely used for atmospheric electricity studies since 1885) became clear. The first high-altitude balloon with the purpose of studying the penetrating radiation was flown in Switzerland in December 1909 with a balloon from the Swiss aeroclub. Albert Gockel, professor at the University of Fribourg, ascended to 4500 m above sea level (a.s.l.). He made measurements up to 3000 m and found that ionization rate did not decrease with altitude as expected under the hypothesis of terrestrial origin. His conclusion was that “a nonnegligible part of the penetrating radiation is independent of the direct action of the radioactive substances in the uppermost layers of the Earth.”

In spite of Pacini’s conclusions, and of Wulf’s and Gockel’s puzzling results on the altitude dependence, the issue of the origin of the penetrating radiation still raised



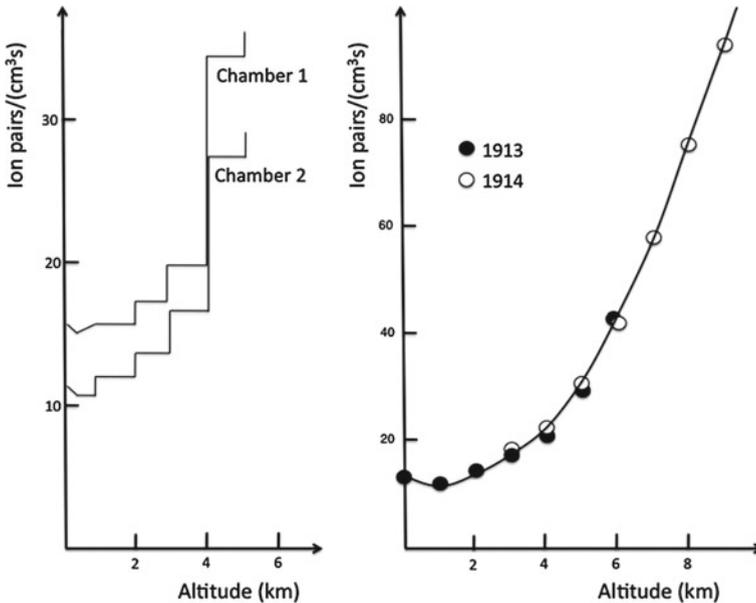
**Fig. 3.5** Left: Hess during the balloon flight in August 1912. [public domain], via Wikimedia Commons. Right: one of the electrometers used by Hess during his flight. This instrument is a version of a commercial model of a Wulff electroscop especially modified by its manufacturer, Günther and Tegetmeyer, to operate under reduced pressure at high altitudes (Smithsonian National Air and Science Museum, Washington, DC). Photo by P. Carlson

doubts. A series of balloon flights by the Austrian physicist Victor Hess<sup>2</sup> settled the issue, firmly establishing the extraterrestrial origin of at least part of the radiation causing the atmospheric ionization.

Hess started by studying Wulf's results. He carefully checked the data on gamma-ray absorption coefficients (due to the large use of radioactive sources he will lose a thumb), and after careful planning, he finalized his studies with balloon observations. The first ascensions took place in August 1911. From April 1912 to August 1912, he flew seven times, with three instruments (one of them with a thin wall to estimate the effect of  $\beta$  radiation, as for given energy electrons have a shorter range than heavier particles). In the last flight, on August 7, 1912, he reached 5200 m (Fig. 3.5). The results clearly showed that the ionization rate first passed through a minimum and then increased considerably with height (Fig. 3.6). "(i) Immediately above ground the total radiation decreases a little. (ii) At altitudes of 1000–2000 m there occurs again a noticeable growth of penetrating radiation. (iii) The increase reaches, at altitudes of 3000–4000 m, already 50% of the total radiation observed on the ground. (iv) At 4000–5200 m the radiation is stronger [more than 100%] than on the ground."

Hess concluded that the increase in the ionization rate with altitude was due to radiation coming from above, and he thought that this radiation was of extraterrestrial origin. His observations during the day and during the night showed no variation and excluded the Sun as the direct source of this hypothetical radiation.

<sup>2</sup>Hess was born in 1883 in Steiermark, Austria, and graduated from Graz University in 1906 where he became professor of Experimental Physics in 1919. In 1936 Hess was awarded the Nobel Prize in Physics for the discovery of cosmic rays. He moved to the USA in 1938 as a professor at Fordham University. Hess became an American citizen in 1944 and lived in New York until his death in 1964.



**Fig. 3.6** Variation of ionization with altitude. Left panel: Final ascent by Hess (1912), carrying two ion chambers. Right panel: Ascents by Kolhörster (1913, 1914)

The results by Hess would later be confirmed by Kolhörster. In flights up to 9200m, Kolhörster found an increase in the ionization rate up to ten times its value at sea level. The measured attenuation length of about 1 km in air came as a surprise, as it was eight times smaller than the absorption coefficient of air for  $\gamma$  rays as known at the time.

After the 1912 flights, Hess coined the name “Höhenstrahlung.” Several other names were used for the extraterrestrial radiation: Ultrastrahlung, Ultra-X-Strahlung, kosmische Strahlung. The latter, used by Gockel and Wulf in 1909, inspired Millikan<sup>3</sup> who suggested the name “cosmic rays,” which became generally accepted.

The idea of cosmic rays, despite the striking experimental evidence, was not immediately accepted (the Nobel prize for the discovery of cosmic rays was awarded to Hess only in 1936). During the 1914–1918 war and the years that followed, very few investigations of the penetrating radiation were performed. In 1926, however, Millikan and Cameron performed absorption measurements of the radiation at dif-

<sup>3</sup>Robert A. Millikan (Morrison 1868—Pasadena 1953) was an American experimental physicist, Nobel Prize in Physics in 1923 for his measurements of the electron charge and his work on the photoelectric effect. A scholar of classical literature before turning to physics, he was president of the California Institute of Technology (Caltech) from 1921 to 1945. He was not famous for his deontology: a common saying at Caltech was “Jesus saves, and Millikan takes the credit.”

ferent depths in lakes at high altitudes. They concluded that the radiation was made up of high energy  $\gamma$  rays and that “these rays shoot through space equally in all directions” and called them “cosmic rays.”

### 3.1.2 *The Nature of Cosmic Rays*

Cosmic radiation was generally believed to be  $\gamma$  radiation because of its penetrating power (the penetrating power of relativistic charged particles was not known at the time). Millikan had launched the hypothesis that these  $\gamma$  rays were produced when protons and electrons formed helium nuclei in the interstellar space.

A key experiment on the nature of cosmic rays was the measurement of the intensity variation with geomagnetic latitude. During two voyages between Java and Genova in 1927 and 1928, the Dutch physicist Clay found that ionization increased with latitude; this proved that cosmic rays interacted with the geomagnetic field and, thus, they were mostly charged particles.

In 1928, the Geiger–Müller counter tube<sup>4</sup> was introduced, and soon confirmation came that cosmic radiation is indeed electrically charged. In 1933, three independent experiments by Alvarez and Compton, Johnson, and Rossi discovered that close to the equator there were more cosmic rays coming from West than from East. This effect, due to the interaction with the geomagnetic field, showed that cosmic rays are mostly positively charged—and thus most probably protons, as some years later it was possible to demonstrate thanks to more powerful spectrometers.

## 3.2 Cosmic Rays and the Beginning of Particle Physics

With the development of cosmic ray physics, scientists knew that astrophysical sources provided high-energy particles which entered the atmosphere. The obvious next step was to investigate the nature of such particles, and to use them to probe matter in detail, much in the same way as in the experiment conducted by Marsden and Geiger in 1909 (the Rutherford experiment, described in Chap. 2). Particle physics thus started with cosmic rays, and many of the fundamental discoveries were made thanks to cosmic rays.

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<sup>4</sup>The Geiger–Müller counter is a cylinder filled with a gas, with a charged metal wire inside. When a charged particle enters the detector, it ionizes the gas, and the ions and the electrons can be collected by the wire and by the walls. The electrical signal of the wire can be amplified and read by means of an amperometer. The tension  $V$  of the wire is large (a few thousand volts), in such a way that the gas is completely ionized; the signal is then a short pulse of height independent of the energy of the particle. Geiger–Müller tubes can be also appropriate for detecting  $\gamma$  radiation, since a photoelectron or a Compton-scattered electron can generate an avalanche.

In parallel, the theoretical understanding of the Universe was progressing quickly: at the end of the 1920s, scientists tried to put together relativity and quantum mechanics, and the discoveries following these attempts changed completely our view of nature. A new window was going to be opened: antimatter.

### 3.2.1 *Relativistic Quantum Mechanics and Antimatter: From the Schrödinger Equation to the Klein–Gordon and Dirac Equations*

Schrödinger’s equation has evident limits. Since it contains derivatives of different order with respect to space and time, it cannot be relativistically covariant, and thus, it cannot be the “final” equation. How can it be extended to be consistent with Lorentz invariance? We must translate relativistically covariant Hamiltonians in the quantum language, i.e., into equations using wavefunctions. We shall see in the following two approaches.

#### 3.2.1.1 The Klein–Gordon Equation

In the case of a free particle ( $V = 0$ ), the simplest way to extend Schrödinger’s equation to take into account relativity is to write the Hamiltonian equation

$$\begin{aligned}\hat{H}^2 &= \hat{p}^2 c^2 + m^2 c^4 \\ \implies -\hbar^2 \frac{\partial^2 \Psi}{\partial t^2} &= -\hbar^2 c^2 \nabla^2 \Psi + m^2 c^4 \Psi,\end{aligned}$$

or, in natural units,

$$\left(-\frac{\partial^2}{\partial t^2} + \nabla^2\right) \Psi = m^2 \Psi.$$

This equation is known as the Klein–Gordon equation,<sup>5</sup> but it was first considered as a quantum wave equation by Schrödinger; it was found in his notebooks from late 1925. Schrödinger had also prepared a manuscript applying it to the hydrogen atom; however, he could not solve some fundamental problems related to the form of the equation (which is not linear in energy, so that states are not easy to combine), and thus he went back to the equation today known by his name. In addition, the solutions of the Klein–Gordon equation do not allow for statistical interpretation of  $|\Psi|^2$  as a probability density—its integral would in general not remain constant in time.

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<sup>5</sup>Oskar Klein (1894–1977) was a Swedish theoretical physicist; Walter Gordon (1893–1939) was a German theoretical physicist, former student of Max Planck.

The Klein–Gordon equation displays one more interesting feature. Solutions of the associated eigenvalue equation

$$(-m^2 + \nabla^2)\psi = E_p^2\psi$$

have both positive and negative eigenvalues for energy. For every plane wave solution of the form

$$\Psi(\mathbf{r}, t) = Ne^{i(\mathbf{p}\cdot\mathbf{r} - E_p t)}$$

with momentum  $\mathbf{p}$  and positive energy

$$E_p = \sqrt{p^2 + m^2} \geq m,$$

there is a solution

$$\Psi^*(\mathbf{r}, t) = N^*e^{i(-\mathbf{p}\cdot\mathbf{r} + E_p t)}$$

with momentum  $-\mathbf{p}$  and negative energy

$$E = -E_p = -\sqrt{p^2 + m^2} \leq -m.$$

Note that one cannot simply drop the solutions with negative energy as “unphysical”: the full set of eigenstates is needed, because if one starts from a given wavefunction, this could evolve with time into a wavefunction that, in general, has projections on all eigenstates (including those one would like to get rid of). We remind the reader that these are solutions of an equation describing a free particle.

A final comment about notation. The (classical) Schrödinger equation for a single particle in a time-independent potential can be decoupled into two equations: one (the so-called eigenvalue equation) depending only on space, and the other depending only on time. The solution of the eigenvalue equation is normally indicated by a lowercase Greek symbol,  $\psi(\mathbf{r})$  for example, while the time part has a solution independent of the potential,  $e^{-i(E/\hbar)t}$ . The wavefunction is indicated by a capital letter:

$$\Psi(\mathbf{r}, t) = \psi(\mathbf{r})e^{-i\frac{E}{\hbar}t}.$$

This distinction makes no sense for relativistically covariant equations and in particular for the Klein–Gordon equation and for the Dirac equation which will be discussed later. Both  $\Psi(x)$  and  $\psi(x)$  are now valid notations for indicating a wavefunction which is function of the 4-vector  $x = (ct, x, y, z)$ .

### 3.2.1.2 The Dirac Equation

Dirac<sup>6</sup> in 1928 searched for an alternative relativistic equation starting from the generic form describing the evolution of a wavefunction, in the familiar form:

$$i\hbar \frac{\partial \Psi}{\partial t} = \hat{H} \Psi$$

with a Hamiltonian operator linear in  $\hat{\mathbf{p}}$ ,  $t$  (Lorentz invariance requires that if the Hamiltonian has first derivatives with respect to time also the spatial derivatives should be of first order):

$$\hat{H} = c\boldsymbol{\alpha} \cdot \mathbf{p} + \beta mc^2.$$

This must be compatible with the Klein–Gordon equation, and thus

$$\begin{aligned} \alpha_i^2 &= 1 \quad ; \quad \beta^2 = 1 \\ \alpha_i \beta + \beta \alpha_i &= 0 \\ \alpha_i \alpha_j + \alpha_j \alpha_i &= 0. \end{aligned}$$

Therefore, parameters  $\alpha$  and  $\beta$  cannot be numbers. However, it works if they are matrices (and if these matrices are Hermitian, it is guaranteed that the Hamiltonian is also Hermitian). It can be demonstrated that the lowest order is  $4 \times 4$ .

Using the explicit form of the momentum operator  $\mathbf{p} = -i\hbar \nabla$  the Dirac equation becomes

$$i\hbar \frac{\partial \Psi}{\partial t} = (i\boldsymbol{\alpha} \cdot \nabla + \beta mc^2) \Psi.$$

The wavefunctions  $\Psi$  must thus be four-component vectors:

$$\Psi(\mathbf{r}, t) = \begin{pmatrix} \Psi_1(\mathbf{r}, t) \\ \Psi_2(\mathbf{r}, t) \\ \Psi_3(\mathbf{r}, t) \\ \Psi_4(\mathbf{r}, t) \end{pmatrix}.$$

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<sup>6</sup>Paul Adrien Maurice Dirac (Bristol, UK, 1902—Tallahassee, US, 1984) was one of the founders of quantum physics. After graduating in engineering and later studying physics, he became professor of mathematics in Cambridge. In 1933 he shared the Nobel Prize with Schrödinger. He assigned to the concept of “beauty in mathematics” a prominent role among the basic aspects intrinsic to the nature so far as to argue that “a mathematically beautiful theory is more likely to be right than an ugly one that fits some experimental data.”

We arrived at an interpretation of the Dirac equation, as a four-dimensional matrix equation in which the solutions are four-component wavefunctions called bi-spinors (sometimes just spinors).<sup>7</sup> Plane wave solutions are

$$\Psi(\mathbf{r}, t) = u(\mathbf{p})e^{i(\mathbf{p}\cdot\mathbf{r} - Et)}$$

where  $u(\mathbf{p})$  is also a four-component spinor satisfying the eigenvalue equation

$$(c\boldsymbol{\alpha} \cdot \mathbf{p} + \beta m) u(\mathbf{p}) = Eu(\mathbf{p}).$$

This equation has four solutions: two with positive energy  $E = +E_p$  and two with negative energy  $E = -E_p$ . We discuss later the interpretation of the negative energy solutions.

Dirac's equation was a success. First, it accounted "for free" for the existence of two spin states (we remind the reader that spin had to be inserted by hand in Schrödinger equation of nonrelativistic quantum mechanics). In addition, since spin is embedded in the equation, Dirac's equation:

- allows the correct computation of the energy splitting of atomic levels with the same quantum numbers due to the spin-orbit interaction in atoms (fine and hyper-fine splitting);
- explains the magnetic moment of point-like fermions.

The predictions of the values of the above quantities were incredibly precise and have passed every experimental test to date.

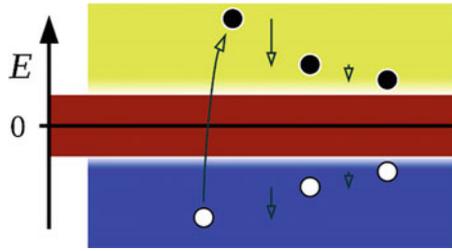
### 3.2.1.3 Hole Theory and the Positron

Negative energy states must be occupied: if they were not, transitions from positive to negative energy states would occur, and matter would be unstable. Dirac postulated that the negative energy states are completely filled under normal conditions. In the case of electrons, the Dirac picture of the vacuum is a "sea" of negative energy states, while the positive energy states are mostly free (Fig. 3.7). This condition cannot be distinguished from the usual vacuum.

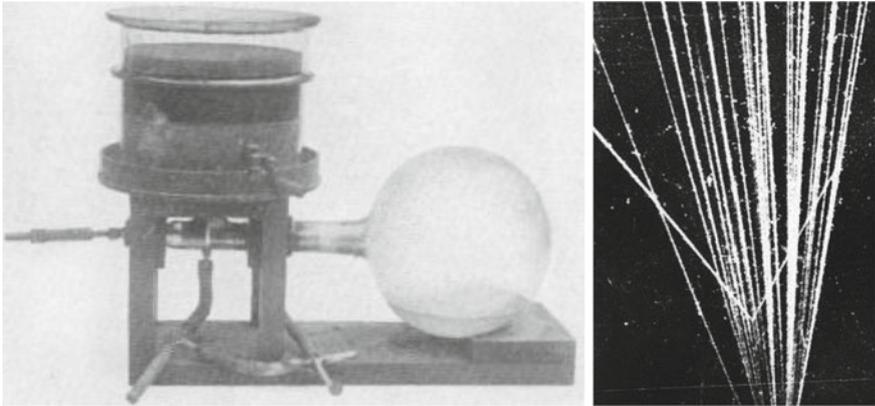
If an electron is added to the vacuum, it finds, in general, place in the positive energy region since all the negative energy states are occupied. If a negative energy electron is removed from the vacuum, however, a new phenomenon happens: removing such an electron with  $E < 0$ , momentum  $-\mathbf{p}$ , spin  $-\mathbf{S}$ , and charge  $-e$  leaves a "hole" indistinguishable from a particle with positive energy  $E > 0$ , momentum  $\mathbf{p}$ , spin  $\mathbf{S}$ , and charge  $+e$ . This is similar to the formation of holes in semiconductors. The two cases are equivalent descriptions of the same phenomena. Dirac's sea model

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<sup>7</sup>The term spinor indicates in general a vector which has definite transformation properties for a rotation in the proper angular momentum space—the spin space. The properties of rotation in spin space will be described in greater detail in Chap. 5.



**Fig. 3.7** Dirac picture of the vacuum. In normal conditions, the sea of negative energy states is totally occupied with two electrons in each level. By Incnis Mrsi [own work, public domain], via Wikimedia Commons



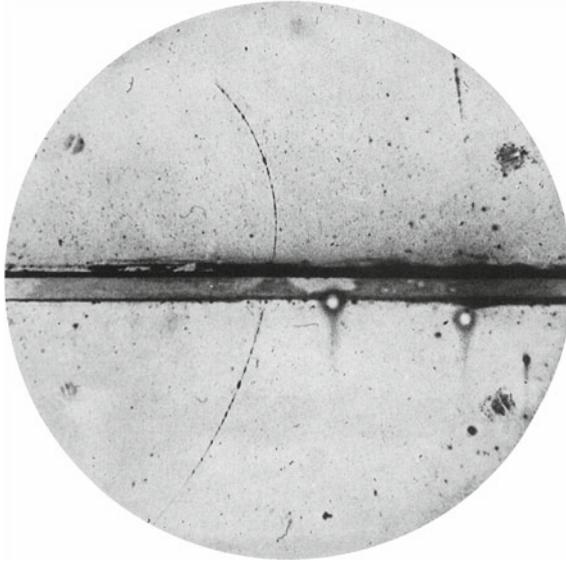
**Fig. 3.8** Left: A cloud chamber built by Wilson in 1911. By C.T.R. Wilson [public domain], via Wikimedia Commons. Right: a picture of a collision in a cloud chamber [CC BY 4.0 <http://creativecommons.org/licenses/by/4.0>] via Wikimedia Commons

thus predicts the existence of a new fermion with mass equal to the mass of the electron, but opposite charge. This particle, later called the positron, is the antiparticle of the electron and is the prototype of a new family of particles: antimatter.

### 3.2.2 *The Discovery of Antimatter*

During his doctoral thesis (supervised by Millikan), Anderson was studying the tracks of cosmic rays passing through a cloud chamber<sup>8</sup> in a magnetic field (Fig. 3.8).

<sup>8</sup>The cloud chamber (see also next chapter), invented by C.T.R. Wilson at the beginning of the twentieth century, was an instrument for reconstructing the trajectories of charged particles. The instrument is a container with a glass window, filled with air and saturated water vapor; the volume could be suddenly expanded, bringing the vapor to a supersaturated (metastable) state. A charged



**Fig. 3.9** The first picture by Anderson showing the passage of a cosmic antielectron, or positron, through a cloud chamber immersed in a magnetic field. One can understand that the particle comes from the bottom in the picture by the fact that, after passing through the sheet of material in the medium (and therefore losing energy), the radius of curvature decreases. The positive charge is inferred from the direction of bending in the magnetic field. The mass is measured by the bubble density (a proton would lose energy faster). Since most cosmic rays come from the top, the first evidence for antimatter comes thus from an unconventional event. From C.D. Anderson, "The Positive Electron," *Physical Review* 43 (1933) 491

In 1933 he discovered antimatter in the form of a positive particle of mass consistent with the electron mass, later called the positron (Fig. 3.9). Dirac's equation prediction was confirmed; this was a great achievement for cosmic ray physics. Anderson shared with Hess the Nobel Prize for Physics in 1936; they were nominated by Compton, with the following motivation:

The time has now arrived, it seems to me, when we can say that the so-called cosmic rays definitely have their origin at such remote distances from the Earth that they may properly be called cosmic and that the use of the rays has by now led to results of such importance that they may be considered a discovery of the first magnitude. [...] It is, I believe, correct to say that Hess was the first to establish the increase of the ionization observed in electroscopes with

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cosmic ray crossing the chamber produces ions, which act as seeds for the generation of droplets along the trajectory. One can record the trajectory by taking a photographic picture. If the chamber is immersed in a magnetic field, momentum and charge can be measured by the curvature. The working principle of bubble chambers is similar to that of the cloud chamber, but here the fluid is a liquid. Along the tracks' trajectories, a trail of gas bubbles condensates around the ions. Bubble and cloud chambers provide a complete information: the measurement of the bubble density and the range, i.e., the total track length before the particle eventually stops, provide an estimate for the energy and the mass; the angles of scattering provide an estimate for the momentum.

increasing altitude; and he was certainly the first to ascribe with confidence this increased ionization to radiation coming from outside the Earth.

Why so late a recognition to the discovery of cosmic rays? Compton writes:

Before it was appropriate to award the Nobel Prize for the discovery of these rays, it was necessary to await more positive evidence regarding their unique characteristics and importance in various fields of physics.

### ***3.2.3 Cosmic Rays and the Progress of Particle Physics***

After Anderson's fundamental discovery of antimatter, new experimental results in the physics of elementary particles with cosmic rays were guided and accompanied by the improvement of the tools for detection, in particular by the improved design of the cloud chambers and by the introduction of the Geiger–Müller tube. According to Giuseppe Occhialini, one of the pioneers of the exploration of fundamental physics with cosmic rays, the Geiger–Müller counter was like the Colt revolver in the Far West: a cheap instrument usable by everyone on one's way through a hard frontier.

At the end of the 1920s, Bothe and Kolhörster introduced the coincidence technique to study cosmic rays with the Geiger counter. A coincidence circuit activates the acquisition of data only when signals from predefined detectors are received within a given time window. The coincidence technique is widely used in particle physics experiments, but also in other areas of science and technology. Walther Bothe shared the Nobel Prize for Physics in 1954 “for the coincidence method and his discoveries made therewith.” Coupling a cloud chamber to a system of Geiger counters and using the coincidence technique, it was possible to take photographs only when a cosmic ray traversed the cloud chamber (we call today such a system a “trigger”). This increased the chances of getting a significant photograph and thus the efficiency of cloud chambers.

Soon after the discovery of the positron by Anderson, a new important observation was made in 1933: the conversion of photons into pairs of electrons and positrons. Dirac's theory not only predicted the existence of antielectrons, but it also predicted that electron–positron pairs could be created from a single photon with energy large enough; the phenomenon was actually observed in cosmic rays by Blackett (Nobel Prize for Physics in 1948) and Occhialini, who further improved in Cambridge the coincidence technique. Electron–positron pair production is a simple and direct confirmation of the mass–energy equivalence and thus of what is predicted by the theory of relativity. It also demonstrates the behavior of light, confirming the quantum concept which was originally expressed as “wave-particle duality”: the photon can behave as a particle.

In 1934, the Italian physicist Bruno Rossi<sup>9</sup> reported the observation of the quasi-simultaneous discharge of two widely separated Geiger counters during a test of his equipment. In the report, he wrote: “[...] it seems that once in a while the recording equipment is struck by very extensive showers of particles, which causes coincidences between the counters, even placed at large distances from one another.” In 1937 Pierre Auger, who was not aware of Rossi’s report, made a similar observation and investigated the phenomenon in detail. He concluded that extensive showers originate when high-energy primary cosmic rays interact with nuclei high in the atmosphere, leading to a series of interactions that ultimately yield a shower of particles that reach ground. This was the explanation of the spontaneous discharge of electroscopes due to cosmic rays.

### 3.2.4 *The $\mu$ Lepton and the $\pi$ Mesons*

In 1935 the Japanese physicist Yukawa, 28 years old at that time, formulated his innovative theory explaining the “strong” interaction ultimately keeping together matter (strong interaction keeps together protons and neutrons in the atomic nuclei). This theory has been sketched in the previous chapter and requires a “mediator” particle of intermediate mass between the electron and the proton, thus called meson—the word “meson” meaning “middle one.”

To account for the strong force, Yukawa predicted that the meson must have a mass of about one-tenth of a GeV, a mass that would explain the rapid weakening of the strong interaction with distance. The scientists studying cosmic rays started to discover new types of particles of intermediate masses. Anderson, who after the Nobel Prize had become a professor, and his student Neddermeyer observed in 1937 a new particle, present in both positive and negative charge, more penetrating than any other particle known at the time. The new particle was heavier than the electron but lighter than the proton, and they suggested for it the name “mesotron.” The mesotron mass, measured from ionization, was between 200 and 240 times the electron mass; this matched Yukawa’s prediction for the meson. Most researchers were convinced that these particles were the Yukawa’s carrier of the strong nuclear force, and that they

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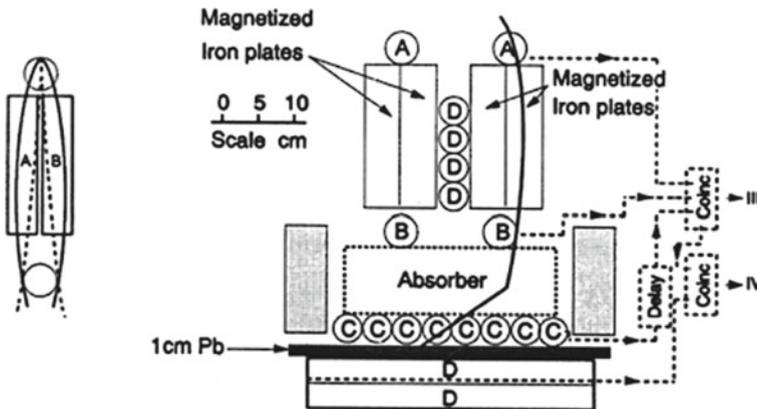
<sup>9</sup>Bruno Rossi (Venice 1905—Cambridge, MA, 1993) graduated from Bologna and then moved to Arcetri near Florence before becoming full professor of physics at the University of Padua in 1932. In Padua he was charged of overseeing the design and construction of the new Physics Institute, which was inaugurated in 1937. He was exiled in 1938, as a consequence of the Italian racial laws, and he moved to Chicago and then to Cornell. In 1943 he joined the Manhattan project in Los Alamos, working at the development of the atomic bomb, and after the end of the Second World War moved to MIT. At MIT Rossi started working on space missions as a scientific consultant for the newborn NASA, and proposed together with his former student Riccardo Giacconi, physics Nobel prize in 2002, the rocket experiment that discovered the first extra-solar source of X-rays. Many fundamental contributions to modern physics, for example the electronic coincidence circuit, the discovery and study of extensive air showers, the East–West effect, and the use of satellites for the exploration of the high-energy Universe, are due to Bruno Rossi.

were created when primary cosmic rays collided with nuclei in the upper atmosphere, in the same way that electrons emit photons when colliding with a nucleus.

The lifetime of the mesotron was measured studying its flow at various altitudes, in particular by Rossi in Colorado; the result was of about two microseconds (a hundred times larger than predicted by Yukawa for the particle that transmits the strong interaction). Rossi found also that at the end of its life the mesotron decays into an electron and other neutral particles (neutrinos) that did not leave tracks in bubble chambers—the positive mesotron decays into a positive electron plus neutrinos.

Beyond the initial excitement, however, the picture did not work. In particular, the Yukawa particle is the carrier of strong interactions, and therefore, it cannot be highly penetrating—the nuclei of the atmosphere would absorb it quickly. Many theorists tried to find complicated explanations to save the theory. The correct explanation was, however, the simplest one: the mesotron was not the Yukawa particle, as it was demonstrated in 1945/46 by three young Italian physicists, Conversi, Pancini, and Piccioni.

The experiment by Conversi, Pancini, and Piccioni exploits the fact that slow negative Yukawa particles can be captured by nuclei in a time shorter than the typical lifetime of the mesotron, about  $2\ \mu\text{s}$ , and thus are absorbed before decaying; conversely, slow positive particles are likely to be repelled by the potential barrier of nuclei and thus have the time to decay. The setup is shown in Fig. 3.10; a magnetic lens focuses particles of a given charge, thus allowing charge selection. The Geiger counters A and B are in coincidence—i.e., a simultaneous signal is required; the C counters under the absorber are in “delayed coincidence,” and it is requested that one of them fires after a time between 1 and  $4.5\ \mu\text{s}$  after the coincidence (AB). This guarantees that the particle selected is slow and, in case of decay, has a lifetime consistent with the mesotron. The result was that when carbon was used as an absorber,



**Fig. 3.10** Left: A magnetic lens (invented by Rossi in 1930). Right: Setup of the Conversi, Pancini, and Piccioni experiment. From M. Conversi, E. Pancini, O. Piccioni, “On the disintegration of negative mesons,” *Physical Review* 71 (1947) 209



**Fig. 3.11** The pion and the muon: the decay chain  $\pi \rightarrow \mu \rightarrow e$ . The pion travels from bottom to top on the left, the muon horizontally, and the electron from bottom to top on the right. The missing momentum is carried by neutrinos. From C.F. Powell, P.H. Fowler and D.H. Perkins, “The Study of Elementary Particles by the Photographic Method,” Pergamon Press 1959

a substantial fraction of the negative mesons decayed. The mesotron was not the Yukawa particle.

There were thus two particles of similar mass. One of them (with a mass of about  $140 \text{ MeV}/c^2$ ), corresponding to the particle predicted by Yukawa, was later called pion (or  $\pi$  meson); it was created in the interactions of cosmic protons with the atmosphere, and then interacted with the nuclei of the atmosphere, or decayed. Among its decay products there was the mesotron, since then called the muon (or  $\mu$  lepton), which was insensitive to the strong force.

In 1947, Powell, Occhialini, and Lattes, exposing nuclear emulsions (a kind of very sensitive photographic plates, with space resolutions of a few  $\mu\text{m}$ ; we shall discuss them in the next chapter) to cosmic rays on Mount Chacaltaya in Bolivia, finally proved the existence of charged pions, positive and negative, while observing their decay into muons and allowing a precise determination of the masses. For this discovery Cecil Powell, the group leader, was awarded the Nobel Prize in 1950.

Many photographs of nuclear emulsions, especially in experiments on balloons, clearly showed traces of pions decaying into muons (the muon mass was reported to be about  $106 \text{ MeV}/c^2$ ), decaying in turn into electrons. In the decay chain  $\pi \rightarrow \mu \rightarrow e$  (Fig. 3.11) some energy is clearly missing and can be attributed to neutrinos.

At this point, the distinction between pions and muons was clear. The muon looks like a “heavier brother” of the electron. After the discovery of the pion, the muon had no theoretical reason to exist (the physicist Isidor Rabi was attributed in the 1940s the famous quote: “Who ordered it?”). However, a new family was initiated: the family of leptons—including for the moment the electron and the muon and their antiparticles.

### 3.2.4.1 The Neutral Pion

Before it was even known that mesotrons were not the Yukawa particle, the theory of mesons was developed in great detail. In 1938, a theory of charge symmetry was formulated, conjecturing the fact that the forces between protons and neutrons, between protons and protons, and between neutrons and neutrons are similar. This implies the existence of positive, negative, and also neutral mesons.

The neutral pion was more difficult to detect than the charged one, due to the fact that neutral particles do not leave tracks in cloud chambers and nuclear emulsions—and also to the fact, discovered only later, that it lives only approximately  $10^{-16}$  s before decaying mostly into two photons. However, between 1947 and 1950, the neutral pion was identified in cosmic rays by analyzing its decay products in showers of particles. So, after 15 years of research, the theory of Yukawa had finally complete confirmation.

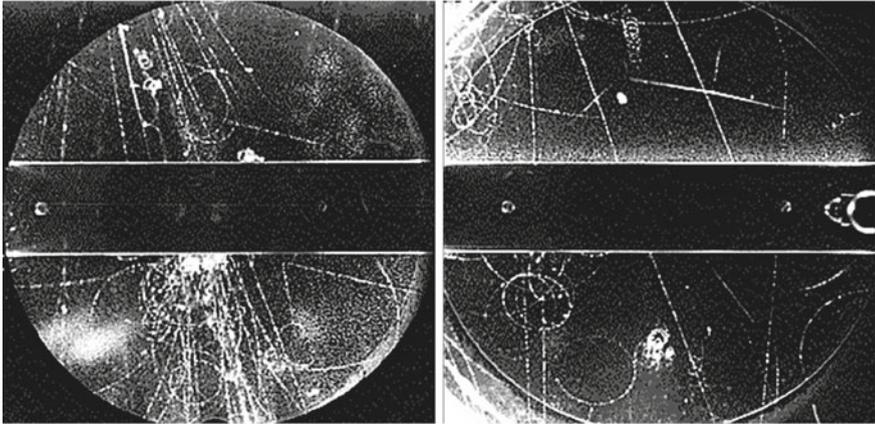
### 3.2.5 *Strange Particles*

In 1947, after the thorny problem of the meson had been solved, particle physics seemed to be a complete science. Thirteen particles were known to physicists (some of them at the time were only postulated and were going to be found experimentally later): the proton, the neutron (proton and neutron together belong to the family of baryons, the Greek etymology of the word referring to the concept of “heaviness”), and the electron, and their antiparticles; the neutrino that was postulated because of an apparent violation of the principle of energy conservation; three pions; two muons; and the photon.

Apart from the muon, a particle that appeared unnecessary, all the others seemed to have a role in nature: the electron and the nucleons constitute the atom, the photon carries the electromagnetic force, and the pion the strong force; neutrinos are needed for energy conservation. But, once more in the history of science, when everything seemed understood a new revolution was just around the corner.

Since 1944, strange topologies of cosmic particles were photographed from time to time in cloud chambers. In 1947, G.D. Rochester and the C.C. Butler from the University of Manchester observed clearly in a photograph a couple of tracks from a single point with the shape of a “V”; the two tracks were deflected in opposite directions by an external magnetic field. The analysis showed that the parent neutral particle had a mass of about half a GeV (intermediate between the mass of the proton and that of the pion) and disintegrated into a pair of oppositely charged pions. A broken track in a second photograph showed the decay of a charged particle of about the same mass into a charged pion and at least one neutral particle (Fig. 3.12).

These particles, which were produced only in high-energy interactions, were observed only every few hundred photographs. They are known today as *K* mesons (or kaons); kaons can be positive, negative, or neutral. A new family of particles had been discovered. The behavior of these particles was somehow strange: the cross section for their production could be understood in terms of strong interactions; however, their lifetime was inconsistent with strong interaction, being too long. These new particles were called “strange mesons.” Later analyses indicated the presence of particles heavier than protons and neutrons. They decayed with a “V” topology into final states including protons, and they were called strange baryons, or hyperons ( $\Lambda$ ,  $\Sigma$ , ...). Strange particles appear to be always produced in pairs, indicating the presence of a new conserved quantum number—thus called strangeness.



**Fig. 3.12** The first images of the decay of particles known today as  $K$  mesons or kaons—the first examples of “strange” particles. The image on the left shows the decay of a neutral kaon. Being neutral it leaves no track, but when it decays into two lighter charged particles (just below the central bar to the right), one can see a “V.” The picture on the right shows the decay of a charged kaon into a muon and a neutrino. The kaon reaches the top right corner of the chamber, and the decay occurs where the track seems to bend sharply to the left. From G.D. Rochester, C.C. Butler, “Evidence for the Existence of New Unstable Elementary Particles” *Nature* 160 (1947) 855

### 3.2.5.1 The $\tau$ - $\theta$ Puzzle

In the beginning, the discovery of strange mesons was made complicated by the so-called  $\tau$ - $\theta$  puzzle. A strange charged meson was disintegrating into two pions and was called the  $\theta$  meson; another particle called the  $\tau$  meson was disintegrating into three pions. Both particles disintegrated via the weak force and, apart from the decay mode, they turned out to be indistinguishable from each other, having identical masses within the experimental uncertainties. Were the two actually the same particle? It was concluded that they were (we are talking about the  $K$  meson); this opened a problem related to the so-called parity conservation law, and we will discuss it better in Chaps. 5 and 6.

## 3.2.6 Mountain-Top Laboratories

The discovery of mesons, which had put the physics world in turmoil after World War II, can be considered as the origin of the “modern” physics of elementary particles.

The following years showed a rapid development of the research groups dealing with cosmic rays, along with a progress of experimental techniques of detection, exploiting the complementarity of cloud and bubble chambers, nuclear emulsions,

and electronic coincidence circuits. The low cost of emulsions allowed the spread of nuclear experiments and the establishment of international collaborations.

It became clear that it was appropriate to equip laboratories on top of the mountains to study cosmic rays. Physicists from all around the world were involved in a scientific challenge of enormous magnitude, taking place in small laboratories on the tops of the Alps, the Andes, the Rocky Mountains, the Caucasus.

Particle physicists used cosmic rays as the primary tool for their research until the advent of particle accelerators in the 1950s, so that the pioneering results in this field are due to cosmic rays. For the first 30 years since their discovery, cosmic rays allowed physicists to gain information on the physics of elementary particles. With the advent of particle accelerators, in the years since 1950, most physicists went from hunting to farming.

### 3.3 Particle Hunters Become Farmers

In 1953, the Cosmic Ray Conference at Bagnères de Bigorre in the French Pyrenees was a turning point for high-energy physics. The technology of artificial accelerators was progressing, and many cosmic ray physicists were moving to this new frontier. CERN, the European Laboratory for Particle Physics, was soon to be founded.

Also from the sociological point of view, important changes were in progress, and large international collaborations were formed. Only 10 years earlier, articles for which the preparation of the experiment and the data analysis had been performed by many scientists were signed only by the group leader. But the recent G-stack experiment, an international collaboration in which cosmic ray interactions were recorded in a series of balloon flights by means of a giant stack of nuclear emulsions, had introduced a new policy: all scientists contributing to the result were authors of the publications. At that time the number of signatures in one of the G-stack papers, 35, seemed enormous; in the twenty-first-century things have further evolved, and the two articles announcing the discovery of the Higgs particle by the ATLAS and CMS collaborations have 2931 and 2899 signatures, respectively.

In the 1953 Cosmic Ray Conference contributions coming from accelerator physics were not accepted: the two methods of investigation of the nature of elementary particles were kept separated. However, the French physicist Leprince-Ringuet, who was going to found CERN in 1954 together with scientists of the level of Bohr, Heisenberg, Powell, Auger, Edoardo Amaldi, and others, said in his concluding remarks:

Let's point out first that in the future we must use particle accelerators. [...] They will allow the measurement of certain fundamental curves (scattering, ionization, range) which will permit us to differentiate effects such as the existence of  $\pi$  mesons among the secondaries of  $K$  mesons. [...]

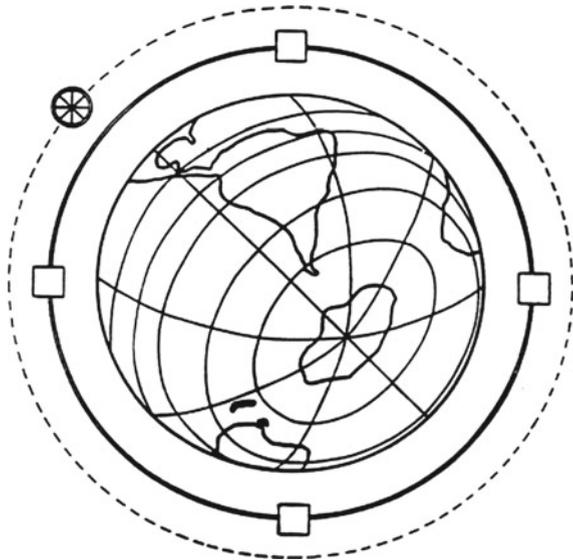
I would like to finish with some words on a subject that is dear to my heart and is equally so to all the 'cosmicians', in particular the 'old timers'. [...] We have to face the grave question: what is the future of cosmic rays? Should we continue to struggle for a few new results

or would it be better to turn to the machines? One can with no doubt say that the future of cosmic radiation in the domain of nuclear physics depends on the machines [...]. But probably this point of view should be tempered by the fact that we have the uniqueness of some phenomena, quite rare it is true, for which the energies are much larger.

It should be stressed that despite the great advances of the technology of accelerators, the highest energies will always be reached by cosmic rays. The founding fathers of CERN in their Constitution (Convention for the Establishment of a European Organization for Nuclear Research, 1953) explicitly stated that cosmic rays are one of the research items of the Laboratory.

A calculation made by Fermi about the maximum reasonably (and even *unreasonably*) achievable energy by terrestrial accelerators is interesting in this regard. In his speech “What can we learn from high-energy accelerators” held at the American Physical Society in 1954 Fermi had considered a proton accelerator with a ring as large as the maximum circumference of the Earth (Fig. 3.13) as the maximum possible accelerator. Assuming a magnetic field of 2 tesla (Fermi assumed that this was the maximum field attainable in stable conditions and for long magnets; the conjecture is still true unless new technologies will appear), it is possible to obtain a maximum energy of 5000 TeV: this is the energy of cosmic rays just under the “knee,” the typical energy of galactic accelerators. Fermi estimated with great optimism, extrapolating the rate of progress of the accelerator technology in the 1950s, that this accelerator could be constructed in 1994 and cost approximately 170 million dollars (the cost of LHC is some 50 times larger, and its energy is 700 times smaller).

**Fig. 3.13** The so-called maximum accelerator by Fermi (original drawing by Enrico Fermi reproduced from his 1954 speech at the annual meeting of the American Physical Society). Courtesy of Fermi National Laboratory, Batavia, Illinois



### 3.4 The Recent Years

Things went more or less as predicted by Leprince-Ringuet.

Between the 1950s and the 1990s most of the progress in fundamental physics was due to accelerating machines. Still, however, important experiments studying cosmic rays were alive and were an important source of knowledge.

Cosmic rays are today central in the field of astroparticle physics, which has grown considerably in the last 20 years. Many large projects are active, with many different goals, including, for example, the search for dark matter in the Universe.

Gamma-ray space telescopes on satellites like the *Fermi* Large Area Telescope (*Fermi*-LAT) and AGILE, and the PAMELA and AMS-02 magnetic spectrometers, provided cutting-edge results; PAMELA in particular observed a yet unexplained anomalous yield of cosmic positrons, with a ratio between positrons and electrons growing with energy, which might point to new physics, in particular related to dark matter. The result was confirmed and extended to higher energies and with unprecedented accuracy by the AMS-02 detector onboard the International Space Station.

The study of very highest energy cosmic ray showers, a century after the discovery of air showers by Rossi and Auger, is providing fundamental knowledge on the spectrum and sources of cosmic rays. In particular the region near the GZK cutoff is explored. The present-day largest detector, the Pierre Auger Observatory, covers a surface of about  $3000 \text{ km}^2$  in Argentina.

The ground-based very high-energy gamma telescopes HAWC, H.E.S.S., MAGIC, and VERITAS are mapping the cosmic sources of gamma rays in the TeV and multi-TeV region. Together with the *Fermi* satellite, they are providing indications of a link between the photon accelerators and the cosmic ray accelerators in the Milky Way, in particular supernova remnants. Studying the propagation of very energetic photons traveling through cosmological distances, they are also sensitive to possible violations of the Lorentz invariance at very high energy, and to photon interactions with the quantum vacuum, which in turn are sensitive to the existence of yet unknown fields. A new detector, CTA, is planned and will outperform the present detectors by at least an order of magnitude.

The field of study of cosmic neutrinos registered impressive results. In the analysis of the fluxes of solar neutrinos and then of atmospheric neutrinos, studies performed using large neutrino detectors in Japan, US, Canada, China, and Italy have demonstrated that neutrinos can oscillate between different flavors; this phenomenon requires that neutrinos have nonzero mass—present indications favor masses of the order of tenths of meV. Recently the IceCube South Pole Neutrino Observatory, a  $\text{km}^3$  detector buried in the ice of Antarctica, has discovered the first solid evidence for astrophysical neutrinos from cosmic accelerators (some with energies greater than 1 PeV). With IceCube, some ten astrophysical neutrinos per year (with a  $\sim 20\%$  background) have been detected in the last 5 years; they do not appear within the present statistics to cluster around a particular astrophysical source.

Finally, a handful of gravitational wave events have been detected in very recent years. In 2015, the LIGO/Virgo project directly detected gravitational waves using laser interferometers. The LIGO detectors observed gravitational waves from the merger of two stellar-mass black holes, matching predictions of general relativity. These observations demonstrated the existence of binary stellar-mass black hole systems and were the first direct detection of gravitational waves and the first observation of a binary black hole merger. Together with the detection of astrophysical neutrinos, the observations of gravitational waves paved the way for multimessenger astrophysics: combining the information obtained from the detection of photons, neutrinos, charged particles, and gravitational waves can shed light on completely new phenomena and objects.

Cosmic rays and cosmological sources are thus again in the focus of very high-energy particle and gravitational physics. This will be discussed in greater detail in Chap. 10.

### Further Reading

- [F3.1] P. Carlson, A. de Angelis, “Nationalism and internationalism in science: the case of the discovery of cosmic rays”, *The European Physical Journal H* 35 (2010) 309.
- [F3.2] A. de Angelis, “Atmospheric ionization and cosmic rays: studies and measurements before 1912”, *Astroparticle Physics* 53 (2014) 19.
- [F3.3] D.H. Griffiths, “Introduction to Quantum Mechanics, 2nd edition,” Addison-Wesley, Reading, MA, 2004.
- [F3.4] J. Björken and S. Drell, “Relativistic Quantum Fields,” McGraw-Hill, New York, 1969.

### Exercises

1. *The measurement by Hess.* Discuss why radioactivity decreases with elevation up to some 1000 m and then increases. Can you make a model? This was the subject of the thesis by Schrödinger in Wien in the beginning of twentieth century.
2. *Klein–Gordon equation.* Show that in the nonrelativistic limit  $E \simeq mc^2$  the positive energy solutions  $\Psi$  of the Klein–Gordon equation can be written in the form

$$\Psi(\mathbf{r}, t) \simeq \Phi(\mathbf{r}, t)e^{-\frac{mc^2}{\hbar}t},$$

where  $\Phi$  satisfies the Schrödinger equation.

3. *Antimatter.* The total number of nucleons minus the total number of antinucleons is believed to be constant in a reaction—you can create nucleon–antinucleon pairs. What is the minimum energy of a proton hitting a proton at rest to generate an antiproton?
4. *Fermi maximum accelerator.* According to Enrico Fermi, the ultimate human accelerator, the “Globatron,” would be built around 1994 encircling the entire Earth and attaining an energy of around 5000 TeV (with an estimated cost of 170 million US dollars at 1954 prices.). Discuss the parameters of such an accelerator.

5. *Cosmic pions and muons.* Pions and muons are produced in the high atmosphere, at a height of some 10km above sea level, as a result of hadronic interactions from the collisions of cosmic rays with atmospheric nuclei. Compute the energy at which charged pions and muons, respectively, must be produced to reach on average the Earth's surface.  
You can find the masses of the lifetimes of pions and muons in Appendix D or in your Particle Data Booklet.
6. *Very high-energy cosmic rays.* Justify the sentence "About once per minute, a single subatomic particle enters the Earth's atmosphere with an energy larger than 10 J" in Chap. 1.
7. *Very-high-energy neutrinos.* The IceCube experiment in the South Pole can detect neutrinos crossing the Earth from the North Pole. If the cross section for neutrino interaction on a nucleon is  $(6.7 \times 10^{-39} E) \text{ cm}^2$  with  $E$  expressed in GeV (note the linear increase with the neutrino energy  $E$ ), what is the energy at which half of the neutrinos interact before reaching the detector? Comment on the result.
8. If a  $\pi^0$  from a cosmic shower has an energy of 2 GeV:
- Assuming the two  $\gamma$  rays coming from its decay are emitted in the direction of the pion's velocity, how much energy does each have?
  - What are their wavelengths and frequencies?
  - How far will the average neutral pion travel, in the laboratory frame, from its creation to its decay? Comment on the difficulty to measure the pion lifetime.