Chapter 2
From the Discovery of Radioactivity to the First Accelerator Experiments

Michael Walter

2.1 Introduction

The article reviews the historical phases of cosmic ray research from the very beginning around 1900 until the 1940s, when the first particle accelerators replaced cosmic particles as a source for elementary particle interactions. Contrary to the discovery of X-rays or the ionising α-, β- and γ-rays, it was an arduous path to the definite acceptance of the new radiation. The development in the years before the discovery is described in Sect. 2.2. The following section deals with the work of Victor F. Hess, especially with the detection of extraterrestrial radiation in 1912 and the years until the final acceptance by the scientific community. In Sect. 2.4 the study of the properties of cosmic rays is discussed. Innovative detectors and methods like the cloud chamber, the Geiger–Müller counter and the coincidence circuit brought new stimuli. The origin of cosmic rays was and is still an unsolved question. The different hypotheses of the early time are summarised in Sect. 2.5. In the 1930s a scientific success story started which nobody of the first protagonists might have imagined. The discovery of the positron by C.D. Anderson was the birth of elementary particle physics. The 15 years until a new era started in 1947 with first accelerator experiments at the Berkeley synchro-cyclotron are described in Sect. 2.6.

It is obvious that this article can only cover the main steps of the historical development. An excellent description of the research on the "Höhenstrahlung" in the years between 1900 and 1936 was given by Miehlnickel (1938). Two other volumes are also recommended: Brown and Hoddeson (1983) and Sekido and Elliot (1985). Both summarise the personal views of the protagonists or their coworkers of the early time.

M. Walter (✉)
DESY, Platanenallee 6, 15738 Zeuthen, Germany
e-mail: michael.walter@desy.de

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2.2 The Way to the Discovery of Cosmic Rays

The technical revolution in the 19th century was related with an explosion-like development, especially in physics and chemistry. On the other hand, many scientists had the impression that all essential discoveries in physics were done. Phillipp von Jolly, a physics professor in Munich, gave Max Planck 1874 the advice not to study physics, since this science had mainly been completed. It would be interesting to speculate what would have happened with physics if Max Planck and all the other young talents would have followed such an advice. Fortunately, they did not. With the discovery of X-rays by Wilhelm Conrad Röntgen , of radioactivity by Henri Becquerel and with the foundation of quantum physics by Planck, the existing building was shaken and it got a completely new fundament with many new floors. Even now, more than 100 years later, the whole building is still under construction.

2.2.1 Conductivity of Air

In general it was assumed that dry air is a good isolator. Then, in 1785, Charles Augustin de Coulomb observed that a very well isolated electrically charged conductor loses its charge with time. Coulomb's hypothesis was that the charge is taken away from the conductor by the contact of dust and other particles contained in the air. But this explanation was not generally accepted and for more than 100 years there was no clear answer to the question why air becomes conductive.

2.2.2 Cathode Rays, X-Rays and Radioactivity

In 1857 the electrical discharge tube was developed by Heinrich Geißler. It consisted of a glass cylinder with two electrodes inside at both ends. Filled with gases like air, neon or argon at low pressure, and operated at a high voltage of several kilovolts, the tube showed a plasma glow. These effects were first used for entertainment demonstrations, but this discharge tube was finally the basis for the development of cathode, X-ray and neon tubes. William Crookes operated in 1869 a tube at lower gas pressure and found that cathode rays are produced at the negative electrode. At the other end of the tube, close to the positive charged anode, they hit the glass wall where fluorescence light was emitted. Like many others, also W.C. Röntgen investigated the properties of cathode rays using a tube provided by Phillip Lenard. In the end of 1895, he observed an energetic radiation penetrating a black cardboard covering accidentally the tube. With the picture of his wife's hand skeleton the discovery of X-rays reached worldwide publicity within a few weeks. The new radiation and the photographic imaging were a breakthrough for new developments in physics and a revolution in medical diagnostics.

Only two months later H. Becquerel discovered also by chance a new penetrating radiation in uranium minerals. Inspired by Röntgen's discovery, he continued in

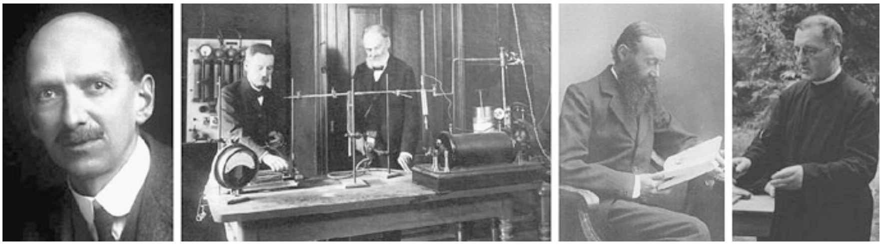

Fig. 2.1 C.R.T. Wilson, J. Elster and H. Geitel, A. Gockel and Th. Wulf

February 1896 his studies on phosphorescence and fluorescence minerals, looking for possible X-ray emissions. Since phosphorescence is initiated by sun light, he wrapped photographic plates in black paper and put it with different minerals on top in the sun. Only the uranium mineral showed an image of its contours on the exposed photography. As he wanted to repeat this experiment, there was a cloudy sky in Paris. Becquerel placed the probe in a drawer and decided a few days later to develop the plate. To his surprise also this probe showed the contours of the uranium mineral which ruled out the working hypothesis of sun light-induced X-ray emission. The only explanation was that uranium emits a new invisible penetrating radiation. In contrast to X-rays, this discovery was not recognised immediately.

Marie Curie started her doctoral thesis in Paris at the end of 1897, investigating the properties of the Becquerel radiation. She studied different minerals and salts containing uranium with an electrometer developed by her husband. With the electrometer, the first device to detect intensities, it was possible to measure the conductivity of air caused by the ionising radiation with high accuracy. Marie and Pierre Curie found with thorium, radium and polonium new elements with higher radiation intensities than uranium. In the presentation of these results she introduced the term ‘radioactivity’ in 1898 for the first time.

Another important discovery was made by Joseph John Thomson in 1897. He showed that cathode rays consist of electrons. Then, investigating the properties of ionising radiation, Ernest Rutherford and others verified that the radiation consists of three different components: α-, β- and γ-rays. The fundament for the development of atom and nuclear physics was settled and, no surprise, all of these protagonists were under the first Nobel prize winners.

2.2.3 Penetrating Radiation

A new effect was discovered when gases were irradiated with α-, β- and γ-rays: ionisation. The radiation is energetic enough to dissociate atoms and molecules into positively and negatively charged ions, as it was assumed before the atomic structure was known. These ions allow the transport of electricity and make gases conductive.

It was the Scottish physicist Charles Thomson Rees Wilson (Fig. 2.1) who found in 1896 that the formation of clouds and fog is connected with the ionisation of air

Table 2.1 Absorption coefficients of γ-rays for different substances and the necessary absorber thickness to reduce the ionisation by a factor of two (Eve, 1906) (It should be emphasised that at this time measured or calculated values were given without errors)

Substance	Density, $g\,cm^{-1}$	Absorption Coeff. λ, cm^{-1}	Absorber Thickness d, cm (for 50 % reduction)
Lead	11.6	0.5	1.4
Earth	2.7	0.092	7.5
Water	1.0	0.034	20.4
Air	0.0013	0.000044	15 700

molecules. But the work on this topic was continued almost 15 years later, when he developed a cloud chamber which visualised α- and β-rays. At first he investigated the ionisation of gases using an electrometer, the standard detector at this time. It consisted of two thin gold leafs mounted on a metal rod enclosed in a metallic vessel. Charging the rod, the gold leafs move away from each other, because of the equal charge. The distance is then a measure of the amount of charge. In a publication in 1900 (Wilson, 1900), Wilson gave an explanation for the conductivity of air in an isolated vessel. The reason that a charged metallic conductor loses its charge in an isolated chamber filled with air is that there are small quantities of radioactive substances. These can be pollutions embedded in the chamber walls and in the surrounding environment. At the same time, Julius Elster and Hans Geitel (Fig. 2.1), two friends and physics teachers at a German school in Wolfenbüttel came to the same conclusion (Geitel, 1900; Elster and Geitel, 1901). In our days forgotten, both were in the time from 1880 to 1920 with about 200 common publications internationally accepted authorities in the fields of electricity in the atmosphere, photo effect and radioactivity (Fricke, 1992). Several times Elster and Geitel were nominated for the Nobel prize. They did not accept an offer of a professorship at the university but preferred independence with school teaching and working in their private laboratory.

The group around Ernest Rutherford at McGill University in Canada went in 1903 a step further. An electroscope was shielded with different materials, like water and lead, to measure the ionisation in dependence on the absorber thickness. A decrease by about a factor of three was observed, but then the ionisation remained constant. There is obviously radiation of high penetration power, which: "… may have its origin in the radioactive matter which is distributed throughout the earth and atmosphere" (Cooke, 1903). Several authors assumed then that the penetrating radiation is γ-rays coming from radium in the earth crust and from radium emanations in the atmosphere. With their own measurements and results of others, A.S. Eve estimated the absorption coefficients λ of γ-rays for different substances given in Table 2.1 (Eve, 1906). The dependence of the ionisation I on the distance d to the γ-ray source is described by $I = I_o \cdot e^{-\lambda d}$. Interesting for later discussions is that 99 % of the γ-rays from radium emanations will be absorbed by 1 000 m atmosphere.

Wilson in Scottland, Elster and Geitel in Germany were probably the first who investigated radioactivity in the environment outside of laboratories. They performed

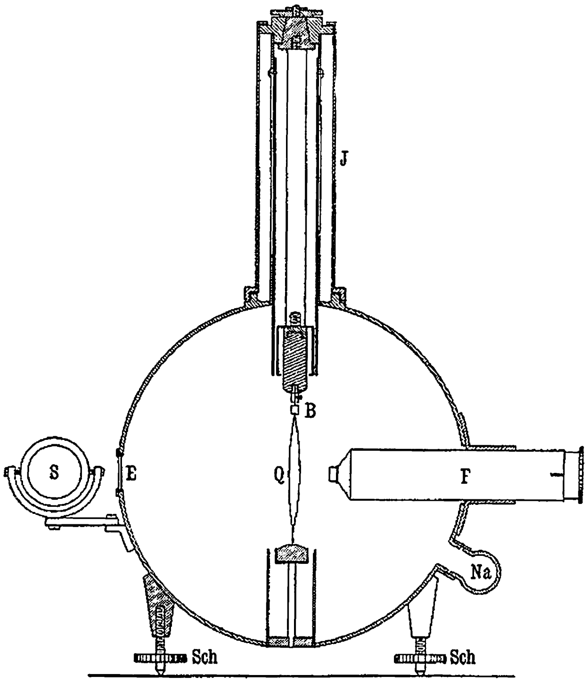

Fig. 2.2 The two-string electroscope developed by Th. Wulf. The ionisation vessel has a volume of 2.7 liter. Q: quartz fibres, B: amber for electrical isolation, J: container for the metallic rod to charge the fibres, F: microscope to measure the fibre distance, S: mirror, E: windows, Na: natrium container to dry the air

measurements in a railway tunnel (Wilson) and in caves, and salt mines (Elster and Geitel). A comparison with the ionisation measured outside in free nature showed different results. Volcanic rock contains in general a higher fraction of radioactive substances than sediment stones. Radioactive pollution is much smaller in rock salt mines and in water.

A new measurement quality was reached by Theodor Wulf (Fig. 2.1), a German Jesuit priest, who studied physics in Innsbruck and Göttingen. As physics lecturer at the Jesuit University Valkenburg in The Netherlands he investigated from 1905 to 1914 the electricity of the atmosphere and radioactivity. Wulf developed a robust, transportable electrometer which became for many years the state of the art instrument. The gold leafs were replaced by two metallised quartz strings. Figure 2.2 shows a schematic view of this two-string electrometer. It was produced by the company Günther & Tegetmeyer in Braunschweig/Germany (Fricke, 2011), as were many of its worldwide distributed succeeding models. In autumn 1908 Wulf performed absorption measurements of γ-radiation in the area of Valkenburg and concluded (Wulf, 1909a):

> Then particularly observations in balloons and with kite flights could give very valuable information whether the starting point of this radiation is the earth, or the atmosphere, or the stars.

One can only speculate why Wulf himself did not explore the atmosphere with a balloon. But he was focused first of all on detailed investigations inside and outside of buildings and caves, in mines up to 980 m below ground, on lakes and the river

Maas above and below the surface. From these ionisation measurements he came to the following summary (Wulf, 1909b):

> Experiments are presented which demonstrate that the penetrating radiation at the place of observation is caused by primary radioactive substances which are located in the upper Earth's layers, up to 1 m below the surface. If a part of the radiation comes from the atmosphere, then it is so small that it is not detectable with the used methods. The time variations of the γ-radiation can be explained by the shift of emanation-rich air masses in the Earth in larger or smaller depths due to variations of the air pressure.

To prove this hypothesis he did at least a small step into the atmosphere. Wulf followed an invitation to perform measurements on top of the Eiffel tower on four days in April 1910. Assuming that the main part of γ-radiation comes from the area near to the ground, one would expect a reduction of ionisation at 300 m height by 27 % (see Table 2.2). In fact, Wulf measured a decrease of ionisation by 13 % compared to the ground (Wulf, 1910). This significant difference was in clear disagreement with his previous assumption that radioactive emanations in the atmosphere are negligible.

In Italy Domenico Pacini, a physicist at the Agency of Meteorology and Geodynamics, confirmed this result. Using electrometers of the Wulf-type, he performed measurements in 1910 and 1911 (Pacini, 1910, 1912) on board of a destroyer of the Italian Navy at more than 300 m distance from the coast, where the water was at least 4 m deep. Assuming that there is no influence of radiation from the Earth's solid ground, he estimated on the sea a fraction of 66 % of the ionisation measured in parallel on land. At the same time George Simpson, an English meteorologist, and Charles Wright, a Canadian physicist, investigated the 'atmospheric electricity over the ocean' (Simpson and Wright, 1911) on the way from England to New Zealand. Both were scientific members of Robert Scott's crew travelling in 1910 on board the 'Terra Nova' to Antarctica. They measured the ionisation also with a Wulf electroscope made by Günther & Tegetmeyer. Whereas Pacini's data showed strong fluctuations on land and on sea, Simpson and Wright measured in average 6–7 ions cm^{-3} s^{-1} over the sea without variations during a day. They stated (Simpson and Wright, 1911):

> ... it was seen that near land a high radioactive-content of the air almost synchronised with a high natural ionisation. That this high ionisation is due to radioactive products deposited on the ship itself is highly probable from the fact that the ionisation persists for some time after the high air radioactivity had disappeared.

At the end of the 19th century balloon flights were very popular for military and scientific purposes. Especially meteorologists and geophysicists used balloons to study weather conditions, the electrical earth field and the electricity of the atmosphere at high altitudes. Probably Elster and Geitel were the first to suggest to use a balloon for ionisation measurements in the higher atmosphere. It was apparently forgotten or ignored that already between 1902 and 1903 the German meteorologist Franz Linke performed 12 balloon flights with interesting results (Linke, 1904). Starting in Berlin he reached altitudes up to 5 500 m and measured the electrical field of the Earth and the ionisation in the atmosphere. There was an agreement that

Table 2.2 Ionisation measurements in the atmosphere at different altitudes. The measured values can be compared with the assumption that the radiation is concentrated close to the ground and is absorbed by the air corresponding to the exponential dependence on the distance (Wulf, 1910; Gockel, 1910)

Scientist	Location	Date	Position	Measured ions, $cm^{-3}\,s^{-1}$	Expected ions, $cm^{-3}\,s^{-1}$
Th. Wulf	Eiffel Tower	29.03.1910	Ground	17.5	
		30.03.1910	300 m	16.2	4.7
		31.03.1910	300 m	14.4	
		01.04.1910	300 m	15.0	
		02.04.1910	300 m	17.2	
		03.04.1910	Ground	18.3	
A. Gockel	Zürich	11.12.1909	Ground	23.8	
			2 500 m	16.2	4×10^{-4}
			4 000–4 500 m	15.8	2×10^{-7}
	Bern	15.10.1910	Ground	11.4	
			2 000–2 800 m	7–9	3×10^{-4}
	Bern	02.04.1911	Ground	14.7	
			1 900 m	14	3×10^{-3}
			2 500 m	11.3	3×10^{-4}

Elster and Geitel measured the ionisation in Wolfenbüttel at the same time for comparison. Linke observed at altitudes between 1 and 3 km about the same ionisation values as at ground and an increase by a factor of four at higher altitudes up to 5 km. Obviously, the existence of penetrating radiation in the higher atmosphere was detected too early to be recognised and appreciated by the physics community. A new series of balloon flights began in 1908 with Flemming and Bergwitz. Because of problems with their detectors, they did not achieve convincing results. In the end of 1909 Albert Gockel (Fig. 2.1) started the first of three balloon flights in Switzerland. With a Wulf electrometer he could establish previous observations that the ionisation of the atmosphere decreases slowly with altitude (Gockel, 1910). In Table 2.2 the results of Wulf and Gockel are summarised.

2.3 Discovery of Cosmic Rays by Victor F. Hess

V. F. Hess studied physics in Graz/Austria. From 1906 until 1910 he worked at University of Vienna under Franz Exner and Egon von Schweidler, both experts for electrical phenomena in the atmosphere. In 1910 the Institute for Radium Research of the Academy of Sciences was founded and Hess became the assistant of the first director, Stefan Meyer. The institute was for many years embedded in the international research of radioactivity and provided other institutes with gauged radioactive sources.

2.3.1 Calibration and Absorption Measurements

Inspired by the work of Wulf, Bergwitz and Gockel, Hess started with own measurements. First, he wanted to prove experimentally the absorption of γ-rays in air. With the strongest radium sources available in the institute Hess investigated the range of γ-rays at different distances to the detector (Hess, 1911, p. 999): "The sources were positioned at distances of 10, 20, 30, ... up to 90 m from the electrometer and then the saturation current was estimated as mean value of 5–10 single measurements." With an absorption coefficient for air of $\lambda = 0.0000447$, Hess confirmed the results of previous estimates of Eve and others and concluded (p. 1 000): "... that the penetrating radiation of the Earth must decrease rapidly with the altitude and at 500 m only few percent would be expected of the values on the ground." As Hess mentioned in the publication (Hess, 1913), Wulf proposed to him in winter 1911/1912 to calibrate two-string electrometers with different gauge radium sources. After some improvements of the electrometer construction carried out by the company Günther & Tegetmeyer, Hess performed the calibration with radioactive sources of different strengths. The accuracy to measure the radioactivity of a source with unknown strength could be improved to few per mille (Hess, 1913). In contrast, the same electrometer reached without this calibration a measurement accuracy of about 3 %.

2.3.2 Balloon Flights

In 1911 Hess planned balloon flights to repeat the investigations of penetrating radiation in the atmosphere. The Royal Imperial Austrian Aeronautical Club provided a balloon for two flights. Already with the first flight he confirmed the results of Gockel (Hess, 1911). The ionisation remained almost constant up to the maximum height of 1 000 m. The second flight in October 1911 was during the night. In general stable thermic conditions guarantee quiet flights at constant altitude, but in this case bad weather conditions did not allow to fly higher than 200–400 m above ground. Nevertheless, the observation of the identical ionisation at day and night became an important argument for later discussions.

That the Imperial Academy of Sciences in Vienna funded seven balloon flights in 1912 shows the high ranking of this research in Austria. To avoid the problems of Bergwitz and Goppel at higher altitudes, Hess had ordered at Günther & Tegetmeyer two pressure-sealed electrometers for γ-rays and a third one with thin zinc walls for β-rays. Six flights were launched from the area of the Aeronautical Club in Vienna's Prater. The balloons were filled with illuminating gas which did not allow one to reach very high altitudes. In Table 2.3 the characteristic data of these flights are summarised, and Fig. 2.3 shows the flight routes.

The results of the six flights at relatively low altitudes can be summarised as follows (Hess, 1912):

(i) All three electrometers showed identical variations with time and altitude.

Table 2.3 Seven balloon flights of V.F. Hess in 1912 (Hess, 1912)

Flight	Date	Time	Height above ground, m	Ions($\gamma - 1$), $cm^{-3}\,s^{-1}$	Ions($\gamma - 2$), $cm^{-3}\,s^{-1}$	Ions(β-rays), $cm^{-3}\,s^{-1}$
1	17.4.1912	08:30–09:30	0	14.4	10.7	
		11:00–12:15	1 700	13.7	11.1	
		12:15–12:50	1 700–2 100	27.3	14.4	
		12:50–13:30	1 100		15.1	
2	26.–27.4.1912	16:00–22:30	0	17.0	11.6	20.2
		23:00–09:35	140–190	14.9	9.8	18.2
		06:35–09:35	800–1 600	17.6	10.5	20.8
3	20.–21.5.1912	17:00–21:30	0	16.9	11.4	19.8
		22:30–02:30	150–340	16.9	11.1	19.2
		02:30–04:30	∼500	14.7	9.6	17.6
4	03.–04.5.1912	17:10–20:40	0	15.8	11.7	21.3
		22:30–00:30	800–1 100	15.5	11.2	21.8
5	19.6.1912	15:00–17:00	0	13.4		
		17:30–18:40	850–950	10.3		
6	28.–29.6.1912	20:10–23:10	0	15.5	12.2	
		00:40–05:40	90–360	14.9	11.4	
7	7.8.1912	06:45–07:45	1 400	15.8	14.4	25.3
		07:45–08:45	2 500	17.3	12.3	31.2
		08:45–09:45	3 600	19.8	16.5	35.2
		09:45–10:45	4 400–5 350	40.7	31.8	
		10:45–11:15	4 200	28.1	22.7	
		11:15–11:45	1 200	9.7	11.5	
		11:45–12:10	150	11.9	10.7	
		12:25–13:12	0	15.0	11.6	

(ii) The ionisation rate is not connected with Sun activities.
(iii) The observation of Wulf, Bergwitz and Goppel that the rate does not decrease significantly with distance to the Earth was established with high confidence.

But the main goal of Hess was the study of the ionisation rate at very high altitudes. With a hydrogen filled balloon provided by the German Aeroclub in Bohemia, he started in the morning of 7 August 1912 in Aussig (now Usti nad Labem, Czech Republic, close to the German border) together with the balloon pilot captain W. Hoffory and the meteorological observer E. Wolf. The maximum height of 5 350 m above ground was reached in the south of Brandenburg. The balloon landed in Bad Saarow/Pieskow, about 60 km south-east of Berlin. Figure 2.4 shows

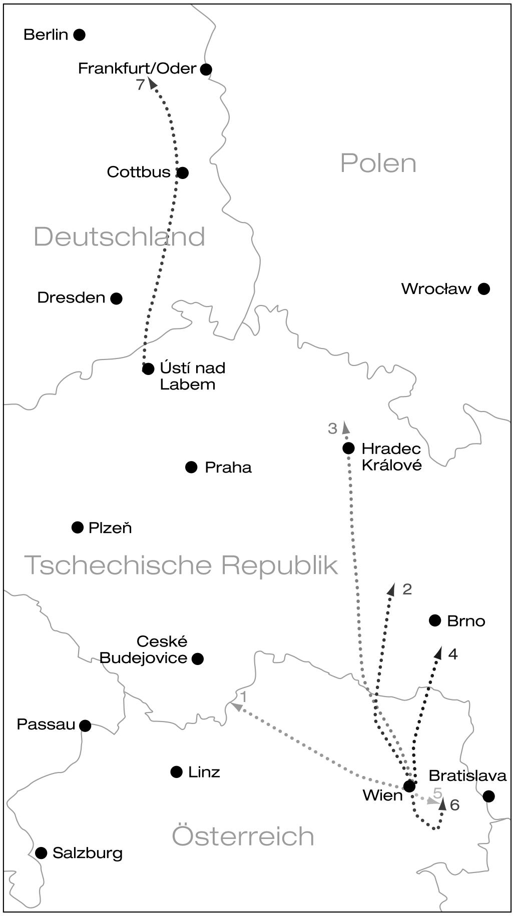

Fig. 2.3 Routes of the seven balloon flights of V.F. Hess in 1912

the mean values of the observed ionisation for all three detectors. Unfortunately, the β-ray detector was damaged accidentally by Hess before the maximum height was reached. But between 500 and 3 000 m a continuous increase of ionisation was measured. Both γ-detectors registered an increase of ionisation by a factor four from 3 000 to 5 200 m. Summarising the results of the seven flights, Hess came to the following conclusion (Hess, 1912):

> The results of these observations seem to be explained by the assumption that a radiation of high penetration power hits our atmosphere from top, which causes also in their lower layers a fraction of the observed ionisation in the closed detectors. The intensity seems to underly variations which are visible in time intervals of one hour. Since I did not find a decrease of radiation during the night or during the sun eclipse, the sun cannot be the reason for this hypothetical radiation, at least if one assumes a direct γ-radiation with straight-line propagation.

The discovery of cosmic rays can be seen as a step-wise approach. First indications seen by Wulf, Bergwitz, Goppel and Pacini were convincingly established

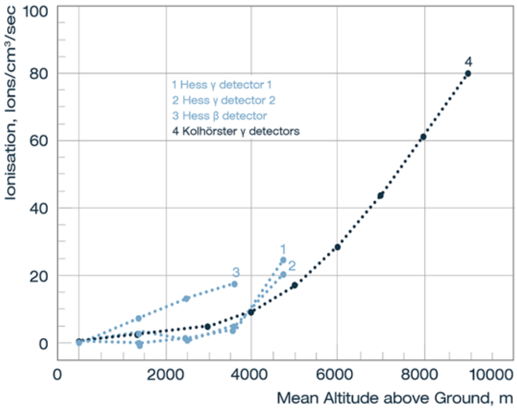

Fig. 2.4 The number of ions measured with the three detectors (*1–3*) at the seventh high altitude flight of Hess (1912) and for the flight of W. Kolhörster up to 9 300 m altitude (*4*). The results of Kolhörster are the mean values of the results of his two γ-ray detectors (Kolhörster, 1914). For all values the ionisation measured at the surface of the Earth is subtracted

by the measurements of Hess. The essential step was the detection of the strong increase of penetrating radiation with growing altitude. Since γ-rays have the largest penetration power of the three known ionising radiations, it was natural to assume that also cosmic rays consist of energetic γ-rays.

2.3.3 Confirmation of the 'Höhenstrahlung'

The discovery of the 'Höhenstrahlung' remained almost unnoticed. Probably nobody of the small number of scientists working in this field was sure that the measurements were correct. And even if there would have been no doubt, contrary to the discovery of X-rays, the possible consequences of the existence of extraterrestrial radiation were unknown. Therefore, it was necessary to establish the existence of the new radiation independently by other measurements.

Werner Kolhörster did this next step as an assistant in the Physics Institute of the University Halle in Germany. He had written his doctoral thesis about the radioactivity of mineral water coming from Karlovy Vary, the famous spa town in the western part of the Czech Republic. So, he was familiar with the problems of measuring small quantities of radioactivity. He knew the activities and publications of Hess and all others working on the penetrating radiation. Supported by the Aero-Physical Research Fund of Halle, Kolhörster could perform several balloon flights. First, he also improved the detector performance with help of the company Günther & Tegetmeyer (Fricke, 2011). Especially the measurement at very high altitude required good temperature and pressure stability of the electrometer corpus. Three flights in summer 1913, where altitudes up to 6 300 m were reached, showed the same behaviour of the ionisation rate (Kolhörster, 1913) as measured before by Hess. A new flight at 28 June 1914 demonstrated then, as stated by Kolhörster 'undoubtedly' (Kolhörster, 1914), the existence of radiation of cosmic origin. At an altitude of 9 300 m he measured an ionisation of 80 ions $cm^{-3}\,s^{-1}$. Figure 2.4 shows the ionisation in dependence of altitude for both, the measurements of Hess and of Kolhörster.

2.3.4 Doubts and Rediscovery

The World War I stopped most activities. Long-term measurements of Gockel and Hess in the Alps confirmed the balloon results for 2 500–3 500 m altitudes (Gockel, 1915; Hess, 1917). This was not important as regards corroborating the balloon results, but was convincing enough to think about research stations on high mountains. There was a group of physicists who had serious doubts that a new radiation of cosmic origin was discovered. Their main arguments ranged from a possible radiation in the upper atmosphere to measurement problems due to insulation leaks caused by the low temperatures at high altitudes.

A problematic role in these scientific debates played Robert A. Millikan at the California Institute of Technology. He received the Nobel Prize in 1923 for the measurement of the elementary charge of the electron, although his data analysis was challenged by experts. As director of the Norman Bridge Lab for Physics he started a cosmic ray research program. First results were presented by Russel M. Otis in 1923. He has measured the ionisation with a Kolhörster-like electrometer in balloons and airplanes up to 5 300 m altitude. A similar dependence was observed as before in Europe, although with a smaller increase. Another approach was tried by Millikan and Bowen, who used a simple and light electrometer with automated data recording. Their goal was to overcome the magic 10 000 m border with low-cost, unmanned sounding balloons. Two of four ascents in 1921 were successful and reached 11 200 and 15 500 m. But with the detector only one averaged ionisation value of 46.2 ions per cm^2 per second was measured above 5 500 m. This was about a factor three larger than at the surface. Nevertheless, Millikan concluded from this doubtful result in April 1926 that there is “complete disagreement” with the data of Hess and Kolhörster and one has therefore a “definite proof that there exists no radiation of cosmic origin having an absorption coefficient as large as 0.57 per meter of water” (Millikan and Bowen, 1926). A second publication from June 1926 summarised the experiments of Otis and measurements in the mountains. Also here no evidence for extraterrestrial radiation was observed. But five months later, measurements in snow-fed lakes at high altitudes (Millikan and Cameron, 1926) showed ‘suddenly’ that “This is by far the best evidence found so far for the view that penetrating rays are partially of cosmic origin.”

An article appeared in the *New York Times* (NY-Times, 1925) at 12 November 1925 with the title “Millikan Rays” which referred to the sounding balloon measurements published five months later in April 1926 (Millikan and Bowen, 1926) with the conclusion given above. This is an interesting example for Millikan’s ‘abilities’ in publicity and science marketing. Parts of this article, which was even reprinted in ‘*Science*’ (Science, 1925), will be presented here:

> DR. R.A. MILLIKAN has gone out beyond our highest atmosphere in search for the cause of a radiation mysteriously disturbing the electroscopes of the physicists. ... The study had to be made out upon the edge of what the report of his discovery calls “finite space,” many miles above the surface of the earth in balloons that carry instruments of men’s devising where man himself cannot go. His patient adventuring observations through 20 years have at last been rewarded. He has brought back to earth a bit more of truth to add to what we

> knew about the universe. ... He found wild rays more powerful and penetrating than any that have been domesticated or terrestrialized, travelling toward the earth with the speed of light ... The mere discovery of these rays is a triumph of the human mind that should be acclaimed among the capital events of these days. The proposal that they should bear the name of their discoverer is one upon which his brother-scientists should insist. ... "Millikan rays" ought to find a place in our planetary scientific directory all the more because they would be associated with a man of such fine and modest personality.

The 'brother-scientists' in Europe insisted, but in the opposite way (Hess, 1926; Kolhörster, 1926). They made clear that what was called the discovery of 'Millikan rays' was nothing else than the radiation discovered in 1912 by Hess.

But Millikans aggressive campaign had a strong impact. In several scientific books of this time, also from European authors (see e.g. De Broglie and De Broglie, 1930, p. 130), Millikan was assigned as the discoverer of the extraterrestrial rays. Finally, with the Nobel Prize awarded in 1936 to V.F. Hess, the real development in this research field was put in perspective. Today it is assumed that Millikan created the terms 'cosmic radiation' and 'cosmic rays' for this radiation (Millikan and Cameron, 1926). But also this can be disputed. Gockel and Wulf used it in a paper from 1908 (Gockel and Wulf, 1908) summarising the results of their investigations in the Alps:

> An influence of the altitude on the ionisation could not be verified. This allows the conclusion that a cosmic radiation, if it exists at all, contributes with an inconsiderable fraction only.

In English, French and Russian publications the term 'cosmic rays' was the standard after Millikans paper in 1926, in German the terms 'Höhenstrahlung' and 'Ultrastrahlung' were in use until end of the 1940s. Afterwards 'cosmic rays' and 'cosmic particle physics' were commonly used.

2.4 Properties of Cosmic Rays

It was the higher penetration power which led to speculations that there could be something else than the known α-, β- and γ-rays. As discussed before, it took years to isolate cosmic rays from background γ-radiations caused by radioactive impurities in the detector walls, in the environment of the detector, in the Earth crust and in the lower atmosphere. Until the early 1930s it was the general consensus that cosmic rays are γ-rays. In many long-term experiments the time variation of the ionisation was measured and correlations were investigated with temperature, velocity of the wind, air pressure, position of the sun and the stars. Most of these results were contradictory, and, finally, the only advantage was a better understanding of the used electrometers and the experimental conditions. Besides the discovery at high altitudes itself, the absorption measurements in water and ice as well as with lead shielding brought new insights. Real progress came with new detection methods like the cloud chamber, the Geiger–Müller counter and the possibility to measure coincident signals.

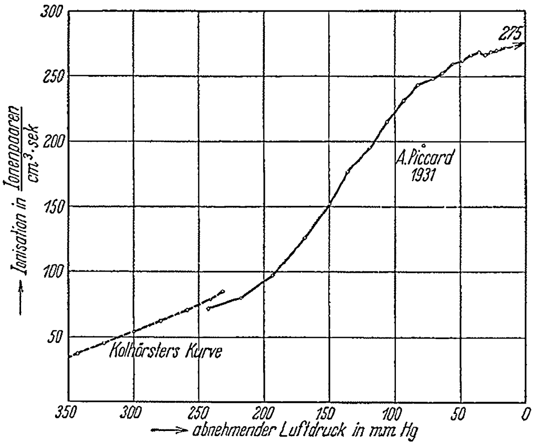

Fig. 2.5 The measured ionisation in dependence on the air pressure. For comparison the results of Kolhörster (1914) and Piccard (1932) were shown (from Regener, 1932b)

2.4.1 Hardness of Cosmic Rays

As discussed in Sect. 2.2.3 the absorption coefficient of γ-rays from radioactive sources was an important material parameter. Consequently, Kolhörster estimated the absorption for cosmic rays in air from his ionisation measurements up to 9 300 m altitude to $\lambda = 1 \times 10^{-5}$ cm^{-1}. This is 4.4 times smaller than for γ-rays from radioactive sources (see Table 2.1), which means that cosmic rays are much harder. Later investigations by Kolhörster and Salis (1923) as well as by Millikan and Cameron (1926) in glacier ice and mountain lakes at altitudes between 1 400 and 3 900 m yielded absorption coefficients for cosmic rays in water of 2.2×10^{-3} cm^{-1} and 1.8–3 $\times 10^{-3}$ cm^{-1}, respectively. The measurements showed also an inhomogeneity of the radiation, which was a first hint on secondary components caused by Compton scattering where a gamma-quant transfers its energy on an electron. Millikan and Cameron estimated the wave lengths of the radiation components to be 3.8–6.3 $\times 10^{-12}$ cm. Secondary Compton electrons would then reach an energy of 1.5×10^7 eV (Kolhörster, 1928).

To complete these considerations the pioneering experiments of Erich Regener will be discussed. With an especially designed automatically recording electrometer enclosed in a compression-proof metal bomb he performed absorption measurements in Lake Constance up to a depth of 250 m (Regener, 1932a). The absorption coefficient of 1.8×10^{-3} cm^{-1} was interpreted to mean that a very hard component of the cosmic radiation reached this depth. However, the relevance of these results was limited, since it was discovered that the primary cosmic radiation was not high energy γ-radiation (see Sect. 2.4.4). As will be seen, Regener came with his own investigations in the stratosphere to the same conclusion. Therefore, the absorption coefficients deduced so far for cosmic rays could not be considered as material constants.

With the same experimental accuracy Regener prepared sounding balloon experiments to measure the ionisation at altitudes where the primary cosmic radiation

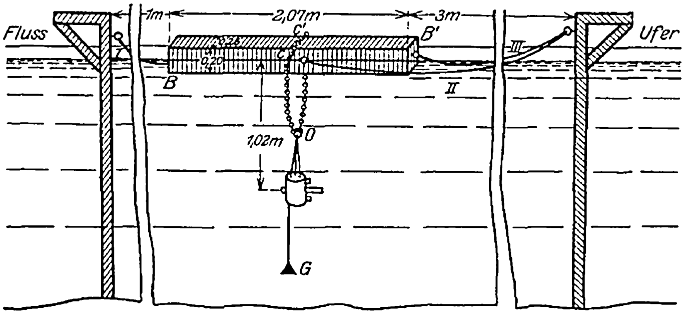

Fig. 2.6 Schematic view of the experimental set-up to measure the ionisation variation with the air pressure in the Neva river (from Myssowsky and Tuwim, 1926)

hits the upper atmosphere (Regener, 1932b). The automatic photographic recording of ionisation, temperature and air pressure was adapted to the conditions at very high altitudes. The balloon flight at 12 August 1932 reached an altitude of 28 km. Figure 2.5 is an impressive demonstration of the continuation of Kolhörster's measurements into the stratosphere. The main conclusions of these investigations were (Regener, 1932b):

> … 3. At pressures below 150 mmHg (above 12 km altitude) the curve becomes flatter, i.e. the intensity of the radiation increases more slowly approaching the end of the atmosphere. … 6. If there would exist a γ-radiation of the known radioactive substances in the cosmos, then it would penetrate … still 20 % of the corresponding air column. This would result in an increase of radiation intensity in the upper part of the curve. Since this is not the case, one can conclude that such kind of radiation does not exist with observable intensity.

2.4.2 *Barometer Effect*

The influence of the air pressure on the ionisation rate was observed years before the discovery of cosmic particles. Simpson and Wright (see also Sect. 2.2.3) stated in their summary of atmospheric electricity measurements over the ocean in 1910 (Simpson and Wright, 1911):

> A slight dependence of the natural ionisation upon barometric pressure has been observed – a high barometer giving low value of ionisation.

The table of Wulf's measurement results on the Eiffel tower (Wulf, 1910) showed the same effect, but Wulf did not comment on it.

The effect was investigated by the Russian physicists L. Myssowsky and L. Tuwim in 1926 in the Neva river (Myssowsky and Tuwim, 1926). To reduce background radiation a Kolhörster electrometer was installed 1 m below the surface (see Fig. 2.6). Between 21 May and 11 June the ionisation and air pressure were registered. An increase by 1 mmHg (1.333224 HPa) reduced the ionisation by

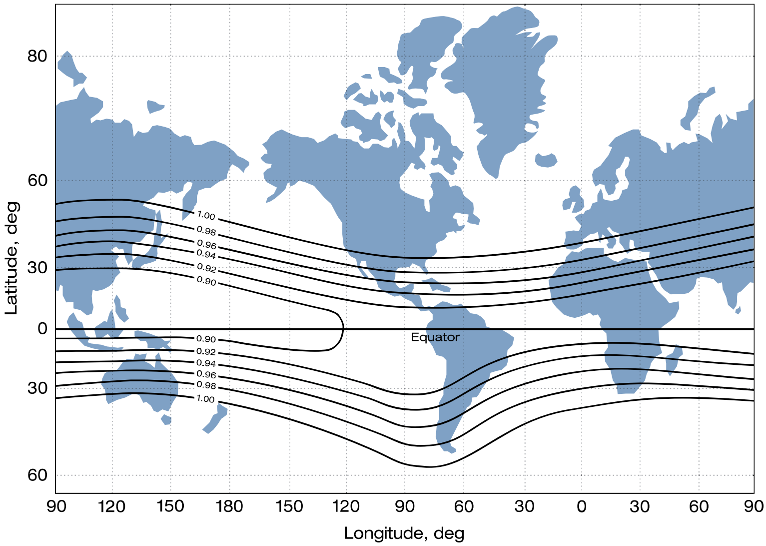

Fig. 2.7 Schematic illustration of the latitude effect. The lines represent the intensity of cosmic particles in dependence on the latitude and longitude (from Johnson, 1938)

0.7 %. Their conclusion that the barometric effect has to be considered for precision measurements was the first result valid until today.

2.4.3 Latitude Dependence

The investigation of a possible latitude dependence of cosmic rays was proposed by Kolhörster in 1919 (Kolhörster, 1919). He interpreted the results of his solar eclipse observation in 21 August 1914, where no dependence on the sun intensity was detected. This was in agreement with earlier and later measurements by others. Kolhörster concluded that electrons could be emitted by the sun instead of γ-rays. They are then influenced by the Earth magnetic field before they hit the atmosphere to produce γ-rays. In this case one would expect a dependence on latitude.

First observations did not give clear results. Only J. Clay from the University of Amsterdam measured in 1926 on the way from Genua to Java a decrease of ionisation in the direction of the equator (Clay, 1927). Others, like Millikan along the American west coast as well as Bothe and Kolhörster on the way to Spitzbergen, did not observe an effect. Then, Clay and Compton initiated international campaigns where different groups measured the ionisation dependence on latitude and longitude with identical electrometers (Compton, 1932, 1933). As seen in Fig. 2.7, the ionisation follows the geomagnetic latitude dependency and not the geographical dependency.

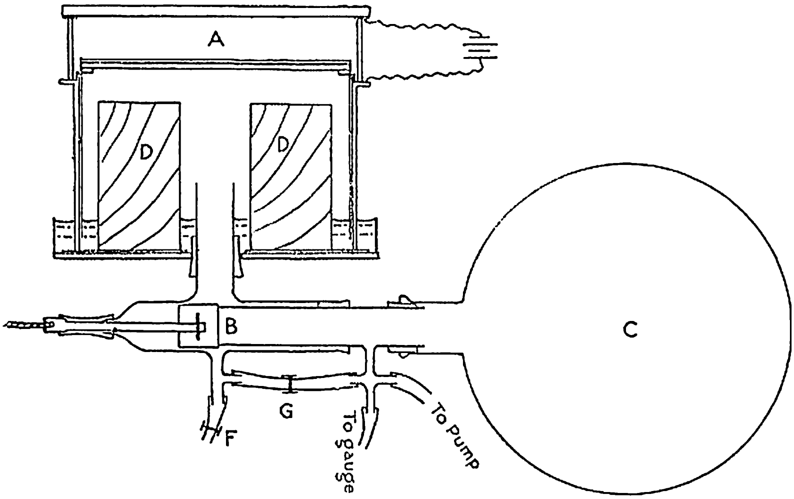

Fig. 2.8 Schematic view of Wilson's cloud chamber from 1912 (from Wilson, 1912)

2.4.4 Particle Character

For many years it was unquestioned that cosmic rays are highly energetic γ-rays. Radioactive decays were the only known source and γ-rays had the highest energy and penetration power. This view changed at the end of the 1920s when century when new detection methods came into operation. The old-fashioned electrometers were driven to high precision and stability. But they could not distinguish if a γ- or a β-ray ionised the air molecules. Only thicker detector walls could shield the lower energetic electrons.

The cloud chamber was not so new. Wilson made first studies in 1894 trying to understand the formation of clouds and fog. Motivated by his investigations on natural radioactivity and the conductivity of air by ionisation, he came back to this idea. In 1911 he published first results entitled "On a method of making visible the paths of ionising particles through a gas" (Wilson, 1911). In the following year Wilson produced, with an improved cloud chamber, impressive photographs of α-, β- and X-rays (Wilson, 1912). The working principle of a cloud chamber is rather simple. A volume containing moist air reaches by fast expansion a supersaturated state. Irradiation with ionising rays produces air ions which then act as nuclei of condensation. Tiny water drops form the track of the ionising particle. Figure 2.8 presents a schematic view of this cloud chamber. Surprisingly on two photographs very straight tracks are visible. Cosmic rays had not been detected at this time. So Wilson misinterpreted these tracks. One of them is shown in Fig. 2.9.

There can be no question that the possibility to visualise the path of atomic particles revolutionised the research. The installation of the chamber between strong magnet coils opened for the first time the possibility of momentum and energy estimates by measuring the track curvature.

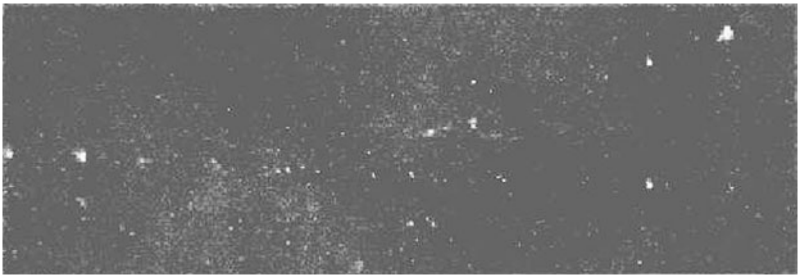

Fig. 2.9 Photograph with a straight charged track, which is possibly the first cosmic ray electron. It was taken with Wilson's cloud chamber before June 1912 (from Wilson, 1912)

In 1927 Dmitri Skobeltzyn worked in Leningrad with a cloud chamber operating in a magnet (Skobeltzyn, 1927). He investigated Compton β-rays produced in the chamber gas by γ-rays of a Ra-C source. The photographs showed two straight tracks not related with Compton electrons. Because of their high energy of $>2 \times 10^7$ eV, Skobeltzyn concluded that these tracks were produced in the electric field of a thunderstorm. This demonstrates that even 17 years after their discovery the extraterrestrial origin of cosmic rays was not a common understanding. One year later Skobeltzyn found with a dedicated investigation in 600 pictures 36 electrons with energies larger than 1.5×10^7 eV (Skobeltzyn, 1929). This was the first 'visible proof' for the existence of charged secondary interaction products of cosmic rays.

A further important development for cosmic ray studies was the Geiger–Müller counter. In summer 1928 Hans Geiger and Walther Müller announced it in a half page article (Geiger and Müller, 1928), not knowing that nowadays it would be still an essential detection device in nuclear and particle physics. The counter consists of a metal tube with a radially spanned thin wire. The anode wire is on positive high voltage, the tube wall on ground. A charged particle traversing the tube ionises the counter gas and the electrons drift to the anode wire. First experiments used an electrometer to count the electrical signals on the wire. Walter Bothe and W. Kolhörster, working on cosmic rays in the 'Physikalisch-Technische Reichsanstalt' in Berlin, immediately saw new applications. Most interesting was the search for coincidences. Two counters give (within reachable accuracy) at the same time signals if both are crossed by a cosmic ray.

They designed a trend-setting experiment (see Fig. 2.10), whose results appeared in 1929 (Bothe and Kolhörster, 1929). Coincidence measurements were performed without and with a 4.1 cm thick gold absorber between the counters. The set-up was installed at two places: On the first floor with 3 m water-equivalent of concrete on top and for comparison below the roof of negligible material. At the first floor the coincident rates were identical, independent from the absorber. Below the roof the absorber reduced the rate by about 25 %. With these results Bothe and Kolhörster demonstrated:

(i) The cosmic rays measured in coincidence must be charged particles, γ-rays would not give coincidences.

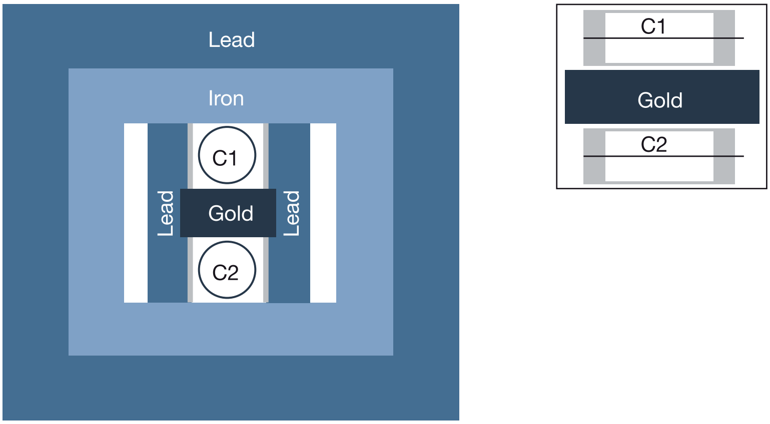

Fig. 2.10 Layout of Bothe's and Kolhörster's coincidence experiment (from Bothe and Kolhörster, 1929). *C1* and *C2* are the Geiger–Müller counters. The coincidence condition requires the particles to cross the detector from *top* to *bottom*

(ii) These charged particles have a penetration power comparable with cosmic rays measured at high altitudes.

Therefore, it could be assumed that primary cosmic rays are also charged particles. The final answer to this question was given then in the following years by measuring the latitude dependence of the cosmic particle rate as discussed in Sect. 2.4.3.

Bothe and Kolhörster achieved the coincidence still with a photographic method. Analysing the registration film strips, which registered the electrometer string position, they looked for amplitudes appearing at the same time for both detectors. But the development of electronic components in the area of broadcast and telephony allowed new solutions. At the end of 1929 Bothe published his pioneering idea under the title 'Simplification of coincidence counting' (Bothe, 1929). With an electronic circuit and a two-grid vacuum tube he could realise an automatic coincidence counting. The circuit and the electronic components were improved in the following by Bruno Rossi and others. But the coincidence method is still an essential component in modern particle and astroparticle experiments.

2.5 Hypothesis About the Origin of Cosmic Rays

From the very beginning, it was the driving idea in all these research activities to identify possible sources of the penetrating radiation. In the following we will try to document the chronological development and then give a summary of the commonly accepted status end of the 1930s.

- 1901: The ionisation of air molecules was just discovered, but Wilson seemed to have visionary abilities, proposing to look also for sources outside the atmosphere (Wilson, 1901).

- 1906: O.W. Richardson studied the diurnal variation of ionisation in closed vessels (Richardson, 1906). He assumed that a correlation with the variation of the electric earth field near the surface could be "caused by radiation from extraterrestrial sources".
- 1908: Gockel and Wulf used in their paper on high altitude measurements in the Alps (Gockel and Wulf, 1908) the term 'cosmic radiation' (kosmische Strahlung) many years before Millikan.
- 1912: Hess discovered the cosmic radiation 7 August 1912. With his previous balloon flights during the night and a solar eclipse, he concluded that the sun can be excluded as source.
- 1913: Kolhörster established the discovery. Why he favoured the sun to be the source is an open question. Perhaps he only wanted to distinguish himself from Hess. Especially in the first years he tried to convince the reader of his papers that Hess's results were not very confident.
- 1915: For the 'Elster-Geitel Festschrift' Egon von Schweidler (Univ. Vienna) performed theoretical estimates "about the possible sources of the Hess radiation" (von Schweidler, 1915). Based on the known knowledge about radioactivity, Schweidler could exclude most sources: The upper atmosphere, the moon, the sun, other planets and fixed stars. He concluded that "the less extreme requirements sets the hypothesis of radioactive substances distributed in the outer space."
- 1921: Walther Nernst, Nobel Prize laureate of 1920 and founder of physical chemistry, gave a public lecture on the status of newest research (Nernst, 1921). He also discussed the implications of the cosmic radiation: "… if many primordial matter is concentrated in the Milky Way, so this could be an area of stronger emissions. … More detailed investigations should be done on high mountains. From here the fundamental question could be decided if it (the radiation) will be emitted uniformly in the space or stronger from the milky way." Subsequent investigations did not give conclusive answers. The reason became clear later with the discovery of the particle character of cosmic rays. The galactic magnet fields prevent a straight path from source to observer.
- 1926: In the publication, where Millikan and Cameron 'rediscovered' cosmic rays, they also presented their view on the origin of the radiation (Millikan and Cameron, 1926): "The cosmic rays are probably … generated by nuclear changes having energy values not far from those recorded above. These changes may be (1) the capture of an electron by the nucleus of a light atom, (2) the formation of helium out of hydrogen, or (3) some new type of nuclear change, such as the condensation of radiation into atoms. The changes are presumably going on not in the stars but in nebulous matter in space, i.e., throughout the depths of the universe." It should be mentioned that Millikan was the last, giving up the γ-ray nature of cosmic rays.
- 1933: With the findings of Skobeltzyn, Bothe and Kolhörster and the proof of the latitude effect by Clay and Compton, the particle character of cosmic rays was established. This changed naturally the assumptions and requirements of their production.

- 1934: Fritz Zwicky, a Swiss, and Walter Baade, a German astrophysicist and astronomer, introduced the term supernova for short flaring, extremely bright objects (Baade and Zwicky, 1934a): "… the whole visible radiation is emitted during the 25 days of maximum brightness and the total thus emitted is equivalent to 10^7 years of solar radiation of the present strength."
  But, more importantly, they demonstrated impressively that supernovae are sources of cosmic rays (Baade and Zwicky, 1934b): "The hypothesis that supernovae emit cosmic rays leads to a very satisfactory agreement with some of the major observations on cosmic rays." This concerns especially the energy release. They estimated the intensity of cosmic rays to be $\sigma = (0.8\text{–}8) \times 10^{-3}$ ergs $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, in rather good agreement with experimental results. Assuming that supernovae are the only source and knowing that very few appeared in our galaxy in the last 1 000 years, Baade and Zwicky argued: "The intensity of cosmic rays is practically independent of time. This fact indicates that the origin of these rays can be sought neither in the sun nor in any of the objects of our own Milky Way."
- 1942: The rebirth of the hypothesis that the sun is a source of cosmic rays came with observations of Scott Forbush, a USA geophysicist. He measured an increase of the cosmic ray rate during a strong solar flare in 1942 and concluded that at least a part of cosmic rays come from the sun (Forbush and Lange, 1942).

There were of course several publications discussing other ideas. Hannes Alfvén proposed in 1937 magnetic fields of double star systems as acceleration mechanism; Alfvén, Robert D. Richtmyer and Edward Teller discussed in 1949 the possibility that cosmic rays could have a solar origin. These and other suggestions were not mentioned here, since they did not have any relevance for future developments.

2.6 Begin of Particle Physics

At the beginning of 1930 three fundamental particles were known, the electron, the proton and the γ-quant. The atom was assumed to consists of a nucleus built by protons and electrons, surrounded by electrons on different orbits. To rescue the momentum conservation in the β-decay, Wolfgang Pauli had introduced a hypothetical neutral particle, later called neutrino. The neutron was detected by James Chadwick in 1932, which corrected then the picture of the atomic nucleus. On the theoretical side, quantum mechanics was developed and Paul A.M. Dirac had just formulated the theory of the electron, where another particle, the anti-electron, was postulated.

As described in Sect. 2.4.4, it was the time where new advanced particle detection devices came worldwide in operation. Their combination, i.e. the cloud chamber in a strong magnet field and, even better, the coincidence of Geiger–Müller counters to trigger a cloud chamber were the most efficient and successful methods to investigate cosmic rays. In the second half of the 1920s, cloud chambers were used to investigate charged particle tracks of radioactive sources. Skobeltzyn initiated a new area with his cosmic particle observations in a cloud chamber. This work was

Table 2.4 Cloud chamber experiments for cosmic particle detection operating in a magnet field

Author	Year	Chamber diameter, cm	Magnet field, tesla	Coincidence trigger counters	Discovery
Skobeltzyn (1927)	1927	7.5	0.1	no	first cosmic rays
Kunze (1933a)	1933	16.0	2.0	no	energy spectrum
Anderson (1933)	1933	17.0	1.5	no	positron
Blackett and Occhialini (1933)	1933	13.0	0.3	yes	e^+e^--pair production, particle showers
Neddermeyer and Anderson (1938)	1937	17.0	0.8	yes	muon

continued in 1931 by Paul Kunze in Germany, Patrick M.S. Blackett and Giuseppe Occhialini in Great Britain and by Carl D. Anderson in the USA (see Table 2.4).

But also other experimental approaches to study the properties of cosmic particles yielded important results. More advanced arrangements of Geiger–Müller counters in coincidence were used by Bruno Rossi, Bothe, Kolhörster and Erich Regener. Another photographic method, photographic emulsion, was brought to perfection by the efforts of Marietta Blau.

2.6.1 Discovery of the Positron

Carl D. Anderson proposed at the end of his time as graduate student in 1929 a magnet cloud chamber experiment. The goal was to study electrons produced in a lead sheet within the chamber by 2.6 MeV γ-rays of a Th-C source. However, Millikan forced him to construct a cloud chamber with a very strong magnet for cosmic ray studies. First photographs taken in 1931 showed negatively and positively charged tracks. Mainly driven by Millikans view of the nature of cosmic rays, they were interpreted as electrons and protons produced by high energy cosmic γ-rays. But Anderson was in doubt, since for many positive particles the ionisation agreed with those of electrons. In August 1932 photographs with a 6 mm lead plate in the centre of the chamber were taken. A short announcement appeared in Science in September 1932. The more detailed publication from February 1933 (Anderson, 1933) presented the often-cited Fig. 2.11. It unambiguously demonstrated that the track must be a positively charged electron. A proton would have a ten times shorter track length.

At the same time, Blackett and Occhialini published a first analysis of photographs taken with their triggered cloud chamber (Blackett and Occhialini, 1933). The efficiency for taking cosmic track photographs was 80 % compared to 2 % for Anderson's untriggered chamber. The sketch in Fig. 2.12 shows the experimental set-up. Many photographs contained particle showers. To estimate momentum or

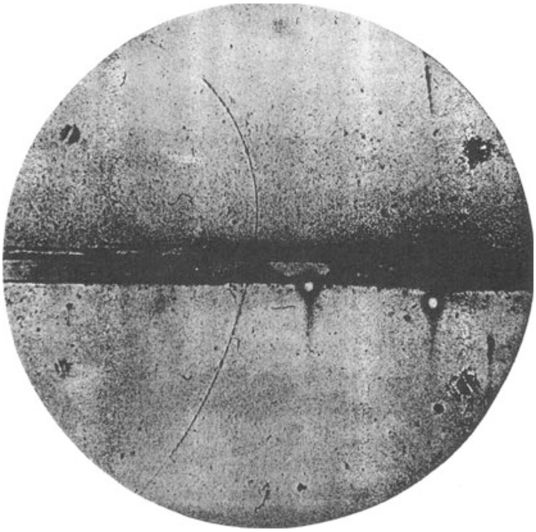

Fig. 2.11 A positron track coming from *below* with 63 MeV energy. Passing a 6 mm lead plate, the remaining energy of the track in the *upper part* is 23 MeV (from Anderson, 1933)

energy of the tracks was difficult because of the small magnet field. But both particle charges were observed with almost identical fractions and ionisation values, which confirmed the assumption that electron–positron pairs were produced. Blackett and Occhialini discussed several hypotheses for the shower production and the properties of the positron:

> In this way one can imagine that negative and positive electrons may be born in pairs during the disintegration of light nuclei. If the mass of the positive electron is the same as that of the negative electron, such a twin birth requires an energy of $2mc^2 \sim 10^6$ eV, that is much less than the translationary energy with which they appear in general in the showers.
> The existence of positive electrons in these showers raises immediately the question of why they have hitherto eluded observation. It is clear that they can have only a limited life as free particles since they do not appear to be associated with matter under normal conditions. … it seems more likely that they disappear by reacting with a negative electron to form two or more quanta. This latter mechanism is given immediately by Dirac's theory of electrons.

Anderson was aware of Dirac's prediction of the positron (Dirac, 1930). But as he stated in (Anderson, 1983), "… the discovery of the positron was wholly accidental. … Dirac's relativistic theory … played no part whatsoever in the discovery of the positron." For the paper of Blackett and Occhialini, Dirac computed the mean free path and the range of positrons in water for different energies. A positron with 1 MeV energy annihilates on average after 0.45 cm, and at 100 MeV the range is about 28 cm.

Probably, the visualisation of electron–positron particle showers initiated new theoretical activities. Heisenberg, Oppenheimer, Bethe, Heitler and others published models and theories. At the same time, experiments with cloud chambers and counter set-ups yielded new results. These important developments on particle showers will be discussed in the following article, by K.-H. Kampert and A. Watson.

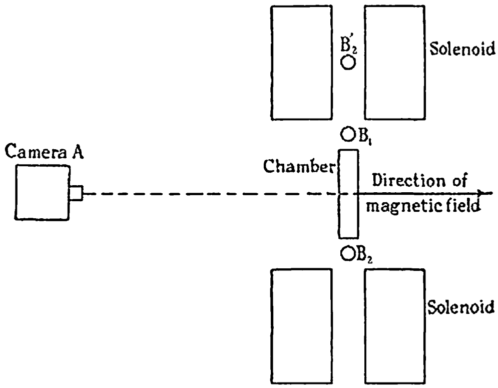

Fig. 2.12 Set-up of Blackett's and Occhialini's cloud chamber experiment with three Geiger–Müller counters (*B*) in coincidence (from Blackett and Occhialini, 1933)

2.6.2 Discovery of the Muon

After the discovery of the positron the main goal of the research with triggered cloud chambers and pure counter experiments was a better understanding of the particle properties. For theorists, the energy spectra of electrons, positrons and protons were important to verify and adjust their models. Cloud chambers in strong magnet fields and triggered by counters had clear advantages against other methods. The track visualisation, their momentum measurement and the mass estimate using the ionisation information allowed one to shed light on the complicated processes.

One of these paradoxes mentioned by Anderson appeared in photographs taken in 1934 with a 0.35 cm thick lead sheet in the centre of the chamber. S.H. Neddermeyer and Anderson found particles which were much less absorbed than electrons but had masses smaller than the proton mass. To solve this problem a new exposure of 6 000 photographs was performed with a 1 cm platinum plate in the chamber centre. Concerning electron absorption, this was more than a factor of five thicker than in the previous experiment. The data contained 55 events where the energy loss in platinum could be measured. Fourteen of them were identified as electrons and positrons with a considerable loss. For a large fraction the absorption was significantly smaller. Neddermeyer and Anderson announced the muon discovery in 1937 (Neddermeyer and Anderson, 1938) and concluded:

> … that there exist particles of unit charge, but with a mass (which may not have a unique value) larger than that of a normal free electron and much smaller than that of a proton; this assumption would also account for the absence of numerous large radiative losses, as well as for the observed ionisation.

The name of the new particle should express that its mass is between those of electron and proton. In the first years the term 'mesotron' was used. After the discovery of the pion it was called 'μ-meson' and finally 'muon' to demonstrate that it is a lepton. Anderson later wrote about the history (Anderson, 1983):

> The discovery of the meson, unlike that of the positron, was not sudden and unexpected. Its discovery resulted from a two-year series of careful, systematic investigations all arranged

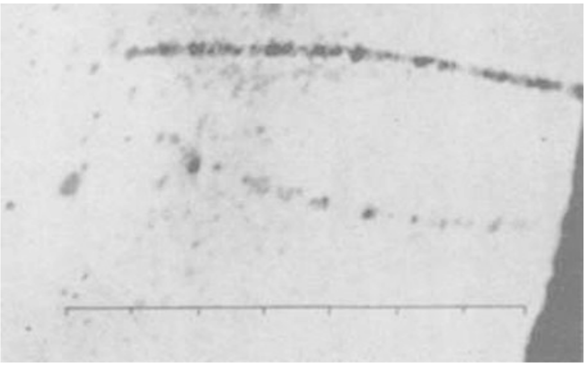

Fig. 2.13 First photograph of a muon (*upper track*). The *lower track* is an electron (from Kunze, 1933b)

> to follow certain clues and to resolve some prominent paradoxes which were present in the cosmic rays.

Paul Kunze published the first photograph of a probable muon in 1933 four years earlier (Kunze, 1933b) without knowing that he had missed a sensational discovery. He interpreted Fig. 2.13 as

> ... a thin electron track of 37 MeV and a considerably stronger ionising positive particle of smaller curvature. The nature of this particle is unknown; for a proton the ionisation is probably too small, and for a positive electron too large.

The existence of a hard, penetrating cosmic particle component consisting of muons was established later by many other experiments. Also the penetrating tracks measured in the pioneering experiment of Bothe and Kolhörster (see Sect. 2.4.4) were muons. The estimated muon mass varied still over a wide range with a mean value of 220 ± 30 electron masses, not so far away from the present value. The first photograph with a decaying muon was presented by E.J. Williams and G.E. Roberts in 1940 in a large cloud chamber at the picture at the University College of Wales (Williams and Roberts, 1940). Franco Rasetti was in 1941 the first who measured the muon lifetime. With a rather complex counter and absorber arrangement (Rasetti, 1941) he estimated a lifetime of $\tau_\mu = (1.5 \pm 0.3) \times 10^{-6}$.

Neddermeyer and Anderson did not know the publication of Hideki Yukawa, which appeared in the end of 1935 in a Japanese journal (Yukawa, 1935). Yukawa formulated a theory to describe the dense packing of protons and neutrons in the nucleus. In analogy to the electromagnetic theory, where the photon is the carrier of the force, here the short-ranged field needs a carrier with a mass inversely proportional to its range. Yukawa estimated a mass of about 200 electron masses and concluded: "The massive quanta may also have some bearing on the shower produced by cosmic rays." Thus, it is no surprise that the discovered muon was identified with the predicted Yukawa particle. This created new paradoxes which kept theoreticians and experimentalists busy. The main problem was that the muon with its penetration capability did not 'feel' the strong force. But the solution was found ten years later and will be discussed in the following section.

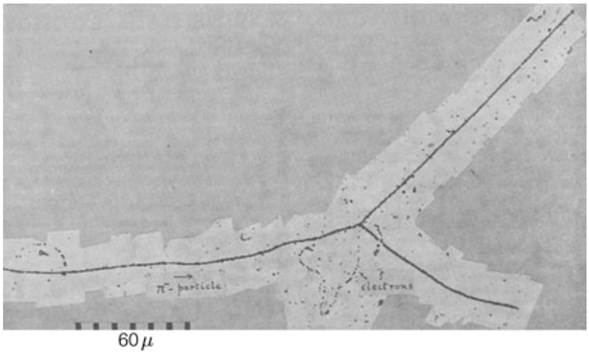

Fig. 2.14 A pion entering the photographic emulsion from the left produces in the interaction two heavy particles and electrons (from Brown et al., 1949)

2.6.3 Discovery of the Pion

In 1938 Yukawa and Sakata published a more detailed version of the theory. The lifetime of the Yukawa particle was predicted to be about 10^{-8} seconds, 100 times larger than the measured lifetime of the muon (Yukawa et al., 1938). This contradiction made it even more difficult to accept the possible identity of both particles. Almost ten years later, the mystery was finally solved with the discovery of the Yukawa-meson in a photographic emulsion plate.

This detection method was developed by Marietta Blau in the 1930s in Austria. Photographic emulsions accumulate the ionisation information of through-going tracks or interactions. The big advantage for the registration of rare processes is the long-term exposure from hours to months. Supported by Hess, Marietta Blau exposed an emulsion package in 1937 at the Hafelekar cosmic ray station in the Alps. One of the developed emulsion plates showed a 'star' of heavy particles (Blau and Wambacher, 1937). It was interpreted as the interaction of a cosmic particle with a nucleus of the emulsion material, leading to its disintegration into several parts. Because of her Jewish roots, Blau immigrated to Mexico, Her successful work was continued after the war, but, unfortunately, she had no possibility to participate.

In Great Britain Cecil Powell, Donald Perkins and others started in 1946 the development of photographic emulsions in cooperation with the Ilford company. Perkins, a graduate student at the Imperial College, performed an exposure of emulsion plates in an airplane at 10 km altitude (Perkins, 1947). He found about 20 'stars', one of them with an incoming particle track. From the measured ionisation and estimates for the elastic scattering of protons and lighter particles in the emulsion, Perkins concluded that the incoming particle is a meson of 100–300 electron masses.

Just a month later Occhialini and Powell published six events of the same signature (Occhialini and Powell, 1947), confirming Perkin's discovery. The group of the University of Bristol around Powell subsequently analysed 65 meson tracks, where 25 of them showed an interaction in the emulsion (Lattes et al., 1947). The estimated meson mass of 240 ± 50 electron masses agreed rather well with the pion mass. In Fig. 2.14 a pion interaction in a photographic emulsion is shown.

Table 2.5 Results in elementary particle physics with cosmic rays and with experiments at the first particle accelerator, the 184 inch synchro-cyclotron at LBL Berkeley

Year	Discovery with cosmic part.	Reference	Detector
1929	Charged secondaries	Skobeltzyn (1929)	Cloud chamber
1929	Charged secondaries	Bothe and Kolhörster (1929)	Counters and absorbers
1932	Charged primaries	Clay and Berlage (1932)	Electroscope
1932	Positron	Anderson (1933)	Cloud chamber
1937	Muon (μ)	Neddermeyer and Anderson (1938)	Cloud chamber
1947	Pion (π)	Perkins (1947)	Photographic emulsion
		Lattes et al. (1947)	Photographic emulsion
1947	Strange particles	Rochester and Butler (1947)	Cloud chamber
1947	μ-absorption and decay	Conversi et al. (1945)	Counters and absorbers
1949	K_L^o-meson	Brown et al. (1949)	Photographic emulsion
1951	Λ^o-baryon	Armenteros et al. (1951)	Cloud chamber
1952	Ξ-hyperon	Armenteros et al. (1951)	Cloud chamber
1953	Σ-hyperon	York et al. (1953)	Cloud chamber
1954	K^+, K^--meson	Menon and O‘Ceallaigh (1954)	Photographic emulsion

Year	Discovery at accelerator	Reference	Detector/Accelerator
1948	$\pi^\pm$-lifetime	Richardson (1948)	Photogr. emulsion / 184” SC
1949	π-energy spectrum	Richman and Wilcox (1950)	Photogr. emulsion / 184” SC
1950	$\pi^\pm$- and $\mu^\pm$-mass	Barkas et al. (1951))	Photogr. emulsion / 184” SC
1950	π^o-meson	Bjorklund et al. (1950)	Proportional counter / 184” SC
1950	π^o-mass	Panofsky et al. (1950)	Proportional counter / 184” SC

2.6.4 Cosmic Particle Versus Accelerator Experiments

Just about 50 years have passed since the first investigations on the conductivity of air and the search for the sources of radiation causing the ionisation of gases. With the discovery of cosmic rays, research activities have been started in many countries and over a wide range of scientific topics. Particle physics, one of the very strong and interesting branches since the beginning of the 1930s, began in 1948 with first steps into its own, autonomous life. Discoveries made with cosmic particles, being milestones for the development of elementary particle physics, are summarised in Table 2.5. Results are also shown from the worldwide first accelerator used since 1948 for particle physics investigations. Pions were produced with the 184 inch Berkeley synchro-cyclotron by accelerated α-particles hitting a wire target. Most of the first small experiments used photographic emulsions as detector. Both the success in detecting new short living heavy mesons and baryons in cosmic particle experiments and the convincing first results at the Berkeley synchro-cyclotron triggered the construction of new accelerators and particle detectors. The table demonstrates in some degree the transition that particle physics performed within a few years. Yet in 1954 the 6.2 GeV Bevatron and the first hydrogen bubble chamber initiated a new area in elementary particle physics.

Finally, let some of the heroes in cosmic particle research present their view of this transition time in their own words.

> Carl D. Anderson (Anderson, 1983):
> … the ever-encroaching larger and larger accelerators clearly indicated the end of the period when cosmic rays could be useful in studies of particle physics. … However, undaunted by the irresistible encroachment of the accelerators, Cowan built a complex arrangement of eight flat ionisation chambers and 12 flat cloud chambers of a total height of 20 ft, designed for investigations at energies above those obtainable in any accelerator, and he continued his studies of cosmic-ray particle events until 1971.

> Cecil F. Powell (Powell, 1950):
> Even when the new machines have been brought successfully into operation, however, it will still be necessary to turn to natural sources in order to study the nuclear transmutations produced by particles of greatest energy. … As a result of these developments there is to-day no line of division between nuclear physics and the study of cosmic radiation. The latter can be regarded as nuclear physics of the extreme high energy region.

> Bruno B. Rossi (Rossi, 1983):
> Today, thinking back to the work that produced these results and to the work in which other colleagues were engaged at that time, I am overtaken by a feeling of unreality. How is it possible that results bearing on fundamental problems of elementary particle physics could be achieved by experiments of an almost childish simplicity, costing a few thousand dollars, requiring only the help of one or two graduate students?
> In the few decades that have elapsed since those days, the field of elementary particles has been taken over by the big accelerators. These machines have provided experimentalists with research tools of a power and sophistications undreamed of just a few years before. All of us oldtimers have witnessed this extraordinary technological development with the greatest admiration; yet, if we look deep into our souls, we find a lingering nostalgia for what, in want of a better expression, I may call the age of innocence of experimental particle physics.

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