HUNDRED YEARS OF ELECTRON IN PHYSICS

Helmut Rechenberg

Max Planck Institute für Physik
(Werner-Heisenberg-Institut)
Föhringer Ring 6, D-80805 Munich, Germany

I. Introduction

I.1 The discovery of the electron (1897) [1]

The idea of a smallest electrically charged particle was fairly common among the physicists of the 19th century, though it became quite pushed into the background, when James Clerk Maxwell's field-theoretical electrodynamics defeated after 1870 the competing particle with the action-at-a-distance theories of Wilhelm Weber, Rudolf Clausius and others. Still the concept survived: Thus Hermann von Helmholtz emphasized in his 1881 Faraday Lecture the possibility of an 'atom of electricity', and the Dutch theoretician Hendrik Antoon Lorentz – starting from a theory of diffraction of light (PhD thesis 1875) – developed in the 1890s an electrodynamics of moving (charged) bodies based on the existence of what the Irish physicist George Johnstone Stoney baptized in 1891 the 'electron'. The true discovery of the electron then happened six years later, in connection with an analysis of two different sets of phenomena.

The first approach emerged from the detailed study of cathode rays. Though they were found already in 1858 by Julius Plücker, physicist still debated their nature in the 1890s – thus Cromwell F. Varley and William Crookes in England preferred a particle explanation, while Heinrich Hertz in Germany argued against this (since his experiments revealed no influence of electric fields). When Hertz's assistant Philipp Lenard succeeded to obtain in 1893 cathode rays in a discharge-free space (through a thin metallic foil, the 'Lenard window'), a new experimental epoch began. The first scientist to report about the discovery of the electron was Emil Wiechert of Königsberg. At the end of a detailed lecture, given on 7 January 1987 before the *Physikalisch-ökonomische Gesellschaft* and entitled entitled 'On the nature of electricity', he finally turned to 'experimental facts on the nature of cathode rays'. From own studies on deflecting cathode rays in a magnetic field he arrived at the following conclusion: If one assumed cathode rays to consist of material particles (mass m) carrying a negative electric charge e (obtained from dividing Faraday's electrolytic constant F by the roughly known Avogadro number N), the ratio m/e was lying between 1/4000 and 1/400 of the ratio observed for the lightest ion, or: 'The upper limit shows beyond doubt that the cathode rays cannot represent the usual chemical atoms.'

Independently of Wiechert, Joseph John Thomson, Cavendish professor of Cambridge University, presented on Friday, 30 April 1987, at the weekly evening meeting of the *Royal Institution of Great Britain* a talk entitled 'Cathode rays'. After a detailed overview, including the demonstration of some properties of cathode rays, the speaker proposed the hypothesis that: 'Atoms of elements are aggregations of very small particles, all similar to each other; we shall call such particles corpuscles, so that the atoms of the ordinary elements are made up of corpuscles and holes, the holes being predominant.' Magnetic deflection experiments yielded the result:

> $m/e = 1.6 \times 10^7$ [in grams and electrostatic units]. This is very small compared with the value 10^{-4} for the ratio of the mass of an atom of hydrogen to the charge carried by it.

The speaker then added: 'It is interesting to notice that the value e/m, which we have found from the cathode rays, is of the same order as the value 10^{-7} deduced by Zeeman from his line experiments on the effect of a magnetic field on the period of sodium light.'

The reference to the experiments of the physicist Pieter Zeeman of Leyden was indeed adequate. Since 1891 the latter had looked at the influence of magnetic fields on spectral lines (a search begun already by Faraday in 1862). On 2 September 1896 he observed first that 'sodium lines become wider when the magnet is switched on' (report of 31 October to the Amsterdam Academy). Now his colleague Hendrik Lorentz entered and proposed that the observed width corresponded to a frequency shift of the original spectral line in a magnetic field H, given by the product expression $(H/2c)(e/m)$. Zeeman noted in his diary on 23 November 1896:

> Finally confirmed that an action of magnetization on light vibration does indeed exist. With the help of Lorentz shown that the explanation through a modified motions of 'ions' is correct or at least highly probable. Shown Lorentz the experiment in the morning of 24th. He calls it a 'lucky break and a direct proof for the existence of ions.

On 28 November 1896, Zeeman submitted a second publication giving a value of 10^{-7} EMU g^{-1}. He and Lorentz were surprised about the big number obtained as compared to the value for normal ions. The splitting into three lines, i.e., the (normal) Zeeman effect, then came only in Zeeman's third publication of May 1897.

To complete the story of the electron's discovery, we must mention another scientist, Willy Wien of Aachen. In a paper, which was received by the *Berliner Physikalische Gesellschaft* on 10 November 1897, he resolved the discrepancy between Wiechert and Thomson's recent observations and earlier negative attempts of Hertz and Lenard to prove the electric charge of cathode rays. Wien concluded two facts to be certain: First, cathode rays are negatively charged particles; second, the positive canal-ray particles have much larger mass than the cathode-ray corpuscles.

In pondering about the relative merits in the discovery story, one normally gives Thomson the greatest credit. This may be justified by the continuous concern, which he devoted in the following years to a study of the properties of his 'corpuscles', while Wiechert and Wien turned their attention to other topics of physical research.

I.2 Short chronology of 100 years of electron in physics [2]

1896 Pieter Zeeman of Leyden discovers the broadening of spectral lines in a magnetic field (October), later split into a triplet.

1897 Emil Wiechert in Königsberg (January) and Joseph John Thomson in Cambridge (April) discover the electron. Hendrik Lorentz in Leyden interprets the Zeeman effect with his 'ion' theory (September).

1899 Thomson and J.S.E. Townsend obtain a value for the electric charge of the electron ('elementary charge').

1899-1900 Friedrich Giesel (Braunschweig), Henri Becquerel (Paris), Stefan Meyer and Egon von Schweidler (Vienna), Marie and Pierre Curie (Paris) identify radioactive beta-rays as fast electrons.

1900 February: Paul Drude (Leipzig) proposes an electron theory of metals. December: Max Planck (Berlin) obtains from his radiation formula the 'Boltzmann constant' k and determines with it the elementary charge e.

1903 Thomson expounds the 'raisin-pudding model' of the atom.

1905 May: Paul Langevin (Paris) formulates the electron theory of para- and diamagnetism.
June-July: Albert Einstein (Bern) and Henri Poincaré (Paris) submit papers founding the theory of (special) relativity.

1907 Planck formulates relativistic mechanics and thermodynamics.

1911 Heike Kamerlingh-Onnes (Leyden) discovers superconductivity of mercury and other metals.
Ernest Rutherford (Manchester) expounds the 'nuclear atom'.

1913 Niels Bohr (Copenhagen) combines Rutherford's nuclear atom with Planck's quantum theory to the 'Bohr model of atomic structure'.

1915 February: Einstein and Wander Johannes de Haas (Berlin) detect the gyromagnetic effect in metals.
December: Arnold Sommerfeld (Munich) extends Bohr's model, also to include relativistic electron orbits.

1922 Otto Stern and Walther Gerlach (Frankfurt) observe their effect.

1923 Louis de Broglie publishes the matter-wave hypothesis.

1925 January: Wolfgang Pauli (Hamburg) expounds the 'exclusion principle', from which George Uhlenbeck and Samuel Goudsmit derive the electron-spin (October).
July: Werner Heisenberg (Göttingen) formulates quantum mechanics.

1926 January: Erwin Schrödinger (Zurich) submits the first paper on wave mechanics.
February: Enrico Fermi (Rome) presents the quantum statistics of the electron ('Fermi statistics').

1927 March: Werner Heisenberg (Copenhagen) obtains the 'uncertainty relations' for electron and other microscopic objects. March-May: Clinton J. Davisson and Lester H. Germer (New York) and George Paget Thomson and Alexander Reid (Aberdeen) demonstrate the wave properties of the electrons.
May: Friedrich Hund (Göttingen) introduces the penetration of electrons through potential barriers in molecules ('tunnel effect').
September: Sommerfeld formulates the wave-mechanical theory of metal electrons removing many problems of the classical approach.

1928 January: Paul Dirac (Cambridge) submits his relativistic electron equation.
May: Heisenberg (Leipzig) solves the problem of ferromagnetism.

1930-1931 Subrahmanyan Chandrasekhar (Madras/London) applies Dirac's electron theory to the interior of stars and derives the 'Chandrasekhar limit' for the masses of white dwarfs.

1931 Dirac predicts the 'anti-electron' (later called 'positron').

1932-1933 Carl Anderson (Pasadena) discovers the positron (August 1932); Patrick M.S. Blackett and Giuseppe Occhialini (Cambridge) observe electron-positron pair creation (Cambridge), both in cosmic rays.

1933 Fermi proposes a quantum field theory of beta-decay, including Pauli's hypothetical 'neutrino' (of December 1930).

1934 January: Irène Curie and Frédéric Joliot (Paris) detect artificial positive beta-decay.
November: Hideki Yukawa (Osaka) introduces his 'meson theory of nuclear forces' and distinguishes between 'strong' and 'weak' interactions of elementary particles.

1936-1937 The 'mesotron' or 'heavy electron' is discovered by several groups in USA and Japan.

1938 The decay time of the mesotron is first derived by Hans Euler and Heisenberg (Leipzig).

1942 Soichi Sakata and Takesi Inoue (Nagaoya) publish a two-meson theory.

1947 May: The group of Cecil F. Powell (Bristol) discovers the 'pi-meson' (or 'pion', the real Yukawa particle) and its decay into the 'mu-meson' (or 'muon', the old cosmic-ray mesotron).
December: John Bardeen, Walter Brattain and William Shockley (Murray Hill) find the transistor effect.

1947-1950 The renormalized quantum electrodynamics is developed in USA (Richard Feynman, Julian Schwinger and Freeman Dyson), Japan (Sin-itiro Tomonaga) and England (Abdus Salam and John Ward).

1956 Tsun-Dao Lee and Chen Ning Yang (Chicago) consider parity violation in weak interactions of nuclei and elementary particles.

1957 Bardeen, Leon Cooper and John Schrieffer (University of Illinois) propose the first successful theory of superconductivity.

1964-1971 The renormalized 'unified electroweak theory' is developed in Britain, USA and Holland (Peter Higgs, Sheldon Glashow, Steven Weinberg, Abdus Salam and Gerard 't Hooft).

1975 Michael Perl et al. (Stanford) find the 'tau-lepton', the third heavier partner of the electron and the muon in the lepton family.

1980 Klaus von Klitzing (Grenoble) discovers the quantum-Hall effect.

1983-1984 The 'intermediate weak bosons' W and Z are observed at CERN.

1986 Alex Müller and Klaus Bednorz (Zurich) detect high-temperature superconductors.

II. Decisive developments during the first fifty years

In this section we shall illustrate the very active role of the electron in physics during the first half of the 20th century.

II.1 From Planck's radiation law to Bohr's atom (1900-1922) [3]

On 14 December 1900 Max Planck presented at the Berlin meeting of the *German Physical Society* the theoretical derivation of his law describing the energy distribution in black-body radiation. At the end of his talk, he referred to consequences following from the values of the two constants h (now called 'Planck's constant') and k (which Planck baptized 'Boltzmann's constant'). Especially, he obtained with the help of k a new value for the elementary quantum of electricity: $e = 4.69.10^{-10}$ ESU, claiming that this was 'far superior to the determinations so far'.

Less than five years later, Albert Einstein formulated the theory of special relativity in the famous paper submitted to *Annalen der Physik* in June, to which he added a note in September, entitled 'Does the inertia of a body depend on its energy?' From the very beginning, Planck showed great interest in Einstein's theory, and he advocated it publically first in his presentation to the Stuttgart *Naturforscherversammlung* on 19 September 1906. In an extended review of 'Kaufmann's measurements of the deflection of β-rays and their importance for the dynamics of the electron', the speaker compared the recent data with two competing theories, Max Abraham's *Kugeltheorie*' (i.e., the 'rigid electron') and the 'Lorentz-Einstein *Relativtheorie*'. While he admitted that the measurements preferred the rigid electron, he stressed: 'In my opinion the data cannot be counted as a definite confirmation of the former and a refutation of the latter.' About two years later A.H. Bucherer from Bonn improved on Kaufmann's experiments and established the relativity theory of Einstein and others.

At about the same time another event, important not only for the history of the electron, happened in England. As Ernest Rutherford recalled twenty years later:

> I may refer to experiments made by Professor Geiger and myself in 1908 when we measured the charge carried by an α-particle from radium and deduced that the value of the electron was $4.65.10^{-10}$ electrostatic units. Before that time the accepted value of e was $3.4.10^{-10}$. In the course of the publication of these results in the Proceedings of the Royal Society, my attention was drawn by Sir Joseph Larmor too the fact that Planck deduced a value of $4.69.10^{-10}$ from his theory...

> On my side, the agreement with Planck's deduction made me adherent to the general idea of an quantum of action. I was in consequence able to view with equanimity and even to encourage Professor Bohr's bold application of the quantum theory to explain the origin of spectra – a direct development of Planck's hypothesis which has had such revolutionary consequences in physics.

Indeed, the Rutherford-Geiger determination of the charge of α-particles – it turned out to be twice the elementary charge e-convinced Rutherford to interpret later the experimental findings of Geiger and Ernest Marsden (1909) in terms of a 'nuclear atom', i.e., his famous planetary atomic model of 1911, consisting of a central heavy nucleus with positive charge $Z\,e$ surrounded by orbiting electrons of negative electric charge $-\,e$. Then, in early 1913, Niels Bohr took up this model and added Planck's quantum of action h, in order to arrive at the stationary states of the hydrogen atom and, via the Planck-Einstein energy-frequency relation, also at an explanation of discrete line spectrum.

During the following decade Bohr and Arnold Sommerfeld extended 'Bohr's atom' and accounted, at least qualitatively, for most properties of atomic spectra and the Mendeleev periodic system of chemical elements. This theory scored in December 1922 a last great triumph through the discovery of the new element, 'hafnium', by Dirk Coster and Georg von Hevesy in Copenhagen. At the same time Bohr received the Physics Nobel Prize in Stockholm. Then came the breakdown of this model and the whole old quantum theory, leading in 1925 to the new concepts of quantum mechanics.

II.2 The electron as a matter wave (1923-1928) [4]

In September and October 1923, Louis de Broglie of Paris submitted three notes to the Paris *Academie des Sciences*, in which he proposed the hypothesis of a 'fictive wave associated with the movement of a particle'. In summer 1924, in his PhD thesis, he first wrote down the equation $\lambda = h/p$ between the wavelength λ of the particle's wave ('matter wave') and its momentum p. More than a year later, in fall 1925, Erwin Schrödinger started from de Broglie's matter-wave hypothesis on his path to wave mechanics, the alternative form to the quantum mechanics of Heisenberg and others.

At the Oxford meeting of the *British Association for the Advancement of Science* in August 1926, Max Born talked on the wave-mechanical description of atomic collision processes, proposing also an interpretation of earlier observations of Clinton J. Davisson and Henry Kunsman on the scattering of electrons by crystals. Davisson, who had come from New York to England, participated in the meeting, and Born's hint started the last, decisive phase of investigations, which he had begun in 1920 at Western Electric Research Laboratories and conducted since 1924 with Lester H. Germer. In studying the scattering of electrons having definite velocities by a nickel target, they had found that the earlier observed maximima and minima in the angular reflection intensified after an accident occurring in early 1925. The explosion of a bottle of liquid air had broken the glass containing the target and oxidized the latter at high temperatures, and the effect had to be removed by lengthy heating in a hydrogen atmosphere – as a consequence, nickel single crystals had been formed. As Davisson recalled this last phase in his Nobel lecture of 1937:

> The search for diffraction beams was begun in autumn of 1926, but not until early in the following year were any found – first one and then 20 others in rapid succession. Nineteen of these could be used to check the relation between wave-length and momentum, and in every case the correctness of the de Broglie formula $\lambda = h/p$ was verified within the accuracy of the measurements.

On 3 March 1927, Davisson and Germer quickly signed a letter to *Nature* containing the first report about the observations; the following August they submitted a detailed account to *Physical Review*. They were lucky to have done so, because on 24 May the British physicists George Paget Thomson, son of the elctron as a particle discoverer, and Alexander Reid of Aberdeen University sent their letter on 'Diffraction of cathode rays by a thin film' also to *Nature*. They obtained rings around a central spot on the photo plate, which they interpreted as due to the diffraction of electron waves according to de Broglie. In their extended paper, received on 4 November 1927 by the *Royal Society of London*, Thomson and Reid demonstrated how the rings on the photo plate emerged from a 'Debye-Scherrer effect' of the polycrytalline foil material. Further studies provided spectacular diffraction patterns of the type obtained first in 1915 with X-rays by Peter Debye and Paul Scherrer in Göttingen.

II.3 From the exclusion principle to Dirac's electron equation (1925-1928) [5]

Between 1925 and 1928 further fundamental properties of the electron were recognized, by which the object became a unique partner in the new atomic theory. First, Wolfgang Pauli introduced in January 1925 a new quantum number of the electron and expounded his 'exclusion principle', which states that never two electrons can exist in a state having all quantum numbers identical. In June of the same year, Werner Heisenberg proposed the first quantum-mechanical description of atomic systems by what his Göttingen colleagues Max Born and Pascual Jordan soon recognized to be matrix variables. In January 1926 Erwin Schrödinger in Zurich proposed his alternative wave mechanics, which he soon demonstrated to be equivalent to the Göttingen matrix mechanics. Paul Dirac in Cambridge then demonstrated in August 1926 that by taking antisymmetrical wave functions one would describe systems of many electrons satisfying Pauli's exclusion principle and the peculiar statistics derived by Enrico Fermi already in February. Finally, in March 1927, Heisenberg discovered a general property of atomic objects: two canonically conjugate properties, like momentum and position of, say, an electron cannot be simultaneously measured accurately but satisfy the 'uncertainty relation'.

Less than a year later, in January 1928 Paul Dirac obtained a linear equation for the relativistic electron, involving characteristic 4×4 gamma matrices, which automatically supplied the electron with the proper angular momentum or 'spin', $1/2\ h/2\pi$, that George Uhlenbeck and Samuel Goudsmit has assigned to it in October 1925 (as a consequence of Pauli's fourth quantum number). Presenting his new theory at the Leipzig *Universitätswoche* in June 1928, Dirac could report already a successful application – Sommerfeld's finestructure formula for hydrogen followed – but simultaneously had to stress the serious problems connected with the existence of negative-energy states. Only three years later, the author found a suitable interpretation by identifying them with a new elementary particle, the 'anti-electron'. In August 1932 Carl Anderson of Pasadena discovered the 'positron' in cosmic rays, and the subsequent creation of electron-positron pairs established its identity with Dirac's anti-electron.

II.4 Friedrich Hund and quantum chemistry (1926-1929) [6]

Usually, Walter Heitler and Fritz London's paper '*Wechselwirkungen neutraler Atome und homöopolare Bindung nach der Quantenmechanik* (Interaction of neutral atoms and covalent binding according to quantum mechanics)' is counted as initiating the path to quantum chemistry. However, as John Slater, a first-hand witness of the development, pointed out in 1975:

> Heitler and London were not the only ones working on molecular theory in the early days of quantum mechanics. Hund started in 1927, applying a quite different method which came in 1932 to be called method of molecular orbitals. Robert Mulliken, a young American followed almost immediately. And J.E. Lennard-Jones, a somewhat older Englishman, wrote his first paper on the subject in 1929.

Friedrich Hund, to whom Slater assigned a pioneering role, died recently, on 31 March 1997, being 101 years old. Already in fall of 1925, immediately after having scored success in explaining the spectra of complex atoms with the exclusion principle ('Hund's rule', etc.), he turned to molecular spectra. During his Copenhagen visit in winter 1926/27, he submitted two papers containing a wave-mechanical investigation of molecules to *Zeitschrift für Physik* in May 1927, after his return to

Göttingen, a third followed. We should mention that the author, besides giving a systematic treatment of molecular states, also introduced (in the third paper) for the first time what we know as the 'tunnel effect' (in order to explain the slow transformation of optical isomeric molecules).

The spectra of molecules continued to be the main research topic of Hund in Rostock, where he obtained a professorship in fall of 1927. Especially based on the group-theoretical method, he now discussed the consequences from molecular structure for the problem of chemical binding in a programmatic report at the Hamburg *Naturforscherversammlung* of September 1928. Again we quote Slater to characterize the work of Hund and others:

> Their ideas were very much alike, and quite along the lines of Hartree's self-consistent field. Hund's paper came before Hartree's, he did not use the term self-consistent field, but his idea was the same: An electron in a molecule, just as in an atom, should move in the field of the nuclei and other electrons.

Mulliken, on the other hand, picked up Hund's theory in 1928 and added empirical material. In early 1929, Hund traveled to the United States: he had obtained an invitation to deliver a course on 'molecular structure' at Harvard University, and then moved to other places. The decisive result of the American visit he recalled later:

> At that time it became urgent to establish an uniform nomenclature of molecules. Mulliken and I discussed the possibilities in a long trip [by train] between Chicago and New York; the other colleagues agreed. A picture I took during a meeting of the American Physical Society in Washington shows Morse, Crawford, Mulliken and Dennison and has a note: '*Einigung über die Bezeichnung der Molekülzustände* (Agreement about the notion of molecular states)'.

In spite of his important pioneering work, Hund later did not claim that either he or Mulliken had invented quantum chemistry but rather suggested that Heitler and London did so (although these authors submitted their first paper in 1927 a couple of months later than Hund). Further he mentioned the work of Gerhard Herzberg, who used the molecular-orbital method in 1929 for explaining in 'a convincing manner chemical binding'. Still it is fair to state today that the foundations of quantum chemistry were provided independently by the two competing methods of Heitler and London, and Hund and Mulliken, respectively. Mulliken got the Chemistry Nobel Prize of 1966 for the molecular-orbital method; he always mentioned that he wished to have shared it with Friedrich Hund.

Up to now we have treated only those fields of physics, in which the electron entered through its electric and magnetic interactions with distant microscopic particles (in atoms, molecules, etc.). However, the phenomenon of β-decay reminds us that electrons might be a constituent of atomic nuclei – at least, they come out from them. This very observation provided quite serious troubles for the understanding in terms of quantum mechanics and relativity theory. Especially, the conservation laws of energy, momentum and angular momentum seemed to be violated in β-decay, also electrons if contained in nuclei, obviously contradicted the uncertainty relation besides having possibly faster-than-light velocity. The discoveries of the year 1932 and their consequences, however, removed most of the troubles mentioned:

(i) The neutron as a nuclear constituent made the existence of electrons in nuclei unnecessary (except perhaps for β-decay).

(ii) The electron-positron pair creation suggested the possibility of the electron being *freshly created* in β-decay.

(iii) The β-decay theory of Enrico Fermi in 1933 then solved also the difficulties with the conservation laws by introducing the joint creation of an electron-neutrino pair through nuclear forces.

(iv) The nuclear exchange forces introduced by Heisenberg in 1932 in order to describe the mass defects of nuclei (consisting of neutrons and protons) perhaps were identical with Fermi's β-decay forces.

From 1932 onwards, Hideki Yukawa in Kyoto and Osaka pondered about the nature of nuclear forces, and in fall of 1934 he was certain: Heisenberg's exchange forces could not be obtained from the exchange of electron-neutrino pairs (as suggested by his Western colleagues) but arose from the exchange of a new particle, the 'heavy U-quantum', whose mass was to be derived from the range b of nuclear forces, namely $m_U c^2 = b(h/2\pi)$. In the ingenious paper 'On the interaction of elementary particles. I', which the author read on 17 November 1934 at the Tokyo meeting of the *Physic-Mathematical Society of Japan* (and published in the first 1935 issue of the society's proceedings), he further introduced *two types of nuclear forces*: the 'strong' ones characterizing the coupling of U-quanta to the heavy nuclear particles proton and neutron (later called 'nucleons'), and the 'weak' ones characterizing the coupling to the light nuclear particles electron and neutrino (later called 'leptons') – the latter should be responsible for the β-decay.

Yukawa thus predicted a particle unknown in 1934 and having a mass of about 200 m_e. As was noticed (later in 1937) by several colleagues (including the Swiss

Ernst Stueckelberg, Heisenberg and the Indian Homi Bhabha), it had to be unstable with respect to β-decay. In fall of 1936, Carl Anderson and Seth Neddermeyer of the California Institute of Technology found in their cloud chamber pictures of cosmic ray events some strange tracks bent by magnetic fields, which they eventually claimed to be new particles in December 1936 (when Anderson received the Nobel Prize for the discovery of the positron). Two other groups, namely Jabez Street and E.C. Stevenson of Harvard University and Yoshio Nishina and collaborators of the RIKEN Institute of Tokyo confirmed in spring and summer 1937 the existence of these objects, soon to be called 'mesotrons'. Were these the Yukawa particles?

As Hans Euler and Heisenberg demonstrated in 1938 by analyzing the observations of the 'hard' or mesotron component of cosmic rays, the new particle decayed indeed weakly having a mean lifetime of about 2.10^{-6}s. This result initially seemed to agree with the predictions from Yukawa's theory, but then turned out to be too large by a factor 100. While direct observations of the mesotron decay confirmed the Euler-Heisenberg result, the difficulties to identify the known cosmic-ray particle with U-quantum of nuclear forces increased. Finally, Cecil Powell and collaborators in Bristol discovered in spring of 1947 that there were two particles of intermediate mass about 200 m_e available in cosmic rays, the 'pi-meson' and the 'mu-meson'. The former serves as Yukawa's nuclear-force particle and is responsible for the strong interactions. It decays by weak interactions, or β-decay, into a mu-meson, the cosmic ray object discovered in 1936/37.

III. Fundamental physics, electronics and beyond

As may be concluded from the above episodes, the electron constituted the most influential actor in the development of physics in the first half century after its discovery. Did its role become weaker in the following 50 years? We would rather like to answer 'no', and refer for a proof of this assertion just to two topics, one in fundamental and the other in applied physics.

III.1 Elementary particle physics: From QED to the 'Standard Model' [8]

In the years between 1947 and 1950, i.e., shortly after World War II, a theoretical line of arguments converged into the first successful relativistic quantum field theory, quantum electrodynamics (QED). The original approach started in 1929 by Heisenberg, Pauli and Fermi had led to infinite expressions for some properties of electrons and radiation but, based on ideas suggested in the 1930s and early 1940s (notably by Dirac, Heisenberg, Hendrik Kramers and Stueckelberg) and new experimental findings (such as the 'Lamb shift' 1947), Sin-itiro Tomonaga in Japan, Julian Schwinger, Richard Feynman and Freeman Dyson in the United States and Abdus

Salam and John Ward in England obtained the so-called 'renormalized quantum electrodynamics', which allowed to derive finite results fitting observations.

While one did not manage to treat by the same techniques all other available quantum field theories of elementary particles (e.g., the meson theory of nuclear forces), great progress was achieved in the 1950s in obtaining a preliminary description of weak interactions. Thus in 1957/58 the '*(V-A) theory* of George Sudarshan and Robert Marshak and Feynman and Murray Gell-Mann was shown to account perfectly for decay processes (in first approximation). Between 1964 and 1971 new ideas (like the symmetry-breaking 'Higgs mechanism' and the hypothesis of new particles, the 'intermediate bosons') were called in to unite weak and electromagnetic quantum field theories into the renormalizable 'electroweak theory' (Steven Weinberg, Sheldon Glashow, Abdus Salam and Gerard 't Hooft). The predicted weak bosons were finally discovered in the early 1980s. Together with the likewise renormalizable field theory of strong interactions, quantum chromodynamics (QCD) of Yoshiro Nambu, Gell-Mann and others (established in the same period), the electroweak theory forms today's 'Standard Model' in elementary particle physics.

III.2 Transistor and solid-state technology [9]

Towards the end of year 1947 also a quite different development began, which revolutionized applied physics and technology. On 24 December Walter Brattain of Bell Telephone Laboratories in Murray Hill, New Jersey, noted in his laboratory book that an electronic device had been built, which allowed an amplification of the current by a factor 18 and that device was demonstrated on the previous day in the lab. The three inventors, the theoretician John Bardeen, the group leader William Shockley and the engineer Brattain, called their invention 'transistor'. In it a semiconductor replaced the usual electronic valve, hence no vacuum was needed. After a decade had passed, the transistor indeed had replaced vacuum tubes in nearly all electronic apparatus, thus opening the path to an unforeseen miniaturizing of electronic circuit systems, notably suitable for electronic computing and data handling machines. Shockley, who together with Bardeen and Brattain received in 1956 the Nobel Prize in physics, left Bell in 1954 and founded in Palo Alto, California, the *Shockley Transistor Company* and started 'Silicon Valley'.

The discovery of the transistor rested on a clever use of the electronic properties of solids, which had been pioneered between 1928 and 1932 by Felix Bloch, Rudolf Peierls, Lothar Nordheim and Hans Bethe in Germany (all of them had to leave their country in 1933), Leon Brillouin in France and Allan Harris Wilson in England. While their researches fixed the theoretical principles, further theoretical and experimental studies afterwards refined important details and opened new applications of electrons in crystals and other materials. One of the physicists, who contributed particularly to this field, was the English theoretician Nevill Francis Mott (born in 1905, died in 1996). After a remarkable early career as nuclear physicist in the Cavendish Laboratory under Rutherford (see, e.g., 'Mott scattering'), he started in 1933 a second scientific life, when he obtained a theoretical chair at Bristol University. There and later back in Cambridge (on the Cavendish chair) he worked on the properties of metals and alloys, using 'simple visualizable and seemingly uncomplicated models and mathematics'. Thus he succeeded in clarifying and predicting over half a century an enormous range of detailed effects in metals and semiconductors; especially, he explored the transition metal-to-insulator and new quantum effects (like 'Mott' and 'Anderson transitions') connected with it. For his pioneering contributions to understand electric conductivity in disordered systems, Mott shared with Phil Anderson and John H. Van Vleck the 1977 Nobel Prize in physics.

Mott's work on solid state physics, which had large implications on technology, represents a particular example for the fact that, even after the discovery of quantum mechanics and its consequences, visualizable pictures and models – resembling those used in the classical and pre-quantum mechanical period – can lead to essential progress. However, these models must be based on strict quantum-mechanical calculations, which provides the quantitative results.

III.3 Conclusion [10]

Eugene Wigner has stated repeatedly that the main progress achieved by quantum and wave mechanics is that 'for microscopic systems, atoms, molecules, etc., it also permits the derivation of the *properties* of macroscopic bodies, at least as long no living system is involved'. But even the elementary processes occuring in biological structures seem to follow the rules of the modern atomic theory. The study of electronic states in complex molecules (such as DNA) or subgroups of them, their excitation and changes (e.g., in the transmutation of genetic material) constitutes a vital part of modern biology. This shows that the celebrant of today's jubilee, the electron is a main actor also in the game of life.

References

[1] For the discovery of the electron, see H. Rechenberg: The electron (born 1897) – centenary of a star in physics and chemistry; N. Robotti: The discovery of the electron. I; A.J. Kox: The discovery of the electron. II. The Zeeman effect. Eur.J.Phys. *18*, 131-132; 133-138; 139-144 (1997), and the original literature quoted there. Further E. Wiechert: I. Über das Wesen der Elektrizität. II. Experimentelles über Kathodenstrahlen. Schriften d. phys.-

ökon.Ges. (Königsberg) *38*, 3-16 (1897), esp. p. 16; W. Wien: Die elektrostatischen Eigenschaften der Kathodenstrahlen. Verh.Phys.Ges. (Berlin) *16*, 165-172 (1897). For the name 'electron', see G.J. Stoney: On the cause of double lines and the equidistant statellites in the spectra of gases. Trans.Roy.Soc.(Dublin) *4*, 563-607 (1891).

[2] A more extended chronology is given by H. Rechenberg: The electron in physics – selection from a chronology of the last 100 years. Eur.J.Phys. *18*, 145-149 (1997).

[3] For details, see J. Mehra and H. Rechenberg: *The Historical Development of Quantum Theory*, Vol. 1. Springer, New York 1982. Quotations from M. Planck: Zur Theorie des Gesetzes der Energieverteilung im Normalspektrum. Verh.Deutsch.Phys.Ges. *2*, 237-245 (1900), esp. p. 245; M. Planck: Die Kaufmannschen Messungen der Ablenkbarkeit der Beta-Strahlen und ihre Bedeutung für die Dynamik der Elektronen. Phys.Z. *7*, 753-761 (1906); E. Rutherford: Note (on Max Planck's golden PhD jubilee). Naturwiss. *17*, 482 (1929).

[4] For a short history, see H. Rechenberg: Quanta and quantum In L.M. Brown et al., eds.: *Twentieth Century Physics.* Vol. I, IOP and AIP, Bristol and New York 1995, pp. 143-248, esp. pp. 168-171. For personal accounts, see C.J. Davisson: The discovery of electron waves; G.P. Thomson: Electronic waves. In *Nobel Lectures: Physics 1921-1941.* Elsevier, Amsterdam 1965, pp. 386-394; 397-403.

[5] See H. Rechenberg, ref. 4.

[6] H. Rechenberg: Die erste Göttinger Zeit und die Rostocker Professur. In M. Schroeder, ed.: *Hundert Jahre Friedrich Hund* (Nachr.Akad.Wiss.Göttingen, Nr. 1, 1996), pp. 4-32. Quotation from J. Slater: *Solid State and Molecular Theory.* John Wiley, New York 1975, p. 93.

[7] For a detailed account, see L.M. Brown and H. Rechenberg: *The Origin of the Concept of Nuclear Forces.* IOP, Bristol and Philadelphia 1996.

[8] For a detailed history of *QED*, see S. Schweber: *QED and the Men Who Made It.* Princeton University Press, Princeton 1994. For the other parts, see V.L. Fitch and J.L. Rosner: Elementary particle physics in the second half of the twentieth century. In L.M. Brown et al., eds.: *Twentieth Century Physics.* Vol. *II.* IOP and AIP, Bristol and New York 1995, pp. 635-794.

[9] L. Hoddeson et al., eds.: *Out of the Crystal Maze.* Oxford University Press, New York 1992. For a more popular account, see H. Queisser, *Kristallene Krisen.* Piper, Munich and Zurich 1985.

[10] E. Wigner: The extension of the area of science (1981). In *Collected Works.* Springer-Verlag, Berlin, etc. 1992, pp. 603-609, esp. p. 605.