GRAND SCHOOLS OF PHYSICS

The Berlin School of Thermodynamics founded by Helmholtz and Clausius

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Abstract. The history of thermodynamics is closely connected with a scientific school founded in Berlin by Hermann Helmholtz and Rudolf Clausius in the forties of the last century. Other great scientists which belonged to this school were Krönig, Kirchhoff, Planck, Nernst, Caratheodory, Einstein, Warburg, Debye, Schottky, Schrödinger, Szilard and von Neumann. Not only the foundation of the three laws of thermodynamics but also many important applications especially to chemical reactions and to radiation processes, as well as the statistical foundation of thermodynamics are closely connected with the work of these pioneers and their students.

Zusammenfassung. Die Geschichte der Thermodynamik ist eng verbunden mit einer wissenschaftlichen Schule, die in Berlin durch Hermann Helmholtz und Rudolf Clausius in den vierziger Jahren des vorigen Jahrhunderts begründet wurde. Andere große Wissenschaftler, die zu dieser Schule gehörten, waren Krönig, Kirchhoff, Planck, Nernst, Caratheodory, Einstein, Warburg, Debye, Schottky, Schrödinger, Szilard und von Neumann. Nicht nur die Aufstellung der drei Hauptsätze, sondern auch viele wichtige Anwendungen insbesondere auf chemische Reaktionen und auf Strahlungsprozesse sowie die statistische Begründung der Thermodynamik sind eng mit dem Wirken dieser Pioniere und ihrer Studenten verknüpft.

'During nearly 60 years which spanned the call of Hermann Helmholtz to become professor of physics in the Berlin University . . . in 1871, and the call of Erwin Schrödinger to the chair of theoretical physics, the general history of physics was closely connected with the history of physics in Berlin'. This general statement, made by H-J Treder (Kirsten and Körber 1975, p. 11), applies particularly to one of the most important physical disciplines—thermodynamics. It is noteworthy that the history of the discovery of all three laws of thermodynamics is closely linked with Berlin—the developments in thermodynamics by Hermann Helmholtz (1821–1894) as well as by Rudolf Clausius (1822–1888) and Walter Nernst (1864–1941) coincide with their working periods in Berlin. Apart from these, many more scientists who contributed fundamentally to the development of thermodynamics worked there in the last hundred years. These include: August K Kronig (1822–1879), Gustav Robert Kirchhoff (1824–1887), Max Planck (1858–1947), Jacobus Henricus van't Hoff (1852–1911), Constantin Caratheodory (1873–1950), Albert Einstein (1879–1955), Otto Warburg (1883–1970), Peter Debye (1884–1966), Walter Schottky (1886–1976), Erwin Schrödinger (1887–1961), Leo Szilard (1898–1964) and Johann von Neumann (1903–1957).

All of them are heroic figures in the history of thermodynamics and many of them were awarded the Nobel Prize in this century. Guided by the great personality of Helmholtz, scientists in Berlin not only developed the basic laws but established a specific style of thermodynamic reasoning whose tradition justifies the use of the term 'Berlin School of Thermodynamics' at least for the second part of the nineteenth century and the first decades of this century.

The heyday of physics and thermodynamics in Berlin came neither by chance nor out of the blue: it resulted from a long historical process, at the beginning of which was the foundation of the Brandenburg Academy of Sciences in 1700 by G W Leibniz (1646–1716). Today's Academy of Sciences in Berlin is the descendant of that society. With the founding of the Academy in the capital of Prussia, science established itself in Berlin as a constituent part of the

Figure 1. The house of H G Magnus at the street 'Am Kupfergraben'. In 1842 H G Magnus founded his physical laboratory here, in which many of the leading German physicists of the late nineteenth century studied.

social life. It was predominantly in the context of mathematical research and the fields of mechanics and astronomy that physics was practised. The names of such renowned scientists as Leonhard Euler (1707–1783), Johann Heinrich Lambert (1728–1777), Joseph Louis Lagrange (1736–1813) and Franz Ulrich Theodosius Aepinus (1724–1803) bear witness to the remarkable level that physical research had reached in Berlin as early as the eighteenth century. There was no other place in Germany at that time where such a community of so many and such extraordinary teachers of physics and chemistry existed.

The actual beginning of a genuine and continuous development of physics in Berlin, however, came with the foundation of the Berlin University of 1810. Of course, from the very outset a chair of physics has been part of the tutorial staff of the university. Paul Erman (1764–1851) held the first professorship in physics. His reputation as a scientist did not reach beyond local borders, but nevertheless he had been tutor to Heinrich Wilhelm Dove (1803–1879), Heinrich Gustav Magnus (1802–1870) and Johann Christian Poggendorff (1796–1877) who began to spread the fame of physics beyond the town's limits. For instance Dove was to become one of the founders of modern meteorology and Poggendorff was not only one of the co-inventors of the galvanometer but for more than half a century (from 1824) edited '*Annalen der Physik* (*und Chemie*)', which he developed into a prestigous international periodical.

Beyond doubt Magnus was the star of this triumvirate—as much for his scientific prestige (the Magnus effect in aerodynamics) as for the development of physics in Berlin. He gathered young and talented scientists at the private laboratory which he had established—basically at his own expense—in his pleasant house (*Magnus-Haus*) in the street '*Am Kupfergraben*' (figure 1) which soon became the centre of one of the most important schools of physics in the nineteenth century. The colloquium founded by Magnus in 1843 developed into the world famous Berlin Physical Colloquium.

Most of the scientists who enjoyed great prestige in physics in Germany and especially in Berlin had attended the Magnus School or, at least, had had some connection with it; figure 2 gives a 'genealogy' of the school and figures 3 and 4 show two of the most prominent members.

The list includes the names of the great physicists Helmholtz, Clausius and Kirchhoff as well as August Kundt (1838–1894), Emil Warburg (1846–1931), the co-founder of modern physiology Emil du Bois-Reymond (1818–1896) and the father of electrical engineering Werner von Siemens (1816–1892); John Tyndall (1820–1893) also received part of his scientific training at Magnus' laboratory in Berlin.

The idea of establishing a Physical Society in Berlin emerged in 1845 from this 'stimulating circle of gifted young scientists' (Siemens). The mostly very young physicists (E du Bois-Reymond, at the age of 27, was the oldest) demonstrated in this way their opposition to the established community and the ominopotence of the old professors. The celebrities of physics in Berlin accepted the Society very quickly and as early as 1845 it had 53 members. It soon became a forum of productive discussions, in which many important scientific ideas were presented to the public. Wiedemann's preface to the 'Scientific Papers' of Helmholtz (1885) says of this creative scientific community: 'The performance of each and everyone was sincerely and kindly acknowledged and mutally promoted in this unforgettable circle of the Physical Society. In fair competition the contemporaries jointly strove towards their common goals. Their work style and their achievements are still reflected in scientific research'.

This community played a special role in shaping the

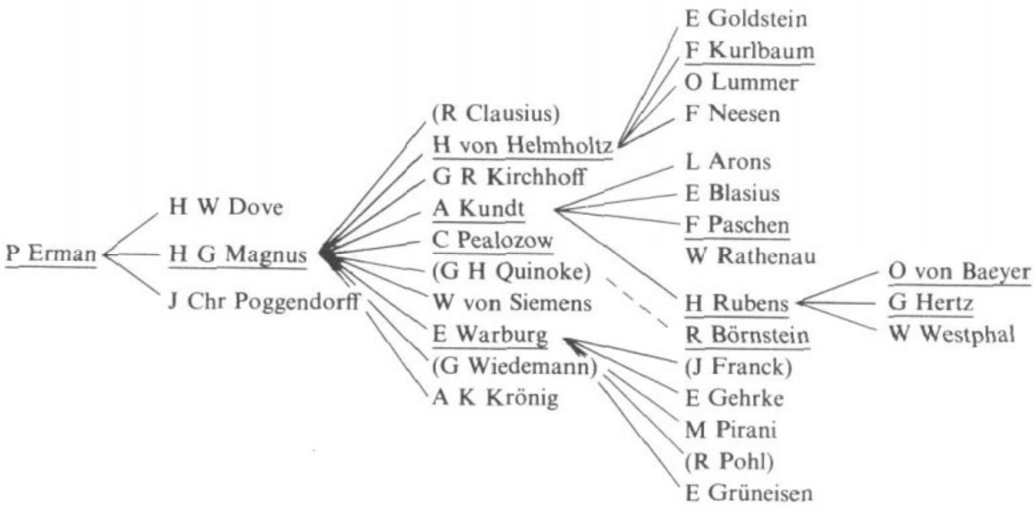

Figure 2. Genealogical tree of the Magnus School in Berlin. Underlined physicists held professorships at the university or other high schools of Berlin as well as the presidentship of the Physikalisch–Technische Reichsanstalt.

science of thermodynamics, and without doubt it was the genius of Helmholtz (see figure 4) who determined the direction and the common style of research. On 23 July 1847 he reported to the society his fundamental research into the principle of conservation of energy. At 27 years of age he was working as a military surgeon to a regiment of hussars in Potsdam, near Berlin. He could follow his interest in physics only in his leisure time, since his family's financial situation did not allow him to enjoy full-time study. The experimental research which he carried out from the beginning of the forties in Magnus' laboratory was primarily devoted to the conversion of matter and heat in such biological processes as rotting, fermentation and muscular activity. Helmholtz's insight led him to infer a new law of nature from the complexities of his measurements on juices and extracts of meat and muscles. From experiments and brilliant generalization emerged the principle of conservation of energy or what is called now the first law of thermodynamics. Neither J R Mayer nor J P Joule (not to speak of the other pioneers of the energy principle) recognized its fundamental and universal character as clearly as did Helmholtz, who must therefore be regarded as one of the discovers of the principle, although his talk to the Berlin Physical Society was given later than the fundamental publications of Mayer and Joule. Both were unknown to Helmholtz at the time.

Helmholtz had to fight hard for the recognition of his result—Poggendorf, the influential editor of the '*Annalen der Physik und Chemie*', had no wish to publish what seemed to him rather speculative and

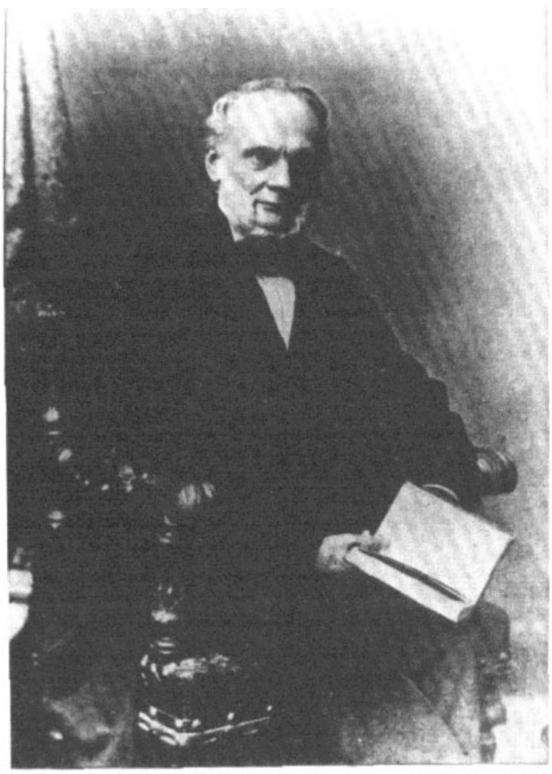

Figure 3. Rudolf Clausius (1822–1888).

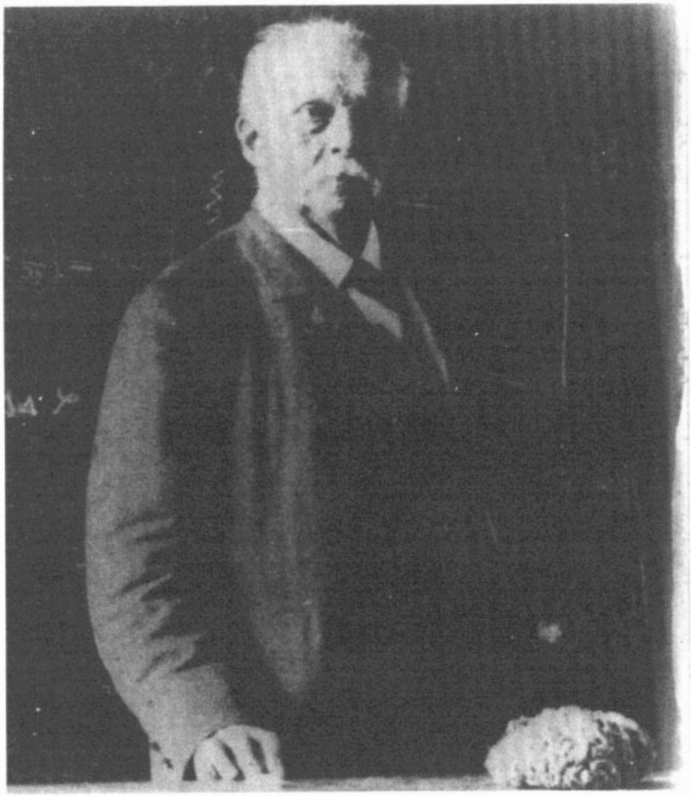

Figure 4. Hermann von Helmholtz (1821–1894).

philosophical. Magnus also regarded it with disfavour, but at least recommended that it be printed as a separate brochure, as was very quickly managed with the help of the influential Berlin mathematician C G Jacobi.

The new law of nature quickly demonstrated its fruitfulness and universal applicability. For instance Kirchhoff's law for electrical circuits are essentially a particular case of the energy principle. These laws, nowadays among the most frequently applied laws in the field of electrical engineering and electronics, were discovered during Kirchhoff's early life in Konigsberg and Berlin, and their discovery was a motive for the Berlin Physical Society to offer him foreign membership. After working at several German universities he returned, in 1875, to occupy the first chair of theoretical physics in Germany, until his death in 1887.

Rudolf Clausius (see figure 3) also played an essential role in the history of the law of conservation of energy and its further elaboration. After study in Berlin he taught for some years at the Friedrich-Werdersche Gymnasium and as a member of the Magnus circle. His report, on Helmholtz's fundamental work, to Magnus' colloquium was for Clausius the beginning of a deep involvement with thermodynamical problems. Building on the work of Helmholtz and Carnot (1796–1832) he had by 1850 developed, and published in Poggendorff's *Annalen* (see Clausius 1921) his formulation of the second law of thermodynamics. Clausius was fully aware of the impact of his discovery: the title of his paper explicity mentions 'Laws'. His formulation of the second law, the first of several, that heat cannot pass spontaneously from a cooler to a hotter body, already expresses its essence. Unlike Carnot, and following Joule, Clausius interpreted the passage of heat as the transformation of different kinds of energy, in which the total energy is conserved (see Clausius 1921). For generating work, heat must be transferred from a reservoir at a high temperature to one at a lower temperature, and Clausius here introduced the ideal cycle of a reversible heat engine. However the central ideal in his work was that not all processes which are possible according to the principle of the conservation of energy can be realized in nature. In other words the second law of thermodynamics is a selection principle of nature.

Although it took some time before Clausius' work was fully acknowledged it was fundamental not only for the further development of physics, but also for science in general. In his later works he arrived at more general formulations of the second law—the form valid today was reported by him at a meeting of the '*Züricher Naturforschende Versammlung*' in 1865.

Figure 5. The world renowned Physical Institute of the Berlin University at the street 'Am Reichstagsufer'. In 1879 it was opened under the directorship of Helmholtz and in the last days of the Second World War—during the battle of Berlin—it was destroyed. At the left corner of the building is the Institute of Physical Chemistry, where Nernst developed the third law of thermodynamics and in which he worked between 1905 and 1922.

Then for the first time, he introduced the quotient of the quantity of heat absorbed by a body and the temperature of the body (dQ/T) as the change of entropy.

August Karl Kronig (1822–1879), also a student of Magnus and a member of the Berlin physical community, was another pioneer of thermodynamics. In 1856 he published a paper in which he described a gas as a system of elastic, chaotically moving particles and his attempt at this time to apply probability theory to the description of molecular motion, makes him one of the pioneers of the modern kinetic theory of gases.

In 1871, after professorships in anatomy and physiology at several German universities, Helmholtz returned to Berlin to succeed Magnus as director of the physical institute of the university. Then began a very productive period in the history of physical research in Berlin. During the next two decades Helmholtz's direction of physical research in Berlin made it world famous. In this period, as Professor of Physics, Director of the Physical Institute (see figure 5), President (after 1887) of the newly founded Physikalische-Technische Reichsansalt, knighted in 1882, Helmholtz was acknowledged representative of scientific research in Imperial Germany. Being also engaged in the field of science policy, and seeking to connect physics and technology more strenuously than any other contemporary scientist, he attracted the reverential (and ironic) 'title' of Reichkanzler der Physik. No burning questions of contemporary physics remained untouched by Helmholtz or his fellow workers, but thermodynamical problems remained central. Just as the social need for powerful and efficient power engines gave strong impetus to the discovery of the two laws of thermodynamics, so Helmholtz's later thermodynamical research was socially determined. The chemical industry, especially the large-scale production of fertilizers and dyes grew enormously during the second part of the nineteenth century, and necessitated a thermodynamic description of chemical processes. A very stimulating atmosphere existed in Berlin for such research—many excellent chemists worked at the university and in several industrial laboratories. August Wilhelm Hofmann (1818–1892), who had held the Chair of Chemistry since 1868 and was a world famous scientist and the pioneer of the English and German dyestuff industry, stimulated the building of a second chemical institute at the university with a physical–chemical orientation. One of its directors was Walther Nernst (1864–1941).

During Helmholtz's second period in Berlin his work revolved around pure and applied problems of thermodynamics. Using the general laws for thermochemical and galvanical processes he advanced the theory and opened up new fields of practical application. He developed the concept of free energy and investigated the relationship between the heat of reaction and the electromotive force of a galvanic cell. The thermodynamics of electrical double layers at boundaries also proved important when it became a keystone of modern physical chemistry and biophysics, as well as semiconductor electronics. We may also note that thermometric and calorimetric investigations dominated the activities of the Physikalische-Technische Reichsanstalt during Helmholtz's presidency. The Reichsanstalt's studies of lighting stimulated the scientific exploration of the

Figure 6. Walther Nernst (1864–1941) painted by Max Liebermann.

physical basis of light generation, and led to the development of a thermodynamical theory of heat radiation. Helmholtz's pupil and co-worker Wilhelm Wien (1864–1928) was a leader in this field and in collaboration with the Reichsanstalt concerned himself with measuring the spectral distribution of radiation and established it on a sound theoretical foundation. The critical explanation of Wien's formula and attempts to derive it from the basic laws of electrodynamics and thermodynamics formed the starting point for Max Planck's quantum theory.

In 1889 Planck was called to succeed Kirchhoff in the Berlin Chair of Theoretical Physics where he became one of the most famous of theoretical physicists, in particular a world authority in the field of thermodynamics. He was a pioneer in understanding the fundamental role of entropy and its connection with the probability of microscopic states. Later he improved Helmholtz's chemical thermodynamics and his theory of double layers, as well as developing theories of solutions, including electrolytes, of chemical equilibrium and of the coexistence of phases.

In Max Planck, Helmholtz found a worthy successor, and not only in relation to his merits in thermodynamics. The universality of Planck's work embraced practically all branches of contemporary theoretical physics, while his unique personality entitled him to succeed Helmholtz as uncrowned head of the Berlin physics community and pivot of the scientific life in Berlin during the first part of this century.

Planck reinforced thermodynamics in Berlin through invitations to other leading specialists, such as Jacobus Henricus van't Hoff (1852–1911) whom, supported by Nernst and others, he nominated for a professorship at the Academy. There van't Hoff had no teaching duties and could choose his topics of research absolutely freely. As 'the creator of a fruitful new branch of molecular physics' (Kirsten 1975, p 136) he made important contributions to the theory of solutions and solution–salt equilibria. Furthermore he showed by thermodynamic methods the dependence of chemical equilibrium on temperature and pressure and discovered the fundamental laws of chemical kinetics, which remain the basis for the calculation of chemical processes. Finally he gave the first correct interpretation of osmotic pressure and introduced chemical affinity as the driving force for chemical reactions. These last researches persuaded the Stockhom Nobel committee to award van't Hoff the first Nobel prize in chemistry (1901) which opened the long list of Berlin Nobel laureates.

The call of Walther Nernst (see figure 6) in 1905 was another remarkable event for the Berlin school of thermodynamics. Nernst was one of the founders of physical chemistry and his work on the thermodynamical foundations of electrochemistry had made his reputation as a leading contemporary scientist. He quickly justified his high reputation—as early as his first year in Berlin he developed the third law of thermodynamics.

Nernst's seminal idea arose from the critical analysis of experimental data on chemical and electrochemical reactions in the liquid phase at low temperatures, where it appeared there was good correspondence between the free energy and the internal energy—already M P Bertholet had hypothesized the identity of these quantities, and Nernst found by his analysis that the correspondence improved at lower temperatures. This led him to suggest that the difference between the two vanishes asymptotically at the zero point. Some years later Planck gave Nernst's new principles the following general and widely known formulation. 'The entropy of all bodies which are in internal equilibrium vanishes at the zero point of temperature.'

After postulating his new theorem Nernst and his collaborators took great pains to prove and develop further this new law of nature. The specific heat, being of special importance, was determined for several substances at low temperatures. At that time this was a very difficult scientific problem which called for the construction of equipment and instruments from scratch. During the decade until the outbreak of the First World War Nernst could rely on the collaboration of an international group of gifted students, among whom Arnold Eucken (1884–1950) and Frederick Alexander Lindemann (1886–1957) (later Lord

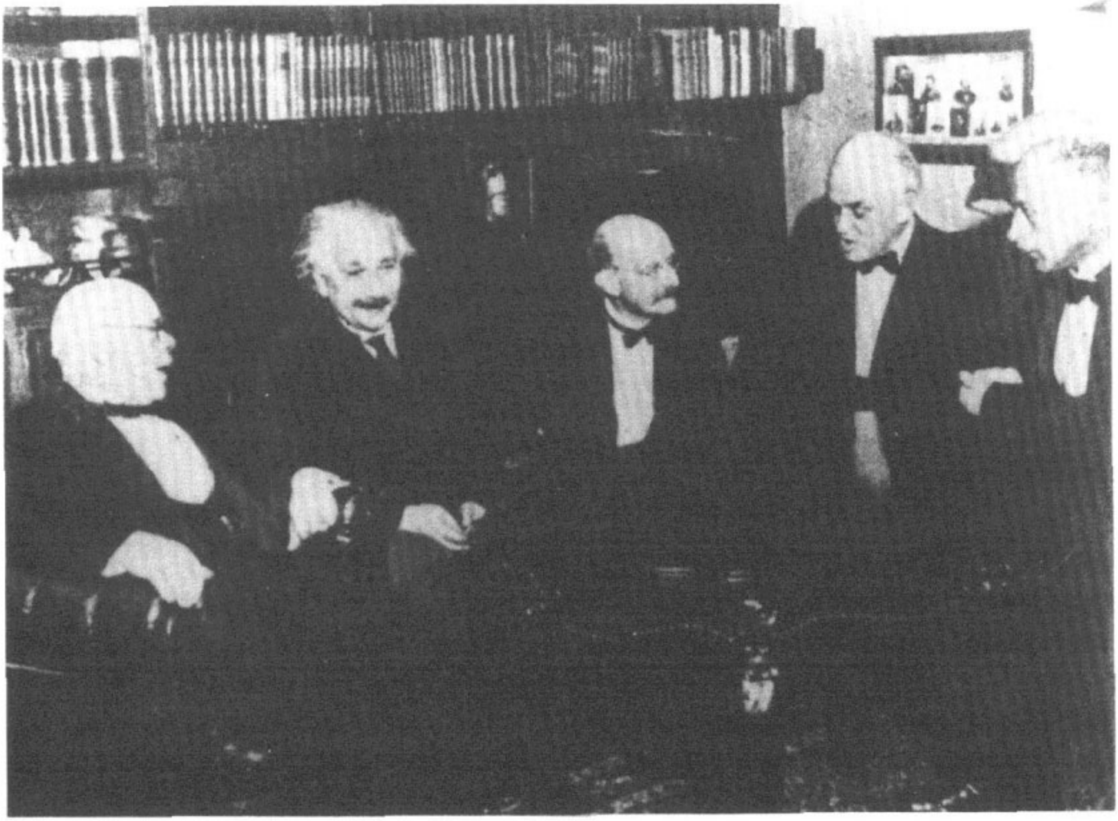

Figure 7. The heroes of Berlin Physics of the twenties—W Nernst, A Einstein, M Planck and M von Laue—with their American colleague R Millikan (second from right) during a meeting in the flat of M von Laue (1923).

Cherwell) took a leading part. Their excellent measurements corroborated the Nernst theorem at low temperatures, and with these investigations Berlin became one of the leading centres of the young field of low-temperature physics. This tradition was continued later at the Reichsanstalt by Walther Meißner (1882–1974) who liquified helium in 1925 and discovered the Meißner–Ochsenfeld Effect in 1933, and after 1936 by Peter Debye (1884–1966) at the new Kaiser-Wilhelm-Institut for Physics where he proposed the technique of adiabatic demagnetization. As one of the most universal physicists of our century Debye contributed to almost all branches of molecular physics as well as to the development of thermodynamics.

At the same time (1907) as Nernst's group was working on the experimental verification of the heat theorem, a theoretical work was published by Albert Einstein who was still working at the time at the Bern patent office. Einstein proposed that quantum statistics led to the vanishing of the specific heat of a solid at zero temperature. His theory attracted the attention of Nernst and his collaborators and by 1910 they succeeded in confirming this prediction. In this way the third law of thermodynamics as well as the young and still controversial quantum theory found one of its first experimental verifications.

Through these investigations Nernst became not only one of the earliest and most committed prophets of the quantum theory—he was the initiator of the first Solvay conference (1911)—but also a firm supporter of the young Einstein.

In 1913, together with Planck, he was able to bring the 'new Copernicus' into the exclusive circle of Berlin physicists and they could offer the unconventional genius excellent working and living conditions.

As a 'paid genius' in Berlin, Einstein could complete his general theory of relativity, and make further important contributions to thermodynamics. In 1924 he gave a correct explanation of gas degeneracy by means of a new quantum statistics—the so-called Bose–Einstein condensation. In addition to the Bose–Einstein condensation his ideas about the interaction between radiation and matter should be emphasized. His discussion (in 1916) of spontaneous emission of light and induced emission and absorption forms the theoretical basis of modern laser physics.

Concerning the many other fundamental contributions of the Berlin school of thermodynamics we must restrict ourselves to brief remarks. The German–Greek mathematician Constantin Caratheodory who formulated thermodynamics on an axiomatic basis held a professorship at the Berlin University between 1908 and 1920. His analyses of such fundamental concepts as temperature and entropy in terms of the mathematical theory of Pfaffian differential forms were not appreciated by most of his contemporaries, although Planck was an early supporter of what has become one of the important branches of modern thermodynamics.

If Carathedory was an excellent theorist of thermodynamics, Walter Schottky (1886–1976) did much for the practical application of the theory. Schottky studied physics and mathematics at the University of Berlin, graduating in 1912 as one of Planck's few students. His scientific work was closely connected with the electrical firm Siemens, of Berlin. Thermodynamics owes him the formulation of the thermodynamical foundations of gas and semiconductor electronics; moreover he was co-author of an important textbook '*Thermodynamik*' (published in 1929).

In addition to Einstein, the Hungarian Johann von Neumann (1903–1957) as well as the Austrian Erwin Schrödinger (1887–1961), made important contributions to the statistical and quantum-theory foundations of thermodynamics in Berlin. Von Neumann belongs to the group of 'surprisingly intelligent Hungarians' (D Gabor, L Szilard, E Wigner), who studied and worked in Berlin around this time, during which period he wrote his fundamental book '*Mathematische Grundlagen der Quantenmechanik*' (published in 1932). It is here that he presented the well known von Neumann equation and other ideas which have since formed the basis of quantum statistical thermodynamics.

Another prominent assistant and lecturer at the University of Berlin was Leo Szilard. His thesis (1927) 'On the increase of entropy in a thermodynamical system by the action of intelligent beings' shows the connection between entropy and information. This now classic work is probably the first thermodynamical approach to a theory of information processes and, as in the work of von Neumann, deals with thermodynamical aspects of the measuring process.

Finally mention must be made of the important contribution of the Berlin school to the development of biological thermodynamics. This problem was raised earlier by Helmholtz and received a fresh impetus through the work of Otto Warburg (1883–1970). After working in several institutions in Berlin this very successful and ambitious scientist obtained the directorship of the Institute for Cell Physiology, founded in 1931. Warburg's fundamental investigations of thermodynamical processes in living cells earned him the Nobel prize for medicine and physiology in 1931.

Later Erwin Schrödinger contributed significantly to the foundation of biological thermodynamics. In 1927 he moved to Berlin to succeed Planck in the chair of theoretical physics. In the fall of 1933 he resigned from this post and after some years of travelling (England, Belgium, Austria) in 1939 he found his final refuge in Dublin. Here in 1944 he published his little book '*What is Life*?', which considerably influenced the development of science and molecular biology through its ideas about the gene and its mutations. Such ideas had already been discussed in the thirties within the small circle of Berlin scientists around the Russian geneticist Nikolai W Timofeeff-Ressowsky (1900–1981) and the physicists Max Delbrück (1906–1981) and Karl G Zimmer (1909–1981)—indeed without perceptible connections with their colleague Erwin Schrödinger.

A historical review of the great tradition of thermodynamical research in Berlin cannot conclude without notice how this epoch of important physical research suddenly ended when in January 1933 German fascism gained power. Many scientists, from the Nobel laureates Einstein and Haber to the greatly talented Szilard and Delbrück and countless others, were discharged from their positions. The University of Berlin alone lost about 250 lecturers, and academic life in Berlin more than 500 qualified scientists. Physics was blasted by this mass exodus of high talent. It is impossible to determine the total damage which German fascism and the war caused in the field of physics (not the speak of the other felonies of German fascism) but the effects still persist. Destroyed scientific institutions can be re-constructed (though only with considerable efforts); talents can develop once again; but the atmosphere of high creativity that characterized the cultural climate of Berlin scientific life in general, and its school of thermodynamics especially, was the work of many generations—a work constructed with difficulty, but easily destroyed. The physicists, and especially the researchers in thermodynamics, working nowadays in Berlin look to the spirit of Helmholtz, Clausius and their followers as the guiding star for their efforts.

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