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(*b*, Breslau, Germany [now Wroclaw, Poland], 11 December 1882; *d*. Göttingen, Germany, 5 January 1970)

theoretical physics.

Born was the son of Gustav Born, a professor of anatomy and Margarethe Kauffmann, who came from a family of Silesian industrialists. Born attended the König-Wilhelms-Gymnasium in Breslau and began his university studies in that city in 1901. At first he attended lectures on a wide variety of subjects, but he soon discovered that his interest lay in mathematics and the exact sciences.

After three semesters at Breslau and two summer semesters at Heidelberg and Zurich, in 1904 Born entered the University of Göttingen, where he immediately established a close relationship with Hilbert. Born was given the honor of preparing the lecture transcripts for the mathematics reading room, and in this capacity he became Hilbert's private assistant in 1905, Born never let these manuscripts, which are written in an exceptionally clear hand, out of his possession; they later accompanied him when he emigrated and when he returned to Germany. The extensive knowledge of mathematics that Born acquired in preparing Hilbert's lectures became one of his greatest assets.

Even before the publication of Einstein's papers, Born had been introduced to the problems of relativity in Hermann Minkowski's seminar on the electron theory. There he became familiar with the works of Fitzgerald, Lorentz, Larmor, Poincaré, and others, as well as with Minkowski's own ideas (first published in 1907).

At the same time, in the winter semester of 1904–1905, Born attended the seminar on selected topics in the theory of elasticity given by Felix Klein in collaboration with Ludwig Prandtl, Carl Runge, and Woldemar Voigt. His report on the stability of elastic wires and tapes impressed Klein, who persuaded the philosophical faculty to set this problem as the subject of a prize competition. Born's decision not to submit an entry but to turn his attention, instead, to relativity angered Klein, who was virtually all-powerful at Göttingen. Born found himself obliged, against his will, to write a paper for the contest. This circumstance also determined the subject of his dissertation, for papers accepted in the prize competition automatically qualified as dissertations.

After receiving his doctorate in 1907, Born returned to Breslau. His plants to learn scientific experimentation from Lummer and Ernst Pringsheim were not realized; and he decided to pursue the questions raised by Minkowski. In 1908 he sent the manuscript of a paper to Minkowski, who immediately invited him to come to Göttingen as an associate. What should have been a fruitful collaboration ended with Minkowski's sudden death at the beginning of 1909. It fell to Born to put Minkowski's scienfic papers in order, and from them he was able to produce a paper "Eine Ableitung der Grundgleichungen für die elektromagnetischen Vorgänge in bewegten Körpern vom Standpunkte der Elektronentheorie (Aus dem Nachlass von Hermann Minkowski bearbeitet von Max Born)," *in Mathematische Annalen* ,**68** (1910), 526–551.

When Born presented his own, independently developed ideas on the self-n energy of the relativistic electron to the Mathematische Gesellscaft in Göttintgen, Klein interrupted him so often that he became completely confused. But Hilbert and Runge took his part and arranged for him to speak again at a later session. This time it went well, and Born was invited by the theoretical physicist Woldemar Voigt to use this work for his habilitation

In 1909 Born went to Cambridge, to J. J. Thom son and Joseph armor, "in order to learn something about the electron at the source." After several months he returned to Breslau, where Stainslaus Loria acquainted him with the works of Einstein. Born wrote, "Although I was thoroughly familiar with the notions of relativity and the Lorentz transformations, Einstein's train of thought came as a revelation to me."

In 1912 Born accepted an invitation from Michelson to lecture on relativity theory at the University of Chicago. The following year he married Hedwig Ehrenberg, the daughter of Viktor Ehrenberg, a professor of law in Leipzig. They had two daughters and one son, Gustav, who, like his paternal grandfather, became a biologist.

While Born's initial scientific works concerned relativity theory, the second major group of his publication was inspired by Einstein's work of 1907 on specific heat. In 1912 Born and Theodor von Kármán published "Über Schwingungen in Raumgittern," which contains a theretical foundation for the deviations from Einstein's quantum formula that had been experimentally ascertained by Nernst and his collaborators. Einstein considered only the case of crystals with a single frequency. Born and Kármán. however, showed that it is not the atoms of a crystal that should be considered as independent resonators but, rather, the principal oscilations, which lie in a determined frequency range. Their paper was recorded as "received on 20 March 1912" by the *physikalische Zeitschrift*. A few days earlier, Peter Debye had reported similar results (reached, however, by an entirely different approach) to the March session of the Swiss Physical Society. Born and Kármán did not learn of these findings until after the publication of their own paper. Scientists generally preferred Debye's theory, which was easier to work with and clearer from a physical point of view. This theory fails at very low temperatures, however, whereas that of Born and Kármán gives the correct observed values in this region as well.

Born undertook to erect a unified crystal physics on atomic foundations. This work soon exceeded the normal compass of a journal article and appeared in 1915 as *Dynamik der Kristallitter*. The physical nature of the forces between the atoms in the lattice was unknown at the time (except in the case of the ionic crystals); it was only decades later that the question was elucidated with the help of the quantum theory. Nevertheless, by assuming very small deviations of the "crystal particle" from the position of rest – an assumption that, independently of the universally valid force law, always leads to a linear relationship between displacement and force–it was possible to derive the essential elastic, thermal, electric, and optical properties of the crystals. Born provided a comprehensive exposition of lattice dynamics, in brief, through *Dynamik der Kristallgitter and* and his article in *Encyclopadie der mathematischen Wissenschaften* which appeared in 1923 as a book entitled *Atomtheorie des festen Zurstandes*. Simultaneously, he laid one of the cornerstones of solid-state physics.

Born also devoted a considerable part of his later work to these problems. In *Handbuch der Physik* he and Maria Göppert-Mayer reported on developments up to 1933. After World War**11** he collabo- rated with Kun Huang, professor at the University of Peking, on a new version of this work, based completely on quantum theoretical foundations. *Dynimial l'Theory of Crystal Lattices* (1954).

In 1915 Born was called to Berlin as extraordinary professor, to relieve Max Planck of his lecture obligations. ;"It is really an uncommon stroke of good luck for me;" he wrote to Johann Jakob Laub in Buenos Aires, "to be appointed in the middle of the war . . . . I have been assigned to the army service corps (telegraph, etc.) . . . Germany's power is great and her cause is good; we are happy to be her sons." Born was able to spend most of his time in the army in Berlin, in the office of the ordnance testing commission. Despite the difficulties and privations of the war and of the postwar period, his years in Berlin (1915 1919) were, in his own judgment, among the best of his life. He was close to Planck and Einstein, and with the latter he began a deep friendship to which both have left ample testimony.

In 1919 Born and Max von Laue exchanged their teaching positions. Born assumed Laue's post at Frankfurt, where he had a small laboratory at his disposal. Here his assistant, Otto Stern, working with Walther Gerlach, conducted experiments that later became famous on the directional quantization of atoms in the magnetic field. Stern began in 1919 with a direct demonstration of Maxwell's law of velocity distribution. "This gave me the idea", Born stated, "of making other quantities appearing in the gas theory, which up to now have been established only indirectly, accessible to measurement by means of molecular rays." This intention was the origin of a series of experimental works, above all a direct measurement of the free path length of gas molecules, which he did with his assistant Elisabeth Bormann.

Two years later Born was offered a post at the University of Göttingen, where more than a decade earlier he had made a strong personal impression by earning the doctorate with a prize work and by his habilitation. In negotiations with the farseeing Prussian minister of education, Carl Becker, Born succeeded in having James Franck appointed at Göttingen at the same time as himself. Since it now included Hilbert, Born, Franck, and Robert Pohl–all of whom were deeply immersed in current scientific problems– the Göttingen faculty covered the whole range from mathematics,through theoretical physics. to experimental physics. The preconditions were thereby created productive collaborative efforts.

At first Born continued his investigation of the dynamics of the crystal lattice, but later regretted having devoted so much time to it. (He encouraged his students to choose dissertation topics in this field until 1926.) After the "Bohr-Festspiele"–a major lecture series that Bohr gave at Göttingen in June 1922–questions concerning the quantum theory became paramount. In the seminar on the structure of matter, which was attended by mathematicians as well as physicists, the structure of the atom henceforth held the center of attention.

Through his "correspondence principle,"Bohr had explained that any future "quantum theory" must differ fundamentally from classical physics but that a relationship nevertheless exists between them and that, accordingly, the task is to find the "transition." Thus Born, inspired by Bohr's remarks, sought to establish a "quantum mechanics" The new term first appeared in "Über Quantenmechanik," in *Zeitschrift fur Physik* (1924). Born believed that in substance this work was only a precursor employing a method already known (by Kramers, Heisenberg, and others) in which certain differential operators of classical mechanics were replaced by difference operators. The resulting second-order perturbation formula for the energy was in full agreement with the one later developed in quantum mechanics. The paper "Zur Quantenmechanik aperiodischer Vorgänge." in *Zeitschrift fur Physik*,**33** (1925), 479–505, written with Jordan, utilized this same method to calculate the absorption and emission of a resonator in the radiation field, with the goal of overcoming the contradiction between classical field theory and quantum hypothesis in the derivation of Planck's radiation formula. In the course of this investigation it was found that the quantum physics pertained not to individual states but, rather, to pairs of states, to which a "transition amplitude" must be assigned.

Building on this foundation, the twenty-four-ycarold Heisenberg, who was Born's assistant, succeeded in cutting the Gordian knot in a manuscript he gave to Born in July 1925 with a view toward publication. Entitled "Über quantentheoretische Umdeutung kinematischer and mehanischer Beziehungen:", this paper contains the conceptual foundations of matrix mechanics.

Born immediately recognized the work's, recognized reaching significance. Heisenberg's multiplication rule left him peace, and after eight days of intensive thinking and examining, he suddenly remembered an algebraic theory he had learned at Breslau from his teacher Rosanes. Such quadratic schemata, well-known to mathematicians, are called "matrices" when they are in conjunction with a definite multiplication rule. He applied this rule to Heisenberg's quantum condition and found that the latter agreed with the quantities appearing in the diagonal. It was easy to guess what the remaining quantities must be – null–and he was immediately confronted with the formula $pq - qp = h/2\pi i$. This meant that the coordinates q and the impulses p could not be represented by numerical values but, rather, through symbols the product of which is dependent on ordering– they do not commute. This result convinced Born that they were on the right path. Yet a large portion of it had only been guessed at: the disappearance of the nondiagonal members in the above expression. In this connection Born enlisted the aid of his student Pascual Jordan, and in a few days they succeeded in showing that Born had guessed correctly.

Born and Jordan published "Zur Quantenme-chanik" (1925) as a sequel to Heisenberg's work. After this joint paper had been sent to *Zeitschrift für Physik,* Born traveled with his family to the Engadine. After returning in October, he continued his collaborative study with Jordan. At first they maintained a lively correspondence with Heisen-berg, who was with Bohr in Copenhagen: Heisenberg then returned to Göttingen before the end of the month and participated in writing a definitive account of the new ideas. They had to work quickly , since Born had to leave Göttingen at the beginning of November to give a series of lectures at the Massachusetts Institute of Technology. This was the origin of the *Dreimännerarbeit* ("Zur Quanten-mechanik II"), written shortly before Born's departure for the United States.

The new matrix mechanics was at first applied only to the very simplest cases, such as the harmonic and the anharmonic oscillator; but by October 1925 Wolfgang Pauli had calculated the complete hydrogen spectrum. Physicists finally had at their disposal the long-sought new method for computing the atom's stationary states, which had so long resisted an exact mathematical treatment. As Pauli had shown in the first nontrivial example, the results were correct. Still, in its original formulation matrix mechanics was suited to the description only of periodic processes.

In the summer of 1925 Norbert Wiener gave a well-received lecture at Göttingen; and as a result he was invited by Born, Hilbert, and Richard Courant to work at the university during the summer session of 1926. Before that, however, in the winter of 1925- 1926, Born had been a guest lecturer at the Massachusetts Institute of Technology, where he began a highly productive collaboration with Wiener. At the latter's suggestion, "matrix" was replaced by the general concept of an operator. Wiener has said that Born had some doubts; Hilbert was consulted and gave his approval. The idea was elaborated in "Eine neue Formulierung der Quantengesetze fur periodische und nicht periodische Vorgänge" (1926).

Very soon after publication of Erwin Schrö-dingcr's works on wave mechanics. Born recognized–despite Heisenherg's and Pauli's objections to its basic conceptions–that the new theory was acceptable from a mathematical point of view; and he used Schrödinger's method of treating atomic scattering processes. Applied to a standard scattering problem with known interaction–the scattering of a particle in an external field –the quantum theory permitted an exact calculation only in principle; except in special cases the basic differential equations could not be solved. With "Quantenme-chanik der Stossvorgänge" (1926) Born elaborated the basis of the "Born approximation method" for carrying out the actual computations; the method has since grown steadily in importance.

Rutherford's formula for the scattering of α particles by atomic nuclei, which he derived in 1911 from nonrelalivistic mechanics and confirmed experimentally, was derived as the first Born approximation by Born's student Gregor Wentzel. It is characteristic of the entire method that it yields the statistics of the scattering process directly without having to introduce physically meaningless –because not measurable –quantities. If the question is treated by means of classical mechanics, it is necessary to work with the concept of the collision parameter and then to ascertain its mean value. From the formalism Born was also able to derive the existence of energy thresholds, a typically quantum mechanical effect in inelastic scattering processes. He thereby established a connection between the theory and the experiments of Franck and Hertz.

With Born's method it became possible to provide a systematic treatment of a large portion of the atomic scattering processes. This point can be illustrated, for example, by the great extent to which N. F. Mott and H. S. W. Massey draw on Born's work in their *Theory of Atomic Collisions* (1933). The fact that the Born approximation converges to a steadily increasing degree with the growth of energy of the colling particles makes the method very useful in modern high energy physics. Further, quantum electrodynamics, which is so far the only area of elementary particle theory that has received a satisfactorily coherent elucidation, is based on version of Born's approximation method. Richard Feynman accomplished this in a clear and elegant form with his "Feynman diagrams."

Born's" Quantenmechanik der Stossvorgänge "furnished the basis not only of the approximation method named for him but also of the statistical interpretation of the quantum theory, for which he was awarded the Nobel Prize in 1954. Born considered the square of the amplitude of the of the scattered wave $|f(k,\Theta)|^2 d\Omega$ as the probability that the scattered particle is deflected through the angle in the solid angle $d\Omega$ The next step was to conceive of the square of the absolute value of the wave amplitude $|\psi(x,y,z)|^2$ as a quantity indicating the probability that the particle will be encountered in the region of space dV

about the point (x,y,z). The current density to be assigned according to the continuity equation. to the volumetric density $|\psi|^2$gives the probability per unit area that after the collision the scattered particle will pass through a surface perpendicular to the direction of impact.

In order to obtain additional verification for this conception. Born prepared two studies (the second with Vladimir Fok) in which he considered the influence of external forces on the state of a physical system. Thus, in the summer of 1926 Born complemented the computational schema of the quantum theory with precise physical representations. The interpretation of the new calculus, further elaborated by Heisenberg and Bohr, culminated in the "Copenhagen interpretation."

Born's works found worldwide recognition, and gifted young researchers flocked to work under him. The "Born school" at Göttingen was its important to the flowering of theoretical physics as the school of Bohr at Copenhagen and of Arnold Sommerfeld at Munich. Born's students and associates included Max Delbrück, Walter Elsasser, Enroci Fermi, Vladimir Fok, Yakov Frenkel, Maria Göppert-Mayer, Werner Heisenberg, Walter Heitler, Friedrich Hund, Pascual Jordan, Theodor von Kármán, John von Neumann, Lothar Nordheim, J. Robert Oppenheimer, Wolfgang Pauli, Léeon Rosenfeld, Edward Teller, Victor F. Weisskopf, Norbert Wiener, and Euggene P. Wigner.

From his lectures Born produced the lengthy textbook *Optik* (1933), which was photostaticaily copied and widely used in the United States. He often returned to optics later in his career and in 1959 published *Principles of Optics,* written with Emil Wolf and limited to optics in the strict sense

Through his contributions to crystal physic, matrix mechanics, the statistical interpretation of the quantum theory, and the creation of his approximation method in quantum mechanics, Born showed himself to be one of the most capable physicists of his day. All this counted for nothing in 1933. On 25 April he was placed on "leave of absence," in conformity with stipulations of the "Gesetz zur Wiederherstellung des Berufsbeamtentumd" (law for the restoration of the professional civil service), which was directed against Jewish civil servants. He left Germany on 15 May and spent several months in Wolkenstein in the South Tyrol. On 25 June, at a conference in Zurich, he met Patrick M. Blackett, who invited him to Cambridge. He was appointed to the Stokes lectureship in applied mechanics, a minor post compared with his position at Göttingen. The Rockefeller Foundation gave him an additional stipend for research.

During his stay in Wolkenstein, Born had the use neither of his own books nor of a public library. Under this constraint he turned to nonlinear electrodynamics, on which very little literature existed. He discovered a deviation from Maxwell's theory, in which the energy of a point charge is finite. He worked out this idea at Cambridge with Leopold Infeld, and their account of the phenomenon is known as the Born Infeld theory.

Finding it necessary to earn additional money. Born published *Atomic Physics* (1935), based on his 1932 lectures at the Technische Hochsclude in Berlin Charlottenburg. The German edition, *Moderne Physik* (1933), had been suppressed by the Nazis.

In October 1936 Born was named Tait professor of natural philosophy at the University of Edinburgh, succeeding Sir Charles G. Darwin. Gradually he gathered a circle of students, including a number of Chinese (Peng, Cheng, L. M. Yang, and, above all, kun Huang). Born now had heavy teaching responsibilities, and he and his associates published many works based on the subjects he taught. Thus Born again became the leader of a large group of researchers. Nevertheless, as he himself stated, Edinburgh, where he was obliged to teach many basic courses, was not what Göttingen had been in its glorious period.

Besides Klaus Fuchs (who later became famous as an "atom spy"), Born's most important student at Edinburgh was Herbert S. Green. After World War II he and Born jointly published many works on the statistical mechanics of condensed systems. These publications, along with the virtually contemporaneous ones of J. E. Mayer, J. G. Kirk-wood, J. Yvon, and G. E. Uhlenbeck, established the rational theory of liquids. Born and Green provided an overall picture of the subject in *A General Kinetic Theory of Liquids* (1949).

In 1953 Born became professor emeritus at the University of Edinburgh. He returned to Germany the following year and retired with his wife to Bad Pyrmont, where he spent the rest of his life. When his name became known to the public through the awarding of the Nobel Prize, Born discovered a new mission: to draw attention to the dangers confronting man in the atomic age. On 15 July 1955, at a meeting of Nobel laureates on Mainau Island in Lake Constance, he signed, along with fifteen of his colleagues, a statement condemning the development of atomic weapons. Eventually fifty-one Nobel laureates signed the statement. In the debate over equipping the German army with atomic weapons (April 1957), he joined other leading German physicists in drawing up the" Appeal of the Göttingen 18" which strongly influenced public opinion in the Federal Republic of Germany.

Born's later essays on the history of science are, in part, extracts from the posthumously published autobiography (1975). written in two parts in 1944–1948 and 1961–1963. He wrote the latter in English so that it could be read by his grandchildren, who had become British citizens. The essays and autobiography reflect the profound change in Born's views on science and politics. From a loyal German citizen he had become a cosmopolite with British citizenship who viewed Germany's postwar problems (such as the partition of the country) with the cool detachment of a foreigner.

To ease his disposition after the depressing political analyses, he translated into English the humorist Wilhelm Busch. Finally, after some hesitation, he published his correspondence with Einstein, accompanied by an extensive commentary. Altogether Born published more than twenty books; and his bibliography lists more than 300 articles in physics journals, including those written with his students and friends.

Born was awarded the Grosses Bundesver-dienstenkreuz and nine honorary doctorates. A member of numerous scientific societies, he also received the Stokes Medal (Cambridge, 1936), the Macdougall-Brisbane Prize (Edinburgh, 1945), the Max Planck Medal of the Deutsche Physikalische Gesellschalt. and the Hughes Medal of the Royal Society.

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