served as an assistant physician, then later chief physician, of the anatomical laboratory of the psychiatric clinic. This clinical work drew his attention to various cognitive deficits, including aphasia, agnosia, and apraxia. The outbreak of the First World War placed additional demands on Brodmann's time, which included his volunteering for work in a military hospital. In May of 1916, he assumed an appointment as the prosector at the Nietleben Mental Asylum in Halle an der Saale. Here he met the much younger Margarete Franeke, an assistant at the asylum, whom he married on 3 April 1917. Although Brodmann's personal life was much enriched, Germany's growing military losses in the war brought Brodmann's scientific work to a halt.

In 1917, Emil Kraepelin, one of the early leaders in German psychiatry, opened the German Research Center for Psychiatry in Munich. Kraepelin was interested in determining how anatomy could aid our understanding of neuropathology. To this end, Kraepelin recruited Franz Nissl and Walther Spielmeyer, both with an extensive research background in neuropathology. Kraepelin had also known Brodmann during Brodmann's years in Berlin and convinced him to move to the center to work with Nissl. For Brodmann, the prospects looked bright. He anticipated a happy family life, economic security, and a prestigious academic position. The Brodmanns' first child had been born in early 1918. He would also be able to focus on scientific research with Nissl, whose work he greatly respected. Yet Brodmann did not live to enjoy the fruits of his labors. In an era lacking in antibiotics, Brodmann succumbed to a massive infection on 22 August 1918.

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Ken Aizawa

BROGLIE, LOUIS (VICTOR PIERRE RAYMOND) DE

(*b.* Dieppe, France, 15 August 1892; *d.* Louveciennes, France, 19 March 1987), *physics, quantum theory, wave mechanics.*

Louis de Broglie achieved a worldwide reputation for his discovery of the wave theory of matter, for which he received the Nobel Prize for physics in 1929. His work was extended into a full-fledged wave mechanics by Erwin Schrödinger and thus contributed to the creation of quantum mechanics. After an early attempt to propose a deterministic interpretation of his theory, de Broglie joined the Copenhagen school's mainstream noncausal interpretation of the quantum theory. Stimulated by David Bohm's revival of his views in 1952, however, de Broglie returned to his early interpretation. Throughout his career, de Broglie wrote an impressive number of specialized books, together with more general accounts aimed at popularizing modern twentieth-century physics and discussing its philosophical issues.

Early Life. Louis-Victor de Broglie was the son of Victor, duc de Broglie, and Pauline d'Armaillé; he was the younger of two brothers in a family of five children. His family, from a noble Italian (Piedmont) lineage, the Broglia, settled in France when Francesco Maria Broglia followed Cardinal Jules Mazarin in the seventeenth century. After that time, the family served the French kings and then the French state in military and diplomatic affairs. With the brothers Maurice and especially Louis, it added to its famous representatives (among them three state marshals) two world-rank physicists of the twentieth century.

In 1901, Louis's family moved to Paris where he studied at the Lycée Janson de Sailly. He entered the university La Sorbonne in 1909 and first studied history, obtaining his *licence ès lettres* in 1910 before briefly switching, apparently without much conviction, to law. Soon, however, deeply impressed by Henri Poincaré's writings, he changed his mind and enrolled in the Faculty of Sciences, studying physics and mathematics in the years 1911–1913. Louis did not have to try hard to convince his family of his choice: His elder brother, Maurice, himself a physicist, who had been in charge of supervising Louis's education since the death of their father in 1906, encouraged this decision. To supplement the somewhat conservative education dispensed at the Sorbonne, Louis caught up with the most recent theoretical research, independently reading the works of the leading theorists of his time, Paul Drude, Paul Langevin, Hendrik Lorentz, Max Planck, and Poincaré. He obtained his *Licence ès sciences* in 1913. This same year, he joined the army to complete his military service. Maurice, who served for a long time in the navy's wireless communications, arranged for him to

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fulfill his duties with the team at the Eiffel Tower's radiotelegraphy station.

The outbreak of World War I marked a pause in Louis's pursuit of strictly theoretical speculations. Instead of being released after the regular three years of service, he stayed in the army until 1919. Throughout the whole duration of the conflict, he remained on the team at the Eiffel Tower station. Though he was involved in rather innovative applied research (for instance, in collaboration with Leon Brillouin and his brother Maurice, he contributed to the development of wireless communication for allied submarines), he longed for more theoretical and fundamental work. When the war ended, Louis de Broglie resumed his studies and research work in physics. While attending the lectures of Langevin at the College de France, he also began to assist his brother with experimental investigations. At the time, Maurice was already an experimentalist with an international reputation. His private laboratory was renowned for pioneering research on x-ray spectra, and the young Louis there became familiar with the most advanced techniques of the field.

Scientific Career. During this time, de Broglie was already forming ideas which would eventually lead to his discovery of the wave nature of matter. In contrast to his more experimental research, on which he collaborated with other members of Maurice's laboratory, the theoretical ideas that would secure Louis's fame were developed in almost total isolation. After a series of three groundbreaking communications to the Paris Academy in 1923, where he outlined the basics of a wave theory of matter, he exposed his ideas in his PhD thesis *Recherches sur la théorie des quanta* (Researches on the quantum theory), which he defended in 1924. These works suggested that the idea of the dual nature of light (as both a localized particle and a wave extended in space) put forth by Albert Einstein in 1905 should be applied to matter as well. With the successful extension of de Broglie's results by Schrödinger, and then especially with the discovery of electron diffraction in crystals by Clinton Joseph Davisson and Lester Halbert Germer at Bell Labs in the United States in 1927, and by George Paget Thomson at the University of Aberdeen in Scotland in 1928, which demonstrated experimentally that material particles exhibited wavelike properties, de Broglie's ideas were spectacularly vindicated. In 1929 the Swedish Academy of Sciences conferred on him the Nobel Prize for Physics "for his discovery of the wave nature of electrons."

After two years of lecturing at the Sorbonne, Louis was appointed *maître de conferences* in 1928 to teach theoretical physics at the Institut Henri Poincaré, which had been just created in Paris and was devoted to mathematical and theoretical physics. He obtained the chair of physical theories at the Paris Faculty of Sciences in 1933 and taught there until his retirement in 1962. De Broglie led a rather withdrawn life and never married.

De Broglie was elected a member of the Academy of Sciences in 1933 (*section des sciences mécaniques*), and was elected its permanent secretary in 1942 (*division des sciences mathématiques;* he resigned this charge in 1975). In 1929 he was the first recipient of the Henri Poincaré Prize of the Académie des Sciences and in 1932, he was granted the Albert I of Monaco Prize. In 1952 he received the first Kalinga Prize of UNESCO for his efforts to explain aspects of modern physics to the layman. He was elected a member of the Académie Française in 1944, (one of the fellow academicians to greet his election was his brother Maurice, himself elected in 1934). In 1945 he became an advisor to the French Commissariat à l'Energie Atomique (CEA). In 1956 he received the gold medal of the Centre National de la Recherche Scientifique (CNRS) and in 1961 he was decorated with the Grand Cross of the Légion d'Honneur (1961).

He was elected Fellow of the Royal Society in 1953 and was an Officer of the Order of Leopold of Belgium. He was an honorary doctor of the universities of Warsaw, Bucharest, Athens, Lausanne, Quebec, and Brussels, and a member of eighteen foreign academies in Europe, India, and the United States.

Development of de Broglie's Theory. Louis's acquaintance with quanta went back at least to his reading of his brother's reports and notes from the first Solvay meeting in 1911, where Maurice served as scientific secretary. According to Louis's recollections, he was immediately caught by the puzzle of the quanta and promised himself that he would devote all of his energy to understanding it. His work in his brother's laboratory was instrumental in providing him with firsthand knowledge of some aspects of the new phenomenology, essentially those related to the study of x-ray absorption and of the x-ray-induced photoelectric effect. The context of this research was the further study of the atomic structure, where investigation of the inner energy levels was made possible using x-rays instead of visible light. Serving as a house-theoretician, Louis de Broglie had to learn the most up-to-date theories to be able to interpret the experimental results. Alone, with Maurice, or with his collaborator Alexandre Dauvillier, Louis published numerous observations on the inner atomic levels and their occupation numbers, on the relation between absorption intensities and the number of levels and of the electrons, and on the photoelectric effect. This enabled Louis to enter the restricted field of quantum researchers; however, his important work on the absorption intensities did not bring him only praise. In spite of the agreement of de Broglie's results with the data, Niels Bohr's close followers from Copenhagen and Munich found his derivations rather unorthodox, if not simply inconsistent with the subtle usage of Bohr's correspondence principle. This principle—that any quantum behavior must reproduce successful classical predictions at the limit where quantum effects can be neglected—was one they felt only "insiders" could properly handle.

Besides Bohr's atomic theory, Louis became familiar with Albert Einstein's light quantum hypothesis, which, at the time, was still rejected by most researchers in the quantum community. The experimentation in Maurice's lab, especially the latter's study of the x-ray-induced photoelectric effect in 1921, was making this hypothesis seem quite natural, and offered renewed arguments for those who, like Maurice, were defending the corpuscular hypothesis against more conservative (purely Maxwellian) views. Although he was not successful in persuading his colleagues of the validity of Einstein's thesis at the Solvay 1921 congress, Maurice de Broglie did not renounce his ideas about the validity of the corpuscular structure of light, but went even further in advocating, in vaguer terms, a kind of general wave-corpuscle duality valid not only for light, but for electrons (matter) as well. As is known, these ideas did not really express a clear-cut ontological thesis; however, they definitely had an impact on Maurice's younger brother.

In the years following the end of the war, many of Louis's theoretical considerations, fueled by his brother dualistic ideas and the continuation of his own prewar meditations, were centered on the formal analogy between the geometry of light ray propagation and the classical mechanics of point particles. This analogy, which had been the starting point for William Rowan Hamilton's famous nineteenth-century formulation of mechanics, if not simply ignored by Louis's contemporaries, was at any rate not taken as having the slightest physical relevance. However, Louis soon felt that it could prove crucial for better understanding the Bohr-Sommerfeld quantization scheme, which selected, among a continuity of classical motions, only a discrete range of quantically allowed ones. As explained by historian Olivier Darrigol, there did exist at the time interpretations of the Bohr-Sommerfeld quantization conditions, and some might have helped Louis in reaching his own (specifically Marcel Brillouin's "hereditary field" mechanism, or Einstein's considerations of the multivaluedness of the action). However, Louis obtained his own interpretation within a much broader scheme of a general wave-particle duality, using relativity theory as a guide—a theory that he had ample time to ponder following Langevin's outstanding teaching of the topic in the years 1920–1922.

Wave Theory of Matter. The hypothesis of light quanta was the starting point in Louis's 1922 paper "Rayonnement noir et quanta de lumière" (received on January 26 by the *Journal de Physique*) devoted to the study of the black body radiation. This work marks the beginning of Louis's final progression toward the discovery of waves associated with matter. Aiming at deriving Planck's law from a purely corpuscular standpoint, de Broglie was eventually able to derive only its low-density approximation, Wien's law, because he did not take into account the only later-derived quantum Bose statistics. However, he introduced in his paper, most significantly, the idea of a light quantum with a very small, but nonvanishing, mass. Apparently, de Broglie was guided by his desire to interpret the continuously varying energies of the light quanta as corresponding to the various (sublight) velocities these quanta could then have. As such, his light quanta did not differ from ordinary matter particles, so that the stage was set for the final step. In 1923 Louis de Broglie, in a series of three short communications to the Paris Academy, extended the wave-particles duality of light through his bold hypothesis of waves associated with matter particles. His first communication, "Ondes et quanta," dated 10 September 1923, introduced the idea of a wave associated with a particle, making use of an important observation on the relativistic transformation properties of the frequency of a periodic process as viewed in the rest frame of the corpuscle and in the laboratory frame. To start with, an "internal" periodic process could be associated with a particle of rest mass m_0 if one defined its frequency v_0 by the Bohr quantum condition (where c is the speed of light, h the Planck constant)

$$E_0 = m_0c^2 \equiv h\, v_0$$

But then, transforming to the laboratory frame, where the particle had a velocity defined as Bc (with B > 1), one ended up with two different frequencies, depending if one wanted to transform first the energy:

$$v = E / h = E_0 / h\sqrt{1-\beta^2} = v_0 / \sqrt{1-\beta^2}$$

or transform the rest frame frequency using the relativistic time dilatation formula:

$$v_1 = v_0\sqrt{1-\beta^2}$$

Louis de Broglie, initially puzzled by this discrepancy, eventually realized that one could reconcile both results provided one set the speed of the wave propagating in the laboratory equal to c / B. Indeed, this condition ensured that the wave of frequency v was constantly in phase with the internal oscillating process of the particle. De Broglie readily used this condition to show how one could then

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Louis de Broglie. © BETTMANN/CORBIS.

understand Bohr's quantization conditions in terms of the stationary character of the wave, obtained only when the electron was on one of its Bohr's orbits. In the second communication, "Quanta de lumière, diffraction et interférences," dated 24 September, de Broglie discussed the relationship between the propagation of the particle and that of its associated wave. According to Hamilton's analogy between ray optics and mechanics, the particle had to follow the trajectories of the rays normal to the phase wave fronts. De Broglie also considered the necessity of modifying the free dynamics of the particle, as the obstacles to the propagation of the wave could curve the trajectories of the particles. He identified this as a possible experimental effect that could corroborate his phase waves. The interplay between the propagation of the particle and of the waves could be expressed in more formal terms as an identity between the fundamental variational principles of Pierre de Fermat (rays), and Pierre Louis Maupertuis (particles) as de Broglie discussed it further in his last communication "Les quanta, la théorie cinétique des gaz et le principe de Fermat" (dated 8 October 1923). Therein he also considered some thermodynamic consequences of his generalized wave-particle duality. He showed in particular how one could, using Lord Rayleigh's 1900 formula for the number of stationary modes for *phase* waves, obtain Planck's division of the mechanical phase space into quantum cells.

In the next months, already working on his doctoral dissertation, de Broglie generalized the relations between the particle velocity and the wave velocity for cases where there were external forces. He again used relativity as a guide. He promoted the energy-frequency relation $E = h\,v$ to a full, four-vector (relativistic) relation between a 4-dimensional wave vector and the 4-momentum of the particle. Equating their spatial parts, de Broglie obtained his celebrated relationship between the particle momentum and the wave-length:

$$p = h\frac{1}{\lambda}$$

The more detailed derivations of his results formed the core of his dissertation, which he successfully defended on 25 November 1924 in front of a perplexed audience.

In order to reach an audience wider than the limited readership of the *Comptes rendus,* de Broglie arranged the publication of a summary of his results in *Nature* (October 1923); and a fairly complete account of his three communications appeared in the *Philosophical Magazine* (February 1924). In Germany, a summary of his communications was published in the *Physikalische Berichte* (1924). These accounts did not stir up much reaction from the community. The situation changed when, in the summer of 1924, Langevin personally informed Einstein of Louis's ideas, which the latter embraced quite enthusiastically. Indeed, Einstein quickly recognized that they fit remarkably with his own research on quantum gases. His support made many key actors in quantum research focus on and take seriously de Broglie's ideas in the years 1924–1925. In particular, Schrödinger extended de Broglie's results in the winter of 1925–1926 into a genuine wave mechanics, working out the wave equation of the theory. However, Schrödinger, while extending and completing in an essential way the original framework, altered de Broglie's original picture, granting reality only to the waves and refusing wave-particle dualism. The ensuing events, which led rapidly to the final formulation of quantum mechanics in 1926–1927, did not include the active participation of Louis de Broglie. Although he saw his ideas extended and vindicated, his conception of the meaning of his research and how it should be continued was increasingly at odds with the views of his peers.

The Meaning of Wave Mechanics. In his communications of 1923, and later in his 1924 PhD thesis, de Broglie did not want to commit himself to any physical

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interpretation of the waves. He granted physical relevance only to these wave features which could be directly related to the particle motion, namely their phase, while eluding any questions pertaining to their amplitude and proper dynamics. They were, as he dubbed them, "fictitious." However, in the months following his PhD, de Broglie started to explore the consequences of his wave-particle model for the problem of the interaction of light with matter. He also considered the possibilities of more physically interpreting his particle-associated waves. Willing to acknowledge the reality of the particles, he tried to conceive them as embodied by the singularities of the waves. However, he had then to cope with the Schrödinger view, where only continuous matter waves were considered. He first attempted to save his dualism by conceiving Schrödinger's equation as actually admitting pairs of solutions characterized by a common phase. He thought of each pair as consisting of a singular solution, with the singularity identified with the particle, while the corresponding continuous regular solution (the only one considered by Schrödinger) was interpreted as conveying solely statistical information. In this approach, the probabilistic (Max Born's) interpretation of the continuous wave reflected the inherent neglect of the singularity (the particle). This so-called double-solution interpretation was hence a causal one, conceiving Schrödinger waves as conveying all the potential outcomes, while concealing the realities of the underlying particle dynamics. These dynamics were nonclassical, owing to the fundamental fact that the particle was coupled to the wave via the guiding mechanism which related the particle's velocity to the gradient of the wave phase.

Louis de Broglie met substantial difficulties in justifying his ambitious proposal mathematically. At the Solvay congress of October 1927, feeling unable to defend his interpretation against the more orthodox views, he presented an intermediate position, which viewed the continuous wave as the sole undulatory entity: its role was to guide the particle, because it shared with the singular solution, now discarded, the same phase. This weakened position, called the "pilot wave" interpretation, was nonetheless heavily criticized by the Copenhagen orthodoxy, especially with respect to Bohr's views according to which quantum mechanics was rooted in the uncontrollable disturbance that the observation necessarily brings upon the observed system—which had been presented just weeks before.

Some time after this confrontation, de Broglie, discouraged, joined the orthodox Copenhagen position, which he then consistently defended for the next two decades. From 1930 until 1950, de Broglie turned to study of the various extensions of wave mechanics. He worked on Paul Dirac's electron theory and on the quantum theory of light, developed a general theory of spin particles, and considered some applications of wave mechanics to nuclear physics. This work, however, did not receive as much attention as what he achieved in the early 1920s.

The early 1950s again witnessed a major change in de Broglie's views. Impressed by the nonlocal theory put forth by David Bohm in 1951, which reintroduced pilot-waves, de Broglie turned back to his first theoretical convictions. Surrounded by some faithful followers, de Broglie resumed his quest for a causal interpretation, this time supplementing his initial views with the idea of nonlinear dynamics for the singular wave. This was, however, increasingly perceived as a marginal research program, even in his own country, where quantum theoreticians preferred to stick to more mainstream physics, less fundamental and closer to the wealth of new experimental data emerging in the 1950s. Although revered as one of the fathers of quantum physics, de Broglie became an isolated icon.

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Louis de Broglie published more than 150 scientific papers, about thirty books, and many philosophical and historical studies as well as numerous popular accounts, biographical notes, and obituaries. A list of all his writings has been published in Annales de la Fondation Louis de Broglie *17 (1992): 1–21. Louis de Broglie's papers are deposited in the archive of the Académie des Sciences. On the Web site of the Fondation Louis de Broglie (http://www.ensmp.fr/aflb/) one can find an English translation of de Broglie's PhD dissertation. The Fondation Louis de Broglie, dedicated to the pursuit of the ideas of Louis de Broglie, has edited texts and books of various level of scholarship commenting different aspects of the contributions of de Broglie.*

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Jan Lacki

BRONN, HEINRICH GEORG (*b.* Ziegelhausen bei Heidelberg, Germany, 3 March 1800; *d.* Heidelberg, 5 July 1862), *paleontology, zoology, morphology, geology, Darwin reception.*

Bronn was a great compiler of reference works in zoology and paleontology, but recent scholarship emphasizes that he also broke new conceptual and methodological ground by situating fossil species in geological time, geographic space, and environmental conditions. By considering when, where, and how species lived, quantifying rates and patterns of species turnover and morphological progress, Bronn helped to establish paleontology as a modern scientific discipline at the interface between biology and geology. His reference works and his editorship of an important geological journal also provided practical support for the discipline's growth.

In the 1840s and 1850s, Bronn's explanations of paleontological change centered on the physical evolution of Earth and the continual adaptation of floras and faunas to prevailing conditions. As the planet's environments changed and diversified, obsolescent species became extinct, to be replaced by better-adapted and morphologically similar, but more advanced, ones. He left open the question of how the new species arose, sometimes suggesting that divine intervention was needed, and sometimes invoking a hypothetical "creative force," and focused instead on deriving the laws that any such force would have to obey. The provisional nature of this solution, along with his lifelong attention to adaptation and diversification, made him cautiously receptive to Charles Darwin's theory of evolution by natural selection, which he introduced to German readers in his own translation, with a critical commentary at the end.

Life, Education, and Career. Bronn was the fifth of seven children of Georg Ernst Bronn, a government forestry official, and Elisabeth Margarethe Bronn. He was raised a Catholic, attended elementary school in Ziegelhausen and gymnasium in Heidelberg, and began attending the University of Heidelberg in 1817. He studied cameralism and natural history, possibly with the intention of pursuing a civil-service career like his father's. This course of study contrasts with the medical training that was more usual for German morphologists, and it allowed Bronn to range more broadly into applied sciences such as forestry, mining, and plant and animal breeding. Bronn's most influential teacher at Heidelberg was probably the geologist Karl von Leonhard.

In 1821, after completing his habilitation in natural history and *Encyclopädie der Staatswissenschaften* (general sciences of the state), Bronn began to teach at Heidelberg at the rank of Privatdocent (lecturer; paid from student fees, not on the state payroll). In 1824 and 1827 Bronn traveled to Switzerland, southern France, Austria, and northern Italy for field research. In 1828, back at Heidelberg, he was promoted to *ausserordentlicher Professor* (extraordinary professor) for topics in commerce and natural history. From 1830 on, he coedited the *Jahrbuch* (after 1833, the *Neues Jahrbuch*) *für Mineralogie, Geognosie, Geologie, and Petrefaktenkunde* (New yearbook for mineralogy, geognosy, geology, and fossil studies), which von Leonhard had founded in 1806. In 1833, he took over the directorship of the zoological collection and responsibility for teaching zoology. Finally, in 1837, he received his promotion to *Ordinarius* (ordinary, or full professor) and became head of Heidelberg's first full-fledged institute of zoology, while also retaining responsibility for applied natural history. This places him among the first generation of zoologists to establish their field as a university-based discipline.

Bronn spent the rest of his career at Heidelberg. He rose to the rank of *Hofrat* (court councillor) in the civil service, and served as university *Prorektor* in 1859–1860. Bronn's work in paleontology was honored with a gold medal from the Dutch Scientific Society in Haarlem and a prize from the French Academy of Sciences in 1857. He was married to Luise Bronn, née Penzel, and they had five children. Bronn died suddenly in 1862, apparently of a heart attack.

Paleontological Works—Overview. Bronn made his international reputation as a geologist and paleontologist between 1824 and 1831 with systematic works on fossil shells and zoophytes, and reports on the geology, paleontology, and economy of Heidelberg and of the regions he visited on his scientific travels. From 1835 to 1838 he brought out his *Lethæa geognostica,* the most complete compendium of fossil species of its time. By organizing fossils first by geological time period, and then taxonomically and geographically within each period, it put the organisms into concrete historical contexts instead of arranging them on a timeless scale of nature or in an abstract system. The arrangement also facilitated the practice, already widespread, of dating geological strata by the fossil species they contained. Other reference works followed, which featured alphabetical indexing and continued to add species and eliminate synonyms.