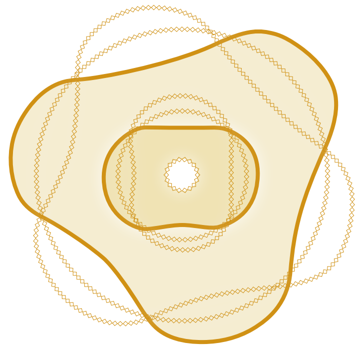
Louis de Broglie,
1929



Louis de Broglie and the Wave Nature of the Electron

Barry R. Masters

Louis de Broglie was a Frenchman of noble birth who many believed would become a great statesman or diplomat. Instead, he changed our understanding of how the universe works by developing a theory for the wave-particle duality of electrons.

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The idea that matter can exhibit the properties of both particles and waves is one of the major tenets of quantum mechanics—but it took centuries to arrive upon. Einstein paved the way in 1909 by proposing that wave-particle duality was a key property of light. This united competing theories dating back to the 1600s, when Christiaan Huygens hypothesized that light was made up of waves, while Newton argued that it consisted of particles.

Louis de Broglie extended the concept of duality to the level of the electron. Thus, he and his contemporaries showed that light and matter exhibited properties of both waves and particles—a profound paradigm shift in 20th century physics.

Early life and education

Louis de Broglie—also known as Prince Louis-Victor-Pierre-Raymond, the seventh duke de Broglie—was born in Dieppe, France, on 15 August 1892. He was the younger of two brothers in a family of five children. Generations of his family served as politicians, diplomats and soldiers and were well-known for their service in French public life. In 1901, his family resettled in Paris where Louis' father, Victor, was a member of the lower house of Parliament.

According to his older sister Pauline, Louis was talkative and inquisitive from the start, and even "the most severe injunctions of silence could not make him hold his tongue" at the dinner table. Nevertheless, since much of his early education was through private tutors, he often felt lacking in companionship among other children. For this reason, "he had read much and lived in the unreal," Pauline said. Seeming to have a taste for history, "… he improvised speeches inspired by the accounts in the newspapers," she said. His family thought he would one day become a great statesman.

Louis was only 14 when his father died in 1906; subsequently, he was raised by his older brother Maurice, an experimental physicist working on X-ray spectra. Maurice arranged for Louis to study at the *Lycée Janson-de-Sailly*, where he completed his secondary education with a major in history in 1910.

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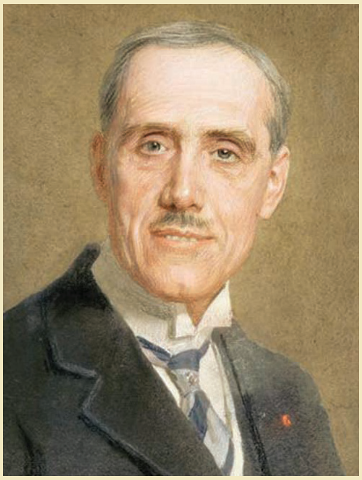
Education and influence

Louis de Broglie attended the Sorbonne in Paris.


Maurice de Broglie, Louis' older brother, was a well-known experimental physicist.


Henri Poincaré's books inspired Louis de Broglie to pursue a career in physics.

Wave-particle duality was at the forefront of Louis' work and was also of interest to Maurice.

When Louis matriculated at the University of Paris (the Sorbonne), he had no definitive career plans—although by that time he knew that he did not want to pursue a diplomatic career. His initial studies were in history and then he changed to the study of law, which could lead to a position in the French civil service.

After graduating with an arts degree at the age of 18, he found himself becoming increasingly drawn to his brother's work in physics. Maurice was likely relieved to see Louis settling on a career path. "… I refrained from imparting a rigid direction to the studies of my brother," he said, "although at times his vacillation gave me some concern. He was good at French, history, physics, philosophy, indifferent in mathematics, chemistry and geography, poor in drawing and foreign languages."

From history to physics

Louis' fascination with physics had begun when he read the works of his brother and books by Henri Poincaré—*La Valeur de la Science* and *La Science et L'hypothese*. At the Sorbonne, he had attended Poincaré's lectures on electrodynamics, thermodynamics and celestial mechanics. Theoretical physics was of particular interest to him. There were so many new theories and discoveries in the 1900s! In 1900, Max Planck had postulated the quantum of energy to derive his black-body radiation distribution law, which accounted for the experimental measurements, but the significance of the quantum was not understood. In 1905, Einstein formulated a new quantum theory of light and in 1909 he conceived of light with wave and particle attributes.

Following these discoveries, the 1911 Solvay Conference was organized to elucidate the nature of the energy quantum in physics. Maurice de Broglie was the secretary to the first Conference and worked with physicist Paul Langevin to edit the proceedings. Reading the reports about the new quantum theory solidified Louis's desire to work in theoretical physics. Later that year, he formally shifted his studies to the faculty of sciences in pursuit of a second degree. Louis wrote: "I decided to devote all my efforts to investigate the real nature of the mysterious quanta that Planck had introduced into theoretical physics 10 years earlier." He submerged himself in the publications of Poincaré, Hendrik Antoon Lorentz, Paul Langevin, Ludwig Boltzmann, Josiah Willard Gibbs, Einstein and Planck.

Louis received his *licence ès sciences* in 1913 and, as required by law, he then joined the French army. He served until 1919 as a radio operator in the Eiffel Tower during World War I. When the war ended, he quickly recommenced research with his brother. Wave-particle duality was at the forefront of his work and was also of interest to Maurice. Louis wrote: "These long discussions with my brother about the properties of X-rays … led me to profound meditations on the need of always associating the aspect of waves with that of particles."

Unlike Maurice, Louis was most interested in theoretical physics. At the Collège de France, which was located near the Sorbonne, Louis took Langevin's courses on quantum and atomic theory, relativity theory and electron theory. He studied the publications of Niels Bohr and Arnold Sommerfeld on the theory of atomic structure. He also read Einstein's papers on light and became convinced that physics required a novel, anomalous synthesis of wave and particle representations.

International Solvay Institutes for Physics and Chemistry

Industrialist Ernest Solvay founded the International Solvay Institutes for Physics and Chemistry, located in Brussels, Belgium, in 1912. The institutes were created following the legendary invitation-only 1911 Solvay Conference, which marked the beginning of the quantum revolution. The institutes run research programs on "curiosity-driven" themes in physics, chemistry and related disciplines; these programs support the Solvay Conferences, which are held every three years or so.

For more information, visit **www.solvayinstitutes.be**.

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International Solvay Institutes

Variational Principles

Louis de Broglie defines Maupertuis and Fermat's variational principles in his Nobel Prize lecture.

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Pierre Louis Maupertuis' variational principle of mechanics gives the trajectory of a particle. It states that the trajectory of the corpuscle passing through two points A and B in space is such that the integral $\delta \int_A^B p\,dl$, where p is the momentum and dl is a differential element, taken along the trajectory, is extreme.

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Pierre de Fermat's varational principle for the light ray states that the ray in the optical sense that passes through two points A and B in a medium having an index $n(xyz)$ varying from one point to another but constant in time is such that the integral $\delta \int_A^B n\,dl$ taken along this ray, is extreme.

Louis wrote: "the wave and particle points of view have been applied … to various fields. … But how can a synthesis be accomplished? Hamilton, and later Jacobi, found many similarities between the laws of mechanics that determine the motion of particles and the wave-theoretic laws that describe the propagation of wave processes." In 1923, Arthur Compton's research verified the theory of quanta.

The stage was now set for Louis to integrate contrary concepts into a new synthesis and apply them to the electron.

Extending duality to electrons

While still a graduate student, de Broglie developed a revolutionary theory that would change our understanding of the physical world: Just as waves can behave as particles, electrons can also possess a wave motion with wavelength $\lambda = h/p$, where h is Planck's constant and p is the momentum of the electron. He went to work developing a new formulation of dynamics in which particle velocities are not determined by classical laws, but by guiding or pilot waves.

By the fall of 1923, de Broglie had published three communications in *Comptes Rendus* on his radical wave-particle hypothesis. English summaries of his work also appeared in *Nature* (1923) and *Philosophical Magazine* (1924).

In his first paper, de Broglie showed that there is a "fictitious" (the wave has mathematical and not physical significance) wave of frequency ν and phase velocity $v_p = c^2/v$, which propagates in the same direction as the particle and remains in phase with the particle. The group velocity, which is the velocity of groups of phase waves with approximately equal frequencies and the velocity of energy propagation, was shown by de Broglie to be equal to the velocity of the particle. He borrowed an idea from Marcel Brillouin's dissertation and derived the Bohr-Sommerfeld quantization condition for atoms: $\oint p\,dq = nh$. He credited Brillouin as the true precursor of wave mechanics.

In his second communication, he stated that a moving body is associated with a non-material sinusoidal wave. He denoted it a "phase wave" because, at the

By the fall of 1923, de Broglie had published three communications in Comptes Rendus on his radical wave-particle hypothesis.

location of the particle, the phase of the wave is equal to the phase of the internal oscillation of the particle. His hypothesis obeys the law of conservation of energy, but negates the conservation of momentum. In de Broglie's third publication, he develops a statistical analysis of a gas of particles that are accompanied by their phase waves.

Next, de Broglie began to write his dissertation, "*Recherches Sur la Theorie des Quanta*" (Research on Quantum Theory), which postulated the idea of matter waves:

> "The presence of a free material particle is connected with the presence of a measurable wave field in space and time. This connection is such that, to a particle of momentum p and energy E, there corresponds a plane monochromatic wave, which travels in the direction of the momentum vector. The wave vector k and the frequency ν are given by the equations $k=p/h$ and $\nu=E/h$ where h is the universal quantum of action, Planck's constant."

The de Broglie hypothesis is expressed mathematically in these equations: $p=hk$ and $E=h\nu$, and the wavelength of matter waves: $\lambda=h/p$.

His relativistic theory was a brilliant unification of Fermat's principle of geometrical optics and Maupertuis' principle of mechanics. The genesis of his radical hypothesis was his analysis of the optical-mechanical analogy.

In late November 1924, Louis submitted his dissertation to the University of Paris' science faculty. Jean Perrin presided over the jury. Other members included the mathematician Élie Cartan and the physician Charles Mauguin. In addition, Langevin was invited from the Collège de France. Jean Perrin asked Louis how his hypothesis of the electron's wave-particle duality could be validated, and Louis responded "… by diffraction experiments of electrons by crystals."

Langevin was astonished by de Broglie's dissertation and sent a copy to Albert Einstein, who also found it interesting and passed it on to Erwin Schrödinger. Einstein's positive comments persuaded Langevin to accept the dissertation for de Broglie's *doctorat ès sciences*.

Einstein's 1925 paper on the quantum theory of the ideal gas demonstrated that the fluctuations connected with the new Bose-Einstein statistics yielded two terms, one related to particles and one to waves—which he interpreted as de Broglie's matter waves. Einstein referenced his dissertation, giving de Broglie's work exposure outside of France. The publication of the Schrödinger equation in 1926 also gave credibility to de Broglie's bold hypothesis. Louis was no longer an obscure physicist known only as "Maurice's younger brother."

However, his theory still needed to be tested.

Experimental verification

In 1925, Walter Elsasser, a German graduate student at the University of Gottingen, suggested that, like X-rays, electrons could be diffracted by crystals. In this case, a crystal lattice is a 3-D diffraction grating, and sharp peaks in the intensity of the diffracted beams should occur at specific angles—which would provide evidence for de Broglie's hypothesis. Unfortunately, Louis couldn't convince French experimentalists to perform it.

He didn't have to wait long. In 1927, Clinton Joseph Davisson and Lester Halbert Germer at Bell Labs in New York City, U.S.A., directed a beam of low-energy electrons at a crystalline nickel target. In order to free the target from absorbed gases, they heated it repeatedly; this resulted in the formation of a single crystal. Their seminal discovery, which also served as proof of de Broglie's hypothesis, was published in the *Bell Laboratories Record*. (Davisson and G.P. Thomson were jointly awarded the 1937 Nobel Prize in Physics for their independent discovery of the diffraction of electrons by crystals.)

Louis was awarded the 1929 Nobel Prize in Physics for his discovery of the wave nature

The 5th Solvay International Conference (1927), where leading physicists discussed the newly formulated quantum theory.
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of electrons. The Nobel committee said to de Broglie: “When quite young, you threw yourself into the controversy raging over the most profound problem in physics. You had the boldness to assert, without the support of any evidence whatsoever, that matter had not only a corpuscular nature but also a wave nature. Experiments came later and established the correctness of your view.”

Wave mechanics

In 1926, Max Born proposed a probability interpretation of the square of the wave function in the Schrödinger equation; if the Schrödinger wave function is ψ, then $\psi\,\psi^*\,d\tau$ is interpreted as the probability of the electron in a volume element $d\tau$. Most physicists accepted Born’s interpretation, but not de Broglie.

In 1927, de Broglie proposed a deterministic explanation of wave mechanics, the “theory of the double solution,” which he published in the *Journal de Physique*. It relates a double system of solutions to the Schrödinger equation and describes a particle as a packet of energy that is guided by a pilot wave, which is interpreted with Born’s probabilistic concept.

During the Solvay Conference that same year, physicists were critical of de Broglie’s proposal. Pauli, Einstein and Schrödinger did not accept it, and de Broglie couldn’t counter their criticisms. He rejected the proposal with disappointment. Starting in 1928, he embraced the Copenhagen interpretation of quantum mechanics that was vigorously promoted by Niels Bohr.

But de Broglie never forgot his theory and, in 1952, after reading David Bohm’s papers, he was inspired to propose a modified version. Bohm had developed a similar theory in the same year, but his was based on acceleration rather than velocity; he extended de Broglie’s theory of pilot waves in quantum mechanics

His prescient proposal resulted in the establishment of the European Organization for Nuclear Research (CERN) in 1954.

and developed his causal interpretation of quantum theory in terms of hidden variables.

Bohm incorporated the pilot-wave theory into a general quantum theory of measurement. Bohm's causal theory was not widely accepted by physicists who strictly adhered to the Copenhagen interpretation of quantum mechanics; de Broglie's modified theory disappeared from the literature as well. Today, however, Bohm's theory is considered a valid alternative to the Copenhagen interpretation.

Professional life

After obtaining his doctorate, de Broglie was appointed a lecturer at the Sorbonne. In 1928, he became professor of physics at the Henri Poincaré Institute, and in 1932, he rejoined the Sorbonne's *faculté des sciences* as professor of theoretical physics. He took his academic appointments very seriously. In recognition of his intellectual achievements, he was elected into the Académie Française in 1944. The Académie regulates and standardizes the French language.

Louis published more than 25 books on various subjects of physics. Some of his important publications include: *Waves and Motions* (1926), *Selected Papers on Wave Mechanics, with Léon Brillouin* (1928), *Electrons and Photons* (1930), *An Introduction to the Study of Wave Mechanics* (1930), *Non-linear Wave Mechanics: A Causal Interpretation* (1960), *Introduction to the Vigier Theory of Elementary Particles* (1963), and *The Current Interpretation of Wave Mechanics: A Critical Study* (1964). In addition to his strictly scientific work, he wrote widely on popular aspects of physics and the philosophy of science, including the value of modern scientific discoveries. Among his popular books on physics are *Matter and Light: The New Physics* (1946), *The Revolution in Physics* (1953), *Physics and Microphysics* (1960) and *New Perspectives in Physics* (1962).

Legacy

Although not a diplomat like his ancestors, de Broglie was committed to cultivating science and education in Europe. At the 1949 Lausanne European Cultural Conference, he called for the establishment of a multinational laboratory to advance European research. His prescient proposal resulted in the establishment of the European Organization for Nuclear Research (CERN) in 1954.

His contributions to society were recognized by several awards. He received the first UNESCO Kalinga Prize in 1952 for his work in popularizing scientific knowledge and was named counselor to the French High Commission of Atomic Energy in 1945 for his efforts to bring industry and science closer together. He established a center for applied mechanics at the Henri Poincaré Institute and inspired the formation of the International Academy of Quantum Molecular Science.

Louis de Broglie lived a full, productive life. He died at the age of 94 on 19 March 1987 in Louveciennes, France. He never married and was succeeded as a duke by a distant cousin. Like other great theoretical physicists, de Broglie had a talent for deciphering the universe's physical laws. OPN

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