Foreword

De Broglie (1892-1987) was a French physicist making groundbreaking contributions to burgeoning quantum theory and establishing *wave mechanics* to be completed by Erwin Schrödinger (1887-1961). His 1924 thesis entitled Recherches sur la théorie des quanta (Research on the Theory of Quanta), translated from French into English in this book, established the wave-particle duality theory of matter, expounding his firm conviction, known as the *de Broglie hypothesis*, that any moving particle had an associated wave. The thesis was intended for his doctoral degree from the examining board of the Sorbonne consisting of Jean Perrin, Paul Langevin, Elie Cartan and Charles Maugin. The examining board, perplexed by apparently radical ideas of de Broglie, asked Albert Einstein (1879-1955) whether the thesis deserved a doctoral degree. Einstein responded quickly by saying that the thesis deserved a Nobel Prize rather than a doctoral degree. Einstein recommended the thesis to Schrödinger, which resulted in celebrated Schrödinger equation. De Broglie, after his theory was verified experimentally by G. P. Thomason's thin metal diffraction experiment of passing a beam of electrons through thin film of celluloid on the one hand and by Davisson and Germer's experiment of guiding their beam through a crystalline grid on the other in 1927, was awarded a Nobel Prize in Physics in 1929. One of the central results of de Broglie's thesis is that, with mass m, velocity v, and momentum p, we have

$$\lambda = \frac{h}{p} = \frac{h}{mv}\sqrt{1 - \frac{v^2}{c^2}}$$

where c is the speed of light in vacuum, h is Planck's constant and λ is the wavelength. The distinction between phase velocity and group velocity is significant, because we should use the former in discussing wavelength and frequencies. Here I should refer to Edward MacKinnon's critical comment [De Broglie's thesis: A critical retrospective, American Journal of Physics, **44** (1976)], which claims that de Broglie's original development rested on confusion between the velocity of a particle and the relativistic phase wave de Broglie associated with it on the one hand and on confusion between the group velocity of a wave packet and the velocity of individual waves in the packet on the other, though de Broglie arrived finally at the well-known right formula.

The wave theory of matter by de Broglie was preceded by that of light. It is said that Euclid (possibly 330 B.C.-275 B.C.) found out the first and second laws of geometric optics. The third law of geometric optics called Snell's law was found out accurately by the Persian scientist Ibn Sahl in 984, being rediscovered by Thomas Harriot in 1602 and being rediscovered again by Dutch astronomer Willebroad Snellius (1580-1626) in 1621. During the 17th and 18th centuries Issac Newton's (1642-1727) corpuscular theory of light, according to which light is emitted from a luminous body in the form of tiny particles, was dominant, though many scientists such as Robert Hooke, Christian Huygens and Leonhard Euler proposed a wave theory of light based on experimental observations, only to be eclipsed by the highest stature of Issac Newton. Thomas Young's famous double-slit experiment at the beginning of the 19th century played a major role in the general acceptance of the wave theory of light. Maxwell's famous equations for classical electromagnetism, discovered by James Clerk Maxwell (1831-1879) in the middle of the 19th century, gave a decisive support to the wave theory of light, meaning that light is no other than a electromagnetic radiation (fluctuating electric and magnetic fields propagating at a constant speed in vacuum).

The old quantum theory began on 14 December of 1900 when Max Planck (1858-1947) proposed the central assumption on black-body radiation, known as the *Planck postulate*, that electromagnetic energy could be emitted only in quantized form, the energy being only a multiple of an elementary unit

$$E = hv$$

where h is Planck's constant and v is the frequency of radiation. In 1905 Albert Einstein explained why the maximum kinetic energy of the outgoing electrons depends on the light frequency rather than on its intensity by depicting light as composed of discrete quanta, now called *photons*, rather than continuous waves and theorizing the above formula, which brought Einstein a Nobel prize in physics in 1921 after Einstein's equation incorporating photons was verified by the American experimenter Robert A. Millikan. Einstein's theory had a great influence on de Broglie and his thesis. Einstein's seemingly far-fetched idea of photons was crazy enough to take several years to be accepted generally, because the wave theory of light was firmly established at that time. In 1905 Einstein also established the equivalence between mass and energy

$$E = mc^2$$

which also had a great influence on de Broglie and his thesis.

Matrix mechanics was the first conceptually autonomous system of quantum mechanics formulated by Werner Heisenberg (1901-1976), Max Born (1882-1970) and Pascual Jordan (1902-1980) in 1925. Matrix mechanics is not easy to handle. Physicists succeeded in calculating the spectrum of a hydrogen atom by matrix mechanics, but they could not proceed to the next stage of calculating the spectrum of a helium atom. Then came wave mechanics, which gave physicists great joy, because they could return from their unfamiliar discrete world to their continuous homeland. The birth of wave mechanics irritated Heisenberg and some others greatly.

However, Wolfgang Ernst Pauli (1900-1958) soon showed the equivalence between matrix mechanics and wave mechanics, Schrödinger arriving at the same conclusion a month later in a bit incomplete way.

It is a familiar episode that Richard Feynman (1918-1988) said

> If you think you understand quantum mechanics,
> you don't understand quantum mechanics.

This statement is like a word of a Zen Buddhist. This means that we have a mathematical formalism well adequate for quantum theory predicting exactly what quantum phenomena will take place, while you can not or should not pursue the meaning of the formalism nor consider what the formalism represents physically. Many great physicists like Planck, Einstein or de Broglie, who were raised thoroughly in classical physics and contributed much to the old quantum theory, could not content themselves with such a practical attitude as the Copenhagen interpretation proposed by Niels Bohr (1885-1962) and Werner Heisenberg from 1925 through 1927, which could not relieve them at all. Perplexed by his own discovery in 1900, Plank felt as if he were Epimetheus, the Titan in Greek mythology who opened Pandora's box. Indeed, Planck seriously attempted in vain to erase quantum theory from the world. Einstein attacked quantum theory by famous paradoxes. De Broglie tried to build a comprehensible quantum theory. In the 1920s de Broglie was vigorously engaged in the *pilot wave model*, and his early considerations on it were already in his thesis. In addition to a wave function on the space of all possible configurations, the pilot wave model postulates an actual configuration existing even when unobserved. The evolution of the configuration over time is determined by the guiding equation which is a nonlocal part of the wave function. The evolution of the wave function over time is provided by the Schrödinger equation. De Broglie was persuaded to give up his pilot wave model in favor of the then mainstream Copenhagen interpretation. David Bohm (1917-1992) rediscovered de Broglie's pilot wave model in 1952, so that the pilot wave model is usually called the *de Broglie-Bohm theory*. The theory is the first known example of a *hidden variable theory*, interpreting quantum mechanics as a deterministic theory and avoiding troublesome notions such as wave-particle duality, instantaneous wave function collapse and the paradox of Schrödinger's cat. The price that the theory should pay for such benefits is its inherent nonlocality. By Bell's theorem no *local* hidden variable theory is possible.

The second half of the thesis was devoted to making use of the equivalence between the mechanical principle of least action and Fermat's optical principle, which resulted in

- Fermat's principle applied to phase waves is identical to Maupertuis's principle applied to the moving body.
- The possible dynamic trajectories of the moving body is identical to the possible rays of the wave.

The thesis was translated into German and published in 1927 (Untersuchungen zur Quantentheorie, translated from French into German by W. Becker. Akademische Verlagsgesellschaf). It is interesting to note that it took only three years for its German translation to be published, while it took almost a century for its English translation to be published. This reminds us of supremacy of the Weimar culture (recall, e.g., Vienna circle, including Moritz Schlick, Hans Hahn, Kurt Gödel, Rudorf Carnap, Richard von Mieses, and so on as regular members, occasionally visited by Alfred Tarski, Hans Reichenbach, Oskar Morgenstern, Willard van Orman Quine, Frank F. Ramsey, and usually in close contact with Karl Popper and Ludwig Wittenstein on the one hand, and the Berlin circle created by Hans Reichenbach, Kurt Grelling and Walter Dubislav and composed of Carl Gustav Hempel, David Hilbert Richard von Mises on the other, the two circles publishing the journal Erkenntnis or Knowledge in English).

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