Centenary of Louis de Broglie's concept about the wave nature of matter [1]

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ABSTRACT. In September-October 1923, three articles by Louis de Broglie were published, in which for the first time the idea of the existence of non-material phase waves associated with the mechanical movement of a particle of matter was presented. The idea of a phase wave, later called the de Broglie wave, which consisted in the absence of a distinction between an atom of matter and an atom of light, became revolutionary. The concept of the de Broglie wave was developed by E. Schrödinger, he obtained a non-relativistic wave equation, which became the basis of the Schrödinger-de Broglie wave mechanics, which then turned into modern quantum mechanics. In this paper, the author analyzes the content of de Broglie's articles, emphasizing the significance of de Broglie's hypothesis that light quanta are relativistic particles with a rest mass. The origins of de Broglie's reasoning are shown, in which he combined the relations of classical mechanics, the wave theory of light and the theory of relativity.

Wave-particle dualism is the basis of modern ideas about the physical world. According to quantum mechanics, any particle, for example, an electron, is both an elementary particle and an elementary (single-particle) wave. The modern concept describing radiation is a quantized field, which combines both the characteristics of a wave and the characteristics of a particle, and emphasizes the equality of field and matter. Substance and field are equal forms of matter. Just as matter can transform into a field, so the field transforms into matter. The emission process is the transformation of matter into a field, the reverse process is absorption. During mutual transformations of matter into a field and vice versa, the states of both change when certain conservation laws,

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the number of which is becoming more and more, since modern experimental technology makes it possible to quantitatively evaluate more and more new aspects and properties of matter and field. The origins of modern ideas about the dualism of matter originate in the works of Nobel laureate Louis de Broglie, written in 1923–1924.

In the history of quantum mechanics, the works of Louis de Broglie, in which the ideas of wave-particle duality were first formulated and developed, occupy a special place. A. Pais called the transition period the time when "matter waves were discussed only by a group of physicists, and the mechanics of matter waves had not yet been created" [1, p. 398]. This period began in September-October 1923, when three short reports by Louis de Broglie were published in the Comptes Rendus de l'Académie des Sciences (weekly reports of the French Academy of Sciences). De Broglle himself called them "the starting point for the creation of wave mechanics" [2, p. 349]. The end of the transition period in January 1926 can be associated with the publication of E. Schrödinger's first work, "Quantization as an eigenvalue problem," in which the wave equation was obtained.

De Broglie's first article was called "Waves and Quanta" and was published on September 10, 1923. Two weeks later, a second small article "Quanta of Light" was published, "Diffraction and interference" and, finally, on October 8, 1923 – the third article "Quantum, kinetic theory of gases and Fermat's principle" (Russian translation of articles [3–5]). In the journal Nature in 1924, de Broglie also published a short note presenting one of the questions of his dissertation, concerning the explanation of the Doppler effect using phase waves [6]. In February 1924, in the Philosophical Magazine, de Broglie published in English an article "Preliminary Theory of Light Quanta," summarizing his three earlier articles [7]. Thus, the theory proposed by de Broglie was known not only in French, but also in English and even in Russian (Frenkel's abstract in UFN, 1924 [8]). But it must be admitted that these three articles by de Broglie did not attract the attention of a wide range of physicists until the defense of his dissertation took place. According to the memoirs of Louis de Broglie, he began writing his dissertation immediately after the publication of three articles in the Comptes Rendus de l'Académie des Sciences in September–October 1923. It should be noted that these articles were submitted for publication by J. Perrin , who a year later signed in a review of the dissertation : "The dissertation was brilliantly defended. The score is very high" (translation of the review of L. de

Broglie's dissertation is given in [9]).

In the articles preceding his dissertation, one can see de Broglie's predisposition to solving fundamental problems, such as the task of creating a synthetic theory of light and generalizing it to all particles of matter. Reading the articles, one can appreciate how revolutionary de Broglie's thoughts and reasoning were. In the very first article, he sets out the main considerations about the transfer of wave concepts to matter. To do this, he insists that the quantum of light must be considered as a particle of very small mass ($\ll 10^{-50}$g), moving at a speed close to the speed of light c, which de Broglie calls the limiting speed in the theory of relativity. Having given light quanta mass, de Broglie was able to approach the solution of the fundamental question posed by H. Poincaré at the Solvay Congress in 1911 : "Is it possible to create the corresponding dynamics of quanta ?" De Broglie believed that quanta of light and particles of matter are not opposite entities, they are one in essence, and should be described in a single way, i.e. there must be a single dynamic description for all particles.

The idea of the existence of a non-zero mass in a photon is one of the central ones in de Broglie's theory. But it was precisely this that was rejected by all physicists. Since the publication of de Broglie's theory in English in 1924, there has not been a single work in which de Broglie's theory was considered without reservations about the rejection of m_0 for the photon. The first such attempt to prove that m_0 does not exist was made by Wilhelm Anderson in the same 1924 [10]. He considered the corollary that follows from the formula adopted by de Broglie :

$$h\nu = \frac{m_0 c^2}{\sqrt{1-\beta^2}}$$

It follows from it that

$$\beta = \sqrt{1 - \frac{m_0^2 \ c^4}{h^2 \nu^2}}$$

or

$$v = c\sqrt{1 - \frac{m_0^2 \ c^4}{h^2 \nu^2}}$$

Anderson writes : "Let's take an oscillator with a period of $T = 726^{2/3}$ seconds and substitute it into Louis de Broglie's formula... and the result will be 0. The wave speed is zero! Our oscillator cannot emit electromagnetic waves! And also the induction effect in an alternating current transformer with a period of T sec should be equal to zero. It would be interesting to test this experimentally.” De Broglie’s response to this note is of interest : “in a recent number of the *Phil. Mag.* (May 1924) Mr. William Anderson has stated a curious and perhaps not very probable consequence of my views. I think that the *isolated* quantum of radiant energy can only be considered in radiations of very high frequency (when Wien’s law is valuable), but that for radiations of mean or low frequencies we must conceive a sort of aggregation of light quanta. This idea suggested by the form of Planck’s law would perhaps allow us to imagine a transition between light quanta and electromagnetic theory and to avoid Mr. Anderson’s conclusion.

Despite all the ambiguity of this issue, the idea of considering light quanta as relativistic particles having a rest mass, from a heuristic point of view, is an important point in the development of de Broglie’s theory.

On the path to creating a new theory, one can note the articles of M. Brillouin, where he proposed a hydrodynamic model of a vibrating atom, and tried to connect the periodic motion of a particle in an elastic medium with the Bohr model of the atom and thus explain the optical properties of the atom [11]. Jammer’s study quotes de Broglie as saying : “I knew this story... Yes, of course, it plays some role in everything...” [12, p. 238]. In the same place, according to de Broglie, M. Brillouin is called “the true predecessor of wave mechanics.”

The first equation from which a new one begins quantum dynamics, unexpected in its simplicity. De Broglie equated the two well-known equations of Planck and Einstein : $h\nu_0 = m_0c^2$. In the article "Waves and Quanta" after the statement that inside any body with mass m_0, a certain oscillatory process occurs with a frequency

$$\nu_0 = \frac{m_0c^2}{h}.$$

De Broglie considers two more frequencies associated with a moving body. Frequency $\nu_1 = \nu_0\sqrt{1-\beta^2}$ corresponds to measurements of the frequency of the internal oscillatory process by a stationary observer who perceives it as slow. The total energy of a moving body for a stationary observer corresponds to the frequency

$$\nu = \nu_0/\sqrt{1-\beta^2}$$

.

These three frequencies assigned to one and the same body, upon a superficial reading of the article, cause some complexity and confusion. The process of reconciling these different frequencies for de Broglie was also difficult. The difference in frequencies ν and ν_1 determined the further development of de Broglie's concept. Here his imaginative thinking played a big role [13]. He imagined that, along with the periodic process occurring inside the particle (body), a wave with frequency ν appears in space. This the wave accompanies a body that moves with speed $v = \beta c$. He calls oscillations with frequency ν propagating in space an "artificial wave" or a "fictitious wave"; the phase velocity of these waves is equal to c/β.

In the creation of a physical theory, Einstein wrote, "Fundamental ideas play an essential role. Physics books are full of complex mathematical formulas. But the beginning of every physical theory is thoughts and ideas... Ideas must later take the mathematical form of a quantitative theory, making comparison with experiment possible" [14, p. 225]. Before experimental confirmation of the de Broglie waves that he introduced into 1923, trying to preserve the idea of an internal periodic process inherent in any material particle, was still far away. But the obvious success of the idea of phase waves already in the first article was a physically clear explanation in terms of the particle trajectory of Bohr's semiclassical quantum postulate about stationary orbits in an atom. Using the concept of a fictitious wave, de Broglie showed that "the trajectory of an electron is stable only in the case where, when a fictitious wave meets an electron, their phases are the same... this stability condition is the same as the stability condition of the theories of Bohr and Sommerfeld."

The main ideas of the first article in 1923, which has only three pages, were the key ideas for the future concepts of L. de Broglie. One can highlight the following provisions of this article.

1. There are no differences between light quanta and any other particles, for example, electrons.
2. The postulates and provisions of the special theory of relativity are applicable to all particles.
3. All particles have a non-zero rest mass and their speed is less than the speed c, which, according to STR, is the limiting speed.
4. For all particles, we can apply the relations $E = h\nu$ and $E = mc^2$.

5. All particles have internal vibrations, the frequency of which is defined as $\nu_0 = \frac{m_0 c^2}{h}$.
6. The movement of any particle is associated with the propagation of a wave with phase velocity $V = c/\beta$ and frequency $\nu = \nu_0/\sqrt{1-\beta^2}$.
7. The oscillations of a particle and the oscillations of the accompanying wave have the same phase.
8. In the case of movement along a closed trajectory, the movement will be stable if an integer number of phase wavelengths fits along the length of the trajectory.

De Broglie's first article has the nature of a thesis, announcing "important results that will be published soon." The final phrase of the article : "From today we are already able to explain the phenomena of diffraction and interference, taking into account light quanta," demonstrates the author's confidence and suggests continued publications. In the next two articles, de Broglie shows the application of the waves he introduced, which he further calls phase waves, to solve various tasks : give a physical explanation of circular stationary orbits in the Bohr atom, introduce elements of quantum statistics, explain the phenomena of interference and diffraction.

De Broglie's second article begins with a clarification the concept of an immaterial fictitious wave associated with the movement of a body. Here for the first time Broglie introduces the term "phase wave". He's writing : "Leaving aside the physical meaning of this wave (it will be the difficult task of an expanded electromagnetism to explain it), we recall that the mobile has the same internal phase as the portion of the wave located at the same point : let's therefore call it 'phase wave' "[4, p. 196]. The entire further article is based on assumptions and reasoning, it contains words such as : "It seems necessary to change the principle of inertia", "We therefore conceive of the phase wave as guiding the movements of energy", "By thinking about it we will see that the proposed synthesis seems the logical crowning achievement of the comparative development of dynamics and optics since the 17th century." This highly speculative work of de Broglie, built on hypotheses and reflections, proves that without such work new ideas and theories are not born, that they form an integral part of physics.

In his second article, de Broglie introduces the concept of "new dynamics" for moving bodies. De Broglie writes : "It seems necessary to change the principle of inertia." He proposes to consider at each point of the trajectory the movement of a free body along the ray of the corresponding phase wave, i.e. along the perpendicular to the surfaces of equal phase of the wave. De Broglie formulates the basic principle of the new dynamics : "The new dynamics of a free material point appears in relation to the previous dynamics (including Einstein dynamics) in the same way as wave optics in relation to geometric optics." Here de Broglie provides an explanation for the appearance of the interference pattern, which has hitherto caused difficulties when using the concept of light quanta. Now this is an interference pattern of phase waves. De Broglie writes : "A quantum of light, emitted for any reason from a point source, hitting neighboring atoms, its phase wave will cause other acts of quantum emission, while internal vibrations, as we believe, are in phase with the wave itself. All emitted light atoms will thus have the same phase wave as the first atom." [ibid., p. 197].

The third article examines statistical properties of a gas whose atoms have wave properties. De Broglie views atoms as radiation enclosed in a cavity, and instead of atoms, counts the number of waves : "The state of a gas can be stable only if the waves corresponding to all atoms form a system of stationary waves" [28, p. 198]. Work by S.N. Bose, in which he obtained Planck's formula, considering radiation as a "quantum" or "light" gas, appeared in the summer of 1924 [6]. The idea of considering a gas consisting of quanta using methods from the kinetic theory of gases belongs to M. Planck and W. Nernst. And the idea of considering gas as a system of phase waves, belongs to L. de Broglie. A year earlier than Bose, de Broglie, using phase waves, found expressions for the number of stationary waves contained in a unit volume of such a quantum gas, in a certain frequency range. Here de Broglie showed that the formula he obtained using phase waves coincides with Maxwell's law for an ideal gas and with Planck's formula for light atoms. This method will become the basis of quantum statistics, and he will return to its refinement in the last chapter of his dissertation.

These are the main provisions of the three articles by L. de Broglie, in which he proposed the concept of waves accompanying the movement of any material particles. Each particle of matter must have a corresponding wave of matter. In a more detailed form, this concept will be presented in his doctoral dissertation in 1924, and experimental confirmation of Louis de Broglie's hypothesis about the wave properties of the electron will occur in 1927 in experiments on observing electron diffraction by the

English physicist J. Thomson and, independently, in the experiments of American scientists K. Davisson and L. Germer.

Radiation (light) and matter are types of matter, and wave and particle represent forms of their existence. At different periods in the development of physical ideas about the forms of existence of two opposite types of matter, Democritus, Newton, Huygens, Fresnel, and Einstein made their contributions. De Broglie became the last link - the scientist who discovered the fundamental connection between wave processes and the movement of material particles of matter. Chairman of the Nobel Committee on Physics K.V. Oseen, when presenting the Nobel Prize to L. de Broglie in 1929, said : "De Broglie discovered a completely new aspect of the nature of matter, which no one had previously suspected. De Broglie's brilliant guess resolved a long-standing dispute, establishing that there are no two worlds, one of light and waves, the other of matter and corpuscles. There is only one common world" [16, p. 368].

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