
**PHYSICS OF ELEMENTARY PARTICLES
AND ATOMIC NUCLEI. THEORY**

Does a Single Electron Have Wave Properties?

V. A. Bednyakov*

Dzhelepov Laboratory for Nuclear Problems, Joint Institute for Nuclear Research, Moscow oblast, Dubna, 141980 Russia

*e-mail: bedny@jinr.ru

Received November 11, 2020; revised March 12, 2021; accepted March 12, 2021

Abstract—An attempt is made to substantiate the absence of wave properties for a single electron. What is commonly called the corpuscular-wave duality or the wave properties of matter, which appear in the form of a diffraction pattern on the target of certain kind, is a result of the obligatory involvement of a large number of electrons in the diffraction process. In the context of quantum mechanics, a form of the diffraction pattern can be predicted using the rule of adding probability amplitudes, which, in the simplest case, are solutions to the Schrödinger equation for free particles. Therefore, the answer to the question posed in the title sounds something like this: *a single electron has no wave properties; however, they become apparent whenever there are many electrons and a suitable target.*

DOI: 10.1134/S1547477121040038

1. INTRODUCTION

In the process of theoretically comprehending the data of coherent scattering of neutrinos by nuclei as complex composite systems [1–4], the question has arisen about the admissibility of applying the addition rule of probability amplitudes and about the role of corpuscular-wave duality in the case of neutrinos. As a result, the following text is offered to the reader's judgment.

As is known, even Isaac Newton considered light to be a movement of corpuscles. The interference pattern from two slits that is characteristic of waves (in an elastic medium) allowed Thomas Young to demonstrate the wave nature of light almost 200 years ago [5]. However, Einstein's explanation of the photoelectric effect in 1905, based on Planck's hypothesis of energy quantization, followed by an experiment in Compton scattering of light in 1923, provided irrefutable evidences of precisely the corpuscular (intermittent) behavior of light.

A situation arises that has no precedent: when analyzing problems of atomic structure, the emission of light, etc., scientists relied on quantum concepts, while when they moved to studying the phenomena of interference and diffraction, they argued their statements using wave ideas. For example, in Messiah's textbook on quantum mechanics [6] (p. 51), it is put like this: "The photoelectric effect, the Compton effect, can be explained only if we imagine light as a flow of corpuscles, but the hypothesis of the photon existence does not agree with the interference and diffraction phenomena, in which the light behaves like a superposition of waves. If we adhere to the language of classical physics, then the coherent and consistent description of the entire set of light phenomena is impossible. Depending on conditions of the experi-

ment, to interpret it, we have to resort to one of two incompatible concepts: a flow of corpuscles or a superposition of waves."

This could not continue for a long time, and the creation of a theory that would take into account the corpuscular-wave aspects was an extremely urgent task. The first to initiate a new radical stage in solving this problem was Louis de Broglie. It was he who tried to synthesize the corpuscular and wave properties of matter. The famous formula of Louis de Broglie [7], in which a certain wave is assigned to a microparticle¹ with a momentum p , the length of which has the form²

$$\lambda = \frac{h}{p}, \quad (1)$$

as known, appeared in 1923. Its validity was first confirmed experimentally in 1927 by Davisson and Germer [9]. They studied the angular dependence of intensity of the electron beam, reflected from the crystal surface, and found that this distribution of electrons is similar to the X-ray intensity distribution (Laue spots) during the crystal diffraction. In 1928, J.P. Thomson (Nobel laureate) and, independently of him, P.S. Tartakovsky investigated the Debye–Scherrer rings that arise when an electron beam passes through a thin polycrystalline target. The comparison of the diffraction maxima positions with the electron energy confirmed the validity of Eq. (1), which relates a wavelength to an electron momentum.

These electron diffraction experiments were of decisive importance, not inferior in significance, per-

¹ We will use the terminology of D.I. Blokhintsev [8], understanding microparticles as objects of the microworld.

² Here, $h = 6.6262 \times 10^{-27}$ Erg s is the Planck constant.

haps, to the very formula of Louis de Broglie. “Diffraction of waves of matter,” so similar to the diffraction of elastic waves and light, had a magical effect on the best minds in physics of the early 20th century.

For example, D.I. Blokhintsev [8] writes: To consider the most important feature of microphenomena, we will be based on experiments in diffraction of microparticles. The main conclusion of these experiments lies in the de Broglie formula connecting a momentum with a wavelength. Here is what is written about this in Messiah’s textbook [6]: “In the case of objects of atomic dimensions, it is possible to form beams with a wavelength comparable to the wavelength of X-ray radiation and carry out experiments similar to X-ray diffraction by crystals. Knowing the crystal lattice parameters, it is possible, using the interference pattern, to obtain the electron wavelength value, which is in excellent agreement with the de Broglie’s value. Similar experiments for diffraction by crystals were carried out with monoenergetic beams of helium atoms and hydrogen molecules. All experiments show that wave properties are inherent not only in electrons, but they are a general phenomenon that is characteristic of all material objects.”

Ya.I. Frenkel [10] also writes: “Atomic concepts of matter and light are an incomplete reflection of wave concepts, because fundamental phenomena such as interference and diffraction turn out to be completely incomprehensible from the viewpoint of the former, while they are extremely simply explained by the latter.”

According to V.A. Fok [11], “After the discovery of electron diffraction, we were convinced with no doubt that in the atomic world we are dealing with manifestations of some wave properties of particles. The diffraction of electrons was discovered already after the concept of the wave nature of material particles was developed on the basis of theoretical considerations. This means that the wave nature of material particles has been established with certainty.”

Even Einstein, in his article³ devoted to the Compton experiment (in 1924), wrote that the wave theory explained the diffraction and interference phenomena right with astronomical accuracy and his belief in its correctness became unshakable like a rock.

Let us emphasize a key point here (for the rest of history): the problem lay in the fact that the diffraction (interference) of “waves of matter” could not be explained from the corpuscular viewpoint. If this diffraction of particles of matter did not exist, there would be no need for wave–particle duality.

Thus, it was de Broglie’s idea of the wave–particle that allowed a number of serious internal contradictions in the rapid development of the early 20th century physics to be resolved and actually served as the starting point of modern quantum mechanics.

³ A. Einstein, *The Collection of Scientific Papers*, vol. 3, p. 465.

Nevertheless, for a very long time, the concept of wave–particle duality and the quantum mechanics interpretation itself have been the subject of extensive discussions and research into which, in particular, Louis de Broglie himself put a lot of efforts. As a result, the “Copenhagen Interpretation” has become generally recognized. Here are some quotes.

From Feynman [12]: “In quantum mechanics, all events are represented in the form of probability amplitudes, which behave like waves and have a certain frequency and wavenumber (vol. 3, p. 231). Concerning the meaning of wave function: It was Born who correctly identified Ψ in the Schrödinger equation with the probability amplitude, assuming that the square of the amplitude is not the charge density, but only the probability of finding an electron there, and that if you find an electron in some place, then all its charge will be there” (vol. 9, p. 233.).

From the textbook by D.I. Blokhintsev [8] (pp. 48–49): If we are talking about a single electron, then the intensity of de Broglie waves indicates only the probability of the electron hitting, but does not oblige this electron to behave in one or another particular manner. Only the ratio of intensities in different parts of space is important. De Broglie waves provide a statistical description of the movement of microparticles. They determine the probability of finding a particle in a given place of space at a given time.

From Messiah [6] (p. 67): “The simplest interpretation of the wave–particle duality has a statistical basis: the wave intensity at each point of the screen gives the probability that an electron hits this point.”

Finally, from P.A.M. Dirac [13]: “The result of the experiment is not determined identically by the conditions which are possessed by the experimenter, as it should be from the viewpoint of classical concepts. The greatest that can be predicted is the totality of possible outcomes and the probability of occurring of each of them.”

Nowadays, everyone agrees with this statistical–probabilistic nature of quantum mechanics. The “tension” here has long eased off and probably is not of much interest for discussion by most of the physics community.

Nevertheless, to complete the picture, we give some quotes from the (Soviet) past. They do not seem meaningless even today. For example, as Frenkel wrote in 1928 [10]: “According to Born, these waves have no immediate reality, representing only auxiliary images that serve to determine the probability of real events, the objects of which are ordinary⁴ material particles. The essence of the new mechanics is not at all in the waves introduced by it, but in the replacement of the deterministic description of events with a probabilistic one, in which not the events themselves are determined, but only their probabilities.”

⁴ In other words, these are particles without any individual wave properties.

Several quotes from the article by P.S. Tartakovsky are also relevant [14]: “‘Waves’ exist only because the equations defining the Ψ -functions inadvertently have a wave form. For Schrödinger, the basis of everything, following de Broglie, was waves, while everything else was their manifestation. Heisenberg saw the essence of new objects of the theory in particles. For him, particles, rather than waves, are the basis of reality. Waves are only manifestations of the particle behavior.”

K.V. Nikolsky [15] considered the thesis about the presence of corpuscular and wave properties in micro-objects as the main mistake of the Copenhagen Interpretation of quantum mechanics, which, in his opinion, is in the fact “that the relations that are valid and found experimentally for a statistical team are uncritically transferred to a separate individual experimental process performed with a separate quantum object.”

Today it is well known that the mathematical apparatus of quantum mechanics works well and fruitfully; the results obtained with its help fully correspond to the data and new predictions are made which are confirmed very well in practice.

On the other hand, the formulation of the mathematical apparatus, as is known, is an important (first) step towards the formation of a new theory, but this solves only a part of problems. The mathematical structure underlying the physical theory can be interpreted in different ways; therefore, the next necessary step in creating a physical theory is a meaningful interpretation of the mathematical formalism, since the abilities of a physical theory to predict new phenomena depend on the “correct interpretation.”

Here is what Messiah writes about this (p. 149): “No doubt the representation of the state of a quantum system by the wave function has an abstract nature, while the statistical interpretation of the theory is difficult to perceive intuitively. However, attempts to describe microscopic phenomena on the basis of more specific and intuitively clear models inevitably come across a number of contradictions.... One should be aware that, from the viewpoint of logic, more or less abstract concepts of physical theory are not at all obliged to be expressed in a specific language. All of our intuition, all our sense of specifics, is based on the everyday experience, and the concepts and images used to specifically describe the phenomenon, whatever it may be, are also taken from this experience. There is no reason to think that the language of such concepts can be used without contradictions to describe the phenomena of microscopic physics, so far removed from the everyday experience.”⁵

⁵ These “exculpatory” statements seem convincing. However, the history of the science and technology development has not yet presented any arguments against the (opposite) point of view that the human mind has always found an opportunity to adequately reflect (understand) new and previously unknown processes and phenomena. It is not obvious that the microcosm will become an insurmountable obstacle here.

Recognizing all this, let us go back a little bit, to the middle of the 20th century, to the Feynman Lectures on Physics (1965) in their quantum mechanical part.

Let us recall that Richard Feynman positioned the electron diffraction by two microslits (Fig. 1) as a phenomenon that completely defies classical explanation, which conceals the “very essence and main secret” of quantum mechanics [12]. With his characteristic pedagogical brilliance and persuasiveness, Feynman carefully analyzed all the refinements of this (at that time mental) experiment to explain the foundations of quantum mechanics and illustrate the phenomenon of wave–particle duality, which postulates that all particles exhibit both wave and corpuscular properties. This double-slit experiment is included in most textbooks on quantum mechanics to illustrate the consequences of de Broglie’s hypothesis [6, 12, 17]. It was the subject of a discussion between Bohr and Einstein about the wave–particle causality and complementarity [18].

The practical implementation of this experiment is an extremely difficult task. No wonder Feynman wrote [12] that “this experiment with electrons was never conducted as such by anyone. The fact is, to obtain the effects of interest to us, the device must be too miniature. We now are setting up a ‘thought experiment’ that differs from others in the fact that it is easy to think about. What should happen in it is known in advance, because many experiments have already been conducted on devices, the sizes and proportions of which were selected so that the effect that we will describe became noticeable.”⁶

The experiment with the passage of electrons through slits was first performed by C. Jönsson [20, 21] in 1961; he demonstrated diffraction by single, double, and multiple (up to five) slits, but he could not yet observe the single-electron diffraction and did not cover individual slits. Thereafter, the experimental implementation of the Feynman experiment with electrons was undertaken, for the most part, directly with real (micro) slits and in a “roundabout” way, where (electronic) biprisms were used instead of double slits [22]. In the second case, at first (in 1976), the interference patterns were obtained at different densities of the electron beam [23]. Then Tonomura [24] could record the acts of detecting individual electrons as a time function and used them to construct an interference pattern. The improvement of techniques with

⁶ Feynman here does not distinguish between diffraction and interference, since he considers the first to be the result of the “work” of the second. He also ignores single-slit diffraction. As is known, the diffraction (deflection) of light takes place even at the macroslit boundary. The impression may be created that wave phenomena do not manifest themselves with the diffraction by one slit, but arise only as a result of the combined action of two slits. In modern work [19], it is said that the results of studying the wave nature of electrons, obtained at an electron microscope, show that the consideration of the electron diffraction by one round hole gives a full proof that an interference experiment on two holes, generally speaking, is not required for demonstrating the superposition of electron waves.

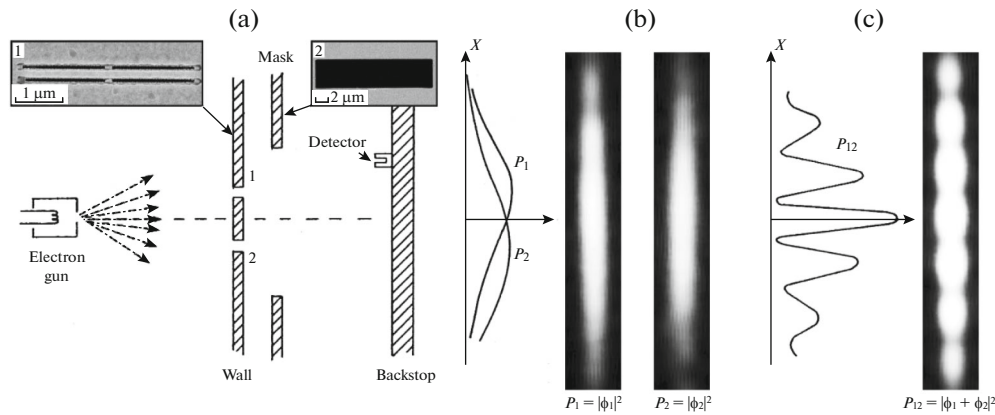


Fig. 1. Scheme for implementing the Feynman mental experiment in [16]. The images of slits, movable mask, and the real view or interference patterns are added to the ‘classical’ picture from Feynman lectures [12]. The figure is borrowed from [16].

biprisms in this direction continued, and a number of more accurate measurements was carried out (see, e.g., [25, 26]). The results of direct experiments in electron diffraction by two slits and one slit were presented in [16, 27–35].

For example, by placing a movable mask in front of a double slit (in order to be able to monitor and operate the passage of electrons through one or another slit), the authors of [16] experimentally observed (see Fig. 1) the diffraction patterns (probability distributions) from the first (P_1), second (P_2), and both slits ($P_{12} \neq P_1 + P_2$), which, according to them, is “a direct observation of the wave properties of electrons.” By writing the events of recording of single electrons, “passing through a double slit,” they built a characteristic diffraction pattern, which, in their words, is “an observation of the corpuscular properties of electrons.”

Similar studies were carried out on photons [36], neutrons [37, 38], atoms [39, 40], small [41–47] and large molecules [48, 49], and even (in 2019, for the first time) on antimatter (diffraction individual positrons) [50].

Despite the conceptual and mathematical simplicity, at least from the viewpoint of wave optics, the experimental implementation of the Feynman experiment, as was mentioned, is a very difficult task that requires the most advanced technologies and unique equipment. For example, new advances in the development of resonator quantum electrodynamics were applied to conduct an even more sophisticated “which-path” experiment [51]. As a supplement to the electron experiments on two spatial slits [24, 25], experiments with electron diffraction by two so-called time slits [52, 53] were performed, all of which, according to the generally accepted point of view, provide further confirmation of the wave–particle duality.

Therefore, the most important feature is that the experimental conditions make it possible to reliably

state that, at each moment of time in the installation, there is only one microparticle (electron). The formation of a diffraction pattern is achieved due to the gradual accumulation of events caused by individual microparticles (electrons).

2. WHAT, IN FACT, IS AVAILABLE EXPERIMENTALLY?

There are two strict experimental facts available.

Experimental fact number 1 has been well-known since the birth of quantum mechanics (see, e.g., [5, 6, 8, 9, 12, 17]). Let us formulate it here as follows: the wave properties of matter (diffraction and interference) manifest themselves (are recorded) only when there is a sufficiently large flow of microparticles, the momentum of which (in a quite definite way), according to de Broglie’s formula (1), is correlated with the characteristic dimensions of the obstacles scattering them (the size of one or two slits, the spacing of the crystal lattice and/or diffraction grating, etc.; see Fig. 2, left).

Experimental fact number 2, reliably experimentally substantiated quite recently [16, 20, 21, 23, 25], is that a single electron, having flown through the above-mentioned *characteristic* obstacle unaccompanied, creates no diffraction pattern, but leaves its own individual trace at some arbitrary, generally speaking, point of the recording screen. The diffraction pattern (wave phenomenon) is formed only when the “fate” of a single electron is repeated by many other electrons (overcoming the same obstacle) (Fig. 2, right).

From these two experimental facts, according to the generally accepted interpretation of corpuscular-wave duality, a conclusion follows that a single microparticle (electron or photon) has wave properties. It is remarkable that this very conclusion is made literally in all the experimental works mentioned in the introduction, where microparticles are recorded one by one. For example, the Nobel laureate Tonomura

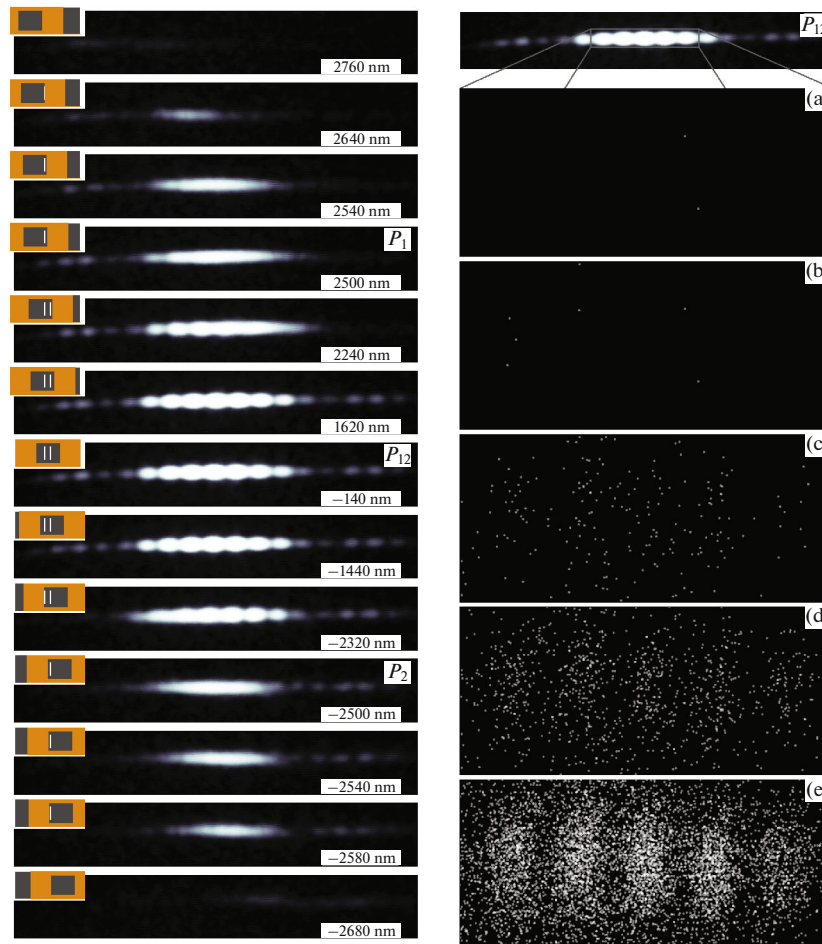


Fig. 2. (On the left) The movement of the mask along two slits (see Fig. 1) causes a characteristic evolution of the interference pattern. (On the right) Formation of the central part of this diffraction pattern. White dots indicate the places of arrival of individual electrons; their number grows from top to bottom as 2, 7, 209, 1004, and 6235. Borrowed from [16].

writes [25]: “Since the interference pattern is formed only when two waves simultaneously pass on both sides of the biprism (Fig. 3) and overlap in the observation plane, then it turns out as if a single electron is split into two. According to the generally accepted quantum mechanical interpretation, even one electron passes on both sides of the biprism in the form of a wave function. These two ‘partial’ waves overlap, forming the probability interference pattern on the observation plane. At the moment of detection, this wave function collapses into one particle.”

Let us recall what P.A.M. Dirac wrote about the interference of a single photon [13] (p. 18): “It is impossible to predict in which of the two beams the photon will be found. As long as the photon is partly in one beam and partly in another beam, the interference can occur with the superimposition of the beams, but this possibility disappears as soon as the photon is transferred by means of measurement entirely into one of the beams. In this way, the quantum mechanics is able to reconcile the contradictions between the cor-

puscular and wave properties of light. It believes that a photon enters partly into each of the two components of the beam, and then this photon interferes only with itself.”

However, if one does not know or forgets about the generally accepted interpretation of corpuscular-wave duality, then it is quite possible to draw other conclusions from these experimental facts. For example, the following two.

The first conclusion is that the wave properties of light are inseparable from the presence of a (very) large number of photons, a flow of photons of the same energy. Strictly the same applies also to the need for a large number of electrons or other microparticles for the manifestation of what is commonly called the wave properties of matter.

The second conclusion is that the de Broglie wavelength (λ) is a parameter characterizing the typical internal scale of the target (crystal lattice spacing, distance between atoms, slit size, etc.) at which particles

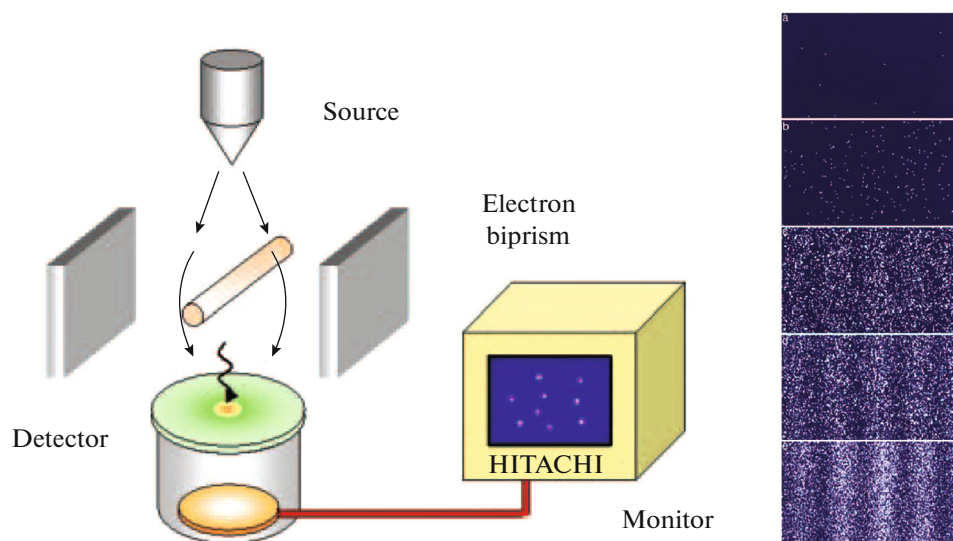


Fig. 3. (On the left) Two-beam interference of electrons. (On the right) Formation of a diffraction pattern by 10, 200, 6000, 40000, and 140000 electrons. Borrowed from [25].

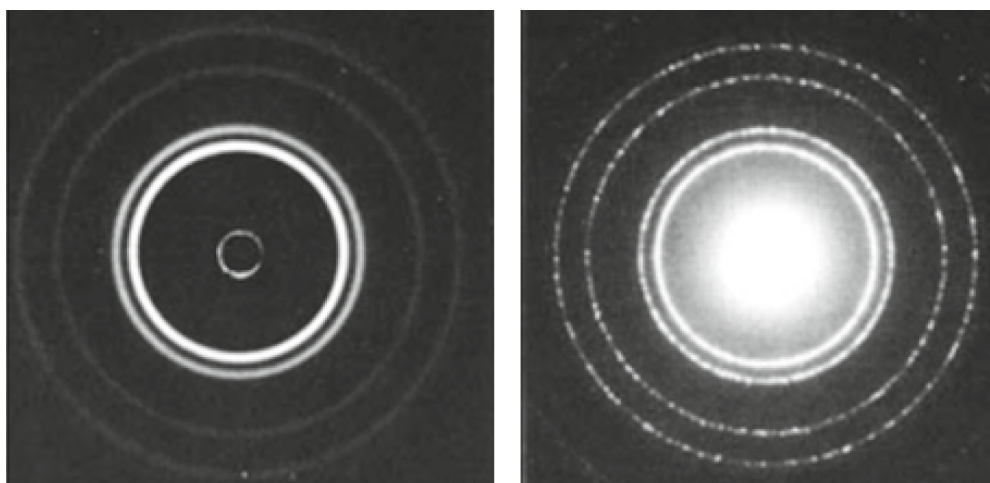


Fig. 4. Diffraction patterns obtained by the transillumination of the aluminum foil with (on the left) X-rays and (on the right) electrons of the same wavelength. Due to the higher probability for electrons to experience inelastic collisions in the foil, the central part of the electron diffraction pattern is more strongly exposed to light, but the radii of the diffraction rings are the same (see, e.g., [55]).

with a given momentum can create a (pronounced) diffraction pattern [54]. Let us call this de Broglie's target. With noticeably larger or noticeably smaller characteristic scales of a target (not de Broglie target), particles with the given momentum do not create a diffraction pattern.

From this, it follows that the nature of the diffraction pattern during the scattering of particles of matter is determined exclusively by properties of the target-obstacle (see Fig. 4).

Electron-diffraction patterns obtained by means of electron waves and Laue diffraction patterns acquired using X-rays demonstrate coincident rings that differ only in intensity. Then, the meaning of the X-ray diffraction pattern (Laue diffraction pattern), electron-

diffraction pattern, neutron-diffraction pattern, etc., becomes clear. They, as is known, are used to obtain various information on the structure of the sample under study [56], rather than on the wave nature of the particles probing this sample. If the experimenter chooses particles with a momentum that is "inappropriate for the given sample," then he will see nothing interesting. On the other hand, by varying this momentum (by choosing a suitable de Broglie wavelength), it can probe various structural sublevels of the sample under study, if any.

In this respect, we recall the key position of quantum mechanics regarding a trajectory of microparticle. Fok writes [11]: "From the uncertainty principle, the meaninglessness of a concept of trajectory follows.

It cannot be assumed that there is a trajectory in reality, because it cannot even be measured in principle, because only provisions, taken from experience, are admissible metaphysically, and, consequently, there exists only what is measurable.”

In the textbook by Dmitry Ivanovich Blokhintsev [8], we find (pp. 9–11) “Electrons exhibit wave properties: if a stream of electrons is passed through a crystal, then the particles are distributed on the screen in the same way as the intensity of waves of a suitable wavelength is distributed. We get the phenomenon of diffraction of microparticles, which is alien to classical mechanics. The movement of a microparticle in many respects proves to be more related to the movement of waves than to the movement of a material point along a trajectory. The phenomenon of diffraction is incompatible with the concept of the particle motion along a trajectory.”

In the context of this discussion, the statement about the absence of a trajectory for microparticles should probably be formulated in a slightly different way. More precisely, it is something like this: in the context of quantum mechanics, there is no possibility to predict the trajectory of a microparticle—only when it encounters a de Broglie obstacle on its way (i.e., interacts with it). If this obstacle is not de Broglie’s (i.e., in fact, there is no interaction with it), then the microparticle flies in a completely understandable and predictable way, in the simplest case, simply “along a straight line.”

It is unlikely that anyone will argue that this is what takes place for cosmic rays (photons, protons, neutrinos, etc.) arriving from distant stars to the Earth, or that this is how cathode rays (electrons) behave in (the once very popular) television electron beam tubes. Finally, it is obvious that, in the Large Hadron Collider (LHC), proton beams of enormous energies almost 10000 times per second sweep along circular paths in order to precisely collide with each other at some point. If they did not have well-controlled and predictable trajectories, how could they be pushed together so accurately on a constant basis every 25 ns?

Therefore, for showing the wave properties of matter (diffraction and interference), it is necessary to have only two “things”: a huge flow of electrons and a de Broglie target. The electrons do exhibit a wave phenomenon, but there is no evidence for belief that the de Broglie wave detection of an individual electron takes place, and no reason is seen to endow this electron with properties of any wave.

It is possible to stop at that phrase; however, the diffraction-interference pattern of the waves of matter, which served as a reason for the occurrence of corpuscular-wave duality, really takes place.

What are then the sufficient conditions for these waves of matter? In other words, if the idea of wave-particle duality for a single electron (since it gives no diffraction pattern) is not used, then how can the emergence of a pattern of electron diffraction by two

narrow slits be explained without recourse to the (attractive) analogy in the form of a simple formula that easily elucidates the diffraction of ordinary elastic waves (light)?

It is probably necessary to try to explain this diffraction pattern by the statistical nature of the phenomenon, by the obligatory presence of a larger ensemble of electrons, by suitable properties of the target obstacle, and by “normal reasons” such as electron scattering by slits due to one interaction or another.

3. WHAT DOES QUANTUM MECHANICS ITSELF SAY ABOUT THIS?

Three variants of this explanation were found in the literature. The key role in them is played by the amplitude of probability of a free particle (electron) with the momentum \mathbf{p} to go from point \mathbf{r}_1 to point \mathbf{r}_2 (solution to the Schrödinger equation). In the Feynman Lectures on Physics [12] (vol. 8, p. 14), it is given in the form

$$\langle \mathbf{r}_2 | \mathbf{r}_1 \rangle \propto \frac{e^{i\mathbf{p}\mathbf{r}_{12}}}{r_{12}} \quad \text{where } \mathbf{r}_{12} = \mathbf{r}_2 - \mathbf{r}_1, \quad (2)$$

Let us consider the first variant, in which, apart from Eq. (2), only the Fundamentals of Quantum Mechanics [12] (vol. 3, p. 213) are used, which determine the rules for adding the probability amplitudes for indistinguishable events. On this basis, R. Feynman gives an explanation of the picture of interference-diffraction of electrons by two slits, analyzing the solution of Problem 1.1. on quantum mechanics from the book of problems that supplemented the Feynman lectures.

This is what it looks like briefly. The probability that a particle will reach the screen (see Fig. 1) at some point x , if slit 1 is open, is expressed as $P_1 = |\langle x|1\rangle\langle 1|s\rangle|^2 \equiv |\varphi_1|^2$, where $\langle 1|s\rangle$ is the amplitude of probability for a particle emitted from a point s to reach slit 1, while $\langle x|1\rangle$ is the amplitude of probability for this particle, having escaped from slit 1, to successfully reach the point x . If slit 2 is open, then similarly $P_2 = |\langle x|2\rangle\langle 2|s\rangle|^2 \equiv |\varphi_2|^2$. When both slits are open, two equivalent possibilities—alternatives appear in front of the electron; therefore, to obtain the probability, it is necessary at first to add the amplitudes⁷:

$$P_{12} = |\langle x|1\rangle\langle 1|s\rangle + \langle x|2\rangle\langle 2|s\rangle|^2 \equiv |\varphi_1 + \varphi_2|^2. \quad (3)$$

Taking into account the symmetrical arrangement of the slits and assuming that the source emits particles

⁷ Here it is tacitly assumed that an *interaction* occurs with probability $q_{1,2} = 1$ at each slit, or, equivalently, both slits are “in action.” If $q_{1,2} \neq 1$, then (3) should be written as

$P_{12} = |\langle x|1\rangle q_1 \langle 1|s\rangle + \langle x|2\rangle q_2 \langle 2|s\rangle|^2$ and the “cutoff”, e.g., of slit 1, means that $q_1 = 0$.

isotropically, it can be written that $\langle 1|s\rangle = \langle 2|s\rangle = c$. Assuming the slits to be infinitely narrow, we can use Eq. (2). Then, up to an insignificant numerical factor, the amplitudes of the probability that a free electron propagates from each slit to the point x are written in the key form:

$$\langle x|1\rangle = \frac{e^{ikl_1}}{l_1} \quad \text{and} \quad \langle x|2\rangle = \frac{e^{ikl_2}}{l_2}, \quad (4)$$

where $l_1 = \sqrt{l^2 + (x - a/2)^2}$ and $l_2 = \sqrt{l^2 + (x + a/2)^2}$ are the distances from slits 1 and 2 to point x , and it does not matter at all that the parameter of momentum dimension $k = \frac{2\pi}{\lambda}$ has the form of wavenumber.

Here l is the distance from slits to the screen and a is the distance between the slits. Then we have

$$P_1 = \frac{|c|^2}{l_1^2}, \quad P_2 = \frac{|c|^2}{l_2^2} \quad \text{and} \quad P_{12} = |c|^2 \left| \frac{e^{ikl_1}}{l_1} + \frac{e^{ikl_2}}{l_2} \right|^2.$$

Let the distance l be large enough, $l \gg a$, $l \gg x$. Then l_1 and l_2 in the denominators of the formula for P_{12} can be taken equal, $l_1 = l_2 = l$; however, in the phase factors of this expression, the ‘‘path difference,’’

$l_2 - l_1 \approx \frac{ax}{l}$, must be taken into consideration. As a result, we get the formula

$$P_{12} = \frac{|c|^2}{l^2} \left| 1 + \exp \frac{ikax}{l} \right|^2,$$

which is easy to convert to the form

$$P_{12} = \frac{2|c|^2}{l^2} \left(1 + \cos \frac{kax}{l} \right). \quad (5)$$

Maxima of this expression, obviously, are determined by the expression

$$\frac{kax_n}{l} = 2\pi n, \quad \text{where} \quad n = 0, \pm 1, \pm 2, \dots$$

Simple expression (5) completely sets the potential form of the entire diffraction pattern. To obtain it, only two things were needed that have nothing to do with the wave nature of the electron: the rule of addition of probability amplitudes (3) and the form of these amplitudes (4). We emphasize that diffraction pattern (5) can be seen on the screen only when a huge number of electrons will be involved in a real experiment with two slits, as it was verified, e.g., in [16, 25]. In other words, to ‘‘materialize’’ potentially the possibility, predicted by quantum mechanics, for sort of one particle, a large statistical ensemble is needed [8].

The *second variant* of a purely quantum mechanical explanation of interference can be found, e.g., in [57], where it is schematically shown that an experiment with two slits is described by solving the Schrödinger equation for a free particle, taking into account the corresponding initial (boundary) conditions. Accord-

ing to [57], the state vector of a free particle in the momentum representation is given by the formula

$$\Phi(\mathbf{p}; t) \equiv \langle \mathbf{p} | \Psi(t) \rangle = \frac{e^{-ip^2 t / 2m\hbar}}{(2\pi\hbar)^{3/2}} \int d\mathbf{r} e^{-i\mathbf{p}\cdot\mathbf{r}/\hbar} \Psi(\mathbf{r}; 0). \quad (6)$$

The initial condition for this state vector can be presented schematically as

$$\Psi(\mathbf{r}; 0) = \delta(x) \left[\delta\left(y - \frac{a}{2}\right) + \delta\left(y + \frac{a}{2}\right) \right] e^{ip_0 z / \hbar}. \quad (7)$$

It corresponds to the motion of a particle with an initial momentum p_0 in the z direction and to the presence of two pointed slits in the y direction, located at a distance a from each other. Delta functions are used for simplicity. Substituting (7) to (6), we can obtain

$$|\Phi(\mathbf{p}; t)|^2 \propto \cos^2 \left[\frac{p_y a}{2\hbar} \right]. \quad (8)$$

From whence it follows that the particle acquires a momentum in the y direction, with alternating maxima and minima. These maxima and the corresponding angles θ_n (with respect to the z axis) are found from the relations

$$\frac{p_y a}{\hbar} = 2\pi n \quad \text{and} \quad \sin \theta_n = \frac{p_y}{p_0} = \frac{2n\pi\hbar}{ap_0}, \quad (9)$$

where $n = 0, \pm 1, \pm 2, \dots$

The peak in the forward direction takes place, $\theta_0 = 0$, which is followed by adjacent peaks at the angles of $\sin^{-1}(\pm h/ap_0)$. Thus, the well-known result from textbooks is demonstrated [6, 17].

It is also shown in [57] that the interference pattern disappears if one of the slits is closed. It can be seen if ‘‘weights’’ for each slit are introduced into initial condition (7), e.g., in the form $[\alpha\delta(y - a/2) + (1 - \alpha)\delta(y + a/2)]$, where α is varied between 0 and 1. The substitution of this initial condition to Eq. (6) gives

$$|\Phi(\mathbf{p}; t)|^2 \propto (2\alpha - 1)^2 + 4\alpha(1 - \alpha) \cos^2 \left[\frac{p_y a}{2\hbar} \right], \quad (10)$$

which demonstrates the (gradual) disappearance of the interference as soon as α approaches 0 or 1. As was mentioned, this effect of smooth disappearance of the interference pattern was confirmed experimentally (see, e.g., [16, 25]).

The *third variant* is taken from [58], where the Fraunhofer diffraction pattern was reproduced with the use of nonstationary perturbation theory for the electron scattering by macroscopic obstacles (a disk and two rectangular slits) specified by the corresponding potentials. Results obtained, according to the authors of [58], in the case of real potentials, when the terms corresponding to multiple scattering of an elec-

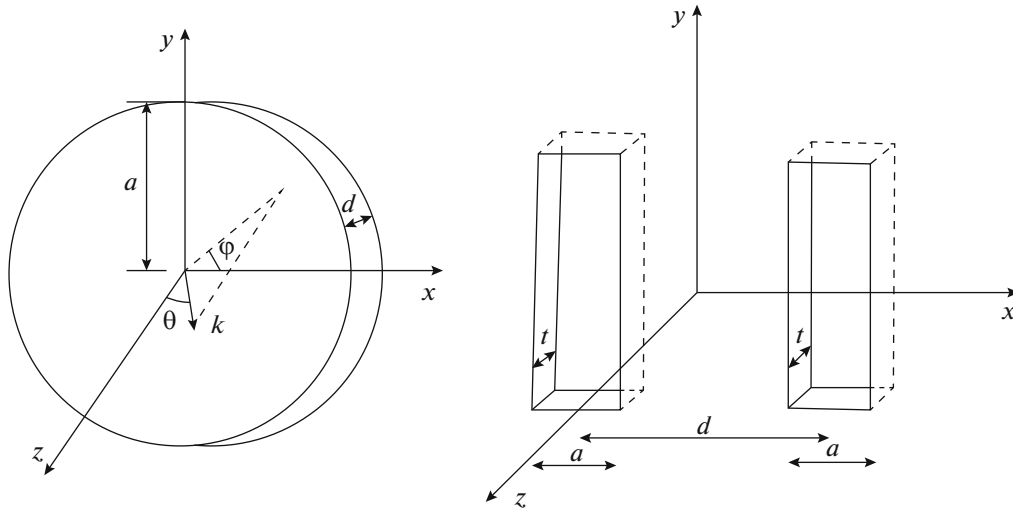


Fig. 5. Electron scatterers: (on the left) a disc of radius a and width d ; (on the right) rectangular slits with thickness t , width a , height h , and distance d between them. An explicit form of the potentials $U(\mathbf{r}) \propto (U_R + iU_I)$ is given in [58].

tron must be taken into account are given below. Therefore, in contrast with the two variants considered above, the probability amplitude of the initial electron was taken in the eikonal approximation (rather than in the form of a free particle $\psi(\mathbf{k}_i) \propto \exp(i\mathbf{k}_i \cdot \mathbf{r})$):

$$\psi_s(\mathbf{k}_i) = C \exp\left(ikz - \frac{i}{2k} \int_{-\infty}^z U(r, z') dz'\right) \quad (11)$$

and $\psi(\mathbf{k}_s) = C \exp(i\mathbf{k}_s \cdot \mathbf{r})$,

where the vector $\mathbf{k}_i = k\hat{z}$ is directed along the z axis perpendicularly to the scatterer surface, while the vector $\mathbf{k}_s = k\{\hat{x} \sin \theta \cos \varphi + \hat{y} \sin \theta \sin \varphi + \hat{z} \cos \theta\}$ ⁸.

In [58], the measured quantity—a number of particles scattered per second per unit solid angle in the direction of the vector \mathbf{k}_s is given by the expression

$$S(\mathbf{k}_s) = \frac{I}{16\pi^2} |\langle \mathbf{k}_s | U | \mathbf{k}_i \rangle|^2, \quad (12)$$

$$\text{where } \langle \mathbf{k}_s | U | \mathbf{k}_i \rangle = \int \psi^*(\mathbf{k}_s) U(\mathbf{r}) \psi_s(\mathbf{k}_i).$$

Here, $I = vC^*C$ is the flux density of falling particles and $v = \hbar|\mathbf{k}_i|/m$ is the velocity of electrons. If the detector is seen at a constant solid angle with the apex in the scatterer, then quantity (12) can be considered an “intensity” of diffraction in the direction of \mathbf{k}_s .

Let us present the results of describing the electron diffraction by a disk and by two slits (Fig. 5). For this,

⁸ Further in (11), \mathbf{r} is the radius vector of an electron; C is the normalization constant; \mathbf{k}_i and \mathbf{k}_s are the wavevectors of the initial and scattered electrons; $|\mathbf{k}_i| = \sqrt{2mE}/\hbar$, where E, m are the energy and mass of an electron, and $\hbar = 2\pi\hbar$ is the Planck constant. In elastic scattering, $|\mathbf{k}_i| = |\mathbf{k}_s|$.

it is necessary to have a matrix element $\langle \mathbf{k}_s | U | \mathbf{k}_i \rangle$ from (12) at the corresponding potentials $U(\mathbf{r})$ and to make, according to [58], a number of simplifying assumptions. For a circular disk with the radius a , the integration in the approximation of $\cos \theta \approx 1$ and $ka \gg 1$ gives

$$\begin{aligned} \langle \mathbf{k}_s | U | \mathbf{k}_i \rangle &= 4\pi i k a^2 \frac{J_1(ka \sin \theta)}{ka \sin \theta} [e^{-(U_R + iU_I)d/2k} - 1], \end{aligned}$$

where J_1 is the Bessel function. In the case of a strongly absorbing target, the expression for electron diffraction by the disk is obtained [58]:

$$S(\mathbf{k}_s) \propto a^4 k^2 \left(\frac{J_1(ka \sin \theta)}{ka \sin \theta} \right)^2.$$

This result coincides with the Fraunhofer formula for the diffraction of electromagnetic waves by an opaque disk (see, e.g., [59, 60]).

The matrix element for the electron scattering by the potential U , calculated over the area of a single slit, is given by the expression from [58]:

$$\begin{aligned} \langle \mathbf{k}_s | U | \mathbf{k}_i \rangle &= -(U_R + iU_I) \int_{-d/2-a/2}^{-d/2+a/2} \int_{-h/2}^{h/2} \int_{-t/2}^{t/2} dx dy dz \\ &\times \exp[-ik(x \sin \theta \cos \varphi + y \sin \theta \sin \varphi)] \\ &\times \exp\left(\frac{i}{2k} \int_{-t/2}^z (U_R + iU_I) dz'\right) \\ &\propto 2ikha \operatorname{sinc}\left[\frac{kh \sin \theta \sin \varphi}{2}\right] \\ &\times \operatorname{sinc}\left[\frac{ka \sin \theta \cos \varphi}{2}\right] \exp\left(\frac{ikd \sin \theta \cos \varphi}{2}\right). \end{aligned}$$

The last line takes into account that the absorbing part of the potential U_I is large enough [58]. In the case of a very long slit, the first function sinc is non-zero (equal to 1) only at $\varphi = 0$. With allowance for a similar contribution from the second slit, for the intensity of electron scattering in the direction θ , the following expression was obtained:

$$S(\mathbf{k}_s) \propto \frac{k^2 (ah)^2}{\pi^2} \text{sinc}^2 \left[\frac{ka \sin \theta}{2} \right] \cos^2 \left(\frac{kd \sin \theta}{2} \right).$$

The angular dependence here completely coincides with the angular dependence of the Fraunhofer formula, which describes the diffraction of electromagnetic waves by two slits (see [59, 60]).

The authors of [58] themselves emphasized that the two considered cases illustrate a common result: the scattering intensity is determined by the square of the Fourier transform of the function describing the diffracting properties of the obstacle, in other words, by the Fourier transform of the region Ω occupied by the scatterer:

$$S(\mathbf{k}_s) \propto \frac{k^2 I}{4\pi^2} \left[\int_{\Omega} d^2 \rho e^{-i\mathbf{k} \cdot \rho} \right]^2.$$

Therefore, on the same obstacle Ω , the form of the diffraction pattern for electrons coincides with the classical Fraunhofer diffraction pattern for electromagnetic waves.

Let us note that in the third variant it is already clearly seen that the concept of “diffraction of electrons” is almost in no way different from the concept of “scattering of electrons” (by a potential, crystal, atom, nucleus, or nucleon) due to the interaction of one or another nature, which is customary for high-energy physics [56].

Completing the purely quantum mechanical explanation of electron diffraction, we emphasize that the key place is the probability amplitude for a free particle (the solution to the Schrödinger equation) in the form of Eq. (2). Therefore, recalling the long history of the formation of quantum mechanics, its wave origins, and analogies, someone will immediately say that the Schrödinger equation is a wave equation, and all its solutions are waves, since they contain a wave nature by their origin. Actually, Feynman, looking at Eq. (2),

$\langle \mathbf{r}_2 | \mathbf{r}_1 \rangle \propto \frac{e^{i\mathbf{p}\mathbf{r}_{12}}}{r_{12}}$, says that “a particle has wave properties” and that the probability amplitude propagates like a wave with the wavenumber $\mathbf{k} = \mathbf{p}/\hbar$.

If the second statement is quite acceptable, then the first one does not look convincing. Moreover, Feynman himself emphasizes “that the wave function that satisfies the wave equation is not similar to a real wave in the space. With this wave, no reality can be associated, as it is done with a sound wave.”

On the other hand, without going into “lyrical details,” the Schrödinger equation can be considered to have “fallen from the sky.” Then its solution for a free particle is the probability amplitude in the form of Eq. (2). For practical calculations, only this explicit form of the probability amplitude is needed, and it does not matter in the least that it bears the name *plane wave*. Here it is appropriate to quote P.A.M. Dirac [13] that “the ‘wave function’ name was given because at the dawn of quantum mechanics all examples of these functions had the form of waves. From the viewpoint of the modern general theory, this name does not reflect the characteristic properties of these functions.”

4. WHAT NEXT?

If we do not rely, as was illustrated above, on quantum mechanics itself, then it is necessary to find physical reasons for the occurrence of the diffraction pattern during the scattering of electrons (one by one) by two slits and crystals. In other words, the question is reduced to an old problem: how do we explain the diffraction of the particles of matter in the context of corpuscular concepts, i.e., without invoking the hypothesis that a corpuscle itself, taken individually, already possesses the properties of a wave.

In the textbook by D.I. Blokhintsev [8], we find (p. 47) “It cannot be assumed that the waves themselves are the formation of particles or arise in a medium formed by particles. Experience shows that the diffraction pattern does not depend on an intensity of the incident particle beam. Only the total number of particles is important. This fact definitely shows that each electron diffracts independently of the others. Therefore, the existence of wave phenomena cannot be associated with the simultaneous⁹ presence of a large number of particles.”

In his textbook, Messiah writes (pp. 31–32) “all attempts to explain the phenomenon of interference in the context of a purely corpuscular theory, based only on experimental results, can be discarded a priori. Further: although the observed discontinuities can be explained only using the concept of light corpuscles, to give up the concept of a light wave is out of the question. Depending on what phenomenon is under study, the light manifests itself in two aspects: wave and corpuscular. The probability that a photon is located at a certain point is proportional to the intensity of the light wave at this point, which is calculated on the basis of methods of wave optics. Light cannot be regarded either as a stream of classical corpuscles or as a superposition of classical waves without contradicting the experimental data. Finally: on the way to the detecting device, the light propagates as a wave; the

⁹ If the combination of words “cannot ... simultaneous” is removed, then hope remains that wave phenomena can be associated simply with the presence of a large number of particles.

corpuscular aspect of the photon appears only at the moment of detection.”

Here, however, there is an objection. If the second statement is not in doubt today, then the first one cannot be verified, because to learn something, it is necessary to implement the interaction disturbing this flight of the wave.

For illustration, let us carry out the thought experiment so beloved by the classics.

Imagine that we are looking at the bright North Star in the night sky. In scientific terms, this means that the photons emitted (many years ago) fall (with enviable consistency) into our eye or onto the recording matrix of a suitable telescope, irritating the retina of the eye or causing the corresponding energy release in elements of the recording matrix. At this case, we are convinced that the star is located exactly where we see it (forgetting for a while about the long-term path of photons to us and the shift of the star itself to somewhere during this time). In other words, we believe that the light from it to us will propagate in a straight line, without seriously touching anything along the way and without seriously interacting with anything (at least, those photons that reach our eyes do so). Nothing can be said about the rest: they simply do not reach us (maybe they were forced to interact with something), and we do not see them. Therefore, due to the “straightness” of noninteracting photons, we see this star as one small luminous point. It is easiest to assume that namely these photons just fly towards us like ordinary particles—corpuscles, without any kind of wave properties or complex probability amplitudes.

Now, on the direct path of these photons from the star to us, we will place a de Broglie obstacle, for example, a crystal with a suitable lattice spacing. Obviously, a beautiful and simple image of a star will turn into a diffraction pattern, which is characteristic namely of our chosen de Broglie obstacle.

And here we realize that it is the interaction of “stellar” photons inside this obstacle [54], leading to the given diffraction pattern, that calls into being both the probability amplitude and the very rule of adding these amplitudes. These two key “tricks” of quantum mechanics work only inside our de Broglie obstacle, where the stellar photons are forced to feel somehow this obstacle, i.e., interact with it. Our quantum mechanical “tricks” are in no way applicable; they give us nothing, and so they simply are not needed until the de Broglie obstacle is encountered, and they have the same degree of usefulness (are completely useless) after the de Broglie obstacle is abandoned.

The conclusion from our “thought experiment” is the need for interaction; this is the hidden reason for all the achievements and “troubles” of quantum mechanics. It is essential that this interaction must be local, which has no place in quantum mechanics itself.

To try to find an answer to the question posed at the beginning of this section, let us briefly recall the fateful sequence of events. It looks something like this:

(1) The diffraction of material particles (photons, electrons, etc.) is reliably established¹⁰.

(2) This diffraction pattern was visually very similar to the diffraction patterns of light (X-rays) and elastic waves. It was well described by simple formulas applicable both for elastic waves and light and for particles.

(3) From this the concept of the waves of matter come from; i.e., particles of matter under certain conditions behave like elastic waves and light (γ quanta): they give the same visual imagery.

(4) On this basis, it is concluded that an individual material particle has wave properties.¹¹

(5) In this case, no one pays attention to the fact that the wave properties of matter (diffraction) appear only when there is a lot of matter particles (and photons).

(6) The result is a triumph of quantum mechanics based on corpuscular-wave duality.

In fairness,¹² it should be said that at that time there was no alternative to items (4) + (5). On the formal side, there was no experimental fact number 2, while actually, always and everywhere, literally in all experimental situations, a huge stream of particles (photons, electrons, atoms, etc.) was invisibly present. It was inevitable; omnipresent; and, therefore, completely unnoticed (like air). Probably nobody thought about experimenting with photons and electrons one by one¹³.

Now that “who is to blame” is clear, we need to understand “what is to be done”: look for a new solution to an old problem, i.e., try to explain the wave properties of matter—interference and diffraction—without invoking the idea of wave-particle duality.

The mention by L.I. Mandelstam [60] of the work by Epstein and Ehrenfest [61], where a simple explanation of the diffraction of light from the corpuscular viewpoint is given (1924), looks amusing for that reason. They considered diffraction as the collision of a photon (momentum $\frac{h\nu}{c}$) with a diffraction grating (mass M), considering the energy imparted to the grating to be negligible. In this case, the law of conser-

¹⁰The fact that the wave properties of matter were already predicted by de Broglie is secondary in this case.

¹¹With special consideration, it turns out that these wave properties are very unusual, but this is already later.

¹²Of course, for the sake of respect for the great merits of the founders of quantum mechanics.

¹³Since today it is already possible to work with a single electron, the proof of the wave-particle duality would be an experiment with one electron, demonstrating the wave properties of this particular electron. It is not at all clear yet how this can be done, though.

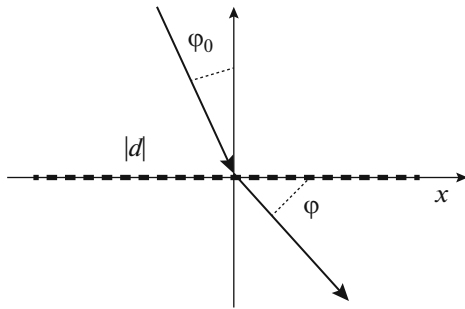


Fig. 6.

vation of momentum along the x axis (see Fig. 6) has the form

$$\frac{h\nu}{c} \sin \varphi + P_x = \frac{h\nu}{c} \sin \varphi_0. \quad (13)$$

After the collision, the grating moves along the x axis with a constant (negligible due to the massiveness of the grating) velocity v or momentum $P_x = Mv$.

The passage of its grooves is a periodic process with a grating spacing d . According to the old quantum mechanics for a periodic process, the condition (quantization) $\int P_x dx = mh$ must be satisfied. The integration over the period d gives $P_x = Mv = \frac{hm}{d}$. Then, from (12), the well-known relation for the diffraction of light by a diffraction grating immediately follows [61]:

$$\sin \varphi - \sin \varphi_0 = \frac{m\lambda}{d}. \quad (14)$$

It seems that the old quantum mechanics is outdated and the modern quantum mechanics does not consider this explanation satisfactory.

Within modern quantum mechanics, the answer was given in Section 3. However, something has been left behind: can this “intra-quantum-mechanics” answer be considered completely free from the presence (albeit invisible and, as it were, already nonconstructive) of wave ideas? Some may be satisfied with this explanation, while others will not.

Therefore, most likely, the new correct answer must be sought in two ways. First, by a careful analysis of individual acts of local interaction of microparticles with the substance from which the de Broglie obstacle is made, say, using methods of quantum field theory from the physics of high-energy particles¹⁴ and/or the modern powerful computational resources and methods. In quantum mechanics itself, the interaction is too formalized by the (long-range) potential.

¹⁴ Attempts were made to use the inelastic interaction of electrons in a material of specially prepared nanoslits to determine the place of electron penetration through the slit [34, 35].

For example, A.A. Sokolov and colleagues [62] believed “that the key to solving the problem of the statistical nature of electron motion (diffraction and interference) should be sought in taking into account the effect of vacuum fluctuations on a real electron. For instance, the electrons should begin to move according to the quantum theory laws, due to the fluctuation effect on them by the photons which they really emit. The authors write that the wave properties of an electron beam can be considered a statistical spread arising due to the effect of vacuum fluctuations on them. This scatter in the interaction of electrons with macrodevices just manifests itself, for example, in the form of a diffraction pattern. In other words, the conditions of motion of an electron, which are the same macroscopically, do not have to be the same from a microscopic viewpoint, and/or an electron is a complex object, say, consisting of a point electron and a vacuum “trailing behind it.”

Secondly, to find a “new correct answer,” it is necessary to use the novelty potential, which is usually well hidden in the transition from individual events to a large statistical population of similar events. In favor of the existence of this possibility, we can give two arguments of our own.

The first argument, as they say, is metaphysical. For example, B.M. Gessen [63], comparing the relations of dynamic and statistical regularities, concluded that “a statistical regularity is intensional (‘catches and studies nonadditive properties’) and that by its very essence it cannot be referred to separated individuals which make up the totality. This is not its disadvantage. This is its specific feature, since it is studying precisely those properties that are manifested only by the totality and which are absent in individual members.” That is, in a simple way, the transition from one to many is fraught with something new. Statistical regularities (when very many identical particles do something the same very many times, say, fly one at a time through two microslits) are a potential source of new properties and new knowledge.

The second argument is extremely modern and pragmatic. It arises from the experience of using Big Data and Machine Learning: by analyzing, due to the unique computer capabilities, unprecedentedly large sets of data of the same type, people find in them very significant correlations of great practical importance, even without realizing the true causes of these correlations.

On this path, we will probably also have to deal with the following problems:

(1) Since the diffraction of electrons takes place on the surface of the crystal, it should also occur on (2 or 4) edges—boundaries of (1 or 2) real (not abstractly infinitely narrow) slits. No reasons are seen why the electron diffraction at the slits cannot be predicted (recalculated) based on the electron diffraction at the crystal surface. A rather narrow, say, trapezoidal, edge

of a real slit may well represent a sequence of several crystalline layers with a decreasing (towards the edge of the slit) number of scatterers—atoms. As a result, it is quite possible to expect a certain regularity in the directions of emission of electrons interacting with this target. For example, an electron flying at a distance of the crystal lattice spacing h from the edge of the slit, due to the interaction at the distance h , will be deflected, say, by an angle φ . If the electron flies noticeably closer to the crystal lattice, e.g., at a distance $h/2$ from the edge of the slit, then the interaction force will be greater (the second layer of the lattice will “turn on”) and the electron will already be deflected by an angle, say, 2φ . It is more or less clear that the periodicity (regularity) of the crystal lattice of this slit should somehow manifest itself in the periodicity of the angular distribution of scattered electrons. Another question is what kind of diffraction pattern will be obtained in this case?

(2) A description of the diffraction of light, elastic waves, and diffraction of the waves of matter is based on a simple formula (13) or $d \sin \varphi = m\lambda$, where λ is the de Broglie wavelength, which does not depend on the diffraction source (light, particle, and wave on water). The main problem is this “surprising” similarity of diffraction patterns. It is aggravated by the fact that the diffraction physics in all three cases is completely different. The diffraction of elastic waves occurs due to the interference of waves excited in the carrier medium by secondary sources of waves on the obstacle surface. The diffraction of single particle corpuscles, i.e., their deviation from the original direction of motion, is a result of the particle scattering (maybe multiple) by the structural elements (nodes) of the target due to interaction with them. Neither light nor, moreover, electrons, have a medium carrier of (light/electronic) waves. The need for the complexity of the probability amplitude for corpuscles is a fundamental difference from the amplitude of elastic waves. It is a mystery why, with this fundamental difference, there is an amazing visual similarity of diffraction patterns, and solving it will undoubtedly shed a new light on the old problem.

(3) Further discussing this difference, we note that photons (γ quanta) and electrons (neutrons and other particles of matter) are also too different corpuscles. A photon has no rest mass and it moves at the speed of light¹⁵; an electron is unable to do this, since it has a

nonzero rest mass. A photon passes through a transparent medium, but an electron does not. An electron has an electric charge, but a photon does not. The visible photon wavelength is much longer than the electron wavelengths. Finally, the most fundamental thing is that a photon is a boson with spin 1 and an electron is a fermion with a spin of 1/2. A quote from Feynman [12] (vol. 9, pp. 233–236) is appropriate here: “The physics of light quanta coincides with the classical physics, because photons are noninteracting Bose particles and many of them can be in the same state. Moreover, they like to be in the same state. At the moment when myriads of them are found in the same state (i.e., in the same electromagnetic wave), you will be able to measure directly the wave function (i.e., the vector potential). The difficulty with an electron is that you cannot put more than one electron in the same state.”

However, when experiments with a double slit are discussed, photons and electrons are not separated at all, if, of course, the momentum of electrons, according to de Broglie’s Eq. (1), is related to the energy (wavelength) of photons. The diffraction patterns for photons and electrons are very similar (Figs. 2–4). It is difficult to keep from saying that the role of the target by which both those and other particles are diffracted (scattered) is much greater than the differences between them. Nevertheless, a comparison of X-ray diffraction with electron diffraction, carried out at the beginning of the last century [56], showed that electrons are capable of forming a much richer set of diffraction patterns corresponding to probing various structures of the sample under study.

5. CONCLUSIONS

It seems that the internal paradoxicality of corpuscular-wave duality (a particle is a wave) has lost its relevance. On the one hand, the scientific community, by efforts of the Copenhagen School luminaries, is completely accustomed to this paradoxicality and no longer thinks about it. On the other hand, this duality in fact no longer plays any role in modern physics of elementary particles. Therefore, the impression may well be created that the entire discussion above (even if it is devoid of internal flaws) is exclusively of “academic interest” and is in no way connected with the tasks and problems of the modern stage of development of the particle physics.

In principle, we can agree with this viewpoint, and end it there. However, even a purely speculative possibility of getting closer to resolving one or another paradox is of certain interest.¹⁶ It opens up new horizons closed by the ruling paradigm. Therefore, the wave–particle duality (together with the Indeterminacy Principle and the mysterious Planck’s Constant)

¹⁵Why is the speed of movement (emission) of a photon is constant? The answer is simple: a photon has zero inertial mass and, because of this, its speed can be changed in no way and it has to be constant! Logically, there are only three options. This constant speed is infinite, but there are no infinities in nature; infinity only exists in the brains of mathematicians. This speed is equal to zero, but then the photon cannot leave its source; i.e., it simply does not exist. There is only one constant left. Why is it equal to 3×10^{10} cm/s? This is how our world works (anthropic principle); that is the most accurate answer so far.

¹⁶Here you can recall the statements of Einstein, e.g., from his book *The Evolution of Physics* [64].

works as a barrier, which, by its categoricalness, does not allow us to think, e.g., about how a new property could arise in the transition from an individual particle to a large aggregate of particles, from one event (scattering of one electron) to a large set of events of the same type. Or, why are diffraction patterns so similar for different objects such as elastic waves, photons, and electrons?

On the other hand, modern advances in the field of computer technologies and the creation of unique, never-before-seen, equipment (capable, e.g., of recording individual photons) more and more stimulate the researcher to engage in biological, chemical, and physical processes involving a single particle: a gene, virus, molecule, atom, neutron, or gamma quantum. For example, a human eye, under certain conditions, is quite capable of recording individual photons. But does a modern researcher have an adequate theoretical basis allowing him to confidently manipulate individual microobjects? Quantum mechanics is a statistical theory that deals well with large aggregates of objects. The modern scattering theory based on it also always implies the permanent presence of a (large) flow of particles.

The impression is created that the most advanced physics of particles and atomic nucleus—the foundation of the modern worldview—“got stuck” in extensive, analytical methods of research, when something hits something else very many times and then tries to find something worthwhile from a huge amount of unnecessary material. It is time, apparently, to look for ways of transitioning to intensive, synthetic methods with which, on the basis of already existing knowledge, consciously, from two or three specific elements (ideally, say, quarks), a new entity (nucleon) is created/synthesized. To do this, we must learn to operate with specific individual microparticles, say, atoms or molecules (in the future, protons, nucleons, electrons, etc.) and make new objects with new, necessary properties out of them.

Unfortunately, the world-famous successes in the synthesis of superheavy elements are not actually such a manmade synthesis. Without depreciating the outstanding merits of our Dubna colleagues, it can be noted that what they do remarkably well is create conditions in which the nature itself sometimes gives birth to the desired nucleus, while they (and this is their main achievement) manage, in a huge amount of “garbage,” to find exactly the only nucleus that nature granted them.

The most interesting thing is that the time for predicting and creating new materials in a truly synthetic way has already come, at least in the field of condensed matter physics, on the basis of already well-tested methods of quantum physics and quantum chemistry there (see, e.g., works by Artem Oganov [65]).

The concept of a wave accompanying a microparticle has become a convenient method for qualitatively

estimating microworld events, and it is hardly worth giving up on it. It is necessary to realize only its “limits of applicability,” e.g., recognize that the de Broglie wavelength (λ) refers not to a single electron, but to a whole ensemble of electrons.

In conclusion, let us recall M.P. Bronstein [66]. He wrote “The formal similarity between the mechanics of an electron and the laws of wave propagation is rather a feeble semblance (it does not take into account the fundamental difference between the waves as X-ray propagation and the waves in quantum mechanics). In this regard, it becomes quite obvious that the question ‘is an electron a particle or a wave?’ can be posed only due to a misunderstanding. After all, a wave is a process and an electron is a thing. Hence it is clear that the expression ‘an electron is an elementary particle’ has only the meaning that a fractional part of an electron cannot be ever observed. Therefore, the answer is that ‘an electron is a particle obeying wave mechanics.’”

In other words, an electron is an elementary particle that obeys quantum mechanics. Without any individual wave properties. To illustrate, let us imagine for a moment that there are two types of electrons. An electron of the first type is a truly elementary particle in the literal sense of the word; it is the same electron that enters, together with the neutrino, into the weak doublet of the Standard Model. No wave properties are implied for this representative of particle physics. An electron of the second type is a quantum-mechanical electron, i.e., a certain “average” or “fictitious” (as Nikolsky¹⁷ called it) representative of a large statistical ensemble of electrons; it is the electron which is mentioned in the context of quantum mechanics. Then the question posed in the title of the article should be answered like this: an individual electron does not have wave properties; however, from the point of view of quantum mechanics, they are manifested due to the presence of a large ensemble of electrons.

REFERENCES

1. D. Z. Freedman, “Coherent effects of a weak neutral current,” *Phys. Rev. D* **9**, 1389–1392 (1974).
2. D. Z. Freedman, D. N. Schramm, and D. L. Tubbs, “The weak neutral current and its effects in stellar collapse,” *Ann. Rev. Nucl. Part. Sci.* **27**, 167–207 (1977).
3. V. A. Bednyakov and D. V. Naumov, “Coherency and incoherency in neutrino-nucleus elastic and inelastic

¹⁷He wrote [15] that “in quantum mechanics, a statistical aggregate is analyzed from a certain process of interactions of quantum particles and a macroscopic body. On the basis of a series of such individual processes, the concept of a fictitious average process is established; it is the process that is meant in the uncertainty principle. Quantum mechanics is a theory of the properties of this average fictitious representative of quantum particles and only of the properties which appear during the interaction with macroscopic bodies.”

- scattering,” *Phys. Rev. D* **98**, 053004 (2018); arXiv: 1806.08768.
4. V. A. Bednyakov and D. V. Naumov, “On coherent neutrino and antineutrino scattering off nuclei,” *Phys. Part. Nucl. Lett.* **16**, 638–646 (2019); arXiv: 1904.03119.
 5. T. Young, *A Course of Lectures on Natural Philosophy and Mechanical Arts* (Johnson, London, 1807).
 6. A. Messiah, *Quantum Mechanics* (Dunod, France, 1962).
 7. L. Broglie, “Waves and quanta,” *Nature* (London, U.K.) **112**, 540 (1923).
 8. D. I. Blokhintsev, *Fundamentals of Quantum Mechanics* (Vyssh. Shkola, Moscow, 1963; Springer, Netherlands, 1964).
 9. C. Davisson and L. Germer, “Reflection of electrons by a crystal of nickel,” *Proc. Natl. Acad. Sci. U. S. A.* **14**, 317–322 (1928).
 10. Y. I. Frenkel’, “Particles and waves,” *Nauch. Slovo* **8**, 3 (1928); Y. I. Frenkel’, “Origin and development of quantum mechanics,” *Priroda*, No. 1, 3–27 (1930).
 11. B. A. Fock, *Lecture on Quantum Mechanics* (Leningrad, 1937) [in Russian]; “What did quantum theory bring to the basic concepts of physics?,” *Sots. Rekonstr. Nauka*, No. 6, 3–8 (1935).
 12. R. Feynman, R. Leighton, and M. Sands, *The Feynman Lectures in Physics*, Vol. 3: *Quantum Mechanics* (Addison-Wesley, Reading, USA, 1965).
 13. P. A. M. Dirac, *The Principles of Quantum Mechanics* (Clarendon, Oxford, 1958).
 14. P. C. Tartakovskii, “Wave views on the nature of matter and experience,” *Usp. Fiz. Nauk* **8**, 338–341 (1928).
 15. K. B. Nikol’skii, “Answer to V. A. Fok,” *Usp. Fiz. Nauk* **17**, 557–560 (1937); K. B. Nikol’skii, “Quantum optics,” in *Physical Glossary* (1940), Vol. 2, p. 774.
 16. R. Bach, D. Pope, S. H. Liou, H. Batelaan, and U. Nebbraska, “Controlled double-slit electron diffraction,” *New J. Phys.* **15**, 033018 (2013); arXiv: 1210.6243
 17. L. Schiff, *Quantum Mechanics* (McGraw-Hill, USA, 1955).
 18. N. Bohr, in *Albert Einstein: Philosopher Scientist*, Ed. by A. Schlipp (Open Court, La Salle, IL, 1949).
 19. G. Matteucci, “On the presentation of wave phenomena of electrons with the Young–Feynman experiment,” *Eur. J. Phys.* **32**, 733–738 (2011).
 20. C. Jönsson, “Elektroneninterferenzen an mehreren künstlich hergestellten Feinspalten,” *Z. Phys.* **161**, 454–474 (1961).
 21. C. Jönsson, “Electron diffraction at multiple slits,” *Am. J. Phys.* **42**, 4–11 (1972).
 22. G. Matteucci, “Electron wavelike behavior: A historical and experimental introduction,” *Am. J. Phys.* **58**, 1143–1147 (1990).
 23. P. Merli, G. Missiroli, and G. Pozzi, “On the statistical aspect of electron interference phenomena,” *Am. J. Phys.* **44**, 306–307 (1976).
 24. A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki, and H. Ezawa, “Demonstration of single-electron buildup of an interference pattern,” *Am. J. Phys.* **57**, 117–120 (1989).
 25. A. Tonomura, “Direct observation of thitherto unobservable quantum phenomena by using electrons,” *Proc. Nat. Acad. Sci. U. S. A.* **102**, 14952–14959 (2005).
 26. A. Tavabi, C. Boothroyd, E. Yucelen, S. Frabboni, G. C. Gazzadi, R. Dunin-Borkowski, and G. Pozzi, “The Young-Feynman controlled double-slit electron interference experiment,” *Sci. Rep.* **9**, 10458 (2019).
 27. B. Barwick, G. Gronniger, L. Yuan, S.-H. Liou, and H. Batelaan, “A measurement of electron-wall interactions using transmission diffraction from nanofabricated gratings,” *J. Appl. Phys.* **100**, 074322–074322 (2006).
 28. S. Frabboni, G. C. Gazzadi, and G. Pozzi, “Young’s double-slit interference experiment with electrons,” *Am. J. Phys.* **75**, 1053–1055 (2007).
 29. S. Frabboni, G. C. Gazzadi, and G. Pozzi, “Nanofabrication and the realization of Feynman’s two-slit experiment,” *Appl. Phys. Lett.* **93**, 073108–073108 (2008).
 30. S. Frabboni, A. Gabrielli, G. C. Gazzadi, F. Giorgi, G. Matteucci, G. Pozzi, N. Cesari, M. Villa, and A. Zoccoli, “The Young–Feynman two-slits experiment with single electrons: Build-up of the interference pattern and arrival-time distribution using a fast-read-out pixel detector,” *Ultramicroscopy* **116**, 73–6 (2012).
 31. A. Gabrielli, F. Giorgi, N. Semprini, M. Villa, A. Zoccoli, G. Matteucci, G. Pozzi, S. Frabboni, and G. C. Gazzadi, “A 4096-pixel MAPS detector used to investigate the single-electron distribution in a Young–Feynman two-slit interference experiment,” *Nucl. Instrum. Methods Phys. Res., Sect. A* **699**, 47–50 (2013).
 32. S. Frabboni, G. C. Gazzadi, and G. Pozzi, “Ion and electron beam nanofabrication of the which-way double-slit experiment in a transmission electron microscope,” *Appl. Phys. Lett.* **97**, 263101–263101 (2010).
 33. S. Frabboni, G. C. Gazzadi, V. Grillo, and G. Pozzi, “Elastic and inelastic electrons in the double-slit experiment: A variant of Feynman’s which-way set-up,” *Ultramicroscopy* **154**, 49–56 (2015).
 34. R. Egerton, “Limits to the spatial, energy and momentum resolution of electron energy-loss spectroscopy,” *Ultramicroscopy* **107**, 575–86 (2007).
 35. R. Egerton, “Electron energy loss spectroscopy in the TEM,” *Rep. Prog. Phys.* **72**, 16502–25 (2009).
 36. A. Aspect, P. Grangier, and G. Roger, “Experimental tests of realistic local theories via Bell’s theorem,” *Phys. Rev. Lett.* **47**, 460–6443 (1981).
 37. R. Gahler and A. Zeilinger, “Wave-optical experiments with very cold neutrons,” *Am. J. Phys.* **59**, 316–324 (1991).
<https://doi.org/10.1119/1.16540>
 38. A. Zeilinger, R. Gahler, C. Shull, W. Treimer, and W. Mampe, “Single and double-slit diffraction of neutrons,” *Rev. Mod. Phys.* **60**, 1067–1073 (1988).
 39. H. Schmidt, D. Fischer, Z. Berenyi, C. Cocke, M. Gudmundsson, N. Haag, H. Johansson, A. Kullberg, S. Levin, P. Reinhed, U. Sassenberg, R. Schuch, A. Simonsson, K. Stochkel, and H. Cederquist, “Evidence of wave-particle duality for single fast hydrogen atoms,” *Phys. Rev. Lett.* **101**, 083201 (2008).

40. O. Carnal and J. Mlynek, "Young's double-slit experiment with atoms: A simple atom interferometer," *Phys. Rev. Lett.* **66**, 2689–2692 (1991).
41. A. Cronin, J. Schmiedmayer, and D. Pritchard, "Optics and interferometry with atoms and molecules," *Rev. Mod. Phys.* **81**, 1051 (2009).
42. C. Bordé, N. Courtier, F. du Burck, A. Goncharov, and M. Gorlicki, "Molecular interferometry experiments," *Phys. Lett. A* **188**, 187–197 (1994).
43. M. Andrews, C. Townsend, H. Miesner, D. Durfee, D. Kurn, and W. Ketterle, "Observation of interference between two Bose condensates," *Science* (Washington, DC, U. S.) **275**, 637–41 (1997).
44. K. Davis, M.-O. Mewes, M. Andrews, N. van Druten, D. Durfee, D. Kurn, and W. Ketterle, "Bose-Einstein condensation in a gas of sodium atoms," *Phys. Rev. Lett.* **75**, 3969 (1995).
45. W. Schollkopf and P. Toennies, "The nondestructive detection of the helium dimer and trimer," *J. Chem. Phys.* **104**, 1155–1158 (1996).
46. W. Schollkopf and P. Toennies, "Nondestructive mass selection of small Van der Waals clusters," *Science* (Washington, DC, U. S.) **266**, 1345–8 (1994).
47. I. Estermann and O. Stern, "Beugung von Molekularstrahlen," *Z. Phys.* **61**, 95–125 (1930).
48. S. Eibenberger, S. Gerlich, M. Arndt, M. Mayor, and J. Tuxen, "Matter-wave interference of particles selected from a molecular library with masses exceeding 10000 amu," *Phys. Chem.* **15**, 14696–14700 (2013).
49. O. Nairz, M. Arndt, and A. Zeilinger, "Quantum interference experiments with large molecules," *Am. J. Phys.* **71**, 319–325 (2004).
50. S. Sala, R. Ferragut, C. Pistillo, A. Ereditato, A. Ariga, M. Giammarchi, and P. Scamporrì, "First demonstration of antimatter wave interferometry," *Sci. Adv.* **5**, 1–7 (2019).
51. S. Haroche, J. Raimond, and P. Meystre, "Exploring the quantum: Atoms, cavities, and photons," *Phys. Today* **60**, 61 (2007).
52. F. Lindner, M. G. Schätzel, H. Walther, A. Baltuska, E. Goulielmakis, F. Krausz, D. B. Milosevic, D. Bauer, W. Becker, and G. G. Paulus, "Attosecond double-slit experiment," *Phys. Rev. Lett.* **95**, 040401 (2005).
53. M. Wollenhaupt et al., "Interference of ultrashort free electron wave packets," *Phys. Rev. Lett.* **89**, 173001 (2002).
54. B. N. Ivanov, *Principles of Modern Physics* (Nauka, Moscow, 1973) [in Russian].
55. L. Biberman, P. Sushkin, and B. Fabrikant, "Diffraction of alternately flying electrons," *Dokl. Akad. Nauk SSSR* **66**, 185 (1949).
56. H. Mark and R. Wierl, *Die Experimentellen und Theoretischen Grundlagen der Elektronenbeugung* (Verlag von Gebrüder Borntraeger, Berlin, 1931).
57. M. Bauer, "On time and space double-slit experiments," *Am. J. Phys.* **82**, 1087–1092 (2014).
58. G. Anido and D. Miller, "Electron diffraction by macroscopic objects," *Am. J. Phys.* **52**, 49 (1984).
59. M. Born and E. Wolf, *Principles of Optics* (Cambridge Univ. Press, Cambridge, 1975).
60. L. I. Mandel'shtam, *Lectures on Optics, Theory of Relativity and Quantum Mechanics* (Nauka, Moscow, 1958) [in Russian].
61. P. Epstein and P. Ehrenfest, *Proc. Natl. Acad. Sci. U. S. A.* **10**, 133 (1924).
62. A. A. Sokolov and I. M. Ternov, *Quantum Mechanics and Atomic Physics* (Prosveshchenie, Moscow, 1970); A. A. Sokolov and I. M. Ternov, "To the quantum theory of the glowing electron," *Zh. Eksp. Teor. Fiz.* **25**, 698 (1953); A. A. Sokolov, D. D. Ivanenko, and I. M. Ternov, "On excitation of macroscopic oscillations by quantum fluctuations," *Sov. Phys. Dokl.* **1**, 658 (1957); A. A. Sokolov and V. S. Tumanov, "Uncertainty relation and the theory of fluctuations," *Sov. Phys. JETP* **3**, 958 (1956).
63. B. M. Gessen, "The nature of quantum physics," *Nauch. Slovo* **7**, 19 (1929); B. M. Gessen, "Statistical approach in physics and new substantiation of the theory of probability by R. Mises," *Estestvozn. Marksizm*, No. 1, 34 (1929).
64. A. Einstein and L. Infeld, *The Evolution of Physics* (Simon and Schuster, New York, 1954).
65. A. Oganov and C. Glass, "Crystal structure prediction using ab initio evolutionary techniques: Principles and applications," *J. Chem. Phys.* **124**, 244704 (2006).
66. M. P. Bronshtein, "New crisis of quantum theory," *Nauch. Slovo* **1**, 40–48 (1931); M. P. Bronshtein, "The doctrine of chemical valence in modern physics," *Priroda*, No. 10, 879–881 (1932).

Translated by M. Samokhina