PHYSICAL SCIENCES

DOUBLE SLIT EXPERIMENT AND WAVE-PARTICLE DUALITY

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Abstract

The double-slit experiment is a classic experiment that presents the clearest manifestation of wave-particle duality, one of the fundamental principles of quantum mechanics. The double-slit experiment still remains the phenomenon that demonstrates wave-particle duality at the most fundamental level. This phenomenon quantitatively and conceptually demonstrates that microscopic objects can behave like both waves and particles at the same time. This article provides an in-depth analysis of the physical nature of dualism, the mechanism of formation of the interference pattern, and the impact of the act of observation on the dynamics of quantum systems. The need for a new perspective on this topic is due to the fact that the current uncertainty in the interpretation of quantum reality has not yet been completely eliminated, and the boundaries between classical and quantum behavior in microscopic objects are still being explored. The results presented here restructure the deep mechanisms of the interference picture, more clearly frame the relationship between observation and wavefunction collapse, and provide a quantum. Since the article attempts to provide a complete answer to the mechanism of the formation of wave-particle duality, extensive space is given to sections such as historical development, theoretical models, modern research, etc. New approaches to this phenomenon have been developed using modern research and string theory. As a result, a new mathematical expression has been proposed that explains the reasons for the initial emergence of wave-particle duality, and is also important for string theory. The article explains the measurement problem with a more effective physical structure and ontological model.

Keywords: Double-slit experiment, wave-particle dualism, interference pattern, measurement problem, observer effect, Copenhagen interpretation, string theory.

İntroduction. Attempts to understand the nature of reality in the subtlest layers of the universe sometimes result in paradoxes that exceed the limits of the human mind. The most profound and thought-provoking of them is undoubtedly the double-slit experiment - a fundamental event that has become a symbol of how particles behave both as waves and as particles[1]. The double-slit experiment challenged the logic of classical physics and introduced into science the idea that observation itself affects reality. The double-slit experiment has puzzled physicists and philosophers for centuries, redefining the relationship between the observer and the observed in the depths of reality[2].

Historical development. The concept of wave-particle duality led to one of the most profound philosophical and scientific changes in the history of physics. This idea brought a new perspective on the nature of the Universe, explaining how light and matter can behave as both particles and waves. The scientific roots of wave-particle duality extend from observations several centuries ago to the fundamental principles of modern quantum mechanics[3].

In the 17th century, there were two main ideas about the nature of light. In his work "Optics", I.Newton proposed that light consists of material particles, that is, it has a corpuscular nature[4]. In response to this idea, Christiaan Huygens proposed the wave theory in 1690, which showed that light propagates in the form of waves[5]. Since I.Newton's influence was stronger at that time, the particle model remained dominant in the scientific world for a long time[6].

However, precise experiments conducted in the early 19th century radically changed this perception. The famous double-slit experiment performed by Thomas Young in 1801 conclusively proved the wave nature of light. T. Young observed that light passing through two adjacent narrow slits (or apertures) in a perforated screen placed in front of a light source produces an interference fringe pattern on a second screen positioned behind it. The result showed that light waves overlapped each other, forming zones of amplification and attenuation[7].

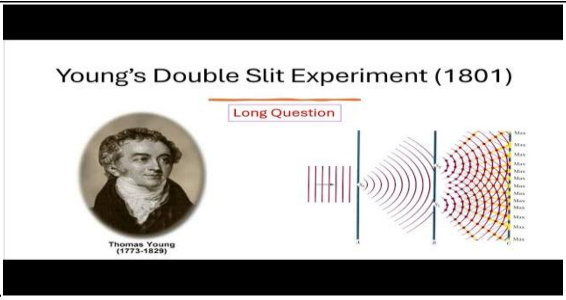

Figure 1. T.Young's double slit experiment

The double-slit experiment strengthened the mathematical basis of the wave model by clarifying the scientific content of concepts such as "interference"*¹, "coherence"*², and "phase difference"*³ for practice[8]. In the second half of the 19th century, James Clark Maxwell formulated the electromagnetic equations. James Clark Maxwell showed that light is an electromagnetic wave consisting of correlated fluctuations of electric and magnetic fields[9].

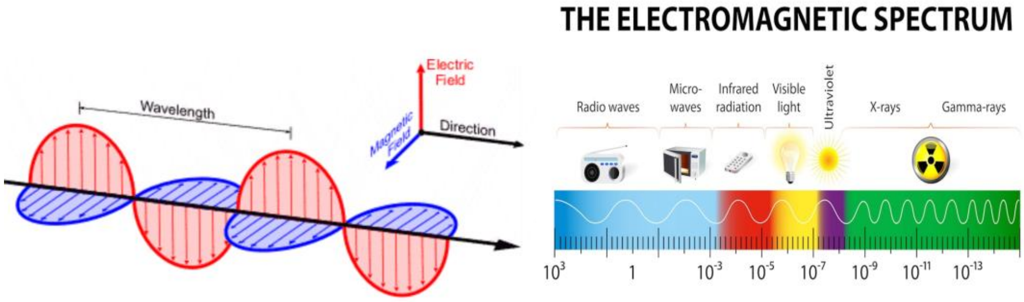

Figure 2. Electromagnetic waves and their spectrum

Thus, the wave nature of light was fully confirmed within the framework of electromagnetic theory.

*¹Interference is a fundamental wave phenomenon in which two or more coherent waves of the same physical origin overlap in space, and depending on their phase difference, regions of enhancement and attenuation are formed in the intensity (or amplitude) of the resulting wave. This phenomenon manifests itself in both classical (light, sound) and quantum (matter waves) physics[10].

*²Coherence is the degree to which waves (classical or quantum) have a stable phase relationship in time and space. High coherence is a condition for the ability of waves to interfere and thus form clear interference patterns. It is divided into two main types: temporal (over time) and spatial (over space) coherence[8].

*³Phase difference is the main parameter that quantitatively determines the location of the fringes in an interference pattern. It arises from the optical path difference of waves emerging from two slits and reaching the same point on the screen. This path difference determines how far the waves are behind or ahead of each other, that is, the phase difference ($\Delta\varphi$).

•Bright fringe (maximum): When the phase difference is equal to 0, 2π, 4π, … (or $\Delta\varphi = 2\pi m$, where $m = 0, \pm1, \pm2, \dots$ is an integer), that is, when the optical path difference is an integer multiple of the wavelength ($m\lambda$), the waves overlap in phase and reinforce each other.

•Dark fringe (minimum): When the phase difference is equal to π, 3π, 5π, … (or $\Delta\varphi = \pi(2m + 1)$), that is, when the optical path difference is an odd multiple of half the wavelength ($(m + 1/2)\lambda$), the waves overlap in opposite phase and cancel each other[11].

But at the beginning of the 20th century, some experiments shook this solid wave model. In 1905, when Albert Einstein explained the photoelectric effect, he considered the energy of light to be divided into quanta—that is, photons. This fact showed that light could also behave like a particle. According to A.Einstein, the energy of each photon is equal to the product of the Planck constant and the corresponding frequency[12].

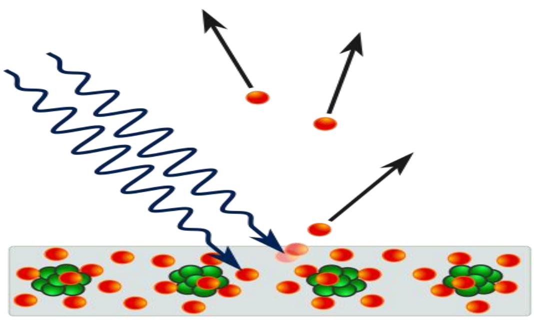

Figure 3. Photoelectric effect phenomenon

Thus, the conclusion was formed that light has both a wave and a particle nature.

In 1924, French physicist Louis de-Broglie generalized this dual nature of light and proposed the bold idea that matter particles had wave properties. Inspired by the relationship between the expression E=hν used for the energy of a quantum and the momentum of a photon ($p = h/\lambda$), L. de Broglie assumed that every particle with mass would also have momentum p and wavelength $\lambda = h/p$.[13;15]. L. de-Broglie put the issue this way: for hundreds of years, corpuscular concepts were ignored in optics and the wave theory was preferred.; In the theory of matter, the opposite has happened, that is, excessive attention has been paid to the "particle" concept and the wave picture has been forgotten. If, for light and electromagnetic radiation in general, quantum phenomena consist in the coexistence of corpuscular properties alongside wave characteristics, then for particles of matter (such as electrons, protons, neutrons, atoms, and molecules), quantum phenomena consist in the coexistence of wave properties alongside corpuscular characteristics[14]. L. de-Broglie's idea was that it was necessary to understand the similarity between mechanics and optics in a broader sense and to accept the existence of wave mechanics, similar to wave optics. Wave mechanics itself is more general than classical mechanics, and should be applicable to intraatomic motions, and under certain conditions should be able to pass into Newtonian mechanics[14]. His proposal gave rise to the concept of "de-Broglie waves" and became one of the main pillars of quantum mechanics[15].

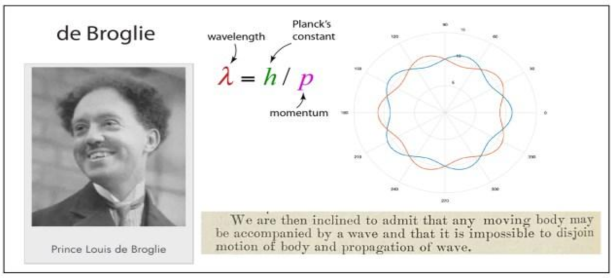

Figure 4. De-Broglie hypothesis

What distinguishes de-Broglie waves from ordinary waves is that the waves passing by the observer cannot be counted[14].

The electromagnetic diffraction experiment carried out in 1927 by Clinton Joseph Davisson and Lester Halbert Germer experimentally confirmed de-Broglie's idea. When electron beams were directed into a crystal lattice, an interference pattern was observed, definitively proving that electrons behaved like waves[16].

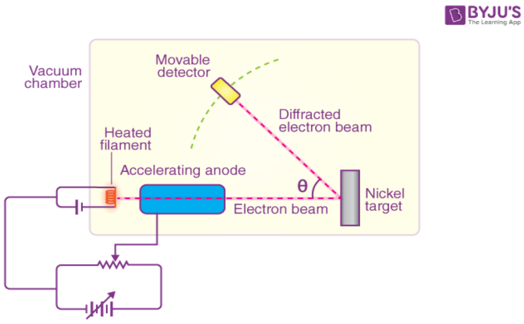

Figure 5. Davisson-Germer experiment

This experiment was a fundamental result showing that both light and matter behave as both waves and particles at the same time.

The double slit experiment became the deepest and most effective expression of this dualism. One of the most famous events during this period was the Einstein-Bohr conflict; Einstein's position: quantum mechanics is incomplete. The disappearance of the wave pattern during observation is not without reason, it is caused by the interaction of the measurement with the system. However, this effect is local and explainable. He rejected chance with the statement "God does not play dice."

Bohr's position: quantum mechanics is now complete. The experimental setup determines the outcome. The interaction with the measuring device irreversibly changes the system and collapses the wave function. An unobserved system has no properties in the classical sense[17].

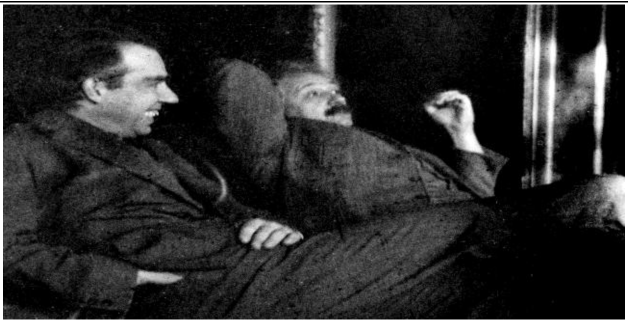

Figure 6. Bohr (left) and Einstein (right)

That is, he considered Einstein's quantum mechanics "incomplete" and thought that complete information could be obtained through measurement without disrupting the system. In his double-slit experiment, A.Einstein was trying to find a way to find out which slit a photon passed through without destroying it (for example, by moving the slit and measuring its momentum). This was an attempt to bypass the Heisenberg uncertainty principle. Bohr argued that this was impossible, that the attempt at measurement would inevitably change the system itself, thereby destroying the interference pattern[18].

In modern double-slit experiments with light and electrons, it is observed that wave behavior (interference) appears when no path detector is placed in the system (measured)., but when a detection or measurement is made that determines which slit the particle passes through, the result is purely particle behavior.This experimental fact reveals the fundamental influence of the measurement process on quantum systems and constitutes the empirical basis of the central conceptual difficulty of quantum mechanics known as the “measurement problem"[19]. Thus, the double-slit effect and wave-particle duality are not just an experiment or a model, but a revolution that has radically changed human thinking about the fundamental structure of the Universe. This history is the story of a great scientific journey, from classical optics to quantum theory of light, showing that matter and energy are essentially the same entity[17].

Description of the event. As we have seen, there are experiments in the history of physics that have left a deep mark not only with their results, but also with the paradoxical truths they teach us about nature. This seemingly simple experiment reveals one of the most puzzling truths of quantum mechanics. Let's explore this miraculous phenomenon step by step.

1. In the classical world.

Imagine firing a machine gun at a curtain with two narrow slits in front of it. The bullets will pass through the slits and leave marks on the curtain behind. The result we expect is clear: we will see two distinct stripes on the curtain corresponding to the slits.

Now let's change the hypothesis. Let's send waves from a bucket into the water. When the waves reach two slits, each slit becomes a new wave source. These two new waves are facing the curtain behind. In some places they reinforce each other (hills overlap with hills, valleys overlap with valleys), and in some places they cancel each other out (hills overlap with valleys). The result is an image of bright and dark stripes called an interference pattern[10].

Figure 7. Passage of classical waves through odd and even halves

2. In the quantum world.

Now let's repeat this experiment at the quantum level, for example with electrons. The electron is a tiny particle as far as we know. What was expected? If we fired the electrons one by one, each one would have to pass through one of the slits and create a streak on the curtain behind it, like bullets. However, the experiment gave a completely different result.

As the electrons gradually accumulate on the screen, something amazing happens: an interference pattern appears. The electrons sent out one by one, as if aware of the electrons that came before and after them, created this pattern by behaving like waves and not falling into their undying streaks. This fact was as if each electron, even though it was alone, had passed through both slits at the same time. This event revealed a fundamental principle of quantum physics: wave-particle duality[20].

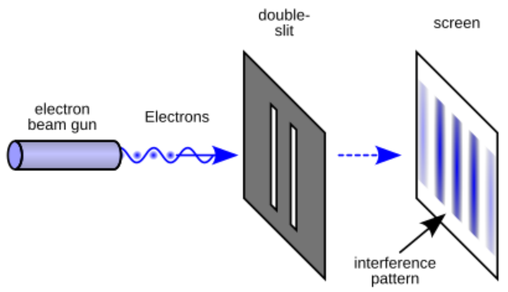

Figure 8. Double slit experiment with electrons.

3. The confusing part of the experiment: the observation problem.

Physicists asked the question: 'If an electron passes through both slits, can we measure its path?' The experimenters placed detectors near the slits. As the detectors interacted with the electron, one of the most fundamental principles of quantum mechanics became apparent: the measurement process changes the system. The interference pattern immediately disappeared, and the electrons behaved like classical particles, forming two distinct bands on the screen. It was as if the measurement of his path prevented him from taking both paths at the same time[20].

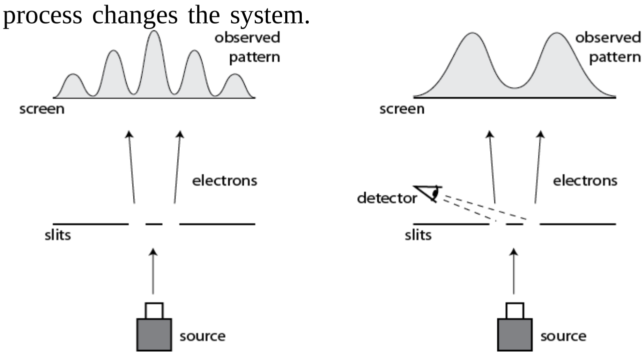

Figure 9. The observer effect in the double slit experiment

The measuring device and the quantum system were inextricably linked.This paradoxical result gave rise to the idea that the properties of a quantum system depend on the measurement context[21;22]. When we imagine the electron not as an object, but in terms of its wave function, we see that when the electron passes through two slits, it falls into a superposition of its two quantum paths. This means that the electron is moving from both the right and the left at the same time, and these two traces interfere with each other. It is the electron's own interaction with itself that creates this interference[21;22].

This very idea culminated in Schrödinger's famous "cat" thought experiment. Here, the notion that quantum states can exist and disappear simultaneously while not being observed demonstrates that reality itself is shaped by observation[15].

Schrödinger's thought experiment. In the scenario imagined by Schrödinger, the following elements are placed inside a completely closed box: A cat, a sample of radioactive material, a Geiger counter, a mechanical system (a mechanism that activates when the detector signals, opening a toxic gas chamber). The half-life of a radioactive substance is chosen so that there is a 50% chance that the atom will decay within a certain time. According to quantum mechanics, when no observation is made, the atom exists in a linear superposition of both "split" and "unsplit" states. This means that the system as a whole - the atom, the detector, the mechanism, and the cat - is described in two possible states at the same time:

•The atom has split, the mechanism has been activated, and the cat is dead.

•The atom has not split, the mechanism has not worked, the cat is alive[23].

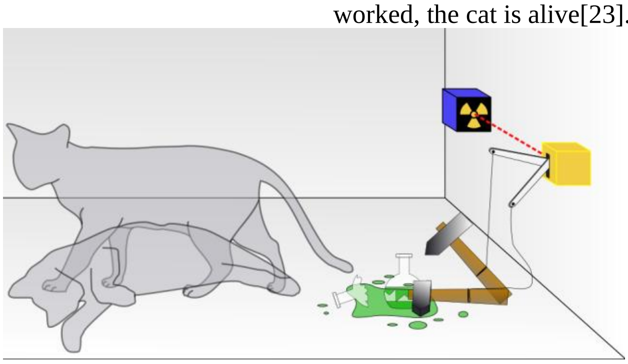

Figure 10. Schrödinger's thought experiment

These two states exist simultaneously until an observation (measurement) is made. That is, before opening the box, the cat is neither fully alive nor fully dead; it is described by a wave function in which both the alive and dead states exist simultaneously in a quantum superposition state. When the box is opened and an observation is made, the wave function "collapses" into one of two possible outcomes. As a result, the observer sees either a live or a dead cat. This phenomenon is known as the measurement problem in quantum mechanics: the act of observation causes the system to transform from a superposition state into a concrete state of reality[24].

This mechanism highlights the principal philosophical and theoretical difficulty in reconciling quantum systems with classical physics—namely, the absence of observable quantum superposition in macroscopic objects and the issue of the influence of consciousness on physical reality. This thought experiment later inspired the formation of various approaches such as the American physicist Hugh Everett's theory of parallel universes, the Copenhagen interpretation, and the Decoherence models[25]. Now let's look at these solution models.

1. Pilot-wave theory.

Proposed by Louis de Broglie in 1927 and later fully formulated by British physicist David Bohm, this theory returns quantum processes to a deterministic framework. Here, particles actually exist and their motion is controlled by a "pilot wave." That is, a particle does not move without a reason. An invisible wave determines the motion of the particle. The wave function obeys Schrödinger's equation, but this wave "guides" the particle and shapes its trajectory. Pilot-wave theory eliminates the observer's influence on reality and allows us to explain the EPR paradox and Bell's inequality. However, it is difficult to directly apply the theory to relativistic systems and field theories[26].

2. Decoherence.

This model, developed by H.Dieter Zeh and Wojciech Zurek, explains the problem of quantum observation without a collapse mechanism. Decoherence is the phenomenon of the disappearance of interference terms as a result of the system's exchange of information with its environment. In this process, the wave function mathematically remains in superposition, but the observed classical reality appears to be a single result. Interaction with the environment "separates" the states of the system and coherence disappears. Thus, we observe only one "classical" result. This fact provides a real physical explanation for Schrödinger's cat paradox - the cat's superposition becomes physically unobservable as a result of its interaction with the environment[27].

3. Copenhagen interpretation.

In this explanation, put forward by Niels Bohr and Heisenberg, the wave function is not the essence of the object itself, but the probability distribution of the knowledge known to the observer. The system exists in a state of multiple superpositions unless observed. During observation, the wave function "collapses" into a probabilistic state and appears as a particle. N.Bohr's complementarity principle plays a key role here - the concepts of particle and wave are two complementary forms of reality that do not negate each other, but do not manifest at the same time. This interpretation is consistent with experimental results, but leaves a serious philosophical gap in the question of the objective existence of reality. The problem arises when the observer is given too much "metaphysical" power[28].

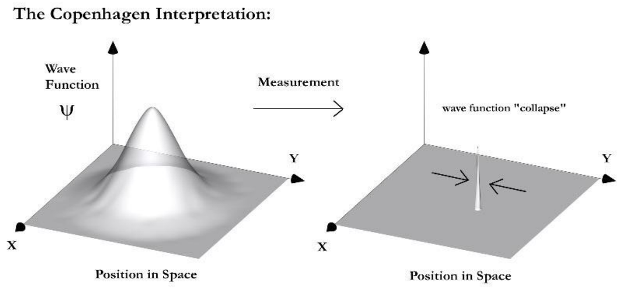

Figure 11. Wave function collapse.

The Copenhagen interpretation postulates the collapse of the wave function at the moment of measurement and thereby accurately predicts the observed outcomes of quantum systems; however, it leaves unresolved ontological questions concerning the mechanism and objectivity of the measurement process[29]. Taking this gap into account, British physicist Sir Roger Penrose presents the collapse of the wave function as an objective process related precisely to physical gravity: different superpositions create different space-time geometries, and when space-time reaches a certain level of instability, an objective "reduction" occurs[30]. This approach offers a mechanical solution to the measurement problem and makes testable predictions, but its mathematical details and experimental confirmation have not been fully completed[31]. Therefore, with the practical effectiveness of the Copenhagen interpretation, R.Penrose's active ontological proposal enriches the scientific discussion and is one of the possible paths to quantum-gravity integration. The collapse of the wave function is not due to observation, but is the result of objective physical mechanisms. In macroscopic systems, this process occurs extremely quickly and superposition is virtually unobservable. Therefore, whether we look or not, reality exists only in a specific situation[30].

We see that each of these models has certain shortcomings. The reason for this is the difficulty of explaining two properties of matter in a quantum system. Initially, attempts were made to view particles as wave packets to resolve the particle-wave contradiction. The following considerations formed the basis of these attempts: An electron or any particle cannot be identified with a plane monochromatic wave. Because, while such a wave is boundless in space and time, a particle is localized in space and time, meaning it occupies a specific location in space at a specific moment in time. However, it is known that by choosing the **k**-wave vectors of plane monochromatic waves at an appropriate speed, wave packets of any size can be constructed[14;15]. However, the attempt to view a particle as a wave packet is not justified. So, unlike a particle, a wave packet disappears over time. One of the important characteristics of elementary particles is their indivisibility. Waves, however, do not have this property of indivisibility. If one were to regard the electron as an aggregate composed of waves, then during the diffraction of a very weak beam of electrons passing through a crystal, each diffraction beam would carry only a fraction of the electron with it, which is clearly not the case[14].

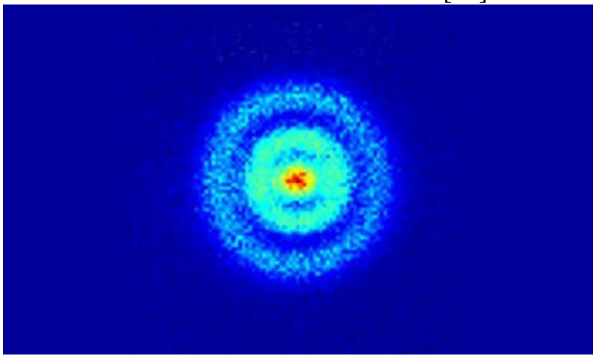

Figure 12. Electron cloud of hydrogen atom.

A micro-object (molecule, atom, electron, proton, etc.) does not directly affect our sense organs, that is, it cannot be felt by seeing or touching it. In the world we perceive, there is nothing like micro-objects[14;22]. As Nobel laureate Richard Feynman wrote in the third volume of his multi-volume "Feynman Lectures on Physics," "microscopic objects are unlike anything you've ever seen. Because the way atoms behave is so unlike our everyday experience, it is very difficult to get used to it. To both a person new to science and an experienced physicist, the behavior of atoms seems peculiar and nebulous. Even great scientists cannot understand it to the extent they would like, and this is completely natural. Because all of man's experience, all of his intuition, has been applied to large objects. We know what will happen to a large object, but small objects don't behave that way. "Therefore, when studying microparticles, it is necessary to use various kinds of abstractions, strain the imagination, and not try to connect them with our direct experience"[14;32]. Although microparticles combine the properties of both waves and particles, as R. Feynman said, "they behave neither like waves nor like particles." The difference between a microparticle and a wave is that it is always observed as an indivisible whole. For example, no one has ever observed half of an electron. At the same time, you can divide the wave into parts and then perceive each part in monthly[14;15;32]. The difference between a microparticle and the macroparticles familiar from everyday experience lies in the fact that the coordinates of a microparticle and the corresponding momenta cannot be known simultaneously with arbitrary precision; as a consequence, the very concept of a definite trajectory for a microparticle loses its meaning[14;15].

Recent studies. Conceptual analogies can be drawn between the nature of the measurement problem in quantum mechanics and the information processing process of complex algorithms.However, current artificial intelligence systems do not act as a physical 'observer', which leads to quantum collapse. Rather, it provides a framework for philosophical and theoretical discussions about the nature of reality, the role of consciousness, and the relationship between the nature of the intellect[30].

When we talked about the pilot-wave theory (de Broglie-Bohm theory), we said that an invisible guide wave deterministically controls the trajectory of a particle. Although this theory is viable as an alternative interpretation of quantum mechanics, it is compelled to be nonlocal in order to remain consistent with the experiments confirmed by the 2022 Nobel Prize in Physics, namely quantum entanglement and the violation of Bell inequalities. That is, the wave's effect must propagate faster than the speed of light, which makes it problematic for some physicists[26;33].

Scientists at MIT have put an end to the debate between Bohr and Einstein. In their experiment, they showed that even slits are cracks at the quantum level. Ultimately, it turned out that Bohr was right and Einstein was wrong[34].

The moving double-slit experiment, which once again caused a disagreement between Einstein and Bohr at the 1927 Solvay Conference, was finally realized in 2025 by scientists at the University of Science and Technology of China. Perhaps the observation effect is not as significant as we thought. Scientists set up an experiment in which they could obtain the smallest momentum exchange between a photon and an atom by using a single Rubidium atom as a moving slit. Thanks to the trace left by the photon in the slit, it is possible to understand where the photon passed through without even looking at the photon. As a result of the experiment, the path traveled by the photon was measured and the same results as the double slit experiment were obtained. Even if the photon has never been measured, the wave behavior of the photon disappears as soon as the path information is obtained. The result proves Niels Bohr right again[34*].

Two scientists from the Stevens Institute of Technology in America have claimed to have solved the causes of wave-particle duality both experimentally and mathematically. The greater the phase difference, the weaker the wave nature of the photons. When this happens, the system already chooses a path and the photon exhibits particle properties. In the double-slit experiment, a photon can pass through more than one slit as it travels along its path. When the difference between the first transition and the second transition exceeds a certain limit, the wave function collapses and the photon exhibits particle properties[35].

The universe's own internal physical processes (interactions and heat) are sufficient for it to transition from a quantum state to a classical state, without any "outside observer". This completely rejects the claim that "there were no observers in the early moments of the universe," and that it does not obey quantum laws. Rather, it explains how the classical universe could naturally arise from quantum roots through the mechanism of decoherence[36].

In 2017, former NASA physicist Thomas Cranpel and his team conducted several experiments with the classic double-slit experiment to test the simulation theory. The slit through which the entangled photons passed was measured, and this measurement reached the observer. In this case, the photon showed particle properties. The slit through which the photon passed was measured, and this measurement did not reach the observer. In this case, the photon showed wave properties. The result obtained was in the direction that the simulation theory was correct[37]. However, this result has been widely criticized. If there is a simulation, it is impossible to falsify the simulation theory with any experiment.

A team of physicists led by Mir Faizal at the University of British Columbia, in a new and detailed analysis of existing theories, demonstrated that there is no theory of everything describing the Universe that flawlessly reconciles general relativity with quantum mechanics—at least not in an algorithmic sense. As a natural consequence of this research, it turned out that the Universe is not a simulation. Because such a simulation needs to be prepared algorithmically[38].

Holger F.Hofmann and his team from Hiroshima University in Japan directly demonstrated that the photon passed through both slits. This result shows that the wave function is not just a simple mathematical expression, but rather an entity that corresponds to real physical phenomena. The wave function no longer needs other worlds to explain the double-slit experiment. So, this experiment disproves parallel universes[39].

Italian physicists have performed a double-slit experiment with antimatter particles. They were looking for an answer to the question: Do antimatter particles exhibit wave properties when they have dimensions, and particle properties when they do not? The antimatter passed through the gold slits and reached the detectors behind. The result was a landscape created by waves. Antimatter also has the same wave-particle properties as normal matter. That is, the laws of quantum mechanics are fully satisfied[40].

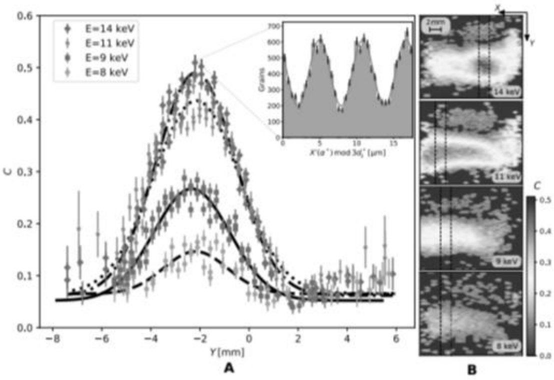

Figure 13. Antimatter particles passing through a kind of slit.

In an article published in PRL in 2025, Brazilian scientists gave a radical answer to this duality (wave-particle). Perhaps we misunderstood the wave-particle concept from the very beginning. Light can just be a particle. According to them, photons may actually still exist where we say there is no light in classical physics. However, these photons are in such a superposition that the detectors cannot establish any connection with the observer. This situation is called a dark situation. That is, there is no wave property, but instead there is a special superposition of photons. The mere perception of light as a particle eliminates the problems in this experiment. However, this idea has not been confirmed in practice[41].

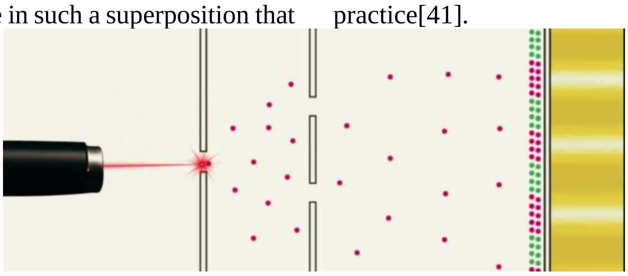

Figure 14. ● - bright photons, ● - dark photons.

Researchers at Imperial College London conducted a completely new version of the experiment. The goal was to find an answer to the question, "What would happen if we opened rifts in time?" The light was reflected differently at different times. This event took place on a femtosecond timescale. As a result of the experiment, an interference pattern emerged[42].

In another experiment, a theoretical answer to the double-slit mystery came from Brazilian scientists using entropy and the theory of general relativity. As a result, it was understood that quantum mechanics and the theory of general relativity are compatible with each other. The entropy of a particle is related to the observer's space-time fragment. It turns out that the observer is in an information exchange with the system. The observer is an inevitable member of the entropy of the quantum system. If the guess is high, the entropy is high. Observation decreases the entropy. If the observer reduces the entropy of the quantum system, that is, if the observer and the quantum system are in communication, then changing the curvature of space by the observer should change the amount of entropy of the system. The entropy level of a quantum system varies depending on the space-time state of the observer, and this test is consistent with[43]. In short, the fate of Schrödinger's cat depends on the state of the observer.

According to a 2014 paper, if there is no observation in the middle, the wave behavior of a quantum system prevails and the entropy is maximum. When observed, entropy decreases, the system behaves like a particle[44]. Researchers from Linköping University, working together with teams from Chile and Poland, carried out this experiment in a different form. What determines whether a light particle behaves like a particle or a wave is the level of information in the system. A laser was used in this experiment. In order to study the quantum properties of light in detail, this laser has been attenuated to the level of a single photon. The attenuated light is passed through a beam splitter and split into two different paths. One path of light sent on two separate paths was observed, and the light on this observed path exhibited particle behavior. At the same time, the other path of light was not observed, and it was determined that the wave nature of this path continued. These two light paths were then combined. They saw that during this combination, the system still exhibits particle properties. As a result, in a quantum system, the result is a certain amount of entropy of the system[45].

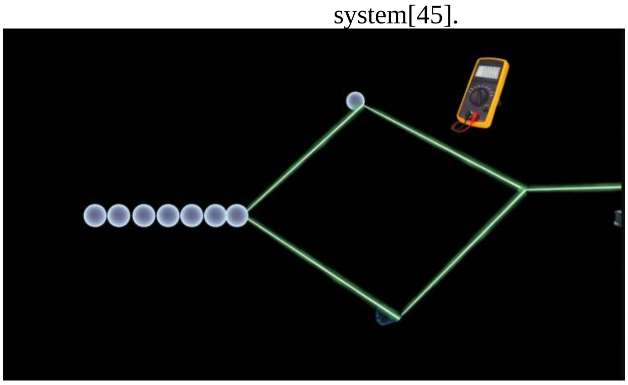

Figure 15. Scheme of the experiment

So far, we've been pointing to the nature of particles as the cause of this phenomenon. However, the secret to the strangeness in the double-slit experiment may also be the slits themselves. To solve the problem, it is necessary to consider not just the particle, but also the gap. As we expect, the gap behaves like a classic barrier. In the absence of measurement, slits temporarily obey the laws of quantum mechanics. The electron interacts with the slit in such a way that it changes the laws of experience. For a moment, a single, unified and inseparable quantum system exists. At this point, it no longer matters which slit the electron passes through. According to the article, there is no gap at that moment. Trying to understand the essence of wave-particle duality actually takes us away from studying quantum physics. Wave-particle properties emerge when we forcefully apply phenomena from our classical world to particles[46].

The final theory problem. As it turns out, particle-wave dualism is at the heart of quantum mechanics and appears to be the cause of a number of inexplicable phenomena. However, this dualism cannot fully explain the deeper structural causes of phenomena observed at the subatomic level[32;47]. Undoubtedly, the final theory must fully explain the causes of this phenomenon. After 50 years, the leading candidate for a "theory of everything" is a theory called "superstring theory." This is actually the only theory we have, since all other competing theories have been defeated.[48]. As physicist Steven Weinberg put it, "string theory has provided us with the first true candidate for a primary theory"[48;49]. It is in this respect that string theory brings a unified approach to one of the deepest problems of quantum physics. The basic ideology of string theory is that the initial fundamental unit of matter is not a point particle, but a very small vibrating string[50;51].

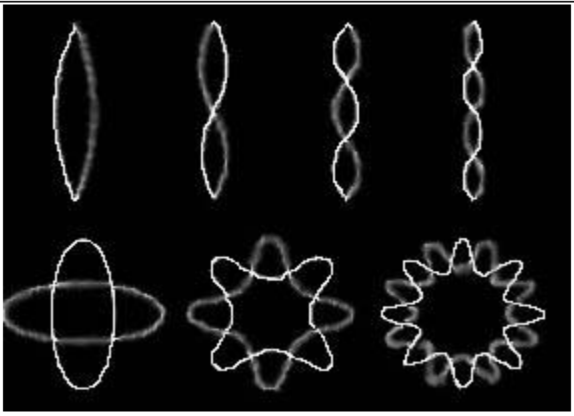

Figure 16. Strings vibrating in different shapes

The different vibrational modes of these strings determine the mass, charge, and interaction properties of elementary particles[50]. Researchers such as Edward Witten, Brian Greene, and Juan Maldacena point out that this idea could become a unifying model of physics[50;51;52]. As a result of this approach, the long-standing inconsistency between quantum mechanics and general relativity is eliminated through the concept of geometric vibrations and multidimensional space[50]. Edward Witten argues that string theory will one day dominate physics, just as quantum mechanics has dominated physics for the past half century[48]. The advantages of string theory are manifested not only in its theoretical coherence, but also in its cosmological applications. Strings provide a scientific bridge to the "God equation" by showing that both quantum fields and gravitational effects can be expressed by the same equations[53]. However, there are still daunting obstacles that need to be overcome. Those who don't believe in string theory point out that it has some weaknesses. First, it is impossible to directly test strings[48;54].Since superstring theory is a theory of the Universe, the only way to test it experimentally would be to recreate the Big Bang, that is, to generate energies comparable to those of the beginning of the Universe within a particle accelerator. To do this, an atomic fission the size of a galaxy would be required. This is impossible even for technologically advanced beings[48]. In short, it seems impossible to define a string, as it is a thread of pure energy that forms the basis of everything, including the initial part of technological devices. However, recent studies based on DESI observations are at a level that can prove the correctness of string theory. Thus, the decrease in dark energy over time is considered the initial evidence for string theory[55].

Problem statement: The double-slit experiment, which constitutes one of the fundamental pillars of quantum mechanics, demonstrates that microscopic objects simultaneously exhibit both wave-like and particle-like properties, thereby marking a radical departure from classical physical conceptions[15;32]. Despite more than a century of experimental and theoretical investigations, the essence of this phenomenon has not yet been fully explained, and in particular, no universal and conclusive theoretical framework has been established that rigorously accounts for the mechanism underlying wave–particle duality [56]. Richard Feynman famously described this experiment as “the phenomenon at the heart of all the mysteries of quantum mechanics,” emphasizing that although its full implications may not be completely understood, its experimental validity is beyond any doubt[32]. Although various theoretical models and experimental approaches have attempted to explain this problem, fundamental questions remain regarding the precise physical nature of the measurement act and the objective reality of the superposition state, which together underlie the interference pattern observed in the double-slit experiment[57]. The central problem investigated in this article is to resolve the discrepancy between existing theoretical models that experimentally describe wave–particle duality and the deeper nature of microscopic reality. In particular, the following decisive questions form the foundation of this investigation:

1. By what fundamental mechanism do electrons or other quantum objects create an interference pattern?
2. What is the physical meaning of the phenomenon of "self-interference" when a particle moves towards a single slit?
3. How does the dynamics of measurement occur and does superposition collapse at the moment and by what mechanism?
4. Is the ability of a wave function to produce interference related to more fundamental structures of space and time (such as vacuum fluctuations, quantum fields, or possible hidden variables)?
5. How can the interference pattern observed in the double-slit experiment be related to the multidimensional vibrational modes of strings?
6. How exactly can particle-wave dualism be explained with string theory?

Each of these questions touches on the foundations of quantum mechanics and is crucial to fully understanding the fundamental mechanism behind the double-slit experiment. Since none of the existing theoretical frameworks provide complete and conclusive answers to these questions, the problem of wave-particle duality remains one of the most open and strategic issues in physics.

Problem solving: Using the above empirical facts, it is possible to propose a new theoretical model that answers the problematic questions that arise. In general, existence in the Universe has two forms of manifestation: matter and the physical realm, and the current structure of the Universe was formed by the Big

Bang. The universe expanded from a single initial point, and the energy within it took on its known state, taking the form of both matter and physical fields[58]. From this perspective, we can say that matter, which is the form of matter, and the physical field have the same source. This source was created when the Universe first began to form. It is clear that the simplest structure that could have formed in the early moments of the Universe must have been the first particle. From these two approaches, we conclude that the smallest structural particle of the Universe is the source of matter and the physical field. Therefore, the actions of the first fundamental particle created the diversity in the Universe. In short, the study of the first fundamental particle can eliminate all problems, including those in wave-particle duality. The best and most proven theory that defines this elementary particle is string theory. We said that string theory states that the initial indivisible part of the Universe was vibrating strings. Different vibration patterns create different fields and particles[58]. If we summarize what we have said, we come to the conclusion that the properties of matter and field (as well as wave-particle) coincide in the string, which is the primary particle of the Universe. The vibrations of the strings in different patterns create different fields, and the sum of these vibrations at a local location creates the corresponding particle. This logical conclusion serves the development of the best-working theory in physics - "quantum field theory". Different quantum fields are, as it were, "woven" from strings that vibrate differently[59]. At the same time, these quantum fields are also connected through strings, forming the entire network of the Universe. These facts provide a confident step towards the final theory. This logically derived result can be proven mathematically:

First, let's list the main quantities:

•$\omega(\lambda,l_s)$ is the spectral (energy) density function of the string, λ is the wavelength or mode index, and l_s is the length of a string.

•Observation parameter: $\varepsilon>0$ Small particle types are described as ($\lambda\in[0,\varepsilon]$), large field types as ($\lambda\in[\varepsilon,\infty]$).

First of all, we determine:

$$\rho_p(\varepsilon,\ell_s)=\int_0^{\varepsilon}\omega(\lambda,\ell_s)\,d\lambda, \quad (1)$$

$$\rho_f(\varepsilon,\ell_s)=\int_{\varepsilon}^{\infty}\omega(\lambda,\ell_s)\,d\lambda \quad (2)$$

here,

ρ_p and ρ_f are the particle and field fractions, respectively. What we want is the equality of the fractions under certain conditions: $\rho_f/\rho_f=1$.

The goal is to take an expressive, yet realistic, predetermined specific form. A typical useful theory:

$$\omega(\lambda,\ell_s)=\ell_s^{-1}\Phi\frac{\lambda}{\ell_s} \quad (3)$$

Here, the $\Phi(u)$-function is a function expressing the spectral distribution of the energy density at the string level and is defined in the interval $0<u<\infty$. This function can represent both the particle mode and the field mode in a completely symmetrical manner.

Note: This structure assumption means "scale invariance" in the physical sense and that the string spectrum changes only in terms of λ/l_s.

Let's simplify the integrals with respect to the change ($U=\lambda/l_s$);

•particle fraction:

$$\rho_p(\varepsilon,\ell_s)=\int_0^{\varepsilon}\ell_s^{-1}\Phi\frac{\lambda}{\ell_s}d\lambda=\int_0^{\varepsilon/\ell_s}\Phi(U)\,dU \quad (4)$$

• field share:

$$\rho_f(\varepsilon,\ell_s)=\int_{\varepsilon}^{\infty}\ell_s^{-1}\Phi\left(\frac{\lambda}{\ell_s}\right)d\lambda=\int_{\varepsilon/\ell_s}^{\infty}\Phi(U)\,dU \quad (5)$$

will be. So the ratio

$$R(\varepsilon,\ell_s)=\frac{\rho_f}{\rho_p}=\frac{\int_{\varepsilon/\ell_s}^{\infty}\Phi(U)\,dU}{\int_0^{\varepsilon/\ell_s}\Phi(U)\,dU} \quad (6)$$

and as a result R will depend only on the argument ε/l_s.

Our main idea is that when we take both the observation parameter $\varepsilon\to0$ and the fundamental string length $l_s\to0$, these two shares can coincide. But the result depends on the ratio between ε and l_s. So we take a general relationship.

$l_s\sim\varepsilon^{\beta}$ or equivalently $l_s/\varepsilon^{\beta}\to C\in(0,\infty)$. C is a constant positive number.

Let's solve for ε/l_s

$$\frac{\varepsilon}{\ell_s}=\frac{\varepsilon}{\varepsilon^{\beta}\cdot C}=\frac{1}{C}\varepsilon^{1-\beta}$$

. Now three main cases emerge: •If $\beta<1$, then $\varepsilon/l_s\to0$

• If $\beta>1$, then $\varepsilon/l_s\to\infty$

•If $\beta=1$, then $\varepsilon/l_s\to1/C$

But to be more general and flexible, we want to write the condition $\varepsilon/l_s \to a \in (0,\infty)$ directly instead. This condition can be expressed in the same way as $l_s/\varepsilon^\beta \to C$ (if an appropriate β is chosen).

The condition for overcoming inequality.

$$\text{İf} \lim_{\substack{\varepsilon\to 0 \\ \ell_s \to 0 \\ \varepsilon/\ell_s \to a}} \frac{\varepsilon}{\ell_s} = a, \ a \in (0,\infty) \quad (7)$$

then

$$\lim_{\substack{\varepsilon\to 0 \\ \ell_s \to 0}} R(\varepsilon, \ell_s) = \frac{\int_a^\infty \Phi(U)dU}{\int_0^a \Phi(U)dU} \quad (8)$$

It will be. For the consistency of the approach put forward

$$\int_0^a \Phi(U)dU = \int_a^\infty \Phi(U)dU \quad (9)$$

It is important to have. That is, the cumulative distribution of the function a must have a 1/2 cutoff point. Thus

$$\int_0^a \Phi(U)dU = \frac{1}{2}\int_0^\infty \Phi(U)dU \quad (10)$$

When such a function a exists, the ratio is $\to 1$. This means that the relationship between ls and ε should be chosen such that ε/l_s corresponds to the median of the spectrum.

It can be seen from the above that if the cumulative parliamentary bisection condition of Φ is satisfied when a-transformed to C, then the following final result will be obtained.

$$\lim_{\substack{\varepsilon\to 0 \\ \ell_s \to 0 \\ \ell_s/\varepsilon^\beta \to c}} \frac{\int_\varepsilon^\infty \omega(\lambda;\ell_s)d\lambda}{\int_0^\varepsilon \omega(\lambda;\ell_s)d\lambda} = 1 \quad (12)$$

This result shows that on an ultrasmall scale, field and matter energy are indistinguishable - a "superposition" is obtained. At the string level, as a result of the median symmetry of the energy distribution function Φ(u), the differences between wave and particle energy disappear, and both descriptions become equivalent forms of the same physical reality.

As can be seen, since the concepts of field and matter are identical at the string level, the wave and particle natures also originate from this source, and the scale of observation causes these properties to be separated. This approach explains what caused the wave-particle duality in the first place. In this regard, the reason why dualism mainly manifests itself in microparticles is that they contain fewer strings (fewer interactions) than macroobjects. However, since matter of any size is made up of strings, it will have wave properties regardless of its size. From this perspective, as the mass increases, the wavelength, as is known, should decrease. For example, the wavelength of a basketball moving at a normal speed is on the order of $\sim 10^{-34}$ meters (based on the expression λ = h/p). In this respect, this feature may not be noticeable in macroscopic objects. In fact, particles are neither waves nor particles. These properties are properties of our microcosm. We require that particles have these properties. However, the reality is not like that at all: micro-objects are unlike anything we have ever seen. This unique property is a form that combines both wave-like and particle-like properties at the same time. However, it cannot be exactly the same property. Because, the complete wave and complete particle properties cannot be the same, and we have explained why. This unity was achieved in the form of an image by a group of scientists from the Swiss Polytechnic School using highly advanced nanotechnology, electron microscopy, and laser shooting systems[60].

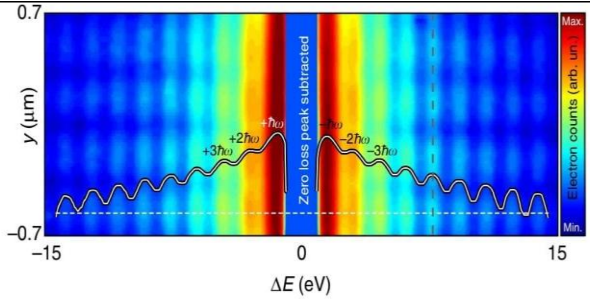

Figure 17. A snapshot of wave-particle duality at the same time.

Red is where there are the most electrons, and blue is where there are the fewest. The blue line in the middle is where there is no electron exchange. The energy exchange is characterized by integers. High electron counts are at the crests of the wave, and low electron counts are at the troughs of the wave[60].

Therefore, when we use the mathematical expressions used to explain phenomena in the macrocosm to describe properties we have never seen, a number of inconsistencies emerge. The reason this duality is more pronounced in particles is that the number of strings inside them differs sharply from those in macroscopic objects. This sharpness is distinguished by the area of the field that surrounds the objects. The passage of particles with properties we are not accustomed to through a double slit will, of course, result in an event we are not accustomed to. This may seem a little strange to some people. However, when we look deeper, we see that there are events around us that we have difficulty understanding. For example, when one considers facts such as the absence of color as an intrinsic property of reality, the fact that nothing ever truly comes into direct contact, that everything is interconnected at the smallest scales, and that true empty space does not exist, one must also accept this reality. As it turns out, our new approach to the double-slit experiment does not contradict the Big Bang in any way, but rather helps us explain it. According to the results obtained, parallel Universes are not needed to fully explain the double-slit experiment. However, this result does not mean that parallel Universes do not exist. The nature of dualism does not depend on its being a rift in time or space, on the rift being in motion, or on whether it is a normal or antiparticle. This property is determined solely by the number of strings within the object. The discovery of the double-slit experiment in time rifts and the successful explanation of its essence with string theory mean that it will be possible for us to explain time with string theory as well. This fact reinforces the idea that the Big Bang, the primordial particle, and the source of space-time are one. The double slit effect is not just caused by particles. You also need to look at the slits. When a particle passes through a slit, it behaves with the slit as a single system. Based on the non-classical properties of particles and the particle–slit interaction (according to string theory, all physical entities are interconnected [58]), a single unified system emerges, within which the question of which slit the particle passes through loses its physical significance. As the wave-like nature of the particle decreases, the phase difference will increase. What determines whether a particle behaves like a particle or a wave during observation is the level of entropy of the system. The observer is an inevitable member of the entropy of a quantum system. According to string theory, it is also suggested that there is a harmony between quantum mechanics and the theory of general relativity. As N.Bohr rightly said, the experimental setup changes the result. Measurement and interaction are irreversibly linked. Any change in the space-time fabric caused by an observer changes the entropy. If there are many guesses, there is high entropy. Thus, observation reduces entropy, and this information exchange is consistent with experimental results. With simple logic, we can say that during observation, the particle is no longer normal, but becomes an observed particle. When a particle is sent to a single or double slit, it exhibits only one property, and that is its own property. Therefore, the wave function is not a probability distribution of knowledge known to the observer, but rather an entity that corresponds to real physical phenomena. The role of the observer here is not to "create reality", but to choose reality. If this phenomenon is to be called a collapse, it should be known that this phenomenon is the result of objective physical mechanisms. We see that the Copenhagen interpretation is flawed in many ways. Thus, when explaining dualism, we say that there is no need for parallel Universes and, as a result, additional dimensions. That is, the real reasons for dualism must be consistent with the properties of 3-dimensional space. In 3-dimensional space, everything that exists must have a certain shape and size. From this perspective, everything must be located in a specific place in space-time. Therefore, reality exists only in a specific state, whether we look at it or not. That is, the existence of physical form and structure in the underlying model is inevitable. The Copenhagen interpretation works purely mathematically. This approach provides a physical structure and an ontological model. The probability of the particle being in other places is actually the places where the particle is affected. As it turns out, simply varying vibrations of strings in 3-dimensional space allow us to explain the double-slit experiment. The "extended" form of quantum field theory proves that all processes occurring are in a coherent state. This consistency proves that the Universe is not a simulation, but rather a vast and orderly creation. In fact, these phenomena, which seem strange to us, follow a certain order.

Result: A number of important conclusions are drawn from the new approach, which is based on modern research and uses string theory. The Universe we observe was formed by the Big Bang and expanded over time to take its current form. With the Big Bang, the Universe expanded from a single initial point and the forms of matter, matter and the physical realm, emerged in a way that was clearly distinguishable. The types of matter have the same origin at the smallest size, that is, at the smallest primary particle. The most successful theory that provides us with the smallest primordial particle of the observable Universe is string theory. From this perspective, on the fundamental length scale of the Universe—the level of the most primitive string—the concepts of matter and physical field are indistinguishable. The wave and particle representations no longer appear here as separate, but as equivalent representations of a single physical object. At the deepest level of reality, matter and field merge; wave and particle are just two perspectives of the same entity. This logical conclusion was proven mathematically.

$$\lim_{\substack{\varepsilon\to 0\\ \ell_s\to 0\\ \ell_s/\varepsilon^{\beta}\to c}} \frac{\int_{\varepsilon}^{\infty}\omega(\lambda;\ell_s)d\lambda}{\int_{0}^{\varepsilon}\omega(\lambda;\ell_s)d\lambda}=1$$

As a result, it was determined where wave-particle duality originally originated. Particles made up of strings are neither waves nor particles. Because, in reality, the properties of a complete wave and a complete particle cannot be compatible. Wave-particle properties are properties that we take from the macrocosm and want particles to obey. Particles are a form of matter that combines both wave-like and particle-like properties at the same time. Therefore, the particles are unlike anything we have ever seen. When we apply the mathematical expressions for these properties to particles that are unlike anything we observe, we get inconsistencies, and this is completely natural. The reason why the property of duality manifests itself more clearly in particles is that there are fewer strings and fewer interactions within them. Every object, regardless of its size, has wave properties. However, as the interaction (number of strings) increases, this property weakens to the point of being negligible. The passage of particles with such a unique property through a double slit naturally gives rise to strange phenomena. The double-slit experiment does not contradict the Big Bang in any way. According to the results obtained, parallel Universes are not needed to fully explain the double-slit experiment. However, this result cannot be considered strong evidence for the absence of parallel Universes. The nature of dualism does not depend on its rift in time or space, or whether it is a normal or antiparticle. For this, cracks also play an important role. When a particle passes through a slit, the results from string theory essentially treat the slit as a complete system, and the question of which slit the particle passes through becomes irrelevant. The decrease in the wave-like nature of the particle will increase in proportion to the phase difference. What determines whether a particle behaves like a particle or a wave during observation is the entropy level of the system. The observer is an inevitable part of the entropy of a quantum system. Bohr was right in that the experimental setup changes the outcome. The observer himself creates changes in the space-time fabric, and this fact changes entropy. String theory describes this phenomenon very precisely. When a particle is sent to a single or double slit, the particle exhibits only one property, which is its own intrinsic property. The wave function is not a probability distribution of knowledge known to the observer, but rather an entity that corresponds to real physical phenomena. If this phenomenon is to be called a collapse, it should be known that this phenomenon is the result of objective physical mechanisms. The Copenhagen interpretation is flawed and even wrong in many ways. Thus, when explaining dualism, we say that there is no need for parallel Universes and, as a result, additional dimensions. The real causes of dualism correspond to the properties of 3-dimensional space and should be explainable by form and physical description. Therefore, reality exists only in a specific situation, whether we look at it or not. In a model that explains the first cause, it is essential that physical form and structure exist. The Copenhagen interpretation simply works mathematically. This approach presents a physical structure and an ontological model. The probability of the particle being in other places is actually the places where the particle is affected. The different vibrations of strings in 3-dimensional space allow us to explain the double slit experiment. The "extended" form of quantum field theory proves that all processes occurring are in a coherent state. The Universe we live in is not a simulation. Because, when analyzed with the right models, it becomes clear that there is a specific reason behind all strange phenomena. Returning to the Einstein-Bohr debate, we realize that both sides are right: N.Bohr is right about the incident, but this incident does not fully justify the position of N.Bohr and his associates. The fact that there is a reason behind all phenomena shows that, as A.Einstein said, "God does not roll dice." When we examine all the facts, it becomes clear that the basic model does not completely disprove the ideas of all scientists, it simply shows that they have shortcomings, but that they are very close.

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