

Quantum Mechanics and Electrons: The Dual Nature of Electrons as Particles and Waves

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Abstract: *Quantum mechanics, as a fundamental theory describing the microscopic world, has driven a revolution in physics over the past century. The wave-particle duality of electrons, as one of the core features of quantum mechanics, challenges the traditional understanding of matter in classical physics. Through wave-particle duality, electrons exhibit wave-like behavior in certain experiments and particle-like properties in others. This paper explores key concepts of quantum mechanics, such as the wave function and the Schrödinger equation, and verifies the wave and particle nature of electrons through experiments such as the double-slit experiment and Compton scattering. In addition, this paper discusses the integration of quantum field theory and quantum mechanics, emphasizing the profound impact of electron duality on modern physics and quantum technology. With the continuous development of quantum technology, the duality of electrons not only provides a theoretical foundation for fields such as quantum computing and quantum communication but also offers new directions for technological innovation in the future.*

Keywords: *quantum mechanics; electrons; wave-particle duality; double-slit experiment; Compton scattering; quantum field theory; quantum technology*

Introduction

The development of quantum mechanics originated from the exploration of the microscopic world, with one of its core theories being the wave-particle duality of electrons. Electrons, as one of the most fundamental microscopic particles, possess both particle-like and wave-like properties, and the unity of these two aspects profoundly reveals the uniqueness of quantum mechanics. Classical physics cannot explain this dual nature of microscopic particles, and only within the framework of quantum mechanics can an appropriate theoretical model be provided for the behavior of electrons. Understanding the duality of electrons not only deepens the comprehension of the fundamental concepts of quantum mechanics but also provides theoretical support for modern technological applications such as quantum computing and quantum communication. With the continuous integration of quantum mechanics and quantum field theory, the wave-particle duality of electrons has become a key factor driving scientific and technological innovation. This paper aims to explore the wave-particle duality of electrons, combining classical experiments with modern theories to analyze its impact on physical theories and its application prospects in quantum technology.

1. Fundamentals of Quantum Mechanics and the Wave-Particle Duality of Electrons

1.1 Core Concepts and Mathematical Framework of Quantum Mechanics

Quantum mechanics, as a theoretical framework describing the behavior of microscopic particles, mathematically relies on core concepts such as the wave function and operators. The wave function (Ψ) serves as the fundamental representation of a quantum state, carrying all measurable information about a particle, and its squared modulus represents the probability density of the particle's position. The mathematical foundation of quantum mechanics originates from the Schrödinger equation, which reveals the time evolution of a particle's wave function. Within this framework, the physical state of a system is governed by the Hamiltonian operator (H), which reflects the energy and interactions of a particle in a given environment.

The uniqueness of quantum mechanics is embodied in the uncertainty principle and the superposition principle. The uncertainty principle reveals the limitation that a particle's position and momentum cannot be precisely measured simultaneously, a feature that stands in sharp contrast to the deterministic worldview of classical mechanics. The superposition principle states that a quantum state can be a linear combination of multiple basis states, meaning that a system can exist in multiple states simultaneously until a measurement causes it to "collapse" into a specific state. This phenomenon provides theoretical support for the realization of quantum computing and quantum information technology, forming the foundation for the integration of quantum mechanics and modern technology [1].

1.2 Wave Nature of Electrons and the Limitations of Classical Physics

In classical physics, matter is regarded as being composed of localizable particles, a view that faces significant limitations when describing the microscopic world. Classical physics fails to explain certain microscopic phenomena, such as the blackbody radiation spectrum and the interference of light. Electrons, as microscopic particles, exhibit wave-like behavior, which cannot be reasonably explained within the framework of classical mechanics.

The wave nature of electrons was first theoretically supported by de Broglie's hypothesis. De Broglie proposed that all material particles possess wave-like properties, with their wavelength inversely proportional to their momentum. When electrons pass through a double-slit experiment, they produce an interference pattern similar to that of light waves, confirming their wave nature. This wave-like behavior directly challenges the classical definition of particles. The particle perspective in classical physics cannot account for this phenomenon, as traditional particles are considered discrete entities with definite positions and velocities, whereas the wave nature of electrons indicates that they do not fully conform to this description, exhibiting dual characteristics of both waves and particles.

1.3 Quantum Mechanics and the Dual Nature of Electrons

The dual nature of electrons, possessing both particle-like and wave-like properties, is one of the core concepts of quantum mechanics. Traditional physical theories cannot explain this dual nature of microscopic particles, whereas quantum mechanics, through the theory of wave-particle duality, provides a profound understanding of this phenomenon. Electrons exhibit particle-like behavior in certain experiments, such as in Compton scattering, where collisions between electrons and photons display characteristics of particle exchange; however, in other experiments, electrons demonstrate wave-like behavior, such as the interference pattern observed in the double-slit experiment.

Wave-particle duality not only changes our understanding of electron behavior but also provokes new reflections on the nature of the physical world. The behavior of electrons shows different properties under different experimental conditions, a phenomenon referred to as wave-particle duality. Quantum mechanics describes this behavior through the superposition of wave functions and interference effects, proposing that electrons do not possess a definite particle position before measurement but exist in a fluctuating probability amplitude, with the wave function "collapsing" into a specific particle state only upon observation [2].

Wave-particle duality challenges the deterministic and continuous concepts of classical physics and has triggered extensive discussions on the probabilistic nature of quantum states. The mathematical structure and experimental results of quantum mechanics demonstrate that electron behavior cannot be described solely by classical wave or particle models; both properties must be considered simultaneously. This theory of dual nature not only provides a new perspective for fundamental physics but also lays a theoretical foundation for the development of quantum technologies, such as quantum computing and quantum communication.

2. Particle-like and Wave-like Properties of Electrons: Experimental Verification and Theoretical Interpretation

2.1 Double-Slit Experiment and the Wave Nature of Electrons

The double-slit experiment is one of the most representative experiments in quantum mechanics, revealing the wave nature of electrons and challenging the inherent behavioral model of particles in classical physics. In the classical particle model, when particles pass through double slits, two bright

bands are expected to appear on the detection screen because particles should pass only through one slit. However, when electrons are used in the experiment, an interference pattern appears on the screen, resembling the interference fringes produced by waves passing through double slits. This phenomenon indicates that electrons are not merely discrete particles but possess wave-like properties, capable of passing through slits and interfering with each other in a manner similar to light waves.

This result directly demonstrates the wave nature of electrons and highlights the limitations of the classical particle model. The theory of wave-particle duality in quantum mechanics provides an explanation for this behavior. Electrons do not propagate along a single definite path when passing through double slits; instead, they exist in a wave-like state, representing a superposition of all possible paths. The core concepts of quantum mechanics—superposition of wave functions and interference effects—are confirmed by this experiment. Before observation, the state of electrons is probabilistic, and only upon measurement does the wave function “collapse” to a definite position. This phenomenon not only proves the wave nature of electrons but also reveals the unique probabilistic nature of quantum mechanics.

2.2 Compton Scattering and the Particle Nature of Electrons

The Compton scattering experiment, by investigating the collision between X-rays and electrons, further verified the particle nature of electrons. In the experiment, when high-energy X-rays interacted with free electrons, the wavelength of the X-rays underwent a significant change, demonstrating that electrons exhibited particle-like properties in this process. According to the laws of conservation of energy and momentum, the scattering results of X-rays were consistent with the classical particle model and could be precisely described through the exchange of momentum and energy between particles. This experiment provided strong experimental support for the particle nature of electrons, revealing the particle-exchange behavior of electrons during collisions with photons ^[3].

The quantitative relationships observed in Compton scattering, such as the scattering angle and wavelength shift, cannot be explained by classical wave theory; they can only be accurately predicted and interpreted through the particle model in quantum mechanics. Within the framework of quantum mechanics, the particle nature of electrons manifests as momentum exchange during interactions between particles, with electrons participating as discrete particles. This phenomenon demonstrates that the wave-like and particle-like properties of electrons are independently yet complementarily verified in different experiments, further confirming the dual nature of electrons in quantum mechanics. The experimental results of Compton scattering provide solid empirical evidence for the particle model in quantum mechanics and deepen the understanding of the complex behavior of electrons in the microscopic world.

2.3 Quantum Interference and the Unification of Wave-Particle Duality

Quantum interference is an important experimental phenomenon that illustrates wave-particle duality, demonstrating the behavior of electrons that simultaneously possess wave-like and particle-like properties. When multiple electrons pass through a double-slit experimental apparatus, they exhibit both particle-like behavior, as if they were individual particles, and wave-like interference patterns. This phenomenon indicates that electrons can display wave-like properties under certain conditions and particle-like properties under others, providing unified experimental verification of wave-particle duality.

Quantum mechanics offers a precise theoretical explanation of this interference phenomenon through the principle of superposition of wave functions. In this framework, the electron's wave function not only represents the probability of its spatial distribution but also superposes across multiple possible paths, resulting in interference fringes under certain conditions. This model is highly consistent with classical wave theory but surpasses its limitations by simultaneously explaining both the wave-like and particle-like properties of electrons.

The unification of wave-particle duality suggests that the behavior of electrons cannot be simply categorized as either wave or particle; instead, it exhibits different properties depending on the experimental setup. This perspective lays a theoretical foundation for the further development of quantum mechanics and provides profound insights for applications of quantum technology, such as quantum computing and quantum communication.

3. Electron Behavior in Quantum Mechanics and Innovative Developments in Modern Physics

3.1 Quantum States of Electrons and the Space-Time Structure of Quantum Mechanics

The quantum state of an electron is a mathematical object that describes its behavior within the framework of quantum mechanics and is typically represented by a wave function. The wave function not only carries information about the spatial distribution of the electron but also reflects its interactions with other particles and fields. The behavior of electrons in quantum mechanics exhibits strong space-time dependence, which is fundamentally different from the deterministic space-time concept in classical physics. In classical physics, a particle's position and momentum can be measured simultaneously with precision, and its motion follows a definite trajectory, representing an absolute space-time structure. In contrast, in quantum mechanics, electrons are no longer particles with definite positions and trajectories but exist in a probabilistic distribution state, and the mathematical object describing this behavior is the wave function ^[4].

The space-time structure of quantum mechanics differs essentially from the classical concept of space-time. In quantum mechanics, space-time is relative, and the behavior of particles is influenced by the fluctuations of the wave function. The position of an electron in space-time is not definite but remains in a probability state determined by the wave function until measurement occurs, at which point the wave function "collapses" to a specific value. This understanding of a non-classical space-time structure allows for a more accurate description of phenomena such as the orbital motion of electrons and the interactions between particles and fields.

3.1.1 Relativity of Space-Time in Quantum Mechanics

In quantum mechanics, the relativity of space-time is reflected not only in the scales of space and time but also in the nonlocality and quantum entanglement between particles. For instance, quantum entanglement refers to the phenomenon in which electrons, even when separated by large distances, remain correlated through the wave function of their quantum state, causing the measurement result of one particle to instantaneously influence the state of the other. This nonlocality challenges the locality assumption in classical physics and profoundly reveals the complexity of particle behavior in quantum mechanics.

3.1.2 Quantum States of Electrons and the Schrödinger Equation

The quantum state of an electron is determined by the Schrödinger equation. The Schrödinger equation is a wave equation that describes the time evolution of a particle, where the squared modulus of the wave function gives the probability density of the particle's position in space. In many-body systems, electron behavior exhibits strong quantum correlations, which become even more significant in quantum fields with complex interactions. Solutions to the Schrödinger equation, when describing the probability distribution of electron motion, not only provide a quantitative description of spatial distribution but also reveal the time-dependent characteristics of electron behavior. This mathematical model offers a powerful computational tool for quantum mechanics and provides a theoretical basis for modern physical applications such as quantum computing and quantum simulation ^[5].

3.2 Integration of Quantum Mechanics and Quantum Field Theory

Quantum Field Theory (QFT) is an important theoretical framework in modern physics that integrates the fundamental principles of quantum mechanics and special relativity, aiming to describe the interactions between particles and fields. While quantum mechanics was originally developed to describe interactions between particles, quantum field theory extends beyond this limitation by treating particles as excitations of fields. In this framework, particles are no longer regarded as isolated, discrete entities but are represented as quantized excitations of their corresponding quantum fields, with each particle being a quantum excitation of a field.

3.2.1 Fundamental Principles and Applications of Quantum Field Theory

Quantum field theory provides a new perspective for understanding particle interactions. In QFT, particles are not static and independent entities but are described as excited states of their respective quantum fields. For example, an electron is no longer considered a fixed particle but is represented as a quantized excitation of the electron field. This theoretical framework successfully explains phenomena such as particle exchange, particle creation, and annihilation, forming the foundation for modern physical theories such as quantum electrodynamics (QED) and weak interactions. Through QFT, the

wave-like and particle-like properties of electrons can be unifiedly explained via field interactions and the exchange-particle model of quantum states.

3.2.2 Integration of Quantum Mechanics and Quantum Field Theory

The integration of quantum mechanics and quantum field theory enhances the understanding of the dual nature of electrons. Within the framework of QFT, the particle-like and wave-like properties of electrons are naturally unified. Through the exchange-particle model of quantum fields, electrons can be described as field excitations in terms of their wave-like properties and as interacting discrete particles in terms of their particle-like properties. This integration provides a new theoretical perspective, enabling the application of the combined theories of quantum mechanics and quantum field theory across broader domains and advancing the study of numerous frontier phenomena in modern physics, such as quantum chromodynamics (QCD) and attempts at quantizing gravity.

3.3 Implications of Electron Duality for Technological Applications and Future Prospects

The wave-particle duality of electrons not only drives theoretical innovation in fundamental physics but also exerts a profound impact on modern technology. The framework of quantum mechanics has enabled the development of quantum information technologies, particularly in quantum computing, quantum communication, and quantum cryptography. The wave-particle duality allows electrons to simultaneously exhibit wave-like and particle-like properties, making parallel computation possible in quantum computing and surpassing the limitations of traditional computers in solving complex problems [6].

3.3.1 Quantum Computing and Electron Duality

Quantum computing takes advantage of the superposition and entanglement properties of electron quantum states, offering significant advantages in computational problem-solving. Through the superposed states of quantum bits (qubits), quantum computing can perform calculations across multiple states simultaneously, greatly enhancing computational efficiency. In certain specific problems, quantum computing can even exceed the computational capabilities of classical computers, with broad application prospects in fields such as quantum simulation, cryptography, and materials science.

3.3.2 Quantum Communication and Quantum Cryptography

Quantum communication and quantum cryptography also rely on the wave-particle duality of electrons. In quantum communication, information can be transmitted in an encrypted manner through quantum entanglement, achieving theoretically unbreakable secure communication. Quantum Key Distribution (QKD) technology, based on the principles of electron wave-like and particle-like properties, provides higher confidentiality during transmission. The wave-particle duality of electrons establishes the theoretical foundation for the security and reliability of quantum information technologies, making it an indispensable component of modern information and communication technology.

3.3.3 Future Technological Prospects

Looking ahead, with the deepening integration of quantum mechanics and quantum field theory, the dual nature of electrons will further accelerate the development of various quantum technologies, particularly in quantum information processing and quantum materials science. By precisely manipulating the quantum states of electrons, it is expected to realize more efficient quantum computers, more powerful quantum communication networks, and more advanced quantum sensors, bringing revolutionary breakthroughs to science, engineering, and communication. The duality of electrons is not only a theoretical breakthrough in physics but also one of the core driving forces behind modern technological progress.

In future quantum technology research, further exploration of the applications of electron wave-particle duality in new materials and quantum systems will become a key research direction. A deeper understanding of electron duality will continuously provide innovative momentum for the development of quantum technologies, propelling various industries into a new quantum era.

Conclusion

This paper provides a detailed discussion of the wave-particle duality of electrons and its manifestation within the framework of quantum mechanics, emphasizing the verification of the

wave-like and particle-like properties of electrons through classical experiments. With the integration of quantum field theory and quantum mechanics, the dual nature of electrons not only contributes to explaining the complexity of particle interactions but also lays the foundation for the development of modern quantum technologies. In the future, advancements in quantum information technology will continue to rely on the manipulation of electron quantum states, driving innovations in quantum computing, quantum communication, and other related fields. As technology continues to evolve, the further integration of quantum mechanics and quantum field theory is expected to bring even more profound impacts on science, engineering, and other disciplines. The duality of electrons is not merely a theoretical breakthrough but also provides unlimited potential for future technological innovations and applications, signaling revolutionary applications of quantum technologies in the future.

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