Essay

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The Illusion of Quantum Mechanics: A Critique and Reflection on the Mainstream Interpretation of the Double-Slit Experiment

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Abstract

The double-slit experiment, as a cornerstone experiment of quantum mechanics, has long been regarded as the ultimate proof of wave-particle duality. However, results from high-precision experiments conducted in recent years by teams including Tonomura and Bach, as well as from the "recoiling slit" experiment by Jianwei Pan's team, have revealed profound contradictions with mainstream quantum mechanical interpretations. These contradictions expose systematic biases in conceptual definitions and the interpretation of physical mechanisms within the mainstream narrative. Based on particle flow scattering theory and incorporating the design details and results of Pan's team's experiment, this paper critiques the mainstream quantum mechanical narrative that mystifies the "cumulative effect of particle flow scattering" as "wave-particle duality" and "wave function collapse." It argues that the essence of the bright and dark fringes in the double-slit experiment is the statistical distribution of particles after their interaction with slit matter, rather than wave interference. Research indicates that the core dilemma of mainstream quantum mechanical interpretation stems from a misreading of the physical essence of experiments and conceptual confusion. Reconstructing a physical picture based on classical scattering theory and statistical laws is the inevitable path for quantum mechanics to overcome its interpretational predicament.

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1. Introduction

Since the debate between Einstein and Bohr over the foundations of quantum mechanics at the Fifth Solvay Conference in 1927, the double-slit experiment has remained a central scenario for testing interpretations of quantum theory. Mainstream quantum mechanics (the Copenhagen interpretation) posits that the alternating bright and dark fringes in the double-slit experiment are a direct manifestation of the "wave-particle duality" of microscopic particles — a single particle can pass through both slits simultaneously and interfere with itself, while the act of observation causes the wave function to collapse, making the interference fringes disappear. This interpretation has long dominated the physics community, even being regarded as the "core mystery" of quantum mechanics.

However, with advancements in experimental technology, a series of high-precision experiments have begun to challenge this traditional narrative: The single-electron experiments by Tonomura et al. [1] and Bach et al. [2] clearly show that the fringes result from the cumulative impact of single electrons hitting the detection screen one by one, and that real-time observation did not cause the fringes to vanish; The 2025 MIT atomic double-slit experiment [3] confirmed that fringe visibility quantitatively correlates with the stability of the experimental setup, consistent with predictions from particle flow scattering theory. Recently, Jianwei Pan's team utilized optical tweezers to trap a single atom, realizing Einstein's proposed "recoiling slit" thought experiment [4,5]. The design details and experimental results further expose the internal contradictions of the mainstream quantum interpretation — this experiment uses a single atom as a "movable slit," observing changes in interference contrast by manipulating the atom's confinement state, yet the results were still interpreted as "verification of the quantum complementarity principle," completely ignoring the deterministic laws governing scattering degrees of freedom behind the experimental phenomena.

Combining particle flow scattering theory [6] with the above experimental evidence, particularly the design logic and results of Pan's team's "recoiling slit" experiment, this paper systematically critiques the erroneous mainstream quantum mechanical interpretation of the double-slit experiment. It reveals the essence of the "mystifying narrative" in quantum mechanics and provides ideas for reconstructing a theoretical framework based on physical reality.

2. The Fundamental Discrepancy Between Experimental Facts and Mainstream Interpretation

The contradiction between mainstream quantum interpretation and experimental facts is not an isolated case. From early single-electron experiments to the recent "recoiling slit" experiment by Pan's team, this divergence persists throughout, centering on the interpretation of the "nature of fringes," "observation effect," and "path information."

2.1. Fringe Formation: Statistical Accumulation Determined by Scattering Degrees of Freedom, Not Wave Interference

A core pillar of the mainstream quantum interpretation is "bright/dark fringes = wave interference." Einstein's 1927 "recoiling slit" thought experiment was based on this logic: he argued that when a single photon passes through a movable slit, it imparts a slight recoil to the slit. Measuring this recoil could reveal the photon's path (particle nature), while precisely controlling the slit's position could preserve interference fringes (wave nature), thereby challenging Bohr's complementarity principle. Pan's team trapped a single rubidium atom using optical tweezers as the "movable slit," cooled the atom to its three-dimensional motional ground state to stabilize its spatial state, and finally observed tunable interference contrast changes dependent on the atom's confinement state, proclaiming it as "proof of the complementarity principle at the Heisenberg limit" [4,5].

However, this interpretation fundamentally conflicts with the core conclusions of particle flow scattering theory [6]. According to this theory, the essence of a particle passing through a slit is a scattering process following its interaction with the edge material of the slit. Scattering inherently possesses randomness, but this randomness is not without rules; it is quantitatively described by "scattering degrees of freedom" — the number of discrete scattering directions possible after the particle flow passes through the slit, determined jointly by the physical parameters of the particle flow and the slit. When the physical parameters of the experimental setup (particle source, slit, detection screen) are fixed, the type of particle scattering and the scattering degrees of freedom are also determined. A large number of particles accumulate along fixed scattering paths, resulting in an alternating pattern of "particle presence" (bright fringe) and "particle absence" (dark fringe) on the detection screen — a "quasi-interference fringe" pattern.

The "interference contrast change" observed by Pan's team essentially stems from deterministic changes in the scattering degrees of freedom of the atomic slit leading to adjustments in the statistical distribution: When the atom is tightly confined by the optical tweezers, its spatial position and interaction mode with photons remain stable, the scattering degrees of freedom are fixed, the regularity of particle scattering directions increases, and the "quasi-interference fringes" are sharp; when the atom is loosely confined, its spatial state fluctuates randomly, causing the determinacy of the scattering degrees of freedom to decrease (equivalent to reduced predictability of scattering paths), and the fringes gradually blur. This process has nothing to do with "wave nature." Just as if a traditional macroscopic slit vibrates (slit parameters are unstable), the determinacy of scattering degrees of freedom would decrease and fringes would blur, this is purely a classical physical process.

Experiments by Tonomura [1] and Bach [2] have clearly demonstrated that fringes result from the cumulative impact of individual particles one by one; a particle existing as a "wave" has never been observed. Pan's team's experiment further corroborates this point — their "single-atom slit" essentially simplifies the "collective scattering by multiple atoms" of a traditional slit into "precise scattering by a single atom." However, the core physical mechanism in both cases follows the rule: "fixed apparatus parameters → determined scattering degrees of freedom → stable fringes," and is unrelated to "wave interference." The mainstream interpretation mystifies this statistical outcome of classical scattering as "quantum wave nature," constituting a fundamental misreading of the experimental essence.

2.2. Observation Effect: Apparatus Perturbation Leading to Changes in Scattering Degrees of Freedom, Not Wave Function Collapse

The mainstream quantum interpretation has long confused the two concepts of "active perturbation" and "passive recording," packaging the narrative that "physical perturbation causes fringe changes" into the mystical story of "observation causes wave function collapse." Pan's team's experiment provides a typical example: The team believed that obtaining "photon path information" by measuring the atom's recoil momentum (observing particle nature) would "destroy wave nature" causing fringes to blur, and this process embodies the "complementarity principle" [4,5].

However, according to particle flow scattering theory [6], the essence of "observing path information" is an "active perturbation" to the stability of the experimental apparatus: By using optical tweezers to manipulate the atom's confinement state to measure recoil, Pan's team actually altered the physical parameters of the atomic slit — this manipulation disrupted the determinacy of the scattering degrees of freedom, leading to decreased regularity in particle scattering paths, manifested as blurred fringes. The core of this process is "unstable apparatus parameters → decreased determinacy of scattering degrees of freedom → fringe change," not "the act of observation itself destroys wave nature." Bach et al.'s experiment [2] had already proven that if only the particle impact points are passively recorded (without changing any parameters of the source, slit, or screen, thus maintaining stable scattering degrees of freedom), the fringes do not disappear, directly refuting the "observation causes collapse" narrative.

Pan's team's attribution of the physical effect — "apparatus perturbation leads to changes in scattering degrees of freedom" — to "quantum complementarity" essentially perpetuates the conceptual confusion of the mainstream interpretation. This confusion distorts the classical logic of "active physical perturbation → change in determinacy of scattering degrees of freedom → adjustment of statistical distribution" into the transcendental narrative of "act of observation → wave function collapse → disappearance of interference," completely neglecting the physically real processes in the experiment.

2.3. Path Information: Traceability of Scattering Paths, Not Quantum Superposition

The mainstream quantum interpretation holds that obtaining "path information" about a particle destroys its "quantum superposition state," causing interference to disappear. Pan's team, by measuring the atom's recoil to obtain photon path information, claimed to have "verified the mutually exclusive relationship between particle nature and wave nature" [4,5]. However, from the perspective of particle flow scattering theory [6], "path information" is essentially the traceability of particle scattering paths — when the determinacy of the atomic slit's scattering degrees of freedom is high, its interaction with the photon follows a clear momentum transfer law, allowing the photon's scattering direction (i.e., "path") to be deduced from the atom's recoil; this traceability merely reflects the regularity of the scattering process and is unrelated to the "quantum superposition state."

In fact, Pan's team's "single-atom slit" precisely confirms the core view that "the essence of a slit is a scattering source" [6]. A traditional macroscopic slit is a "scattering source composed of many atoms," while a single-atom slit is a "single-atom scattering source." Their common feature is: when their own physical parameters are fixed, the determinacy of the scattering degrees of freedom remains stable, and the particle scattering paths are predictable; there are no special quantum properties like "quantum superposition state" or "wave-particle duality." The mainstream interpretation, by interpreting the traceability of scattering paths as a "manifestation of particle nature" and opposing it to "wave nature," completely severs the connection between experimental phenomena and classical physical mechanisms.

3. Conceptual Confusion and Narrative Reconstruction in Mainstream Interpretation

The mainstream quantum mechanical interpretation of the double-slit experiment exhibits systematic conceptual confusion. This confusion is not accidental negligence but rather a narrative reconstruction undertaken to preserve the core tenets of the Copenhagen interpretation. The interpretation of Pan's team's experiment is a typical case of such reconstruction.

3.1. Conceptual Substitution of "Slit"

A traditional slit is a spatial constraint with a clear geometric structure; its core function is to provide a stable scattering environment (ensuring determinacy of scattering degrees of freedom) for particles through fixed edge material. By defining a single atom as a "slit" [4,5], Pan's team essentially substitutes the physical connotation of "slit" — a single atom as a "slit" still primarily functions as a scattering medium interacting with particles. However, because the atom's spatial state can be manipulated via optical tweezers, the determinacy of its scattering degrees of freedom becomes a tunable parameter. This shift precisely exposes the essence of a "slit": regardless of whether its form is a macroscopic multi-atom structure or a microscopic single atom, its role is to provide specific scattering conditions for particles, ensuring the determinacy (or tunability) of scattering degrees of freedom, not "a channel for waves to pass through simultaneously."

The mainstream interpretation has long regarded the "slit" as a "carrier for wave propagation," while the design of Pan's team's experiment inadvertently returns to the physical essence of a "slit" — a provider of scattering conditions. Yet, constrained by the traditional interpretation, the team still interpreted the "scattering interaction between a single atom and a photon" as an "interaction between a quantum slit and a wave" [4,5], completely overlooking the inherent consistency between their experimental design and the core law of "determinacy of scattering degrees of freedom" in particle flow scattering theory [6].

3.2. Erroneous Attribution of "Quantum–Classical Transition"

Pan's team claimed to observe a "continuous transition from quantum to classical" [4,5], arguing that when the atom's momentum uncertainty exceeds the photon's recoil, "quantum characteristics disappear and classical laws take over." However, according to particle flow scattering theory [6], there is no fundamental boundary between a "quantum state" and a "classical state." The so-called "quantum–classical transition" is actually a change in the determinacy of scattering degrees of freedom caused by variations in the stability of experimental apparatus parameters: When apparatus parameters are highly stable (e.g., atom cooled to ground state and tightly confined), the determinacy of scattering degrees of freedom is extremely high, particles accumulate along fixed paths forming sharp quasi-interference fringes; when apparatus stability decreases (e.g., atom loosely confined), the determinacy of scattering degrees of freedom lowers, and fringes blur or even disappear. This process is a manifestation of classical statistical laws, unrelated to "quantum state collapse" or a "quantum-classical boundary."

The mainstream interpretation attributes this classical correlation — "apparatus stability → determinacy of scattering degrees of freedom → fringe pattern" — to a "quantum–classical transition," forcibly fitting classical physical phenomena into the quantum mechanical framework. Pan's team's experiment could have revealed the non-existence of "quantum characteristics," but by adhering to the traditional interpretation, it instead reinforced the erroneous perception of a "quantum-classical dichotomy."

3.3. Circular Reasoning of the "Complementarity Principle"

Pan's team interpreted their experimental results as "proving the complementarity principle" [4,5], but this conclusion is based on circular reasoning: first presupposing the complementarity principle that "particle nature and wave nature are mutually exclusive," then interpreting the phenomenon of "changes in scattering degrees of freedom leading to fringe changes" as a "manifestation of the mutual exclusivity of particle and wave natures," and finally using this to "verify" the complementarity principle in turn.

Such circular reasoning is widespread in quantum mechanical interpretations: defining the statistical result of classical scattering as "quantum wave nature," then using the "existence of wave nature" to prove "quantum theory is correct." Pan's team's experiment could have broken this cycle — all observed phenomena can be explained by the classical logic of "apparatus parameters → determinacy of scattering degrees of freedom → fringe pattern," without introducing the complementarity principle. However, the team still chose to interpret the results within the traditional framework, missing the opportunity to advance theoretical reform.

4. The Unified Explanation of Particle Flow Scattering Theory

Particle flow scattering theory [6] provides a unified classical explanatory framework for all double-slit-type experiments, including Pan's team's "recoiling slit" experiment. This theory requires no introduction of quantum concepts like "wave function," "superposition state," or "wave-particle duality," explaining all experimental phenomena solely through classical scattering physics and statistical laws.

4.1. Core Theoretical Framework

The core viewpoint of particle flow scattering theory [6] is: The essence of a particle passing through a slit is a scattering process following its interaction with the edge material of the slit. Scattering possesses inherent randomness, but the overall pattern of scattering is determined by the "scattering degrees of freedom." The magnitude of the scattering degrees of freedom is jointly determined by the physical parameters of the particle flow and the slit (particle velocity, size, material; slit shape, size, material properties), independent of quantum characteristics.

When the physical parameters of the experimental apparatus (particle source, slit, detection screen) are fixed, the scattering degrees of freedom are determined accordingly. The particle flow will move along fixed discrete scattering directions, and the accumulation of many particles forms the alternating pattern of "presence" and "absence" — quasi-interference fringes. If any part of the apparatus changes (e.g., slit movement, unstable particle emission angle, change in screen position), the determinacy of the scattering degrees of freedom decreases, the regularity of scattering directions weakens, and the fringes become blurred or even disappear.

The core prediction of this theory — "the stability of quasi-interference fringes is determined by the determinacy of scattering degrees of freedom" — has been verified by multiple experiments: The 2025 MIT experiment [3] confirmed that fringe visibility quantitatively correlates with atomic position stability (determinacy of scattering degrees of freedom); Pan's team's experiment [4,5] shows that fringe contrast changes with the atom's confinement state (determinacy of scattering degrees of freedom), fully consistent with theoretical predictions.

4.2. Specific Explanation for Pan's team's Experiment

The design and results of Pan's team's experiment can be completely explained by particle flow scattering theory [6]:

Experimental Apparatus: The single rubidium atom trapped by optical tweezers is not a "quantum slit" but a "tunable scattering source"; the single photon, as the scattering particle, changes its direction of motion after electromagnetic interaction with the rubidium atom.

Key Manipulation: Raman sideband cooling technology reduces the atom's momentum uncertainty, essentially enhancing the stability of the atom's spatial state to ensure the determinacy of scattering degrees of freedom; adjusting the depth of the optical tweezer trapping potential well essentially changes the atom's scattering characteristics, thereby tuning the determinacy of scattering degrees of freedom.

Experimental Results: Changes in interference contrast are a statistical manifestation of the regularity of scattering directions — the higher the determinacy of the atom's scattering degrees of freedom, the more concentrated the scattering directions and the sharper the fringes; conversely, fringes blur.

Recoil Measurement: The atom's recoil momentum is a necessary outcome of momentum transfer during scattering. Using recoil measurement to deduce the photon's path essentially utilizes the determinacy of scattering degrees of freedom to trace the scattering path, unrelated to "quantum observation."

This explanation entirely discards the mystifying narrative of quantum mechanics, reducing the experiment to a classical physical process. It is consistent with all observational results, demonstrating the theory's universality and reasonableness.

4.3. Consistency Verification with Traditional Experiments

Particle flow scattering theory [6] can not only explain Pan's team's new experiment but also provide a unified explanation for all historical double-slit-type experiments: In the single-electron experiments by Tonomura [1] and Bach [2], stable fringes occur because the parameters of the source, slit, and screen are fixed, resulting in high determinacy of scattering degrees of freedom; In Taylor's feeble light experiment [7], the uniform scattering of the photon flow (fixed scattering degrees of freedom) forms quasi-interference fringes; Even in double-slit experiments with large molecules like C60 or bacteria [8,9], their fringes result from the statistical accumulation where the scattering degrees of freedom remain stable after the molecules interact with the slit material — none of these experiments require the introduction of "wave nature" for a reasonable explanation.

5. The Physics Community's Cognitive Dilemma and Path Dependence

Faced with the clear explanations of particle flow scattering theory [6] and supporting experimental evidence, the physics community generally still adheres to mainstream quantum interpretation. This cognitive dilemma stems from profound historical path dependence and a loss of scientific philosophy.

5.1. Historical Path Dependence

Early physicists simplistically analogized the bright/dark fringes of the double-slit experiment to water wave interference, embedding this presupposition into the mathematical formalism of quantum mechanics. Subsequent theoretical developments, to maintain self-consistency, had to introduce abstract concepts like "wave function" and "superposition state," forming a self-enclosed explanatory system. Pan's team's experiment [4,5] presented an opportunity to break this system — their "single-atom slit" clearly demonstrated the decisive role of "determinacy of scattering degrees of freedom" on fringes. However, influenced by path dependence, the team still chose to interpret the results within the traditional framework.

5.2. Loss of Scientific Philosophy

The counter-intuitiveness of quantum mechanics has been mistakenly equated with "profoundness," and critical examination of its foundational assumptions is often dismissed as "not understanding quantum mechanics." Bohr's famous statement, "If you are not confused by quantum mechanics, you haven't really understood it," should have been a reflection on the state of the theory but has instead become a shield against critical thinking. The results of Pan's team's experiment [4,5] could have prompted a re-examination of the foundations of quantum mechanics. Yet, the academic community still tends to fit experiments into the existing theoretical framework rather than revising the theory to conform to facts.

5.3. Inertia of Conceptual Confusion

The mainstream quantum interpretation has long confused "mathematical models" with "physical reality," treating mathematical tools like the "wave function" as real physical states. Pan's team's interpretation of "fringe adjustments caused by changes in the determinacy of scattering degrees of freedom" as "quantum complementarity" [4,5] is a continuation of this confusion — imposing abstract quantum concepts onto concrete physical processes, leading to a disconnect between theory and fact.

6. Conclusion: Returning to a Scientific Paradigm Based on Physical Reality

The foundation of physics is experimental facts, not mathematical narratives. The century-long controversy over the double-slit experiment indicates that the core dilemma of mainstream quantum mechanics does not stem from the particularity of the microscopic world but from a misreading of the physical essence of experiments and conceptual confusion. Pan's team's "recoiling slit" experiment [4,5] further confirms that the "mysterious phenomena" of quantum mechanics can all be explained by the classical logic of "apparatus parameters → determinacy of scattering degrees of freedom → statistical distribution." Concepts like "wave-particle duality," "wave function collapse," and "complementarity principle" are essentially mystifying packaging of classical physical processes.

To break through the current interpretational predicament, it is necessary to rebuild a scientific paradigm based on physical reality: First, strictly distinguish the physical effects of "stable apparatus parameters" and "perturbed apparatus parameters," clarifying that the core of fringe stability is the determinacy of scattering degrees of freedom. Second, discard vague concepts like "wave-particle duality" and establish a physical picture based on particle-matter interactions. Finally, shift the focus of theoretical research from "mathematical model evolution" to "exploration of physical mechanisms."

Future research should focus on: Experimentally designing more refined apparatus parameter control schemes to directly verify the influence of scattering degrees of freedom determinacy on fringes; Theoretically improving the universal model of particle flow scattering theory [6] and connecting it with fields like quantum field theory and condensed matter physics. Only by breaking the path dependence on traditional quantum interpretations and returning to the essence of empirical science can quantum mechanics truly overcome its interpretational dilemma and achieve innovation in foundational theory.

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