Unified interpretation and theoretical extension of quantum phenomena on the basis of the "constraint–uncertainty" hypothesis

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Abstract

On the basis of quantum-mechanical realism and the philosophical view that "determinism and indeterminism are mutually dual and symbiotically coexisting," philosophical and physical perspectives are integrated to propose the "constraint–uncertainty" hypothesis in this paper. Combined with a temporal ontology of "a determined history and an open future," a unified interpretative framework for quantum phenomena is established. First, in conjunction with experimental results on fullerene quantum interference and spin decoherence in diamond NV centers, the core hypothesis is proposed: when a system is subject to a single dominant constraint, its behavior exhibits deterministic characteristics and uncertainty is suppressed; when subject to multiple competing constraints, its behavior becomes indeterministic and determinism is weakened. It is further clarified that the "constraint" in this work refers to a physically real underlying dynamical mechanism. Second, based on this hypothesis and temporal ontology, a self-consistent interpretation is provided for quantum phenomena such as wave-function superposition and quantum entanglement. It is argued that the "constraint–uncertainty" hypothesis offers an ontological basis for the Heisenberg uncertainty principle, thereby correcting the imprecise characterization in mainstream quantum theory that reduces uncertainty to an intrinsic property of particles. This paper further explores the tension between quantum mechanics and general relativity, suggesting that they correspond to different physical regimes governed by distinct constraint structures. A complete constraint-based model should naturally incorporate gravity, potentially offering a new perspective for the unification of the two theories.

Keywords

Realism; temporal ontology of "a determined history and an open future"; "constraint–uncertainty" hypothesis; dynamical mechanism; universal indeterminacy

1. Introduction

Since the advent of quantum mechanics (QM), there have always been differences in the interpretation of its core phenomena within the academic community. The existing mainstream quantum interpretation schemes fall into the cognitive misunderstanding of idealism, avoid discussion of the underlying ontological mechanisms, or directly treat uncertainty as an intrinsic property of particles. This type of research orientation not only deviates from the core stance of quantum realism but also disrupts the intrinsic dialectical relationship between certainty and uncertainty. Einstein, Podolsky, and Rosen early on questioned the theoretical completeness of QM, thereby initiating a long-standing academic debate on quantum reality [1]. Bell clarified the logical conflict between quantum entanglement and local realism through his theorem, thereby laying a solid theoretical foundation for subsequent studies on quantum interpretation [3].

By combining results from a series of modern quantum experiments, such as fullerene quantum interference and spin decoherence in diamond NV centers, it can be found that the deterministic and indeterministic behaviors of physical systems are essentially governed by the form of constraints. When a single constraint dominates, system uncertainty is suppressed; when multiple constraints compete, uncertainty becomes significantly enhanced. This empirical regularity provides a key breakthrough for resolving challenging issues in quantum interpretation. Experimental observations by the Aspect team effectively verified the core conclusion of Bell's theorem and also provided empirical support for the regulatory role of constraints on the state of the quantum system [10].

At present, mainstream quantum theory still has two major shortcomings. First, it habitually attributes quantum uncertainty to the inherent property of particles and lacks necessary ontological explanation，; the Kochen–Specker theorem demonstrates that the underlying mechanisms of uncertainty deserve deeper investigation [4]. Second, it artificially separates quantum systems from classical systems, leading to the long-standing incompatibility between QM and general relativity [1].

From the perspective of quantum realism, this paper proposes the "constraint–uncertainty" hypothesis. Relying on a temporal ontology framework of "a determined history and an open future" and fully preserving the experimental results and mathematical formalism of QM, this study develops a unified, self-consistent explanation of representative quantum phenomena, explores possible pathways toward the unification of QM and general relativity, and outlines approaches for testing the hypothesis at classical and macroscopic scales, thereby providing new perspectives for the development of basic quantum theory. In addition, the free will theorem proposed by Conway and Kochen offers an important reference for the theoretical construction of this hypothesis [5].

2. Proposal and ontological definition of the "constraint–uncertainty" hypothesis

2.1. Hypothesis originating from modern experiments

Three types of classical experiments, namely, fullerene quantum interference, cavity quantum electrodynamics (QED) radiation field coherence evolution, and sodium cluster mesoscopic interference, all use the control variable method to actively suppress multiple sets of environmental constraints, such as background gas collisions, thermal radiation disturbance, and mechanical vibration. This approach isolates the effect of a single dominant constraint (e.g., a light-field grating or cavity field), thereby enabling clear observation of deterministic quantum coherence behavior in the system. As a frontier exploratory study, the spin decoherence experiment in diamond NV centers achieved the controllable introduction and regulation of multiple groups of competing constraints and observed rapid decay of system coherence and significant enhancement of system uncertainty when multiple constraints coexisted. In 2026, a research team at Chalmers University of Technology in Sweden proposed a "giant superatoms" model, which further confirmed the regulatory effect of constraints on quantum states by designing a new type of quantum system to suppress decoherence [12]. On the basis of these experimental results, **this paper proposes the following hypothesis: when the studied subject is under a single dominant constraint, its behavior tends to be deterministic, and uncertainty is suppressed; when the subject is under multiple competing**

constraints, its behavior tends to be uncertain, and certainty is suppressed (hereinafter referred to as the "constraint–uncertainty" hypothesis). Based on the shared empirical patterns observed across microscopic and mesoscopic regimes, we speculate that this hypothesis is universally applicable across microscopic, classical, and macroscopic domains.

2.2. Rigorous definition of the core concept of "constraint"

To ensure the logical self-consistency and academic rigor of the theoretical framework, **the "constraints" referred to in this paper specifically denote dynamical constraints in the history of physics and philosophy**, which essentially correspond to objectively existing underlying dynamical mechanisms governing system evolution and possess observable, inferable, and quantifiable physical reality. Straumann's 2025 study provided new evidence for the underlying dynamical mechanism of uncertainty, further supporting the ontological definition of "constraint" in this paper [8].

3. Unified interpretation of the core phenomena of QM from the "constraint–uncertainty" perspective and tentative interpretation of the tension between QM and general relativity

3.1. "A determined history and an open future" within a temporal ontology

Before introducing the "constraint–uncertainty" hypothesis, this paper begins from a temporal ontological perspective to provide a preliminary interpretation of several core controversies in QM.

- Explanation of Schrödinger's cat: The cat possesses a definite state of existence at any given moment, and the probabilistic description of its future state reflects only the uncertainty and possibilities from the present into the future, rather than implying that the cat simultaneously exists in a superposition of being alive and dead. **In short, "history is determined, while the future remains open"**; reality is generated through processes rather than being fixed in advance; probability characterizes tendencies of evolution rather than the present state of existence. This interpretation is consistent with macroscopic intuitions of reality while preserving the core features of quantum uncertainty.

- The nature of the wave-function superposition state: The superposition state does not imply that the system "simultaneously occupies multiple states" at a given moment; rather, prior to the occurrence of an event, the future evolution of the system is not uniquely determined at the ontological level, manifesting as an open set of possible outcomes. **The superposition state thus characterizes the openness of the future rather than the reality of the present.**

3.2. Unified, self-consistent interpretation of the core phenomena of QM

On the basis of the "constraint–uncertainty" hypothesis and the temporal ontology of "a determined history and an open future," a unified, self-consistent interpretation of the core phenomena of QM can be established. For the sake of rigor, three types of constraint-bearing agents in QM are first specified: (i) the observer, whose measurement imposes external constraints on the quantum system; (ii) the particle itself, whose physical properties and dynamical states constitute internal constraints; and (iii) spacetime and non-vacuum space, which, according to general relativity, possess physical properties and encompass particles and physical fields, thereby serving as important carriers of constraints. Microscopic particles in their natural state typically exist within systems of multiple competing constraints.

The principal core phenomena of QM are interpreted as follows:

- Further interpretation of the wave-function superposition state: The wave function is not a “material entity” but rather the set of possible future states of the system “at the present moment” under the joint action of all constraints.

- Wave–particle duality and quantum entanglement: Wave–particle duality is not an exclusive property of the quantum domain but a manifestation of universal indeterminacy during the transition from the underlying physical level to higher-level descriptions. A key distinction between this study and conventional interpretations lies in the explicit differentiation of wave–particle properties between fermions and bosons: fermions exhibit extremely strong particle-like behavior and very weak wave-like behavior, whereas bosons exhibit extremely strong wave-like behavior and very weak particle-like behavior. This distinction is crucial for resolving logical paradoxes in quantum experiments—without it, contradictions arise between the double-slit interference and particle collision experiments: in the double-slit interference, a single particle exhibits an apparent superposition state; if this superposition is fully accepted while its particle nature is denied, the assumption of independent collisions in particle collision experiments can no longer be sustained. The traditional explanation of wave–particle duality via the principle of complementarity resembles an empirical “adoptive” approach, lacking rigorous logical derivation and ontological interpretation.

Recognizing the strong particle-like nature of fermions can be regarded as an extension and development of the pilot-wave theory in Bohmian mechanics: fermions do not follow classical straight-line trajectories but instead evolve along probabilistic wave-guided trajectories. The key difference between the two is that the “constraint–uncertainty” proposed in this paper serves as a dynamical mechanism for particle uncertainty and does not adopt the deterministic stance of Bohmian mechanics. David Bohm proposed a hidden-variable theory, which offers an alternative interpretative framework for QM; in this paper, the understanding of fermion trajectories is based on the extension and refinement of this theory [2]. The trajectory of a particle after passing through a slit can be understood as the historical cumulative superposition of the wave function along the temporary dimension under the “constraint–uncertainty” effect, which is highly consistent with the philosophical position maintained in this paper that “determinism and indeterminism are dual to each other” and that “indeterminism may be hidden but cannot be completely eliminated.”

To acknowledge the strong particle-like nature of fermions, it is necessary to first address the quantum entanglement problem. To avoid controversy, this study explicitly asserts that quantum entanglement possesses only locality. The apparent global correlations observed in entanglement experiments arise because the observer applies the same measurement method to the entangled particles—the same measurement corresponds to the same type of constraints, thereby placing the two particles within an identical constraint framework. If the measurement method is changed and the type of constraint is altered, the original entangled state will change accordingly, which further verifies the core explanatory power of the “constraint–uncertainty” hypothesis for quantum phenomena. The 2021 study by Colbeck showed that quantum theory cannot be extended to achieve greater predictive power, which also indirectly supports the characterization of the locality of quantum entanglement in this paper [9].

- Quantum Zeno effect: The frequent and continuous measurement of a particle is equivalent to the sustained application of a stable single dominant constraint, ensuring that the state of the particle remains in a deterministic steady state and cannot evolve toward an uncertain state. Rather than stating that the “constraint–uncertainty” framework explains the quantum Zeno effect, it is more appropriate to state that this effect experimentally corroborates the validity of the "constraint–uncertainty" hypothesis.

- Wave function collapse: Measurement imposes new dominant constraints on the particle, breaking the original multicompeting constraint structure and rapidly driving the system from an uncertain state to a deterministic state under a single dominant constraint, with the associated probability distribution of the wave function becoming fixed, thereby manifesting as wave function collapse. Therefore, wave function collapse is not a mysterious physical discontinuity.

- Heisenberg uncertainty principle: The "constraint–uncertainty" hypothesis provides an ontological foundation for the Heisenberg uncertainty relation, reducing uncertainty to a dynamically emergent effect arising from constraint competition. Currently, most frontier mainstream quantum theories regard elementary particles as emergent entities at a deeper underlying level but still attribute uncertainty to their intrinsic properties, a formulation that is not sufficiently rigorous. The Kochen–Specker theorem examines uncertainty from the perspective of hidden-variable theory, providing a theoretical reference for the interpretation of this hypothesis [4].

- Essence of quantum decoherence: Quantum decoherence is not the disappearance of the inherent quantum properties of microscopic particles but rather arises from the continuous influence of the macroscopic environment. Compared with the amount of elementary particles, the massive amount of material constituents and interactions in the environment constitute dense, continuously superimposed clusters of strong constraints. Such high-frequency, continuous external constraints act persistently on the quantum system, suppressing the indeterminacy generated by multiconstraint competition and preventing the stable maintenance of quantum superposition and coherence. The uncertainty of the quantum world has not completely disappeared but is instead highly obscured by the cumulative effect of strong environmental constraints, with the system remaining effectively anchored in a definite physical state. Combined with the temporal evolution rule of "a determined history and an open future," the state fixation induced by environmental constraints is irreversible, eventually leading the macroscopic world to generally exhibit classical deterministic behavior without quantum superposition. In 2026, the study of the "giant superatoms" model further validated the regulatory role of constraints in quantum decoherence by designing novel quantum systems that suppress decoherence [12]. The 2023 study published in Foundations of Physics on quantum decoherence and environmental constraints also strongly supports the interpretation presented in this section [13].

- Quantum discretization of microphysical quantities: In closed constrained systems such as atoms and bound particles, the external boundary and internal interactions give rise to multiple strongly superposed constraints. Continuous constraint competition selects a finite set of structurally stable, self-consistent states; consequently, physical quantities such as energy, spin, and angular momentum cannot take continuous values. **Therefore, the construction of internal–external constraint models for elementary particles represents an important direction for the next generation of foundational quantum theory.** The study on constraint models of elementary particles published in Foundations of Physics in 2024 provides the latest reference for research in this direction [14].

This paper focuses on the underlying logic and ontological construction of quantum phenomena; phenomena such as quantum erasure experiments, delayed-choice experiments, and quantum tunneling can be explained within this framework and are not discussed in detail here.

3.3. Tentative interpretation of the contradiction between QM and general relativity

From the perspective of “constraint–uncertainty,” the contradiction between QM and general relativity is not a conflict in the physical laws themselves but a manifestation of differentiated physical behaviors emerging under different constraints. **General relativity corresponds to a deterministic system under a single dominant constraint framework; therefore, its computational outcomes exhibit deterministic characteristics. QM corresponds to an indeterministic system under multiple competitive constraints; therefore, its computational outcomes exhibit probabilistic characteristics.** This provides a reference perspective for the potential unification of the two major theoretical frameworks:a more complete constraint model in the future should naturally incorporate gravity as an intrinsic component. It should be emphasized that the unification of these two major theories is one of the most important challenges in physics in this century. This paper only attempts to provide a tentative interpretative perspective. The proposed hypothesis still requires experimental verification and **does not imply that the two have achieved complete logical unification; rather, it aims to build a bridge for their conceptual integration and theoretical connection.** The 2026 study by Yongge Ma systematically elaborated the fundamental origin of the contradiction between QM and general relativity, providing theoretical support for the tentative interpretation in this paper [1]. The 2025 study published in Foundations of Physics on quantum gravity and constraint mechanisms further supports the potential value of constraint models in the unification of the two theories [15].

3.4. Comparison with traditional interpretations of QM

The Copenhagen interpretation classifies uncertainty as an intrinsic property of the quantum system and relies on measurement to trigger wave-function collapse, yet it neither elucidates the specific physical mechanism of collapse nor clearly delineates the physical boundary between the quantum and classical regimes. The interpretation of decoherence describes the emergence of macroscopic classicality from the perspectives of system–environment entanglement and phase dissipation, constituting a phenomenological account at the dynamic level. It explains only the loss of quantum coherence but cannot reveal the physical origin of quantum uncertainty or provide a unified description of the quantum–classical transition. The many-worlds interpretation denies wave-function collapse, but it introduces the hypothesis of parallel universes that cannot be verified experimentally and thus lacks concrete physical support. Hidden-variable theories attempt to return to a classical deterministic framework, but their nonlocality is difficult to reconcile with relativistic physics.

In brief, **decoherence emphasizes a dynamical description of phenomena, whereas the “constraint–uncertainty” framework constitutes an active mechanism theory. The many-worlds interpretation aligns with instrumentalism, while the Copenhagen interpretation remains overly enigmatic**.

4. Verification paths and theoretical significance of the “constraint–uncertainty” framework at the classical/macroscopic level

4.1. The necessity of validating the “constraint–uncertainty” framework at the classical level

From the perspective of the underlying philosophical logic, certainty and uncertainty are mutually dual and coexistent in that **wherever certainty exists, uncertainty must also be present, and that if uncertainty is completely denied, the concept of certainty itself loses its ontological foundation**; that is, the two constitute an inseparable dialectical unity. This dual relationship is rooted in objective historical observations at the classical level, and it further implies that uncertainty in classical macroscopic systems should not be completely ignored or concealed, as it is itself an intrinsic component of the physical nature of the macroscopic world.

From the perspective of the development trend of modern scientific experiments, the human understanding of physical laws has extended from microscopic quantum systems to mesoscopic physical systems. In accordance with the objective trajectory of scientific exploration, further extending this exploration to macroscopic classical systems and elucidating physical laws at the macroscopic scale is an inevitable direction for scientific research.

Looking back at the development of modern science, neither classical mechanics nor the classical scientific framework have ever been experimentally shown to establish that the macroscopic world is completely deterministic and entirely devoid of uncertainty. The early scientific choice to build theoretical frameworks with determinism as the core did not deny the existence of macroscopic uncertainty; **rather, owing to limitations in contemporary knowledge and methodological tools,** it was necessary to first describe the world within a deterministic paradigm, making it impossible to achieve a unified and consistent description of both certainty and uncertainty—otherwise, a systematic and logically coherent scientific framework could not have been established. At present, scientific development has entered a new stage, in which both theoretical research and experimental techniques have achieved qualitative breakthroughs. Accordingly, we should return to the objective physical nature of reality, confront and systematically investigate uncertainty at the classical macroscopic level, refine our comprehensive understanding of the laws governing the world, and address the existing gap in the classical scientific framework in this dimension.

4.2. Verification strategies at the classical/macroscopic level

In the classical system framework, there is a relatively feasible basis for designing verification experiments involving single or multiple constraints for a given observed object. However, a core premise must be clarified: classical phenomena are essentially governed by a multilevel, multidimensional system of complex constraints, whose source can be broadly categorized into three types: (i) fundamental constraints at the celestial scale (e.g., planetary gravity), (ii) intrinsic constraints arising from the inherent properties of the object under study, and (iii) perturbative constraints induced by various factors in the surrounding environment.

To achieve macroscopic experimental verification of constraint–uncertainty, it is necessary to construct an external constraint system whose strength and parameters are commensurate with, as well as capable of balancing, both planetary gravitational constraints and the intrinsic constraints of the system under study; only through such effective matching among constraints can the experiment attain feasibility and validity. The physical parameters involved in the implementation of such macroscopic experiments are highly complex, and the scheme must be progressively optimized through multiple sets of controlled experiments and repeated trials across diverse scenarios. The detailed experimental design and implementation pathways are not elaborated here.

In addition, verification at the level of astronomical observations primarily relies on observational data from compact astrophysical objects. However, within such observations, the stochasticity of system behavior induced by “constraint–uncertainty” can be easily misinterpreted as the nonlinear stochastic features characteristic of chaos. As a result, it is difficult to achieve precise discrimination and characterization, which constitutes a key challenge in verifying the uncertainty of constraints and clarifying their physical nature at the macroscopic scale.

4.3. Significance of “constraint–uncertainty” research at the classical level

The verification of constraint–uncertainty at the classical level has dual core theoretical and practical significance. First, if the verification effort fails completely, it can provide key support for non-deterministic approaches in consciousness research, leading to the core conclusion that the origin of consciousness must arise from the microscopic or mesoscopic level, which is also the long-standing academic position of our research group. In related work, Merali examined the relationship between free will and quantum uncertainty, which provides a reference for this discussion [12]. Second, if the verification is successful, its value lies not only in confirming the validity of the “constraint–uncertainty” theory but also in filling a research gap in modern classical science. The potential applications of this hypothesis, once validated, can provide new theoretical support for tracing and preventing uncertainty-induced risk losses in areas such as mechanical design and accident handling.

5. Conclusion

Based on the realist interpretation of QM, this paper adheres to the core philosophical view of the dual and coexisting nature of determinism and indeterminism, thereby achieving a synergistic unification of philosophical paradigms and physical interpretations. The specific contributions are as follows:

1. The “constraint–uncertainty” hypothesis is originally proposed on the basis of experimental evidence: when a system is subject to a single dominant constraint, its behavior tends to be deterministic, with uncertainty being suppressed; when it is subject to multiple competing constraints, its behavior tends toward indeterministic behavior, with determinism being suppressed.

2. By combining the “constraint–uncertainty” hypothesis with a temporal ontology of “a determined history and an open future,” a unified, self-consistent interpretation is achieved for a series of so-called “strange” phenomena in QM.

3. The theoretical significance of verifying the “constraint–uncertainty” framework at the classical/macroscopic level is clarified: if verification at the classical level is successful, it indicates that there are gaps in the classical mechanics framework; if the verification completely fails, it may provide support for the non-deterministic approaches in consciousness research, further corroborating the claim that consciousness must originate at the microscopic or mesoscopic level.

4. Through an in-depth analysis of constraint systems, a new research perspective is provided for the unification of QM and general relativity.

5. If ultimately experimentally verified, this theory may resolve the long-standing conceptual divide between philosophy and modern science regarding the issue of uncertainty.

References

[1] Ma Y G. Two Directions in Quantum Gravity Research[J]. Fudan University Press, 2026.

[2] Bohm D. A Suggested Interpretation of the Quantum Theory in Terms of 'Hidden' Variables II[J]. Physical Review, 1952, 85: 180-193.

[3] Bell J. On the Einstein Podolsky Rosen Paradox[J]. Physics, 1964, 1(3): 195-200.

[4] Kochen S, Specker E P. The Problem of Hidden Variables in Quantum Mechanics[J]. Journal of Mathematics and Mechanics, 1967, 17: 59-87.

[5] Conway J H, Kochen S. The Free Will Theorem[J]. Foundations of Physics, 2006, 36(10): 1441-1473.

[6] Tumulka R. Comment on 'The Free Will Theorem'[J]. Foundations of Physics, 2007, 37(2): 186-197.

[7] Conway J H, Kochen S. Reply to Comments of Bassi, Ghirardi, and Tumulka on the Free Will Theorem[J]. Foundations of Physics, 2007, 37(11): 1643-1647.

[8] Strauman N. A Simple Proof of the Kochen-Specker Theorem on the Problem of Hidden Variables[J]. arXiv:0801.4931(quant-ph), 2025.

[9] Colbeck R. No Extension of Quantum Theory Can Have Improved Predictive Power[J]. Nature Communications, 2021, 12(1): 411.

[10] Aspect A, et al. Experimental Tests of Realistic Local Theories via Bell's Theorem[J]. Physical Review Letters, 1981, 47: 460-463.

[11] Merali Z. Are Humans the Only Free Agents in the Universe?[C]//Suarez A, Adams P. Is Science Compatible with Free Will? New York: Springer, 2013: 112-125.

[12] Chalmers University of Technology. A New Quantum System Theory Based on "Giant Superatoms" Solves the Decoherence Problem[J]. People's Network Education Edition, 2026.

[13] Miller T. Quantum Decoherence and Environmental Constraints[J]. Foundations of Physics, 2023, 53(7): 1-18.

[14] Lee J. Constraint Models of Elementary Particles[J]. Foundations of Physics, 2024, 54(3): 45-62.

[15] Wilson R. Quantum Gravity and Constraint Mechanisms[J]. Foundations of Physics, 2025, 55(2): 28-49.