Entanglement and the "Multi-Spacetime" Scheme for the Measurement Problem in Quantum Mechanics

Authors: Hu Jinwen, Jinwen Hu

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Abstract

This paper investigates the Copenhagen interpretation and the 'many-worlds' interpretation in quantum mechanics, and proposes a reconciliatory framework between them, specifically the 'multiple spacetimes' scheme. This scheme postulates that spacetime in the universe may not be unique, and that any interaction between systems creates an independent spacetime. These systems exhibit 'particle' properties within that spacetime, while from the perspective of other unrelated spacetimes, these systems exhibit 'wave' properties. In the 'multiple spacetimes' scheme, the role of the observer need not be as crucial as in the Copenhagen interpretation, but is relegated to an ordinary status. Furthermore, this paper addresses the issue of measurement objectivity under the 'multiple spacetimes' scheme. The 'multiple spacetimes' scheme provides a new understanding of the measurement problem in quantum mechanics, yet it does not conflict with current physical experiments and remains within the framework of quantum mechanics.

Full Text

Preamble

Entanglement and the "Multi-Spacetime" Scheme for the Measurement Problem in Quantum Mechanics

Jinwen Hu[1], Huan Hu[1]
(1. School of Physics and Technology, Wuhan University, Wuhan 430072)

Abstract

This paper examines the Copenhagen interpretation and the Many-Worlds interpretation in quantum mechanics, revealing that a compromise scheme exists between them—the “multi-spacetime” scheme. This scheme proposes that spacetime in the universe may not be unique; any interaction between systems forms an independent spacetime. Within this spacetime, these systems exhibit “particle” properties, while from the perspective of other unrelated spacetimes, they exhibit “wave” properties. In the multi-spacetime scheme, the observer’ s role need not be as crucial as in the Copenhagen interpretation but is relegated to ordinary status. The objectivity of measurement under the multi-spacetime scheme is also demonstrated. The multi-spacetime scheme provides a new understanding of the measurement problem in quantum mechanics, yet it does not conflict with current physical experiments and remains within the framework of quantum mechanics.

Keywords: quantum measurement; Copenhagen interpretation; Many-Worlds interpretation; decoherence; multi-spacetime

Introduction

It is well known that the quantum measurement problem is a fundamental issue in the interpretation of quantum mechanics. To address this problem, numerous versions of quantum mechanical interpretation have emerged in recent decades, such as the Copenhagen interpretation [1,2], the decoherence interpretation [3], the Many-Worlds interpretation (and relative-state interpretation) [4,5], hidden variable theories 「6,7」, the consistent histories interpretation [8], and semantic reconstruction interpretations [9,10]. These interpretations approach the fundamental question of why the microscopic world governed by quantum mechanics appears so different from the macroscopic classical world we perceive. Among these, the most influential is the Copenhagen interpretation, whose core idea is wave function collapse—that is, due to the existence of an external classical world, the wave function of a microscopic system collapses, a non-unitary abrupt process that cannot be described by the Schrödinger equation.

Clearly, the Copenhagen interpretation has an obvious problem: what constitutes the classical world, and how is the boundary between the microscopic and classical worlds defined? This question leads to the paradox of “Schrödinger’ s cat.” Ultimately, to rescue this “neither dead nor alive” cat, the von Neumann chain culminates in the introduction of humans (or consciousness) to “cut off” the infinite regress of the chain [2]. Another hidden problem in the Copenhagen interpretation is how to select a preferred basis.

Introducing the decoherence interpretation into the Copenhagen interpretation can effectively solve the preferred basis problem through environmental stability criteria [11,12], allowing classical properties to emerge from the quantum world. It is worth noting that quantum decoherence theory has achieved remarkable successes in recent years [13-15], with its phenomena confirmed by numerous experimental practices. However, it is also recognized that decoherence theory remains entirely within the quantum mechanical framework and still cannot adequately resolve the quantum measurement problem [16], because the system and environment together still exist in a larger pure-state wave function after decoherence.

Additionally, there is the famous Many-Worlds interpretation [4], whose core idea is that the wave function never collapses but instead evolves deterministically forever, with each observation causing the world to "split." The significance of this interpretation lies in its insistence on "monism" and its preservation of determinism. In summary, the interpretation of quantum mechanics currently remains in a state of contention. With continued research in quantum theory, these interpretations are constantly being refined and improved. Notably, the rise of quantum entanglement research over the past decades has led to the recognition that spacetime geometry and quantum entanglement may be intimately connected. For example, the work of Mark Van Raamsdonk et al. [17,18] demonstrates that spacetime geometry is the entanglement structure of microscopic quantum states. Based on this idea, Wang Cancan [19] derived the cosmological Friedmann equations. Inspired by this work and these ideas, this paper finds that a compromise interpretation exists between the Copenhagen and Many-Worlds interpretations—the "multi-spacetime" scheme. In Section 2, we elaborate on this compromise scheme and its understanding of the quantum measurement problem. In Section 3, we demonstrate how measurement objectivity is guaranteed under the multi-spacetime scheme. In Section 4, we supplement the decoherence interpretation based on the multi-spacetime scheme. Finally, we conclude the paper.

2. Properties of Spacetime and the Quantum Measurement Problem

In quantum mechanics, the laws of motion in the microscopic world obey the Schrödinger equation and evolve deterministically according to the wave function. Based on the postulates of quantum mechanics, the wave function obeys the superposition principle: if | 1 and | 2 satisfy the equation of motion, then is also a possible state satisfying the equation of motion in the microscopic world. When | 1 and | 2 are eigenstates of some mechanical quantity (with corresponding eigenvalues a1 and a2), then according to Born's probabilistic interpretation, measuring A on | can only yield a1 and a2 randomly, with probabilities $|c1|^2$ and $|c2|^2$.

As can be seen above, the state function undergoes a completely different change before and after measurement. The measurement problem is a core issue in quantum mechanics [20]. In the orthodox Copenhagen interpretation, measurement is described by two principles: (1) Measurement rule: observables are represented by self-adjoint operators, and possible measurement outcomes (with probabilities given by the probability wave function) are the eigenvalues of the corresponding operator; (2) Projection postulate: when not being measured, a microscopic system evolves deterministically according to the Schrödinger equation (called the U process). After measurement, the microscopic system evolves randomly, with the state vector projecting (collapsing) onto the eigenspace corresponding to the result (called the R process).

Clearly, the "observer" holds an important position in the Copenhagen interpretation. Moreover, in Bohr' s view, the "observer" must have classical properties. Based on this Copenhagen interpretation, von Neumann constructed the "von Neumann chain" : if the first apparatus D1 is described by a quantum state, why does the composite state of system + apparatus collapse to | 1 |D1 ? The answer is that because a second classical apparatus D2 exists, the larger total system collapses to | 1 |D1 |D2 . This extends iteratively to the infinite universe—the total system, including the system and all matter outside it (apparatus, observer, environment, etc.)—and the universe ultimately collapses onto the following chain of branches: | 1 |D1 |D2 |DN |Human . Equation (2) introduces the highly controversial human or consciousness factor. Some scholars have questioned this [21], arguing that "consciousness" belongs to metaphysics, while others have acknowledged the role of consciousness [22,23]. This paper does not discuss this non-material factor. The emergence of the "von Neumann chain" is entirely the result of confronting the "measurement" problem head-on within the Copenhagen interpretation, ultimately leading to the awkward situation of requiring humans or consciousness to terminate the infinite regress of the chain. One reason for this is that the Copenhagen interpretation insists on the idea that "only one universe exists or only one spacetime exists in the universe," and that this universe is classical at the macroscopic level [24].

However, insisting on the idea that "only one universe exists or only one spacetime exists in the universe" may not be necessary; the Many-Worlds interpretation is one alternative approach. The Many-Worlds interpretation adheres to a "monistic" viewpoint, holding that the wave function never collapses but evolves deterministically forever, and that all branches of the wave function under observation truly "exist or appear"—corresponding to the creation of "many worlds." In terms of theoretical conception, the most widely questioned aspect of the Many-Worlds interpretation is its perceived lack of simplicity.

Inspired by the work of Mark Van Raamsdonk et al., this paper finds that a compromise interpretation can exist between the Copenhagen and Many-Worlds interpretations—namely, spacetime may not be unique: when two or more systems (whether macroscopic or microscopic) interact, they constitute an independent spacetime. In this formed spacetime, each system exhibits "particle" properties, while the multiple systems as a whole exhibit "wave" properties from the perspective of unrelated spacetimes. Systems that do not interact with each other do not share the same spacetime. It is interaction that "creates or connects" independent spacetimes.

Based on this compromise scheme—the "multi-spacetime" scheme—let us return to the problem of the "von Neumann chain." When the first apparatus D1 measures the system, apparatus D1 and the system form an independent spacetime 「| 1 |D1 」. In this independent spacetime, both the system and apparatus D1 exhibit "particle" properties. For other apparatuses or humans, since they have not yet interacted with apparatus D1 and the system and are not in their spacetime, they can only "perceive" the spacetime 「| 1 |D1 」as a whole with "wave" properties. Under the multi-spacetime scheme, this independent spacetime 「| 1 |D1 」 exists stably, or exists stably in the universe, without needing to introduce the factor of "humans or consciousness" as in the Copenhagen interpretation to cause all apparatuses and systems to collapse into one spacetime . This paper regards the term "universe" as a larger system residing above spacetime.

Clearly, under this multi-spacetime scheme, readers may question the objectivity of measurement: how can we guarantee consistency between measurement results from classical apparatuses and those from humans (or consistency among sequential measurements by multiple classical apparatuses)? When multiple apparatuses measure sequentially, one apparatus first interacts with the system to form an independent spacetime, after which humans or other apparatuses "merge" into this spacetime or form a new spacetime through measurement interactions. The next section addresses this issue.

3. Objectivity of Measurement in the Multi-Spacetime Scheme

In fact, in the Many-Worlds interpretation, the work of Sun Changpu [21,25] and others has demonstrated how to guarantee the objectivity of measurement even when measurement causes "world splitting." Their work is equally applicable to the multi-spacetime scheme, though some modifications and elaborations are needed.

For simplicity, assume observer O measures microscopic system S through macroscopic apparatus D. First, macroscopic apparatus D measures microscopic system S, and the measurement interaction between them forms an independent spacetime, in which both exhibit classical "particle" properties. In other words, macroscopic apparatus D and system S, due to their interaction, both decohere into the spacetime they form, establishing a classical correlation within it:

where {|ds } are the apparatus state basis vectors corresponding to the system basis vectors |S . Since the apparatus is macroscopic and sensitive to quantum states, the apparatus states are orthogonal, i.e., ds ds' = ss', and SD represents an ideal classical correlation. At this point, if the observed quantity is the (Hermitian) mechanical quantity A of the system, |S is its eigenstate, and A|S = aS|S , then the system' s eigenstates are orthogonal.

Subsequently, when O measures D, observer O "merges" into the spacetime of D and S, forming a larger independent spacetime.

In this spacetime, since O is also macroscopic and sensitive to quantum states, we have Os Os' = ss' . Thus, when the observer observes the apparatus, an ideal classical correlation also forms between apparatus and observer:

where {|Os } are the observer state basis vectors corresponding to the system basis vectors |S . This shows that observer O reads S on apparatus D, with probability $|CS|^2$ for as.

The above analysis demonstrates that when observer O measures mechanical quantity A of microscopic system S through classical apparatus D, an ideal measurement (or ideal interaction) requires the entangled state | resulting from the three-body interaction to be a GHZ-type state, meaning that {|ds } and {|Os } are two orthogonal sets.

This guarantees that an ideal classical correlation state with identical coefficients also forms between observer and system: If apparatus and observer are regarded as two different observers, then different observers obtain identical measurement results. Therefore, we can conclude that measurement is objective.

From the above, it can also be seen that if the apparatus state |ds is not orthogonal, the measurement result of apparatus D for system S may (with some probability) differ from that of observer O for system S (i.e., sequential measurements by different apparatuses may yield different results). In Wigner' s friend thought experiments [26], since Wigner's friend consists of a large number of microscopic particles obeying quantum mechanics, they can undergo ideal interaction with Wigner and the cat to merge into the independent spac etime formed by "cat and Wigner," thus yielding consistent sequential observations of the cat state by Wigner and his friend. Conversely, if Wigner' s friend is replaced by a small number of microscopic particles obeying quantum mechanics, they will not undergo ideal interaction with Wigner and the cat and cannot merge into the independent spacetime formed by "cat and Wigner," making it possible (with some probability) for the observations of Wigner and his friend to differ.

4. Supplement to the Decoherence Interpretation

We know that in the orthodox Copenhagen interpretation, there exists the preferred basis problem [24]: in quantum theory, there is no essential difference between various representations, yet measurement results always correspond to a special set of basis representations, such as pointer up or down, rather than others.

To address this, E. Joos and H.D. Zeh [3,27] proposed solving the preferred basis problem through the decoherence process and stability criteria. The main idea of the decoherence process is that through interaction with a macroscopic environment or a composite system of many microscopic particles obeying quantum mechanics, the quantum phases between different components of the system' s originally quantum-coherent wave function gradually lose coherence and instead each establishes quantum entanglement with the environment. In the work of Sun Changpu [21,28] and others, it is proposed that the center-of-mass degrees of freedom of macroscopic objects are intrinsically coupled with internal degrees of freedom, producing natural decoherence. The multi-spacetime scheme can provide further supplementary interpretation of the decoherence process. Taking two-particle entanglement as an example, the entanglement interaction between them forms an independent spacetime . Although in other unrelated spacetimes the two-particle system as a whole exhibits "wave" properties (manifesting the non-locality of quantum entanglement), within the independent spacetime formed by their interaction, both particles exhibit "particle" properties. Thus, it can be indirectly and equivalently considered that the formation of an independent spacetime is the product of system decoherence, with each system after decoherence exhibiting classical "particle" properties within that spacetime—yet the two-particle system exhibits "wave" properties from the perspective of other spacetimes.

Another important concept in the decoherence interpretation is the stability criterion, which states that a series of possible microscopic states of a microscopic system must establish stable and reliable one-to-one correlations with a series of different macroscopic states of a macroscopic apparatus, correlations that cannot be disrupted or destroyed even under various complex interferences. The stability criterion guarantees that a microscopic system has clear, definite microscopic properties that can be macroscopically recorded and measured. Under the requirements of the stability criterion, the multi-spacetime scheme demands that the independent spacetime formed by interaction have reliable stability, which cannot be disrupted even with the "merging or connection" of new spacetimes (i.e., with new interactions).

Furthermore, the work of Sun Changpu et al. also aligns with the multi-spacetime scheme. To describe the macroscopic center-of-mass degrees of freedom of a system' s collective motion mode, a specific spacetime must be designated, and this spacetime is precisely that formed by the system' s internal interactions. In other words, the existence of a macroscopic center of mass necessarily corresponds to the existence of a spacetime, and the emergence of a spacetime necessarily corresponds to interactions existing between some systems. The macroscopic center of mass of a system has decohered with this spacetime (regarding spacetime as an equivalent physical entity).

5. Discussion and Summary

Wave-particle duality is an important property of microscopic particles. However, the world perceived by humans at the macroscopic level is a classical particle world—we have never seen a cat that is "both dead and alive." In the orthodox Copenhagen interpretation, all this stems from wave function collapse caused by measurement, which must involve macroscopic apparatus or environment. This makes the external classical world essential in the Copenhagen interpretation, and measurement plays an important role.

Inspired by the work of Mark Van Raamsdonk et al., this paper finds that a compromise scheme can exist between the Copenhagen interpretation and the Many-Worlds quantum interpretation—the "multi-spacetime" scheme. In the multi-spacetime scheme, wave-particle duality manifests as follows: when two or more systems undergo ideal interaction (whether entanglement, measurement, or other interactions), these systems "construct" an independent spacetime, in which they all exhibit classical particle properties, and the system decoheres with this spacetime (regarding spacetime as an equivalent physical entity). According to quantum mechanics, these multiple systems as a whole still exist in a vast pure-state wave function, which in the multi-spacetime scheme means that these systems as a whole exhibit "wave" properties from the perspective of other unrelated spacetimes (unrelated spacetimes meaning those with no ideal interaction). Alternatively, it can be said that wave-particle duality achieves dialectical unity through spacetime as an intermediary medium.

In the multi-spacetime scheme, since the universe is not considered to have only one unique spacetime but allows multiple independent stable spacetimes to exist, the observer in the Copenhagen interpretation is relegated to ordinary status without special significance (this is also the idea of relational quantum mechanics interpretation). Because there is no longer a need for a universe with only one spacetime overall, entanglement, measurement or interaction, collapse, and decoherence all share a common product: they can all "create or connect" independent spacetimes. In other words, with multiple spacetimes existing in the universe, there is no need to introduce a final non-material factor (such as consciousness) in the "von Neumann chain" to cause these independent spacetimes to form a unified spacetime through ultimate "collapse."

Drawing on some work from the Many-Worlds interpretation, it can be demonstrated that measurement can still be guaranteed to be objective under the multi-spacetime scheme. The multi-spacetime scheme shares some similarities and has fundamental differences with the Many-Worlds interpretation. The similarity lies in that the Many-Worlds interpretation considers "particle" properties to be real in each branching world—that is, after measuring "Schrödinger' s cat," the "dead cat" and "live cat" exist in two branching universes respectively, and the "dead cat" and "live cat" can never perceive each other' s existence. The multi-spacetime scheme places "particle" properties in each independent spacetime, and other unrelated spacetimes outside the spacetime cannot perceive its "particle" properties. Both schemes independently "seal off" the "particle" properties of matter. Their difference lies in that, to preserve determinism, the Many-Worlds interpretation holds that every branch of the wave function truly exists in its corresponding universe, and observers also split accordingly into each universe. The multi-spacetime scheme, however, still inherits the nondeterministic thought of the Copenhagen interpretation and combines it with the decoherence interpretation.

It is worth emphasizing that as a compromise scheme, the multi-spacetime scheme remains within the framework of quantum mechanics. The purpose of introducing this "multi-spacetime" scheme is to remove the special factor of humans or consciousness from the "von Neumann chain" based on the Copenhagen interpretation. The "von Neumann chain" can be cut off at any point, and the point of cutoff forms an independently and stably existing spacetime.

The multi-spacetime scheme does not violate any existing physical experiments; it merely serves as a possible understanding of the measurement problem in quantum mechanics.

References

〔1〕Gomatam R. Niels Bohr' s Interpretation and the Copenhagen Interpretatio –Are the Two Incompatible?[J]. Philosophy of Science, 2007(74): 736–748.
〔2〕Heisenberg W. Physics and Philosophy[M]. Harper, 1958.
〔3〕Joos, E., Zeh, H. D. The Emergence of Classical Properties Through Interaction with the Environment[J]. Z. Phys. B, 1985 (59): 223-237.
〔4〕Everett, H., Relative State Formulation of Quantum Mechanics[J]. Reviews of Modern Physics, 1957(29): 454–462.
〔5〕Zeh, H. D. On the interpretation of measurement in quantum theory[J]. Foundations of Physics, 1970, 1(1): 69-76.
〔6〕Bohm. A Suggested Interpretation of the Quantum Theory in Terms of 'Hidden Variables' [J]. Physical Review, 1952 (85): 166–179.
〔7〕Cushing, F. Goldstein, Bohmian Mechanics and Quantum Theory: An Appraisal[M]. Springer Science & Business Media, 1996.
〔8〕Griffiths, R. B. Consistent Histories and the Interpretation of Quantum Mechanics[J]. Journal of Statistical Physics, 1984(36): 219-228.
〔9〕Rovelli, C. Relational Quantum Mechanics[J]. International Journal of Theoretical Physics, 1996(35): 1637-1678.
〔10〕Born. The Statistical Interpretation of Quantum Mechanics, Nobel Lecture. December 11, 1954.
〔11〕Zurek W. H. Pointer Basis of Quantum Apparatus: Into What Mixture does the Wave Packet Collapse?[J]. Phys. Rev. D, 1981(24): 1516-1523.
〔12〕Zurek W. H. Decoherence, einselection, and the quantum origins of the classical[J]. Rev. Mod. Phys., 2003(75):
〔13〕Pernice A., Strunz W. T, Decoherence and the nature of system-environment correlations[J]. Phys. Rev. A, 2011(84):
〔14〕Hackermuller et al. Decoherence of Matter Waves by Thermal Emission of Radiation[J]. Nature, 2004 (427): 711-714.
〔15〕Almeida et al. Environment-Induced Sudden Death of Entanglement[J]. Science, 2007, 316(5824): 579-582.
〔16〕Adler S. Why Decoherence has not Solved the Measurement Problem: A Response to P. W. Anderson[J]. Stud. Hist. Philos. Mod. Phys., 2003(34): 135-147.
〔17〕M. Van Raamsdonk. Building up spacetime with quantum entanglement[J]. Gen. Rel. Grav., 2010(42): 2323-2334.
〔18〕M. Rangamani, T. Takayanagi. Holographic entanglement entropy[J]. Lect. Notes Phys., 2017(931): 1-12.
〔19〕王灿灿. 量子纠缠与宇宙学弗里德曼方程 [J]. 物理学报, 2018(67): 19501-19512.
〔20〕Albert D. Z. Quantum Mechanics and Experience[M]. Harvard University Press, 2009.

〔21〕孙昌璞. 量子力学诠释问题 [J]. 物理, 2017(46): 481-496.
〔22〕Conway J. H., Kochen S. The Strong Free will Theorem[J]. Notices of the American Mathematical Society, 2009(56):
〔23〕Conway J. H., Kochen S. The Free will Theorem[J]. Foundations of Physics, 2006(36): 1441-1473.
〔24〕唐先一, 张林志. 量子力学诠释综论 [J]. 物理学报自然辩证法通讯, 2016(38): 29-38.
〔25〕Li S W，Cai C Y，Liu X F. Objectivity of quantum measure-ment in many-observer world. arXiv: 1508.01489，2015.
〔26〕Hugh Everett. The Many-worlds Interpretation of Quantum Mechanics[M]. Princeton University Press, 1973.
〔27〕Zurek W. H. Quantum Darwinism[J]. Nature Physics, 2009 (5): 181-188.
〔28〕Dong G H , Ma Y H , Chen J F , et al. Decoherence of Macroscopic Objects from Relativistic Effect[J]. Chinese Physics B, 2017(10): 27-36.

Note: Figure translations are in progress. See original paper for figures.