The Quantum Observer Problem: Understanding Science in the Face of Unresolved Questions

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ABSTRACT

Scientific progress does not always remove difficult conceptual questions about knowledge, reality, and observation. Quantum mechanics is one of the most successful theories in modern science, yet its development has raised persistent questions concerning measurement, observation, and quantum reality. Despite extensive theoretical and experimental progress, the measurement problem remains unresolved and continues to generate different interpretations. This paper examines what this unresolved problem reveals about scientific understanding and how people may approach unresolved scientific questions when established knowledge does not provide a final answer. The discussion uses a conceptual approach, drawing on selected historical and theoretical work and experiments related to the measurement and observer problem. The paper highlights how competing interpretations can remain open while established applications continue to work.

Keywords: Science and Humanity, Physics and Society, Quantum Mechanics, Observer Problem, Measurement Problem

INTRODUCTION

The development of ideas about the nature of light played an important role in the emergence of modern physics. Thomas Young's double slit work provided important evidence for the wave-like behaviour of light, despite historical debate and criticism surrounding its interpretation [1]. This early development helped establish a foundation for the later transformation of physics that led to quantum mechanics.

Scientific progress can transform our understanding of the natural world while also opening questions that challenge existing ways of understanding reality. The development of quantum mechanics provides an important example of this tension. Its foundations emerged from attempts to understand the nature of light, beginning with the work of Max Planck and later developed through Albert Einstein's work, marking a major transformation in modern physics [2].

Quantum mechanics emerged from efforts to explain phenomena that challenged established ideas in physics. Einstein's application of Planck's quantum theory to the photoelectric effect further strengthened the developing quantum framework and contributed to the recognition of this work through the Nobel Prize in Physics [3].

The development of quantum mechanics therefore illustrates a broader challenge in scientific understanding: empirical success does not necessarily settle all conceptual questions. Phenomena such as entanglement and the apparent collapse of the wave function (a mathematical description associated with the transition from probabilistic possibilities to definite outcomes) have contributed to continuing questions and remain part of the mystery surrounding how quantum systems should be understood and interpreted [4]. This makes the

quantum measurement problem a useful case for considering how people may approach unresolved scientific questions when established scientific knowledge does not provide a final answer.

This article uses a conceptual approach to examine selected historical, theoretical, and experimental discussions related to the quantum measurement and observer problem. The discussion traces how questions concerning measurement and observation develop into broader questions involving consciousness, information, and causality. These discussions are then used to consider how people may approach scientific questions that remain conceptually unresolved.

Note to Readers: The following section provides a general discussion of the topic, while more detailed technical examples are presented in the subsequent section. Readers who wish to focus directly on these examples may proceed to the next section.

TRANSFORMATION OF QUANTUM MECHANICS AND THE MEASUREMENT PROBLEM

As quantum theory developed, the nature of light and matter presented an increasingly unusual picture in which wave and particle descriptions were both required, providing an important starting point for the conceptual questions about measurement and observation that followed. The wave function introduced by Schrödinger provided a mathematical description of the quantum state, while the interpretation associated the wave function with the probabilities of possible measurement outcomes. This development introduced a new way of understanding physical phenomena that differed from the deterministic descriptions of classical physics [5]. This also introduced the conceptual question of how quantum systems could exhibit both wave-like and particle-like behaviour.

As quantum mechanics developed further, Niels Bohr and his followers formulated the Copenhagen interpretation, which became an influential and distinctive approach to understanding quantum phenomena. One of its important claims concerned the relationship between a quantum state and measurement, suggesting that a quantum possibility becomes a definite outcome through observation or measurement [3]. This unusual view of measurement opened a deeper question about the role of observation in determining what can be regarded as a physical connection in the real world.

The question of measurement becomes even more intriguing when quantum phenomena involve entanglement between objects that are far apart and the apparent collapse of the wave function. Such phenomena, in which correlated measurement outcomes can appear across large distances (e.g., hundreds of kilometres), have contributed to the mystery surrounding the nature of quantum reality [4]. This deepens the question of how measurement and observation can be understood within quantum mechanics.

This interpretation nevertheless generated controversy and debate. Einstein consistently challenged aspects of the emerging quantum theory, arguing that physical reality should be objective and definite rather than fundamentally probabilistic. His position was expressed most prominently with Boris Podolsky and Nathan Rosen in the 1935 EPR paper, which questioned whether quantum mechanics provided a complete description of physical reality [6]. Their challenge brought the questions of objectivity, completeness, and quantum reality into clearer focus.

The EPR challenge did not end the debate, but instead encouraged further attempts to examine the assumptions underlying quantum mechanics. John Bell later developed a theoretical framework that made it possible to distinguish quantum predictions from certain classes of theories based on local hidden variables. Bell's work therefore shifted the discussion from a mainly philosophical dispute toward questions that could be tested experimentally [3]. These developments opened a new stage in the debate over what quantum mechanics tells us about physical reality. His work was subsequently tested by John Clauser, Alain Aspect, and Anton Zeilinger in experiments conducted across the following decades. Their contributions were ultimately recognised through the 2022 Nobel Prize in Physics, marking an important experimental development in the study of quantum mechanics [7].

Yet, did experimental success settle the deeper conceptual questions surrounding quantum mechanics? The theory could make remarkably accurate predictions, while questions about measurement, observation, and the role of the observer continued to generate debate. Even when consciousness was considered unnecessary for quantum-state collapse, the role of the conscious observer remained a subject of discussion in specific experimental contexts. This continuing tension points to questions about the completeness of our understanding of quantum mechanics [8].

Discussion of More Serious Implications of Quantum Mechanics

The unresolved measurement problem can be seen clearly in the unusual behaviour of light revealed through the double-slit and related experiments. The challenge of testing this strange character of light was highlighted by Wheeler, whose proposal raised questions about how the behaviour of a quantum system could depend on the way it is examined [9]. This implies that when information about the path taken by a quantum object becomes available, the experimental result can change and display particle-like behaviour, illustrating the important role of measurement conditions in quantum phenomena [10]. These findings therefore deepen rather than eliminate the conceptual question of how measurement is related to the physical behaviour observed.

The question of observation becomes more controversial when consciousness itself is considered as a possible factor in the measurement process. Radin and colleagues investigated whether a conscious observer could influence the interference pattern in a double-slit experiment, reporting changes associated with the observer's awareness of the experiment [11]. A later study extended this approach by examining the effect remotely and reported a similar pattern, while the use of a computer-based substitute for a conscious observer did not produce the same result [12]. These findings have led to further consideration of the possibility that a conscious observer may have a role in the measurement process.

Nevertheless, the experimental approach discussed above remains controversial and has not received broad acceptance within mainstream scientific discussion. The unusual nature of the experiment, particularly its attempt to investigate a possible relationship between quantum phenomena and consciousness, makes the interpretation of its findings more difficult. Such an approach carries a higher interpretive risk because observations from a particular experiment may be extended into broader claims about consciousness or spirituality. The experimental work was described as highly controversial [13], suggesting caution in its interpretation and openness to further independent analysis.

However, the issue remains relevant to the historical development of the measurement problem because the experimental investigation recalls the earlier proposal of John von Neumann, who considered measurement as a chain that could extend beyond the measured physical system and terminate in consciousness [14]. The later experimental investigation therefore shows how an earlier conceptual question concerning consciousness re-emerged as a question that some researchers attempted to examine experimentally.

A further development of the question raised by Wheeler [9] emerged through the delayed-choice approach to quantum experiments. Scully and Drühl [15] proposed a quantum eraser experiment based on the earlier double slit framework. The experiment showed that the decision to observe or not observe the path of a quantum particle could be made after the particle had passed through the slits [16].

Interestingly, the choice of whether to observe the path was suggested as associated with the behaviour of light earlier in the experiment. When the experimental arrangement allowed the path information to be determined, the light showed particle-like behaviour, whereas when the information could be erased at a later stage, the interference pattern could be recovered [16]. Any attempt to obtain which path information therefore becomes closely related to whether the wave-like behaviour is observed. This further highlights the difficulty of understanding the relationship between measurement and the behaviour of a quantum system.

These questions about the role of the observer can be examined further through another experimental interpretation concerning consciousness. Yu and Nikolić [17] argued that quantum-state collapse does not require conscious awareness, based on experiments in which the recording of information at the particle

level was sufficient to affect the wave-like behaviour even without the result being consciously perceived by a human observer. This interpretation suggests that consciousness may not be necessary for the measurement process, although it does not by itself settle the broader question of the role of consciousness.

Although consciousness is generally not considered necessary for quantum-state collapse, it remains relevant to discussions of quantum measurement because some experiments have examined whether a conscious observer affects quantum outcomes (e.g. [11]). Such experimental situations may provide indications of limitations in the current formulation of quantum mechanics [8].

Besides the observer problem, another important issue in quantum mechanics concerns causality, particularly the question of local causality and retrocausality. Recent work has examined whether retrocausal approaches (in which an effect may occur before its corresponding cause) could provide a way of addressing the problem of local causality in quantum mechanics. Adlam [18] argues that retrocausal approaches do not restore local causality and that such approaches introduce further difficulties rather than providing a clear solution to the problem.

The paragraph above provides a clear example of how, beyond the observer or measurement problem, quantum mechanics contains many other unresolved conceptual issues. For example, quantum mechanics may appear to challenge the basic principle of causality, particularly the classical assumption that cause and effect should be connected within a local physical space. Such behaviour can challenge ordinary rational understanding. Yet it may also eventually become familiar through technological applications that take advantage of the nonlocal behaviour of quantum systems, such as quantum network security. However, this article does not attempt to resolve all of these broader issues. Instead, the discussion ends by returning to the observer or measurement problem, because it provides a concrete example of how rational thinking can be applied when an important scientific question remains unresolved.

FINAL DISCUSSION AND CONCLUSION

Quantum mechanics demonstrates that scientific knowledge can be highly successful even when important conceptual questions remain unresolved. The observer or measurement problem continues to raise questions about observation and consciousness, while different interpretations continue to provide competing ways of understanding these issues. The discussion in this article does not attempt to provide a final solution to these questions. Instead, the unresolved nature of the measurement problem provides a concrete example of how scientific knowledge can remain successful while important conceptual questions are still open.

Nevertheless, unresolved questions have not prevented humanity from understanding and exploiting quantum phenomena for technological development. Quantum computing, for example, makes practical use of quantum phenomena [19], while the global quantum computing market is projected to grow from USD 1.6 billion in 2025 to USD 7.3 billion by 2030 [20]. This contrast suggests that scientific uncertainty should not be understood as a failure of science, but as part of the continuing development of scientific knowledge.

Rational thinking is therefore required even when an established scientific theory remains conceptually unresolved and may appear difficult to reconcile with ordinary rational understanding. Rationality does not require every scientific question to have a final answer. Rather, it requires people to distinguish between what established scientific theories can successfully predict and use, and what remains conceptually unresolved. Continued scientific investigation should therefore remain a foundation of genuinely rational thinking.

AI Declaration

ChatGPT assisted with language editing, while the author remains accountable for the final manuscript.

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