Journal of Engineering, Science and Technological Trends (JESTT)
Vol. 2, Issue 3, November 2025
DOI: https://doi.org/10.64060/jestt.v2i3.3

Article

Neutrosophic Logic Reveals Ontological Indeterminacy in Quantum Systems

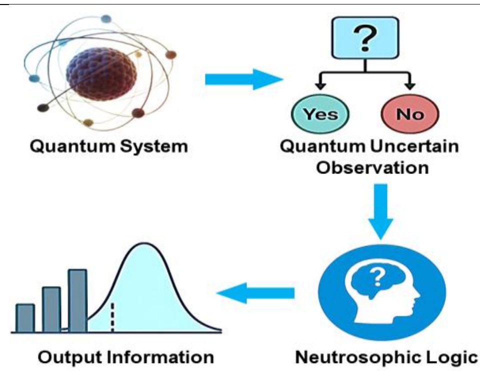
Ansa Firdous[1]* and Hafiza Kanza Maryam[2]

[1]School of Electrical Engineering and Information, Tianjin University, Tianjin 300072, China
[2]School of Chemical Engineering and Technology, Herbin Institute of Technology Shenzhen, Shenzhen, China
* Corresponding Email: ansaeducation7@gmail.com (A. Firdous)

Received: 18 July 2025 / Revised: 03 October 2025 / Accepted: 24 October 2025 / Published online: 15 November 2025

ABSTRACT

Quantum mechanics reveals a reality where uncertainty is not merely epistemic but ontological, challenging classical logics that rely on determinacy. We introduce neutrosophic logic as a novel framework to formalise this intrinsic indeterminacy. Unlike probability or fuzzy systems, neutrosophy treats truth (T), falsity (F), and indeterminacy (I) as independent dimensions, enabling a richer representation of quantum superposition, entanglement, and measurement collapse. We show that neutrosophic triplets capture the undefined yet real state of qubits before observation and provide a coherent description of entangled correlations beyond probabilistic models. This approach offers a unifying formalism that accommodates both structural indeterminacy and outcome probabilities, bridging foundational debates in quantum theory with practical advances in quantum computation and information science. By explicitly integrating indeterminacy into mathematical modelling, neutrosophy advances our understanding of quantum reality and suggests new avenues for experimental validation and quantum technology design.



Keywords: Entanglement; Indeterminacy; Neutrosophic logic; Superposition; Quantum information science; Quantum uncertainty

1. Introduction

Quantum uncertainty is one of the most profound and defining features of modern physics. Unlike the deterministic framework of classical mechanics, where the future trajectory of a system can be precisely predicted given initial conditions, quantum mechanics reveals a world where outcomes are inherently probabilistic and indeterminate [1],[2],[3],[4]. The uncertainty principle articulated by Heisenberg illustrates that certain pairs of physical quantities, such as position and momentum, cannot be simultaneously known with arbitrary precision. Beyond this well-known principle, quantum systems exhibit superposition, where a particle exists in multiple states simultaneously until measured and entanglement, in which particles share correlations that defy classical locality. These phenomena suggest that uncertainty in quantum mechanics is not merely a product of incomplete knowledge but a fundamental characteristic of reality itself [5],[6]. Traditional mathematical and logical tools, which presuppose determinacy and binary truth values, often struggle to adequately capture this intrinsic uncertainty. Thus, the challenge remains: how can we model quantum systems in a way that respects both their probabilistic outcomes and their indeterminate nature before measurement?

Neutrosophic theory, introduced by Florentin Smarandache in the late 1990s, offers a novel framework to address precisely this type of complexity [7],[8],[9]. At its core, neutrosophy generalises classical logic by introducing three independent components: truth (**T**), indeterminacy (**I**), and falsity **(F**) to describe the state of any proposition or system. Unlike classical or fuzzy logic, neutrosophy does not require these three values to be complementary or to sum to unity [10]. Instead, they are treated as independent, allowing a proposition to be simultaneously true, false, and indeterminate to varying degrees. This innovation is especially powerful in contexts where contradiction and incompleteness coexist, as it provides a richer language for describing uncertain and paradoxical states. Beyond its philosophical implications, neutrosophic logic has been formalised through neutrosophic sets and numbers, which allow independent specification of **T**, **I** and **F** values for each element in a system. These tools extend beyond fuzzy or probabilistic models by explicitly incorporating indeterminacy, making neutrosophy particularly suitable for systems characterised by openness, contradiction, and undefined states.

Applied to the quantum domain, neutrosophy provides a powerful means of conceptualising and quantifying quantum uncertainty [11],[12],[13]. A particle in a superposition of states, such as spin-up and spin-down, can be described neutrosophically as being partly true (up), partly false (not-up), and partly indeterminate (undefined until measurement). This differs fundamentally from probabilistic approaches, which only express likelihoods, and from fuzzy approaches, which only allow partial membership values. Neutrosophy instead acknowledges that a system may contain intrinsic indeterminacy, not reducible to ignorance, but built into the structure of quantum reality. Similarly, entangled systems can be modelled as coupled neutrosophic triplets, where the indeterminacy of one particle is directly linked to that of its partner. In this way, neutrosophy not only captures the probabilistic aspects of quantum systems but also provides a formal means to represent their ontological indeterminacy. Such a perspective has potential applications in quantum computation, where qubits inherently exploit indeterminate states; in quantum information theory, where measures of entropy and coherence depend on how uncertainty is defined; and in quantum interpretation, where debates about the meaning of the wavefunction hinge on the role of indeterminacy.

This study aims to explore how neutrosophic logic and neutrosophic sets can enhance our understanding of uncertainty in quantum systems. Specifically, the paper seeks to demonstrate that neutrosophy provides a conceptual and mathematical framework better aligned with the fundamental nature of quantum mechanics than classical probabilistic or binary logics. The objectives are fourfold: (1) to articulate the limitations of conventional approaches to quantum uncertainty and highlight the unique contributions of neutrosophy; (2) to apply neutrosophic principles to key quantum phenomena such as superposition, entanglement, and wavefunction collapse; (3) to discuss potential applications of neutrosophic models in quantum computation and information theory; and (4) to consider the broader philosophical and scientific implications of adopting a neutrosophic perspective in quantum studies. By achieving these objectives, the study aspires to contribute not only to the theoretical foundations of quantum mechanics but also to practical advances in quantum technologies and to ongoing debates about the interpretation of quantum reality.

2. Quantum Uncertainty: Challenges and Phenomena

Uncertainty lies at the heart of quantum mechanics, shaping its formalism and its interpretation. Unlike classical systems, where uncertainty often arises from incomplete information or practical limitations of measurement, quantum uncertainty is intrinsic and structural. The principles of superposition, wavefunction collapse, entanglement, and the Heisenberg uncertainty relation all reveal that quantum systems resist full determinacy in ways that defy classical logic. These phenomena pose challenges not only for physical theory but also for the logical and mathematical tools we use to model them.

2.1. Superposition

One of the most striking features of quantum mechanics is superposition [14],[15]. A quantum system can exist in a linear combination of basis states, such as a qubit described by the state Equation 1:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad (1)$$

Where **α** and **β** are complex amplitudes subject to the normalisation condition $|\alpha|^2 + |\beta|^2 = 1$. Unlike classical probabilities, which represent uncertainty about which definite state a system occupies, superposition represents a genuine co-existence of states before measurement. A qubit in superposition is not "sometimes $|\mathbf{0}\rangle$" and "sometimes $|\mathbf{1}\rangle$," but rather exists simultaneously in both states until a measurement is made.

These challenges classical notions of truth and falsity. A statement such as "the qubit is in state $|\mathbf{0}\rangle$" is neither wholly true nor wholly false while the system is in superposition. Instead, the statement has a truth-like weight associated with $|\boldsymbol{\alpha}|^2$ and a falsity-like weight associated with $|\boldsymbol{\beta}|^2$, but these do not exhaustively describe the system. There is also an additional element: the indeterminacy inherent in the superposed condition, which cannot be reduced to probabilities alone. The system's true condition remains undefined until interaction, highlighting a gap in classical logic that neutrosophic reasoning can potentially fill.

2.2. Measurement and Collapse

A central puzzle in quantum mechanics is the measurement problem, which arises from the apparent discontinuity between unitary evolution and wavefunction collapse [16],[17],[18]. According to the Schrödinger equation, quantum states evolve smoothly and deterministically over time. Yet, when an observation is made, the wavefunction seems to abruptly "collapse" into one of the possible eigenstates associated with the measurement.

For example, measuring the state of the qubit above will yield either $|\mathbf{0}\rangle$ with probability $|\boldsymbol{\alpha}|^2$ or $|\mathbf{1}\rangle$ with probability $|\boldsymbol{\beta}|^2$. After measurement, the superposition vanishes, and the system resides in a definite state. This transition raises profound questions: was the qubit truly in both states before observation, or was the superposition merely a representation of our knowledge? Why does the deterministic evolution suddenly give way to a probabilistic collapse upon measurement?

From a logical perspective, the pre-measurement state resists classification. Propositions such as "the qubit is $|\mathbf{0}\rangle$" cannot be neatly labelled as true or false before observation. The outcome only becomes definite post-measurement, illustrating that truth values in quantum mechanics can be contextual and emergent. Classical binary frameworks are insufficient to capture this discontinuity, and even probabilistic descriptions fail to represent the undefined nature of the pre-collapse state.

2.3. Entanglement

Perhaps no phenomenon illustrates the strangeness of quantum mechanics more vividly than entanglement [19]. When two or more particles interact in such a way that their states become correlated, they can no longer be described independently. Instead, the system is represented by a joint wavefunction that encodes their inseparability.

A simple example is the Bell state as shown in Equation 2:

$$|\,\Phi\rangle^+ = \frac{1}{\sqrt{2}}(|\,00\rangle + |\,11\rangle), \qquad (2)$$

Which describes two perfectly correlated qubits. Measuring the first qubit immediately determines the state of the second, no matter how far apart they are spatially. Einstein famously referred to this as "spooky action at a distance," as it challenges classical notions of locality and realism.

Entanglement complicates the representation of uncertainty in profound ways [20]. For each particle, the state appears maximally indeterminate: each qubit alone is in a mixed state, offering no definite outcome before measurement. Yet, taken together, the pair exhibits perfect correlation. This duality of individual indeterminacy combined with collective determinacy cannot be adequately expressed in conventional logical frameworks. It requires a richer language that can describe how uncertainty is distributed across systems, how indeterminacy can exist locally but be resolved non-locally, and how truth values emerge relationally.

2.4. Heisenberg's Uncertainty Principle

Finally, the uncertainty principle reveals a structural limitation in quantum systems that has no classical analog [21],[22]. Proposed by Werner Heisenberg in 1927, the principle asserts that certain pairs of conjugate variables, such as position (**x**) and momentum (**p**), cannot be simultaneously known with arbitrary precision as mention in Equation 3:

$$\Delta x . \Delta p \geq \frac{\hbar}{2} \quad (3)$$

This inequality does not arise from flaws in measurement apparatus or incomplete knowledge; rather, it reflects the mathematical structure of quantum mechanics. Position and momentum operators do not commute, meaning that the system itself does not possess simultaneous definite values of these properties. Thus, the uncertainty principle captures a structural indeterminacy, not an epistemic one.

The implications are far-reaching. A particle does not have a sharply defined trajectory in space-time; instead, it exists in a spread of possibilities constrained by the uncertainty relation. Classical reasoning, which assumes that an object must have well-defined properties at all times, is insufficient for describing such systems [23]. Logical frameworks that insist on binary truth values, "the particle has a precise position" or "the particle does not", cannot represent the reality of a particle that fundamentally lacks such precision.

3. Quantum Uncertainty: Challenges and Phenomena

Uncertainty has been a central topic of inquiry in both science and philosophy for centuries. Long before the advent of quantum mechanics, mathematicians and logicians developed tools to model unpredictability, vagueness, and incomplete knowledge. Classical probability theory, fuzzy logic, and intuitionistic fuzzy logic represent three of the most influential frameworks for capturing different forms of uncertainty. Each of these approaches has proven highly valuable in domains ranging from statistics and engineering to artificial intelligence and decision theory. However, when applied to quantum systems, they exhibit fundamental limitations. Quantum uncertainty is not simply a matter of incomplete information or linguistic vagueness; it is structural and ontological, embedded in the very fabric of quantum states. In this section, we examine the strengths and shortcomings of these traditional approaches, highlighting why they cannot fully capture the indeterminacy inherent in quantum mechanics.

3.1. Classical Probability

Classical probability theory provides a rigorous framework for quantifying uncertainty about outcomes [24]. Based on the axioms formulated by Kolmogorov, probability describes uncertainty as a measure over a sample space of possible outcomes [25]. Each outcome is assumed to exist as a definite state of the world, even if the observer does not know which state has occurred. For example, the probability of rolling a six on a fair die is **1/6**. The die will, in fact, land on one of the six faces; the probability distribution reflects the observer's ignorance of which particular outcome will occur before the roll.

In many areas of science and engineering, probability theory offers a powerful and reliable language for prediction and inference. In classical statistical mechanics, for instance, probabilities describe ensembles of particles, allowing predictions about macroscopic properties such as temperature and pressure even when the exact microstates are unknown.

However, in the context of quantum mechanics, classical probability fails to capture the depth of indeterminacy. A quantum particle in a superposed state is not in a definite, hidden configuration that the observer is ignorant of. Rather, before measurement, the system genuinely lacks a single determinate value for the observable. When we assign probabilities to measurement outcomes, such as $|\boldsymbol{\alpha}|^2$ and $|\boldsymbol{\beta}|^2$ in a qubit state, these do not represent ignorance about an underlying truth but reflect the structure of potentiality itself. This ontological indeterminacy cannot be fully represented within the Kolmogorov framework, which presumes the existence of well-defined states. Thus, while probability theory is indispensable for predicting quantum outcomes, it is conceptually inadequate for modelling the undefined pre-measurement reality of quantum systems.

3.2. Fuzzy Logic

To move beyond the rigid binaries of classical logic, fuzzy logic was introduced by Lotfi Zadeh in 1965 [26],[27]. Fuzzy logic allows propositions to hold partial truth values, ranging continuously between 0 and 1. For example, the statement "the temperature is hot" may be 0.7 true and 0.3 false. This framework has been particularly effective in modelling vagueness and imprecision, especially in fields like natural language processing, control systems, and approximate reasoning.

Fuzzy sets generalise classical sets by assigning each element a membership function that indicates the degree to which the element belongs to the set. This allows for smooth representation of boundaries, in contrast to the sharp distinctions of classical sets. In practical applications, fuzzy logic has proven extremely useful, offering robust tools for systems where data is imprecise or linguistic categories are subjective.

Yet, fuzzy logic remains insufficient for quantum uncertainty. The key limitation is that fuzzy logic presupposes a complementarity between truth and falsity: the more a statement is true, the less it is false, and vice versa. Even though the values need not be binary, they are still constrained within a single continuum. Quantum mechanics, however, presents situations where a proposition is not merely partially true and partially false but also fundamentally indeterminate, a state not captured by fuzzy membership functions. For example, in a quantum superposition, the proposition "the particle is in state A" cannot be described simply as **0.5** true and **0.5** false, because the system is not in any definite state until measurement. There is a dimension of undefinedness that fuzzy logic does not accommodate.

In short, fuzzy logic is well-suited for vagueness but not for indeterminacy. Vagueness arises when boundaries are unclear, as in linguistic or perceptual categories. Indeterminacy, by contrast, arises when the state itself does not exist until defined by interaction. Quantum mechanics belongs to the latter case, requiring a framework that explicitly incorporates undefinedness as an independent category.

3.3. Intuitionistic Fuzzy Logic

To address some of the shortcomings of fuzzy logic, intuitionistic fuzzy logic was introduced by Krassimir Atanassov in the 1980s [28]. Intuitionistic fuzzy sets extend fuzzy sets by including three components: a degree of membership (truth), a degree of non-membership (falsity), and a degree of hesitation (incompleteness). The hesitation component accounts for the fact that in many cases, the sum of membership and non-membership does not fully capture the situation; there may be uncertainty about the degree to which an element belongs to a set.

This framework represents a significant improvement over classical fuzzy logic, as it acknowledges that information can be incomplete or conflicting. Intuitionistic fuzzy logic has found applications in decision-making, risk analysis, and multi-criteria evaluation, where hesitation is a natural part of the process.

Nevertheless, intuitionistic fuzzy logic still interprets hesitation in an epistemic sense. That is, hesitation reflects the observer's lack of knowledge about the system, not the system's inherent indeterminacy. In other words, hesitation exists because the available information is incomplete, not because the state itself is undefined. In quantum mechanics, however, the indeterminacy is not epistemic but ontological. The system itself lacks a definite state until measured. No matter how much additional information one might acquire, the pre-measurement state remains fundamentally indeterminate. Intuitionistic fuzzy logic, therefore, remains inadequate for capturing the essence of quantum uncertainty.

4. Neutrosophy as a Novel Approach to Uncertainty

Neutrosophy was conceived as a philosophical and logical framework to deal with incomplete, contradictory, and indeterminate information**.** The term derives from *neuter* (neutral, neither one extreme nor the other) and *sophia* (wisdom), reflecting its goal of transcending binary oppositions such as truth/falsehood.

At its core, neutrosophy asserts that every proposition or state is characterised by three independent degrees**:**

Truth (T)**:** the extent to which the proposition is true.

Falsity (F)**:** the extent to which the proposition is false.

Indeterminacy (I)**:** the extent to which the proposition is indeterminate, undefined, or undecidable.

Each of these values is expressed within the real standard or non-standard interval **[0, 1]**, although Smarandache's generalisation even allows them to take values beyond conventional bounds (e.g., "overtruth" > **1**, or "underfalsity" < **0**) to model paradoxical or extreme situations. Unlike in probability or fuzzy logic, the sum of T, **I**, and **F** is not required to equal 1. This absence of a normalisation constraint reflects the recognition that truth, falsity, and indeterminacy can coexist in complex ways.

This independence of components is crucial. For instance, a statement may simultaneously be **0.7** true, **0.4** false and **0.2** indeterminate. In such a case, the values overlap, capturing contradictions and incompleteness that classical, fuzzy, or intuitionistic logics cannot adequately represent.

In philosophy, this move corresponds to the recognition that human reasoning and natural systems often exhibit paradoxes, uncertainties, and gaps. In physics, it provides a formal tool to model quantum superposition, collapse and entanglement**,** where truth values are neither fully determined nor mutually exclusive.

4.1. Mathematical Representation

Formally, neutrosophic sets generalise fuzzy and intuitionistic fuzzy sets by introducing three membership functions instead of one or two. Let **U** be a universe of discourse. A neutrosophic set '**A**' in '**U**' is defined as in Equation 4:

$$A = \{\langle x, T_A(x), I_A(x), F_A(x)\rangle : x \in U\} \quad (4)$$

Where:

$T_A(x)$ is the degree of truth of x belonging to **A**,

$I_A(x)$ is the degree of indeterminacy of x belonging to **A** and

$F_A(x)$ is the degree of falsity of x belonging to **A**.

Each of these functions' maps from U to the interval [0,1]. Importantly, there is no requirement that $T_A(x) + I_A(x) + F_A(x) = 1$; instead, we only have the condition as in Equation 5:

$$0 \le T_A(x), I_A(x), F_A(x) \le 1 \quad (5)$$

This flexibility makes neutrosophic sets capable of representing contradictions and overlapping states.

Example:

Consider a qubit in the state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where $|\alpha|^2 + |\beta|^2 = 1$. If we ask whether the qubit is in state $|0\rangle$, a neutrosophic model might assign as in Equation 6:

$$T = |\alpha|^2 \ \ \& \ F = |\beta|^2 \quad (6)$$

I = a nonzero value representing the indeterminacy of the system before measurement.

Unlike probability, which forces all uncertainty into a normalised distribution between outcomes, neutrosophy captures the indeterminacy dimension that persists until measurement collapses the state.

5. Neutrosophic Representation of Quantum Systems

Building on the foundations of neutrosophy, we now illustrate how quantum systems can be represented using neutrosophic logic and sets**.** This approach treats **T, F** and **I** as independent components, providing a framework for modelling quantum states that are fundamentally uncertain before measurement. We discuss three central phenomena: superposition, entanglement and measurement collapse, demonstrating how neutrosophic logic captures their intrinsic indeterminacy.

5.1. Superposition States

Consider a single qubit in a superposition state in Equation 7:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad (7)$$

Where $|\alpha|^2 + |\beta|^2 = 1$ ensures normalisation. Classical probability theory interprets $|\alpha|^2$ and $|\beta|^2$ as the likelihoods of measuring the qubit in states $|0\rangle$ or $|1\rangle$, respectively. While this probabilistic interpretation predicts measurement outcomes, it does not capture the ontological nature of the superposition: before measurement, the qubit is not in any definite state and its "truth value" relative to a particular basis is undefined.

Neutrosophically, the pre-measurement state can be represented as a triplet (**T**, **I**, **F**) for each basis state. For example, with respect to $|0\rangle$ as mentioned in 8:

$$T(|0\rangle) = |\alpha|^2,\ F(|0\rangle) = |\beta|^2,\ I(|0\rangle) \neq 0 \quad (8)$$

Here, $\mathbf{T(|0\rangle)}$ represents the degree to which the qubit can be considered true in state $|0\rangle$, $\mathbf{F(|0\rangle)}$ the degree to which it is false, and $\mathbf{I(|0\rangle)}$ represents the residual indeterminacy inherent to the superposition. This framework explicitly accounts for the fact that before measurement, the qubit is neither purely $|0\rangle$; it exists in a state that is fundamentally undefined with respect to classical truth assignments.

By modelling superposition in this way, neutrosophy captures both the probabilistic and indeterminate aspects of quantum states. Unlike probability distributions, which collapse uncertainty into likelihoods alone, the neutrosophic triplet preserves the ontological indeterminacy that is essential to quantum mechanics. This allows for a richer and more accurate representation of the system before observation.

5.2. Entangled Systems

Entanglement presents a particularly challenging case for classical and even probabilistic frameworks, as the states of individual particles cannot be described independently. Consider the Bell state as shown in Equation 9:

$$|\Phi^+\rangle = \tfrac{1}{2}(|00\rangle + |11\rangle) \quad (9)$$

In this entangled state, neither qubit possesses a definite individual state before measurement. The measurement of one qubit instantaneously determines the state of the other, regardless of spatial separation, highlighting the nonlocal correlations that are a hallmark of quantum mechanics.

A neutrosophic approach models entanglement by assigning correlated truth, falsity and indeterminacy values to each particle. For the first qubit, we might define as shown in Equation 10:

$$T(|0\rangle_1) = 0.5,\ F(|0\rangle_1) = 0.5,\ I(|0\rangle_1) \neq 0 \quad (10)$$

The second qubit exhibits a similar triplet. Crucially, the indeterminacy components $\mathbf{I(|0\rangle_1)}$ and $\mathbf{I(|0\rangle_2)}$ are linked, reflecting the shared unresolved state of the entangled pair. Only when a measurement is performed does the indeterminacy resolve, simultaneously collapsing the state of both qubits.

Neutrosophic representation is particularly powerful here because it accommodates the simultaneous existence of partial truth, falsity and indeterminacy while maintaining correlations between entangled subsystems. Classical probability can capture outcome correlations but cannot represent the pre-measurement indeterminacy; fuzzy or intuitionistic fuzzy logic captures partial truth but either conflates indeterminacy with lack of knowledge or restricts the independence of **T**, **F** and **I**. Neutrosophy, by contrast, naturally expresses the indeterminate yet correlated nature of entangled states.

5.3. Measurement Collapse

The process of measurement in quantum mechanics is often described as wavefunction collapse marks the transition from indeterminate superpositions to definite outcomes. In neutrosophic terms, this can be interpreted as a reduction of indeterminacy accompanied by a corresponding increase in truth or falsity as mentioned in Equation 11:

$$I \to 0,\ T \to 1 \text{ or } F \to 1 \quad (11)$$

For instance, measuring a qubit in the $|0\rangle/|1\rangle$ basis results in one outcome being fully realised ($\boldsymbol{T}$ = 1) and the other fully falsified ($\boldsymbol{F}$ = 1), with the indeterminacy $\boldsymbol{I}$ dropping to zero. This perspective allows collapse to be understood not as a sudden elimination of possibilities but as the resolution of intrinsic indeterminacy into a determinate state.

This interpretation offers several conceptual advantages:

- **Continuity of Modelling:** Unlike classical logic, which cannot accommodate the intermediate superposed state, neutrosophy provides a smooth transition from indeterminacy to determinacy.
- **Explicit Representation of Quantum Features:** Indeterminacy $\boldsymbol{I}$ is treated as a real, independent component rather than a surrogate for ignorance.
- **Compatibility with Probabilities:** The degrees of truth and falsity remain aligned with measurement probabilities, ensuring that the neutrosophic model is physically meaningful.

Applied to entangled systems, measurement collapse is represented as a simultaneous resolution of indeterminacy across correlated particles, preserving the nonlocal correlations characteristic of quantum mechanics. This unified framework thus integrates probabilistic outcomes, ontological indeterminacy, and correlation structure in a single, coherent model.

6. Broader Role of Neutrosophy in Quantum Mechanics

The application of neutrosophy extends beyond formal modelling of quantum states; it also provides a conceptual and mathematical framework that can inform interpretations of quantum mechanics, quantum decision theory and quantum information science. By explicitly incorporating indeterminacy as a distinct dimension, neutrosophic logic offers new ways of understanding, reasoning, and engineering in domains where uncertainty is fundamental.

6.1. Interpretations of Quantum Theory

Quantum mechanics has long been accompanied by philosophical debates regarding the nature of reality, measurement, and determinacy. Different interpretations propose varying mechanisms for the emergence of definite outcomes, each of which can be enriched by a neutrosophic perspective. In the Copenhagen interpretation, the act of measurement causes the wavefunction to collapse, producing a single realised state. Neutrosophy provides a natural formalism for this process: before measurement, the quantum system is represented with significant $\mathbf{I} \neq 0$, and the collapse corresponds to a reduction of **I** to zero, with **T** or **F** attaining a definitive value.

The Many-Worlds interpretation envisions all potential outcomes as actualised across branching universes. In neutrosophic terms, each branch can be associated with distinct truth and falsity values, while global indeterminacy persists across the multiverse. This allows for a quantitative representation of coexistence and uncertainty across parallel branches, reflecting the simultaneous realisation of multiple possibilities without collapsing indeterminacy in any absolute sense.

For objective collapse theories, which propose that indeterminacy resolves dynamically over time due to intrinsic physical processes, neutrosophic logic can model the gradual reduction of **I** while updating **T** and **F** values correspondingly. In each interpretation, neutrosophy offers a formal mechanism for tracking the evolution of indeterminacy, providing a bridge between abstract philosophical ideas and precise mathematical representation.

6.2. Quantum Decision Theory

Quantum systems are increasingly studied in the context of decision-making under uncertainty, particularly in quantum game theory, cognitive modelling, and adaptive algorithms. Traditional probabilistic models often suffice for calculating expected outcomes, but they do not capture the fundamental indeterminacy that may influence strategies or behaviours. Neutrosophic logic enriches this domain by representing not only the likelihood of different outcomes but also the intrinsic indeterminacy associated with each option.

For instance, in quantum games, a player's decision can be affected by superposed or entangled states. Modelling these states neutrosophically allows for a three-dimensional assessment of each strategy: the degree to which it is advantageous, disadvantageous, and indeterminate before measurement or outcome realisation. This richer representation can enhance the formulation of quantum decision rules, improve predictions of behaviour in quantum-influenced environments, and provide insights into cognitive processes that exploit quantum-like uncertainty. By incorporating indeterminacy as an explicit parameter, neutrosophy enables decision-theoretic models that are more aligned with the ontological nature of quantum uncertainty.

6.3. Quantum Information Science

Quantum information science relies fundamentally on managing uncertain and superposed states. Applications such as quantum error correction, cryptography, and algorithm design require precise handling of probabilistic outcomes while simultaneously accounting for indeterminate aspects of qubits or quantum registers. Neutrosophic logic offers a potentially valuable tool for these tasks by providing a structured way to quantify and manipulate truth, falsity and indeterminacy.

In quantum error correction, for example, neutrosophic sets can represent not only the probability of error occurrence but also the residual indeterminacy of a qubit's state after partial correction. In cryptographic protocols, such as quantum key distribution, neutrosophy can model the indeterminate state of eavesdropping attempts or uncertainties in entangled qubits, providing a more nuanced measure of security risk. Likewise, in algorithm design, incorporating indeterminacy explicitly can aid in optimising operations on superposed or entangled registers, enhancing both efficiency and fault tolerance. Across these applications, neutrosophy provides a formal and computationally tractable way to integrate fundamental quantum uncertainty into the design, analysis, and implementation of quantum technologies**.**

7. Challenges and Future Directions

While neutrosophic logic provides a powerful framework for representing quantum uncertainty, its integration into mainstream quantum mechanics and experimental practice faces several challenges. Addressing these issues is essential for advancing both the theoretical foundations and practical applications of neutrosophy in quantum science.

Formal Integration with Hilbert Spaces: Quantum mechanics is rigorously formulated within the mathematical structure of **Hilbert spaces**, where states are represented by vectors and observables by linear operators. To fully incorporate neutrosophic logic, it is necessary to develop a formal mapping between neutrosophic sets and the Hilbert space formalism. This involves defining how the neutrosophic components **T**, **F** and **I** correspond to vector amplitudes, density matrices, or probability distributions derived from quantum states. A successful integration would allow neutrosophy to complement the existing formalism without violating fundamental principles such as unitarity, superposition, and entanglement. Such a formalism could also enable computational implementations in quantum algorithms, simulations, and error-corrected systems, bridging the gap between abstract neutrosophic reasoning and standard quantum mechanics.

Operational Meaning of Indeterminacy: While neutrosophy provides a philosophically rich notion of indeterminacy, assigning it a precise operational meaning remains an open challenge. To be useful in physical models, indeterminacy must be connected to measurable or calculable quantities. Potential avenues include linking **I** to decoherence rates, quantum entropy or the contextuality of observables. For example, indeterminacy could be formalised as a function of the coherence length in a superposed state or the entropy associated with entangled subsystems. Establishing such links would not only clarify the physical interpretation of **I** but also allow neutrosophic models to produce experimentally testable predictions, thereby grounding philosophical constructs in quantitative science.

Experimental Relevance: A critical step for the broader adoption of neutrosophy in quantum mechanics is demonstrating its empirical relevance. Experimental protocols such as weak measurements, quantum tomography or delayed-choice experiments offer promising platforms for testing neutrosophic predictions. For instance, weak measurement techniques allow partial information to be extracted from quantum systems without full collapse, providing a natural context for measuring residual indeterminacy. Similarly, delayed-choice experiments could reveal how pre-measurement indeterminacy influences correlations in entangled systems. By designing experiments specifically to probe the independent components **T**, **F**, and **I**, researchers can validate the predictive power of neutrosophic models and potentially uncover new quantum phenomena that conventional probabilistic or fuzzy frameworks cannot fully capture.

7. Conclusion

Our results demonstrate that neutrosophic logic provides a fundamentally new language for describing quantum systems, one that directly encodes ontological indeterminacy rather than reducing it to ignorance or vagueness. By applying neutrosophy to superposition, entanglement, and wavefunction collapse, we establish a framework that complements Hilbert space formalism while extending its interpretive power. This perspective has implications not only for the foundations of quantum theory but also for the design of algorithms, error correction, and decision-making in quantum information science. Future integration of neutrosophic models with experimental platforms such as weak measurements and quantum tomography could yield testable predictions that distinguish neutrosophic representations from classical probabilistic approaches. More broadly, embracing indeterminacy as an explicit dimension may reshape how uncertainty is modeled across physics, mathematics, and computation, offering a step toward a more complete understanding of quantum reality.

Declaration

Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Issues: There are no ethical issues. All data in this paper is publicly available.

Author Contribution Statement: A.F and H.K.M conceived idea and designed the research; Analyzed interpreted the data and wrote the paper.

Funding Statement: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Consent to Publish: All authors are agreed to publish version of the manuscript in this journal.

References

1. Berta, Mario, et al. "The uncertainty principle in the presence of quantum memory." Nature Physics 6.9 (2010): 659-662.
2. Zhao, Yuan-Yuan, et al. "Experimental study of quantum uncertainty from lack of information." npj Quantum Information 8.1 (2022): 64.
3. Oppenheim, Jonathan, and Stephanie Wehner. "The uncertainty principle determines the nonlocality of quantum mechanics." Science 330.6007 (2010): 1072-1074.
4. Sen, Debashis. "The uncertainty relations in quantum mechanics." Current Science (2014): 203-218.
5. Ozawa, Masanao. "Quantum limits of measurements and uncertainty principle." Quantum Aspects of Optical Communications: Proceedings of a Workshop Held at the CNRS, Paris, France 26–28 November 1990. Berlin, Heidelberg: Springer Berlin Heidelberg, 2005.
6. Cho, Adrian. "Furtive approach rolls back the limits of quantum uncertainty." (2011): 690-693.
7. Afzal, Usama. "Estimate calculation of discrete energy levels in the hydrogen atom using an indeterministic method." High Energy Density Physics (2025): 101192.
8. Fatima, Adeena, et al. "A Comprehensive Review of Neutrosophic Statistics for Data Analysis in Applied Sciences." Journal of Reliability and Statistical Studies (2025): 25-40.
9. Smarandache, Florentin, and Maissam Jdid. "An overview of neutrosophic and plithogenic theories and applications." (2023).
10. Sarkar, Debasmita, and Pankaj Kumar Srivastava. "Recent development and applications of neutrosophic fuzzy optimization approach." International Journal of System Assurance Engineering and Management 15.6 (2024): 2042-2066.
11. Çevik, A., Topal, S., & Smarandache, F. (2018). Neutrosophic Logic Based Quantum Computing. Symmetry, 10(11), 656. https://doi.org/10.3390/sym10110656

12. Smarandache, Florentin. "Neutrosophic Quantum Theory: Partial Entanglement, Partial Effect of the Observer, and Teleportation." Neutrosophic Sets and Systems 86.1 (2025): 1.
13. Smarandache, Florentin. An introduction to the Neutrosophic probability applied in quantum physics. Infinite Study, 2000.
14. Baghaturia, Iuri, et al. "CRITICAL REVIEW OF FUNDAMENTAL CONCEPTS IN PHYSICS Part 5–"Quantum Superposition"." GSAR J Math Sci. 2025b 4.8: 83-90.
15. Lahiri, Anuradha, Prodyot Kumar Roy, and Bijan Bagchi. "Supersymmetry in quantum mechanics." International Journal of Modern Physics A 5.08 (1990): 1383-1456.
16. Hsu, Stephen DH. "The measure problem in no-collapse (many worlds) quantum mechanics." International Journal of Modern Physics D 26.03 (2017): 1730008.
17. Jordan, Andrew N., and Alexander N. Korotkov. "Uncollapsing the wavefunction by undoing quantum measurements." Contemporary Physics 51.2 (2010): 125-147.
18. Carlesso, Matteo, et al. "Present status and future challenges of non-interferometric tests of collapse models." Nature Physics 18.3 (2022): 243-250.
19. Zhang, Zheshen, et al. "Entanglement-based quantum information technology: a tutorial." Advances in Optics and Photonics 16.1 (2024): 60-162.
20. Yu, Yue. "Advancements in applications of quantum entanglement." Journal of Physics: Conference Series. Vol. 2012. No. 1. IOP Publishing, 2021.
21. Busch, Paul, Teiko Heinonen, and Pekka Lahti. "Heisenberg's uncertainty principle." Physics reports 452.6 (2007): 155-176.
22. Coles, Patrick J., et al. "Entropic uncertainty relations and their applications." Reviews of Modern Physics 89.1 (2017): 015002.
23. Aristarhov, Serj. "Heisenberg's uncertainty principle and particle trajectories." Foundations of Physics 53.1 (2023): 7.
24. Rau, Jochen. "On quantum vs. classical probability." Annals of Physics 324.12 (2009): 2622-2637.
25. Halliwell, Joe, and Qiang Shen. "Linguistic probabilities: theory and application." Soft Computing 13.2 (2009): 169-183.
26. Kindo, Abdoul Azize, et al. "Fuzzy logic approach for knowledge modeling in an Ontology: A review." 2020 IEEE 2nd International Conference on Smart Cities and Communities (SCCIC). IEEE, 2020.
27. Ruspini, Enrique H., James C. Bezdek, and James M. Keller. "Fuzzy clustering: A historical perspective." IEEE Computational Intelligence Magazine 14.1 (2019): 45-55.
28. Melliani, Said, and Oscar Castillo, eds. "Recent advances in intuitionistic fuzzy logic systems and mathematics." (2021).