Infinite Separation and Quantum Entanglement: Extending the Heisenberg Uncertainty Principle

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Abstract

This paper addresses the unresolved question of the instantaneous nature of quantum entanglement and argues that to properly establish this characteristic, the concept of infinite distance must be incorporated into experimental designs. We propose a simplified experiment that introduces the notion of infinite separation between entangled particles to test their instantaneous correlations. Additionally, we extend the Heisenberg Uncertainty Principle to provide a theoretical framework supporting this approach. This extension integrates distance variables to explore how they might influence entanglement properties under conditions of theoretical infinite separation.

Introduction

The Heisenberg Uncertainty Principle, first articulated by Heisenberg in 1927 [1], is a cornerstone of quantum mechanics. It establishes the fundamental limit on the precision with which certain pairs of physical properties, such as position and momentum, can be simultaneously measured (known). The principle is formally expressed by the equation $\Delta x \Delta p \geq \frac{h}{4\pi}$ where Δx and Δp represent the uncertainties in position and momentum respectively, h is the Planck constant. This principle implies that a precise measurement of one quantity results in a complete uncertainty in the other. It should be noted that 'completely uncertain' implies the non-existence of the quantity from a physical standpoint.

When the Heisenberg Uncertainty Principle is applied to two particles that share a history (meaning they are subject to fulfill a conservation law such as spin or momentum) it leads to entanglement. This phenomenon is characterized by a unique correlation where the measurement of one particle instantaneously determines the state of the other. *theoretically* irrespective of the distance separating them.

Two significant issues arise from the concept of entanglement:

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1. The EPR argument concerning "elements of reality."
2. The challenge of non-locality.

In their 1935 paper, Einstein, Podolsky, and Rosen (EPR) argued that entanglement implies that one can determine the value of a property of the second particle without disturbing it [2]. Since either of the two non-commuting quantities can be measured, both must be considered real [1]. This assertion directly conflicts with the Heisenberg Uncertainty Principle. In response, Bohr [3] contended that these two quantities are mutually exclusive; the measurement of one quantity results in the loss of information regarding the other. Therefore, they cannot be simultaneously real.

The concept of non-locality, while only implicit in the original EPR paper, was clearly defined by Bell in 1964 [4]. Bell's inequality brought the argument of non-locality into sharp focus, illustrating the peculiar situation where a particle, unreachable by direct measurement, is nonetheless affected by such measurementsthis is the essence of non-locality. In the case of entangled particles, two significant events occur upon measurement: first, the property being measured in one particle manifests instantaneously in the second particle, effectively bringing it into existence, while the complementary property is irrevocably lost. Second, due to conservation laws, the value of the newly manifested property in the second particle becomes determinable at the moment the first particle is measured.

Numerous experiments[5] have demonstrated the violation of Bell's inequality (and its variants such as CHSH[6]), which signifies the inaccuracy of local realism. Prior to measurement, particles exist in a superposition of states; upon measurement, the superposition collapses into a definite state. Remarkably, the second particle appears to receive instantaneous information regarding the measurement of the first particle, implying that quantum information travels faster than the speed of light. However, this apparent superluminal transfer of information does not contravene Einstein's theory of relativity. There exists a *wall of randomness* that separates the quantum realm from the classical realm, ensuring that any information transferred via a quantum channel becomes truly pure random noise. It is only through the coupling of quantum entanglement with a classical channel that meaningful information transfer can occur.

However, the question of whether entanglement is truly instantaneous remains an unresolved issue. This paper aims to address this by proposing an experiment to investigate the matter and by providing a simple theoretical framework to facilitate understanding.

[1] "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of reality corresponding to that quantity."[2]

The Extended Heisenberg Uncertainty Principle

We propose a generalized form of the Heisenberg uncertainty principle that incorporates the concept of distance. The generalized form is expressed as:

$$\Delta x \Delta p \geq \frac{h}{4\pi}(1 - f(d)) \tag{1}$$

where d represents the distance between particles. The function $f(d)$ is expected to adhere to the following constraints:

$$\lim_{d \to \infty} f(d) = 1 \quad \text{and} \quad f(0) = 0 \tag{2}$$

Given that we do not have a predefined scale of distance for this formula, the most direct method to explore its implications is to investigate scenarios where the distance is infinite. For small enough distances, the uncertainty principle can be restored.

At infinite distances, the uncertainty principle disappears, implying that two entangled particles become independent of each other. In terms of matrix mechanics, two non-commutative operators become commutative when separated by infinite distances. Measuring quantities associated with any of these operators will not affect the other particle. This does not suggest that local realism can be restored; rather, it indicates that entanglement may not be instantaneous. It suggests that there is likely a finite speed associated with the entanglement process.

Entanglement Experiment

It has been demonstrated that entanglement is real and that local realism is not viable. However, these experiments have been conducted over relatively short distances, up to several hundred kilometers [7]. Despite this, there has never been a direct experiment to verify that entanglement is instantaneous. To conclusively demonstrate that entanglement is instantaneous, an experiment would need to show that it occurs at *infinite* distance.

To this end, we propose the following experiment:

1. First, two entangled particles are produced and then separated.

2. Before any measurements are conducted on either particle, an infinite distance is established between them.

3. Once this infinite separation is established, the entanglement of the particles is measured, following the same methods employed in previous experiments.

Critically, there must be a single path connecting the two particles, and the Elin gate is tasked with extending this path to an infinite length.

The Elin (EnabLing INfinity) gate is a hypothetical device capable of introducing an infinite distance between entangled particles by toggling it on or off. In the case of photons, this gate could be realized using a pair of parallel mirrors that reflect the photons back and forth infinitely, thus creating an infinite distance between the entangled photons. During the experiment, the Elin gate is initially switched off. It is then turned on after the entangled particles are produced and separated but before any measurements are made on them.

In the event of a successful experiment, the particles will maintain their entangled state regardless of the infinite distance introduced (whether the Elin gate is on or off). This would indicate that entanglement is instantaneous and unaffected by spatial separation. Conversely, if the experiment shows that entanglement is not instantaneousmeaning the experiment fails to preserve the entangled statethe particles will behave as independent, separate entities. This means they would effectively lose their shared history, and any measurements taken would yield random values. In the experimental readouts, this would manifest as clearly random behavior of the particles, indicating a breakdown in the entanglement.

Discussion

Regardless of whether the experiment succeeds or fails, the results will undoubtedly be fascinating. A successful outcome would demonstrate that entanglement is instantaneous and unaffected by distance, confirming that the spatial separation between entangled particles does not limit their correlation. This would reinforce the existing principles of quantum mechanics regarding non-locality.

Conversely, if the experiment fails, it would suggest that entanglement is not instantaneous, opening up a new avenue of research. Such a result would necessitate further investigations into the speed of entanglement, potentially using the same experimental setup but with varied distances to determine the lower and upper bound of entanglement speed. A failure would also raise significant questions about the applicability of conservation laws over extremely long distances, challenging some fundamental assumptions of physics. Therefore, the breakdown of entanglement in this experiment is very unlikely. This implies significant implications for the foundational principles of physics.

References

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