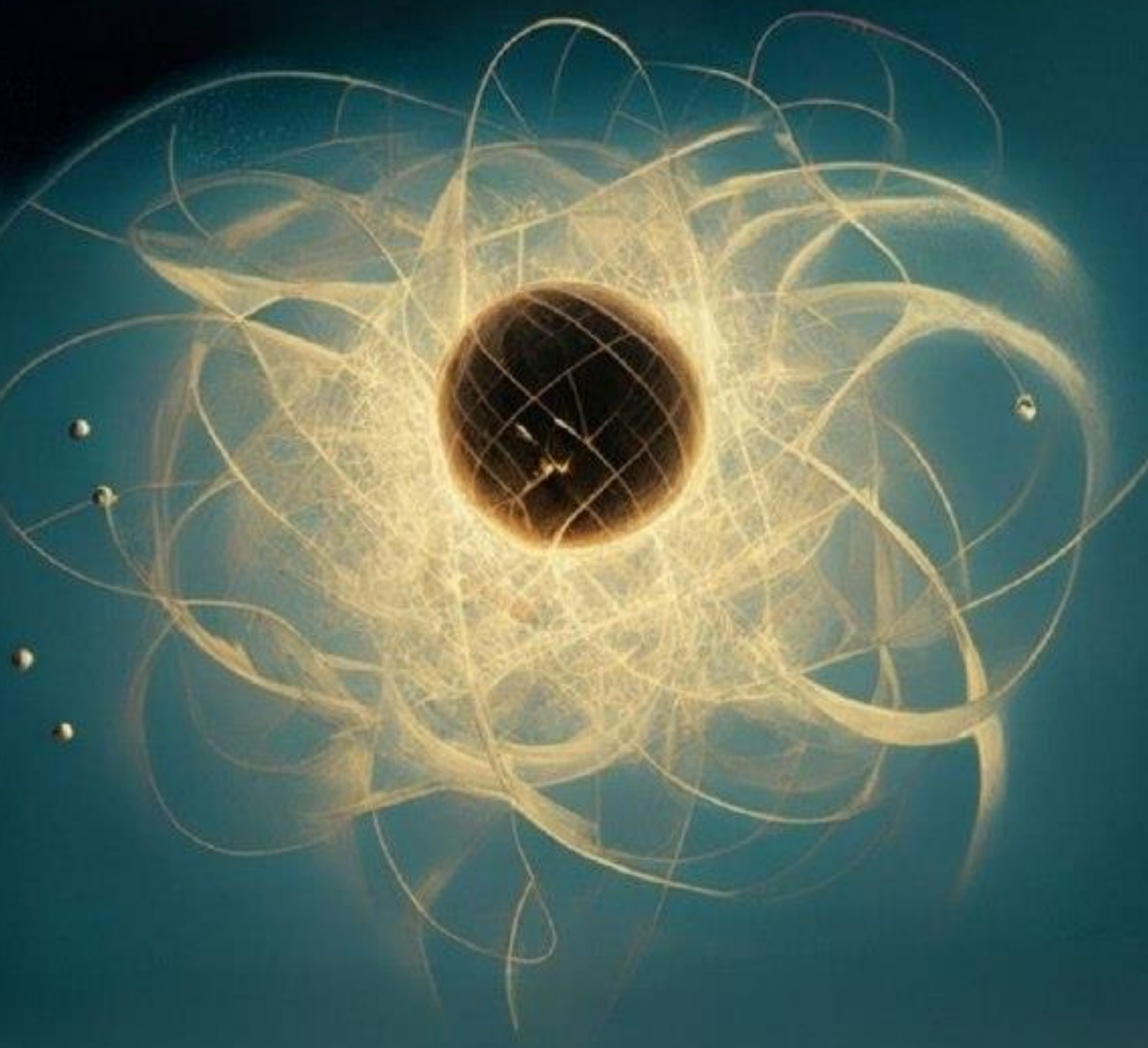
QUANTUM ENTANGLEMENT:

THE POSSIBILITY OF DEFYING SPECIAL RELATIVITY AND TRANSMITTING INFORMATION FASTER THAN LIGHT



Quantum Entanglement: The possibility of defying special relativity and transmitting information faster than light

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Abstract

The founding theories of quantum mechanics are very complex and poorly explained. Since the birth of quantum mechanics on the hands of Neils Bohr and Max Planck, many of the fundamental theories of quantum mechanics have been questionable despite the astounding interpretations surrounding this field. One of those theories is Quantum Entanglement which has been describes by scientists as "the heart of quantum physics." Quantum Entanglement provides a peculiar view of the state of two entangled particles and how they might be defying Einstein's special relativity by communicating in a speed preceding that of light. This paper's aim is to identify the most important theories and experiments leading to our current understanding of quantum physics and quantum entanglement in a simplified approach. Starting from the discovery of the spin state of pair production, Einstein's special relativity and his dismissal of the theory calling it "spooky action at distance", and Bell's inequality. At the end, the paper discusses the multiple views and interpretations accounting for quantum entanglement, and the possibility of human interaction through the state of entanglement.

Key words: Electron spin, Entangled particles, EPR paradox, Hidden variables

I. Introduction

On 26 September, 1905, Albert Einstein published a paper titled "On the Electrodynamics of Moving Bodies", in which he proposed the theory of Special Relativity. According to Einstein's original explanation of special relativity in 1905, the most significant two postulates are:

- The principle of relativity– the laws by which the states of physical systems change remain unaffected No matter which of two systems is moving uniformly in translatory motion with respect to the other.
- The principle of invariant light speed – Light always travels across empty space at a fixed velocity c (299,792,458 m/s) that is independent of the emitting body's state of motion (from the preface). This means that regardless of the state of motion of the light source, light propagates in vacuum with the speed c (a fixed constant, independent of direction) in at least one set of inertial coordinates known as the "stationary system." [1]

The most important fact out of the special relativity's postulates is that nothing can travel faster than light, that is because photons – which make up light- are massless particles, and it's impossible to accelerate any other object to the speed of light because it would require infinite amount of energy to do so. But this idea was shaken by the emerge of Quantum Mechanics and the theory of "Quantum Entanglement"- which will be discussed broadly in the paper. The theory of Quantum Entanglement might dismiss the fact that nothing travels faster than light by suggesting that particles might be communicating through transmitting information faster than light. This is what Einstein called "spooky action at distance", because particles may have communicated with each other to provide certain information in a way the laws of classical mehcanics fails to explain.

To put what "Quantum entanglement" means in simple word; it means that the aspects of one particle in an entangled (synchronized) pair depend on aspects of the other particle no matter how far apart they are from one another in space or what is in between them.

For deep understanding of Quantum entanglement and how it changed the course of quantum mechanics, we first have to understand topics such as Electron spin and the EPR pardox, hidden variables, and Bell's inequality, and review the experiments proving quantum entanglement.

II. Electron Spin

George Uhlenbeck and Samuel Goudsmit, two Dutch graduate students, hypothesized the presence of electron spin on the basis of their research into atomic spectra. A few years later, British physicist P. A. M. Dirac developed a relativistic quantum theory of the electron, which served as the foundation for electron spin.

Whether an electron is free or confined in an atom, it has an intrinsic spin angular momentum $\vec{S}$ often known as *spin*. (The term intrinsic refers to an electron's fundamental properties, such as its mass and electric charge.)

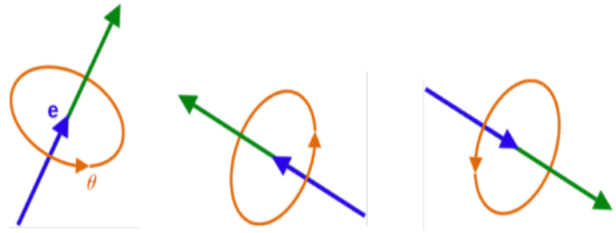
The magnitude of $\vec{S}$ is quantized and is dependent on a spin quantum number s, which is always 1/2 for electrons, as well as protons and neutrons. Additionally, the component of $\vec{S}$ measured along any axis is quantized and depends on a spin magnetic quantum number m_s, which can have only the value +1/2 or -1/2.

We can measure the direction of spin of the electron if we first choose the direction of its measurement. This measurement can only have two outcomes: either an electron is in a state of “spin up”, which also has the value +1/2, or the electron is in state of “spin down”, which has the value -1/2.

The “spin up” and “spin down” directions are dependent on the direction of the measurement which the electron spin is aligned with.

It would make things easier to imagine the electron as a tiny sphere rotating about an axis in order to explain electron spin. That classical model, like the classical one for orbits (a classical object is one that follows classical, that is, Newtonian laws, rather than quantum laws), falls short. The best way to conceptualize spin angular momentum in quantum physics is as a measurable intrinsic characteristic of the electron. [2]

Any direction can be chosen for the axis around which an electron can spin. Think of an orange with an arrow across the middle of it. Any direction could be indicated by the arrow. The spin axis of the orange would be the arrow. Similar to this, an electron's spin axis can point in any direction, and the electron spins around it.



Fig(1): Axes of Electron Spin

Prior to measurement, a particle has the potential to spin along any axis. The axis exists in three dimensions. The blue and green arrows, together, represent the axis (the color difference is not meaningful in this drawing). The orange circle represents the direction that the particle spins around the axis. In these examples, the spin is shown to be counterclockwise, but clockwise spin is as common.

The previous diagram shows three of the many directions in which the axis of a quantum particle could point. There are 360° of directions in each of the three dimensions. Thus, it would be an understatement to remark that the axis can point in "many directions". The axis can actually face in any direction, which is unlimited.

The orange could spin around the arrow in either a clockwise or anticlockwise direction. An electron can spin around its axis in either a clockwise or anticlockwise direction. [3]

As we mentioned before, the directions of the spin are dependent on the direction of the measurement which the electron spin is aligned with. Now, what happens if the electron spin is vertical but we measure it horizontally?

That will give the electron a 50% chance of spin up and 50% chance of spin down. After the measurement, the electron will not change its measured spin direction, that is, the measurement of the spin caused change in its direction from being vertical to horizontal.

Now, what if we measure spin at an angle 60° from the vertical? Well, since the spin of the particle is more aligned to this measurement, it will be spin up 3/4 of the time, and spin down 1/4 of the time. The probability depends on the square of the cosine of half the angle;

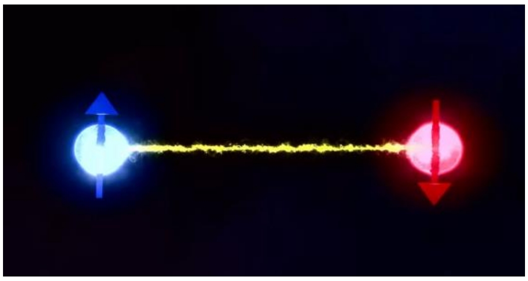
P = $cos^2(\theta/2)$. [4]

III. The EPR Paradox

A very subtle thought experiment was devised in 1935 by Albert Einstein and his two partners, Boris Podolsky and Nathan Rosen, known as the EPR (named after the 3 scientists) paradox.

The experiment argued that if there was a system of energy which caused pair production, an electron and a positron for example, the measured spin of both particles will always be opposite. [5]

Since the total angular momentum of the universe is constant, we know that if one of these particles have a spin up, then simultaneously, the other particle would have a spin down. Note that the particles spin directions would be opposite only if they are measured in the same direction.



Fig(2): two particles caused by pair production in opposite spin state

Now, imagine their spins were vertical and opposite. If they're both measured in a horizontal direction, each one has a 50/50 chance of being spin up. So, there's a 50% chance that both measurements will yield the same spin outcome, and this would violate the law of conservation of angular momentum.

According to quantum mechanics, these particles don't have a well-defined spin at all.

They are “entangled”, which means their spin is simply opposite that of the other particle. So, when one particle is measured, and its spin determined, you immediately know what the same measurement of the other particle will be. These outcomes have been tested repeatedly and proven correct every time. No matter which angles the detectors of spin are set or how far apart they are, the particles always measure opposite spins.

This leads to the conclusion that the measurement of the first spin will influence the measurement of the other spin faster than the speed of light, which the special relativity denies, this is what is called “a violation of locality.” [4]

IV. Hidden Variable Theory

To solve the EPR Paradox, Einstein, Podolsky, and Rosen gave an explanation for the spin behavior of the two particles. They suggested that the two particles have embedded (hidden) information inside each of them since their birth. This information would forever govern the behavior of both particles, making them at opposite spins at all times, not changed upon measurement.

This theory is called “Hidden Variables Theory” which at the time, gave a reasonable explanation for how the particles can never be in the same spin state, and also without violating locality, which is that no particles can have constant communication of an immediate nature because that would violate Einstein’s special relativity. [6]

V. Bell’s Inequality

To test the hypothesis of “hidden variables” that Einstein, Podolsy, and Rosen came up with, scientist John Bell conducted an experiment in 1964 to show whether the particles had hidden information inside them since birth of not.

Although bell’s inequality itself is not hard, but the complete understanding of it is much more complicated, so a simple approach would be used in this paper.

The inequality is

$$P(Z,X) - p(Z,X) - p(Q,X) \geq 1$$

(Note that this is a very simplified version of the inequality for the purposes of this paper.)

Let’s first assume a universe where local hidden variables are true, when two entangled particles (A and B) are released, they are already aware of their final states. As mentioned before that the spin states of each particle will always be opposite in vertical direction, which we refer to as Z, or horizontal direction, which we refer to as X. Now what Bell' inequality does is that it adds another direction somewhere between Z and X, which we will assume 45˚ and is referred to as Q. In the three directions of Z, X, and Q. There would be only 8 possible spin configurations for each particle:

Table 1 Possibilities of spin states in three directions

Probability of event 1	$\boldsymbol{Z+, X+, Q+}$
Probability of event 2	$\boldsymbol{Z+, X+, Q-}$
Probability of event 3	$\boldsymbol{Z+, X-, Q+}$
Probability of event 4	$\boldsymbol{Z+, X-, Q-}$
Probability of event 5	$\boldsymbol{Z-, X+, Q+}$
Probability of event 6	$\boldsymbol{Z-, X-, Q}$
Probability of event 7	$\boldsymbol{Z-, X+, Q-}$
Probability of event 8	$\boldsymbol{Z-, X-, Q-}$

Note that the signs + and – accounts for the spin up and spin down states of the particles respectively.

For $P(Z+, X+) = \frac{P3+P4}{8} = \frac{2}{8} = \frac{1}{4}$

For $P(Z+, Q+) = \frac{P2+P4}{8} = \frac{2}{8} = \frac{1}{4}$

For $P(Q+, X+) = \frac{P3+P7}{8} = \frac{2}{8} = \frac{1}{4}$

Now, what Bell's inequality says is to multiply the total number of probabilities by the probability that particle A is measured to be Z+ and particle B is measured to be X+, this has to be equal to or less than the total numbers of probabilities times the probability that particle A is measured to be Z+ and particle B is measured to be Q+, plus the probability that particle A is measured to be Q+ and particle B is measured to be X+, after the 8 is canceled on both sides, we are left with the following inequality:

$$P(Z+, X+) \leq [\, P(Z+, Q+) + P(Q+, X+)]$$

This inequality is proven by doing simple math since $P(Z+, X+)$ exists on both sides of the inequality. So, this proves that inequality is absolutely true for a universe where the particles have hidden information since birth.

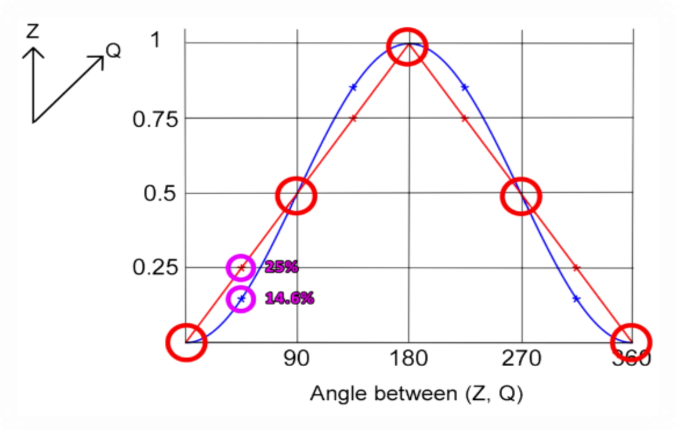
If we were to apply Bell's inequality in a universe where quantum mechanics laws are correct and the particles and entangled instead of having hidden variables, we would find that the laws of quantum mechanics violate Bell's inequality and here's how.

Let's say particle A is measured to have positive spin in the Z direction, then, we know that if we were to measure the spin of particle B in the Z direction, we would get a spin that is negative.

However, we don't measure the spin of particle B in the Z direction, but in the Q direction. What will the spin of his particle be? In hidden variables theory, there is a 50% chance that it would be positive, and a 50% chance that it was negative. But this is not what happens in quantum mechanics, because the measurement of the particle follows the probability laws of the wave function for a particle rotated 45˚. And that probability of particle B measured in Q to be positive, after particle A has been measured in Z to be positive, if the angle between them is 45˚, is given by the following equation:

$$P(Z+, Q+) = \sin^2(\frac{45°}{2})$$

This comes from the math of quantum mechanics. This is the critical difference between quantum mechanics and hidden variables theory. The probability that particle B has been measured to have the same as particle A, depending on the difference in



Fig(3): Difference between the behavior of the two particles according to the predictions of hidden variables theory and quantum mechanics

angle measured is not linear but looks like a sine wave as shown in fig(3).
The graph shows that the two systems agree at 0 and multiples of 90 ˚. However, in the middle, at 45˚ for example, the chance for hidden variables is 25% and for quantum mechanics, it is roughly 14.6%.

After many experiments, the sine function correlation has been confirmed. The particle does not behave linearly. And so, the hidden variables theory doesn't hold true. Bell's inequality is violated.

Let's prove that through the inequality for both theories, in hidden variables, the inequality would be:

$$\because P(Z+, X+) \leq [\, P(Z+, Q+) + P(Q+, X+)]$$

$$\therefore P3 + P4 \leq P3 + P4 + P2 + P7$$

$\therefore 2 \leq 4$, the inequality holds true in hidden variables theory.

For quantum mechanics, the inequality would be:

$$\because \sin^2\left(\frac{90°}{2}\right) \leq \sin^2\left(\frac{45°}{2}\right) + \sin^2\left(\frac{45°}{2}\right)$$

$$\therefore 0.5 \leq 0.146 + 0.146$$

$\therefore 0.5 \leq 0.293$, this isn't true and proves that quantum laws violate Bell's inequality, which has been observed and proven through multiple experiments. [6]

VI. Conclusion

Bell's inequality was the start of a controversial debate among scientists. Some scientists believed that indeed entangled particles can't have hidden information inside them, and it's only reasonable to talk about them once they have been measured, like Neils Bohr suggested.

Others believe that the particles can communicate with a speed faster than light to deliver information to one another upon measurement.

Does that mean we can somehow in the future use quantum entanglement to send messages and hidden information through particles in a speed that is faster than light?

Well, there are other theories which suggest that the wave function of the two particles can theoretically be as large as the universe, when this one wave function collapses, the two particles also do. Moreover, since the collapse is unpredictable, no communication can be done using it. Since we cannot communicate using this seemingly faster-than-light event, so, the majority of theorists do not believe that special relativity is violated.

At the end, it's safe to say that most of quantum mechanics theories are very complicated and we fail to get a complete comprehension for the laws of quantum mechanics, but we are certain that indeed, the laws of quantum govern the way our universe work at its very tiny particles.

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