Quantum Entanglement: Understanding and Harnessing

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Abstract

Quantum entanglement is a bizarre and anti-intuitive phenomenon of Physics that links two particles together in such a way that any change happening to one of them will make a correlated change in the other, even if the particles are far away from each other. Entanglement is one of the aspects of quantum mechanics, a broad and vital branch of physics. This article deals with understanding and harnessing the phenomenon of quantum entanglement, the method of production of entangled particles and their applications in various fields.

Keywords

Quantum entanglement; Superposition of states; Quantum computing

1. Introduction

Quantum entanglement is a phenomenon that comes up in modern science fiction movies. Marvel superhero fans must be very familiar with this idea because this is closely associated with teleportation and also the backbone of the concept of character destinies becoming intertwined. However, quantum entanglement is not just a science fiction buzzword but a natural and useful phenomenon [1]. This is one aspect of quantum mechanics that describes the mechanics of atomic and subatomic particles.

A deeper understanding of quantum entanglement is required to make it suitable for various applications. Two particles are said to be connected when they remain connected even after being separated by a vast distance. Their quantum states or state of being will be strongly correlated and unified. These particles are then not considered individual particles, but an inseparable whole. i.e., In a pair of entangled particles, one of the particles cannot be described without considering the other. Entangled particles are strongly connected even if they are physically far away from each other [2].

2. Quantum superposition of particle states

Quantum entanglement relies completely on the superposition of quantum states. Quantum superposition is a kind of particle state, where they can take multiple states at the same time. For example, consider the case of a coin: it will be in its head-up position and tail-up position simultaneously if it is in its quantum superposition state. Now assume that the coin is flipped in the air: when it is in the air, swirling, the coin is taking a quantum superposition state of being in both head-up and tail-up. But it takes a single state of either head or tail when it strikes the ground. i.e., Until measurement, particles are in a quantum superposition state, and once measured, the superposition state is disturbed. If this coin is correlated to an electron, it could be in a superposition state of spin up position and spin down position until measurement, and once measured, the superposition state collapses, giving rise to either spin up state or spin down state [3].

In quantum entangled particles, both particles are in a quantum superposition state until they are measured, and once the measurement is made both give a correlated result. i.e., If one of the particles shows spin up, the other particle shows spin down, and vice versa. As an example of entanglement, a subatomic particle decays into an entangled pair of other particles. The decay event has to obey various conservation laws and as a result, the measurement of the outcomes of one daughter particle must be highly correlated with the measurement outcomes of the second daughter particle so that the total momenta, angular momenta, energy, and other parameters remain constant before and after the decay.

For instance, a spin-zero particle could decay into a pair of spin $\frac{1}{2}$ particles, since the total spin before and after the decay must be zero according to the conservation of angular momentum. Whenever the first particle is measured to be in a spin-up state on some axis, the other when measured on the same axis is always found to be in the spin-down state. This implies that both particles will be in a quantum superposition state of being both spin-up and spin-down until measured, and this superposition state collapses once measured.

In principle, one could place two entangled particles on opposite ends of the galaxy and still have this instantaneous knowledge. This communication between the particles happens at a speed greater than that of light. This is contradictory to Einstein's theory of relativity as this phenomenon violates the limit of the speed of light. Hence Einstein along with his friends Boris Podolsky and Nathen Rose put forward EPR Paradox [4]. Einstein used this paradox as a piece of evidence that the quantum theory itself is incomplete. He brought up the idea of hidden variables i.e., particles are not connected across space instead the particles themselves are pre-determined about their position at the moment they are entangled. According to Einstein, particles might have been either spin-up or spin-down since the moment they get entangled, but this information is hidden from us until the measurement is done. He ruled out quantum superposition and instead called this arrangement between the particles a "hidden variable" since this is unknown to us. This hidden variable theory of Einstein argued against entanglement. It stated that quantum theories are not mentioning anything about the hidden variable in their theories and hence the theories of quantum mechanics are incomplete [5].

The discussions on quantum entanglement and EPR paradox paved the way for a number of experiments and later, John Stewart Bell proved that we could rule out hidden variable theory. He proposed this idea with his mathematical expression named Bell's inequality [6]. His experiment suggests two possible results: one considers the rules of quantum mechanics which is quantum superposition and their connections, and the Second, considers hidden variable theory. After a series of experiments called the Bell test experiments, Bell provided partial confirmation for entanglement but the hidden variable theory could still explain the probabilistic nature of quantum measurement due to loopholes in Bell's experiments. It was for proving that quantum theory is correct through his groundbreaking experiments using entangled photons and showing entanglement can be supported by quantum theory, John Clauser was awarded Nobel Prize in Physics in 2022. Alain Aspect and Anton Zeilinger were also awarded the Nobel Prize in Physics in 2022 for closing the loopholes in Bell test experiments and demonstrating teleportation [7].

3. Production of entangled particles

Production of entangled particles is not seen at the macroscopic level. If it were, we would be able to experience quantum mechanics in our everyday life and entanglement will not be a surprising phenomenon. So, for now, we need to deal with it at the microscopic level where it is easier to look at the quantum effects. There are some ways to entangle particles: one is to cool down the particles to a very low temperature and place them close to each other so that their quantum states overlap. Another way is to entangle a pair of photons by splitting up a single photon. There is also a possibility to get entangled particles from nuclear decay since subatomic process like nuclear decay automatically produces entangled particles.

4. Application of entangled particles

Even though the real science behind quantum entanglement is yet to explore, we have started making use of entanglement for different technologies. Perhaps, the most widely used application of quantum entanglement is in quantum cryptography. **Figure 1** demonstrates the quantum cryptography model. In quantum cryptography, a sender and a receiver build a secure communication link that includes a pair of entangled particles. The black dots above the receiver and sender are represented as entangled particles in **Figure 1**. The sender and the receiver then generate private keys using the entangled particles, which are known solely to them. They use these keys to encode and decode data. If someone interrupts the signal and attempts to eavesdrop on information, the entanglement breaks. Since measuring an entangled particle changes its state, the receiver will not be able to decode the data or in other words, the data is lost. Now, the sender and receiver have to do the process all over again to transfer the data [8].

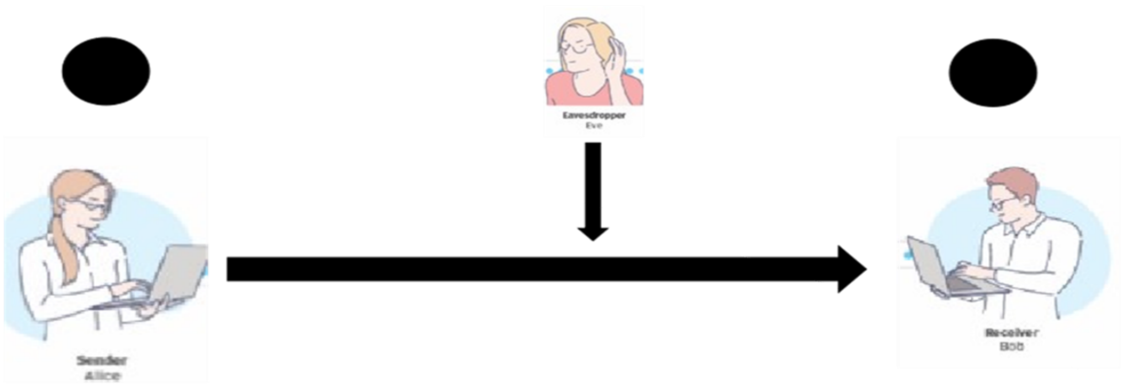

Figure 1: Quantum cryptography model.

Another application of entanglement is quantum computing in which a large number of particles are entangled, thereby allowing them to work together to solve some large complex problems [9]. Still, research is going on based on quantum computing. Ultra-precise clocks represent another application of quantum entanglement. Today, the most precise clocks in the world are atomic clocks that use the principles of quantum theory to measure time. The preciseness of atomic clocks depends partially on the number of atoms used. If we could occupy 100 times more atoms into an atomic clock, 100 times more will be the accuracy. However, there is a limit on the number of atoms that can be accommodated in it.

5. Scope and research developments

Recently, researchers have successfully used entanglement to enhance the precision of atomic clocks that could be used to accurately study dark matter and gravity. In 2014, a team of researchers at Japan's Hokkaido University developed the world's first can be entanglement-enhanced microscope [10]. They use entangled photons to measure the pattern/image. Since the measurement of one entangled photon provides information regarding its partner, the amount of information gathered by the microscope can be enhanced greatly with the use of entangled photons.

Conclusions

Quantum entanglement is one of the bizarre phenomena seen once things are within the quantum realm. When two or more particles link up in a certain way, no matter how far apart they are in space, their states stay linked. That means they share a common, unified quantum state. So, observations of one of the particles can automatically provide information about the other entangled particles, regardless of the distance between them and any action done on any one of these particles will invariably impact the others in the entangled system. Understanding and harnessing entanglement is vital to create many cutting-edge technologies like quantum computers, which can solve issues quicker than standard computers and quantum communication devices that might permit us to communicate with one another without the slightest risk of eavesdropping.

References

1. Frérot, I., Baccari, F. and Acín, A., 2022. Unveiling quantum entanglement in many-body systems from partial information. PRX Quantum, 3(1), p.010342.
2. Zou, N., 2021, March. Quantum entanglement and its application in quantum communication. In Journal of Physics: Conference Series (Vol. 1827, No. 1, p. 012120). IOP Publishing.
3. Friedman, J.R., Patel, V., Chen, W., Tolpygo, S.K. and Lukens, J.E., 2000. Quantum superposition of distinct macroscopic states. nature, 406(6791), pp.43-46.
4. Van Fraassen, B.C., 1976. The Einstein-Podolsky-Rosen paradox. Logic and Probability in Quantum Mechanics, pp.283-301.

5. Hardy, L., 1998. Spooky action at a distance in quantum mechanics. Contemporary physics, 39(6), pp.419-429.
6. Home, D. and Selleri, F., 1991. Bell's theorem and the EPR paradox. La Rivista del Nuovo Cimento (1978-1999), 14, pp.1-95.
7. Dalibard, J. and Gigan, S., 2022. A Nobel prize for Alain Aspect, John Clauser and Anton Zeilinger. Photoniques, 116, pp.23-25.
8. Pirandola, S., Andersen, U.L., Banchi, L., Berta, M., Bunandar, D., Colbeck, R., Englund, D., Gehring, T., Lupo, C., Ottaviani, C. and Pereira, J., 2019. Advances in quantum cryptography. arXiv preprint arXiv:1906.01645.
9. Gill, S.S., Kumar, A., Singh, H., Singh, M., Kaur, K., Usman, M. and Buyya, R., 2022. Quantum computing: A taxonomy, systematic review and future directions. Software: Practice and Experience, 52(1), pp.66-114.
10. Ono, T., Okamoto, R. and Takeuchi, S., 2013. An entanglement-enhanced microscope. Nature communications, 4(1), p.2426.