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Analysis of the Principle, Facilities and Applications for Quantum Entanglements

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Abstract:

Quantum mechanics is a field of physics that became important from the late 19th century to the start of the 20th century and its non-relativistic part seemed to be completed by von Neumann in 1932. However, the EPR paradox by Einstein, Podolsky and Rosen pointed out a strange feature of quantum mechanics known as quantum entanglement, which represented that people are unable to consider the existence of global states of composite system as a product of the states of separate subsystems. The phenomenon promotes to a further study of quantum and a new faster way of communication. The article introduces the discovery and the early research of the quantum entanglement, how the theory about the quantum entanglement was corrected, the fabrication of the entangled particles, and the application of the quantum entanglements phenomena to the quantum communication. The research aims to discuss the importance of the study of the quantum entanglement at current stage

Keywords: Quantum entanglement; quantum communication; EPR Paradox; Bell's Theorem.

1. Introduction

The description of the fundamental factors of non-relavistic quantum had already been completed by von Neumann in his book Mathematische Grundlagen der Quantenmechanik in 1932, which was considered as an axiomatic paradigm of quantum mechanics following Hilbert's line [1-3]. However, Einstein, Podolsky and Rosen (EPR) and Schrodinger were the first who figured out a strange nature of quantum mechanics, which showed thatthe presence of composite system global states that are not the result of the states of separate subsystems [2]. The phenomenon is also known as "entanglement". Schrodinger was inspired by EPR paper and he discovered that the double-particle EPR state does not admit ascribing individual states to the subsystems demonstrating entanglement of foreseeing for the subsystem in 1935. Afterwards, Bell demonstrated that statistical correlations in experiments involving bipartite systems ought to be constrained in the form of Bell inequalities under the assumption that the results of the measurement are decided by the nature of particles instead of the measurement, the result obtained from one location is independent of any behavior that occurs at the spatial difference, and the setup of the instrument is independent of the hidden variable that determines the result at the same location [3].

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Early in 1949, Jianxiong Wu and Irving Shaknov had already obtained entangled particles, but the entangled particles weren't stable enough so that they couldn't be used to prove the Bell's inequality. On May 28th, Li proposed that neutral K-meson (θ) correlation states can be produced by proton-antiproton collisions. In 1972, Clauser and Freedman used the polarization of the light to succesfully complete the Bell experiment for the first time by using a new method to obtain entangled photon. The result overturned Bell's inequality [4-6]. Aftewards, the preparation schemes of three-photon, four-photon and multi-photon entangled states were proposed successively. Superentangled photon states are generally referred to the entangled photon system existed in two or more degrees of freedom.

One sees the early work of quantum entanglement in particle physics. It has historically contributed to the advancement of quantum entanglement research. The article aims to introduce the principle of quantum entanglement, the facilities and measures to obtain the entangled particles and applications for quantum entanglement.

2. Principle

2.1 Quantum Entanglement

A particle has only two possibilities for the angular momentum in one direction. Expressing them using arrows pointing upward $(\uparrow)$ and downward $(\downarrow)$. Sometimes a binary-particle system is in the condition $(|\uparrow\downarrow> \pm |\downarrow\uparrow>)/\sqrt{2}$ [1]. This demonstrates that in the system there are two possibilities. One is that the first particle is upward, the second particle is downward (|↑↓>). The other is that the first particle is downward while the second particle is upward (|↓↑>). In this situation, the two particles are entangled. Once one has measured the state of one particle, one can make certain predictions about the results of the measurement of the second particle. If the two particles are not entangled, their measurements are independent of each other and completely unrelated, i.e., a particle at rest splits and explodes into two particles. One of them flew east, and the eastern detector picked it up; Because momentum is conserved, one knows that the other particle is heading west. The east and west particles are in a state of quantum entanglement [7].

Bring in the quantum mechanical superposition of states and the probabilistic interpretation of measurements, and it's different. The quantum mechanical interpretation is that the system is in a superposition of the first Angle bracket and the second Angle bracket, so the two states are multiplied by a coefficient $1/\sqrt{2}$. Only after measurement, the state collapses into one of the states. The probability of every possibility is the square of the coefficient, 50%.

2.2 Bell's Theorem

Hidden variable theory is an alternative theory proposed by physicists who question the sigmacompleteness of quantum mechanics. Historically, with the development of quantum mechanics, limitations such as Heisenberg's uncertainty principle were put forward. Unlike classical physics, such as position and momentum cannot be accurately measured at the same time. In addition, properties such as particle positions are replaced by probability density descriptions. Some physicists, such as Albert Einstein, believe that quantum mechanics does not fully describe the state of physical systems, that is, it is not complete. Therefore, the observable evolutionary behavior of physical systems should be fully explained by an as-yet-undiscovered theory based on quantum mechanics that eliminates all uncertainty and unpredictability. It is assumed that a source can continuously produce pairs of positives and negatives in a "Spin Singlet", that is, each electron pair in the system is in a superposition, where the positive and negative electrons fly off in opposite directions. After the positron has flown far enough away, it is free to choose a moment to measure the Z-direction spin of its companion particle. By "far enough," one means that the time interval measured by at both sides is not enough for light to travel between them. Following the viewpoint from Quantum Mechanics, measurement makes the spin state of the double particle system $|\psi>$ collapse into two eigenstates $|?_+ > ? |?_- >$ or $|?_- > ? |?_+ >$. What mechanism can guarantee both of the following:

l The measurements presented two random results, but the always with the opposite sign;

l Two measurements cannot influence each other (local realism)

Based on the above two points, EPR obtained a inference that conforms to the basic probability principle, that is, for any given electron pair, the measurement results of their z-spin are determined before the measurement action, only in this way can the measurement results at both ends be random but always opposite signs without mutual influence. Any randomness cannot be generated after the two are out of the range of action, otherwise the measurement results cannot be guaranteed to be "Perfect Anti-correlation".

EPR proposes a theory of physics that is in principle more complete than quantum mechanics, the "deterministic hidden variable theory”. Because it was said to be hidden, one might still not conclude that there isn’t a hidden variable even though one didn’t figure out such thing. Therefore, the appearance of Bell’s Inequality was pretty important. “Bell inequality” is a property derived from the “deterministic hidden variable theory”. And this property is violated by quantum mechanics. This is equivalent to Bell specifying a decision condition for this koan - all deterministic hidden variable theories should obey Bell’s inequality, but under certain conditions, the predictions of quantum mechanics violate this inequality. The result is simply to reproduce “certain conditions” in the experiment to see if the Bell inequality is violated after all, and if it is violated, it proves that the nature does not operate according to the deterministic hidden variable theory [1, 8].

Bell showed that if hidden variables exist, the correlation coefficients obtained by different measurements of two interrelated particles must satisfy some constraints, regardless of the specific form of the hidden variables. Entanglement in quantum mechanics, on the other hand, may not satisfy such a constraint. Bell Explicitly introduced a supplementary parameter, which was indicated as λ. The probability distribution satisfies

$$\rho(\lambda)\geqslant 0,\int d\lambda\rho(\lambda)=1 \tag{1}$$

For a given pair of particles described by the supplementary parameter λ, the result of measurement is given by two two-valued equations. For $A(\lambda,a)=1$, the analyzer I is in the direction of ‘a’. For $B(\lambda,b)=1$, the analyzer II is in the direction of ‘b’. A specific theory of supplementary parameters is completely defined by the exact forms of $A(\lambda,a)$ and $B(\lambda,b)$. Then, the probabilities of the various experimental results can be easily expressed. Similarly, the correlation function has a simple form:

$$E(a,b)=\int d\lambda\rho(\lambda)A(\lambda,a)B(\lambda,b) \tag{2}$$

One considers the following quantity:

$$\begin{aligned} s &= A(\lambda,a)B(\lambda,b)-A(\lambda,a)B(\lambda,b')+\\ &A(\lambda,a')B(\lambda,b)+A(\lambda,a')B(\lambda,b')=\\ &A(\lambda,a')[B(\lambda,b)+B(\lambda,b')]+\\ &A(\lambda,a)[B(\lambda,b)-B(\lambda,b')] \end{aligned} \tag{3}$$

Because AB can only have the values ± 1, one can simply express the second equation above as

$$s(\lambda,a,a',b,b')=\pm 2 \tag{4}$$

Therefore,

$$-2\leqslant\int d\lambda\rho(\lambda)s(\lambda,a,a',b,b')\leqslant 2 \tag{5}$$

Thus, one is able to rewrite the inequality:

$$-2\leqslant S(a,a',b,b')\leqslant 2,\quad S(a,a',b,b')=E(a,b)-E(a,b')+E(a',b)+E(a',b') \tag{6}$$

This is the BCHSH inequality, the Bell inequality generalized by Clauser Horne Shimony Holt. They depend on a combination of four polarization correlation coefficients, which are related to the direction of the two detectors (a and a’ for polarizer I, b and b’ for polarizer II). Nevertheless, the Bell theorem was finally be proved to be wrong and the quantum mechanics was considered to be complete.

3. Fabrication of Entangled Particles

For the spatial mode of light field, the most common is its spatial field amplitude distribution. In 2012, Armstrong et al. completed the preparation of continuous variable entangled states with the highest 8-dimensional cluster states based on the space mode for the first time. Through partial phase delay, amplitude reversal of partial field amplitude on spatial scale is realized, as shown in Figure 1. In the measurement process, a multi-diode zero-beat detector (that is, a detector array composed of multiple diodes) is used to conduct the detection, and each diode array is assigned different electronic gains, and the linear combination of gains constitutes a mode of measurement [9]. By programming the virtual network, that is, the electrical signal network, the different spatial regions of the beam are mixed together to achieve the generation and measurement of cluster states.

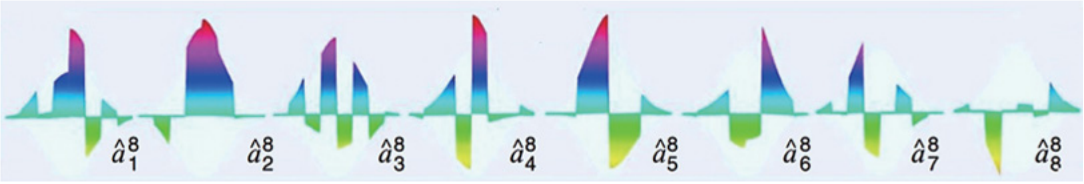

Fig. 1 Amplitude reversal of partial field amplitude on spatial scale [9].

The multimodal entanglement preparation based on time mode generates quantum states by time domain multiplexing, which is equivalent to native phase shift to topologically one-dimensional continuous variable cluster states. In this system, entanglement exists in the time dimension, and multi-mode entanglement can be characterized by reading the quantum correlation of corresponding time series. In 2013, Yokoyama et al. created a very great scale

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entangled state of greater than 10000 entangled wave packets by using time multiplexing. Firstly, two optical parametric oscillation processes are used to generate two compressed beams, which are divided into nodes with time cycle T, where 1/T is less than the bandwidth of the optical oscillator, so the optical wave packets in each node are independent of each other. Then a linear balanced beam splitter is used to combine the two compressed beams to create the entangled state of EPR divided at T time interval. Then, the optical fiber is used to introduce a time delay T. After the delay, the upper rail node of each EPR state synchronizes with the lower rail node of the previous EPR state in time. By combining the interlaced EPR states on the second balanced beam splitter, each EPR state interacts with the previous and subsequent EPR states, resulting in all the wave packets in the two orbits being connected to the adjacent wave packets through entanglement links, resulting in a large-mode entangled state, as shown in Fig. 2. The quantum correlations can be obtained by measuring the orthogonal operators of adjacent wave packets. The experimental results show that there is entanglement between adjacent wave packets, and entanglement is realized in more than 5000 time intervals.

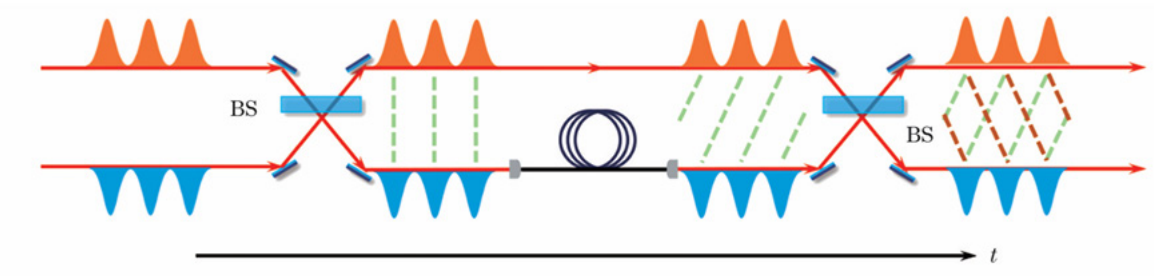

Fig. 2 All the wave packets in the two orbits [10].

As a degree of freedom of the photon, the frequency mode has a good expansion performance. Photoelectric control technology, ultrafast optics and optical frequency comb technology are becoming more and more mature, which lays an important foundation for realizing multi-mode quantum entanglement and quantum manipulation in frequency freedom.

4. Applications

Quantum technology is at the centre of the technological development that support modern society. Basically, it is the quantum theory that represents how matter and energy are used to instantiate and process information. The realization has led to a sharp increase in quantum technology. With fresh, significant worldwide effort from governments and businesses, the race to create quantum technology has become a topic unto itself. When harnessing the resources of quantum mechanics, many technologies can inherit enhanced performance and security.

Quantum communication uses quantum carriers (commonly referred to as quantum channels) to transmit information or signals. Compared with classical communication methods, quantum communication is based on quantum uncertainty principle, quantum state cannot be cloned, quantum state measurement collapse, etc., and has provable security in principle. Since the birth of quantum secure communication in 1984, it has achieved rapid development and is moving towards practical application.

Entanglement is an important part of the transmission of quantum information, as the communicating partners should share entangled qubit pairs. Consequently, the foundation of entanglement-assisted quantum networks needs a quantum technology capable of entangling quantum nodes. Generally, the establishment of entanglement between adjoining quantum nodes is achieved through a couple of key operations: entanglement fabrication and entanglement allocation. Among these, entanglement production seeks to create entangled qubits, and entanglement allocation uses quantum channels to allow physically dispersed quantum nodes to share the created entangled qubits.

The plan that comes the first is implemented with the help of a nonlinear crystal based spontaneous parameter down conversion (SPDC) process. Because effective polarization control is readily available and most materials are rather insensitive to birefringent thermally induced drift, polarized photons are commonly used to generate entangled qubits experimentally. In experiments, this scheme has been used to represent the quantum-dense coding, teleportation and Bell inequality testing. At present, the SPDC process based on nonlinear optical materials is still a research hotspot in the field of entanglement preparation. The future development direction of entanglement light source based on SPDC is to reduce the loss, improve the purity and degree of entanglement, and combine with micro and nano photonic devices to improve the scalability and practicability of entanglement light source [6].

Single-atom excitation is a second method that can be used to generate and distribute entangled qubits across two geographically separated quantum nodes. The scheme uses atoms tightly coupled to the optical cavity to establish entanglement between two quantum nodes directly connected by a photon channel. Stated differently, the laser beam at Alice initially excites the atom, and the photons that are released get entangled with the atom's internal state. After being released from Alice's cavity, the atom-entangled photon travels along the photon channel to another cavity of the quantum node Bob. Photons are coherently absorbed in Bob's cavity, and the polarization of these particles is transferred onto the atom's internal state. As a result, the two atoms at Alice and Bob get somewhat entangled [2, 8].

The last kind of method for the distribution of the entanglement is based on two atoms being excited at the same time. First, two simultaneous laser beams at where Alice and Bob stays excite two atoms. This causes each local cavity to emit a photon that is entangled with the related atom. The two photons entangled with the atom then leave the local cavity and travel in the form of a wave packet along the quantum channel to the spectrometer, where BSM operations are performed to achieve the entanglement exchange. After completing the BSM operation, the atom at where Alice stays become entangled with Bob's atom. Compared with the measure of the excitation of the single atom, the diatom excitation scheme is more effective to extend the distance of entanglement distribution with the help from a third participant. However, for the current situation putting diatomic excitation scheme into practice needs two quantum nodes to be symmetrically connected to a third party that is responsible for the performance of BSM operations and simultaneously distributing entangled qubits, which greatly hinders the scheme's application in entangle-assisted quantum networks [7, 10].

5. Future of Quantum Entanglement

There are still some problems of the usage of the quantum entanglement. First, in an open system, qubits are very vulnerable and therefore is really sensitive to the interruption from the environments. This means that qubits have a short lifetime, that is, after the fabrication, the maintaining time of a single qubit is pretty short. If the state of a single qubit changes, the information it contains is lost. In addition, qubits follow the non-cloning theorem. Making a copy of a single qubit is unlikely to mitigate the effects of its short lifetime. Therefore, qubits are required to be measured as soon as possible after they are created. Second, the photon loss and interruption inherent in quantum channels inevitably cause loss errors and the decoherence of quantum during qubit transmission, with the result that it is difficult to build perfect entangled links between nearby quantum nodes. Third, Quantum memory's intrinsic noise will cause redundant quantum decoherence in quantum systems even if it can extend the lifetime of qubits. In addition, the capacity of quantum memory is limited by the incompleteness of the physical device. Therefore, it is difficult for quantum memory to perform as well as classical memory. Finally, quantum actions in networks aided by entanglement display probabilistic properties. For example, entanglement preparation, entanglement exchange and entanglement purification are generally successful with a certain probability. In addition, due to the inherently noisy environment of quantum hardware, quantum operations inevitably introduce operational errors. The preparation, transmission, storage, and operation of qubits in quantum systems are inherently flawed, as was previously mentioned. This makes it extremely difficult to connect different quantum nodes to create an entangled aided quantum network with good operational performance. Constructing a larger scale and a wider area of the networks that is assisted by the quantum entanglement requires the industry of the field to actively engage in standardization efforts. The main focus on the ways of how to standardize the quantum connection based on the entanglement is to clearly define abstractions and interfaces that can decouple the underlying quantum hardware from software from the upper layer, which is similar to the ordinary and classical networks. Currently, there are several international groups and standardization initiatives (e.g., those in ITU, IEEE, IETF, ETSI) working towards defining architectures, interfaces, and protocols that ensure interoperability between entanglement-assisted quantum networks (including QKDNs) and their seamless integration with existing telecommunications infrastructures

6. Conclusion

To sum up, quantum entanglement plays a vital role in the development of physics today. The article introduces the history of the research of the quantum entanglement, from the EPR paradox, to the falsification of the Bell's Theorem, the application of the quantum entanglement to the quantum communication and the limitation of it at current stage and how this can be solved or improved in the future. The usage of quantum entanglement will possibly become the major tool of communication technology in the future. Therefore, the article aims to draws readers attention to the quantum entanglement and the future possibility of the use of the phenomenon.

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