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Research on the Quantum Entanglement Mechanism

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Abstract

A quantum entangled state is a quantum superposition state. The principle of quantum superposition, and therefore the existence of quantum entanglement, is contingent upon the validity of quantum theory. Thus, the generation of quantum entanglement requires that interactions occur between small-mass particles localized in a confined spatial region, resulting in each particle's quantum state being a bound state. In other words, the prerequisite for the validity of quantum theory must be satisfied. At the same time, conserved quantities must exist between quantum superposition states, as only quantum states with conserved quantities can undergo superposition, allowing the particle system to generate quantum entangled states. Quantum entangled states can occur between electrons within an atom, between atoms, between molecules, or between atoms and molecules. Within the atomic nucleus, quantum entanglement can exist among protons, neutrons, and the quarks. In superconductivity, superfluidity, and Bose-Einstein condensation, they manifest as macroscopic quantum entanglement, which respectively come from the statistical results of a large amount of microscopic quantum entanglement between electrons, atoms or molecules. For massive macroscopic objects, they exhibit classical properties that cannot be described by quantum theory, and the principle of quantum superposition does not hold. Therefore, no entangled state is generated. It should be particularly emphasized that even for microscopic particle systems, if they exist in a large spatial region, they cannot be described by quantum theory. In such cases, the quantum superposition principle does not hold, and quantum entanglement phenomena do not exist. Therefore, within a large spatial region, multi-electron, multi-photon, and other microscopic systems do not have quantum entangled states; under certain conditions, quantum correlated states can be generated. Consequently, in a large spatial region, the mainstream viewpoints about non-locality—such as the so-called instantaneous collapse of entangled particles during measurement, infinite propagation speed, and the "spooky action at a distance"—are all incorrect. In experiments related to quantum communication and the verification of Bell's inequality, the quantum states used are quantum correlated states rather than quantum entangled states. Regardless of whether the systems are microscopic or macroscopic, phenomena occurring in a large spatial region must adhere to the principles of causality, realism, and locality. In other words, Einstein's viewpoint is correct.

Keywords

Quantum Superposition, Quantum Entanglement, Quantum Correlation

1. Introduction

The concept of quantum entanglement originated from the discussion of the EPR paradox. In 1935, Einstein and others first wrote the quantum entangled state of a continuous variable [1], *i.e.*, the EPR state. Soon after, Schrodinger proposed the concept of quantum entangled state based on the EPR paradox [2]. For a two-particle (two-part) composite system, a state that cannot be written in factorized form is called a quantum entangled state. In 1950, David Bohm suggested using the EPR entangled state of discrete variables [3] when discussing the EPR paradox, now known as the Bell state, which is the entangled state of two spin particles. In many fields of quantum information, the creation and distribution of entangled states are very important [4] [5], because it is a key element for performing some tasks of quantum information, such as teleportation or quantum computing [6], quantum communication [7] [8], metrology [9] [10], quantum control of correlated states [11] [12], quantum cryptography [13], atomic [14], molecular [15], optical [16], condensed matter [17] [18], and high-energy physics [19]; as well as in cosmology [20] [21]. Quantum entanglement theory has found broad applications in other fields of physics, where it has provided new insights into several phenomena in many-body systems. In this sense, many-particle quantum states that appear naturally in many physical systems can be considered entanglement resources. Its profound theoretical significance and practical applications have cemented quantum entanglement as a pivotal focus of modern research. Bell's inequality is a formula proposed by physicist John Bell to test whether quantum mechanics is complete. In classical physics, this inequality should hold. If it is found to be broken in the experiment, it indicates that there are strong correlations in nature that cannot be explained by classical theory. This is usually regarded as evidence of the existence of quantum entanglement. Only entangled particles can break Bell's inequality and produce non-local phenomena [22] [23]. The above are the current orthodox views of people on quantum entanglement.

However, a recent experimental research team has, for the first time, observed a violation of Bell's inequality without relying on quantum entanglement, by taking advantage of the path homogeneity of photons. That is, through experiments with non-entangled photons, a violation of Bell's inequality was measured, which provides a new path for quantum information processing [24]. The research team constructed a four-photon blocked interference and obtained a four-photon direct product state through a post-selection mechanism. The experiment measured that the value of the CHSH inequality parameter S corresponding to the correlation function reached 2.275 ± 0.057, significantly exceeding the classical limit of 2, and the statistical confidence level exceeded 4σ. The core of this experiment lies in that through ingenious design, they made the path of photons indistinguishable, thereby triggering quantum correlations similar to entanglement and ultimately breaking Bell's inequality. It is worth noting that the photons used in the experiment, after being coupled and filtered through single-mode optical fibers, have eliminated the potential entanglement characteristics, proving that the observed violation phenomenon does not originate from entanglement but is based on the quantum interference effect of photon path homogeneity, which is essentially different from the traditional Bell experimental scheme based on entangled states in terms of physical mechanism. This experimental discovery overturns the traditional view and reveals the deeper essence of quantum correlation, that is, it is merely a correlation formed under appropriate global conditions and has nothing to do with any real entanglement. Although the experiment did not close the local area and detection vulnerabilities, the significance of its statistics is sufficient to question the necessity of entanglement.

The idea of ghost imaging originated from the entangled light generated by the transformation of spontaneous parameters. In 1995, Pittman *et al.* first completed the experiment of obtaining the image of the object under test on an optical path excluding the object [25], confirming the nonlocality of quantum ghost imaging. At this time, ghost imaging technology was considered to be derived from the characteristics of quantum entanglement. However, in 2002, T. B. Bennink *et al.* successfully completed thermal imaging experiments based on classical light sources [26]. This experiment demonstrated that the realization process of ghost imaging does not necessarily require entangled light sources; classical incoherent light can also achieve ghost imaging. Therefore, the mechanism and implementation scheme of ghost imaging have aroused great interest among people [27] [28].

Through the experimental phenomenon that non-entangled light violates Bell's inequality and classical incoherent light can also achieve ghost imaging, is the current view on quantum entanglement necessarily correct? Are the quantum states used in many experiments entangled states? It can be considered that in all previous experiments verifying Bell's inequality, the light used was not entangled light but quantum correlated light. This not only explains all the results of previous experiments verifying Bell's inequality but also the latest experimental results, that is, conducting experiments with non-entangled light also yields results that violate Bell's inequality. It can be further argued that the previous experiments on ghost imaging using so-called entangled light were not actually entangled light but quantum correlated light. This way, the experimental phenomenon that classical incoherent light can also achieve ghost imaging can be solved.

In this paper, we study the generation mechanism of quantum entanglement. Quantum entangled states are a kind of quantum superposition state. Only under the condition that quantum theory holds true can the principle of quantum superposition be established and quantum entangled states can be produced. The condition for the occurrence of quantum entanglement is that there are interactions among microscopic particle systems, including electrons, atoms, and molecules, and they are localized in a small spatial region close to de Broglie's wavelength, making the quantum state of each particle a bound state. The quantum state of a microscopic particle system can be a superposition state, but it requires that there be conserved quantities between the quantum superposition states, such as energy conservation, momentum conservation, angular momentum conservation, etc. Only quantum states with conserved quantities can superposition, and in such superposition states, it is possible to generate quantum entangled states. It can be seen that quantum entangled states only exist between electrons, atoms, molecules, or between atoms and molecules. In the atomic nucleus, quantum entangled states can exist between protons and neutrons, as well as between quarks in protons and neutrons. In superconductivity, superflow and Bose-Einstein condensation phenomena, quantum entanglement exists between electrons and molecules within them. This is the manifestation of quantum entanglement in macroscopic quantum phenomena. For massive macroscopic objects, they exhibit classical properties, and the principle of quantum superposition does not hold. Therefore, there is no entangled state. It is particularly important to emphasize that even microscopic particles, if they exist in large spatial regions, cannot be described by quantum theory. The principle of quantum superposition does not hold, and the phenomenon of quantum entanglement does not exist. That is to say, within a large spatial region, there are no quantum entangled states in multi-electron, multi-photon, and other microscopic systems. However, quantum correlation states can be generated, while quantum entanglement only exists between bound particles within a small spatial region.

2. The Quantum Entanglement Can be Formed by the Identity Principle

The Hamiltonian operator of a system composed of N identical particles is [29]

$$\hat{H}\left(q_1,q_2,\cdots,q_i,\cdots,q_j,\cdots,q_N\right)=\sum_{i=1}^{N}\left[-\frac{\hbar^2}{2m}\nabla_i^2+U\left(q_i\right)\right]+\sum_{i<j}^{N}W\left(q_i,q_j\right) \tag{1}$$

where $q_i=\left(\boldsymbol{r}_i,s_i\right)$ is the coordinates and spin of i-th particle, $U\left(q_i\right)$ is the potential energy of i-th particle in the external field, $W\left(q_i,q_j\right)$ is the interaction energy between the i-th particle and the i-th particle. From the Equation (1), it can be seen that after swapping the i-th particle and the i-th particle, the Hamiltonian operator of the system remains unchanged, that is

$$\hat{H}\left(q_1,q_2,\cdots,q_i,\cdots,q_j,\cdots,q_N\right)=\hat{H}\left(q_1,q_2,\cdots,q_i,\cdots,q_j,\cdots,q_N\right) \tag{2}$$

The Schrodinger equation for a system of identical particles is

$$i\hbar\frac{\partial}{\partial t}\Phi\left(q_1,\cdots,q_i,\cdots,q_j,\cdots,q_N\right) \\ =\hat{H}\left(q_1,\cdots,q_i,\cdots,q_j,\cdots,q_N\right)\Phi\left(q_1,\cdots,q_i,\cdots,q_j,\cdots,q_N\right) \tag{3}$$

The identical particle wave function must satisfy commutative symmetry

$$\Phi\left(q_1,\cdots,q_j,\cdots,q_i,\cdots,q_N\right)=\Phi\left(q_1,\cdots,q_i,\cdots,q_j,\cdots,q_N\right) \tag{4}$$

and exchange antisymmetry

$$\Phi\left(q_1,\cdots,q_j,\cdots,q_i,\cdots,q_N\right)=-\Phi\left(q_1,\cdots,q_i,\cdots,q_j,\cdots,q_N\right) \tag{5}$$

take the two identical particle as an example, the Hamiltonian operator of the system is

$$\hat{H}\left(q_1,q_2\right)=\hat{H}_0\left(q_1\right)+\hat{H}_0\left(q_2\right)+V\left(q_1,q_2\right) \tag{6}$$

where $V\left(q_1,q_2\right)$ is the interaction operator between two particles, and its energy eigenequation is

$$\hat{H}\left(q_1,q_2\right)\psi\left(q_1,q_2\right)=E\psi\left(q_1,q_2\right) \tag{7}$$

$$\hat{H}\left(q_1,q_2\right)\psi\left(q_2,q_1\right)=E\psi\left(q_2,q_1\right) \tag{8}$$

The state $\psi\left(q_1,q_2\right)$ indicates that the first particle is in the i-th state, with an energy ε_i, and the second particle is in the j-th state, with an energy ε_j. The state $\psi\left(q_2,q_1\right)$ indicates that the second particle is in the i-th state, and the first particle is in the j-th state. The state $\psi\left(q_1,q_2\right)$ and $\psi\left(q_2,q_1\right)$ have the same energy E, it is

$$E=\varepsilon_i+\varepsilon_j \tag{9}$$

where the wave functions $\psi\left(q_1,q_2\right)$ and $\psi\left(q_2,q_1\right)$ are neither a symmetric wave function nor an antisymmetric wave function. Therefore, the condition for the wave function of a homogeneous particle system is not satisfied. However, the sum or difference of these two wave functions can form a symmetric wave function $\Phi_S\left(q_1,q_2\right)$ Or antisymmetric wave function $\Phi_A\left(q_1,q_2\right)$, they are

$$\Phi_S\left(q_1,q_2\right)=\psi\left(q_1,q_2\right)+\psi\left(q_2,q_1\right) \tag{10}$$

$$\Phi_A\left(q_1,q_2\right)=\psi\left(q_1,q_2\right)-\psi\left(q_2,q_1\right) \tag{11}$$

Without considering the interaction between particle spins and orbits, the total wave function of the system can be written as the product of the spatial wave function and the spin wave function, that is

$$\Phi\left(\boldsymbol{r}_1s_1,\boldsymbol{r}_2s_2,\cdots,\boldsymbol{r}_Ns_N\right)=\phi\left(\boldsymbol{r}_1,\boldsymbol{r}_2,\cdots,\boldsymbol{r}_N\right)\chi\left(s_1,s_2,\cdots,s_N\right) \tag{12}$$

For identical fermionic systems, the total wave function Φ is antisymmetric and its antisymmetry can be satisfied in the following two ways

1) If the spatial wave function ϕ is symmetrical, then the spin wave function χ is antisymmetric.

2) If the spatial wave function ϕ is antisymmetric, then the spin wave function χ is symmetric.

For identical boson systems, the total wave function is symmetrical, and its symmetry can be satisfied in the following two ways

1) If the spatial wave function ϕ is symmetrical, then the spin wave function χ is symmetrical.

2) If the spatial wave function ϕ is antisymmetric, then the spin wave function χ is antisymmetric.

For two identical fermion systems, their total antisymmetric wave function is

$$\Phi_A\left(\boldsymbol{r}_1 s_1, \boldsymbol{r}_2 s_2\right) = \phi_A\left(\boldsymbol{r}_1, \boldsymbol{r}_2\right)\chi_S^i\left(s_1, s_2\right) \quad \left(i = 1,2,3\right) \tag{13}$$

or

$$\Phi_A\left(\boldsymbol{r}_1 s_1, \boldsymbol{r}_2 s_2\right) = \phi_S\left(\boldsymbol{r}_1, \boldsymbol{r}_2\right)\chi_A\left(s_1, s_2\right) \tag{14}$$

the spatially antisymmetric **a**nd spatially symmetric wave functions of the two identical particles are

$$\phi_A\left(\boldsymbol{r}_1, \boldsymbol{r}_2\right) = \frac{1}{\sqrt{2}}\left[\psi\left(\boldsymbol{r}_1, \boldsymbol{r}_2\right) - \psi\left(\boldsymbol{r}_2, \boldsymbol{r}_1\right)\right] \tag{15}$$

$$\phi_S\left(\boldsymbol{r}_1, \boldsymbol{r}_2\right) = \frac{1}{\sqrt{2}}\left[\psi\left(\boldsymbol{r}_1, \boldsymbol{r}_2\right) + \psi\left(\boldsymbol{r}_2, \boldsymbol{r}_1\right)\right] \tag{16}$$

Dual-identical fermion spin antisymmetric wave function $\chi_A\left(s_{1Z}, s_{2Z}\right)$ and spin-symmetric wave function $\chi_S\left(s_{1Z}, s_{2Z}\right)$ are

$$\chi_A\left(s_{1Z}, s_{2Z}\right) = \frac{1}{\sqrt{2}}\left[\chi_{1/2}\left(s_{1Z}\right)\chi_{-1/2}\left(s_{2Z}\right) - \chi_{-1/2}\left(s_{1Z}\right)\chi_{1/2}\left(s_{2Z}\right)\right] \tag{17}$$

$$\chi_S^1\left(s_{1Z}, s_{2Z}\right) = \chi_{1/2}\left(s_{1Z}\right)\chi_{1/2}\left(s_{2Z}\right) \tag{18}$$

$$\chi_S^2\left(s_{1Z}, s_{2Z}\right) = \chi_{-1/2}\left(s_{1Z}\right)\chi_{-1/2}\left(s_{2Z}\right) \tag{19}$$

$$\chi_S^3\left(s_{1Z}, s_{2Z}\right) = \frac{1}{\sqrt{2}}\left[\chi_{1/2}\left(s_{1Z}\right)\chi_{-1/2}\left(s_{2Z}\right) + \chi_{-1/2}\left(s_{1Z}\right)\chi_{1/2}\left(s_{2Z}\right)\right] \tag{20}$$

From Equations (15)-(20), it can be known that the possible antisymmetric wave function of the identical fermion system are

$$\Phi_A\left(\boldsymbol{r}_1 s_1, \boldsymbol{r}_2 s_2\right) = \phi_A\left(\boldsymbol{r}_1, \boldsymbol{r}_2\right)\chi_S^1\left(s_1, s_2\right) \tag{21}$$

$$\Phi_A\left(\boldsymbol{r}_1 s_1, \boldsymbol{r}_2 s_2\right) = \phi_A\left(\boldsymbol{r}_1, \boldsymbol{r}_2\right)\chi_S^2\left(s_1, s_2\right) \tag{22}$$

$$\Phi_A\left(\boldsymbol{r}_1 s_1, \boldsymbol{r}_2 s_2\right) = \phi_A\left(\boldsymbol{r}_1, \boldsymbol{r}_2\right)\chi_S^3\left(s_1, s_2\right) \tag{23}$$

$$\Phi_A\left(\boldsymbol{r}_1 s_1, \boldsymbol{r}_2 s_2\right) = \phi_n\left(\boldsymbol{r}_1\right)\phi_n\left(\boldsymbol{r}_2\right)\chi_A\left(s_1, s_2\right) \tag{24}$$

Equations (21) and (22) are expressed as an entangled state in which the spatial state is entangled but the spin state is not. Equation (23) is expressed as an entangled state in which the spatial state is entangled and the spin state is also entangled. Equation (24) is expressed as an entangled state in which the spatial state is not entangled but the spin state is entangled. Where the states $\phi_n\left(\boldsymbol{r}_1\right)$ and $\phi_n\left(\boldsymbol{r}_2\right)$ indicate that the two fermions are at the same energy level ε_n.

For two identical boson systems, the total symmetric wave function are

$$\Phi_S\left(\boldsymbol{r}_1 s_1, \boldsymbol{r}_2 s_2\right) = \phi_A\left(\boldsymbol{r}_1, \boldsymbol{r}_2\right) \chi_A\left(s_1, s_2\right) \tag{25}$$

and

$$\Phi_S\left(\boldsymbol{r}_1 s_1, \boldsymbol{r}_2 s_2\right) = \phi_S\left(\boldsymbol{r}_1, \boldsymbol{r}_2\right) \chi_S^i\left(s_1, s_2\right) \quad (i = 1,2,3) \tag{26}$$

Take two photons as an example, their spin states are respectively [30]

1) Two-photon spin symmetric state of total spin $S = 2$ are

$$\chi_{22} = \chi_1\left(s_{1Z}\right)\chi_1\left(s_{2Z}\right) \tag{27}$$

$$\chi_{21} = \frac{1}{\sqrt{2}}\left[\chi_0\left(s_{1Z}\right)\chi_1\left(s_{2Z}\right) + \chi_0\left(s_{2Z}\right)\chi_1\left(s_{1Z}\right)\right] \tag{28}$$

$$\chi_{20} = \frac{1}{\sqrt{6}}\left[\chi_1\left(s_{1Z}\right)\chi_{-1}\left(s_{2Z}\right) + 2\chi_0\left(s_{1Z}\right)\chi_0\left(s_{2Z}\right) + \chi_{-1}\left(s_{1Z}\right)\chi_1\left(s_{2Z}\right)\right] \tag{29}$$

$$\chi_{2-1} = \frac{1}{\sqrt{2}}\left[\chi_0\left(s_{1Z}\right)\chi_{-1}\left(s_{2Z}\right) + \chi_{-1}\left(s_{1Z}\right)\chi_0\left(s_{2Z}\right)\right] \tag{30}$$

$$\chi_{2-2} = \chi_{-1}\left(s_{1Z}\right)\chi_{-1}\left(s_{2Z}\right) \tag{31}$$

2) Two-photon spin antisymmetric state of total spin $S = 1$ are

$$\chi_{11} = \frac{1}{\sqrt{2}}\left[\chi_1\left(s_{1Z}\right)\chi_0\left(s_{2Z}\right) - \chi_0\left(s_{1Z}\right)\chi_1\left(s_{2Z}\right)\right] \tag{32}$$

$$\chi_{10} = \frac{1}{\sqrt{2}}\left[\chi_1\left(s_{1Z}\right)\chi_{-1}\left(s_{2Z}\right) + \chi_{-1}\left(s_{1Z}\right)\chi_1\left(s_{2Z}\right)\right] \tag{33}$$

$$\chi_{1-1} = \frac{1}{\sqrt{2}}\left[\chi_0\left(s_{1Z}\right)\chi_{-1}\left(s_{2Z}\right) + \chi_{-1}\left(s_{1Z}\right)\chi_0\left(s_{2Z}\right)\right] \tag{34}$$

3) Two-photon spin symmetric state of total spin $S = 0$ is

$$\chi_{00} = \frac{1}{\sqrt{3}}\left[\chi_1\left(s_{1Z}\right)\chi_{-1}\left(s_{2Z}\right) + \chi_0\left(s_{1Z}\right)\chi_0\left(s_{2Z}\right) + \chi_{-1}\left(s_{1Z}\right)\chi_1\left(s_{2Z}\right)\right] \tag{35}$$

where the single photon spin state is

$$\chi_0 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \ \chi_1 = -\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ i \\ 0 \end{pmatrix}, \ \chi_{-1} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -i \\ 0 \end{pmatrix} \tag{36}$$

Since the mass of a photon is zero and there are only two spin states, the spin state χ_0 does not exist. Thus, the spin states of the two photons are

$$\chi_{22} = \chi_1\left(s_{1Z}\right)\chi_1\left(s_{2Z}\right) \tag{37}$$

$$\chi_{2-2} = \chi_{-1}\left(s_{1Z}\right)\chi_{-1}\left(s_{2Z}\right) \tag{38}$$

$$\chi_{10} = \frac{1}{\sqrt{2}}\left[\chi_1\left(s_{1Z}\right)\chi_{-1}\left(s_{2Z}\right) + \chi_{-1}\left(s_{1Z}\right)\chi_1\left(s_{2Z}\right)\right] \tag{39}$$

where the two-photon spin state χ_{10} is a two-photon spin entangled state.

If let $\chi_1 = |H\rangle$, $\chi_{-1} = |V\rangle$ then the spin entangled state of the two photons can be expressed as by the polarization state of light

$$\left|\psi\right\rangle = \frac{1}{\sqrt{2}}\left[\left|H\right\rangle_1\left|V\right\rangle_2 + \left|V\right\rangle_1\left|H\right\rangle_2\right] \tag{40}$$

It can be seen that quantum entangled states can be given by the identity principle of quantum theory. In the system of identical particles, there exist quantum entangled states, including spatial entangled states and spin entangled states.

3. There are Conserved Quantities between Superposition States of Entangled States

The entangled state is a quantum superposition state and cannot be expressed in the form of a direct product of subsystem states, it is

$$\psi(q_1, q_2) \neq \psi(q_1) \otimes \psi(q_1) \tag{41}$$

Equations (15) and (16) are spatially entangled states, which are the superposition of the spatial states $\psi(\boldsymbol{r}_1, \boldsymbol{r}_2)$ and $\psi(\boldsymbol{r}_2, \boldsymbol{r}_1)$. The energy corresponding to these two states are both E. It can be seen that each superposition state in the entangled state has a conserved quantity, the Energy E is conserved.

For the entangled states $\chi_A(s_{1Z}, s_{2Z})$ and $\chi_S^3(s_{1Z}, s_{2Z})$ of two electron spins, they are the superposition states of two spin states $\chi_{\frac{1}{2}}(s_{1Z})\chi_{-\frac{1}{2}}(s_{2Z})$ and $\chi_{-\frac{1}{2}}(s_{1Z})\chi_{\frac{1}{2}}(s_{2Z})$. By applying $s_Z = s_{1Z} + s_{2Z}$ to them, we get

$$s_Z \chi_{\frac{1}{2}}(s_{1Z})\chi_{-\frac{1}{2}}(s_{2Z}) = (s_{1Z} + s_{2Z})\chi_{\frac{1}{2}}(s_{1Z})\chi_{-\frac{1}{2}}(s_{2Z}) = 0\chi_{\frac{1}{2}}(s_{1Z})\chi_{-\frac{1}{2}}(s_{2Z})$$

$$s_Z \chi_{-\frac{1}{2}}(s_{1Z})\chi_{\frac{1}{2}}(s_{2Z}) = (s_{1Z} + s_{2Z})\chi_{-\frac{1}{2}}(s_{1Z})\chi_{\frac{1}{2}}(s_{2Z}) = 0\chi_{-\frac{1}{2}}(s_{1Z})\chi_{\frac{1}{2}}(s_{2Z})$$

It can be seen that there is spin component s_Z conservation between these two spin superposition states, both of which are $s_Z = 0$. For a two-photon spin state χ_{10}, it is the superposition state of the two spin state $\chi_1(s_{1Z})\chi_{-1}(s_{2Z})$ and $\chi_{-1}(s_{1Z})\chi_1(s_{2Z})$. When they are applied to $s_Z = s_{1Z} + s_{2Z}$, it is found that there is spin component s_Z conservation between these two spin superposition states, both of which are $s_Z = 0$.

In addition to quantum entanglement between identical elementary particles, there is also quantum entanglement between identical atoms and identical molecules. Recently, researchers from university of basel, Switzerland, reported the EPR paradox in many-body quantum systems [31]. They used thousands of atoms to prepare a single Bose-Einstein condensate in a trap, and an interaction was designed to cause the atoms forming the condensate to become entangled. It was found that quantum entanglement occurred between two atomic clusters of nearly a thousand identical atoms ^{87}Rb, with the maximum entanglement distance between the two atomic clusters being 100 μm.

There are also experimental reports that identical molecules CaF are confined in a one-dimensional array and cooled to the same quantum ground state by laser cooling technology. On this basis, by utilizing the electric dipole interaction between molecules, the quantum entangled states between molecules CaF were generated.

Through the identical principle of quantum theory, the wave functions of identical particles have symmetry and antisymmetry. Naturally, it is given that identical particles exist quantum entangled states. For instance, there exist quantum entangled states between photon and photon, and between electron and electron, and there are conserved quantities between each quantum superposition state.

It can be seen that quantum entanglement can exist between identical atoms and between identical molecules, and it only occurs at extremely small distances, and it is required that there are interactions between atoms as well as between molecules.

4. The Quantum Entanglement Can Be Formed by the Interaction between Different Particles

In addition to the quantum entanglement between identical particles studied above, the experiment also found that quantum entanglement exists between particles of different types. For instance, quantum entanglement resulting from dipole-dipole interactions between heteronuclear atoms ^{85}Rb and ^{87}Rb.

The quantum entanglement between different types of particles, it is difficult to generate spatial entangled states formed by spatial wave functions. This is because the energy is $\varepsilon_{nA}+\varepsilon_{mB}$ of the spatial state $\psi_n(\boldsymbol{r}_A)\psi_m(\boldsymbol{r}_B)$, and the energy is $\varepsilon_{nB}+\varepsilon_{mA}$ of the spatial state $\psi_n(\boldsymbol{r}_B)\psi_m(\boldsymbol{r}_A)$, in general, $\varepsilon_{nA}+\varepsilon_{mB}\neq\varepsilon_{nB}+\varepsilon_{mA}$, that is, the energy of the superposition state of two spaces is not conserved. Therefore, for particles of different types, the following spatial entangled states do not exist.

$$\phi(\boldsymbol{r}_A,\boldsymbol{r}_B)=\frac{1}{\sqrt{2}}\left[\psi_n(\boldsymbol{r}_A)\psi_m(\boldsymbol{r}_B)-\psi_n(\boldsymbol{r}_B)\psi_m(\boldsymbol{r}_A)\right] \tag{42}$$

$$\phi(\boldsymbol{r}_A,\boldsymbol{r}_B)=\frac{1}{\sqrt{2}}\left[\psi_n(\boldsymbol{r}_A)\psi_m(\boldsymbol{r}_B)+\psi_n(\boldsymbol{r}_B)\psi_m(\boldsymbol{r}_A)\right] \tag{43}$$

Due to the existence of spin-spin interactions or other types of interactions among different types of particles. Therefore, there exist the spin quantum entangled states or other quantum entangled states between different types of particles.

In reference [32], the atomic ions Ca^+ and molecular ions CaH^+ were captured in an ion trap, and experiments found that quantum entanglement occurred between them. In the following, we shall analyze the entanglement generation mechanism.

The spin of Ca^+ ions $S_{\mathrm{Ca}^+}=1/2$, when it is in the ground state S, the orbital angular momentum $L=0$, and the total angular momentum of Ca^+ ions $J=1/2$. In the direction of the magnetic field $\boldsymbol{B}$, the projected component of the ionic Ca^+ angular momentum can be taken as $m_j=+\frac{1}{2}$, the Ca^+ ions can be in the state $|S\rangle=|J,m_j\rangle=\left|\frac{1}{2},\frac{1}{2}\right\rangle$. when the Ca^+ ions is in the metastable excited state D, the orbital angular momentum $L=2$, and the total angular momentum $J=5/2,3/2$. In the direction of the magnetic field $\boldsymbol{B}$, the projected component of the ionic Ca^+ angular momentum can be taken as $m_j = +\frac{5}{2}$, the Ca^+ ions can be in the state $\left|D\right\rangle = \left|J, m_j\right\rangle = \left|\frac{5}{2}, \frac{3}{2}\right\rangle$. The rotational state of molecular ions CaH^+ is $\left|J, m\right\rangle$, where $\boldsymbol{J}$ is the rotational angular momentum of the molecule CaH^+, and m is the component sum of $\boldsymbol{J}$ along the magnetic field $\boldsymbol{B}$ and the spin component of the proton, *i.e.*, $m = m_j + m_p$ ($m_p = \pm\frac{1}{2}$). When the rotational states of the molecular ions CaH^+ are $\left|2, -\frac{3}{2}\right\rangle \equiv \left|-\frac{3}{2}\right\rangle$ and $\left|2, -\frac{5}{2}\right\rangle \equiv \left|-\frac{5}{2}\right\rangle$ respectively (where $J = 2$), the experiment found that the rotational state of molecular ions CaH^+ and the angular momentum state of atomic ions Ca^+ appear the following entangled states

$$\left|\psi\right\rangle = \frac{1}{\sqrt{2}}\left(\left|S\right\rangle\left|-\frac{3}{2}\right\rangle + \left|D\right\rangle\left|-\frac{5}{2}\right\rangle\right) \tag{44}$$

Obviously, the projected components of the total angular momentum $\boldsymbol{J}$ in the magnetic field $\boldsymbol{B}$ direction of the states $\left|S\right\rangle\left|-\frac{3}{2}\right\rangle$ and $\left|D\right\rangle\left|-\frac{5}{2}\right\rangle$ are both $m_j = -1$. It can be seen that the quantum entanglement between atoms and molecules stems from the interaction between their angular momenta or other interactions. Each superposition state has conserved quantities, such as the conservation of angular momentum components, etc.

It can be seen that the quantum entanglement between atoms and molecules stems from the interaction between their angular momenta or other interactions, and each superposition state has conserved quantities, such as the conservation of spin angular momentum or total angular momentum, etc.

5. The Representation of Left-Handed and Right-Handed Polarized Light

Photon can be classified into left-handed circularly polarized light and right-handed circularly polarized light, the following are several representations of them

1) The electric field representation of right-handed circularly polarized light

For the right-handed circularly polarized light, the electric field components E_x and E_y are

$$E_x = E_0 \cos\left(kz - \omega t\right) \tag{45}$$

$$E_y = E_0 \cos\left(kz - \omega t + \frac{\pi}{2}\right) \tag{46}$$

where E_y is $\frac{\pi}{2}$ ahead of E_x in phase, the total electric field is

$$\boldsymbol{E}_R = E_x \boldsymbol{i} + E_y \boldsymbol{j} = E_0 \cos\left(kz - \omega t\right)\boldsymbol{i} - E_0 \sin\left(kz - \omega t\right)\boldsymbol{j} \tag{47}$$

In Figure 1, the electric fields $\boldsymbol{E}_0, \boldsymbol{E}_1, \boldsymbol{E}_2, \cdots, \boldsymbol{E}_n$ are given corresponding moment $t_0 = 0 < t_1 < t_2 < \cdots < t_n$. The electric field of right-handed circularly polarized rotates clockwise.

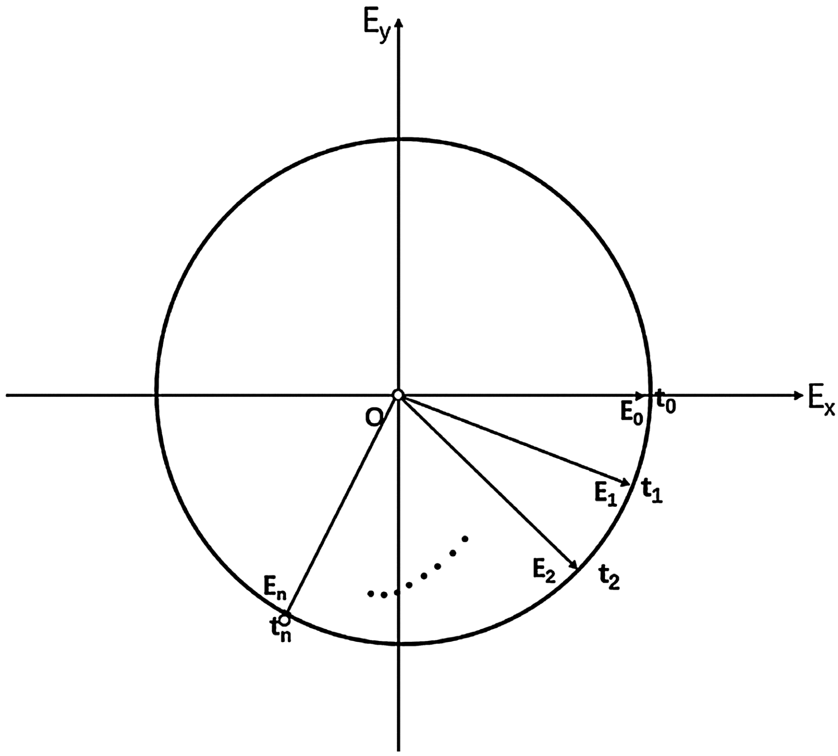

Figure 1. The electric field schematic diagram of the right-handed circularly polarized light, where $E(t)$ is the electric field of a photon at time t.

2) The electric field representation of left-handed circularly polarized light

For the left -handed circularly polarized light, the electric field components E_x and E_y are

$$E_x = E_0 \cos(kz - \omega t) \quad E_y = E_0 \cos\left(kz - \omega t - \frac{\pi}{2}\right) \tag{48}$$

where E_x is $\frac{\pi}{2}$ ahead of E_y in phase, the total electric field is

$$\boldsymbol{E}_L = E_x \boldsymbol{i} + E_y \boldsymbol{j} = E_0 \cos(kz - \omega t)\boldsymbol{i} + E_0 \sin(kz - \omega t)\boldsymbol{j} \tag{49}$$

In Figure 2, the electric fields $\boldsymbol{E}_0, \boldsymbol{E}_1, \boldsymbol{E}_2, \cdots, \boldsymbol{E}_n$ are given corresponding moment $t_0 = 0 < t_1 < t_2 < \cdots < t_n$. The electric field of left-handed circularly polarized rotates anticlockwise.

3) The spin representations of left-handed and right-handed circularly polarized light

The projection of the spin angular momentum of a photon in its momentum direction take the value of $\pm\hbar$, they correspond to left-handed and right-handed circularly polarized light respectively. The spin component of the photon corresponding to the left-handed circularly polarized light is $+\hbar$, and its angular momentum direction is the same as the momentum direction, as shown in Figure 3(a). The spin component of the photon corresponding to right-handed circularly polarized light is $-\hbar$, and its angular momentum direction is opposite to the momentum direction, as shown in Figure 3(b).

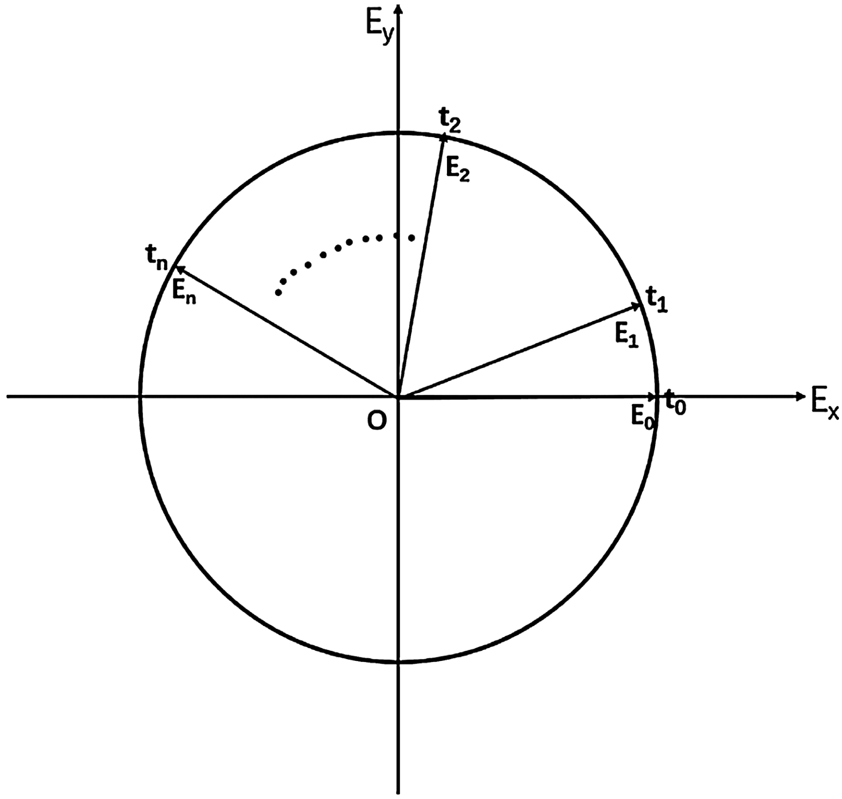

Figure 2. The electric field schematic diagram of the left-handed circularly polarized light, where $E(t)$ is the electric field of a photon at time t.

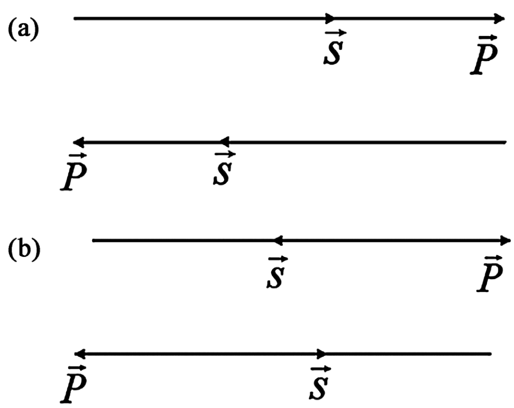

Figure 3. (a) The schematic diagram of left-handed polarized light ($\boldsymbol{S} \parallel \boldsymbol{P}$). Where P and S are the momentum and spin of the photon. (b) The schematic diagram of right-handed polarized light ($\boldsymbol{S} \parallel -\boldsymbol{P}$). Where P and S are the momentum and spin of the photon.

For the left-handed light ($\boldsymbol{P} \parallel \boldsymbol{S}$), the angular momentum of the light is $\hbar$. For right-handed light ($\boldsymbol{P} \parallel -\boldsymbol{S}$), the angular momentum of the light is $-\hbar$.

The definition of the quantum correlation state of two or more particles is given below. If the total quantum state of two or more particles can be written in the form of the direct product of each particle's quantum state, that is

$$\psi(\boldsymbol{r}_1,\boldsymbol{r}_2,\cdots,\boldsymbol{r}_n,t)=\psi_1(\boldsymbol{r}_1,t)\otimes\psi_2(\boldsymbol{r}_2,t)\otimes\cdots\otimes\psi_n(\boldsymbol{r}_n,t) \quad (50)$$

If energy conservation, momentum conservation, angular momentum conservation, etc. exist among particles, then the quantum state $\psi(\boldsymbol{r}_1,\boldsymbol{r}_2,\cdots,\boldsymbol{r}_n,t)$ is called a quantum correlated state, it is different from the quantum entanglement state, the quantum entanglement state is a superposition state, it is not the form of the direct product of each particle's quantum state.

It can be seen that the quantum correlated state is not a superposition state, and thus it is not a quantum entangled state. The following will illustrate with examples that the quantum states generated in some experiments are not entangled states but quantum correlated states.

6. The Generated Photon Pairs Are Quantum Correlated States Rather than Quantum Entangled States

A pair of photon is produced by the decay of a stationary source particle meson π^0 with zero spin through electromagnetic interaction, *i.e.*, $\pi^0\to\gamma+\gamma$, they move respectively in the directions of $+z$ and $-z$, as shown in the two forms of **Figure 4(a)** and **Figure 4(b)**.

In **Figure 4(a)**, by the conservation of momentum and angular momentum, the right-handed light is generated on the left side of the source and propagates along the $-z$ direction, while the left-handed light is generated on the right side

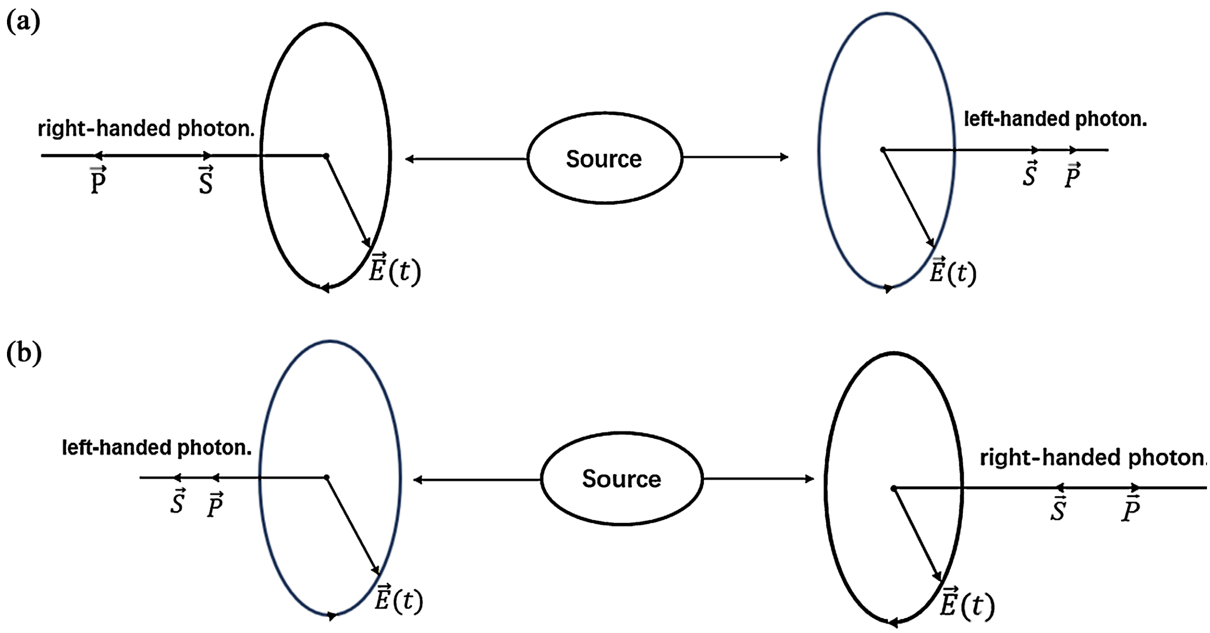

Figure 4. (a) The schematic diagrams of left-handed and right-handed light generated by the source. Where $E(t)$ is photon electric field, P and S are the momentum and spin of the photon. (b) The schematic diagrams of left-handed and right-handed light generated by the source. Where $E(t)$ is photon electric field, P and S are the momentum and spin of the photon.

of the source and propagates along the $+z$ direction.

In Figure 4(b), by the conservation of momentum and angular momentum, left-handed light is generated on the left side of the source and propagates along the $-z$ direction, while right-handed light is generated on the right side of the source and propagates along the $+z$ direction.

The state of a photon can be represented by its polarization electric field, it is

$$\boldsymbol{\psi}(\boldsymbol{r},t)=\boldsymbol{E}(\boldsymbol{r},t) \tag{51}$$

In Figure 4(a), the photon state of the right-handed polarized light is

$$\boldsymbol{\psi}_R(-z,t)=\boldsymbol{E}_R(-z,t)=\boldsymbol{E}_0\cos(kz-\omega t)\boldsymbol{i}-\boldsymbol{E}_0\sin(kz-\omega t)\boldsymbol{j} \tag{52}$$

The photon state of left-handed polarized light is

$$\boldsymbol{\psi}_L(+z,t)=\boldsymbol{E}_L(+z,t)=\boldsymbol{E}_0\cos(kz-\omega t)\boldsymbol{i}+\boldsymbol{E}_0\sin(kz-\omega t)\boldsymbol{j} \tag{53}$$

The total state of two photons can be expressed as

$$\boldsymbol{\psi}_a(+z,-z,t)=\boldsymbol{\psi}_R(-z,t)\otimes\boldsymbol{\psi}_L(+z,t), \tag{54}$$

Similarly, for Figure 4(b), the photon states of left-handed polarized light, right-handed polarized light, and the total state of two photons can be respectively expressed as

$$\boldsymbol{\psi}_L(-z,t)=\boldsymbol{E}_L(-z,t)=\boldsymbol{E}_0\cos(kz-\omega t)\boldsymbol{i}+\boldsymbol{E}_0\sin(kz-\omega t)\boldsymbol{j} \tag{55}$$

$$\boldsymbol{\psi}_R(+z,t)=\boldsymbol{E}_R(+z,t)=\boldsymbol{E}_0\cos(kz-\omega t)\boldsymbol{i}-\boldsymbol{E}_0\sin(kz-\omega t)\boldsymbol{j} \tag{56}$$

$$\boldsymbol{\psi}_b(+z,-z,t)=\boldsymbol{\psi}_L(-z,t)\otimes\boldsymbol{\psi}_R(+z,t) \tag{57}$$

From Equations (54) and (57), it is known that a pair of photons produced by a stationary source with zero spin have two states, both of which are quantum correlated states. On the one hand, they are both in the form of direct products. On the other hand, at any moment, the energy, momentum and angular momentum of the left-handed and right-handed photons are conserved, which conforms to the definition of quantum correlated states. In a large spatial region, Equations (54) and (57) cannot be superimposed and written in the form of superposition states. This is because the principle of quantum state superposition is a fundamental principle of quantum mechanics. Quantum state superposition is only allowed under the condition that quantum theory holds true. The condition for quantum theory to hold true is that there are small-mass microscopic particles and they are localized in an extremely small spatial region. Quantum entangled states are a kind of quantum superposition state. Therefore, quantum entanglement between particles only occurs in extremely small spatial regions, and there are bound particles interacting with each other. Each entangled particle is in a bound state.

Specifically, the core feature of quantum mechanics is the wave nature of particles and the de Broglie wavelength of particle is $\lambda=\frac{h}{p}$. When the influence of the wave nature of particles on motion cannot be ignored, quantum mechanics must be used; if the wave nature can be ignored, classical mechanics can be employed.

This boundary of whether it can be ignored or not is directly determined by the relationship between the de Broglie wavelength λ and the size of the distance r between the two particles. If $\lambda \approx r$ or $\lambda > r$, the wave is significant, the quantum effect cannot be ignored and quantum mechanics must be applied. The principle of quantum state superposition holds. If $\lambda \ll r$, the wave is extremely weak, the particle approximately behaves as a classical particle, and the quantum effect can be ignored. Classical mechanics can be used, and the principle of quantum state superposition does not hold.

For instance, when the distance r between two particles is extremely small (such as at the atomic scale 10^{-10} m or the nuclear scale 10^{-15} m), and when the de Broglie wavelength λ of the particles is close to or greater than r that of the particles, quantum effects are completely dominant. For instance, in a hydrogen atom, the distance between the electron and the proton is approximately 0.5×10^{-10} m, and the de Broglie wavelength of the electron is about 10^{-10} m. The two are comparable, and the probability distribution of the electron must be described by the Schrodinger equation.

In extremely small regions, particles are more like waves than particles, and their interactions need to take into account the superposition and interference of waves. When the distance r between two particles is much greater than the de Broglie wavelength λ, such as above the macroscopic scale of 10^{-3} m, or when the distance between microscopic particles is extremely large, like two electrons 1 m apart, but the wavelength of the particles is extremely short, quantum effects are suppressed, and the superposition and interference characteristics of waves cannot be exhibited. Only the particle nature of the particle is reflected, and the classical description is precise enough. In conclusion, when the system spacing approaches the quantum characteristic scale, quantum effects become prominent and must be handled by quantum mechanics. The principle of quantum state superposition holds true. When the system scale is much larger than the quantum characteristic scale, the quantum effect is very weak and can be dealt with by classical mechanics. The principle of quantum state superposition does not hold. In this case, the quantum entanglement does not exist.

Therefore, the two-photon states in the large spatial regions of **Figure 4(a)** and **Figure 4(b)** cannot exist in the form of superposition states, that is, the following superposition states do not exist

$$\begin{aligned}\boldsymbol{\psi}(+z,-z,t) &= \frac{1}{2}\left[\boldsymbol{\psi}_a(+z,-z,t)+\boldsymbol{\psi}_b(+z,-z,t)\right] \\ &= \frac{1}{2}\left[\boldsymbol{\psi}_R(-z,t)\cdot\boldsymbol{\psi}_L(+z,t)+\boldsymbol{\psi}_L(-z,t)\cdot\boldsymbol{\psi}_R(+z,t)\right]\end{aligned} \tag{58}$$

This superposition state is a form of entangled state, but it is not allowed to exist. It can only exist in the form of the following mixed state

$$\boldsymbol{\psi}_a(+z,-z,t),\quad p_a = 1/2 \tag{59}$$

$$\boldsymbol{\psi}_b(+z,-z,t),\quad p_b = 1/2 \tag{60}$$

In a large spatial area, the superposition state of a pair of photons does not exist, and thus the entangled state does not exist either. In a laser, adjacent photon pairs are localized in a very small area, and they may generate quantum superposition states, and entangled photon states may exist. However, once the entangled photon pair is released from the laser, it is no longer localized in a small area, the superposition state disappears, and the quantum entangled state of the two photons will also disappear in a large spatial area.

In Figure 4(b), the analysis shows that the left-handed photon and right-handed photon generated by the source are quantum correlation states rather than quantum entanglement states. According to Equations (55) and (56), the left-handed and right-handed states of two photons can be represented by Figure 5.

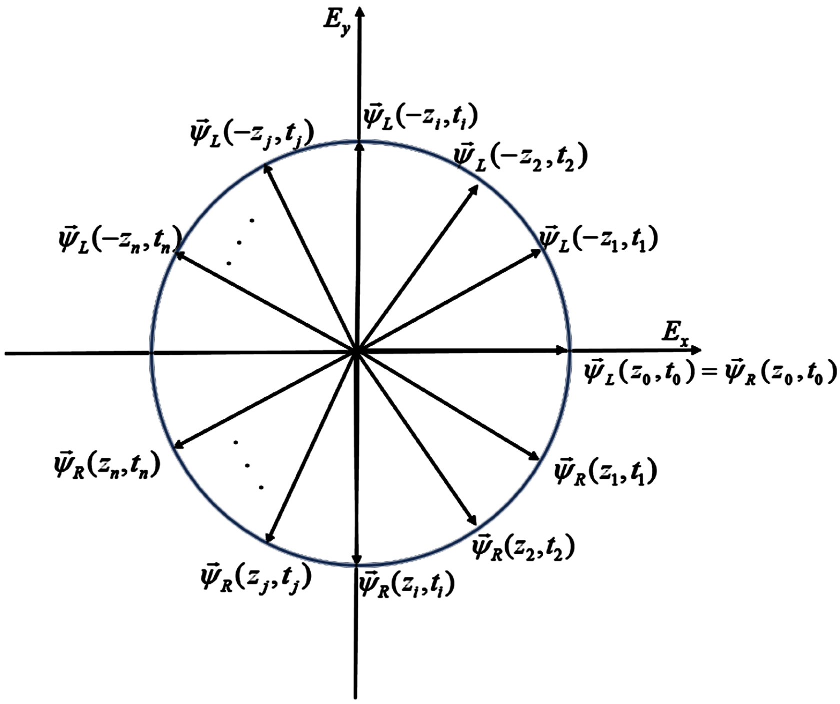

Figure 5. The schematic diagram of the correlation states of left-handed and right-handed photon. Where $\psi_L(-z_i,t_i)$ and $\psi_R(z_i,t_i)$ are the states of left-handed and right-handed photon at time t_i.

As can be seen from Figure 5, at $t=t_0=0$ time, $z_0=0$, both the left-handed photon and the right-handed photon are in a horizontal polarization state. When $t=t_1$, the left-handed photon state is $\psi_L(-z_i,t_i)$, and the right-handed photon state is $\psi_R(z_1,t_1)$. They are symmetrical about the E_x axis. When $t=t_i$, the left-handed photon state is $\psi_L(-z_i,t_i)$, and the right-handed photon state is $\psi_R(z_i,t_i)$, their states are respectively along the $+E_y$ axis and $-E_y$ axis. We can obtain the following conclusions: 1) with the increase of time, the left-handed photon state rotates counterclockwise and the right-handed photon state rotates clockwise. 2) At any moment, the left-handed photon state and the right-handed photon state are mirror symmetrical about the E_x axis, to ensure the conservation of angular momentum at any moment. 3) At any moment, there is a pair of left-handed photon states and right-handed photon states, they did not perform quantum superposition, they are a pair of interrelated quantum states, not quantum entangled states. When measuring any a photon, there are no issues of instantaneous collapse, infinite propagation speed, or non-locality. This correlation stems from the conservation of momentum and angular momentum of this pair of photons at any moment.

7. The Photon Pairs Are Quantum Correlated States Rather than Quantum Entangled States

From conversion under spontaneous parameters

Higher-frequency photons (pump photons) act on a nonlinear crystal and split into two lower-frequency photons. This process satisfies the conservation of energy and momentum, that are

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i \tag{61}$$

$$\boldsymbol{k}_p = \boldsymbol{k}_s + \boldsymbol{k}_i \tag{62}$$

where p, s, i represent pump light, signal light and idle light, respectively. Equations (61) and (62) are called the transformation processes under spontaneous parameters, and the energy conservation and phase matching conditions that must be satisfied. As long as this condition is met, the down-converted photons can be generated arbitrarily. The resulting down-conversions include several matching methods such as I type and II type, collinear and non-collinear, degenerate and non-degenerate.

For I type spontaneous parameter conversion, the pump light input to the crystal is linearly polarized light, it is

$$\left|\psi_p\right\rangle = \frac{1}{\sqrt{2}}\left(\left|H\right\rangle + \left|V\right\rangle\right) \tag{63}$$

From a classic viewpoint, it is composed of two beams of light $\left|H\right\rangle$ and $\left|V\right\rangle$ superimposed, when it passes through a positive uniaxial crystal, the $\left|V\right\rangle$ light within it is converted into output light $\left|H\right\rangle\left|H\right\rangle$. When passing through a negative uniaxial crystal, the $\left|H\right\rangle$ light within it is converted into output light $\left|V\right\rangle\left|V\right\rangle$. This is actually two different beams of emitted light produced by two different incident light beams. Therefore, the output light is not entangled light.

From a quantum viewpoint, when this incident pump light $\left|\psi_p\right\rangle = \frac{1}{\sqrt{2}}\left(\left|H\right\rangle + \left|V\right\rangle\right)$ enters the crystal, it does not enter the crystal in the form of this superposition state, but enters $\left|H\right\rangle$ light or $\left|V\right\rangle$ light respectively with a 1/2 probability. Each time, enter only one kind of light, rather than both $\left|H\right\rangle$ and $\left|V\right\rangle$ at the same time. Therefore, the output light produced is either $\left|H\right\rangle\left|H\right\rangle$ light or $\left|V\right\rangle\left|V\right\rangle$ light, rather than the superimposed state light as follows

$$\left|\psi_{out}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|H\right\rangle\left|H\right\rangle + \left|V\right\rangle\left|V\right\rangle\right) \tag{64}$$

In a large spatial range, quantum states cannot be superimposed, the principle of quantum superposition is only applicable to an extremely small spatial range, that is, the extremely small spatial range that quantum theory can describe. Therefore, the output light generated by the spontaneous parameter conversion of the Ⅰ type composite crystal is not superimposed state light. Therefore, the output light generated by the spontaneous parameter conversion of the I type composite crystal is not quantum entangled light, but quantum correlated light.

For II type spontaneous parameter conversion, a beam of linearly polarized e light is used as the pump light, and the signal light and idle light are generated by the nonlinear crystal, which are mutually orthogonal polarized light, one is e light and the other is o light.

Under the condition of phase matching, the wave vectors $\vec{k}_e$ and $\vec{k}_o$ of e light and o light can vary respectively on two circular conical surface, two conical surfaces have two intersection lines, and the intersection point are A, B. If what is measured at a point A is e light, then what is measured at the B point must be o light at the same time. On the contrary, if what is measured at a point A is o light, then what is measured at the B point must be e light at the same time. These two measurement results are not produced simultaneously. In a large spatial area, quantum states cannot be superimposed, the output light cannot be written in the following superimposed state form

$$\left|\psi_{out}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|H\right\rangle_A \left|V\right\rangle_B + \left|V\right\rangle_A \left|H\right\rangle_B\right) \quad (65)$$

From the previous discussion, it can be known that in a large spatial range, quantum states cannot be superimposed, the output light generated by the spontaneous parametric conversion of II type crystals is either $\left|H\right\rangle_A \left|V\right\rangle_B$ or $\left|V\right\rangle_A \left|H\right\rangle_B$, they are not in a superposition state. Therefore, the output light generated by the spontaneous parametric conversion of the II type is not entangled light, they are correlated light.

8. The Generated Electron Pairs Are Quantum Correlated States Rather than Quantum Entangled States

The spin direction of electrons is usually indicated by an upward arrow $\uparrow$ and a downward arrow $\downarrow$. The corresponding spin quantum numbers are respectively $m_s = +1/2$ and $m_s = -1/2$, and the spin angular momenta are respectively $\hbar/2, -\hbar/2$. In **Figure 6**, electron 1 and electron 2 are a pair of electrons generated from the parent particle, which is at rest and spin $S = 0$. Therefore, the total momentum and total angular momentum of the electron 1 and electron 2 are conserved and both are zero.

The spin state of an electron can be represented in the spin space. Since the spin state $\left|\uparrow\right\rangle$ and $\left|\downarrow\right\rangle$ is orthogonal, that is, $\left\langle\uparrow\middle|\downarrow\right\rangle = 0$, it can be regarded the spin state $\left|\uparrow\right\rangle$ and $\left|\downarrow\right\rangle$ as the basis vector of the spin space.

The spin state of electron 1 can be written as

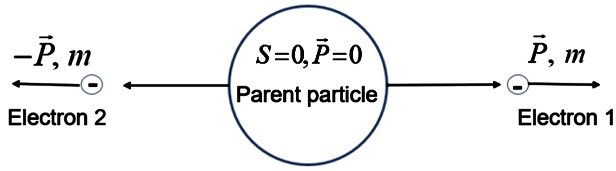

Figure 6. A pair of electrons generated by the source.

$$\left|\chi_1(t)\right\rangle = \sin\omega t\left|\uparrow\right\rangle + \cos\omega t\left|\downarrow\right\rangle \tag{66}$$

Since the sum of the angular momenta of electron 1 and electron 2 is zero, the spin state of electron 2 is

$$\begin{aligned}\left|\chi_2(t)\right\rangle &= -\sin\omega t\left|\uparrow\right\rangle - \cos\omega t\left|\downarrow\right\rangle \\ &= -\left|\chi_1(t)\right\rangle\end{aligned} \tag{67}$$

Only when the spin states of the two electrons satisfy Equations (66) and (67), the sum of the angular momenta of two electrons is zero.

In the spin space, the spin states (66) and (67) of electron 1 and electron 2 can be represented as shown in **Figure 7**.

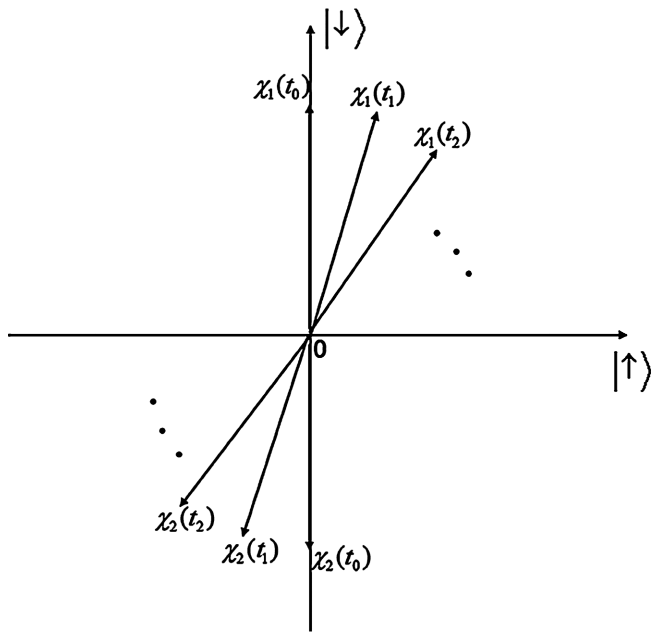

Figure 7. The representation of spin states of electron 1 and electron 2 in spin space. Where $\chi_1(t_i)$ and $\chi_2(t_i)$ are the spin state of electron 1and 2 at time t_i.

As can be seen from **Figure 7**, the two electrons generated from the parent particle, at time $t = t_0, t_1, t_2, \cdots$, the spin states of electron 1 and electron 2 can be respectively expressed as $\chi_1(t_0), \chi_2(t_1), \chi_3(t_2), \cdots$ and $\chi_2(t_0), \chi_2(t_1), \chi_2(t_2), \cdots$. At the same moment, the spin directions of the two electrons are opposite, satisfying the conservation of total angular momentum. There is no quantum superposition state of two electrons within this large spatial region, the total spin state of the two electrons is

$$\left|\chi(t)\right\rangle = \left|\chi_1(t)\right\rangle \otimes \left|\chi_2(t)\right\rangle \tag{68}$$

At every moment t, the electron 1 and electron 2 have definite spin states $\left|\chi_1(t)\right\rangle$ and $\left|\chi_2(t)\right\rangle$, and there is an interconnection among them, this correlation stems from the conservation of angular momentum. The mutual correlation of this spin state is inevitable, there is no issue of instantaneous collapse, infinite propagation speed, and non-locality. The pair of electronic states produced (68) are merely quantum correlation states, not quantum entanglement states.

It is particularly important to emphasize that quantum correlations and classical correlations are distinct. Classical correlations are finite, for instance, if a particle A moves to the left, a particle B moves to the right, or if a particle A moves to the right, a particle B moves to the left. There are only a limited number of correlation forms. In contrast, quantum correlations are diverse, as shown in **Figure 5** and **Figure 7**, which respectively indicate that two photons and two electrons have an infinite number of quantum correlations. It is manifested as any moment having a kind of quantum correlation, and different moments have different quantum correlation. Therefore, with the change of time, there are an infinite number of quantum correlations.

9. Conclusions

The quantum entangled state is a quantum superposition state, and this quantum superposition state cannot be written in the form of a direct product of sub-states. According to the identity principle of quantum theory, that is, the symmetry and antisymmetry of the wave function of identical particles, it is naturally given that there exist quantum entangled states between identical particles, including spatial entanglement and spin entanglement. Quantum superposition is one of the fundamental principles of quantum mechanics. Therefore, quantum entanglement is possible only under the condition that quantum theory holds true. Quantum mechanics describes microscopic particle systems, such as electronics, atoms and molecules, that is, particles of small mass. It also requires that particles exist in a small spatial range. For example, when electrons are in the small spatial region of atoms or molecules, quantum theory needs to be used to describe it, and the principle of quantum superposition is applicable, and quantum entangled states may exist. Therefore, the condition for generating a quantum entangled state is that there exists an interacting small-mass particle system that is localized within a small spatial region. That is, the conditions for the establishment of quantum theory must first be met, and only then can the principle of quantum superposition hold. Furthermore, if the quantum state of each particle is a bound state and there is also a conserved quantity between the quantum superposition states, then the particle system can generate a quantum entangled state.

Quantum entangled states can occur between electrons within an atom, between electrons, between atoms, between molecules, and between atoms and molecules. They can also appear within atomic nuclei, between protons, neutrons, and the quarks within them. Quantum entanglement exists in superconductivity, superfluidism and Bose-Einstein condensation phenomena, which are the manifestations of quantum entanglement in macroscopic quantum phenomena, which respectively come from the statistical results of a large amount of microscopic quantum entanglement between electrons, atoms and molecules For massive macroscopic objects, they exhibit classical properties that cannot be described by quantum theory, and the principle of quantum superposition does not exist. Therefore, quantum entanglement does not exist between massive macroscopic objects. The so-called quantum entanglement **phenomenon** of a massive Schrodinger's cat does not exist.

As we have known in the previous discussion, when the system spacing approaches the quantum characteristic scale, that is, a very small spatial area, quantum effects become prominent and must be handled by quantum mechanics, the principle of quantum state superposition is **effective,** the **Quantum entangled states may be existed**. When the system scale is much larger than the quantum characteristic scale, that is, a large spatial area, the quantum effect is very weak and can be dealt with by classical mechanics. The principle of quantum state superposition does not hold. In this case, the quantum entanglement does not exist. For microscopic particles such as electrons or photons with very small masses, if they are in large or very large spatial regions, the quantum effect is very weak and can not be dealt with by quantum mechanics, the principle of quantum superposition no longer holds, there is no quantum entanglement phenomenon between them. Therefore, the photon pairs emitted by the Mozi satellite from space, as well as those in quantum communication, are not entangled photons but correlated photons.

A pair of electrons or photons generated by a source, including photon pairs produced by spontaneous parameter transformation, are not quantum entangled states but merely quantum correlated states. Quantum entanglement is a quantum phenomenon that exists only in extremely small spatial regions, not in large spatial regions. Consequently, in large spatial regions, issues such as the instantaneous collapse of particles during measurement, infinite propagation speed, and non-locality do not arise. Whether in micro or macro systems, phenomena occurring within large spatial regions must adhere to the law of causality, realism and the principle of locality, that is, Einstein's view is correct. In conclusion, quantum entanglement is a microscopic quantum phenomenon that only exists in extremely small spatial regions. In large spatial regions, what exists are quantum correlation state rather than quantum entangled states.

In summary, quantum entanglement is the interaction of microscopic particles within the extremely small spatial region where quantum theory holds, quantum superposition states are formed by the superposition principle. When there are conserved quantities between the superposition states, quantum entanglement states are formed. When the distance between particles increases to the point where quantum theory fails, the superposition principle no longer holds, and the quantum entangled state disappears, becoming a quantum correlated state. A pair of microscopic particles generated by a source, whose physical quantities satisfy some conservation laws, cannot form a quantum entangled state, but can form a quantum correlated state. For microscopic particles without interaction or those freely distributed in a larger spatial area, neither quantum entangled states nor quantum correlated states can be formed. For any macroscopic object system, an entangled state cannot be formed.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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