Proceedings of the 2023 International Conference on Mathematical Physics and Computational Simulation
DOI: 10.54254/2753-8818/10/20230302

State-of-art applications and the function of quantum entanglement in quantum information

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Abstract. Quantum information is a cutting-edge technology that has numerous applications. It mainly makes usage of some quantum entanglement characteristics and uses the quantum entangled state as a carrier for information transfer. Therefore, compared to traditional information, quantum information has excellent features, e.g., stronger security and reduced susceptibility to interference. This article introduces the definition, concept, characteristics and history of quantum entanglement and quantum information. To be specific, this study lists the applications of quantum entanglement in communication and radar. In addition, it gives an outlook on the future function of quantum entanglement in quantum information based on the advantages and disadvantages of quantum entanglement. Contemporarily, the field of physics is rapidly advancing in both quantum entanglement and quantum information, and there have also been significant technological advancements. In experiments, scientists have been able to extend the transmission distance of quantum information to great distances. At the same time, scholars are looking for ways to minimise the interference of quantum information during transmission. In constant exploration and experimentation, the experimental results have inspired scientists to explore the deeper realms of quantum information.

Keywords: quantum entanglement, quantum information, quantum teleportation, quantum key distribution, quantum radar.

1. Introduction

As technology progressed, the focus of research shifted from the macroscopic to the microscopic level, and quantum physics was born. Among the various fields of quantum mechanics, quantum entanglement is one of the major discoveries in the history of human physics.

The transmission of information is an integral part of people's daily lives today. It can break the limits of space and allowing us to communicate quickly over long distances. However, traditional communication methods are increasingly unable to meet the demands for speed, capacity and confidentiality. As a result, people are looking for help at the microphysical level. Quantum entanglement has some principles and it has the ability to be applied to the fields of messaging and cryptography [1-3]. At the same time, there are interactions between mutually entangled quanta that transcend space [4]. These may enable it to help people to fulfil their needs in messaging, making it one of the hottest objects of research in this field.

This article will investigate the state-of-art applications and the function of quantum entanglement in quantum information. This is the format for the remaining portion of the paper. Sec. 2 will introduce the basic principles of quantum entanglement and the history of its development. Sec. 3 will give examples and introduce cutting-edge applications of quantum entanglement in quantum information. Quantum teleportation, quantum key distribution, and quantum radar are a few examples. Sec. 4 will analyse the limitations and prospects of quantum entanglement as applied to quantum information. Eventually, Sec. 5 will give a conclusion of this article.

2. Quantum entanglement & quantum information

2.1. Definition

Quantum entanglement is the process of fusing the properties of different substances into a single state when multiple particles interact with each other. This means that two substances in an entangled state will form a relationship such that, regardless of the distance between them, if the properties of one substance change, the properties of the other substance with which it is entangled will also change accordingly. These changes are not affected by distance. In two entangled particles, an entangled state$|\psi\rangle$ is formed. Using the Dirac notation, this can be expressed as:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle\otimes|\downarrow\rangle - |\downarrow\rangle\otimes|\uparrow\rangle) \tag{1}$$

In the Equation (1), $|\uparrow\rangle$ means the particle spin is up-spin and $|\downarrow\rangle$ means the particle spin is down-spin. In quantum mechanics, the information about the nature and state of a particle conveyed by quantum entanglement is known as quantum information. Unlike what is referred to as information in everyday life, quantum information is usually measured in quantum bits. Similar to binary, a quantum bit is a quantum system with only two states.

2.2. Development history

At the Solvay Conference in 1927, two rival schools of thought were formed, the Copenhagen School and the Copenhagen Opposition. These two schools of thought made arguments about quantum mechanics at the conference. The Copenhagen School supporting the existence of quantum mechanics and the Copenhagen Opposition putting forward a negative view.

Einstein, Podolsky and Rosen published a milestone in the Physical Review Letters in the year of 1935 [5]. The three authors address the incompleteness of quantum mechanics in the paper [5]. For a long time after the essays by Einstein, Podolsky and Rosen was published in the year 1927, not much attention was paid to this area. In 1964, Bell published a paper supporting fixed-domain positivism and proposed Bell's inequality, which has the mathematical form shown in Equation (2) [6]:

$$|P_{xz} - P_{zy}| \leq 1 + P_{xy} \tag{2}$$

Numerous experiments have been conducted by scientists to validate Bell's inequality. Clauser and Freedman first completed the experiment in 1972. In 1982, Aspect et al. performed experiments to verify Bell's inequality. Although the experimental results are completely consistent with those made by quantum theory, they are diverged by 5 standard deviations from Bell's inequality predictions [7]. In 1998, university students in Innsbruck sent photons flying 400 metres apart. The experimental results deviated from the local hidden variable theory predictions by 30 standard deviations [8]. Although these experimental findings are in line with predictions made by quantum mechanics, they are not in line with those made by the hidden variable theory of definiteness. Therefore, it can be tentatively proved that the theory of fixed-domain hidden variables is not valid, and further confirmed the reality of quantum entanglement.

In recent years, researchers have continued to work on the study of quantum entanglement. Bennett and Brassard proposed the BB84 Protocol and Eckert proposed the E91 Protocol [9, 10]. On 16 June 2017, the Mozi satellite distributed two quantum entangled photons to more than 1200 km apart, achieving for the first time the continued quantum entanglement of these two photons [11]. This study once again verifies the incorrectness of Bell's inequality. Therefore, it favours the development of quantum entanglement. On 25 April 2018, a team led by Sillanpää successfully entangled two 15-micron-wide, solitary vibrating tympanic membranes made of 10 aluminium atoms and made them

DOI: 10.54254/2753-8818/10/20230302

interact for about 30 minutes, in a superconducting microwave circuit and at close to -273.15°C. This experiment demonstrates macroscopic quantum entanglement [12, 13]. Fig. 1, Fig. 2, and Fig. 3 show a diagram of the experimental set-up [14, 15].

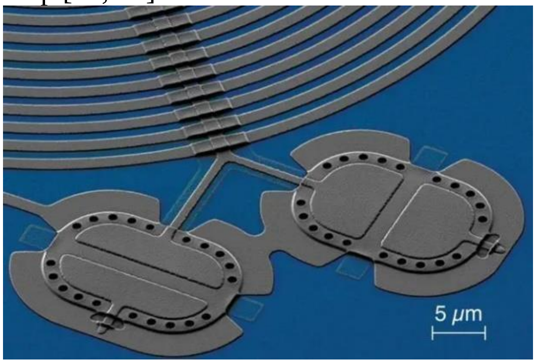

Figure 1. Scanning electron microscope photograph of the aluminum tympanum used in the experiment (pseudo-colour image).

Figure 2. Schematic diagram of the experimental system.

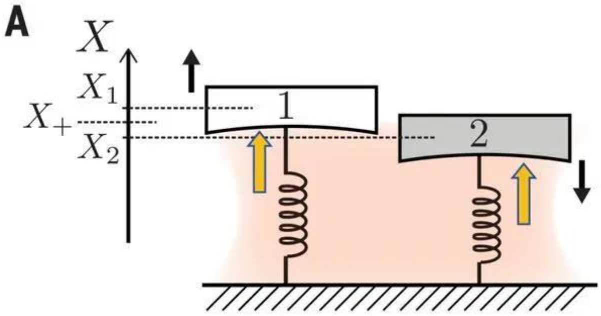

Figure 3. Schematic diagram of the experiment.

3. Applications of quantum entanglement

There are not many applications that apply to a broader scale because quantum mechanics is a science that is still relatively new. As a result, applications of quantum entanglement are still mainly in the experimental part.

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3.1. Quantum communication

Quantum mechanics is characterised by Uncertainty Principle, Collapse Measurement and No-Cloning Theorem [1-3]. Once a quantum message receives interference during transmission, it immediately changes state and will be detected by both the sender and receiver. Quantum communication therefore has a security that is difficult to eavesdrop and computationally decipher. Quantum communication is mainly divided into quantum teleportation and quantum key distribution. Quantum teleportation of states makes use of dispersive quantum entanglement with the conversion of some physical messages. It is a method for sending a quantum state and the quantum information it contains to a destination that is any distance away [16]. The Fig. 4 shows the schematic diagram of quantum teleportation [17].

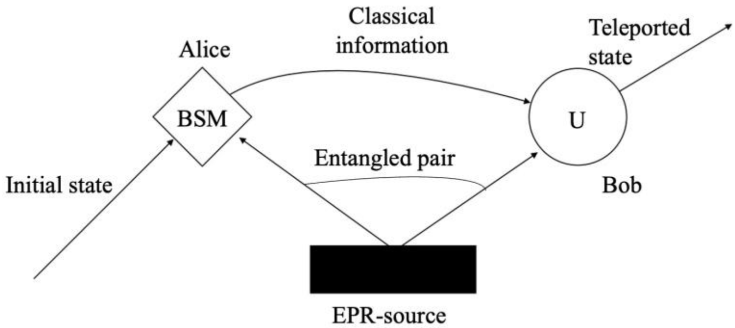

Figure 4. Fundamentals of quantum teleportation.

The first proof of principle experiment of quantum teleportation was done indoors by Zeilinger's group in Austria in 1997 [18]. This group went on to increase the distance of quantum teleportation to 600 metres in 2004 [19]. In 2005, Pan of the University of Science and Technology of China and others achieved a bidirectional quantum entanglement spread of 13 kilometres [20]. This distance broke the previous record [20]. At the same time, they have verified the feasibility of distributing entangled photon pairs between outer space and Earth [20]. In August 2012, scientists from China, including Pan, successfully achieved international quantum teleportation and entanglement distribution in free space on the order of 100 km [21, 22]. This is the first time this experiment has been done in the world. Quantum teleportation is the simplest of the many types of quantum communication. In recent years, scientists around the world are still working on quantum teleportation.

In addition to quantum teleportation, quantum key distribution is also an important manifestation of quantum entanglement applied to quantum information. Text that is normally seen and from which information can be obtained directly is called plaintext. Texts that people cannot read, that are encrypted or that have been disrupted in some ways are called ciphertexts. There is a correspondence between the plaintext and the ciphertext. Converting plaintext into ciphertext (encryption) or deciphering ciphertext into plaintext (decryption) requires a parameter, namely a secret key. Quantum key distribution belongs to the cryptographic field of cryptography. It makes use of the quantum mechanics properties, which was mentioned by the author in the previous section, enabling two parties to a communication to generate and share a key. This secret key is random and secure and can be used to encrypt and decrypt the message, thus securing the communication [23]. The protocols involved in quantum key distribution are the BB84 protocol (its basic principle is shown in Fig. 5), the BBM92 protocol and the E91 protocol [9, 10, 24]. In February 2022, the world record for secure transmission distance for quantum key distribution was raised by more than 200 km, bringing fiber optic quantum key distribution to 833 km. This achievement was accomplished by Professor Han and his collaborators from Academician Guo's team at the University of Science and Technology of China [25].

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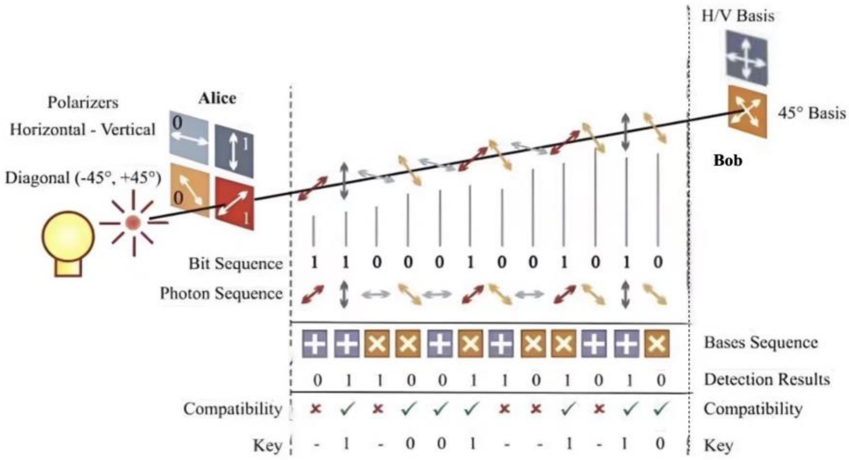

Figure 5. The basic principle of BB84 protocol.

3.2. Quantum radar

Radar is used to calculate the position of the object to be measured by transmitting an electromagnetic signal and receiving the reflected signal from the object to be detected through time and angle. It is mainly used for early warning, surveillance, weather forecasting, tracking, etc. [26]. Due to objective physical laws limiting its measurement accuracy, conventional radar can no longer meet the increasingly demanding requirements of today [27]. In contrast to conventional radar, quantum radar utilises quantum phenomena and is a quantum remote sensor for target state sensing and information acquisition, which is showed in Fig. 6 [28]. Quantum radar can be used to identify stealthy combat aircraft. At the same time, it is not subject to interference from other radars.

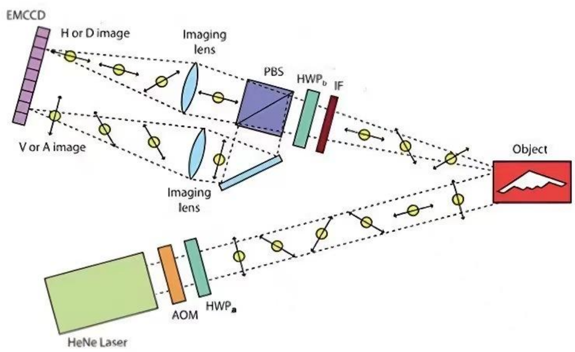

Figure 6. Quantum radar utilises quantum phenomena and is a quantum remote sensor for target state sensing and information acquisition.

4. Limitations & prospects

Quantum entanglement has some aspects of unparalleled superiority. If it is applied to quantum information, it can largely secure information and improve transmission efficiency. Quantum entanglement has wonderful characteristics not present in conventional physical phenomena. As a result, it might have a unique function in quantum communication [29]. However, quantum entanglement still has certain limitations and technical difficulties. For example, the way to avoid noise interference, the rigour of the conditions required for the experiment, the difficulty of measurement and the number of manipulable quanta. These limitations and technical difficulties can make it difficult for both sides of the communication to tell whether the message has been interfered with by external factors or is being listened to. At the same time, these problems have led to many applications of quantum entanglement being done only in the laboratory, but not being applied on a large scale. In the future, the applications of quantum entanglement might be extended. It can provide security for national information. At the same time, quantum entanglement will also make a great contribution to quantum computing. Scientists still need to explore and try a lot to find the right materials and conditions for their experiments. Perhaps someday in the future, quantum entanglement will be widely used, coming into people's homes, and participating in their lives.

5. Conclusion

In summary, this study investigates the state-of-art applications and the function of quantum entanglement in quantum information, and shows the limitations and prospects of them. Overall, these results offer a guideline for the development of quantum information. However, one thing is for sure, once researchers have achieved the wide application of quantum entanglement, it will be a very significant milestone in the history of human physics.

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