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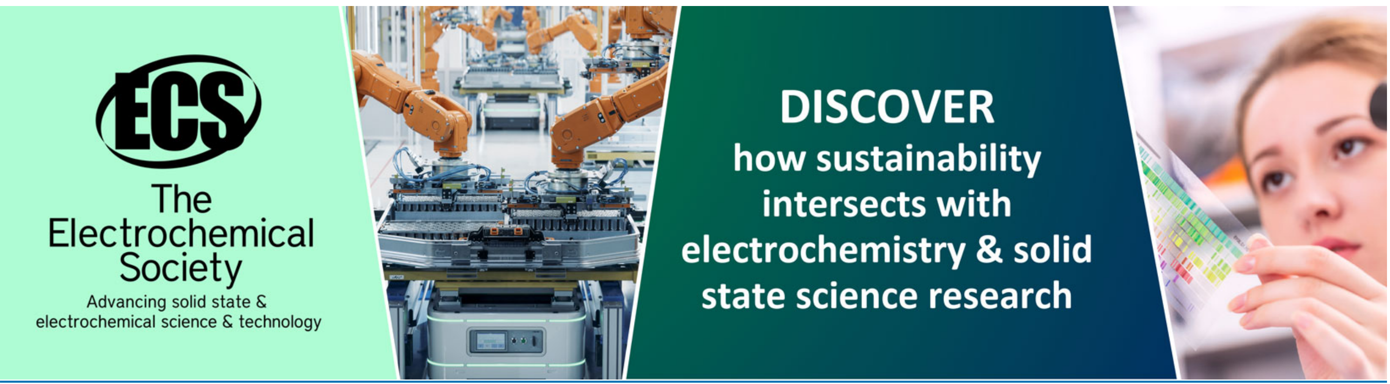

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Some Major Studies in Experimental Verifications of Bell Inequality

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Abstract. Bell inequality plays a crucial role in the debate between quantum mechanical completeness and local realism. It vigorously promoted researches on these aspects, macroscopic quantum superposition states, especially entangled states, and it has brought the debate from theory to experiment, which generated a new discipline, quantum information theory. Thus, this work briefly summarizes some major situations in the verification process of Bell inequality. At the same time, this work analyses existent some problems in the verification process of Bell inequality, and states own perception for the debate.This work can help people better understand the foundation knowledge of quantum information theory, thus quantum information theory can be applied to more actual situations.

1. Introduction

Since the early 20th century, the debate between the quantum mechanical completeness and local realism started, Bohr is supporting the quantum mechanical completeness, while Einstein is holding viewpoint of the local realism, the debate between them had a balance in power for a long time. Though a variety of tortuous and difficult courses, the quantum mechanical completeness has been occupying mainstream thought. The argument had a significant transition in the middle of the 1960s. In 1964, Bell proposed a well-known inequality (Bell inequality) [1]. According to this inequality, quantum mechanical completeness and local realism can be experimentally judged, if experimental results violate Bell's inequality, the former is right, otherwise, the latter is right.

The Bell inequality put forward the quantization criteria for the duel between the local realism and quantum mechanical completeness, which makes experimentally distinguishing two theories become possible. The Bell inequality not only helps people further understand the foundation knowledge of quantum information theory but also introduces it to a wide range of practical applications. Since the Bell inequality was proposed, many scientists have successively verified the above two theories experimentally. Some basic situations in Bell inequality experimental verifications are summarized in this paper, including a few major advances and transitions, existent some problems and corresponding solutions, some especial classes, and some recent research progresses.

2. Early existent some problems in the experimental verification of Bell inequality

The entire historical process of testing Bell inequality can be roughly divided into three stages, also known as the “three generation tests” [2]. The first-generation test began in the early 1970s, the

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entangled photon pairs are generated by atomic cascade or annihilation radiations [3], and most of the tests are the Clauser-Horne (CH) type Bell inequality [4]. In 1972, Freedman and Clauser used calcium as the light source [5] first to test Bell inequality, the calcium was heated to produce a series of energetic calcium gas in the oven. When the calcium gas flows out of the oven, it is illuminated with a powerful purple light as shown in Fig.1. Some energy of light is absorbed by electrons in calcium atoms, which leads to electrons' energy increased (this small change is one example of quantum transition). After a short period, electrons with excess energy will return to their normal state, most electrons emit an individual photon, but some electrons (about one in a million) emit two photons (a green photon and a purple photon), and their polarizations are naturally correlated, and entanglement makes two photons correlated each other.

Although most experimental results are consistent with quantum mechanical predictions, but early experiments were very close to the limitation of the device, resulting in variable results, thus they have no good credibility. At that time, there were three main loopholes, local, detection efficiency, and the freedom-of-choice loopholes in the experimental verification of Bell inequality. Local loophole: The two entangled photons are too close to rule out randomness, the violation of Bell inequality may be caused by a certain kind of communication with no greater than the speed of light. Detection efficiency loophole: The detector has very low efficiency, it only can detect 5% ~10% of all photons, thus a hypothesis that the detected part photons represent all photons is needed. Freedom-of-choice loophole: To fill the local loophole, random numbers are introduced, however, another loophole is simultaneously introduced because the random numbers can be affected by the unknown hidden variables.

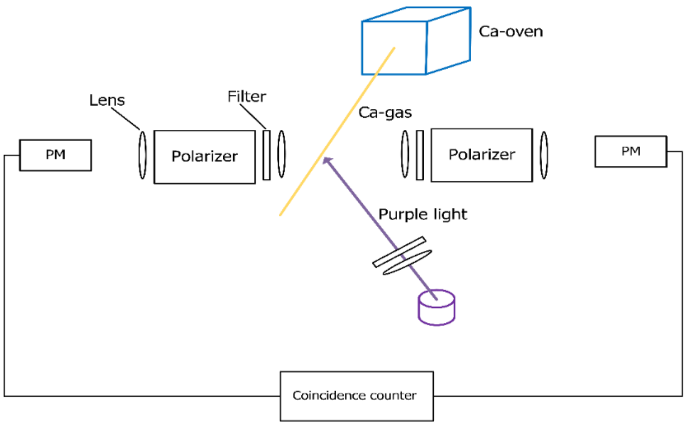

Figure 1. Schematic diagram of first experimental verification Bell Inequality, where PM is photomultiplier tubes used to detect photons, the coincidence counter is used to record the number of photons detected.

3. The most influential experiments

The second-generation detection began in the early 1980s, the entangled light source mainly used twin photons excited by laser-atomic cascade radiation. The violation of Bell inequality had been more clearly presented by experimental results at this stage. In 1981-1982, French physicists Aspect's team published three papers [6-8] to report results of their experiments in succession, all experimental results were in accord with quantum mechanical completeness and violated the Bell inequality. Among the third experiment is particularly significant and the most influential, Aspect realized that previous experiments did not reach a certain result because of the defects of existing in experimental equipment. In order to improve this situation, a double laser with controllable power was used to illuminate the calcium atoms, which can generate more entangled photons. In addition, Aspect also made some other changes to the experiment, and considered that summarizing the elusive quantum entanglement behavior is difficult because the results were always suspected misleading the people. For example, perhaps the acquired results of polarization were measured by two side detectors working together in some way, which is generally impossible but can happen in some cases. Relying on a little spark of genius, Aspect invented a device that can change the direction of detection to make detectors unable to be in a conspiracy when photons are still in flight according to Bohm's suggestion many years ago. This way can close the local loophole by comparing with each other the experiment results with the detector's various setting angles. The experimental principle is as shown in Fig. 2, Aspect team's experiment obtained extremely high comments because this experiment firstly considered locality loophole, and the results were consistent with the predictions of quantum mechanics, violating the Bell inequality with five standard deviations. However, some people also pointed out that this experiment has a fatal weakness in that the switch is quasi-periodic (no randomness), and parameters awkwardly overlap, thus the experiment cannot entirely exclude the locality loophole.

In 1999, Aspect also thought that the distance of two polarization analyzers is too small (12m) to randomly set the polarizer, signals need 40ns from one analyzer to another at the speed of light, while setting polarizer once demands 10ns [9]. Aspect also pointed out two test stations that had been separated 400 meters in Weihs group's experiment [10], thus physicists had 1.3us time to randomly set the polarizer and recorded test results, and experimental results clearly violated the Bell inequality, which strongly supported quantum mechanical predictions and truly closed the locality loophole because of implemented Einstein locality conditions for the first time.

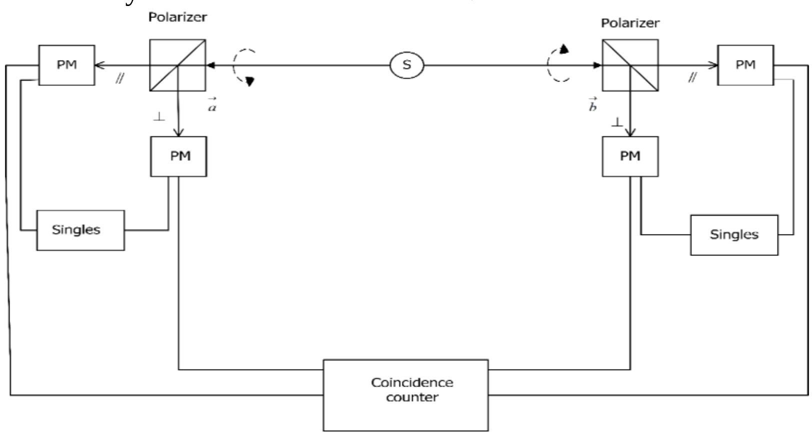

Figure 2. Schematic diagram of Aspect team's experiment, PM is photomultiplier tubes used to detect photons. A polarizer is set up at about 6m from the light source on both sides, and the polarizer rotates around the photon incident axis. The coincidence counter is used to record the number of photons detected

4. Spontaneous parametric down-conversion technology

Though lasers can more reliably get entangled photons, but it is a complex thing to determine two photons as entangled pairs rather not random and unconnected photons. With the further understanding for entanglement, people strenuously designed a more reliable source to produce strange entangled particles. Spontaneous parametric down-conversion, a special phenomenon that occurs in crystals when crystals are illuminated with ample intensity laser, some photons after absorbing energy reradiate no longer one photon rather than two photons. The third-generation detection started in the late 1980s, Ou [11] and Shih [12] two groups pioneered using the entangled photon pairs by spontaneous parametric down-conversion generated to test the Bell's inequality. There are three very large advantages using this technique. Firstly, although photon pairs are still in a significant minority, this technology produces more entangled photon pairs compared with laser-atomic cascade radiation. Secondly, this physical environment is more stable. Finally, the most important point is that not only the two photons entangle each other, their direction from the crystal is more predictable, if one photon is emitted from direction A, another will also always be launched from B. The schematic of spontaneous parametric down-conversion is shown in Fig. 3, and many experiments have used it to verify the Bell inequality, such as the literature [13-14], and all experimental results violated the Bell inequality.

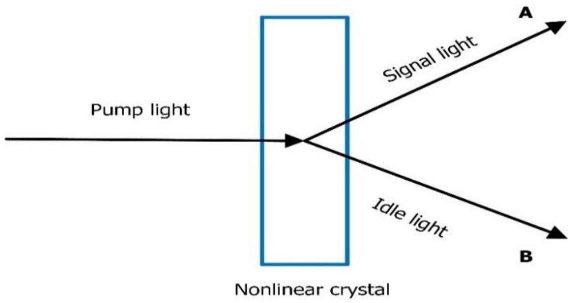

Figure 3. Schematic of the spontaneous parametric down-conversion process [15]

5. Simultaneously closing several experimental loopholes

With the improvement of detector efficiency, the detection efficiency loophole has been gradually filled. In 2001, Rowe's group used trapped beryllium ion pairs to verify Bell inequality, the experiment closed the efficiency loophole with 98% efficiency [16], This experiment caused a great sensation after publication on nature, its detection efficiency reached almost 100%, and many famous scholars also noted that it had closed the efficiency loophole. Although it did not simultaneously close the local loophole because two ions were too close.

Locality and efficiency loopholes are considered as two biggest in Bell's inequality test experiments. Weihs and Rowe groups' experiments are the two most important of numerous experiments completed since 1982. However, some austere scholars (they usually support locality realism) believe that locality and efficiency loopholes must be simultaneously closed in the same experiment, rather than alone closed a loophole like experiment completed, only in this way the local realism theory can be finally ruled out.

In 2016, Giustina and his colleagues reported an experiment [17], they simultaneously closed three loopholes, freedom-of-choice loophole by using a random number generator, locality loophole by space-like separated to finish selection setting, testing and other work, and detection efficiency loophole by using superconducting detection device with high efficiency, this experiment violated Bell inequality with high data statistics. But some scholars commented that Giustina team's experiment did not close the locality loophole in many cases, for example in fluid dynamics [18]. Some scholars also argued that although have conducted many experiments [19], there is no evidence to indicate quantum entanglement existence, and these experiments' results are not reliable, because they rely on specific methods.

6. Some especial entangled objects classes

During the validation of the Bell inequality, the objects tested mainly are entangled photons with spin 1, however the original Bell inequality discussed entangled pairs with spin 1/2, In addition, continuously variable momentum and position are needed to test Bell inequality in the original EPR paper, however most experiments completed are based on discrete spin or polarization variables, thus some people started to question experimental conclusions from a rigorous standpoint. Based on this cognition, some other experiments were carried out. In 1989, Franson used continuously changeable energy and time to examine the Bell inequality [20]. In 1990, Rarity and Tapster finished an experiment [21], experimental results clearly violated the CHSH inequality with 10 standard deviations based on phase and momentum variables. In 1995, Pittman et al reported an experiment [22], the entangled photon pairs with orthogonal polarization were generated from the II class parametric down-conversion, the experiment violated the Bell inequality using continuous variables.

In 2003, Giorgi et al reported an experiment [23] that its polarized entangled photon pairs are engendered by a high luminosity source, the CHSH inequality is violated with 213 standard deviations. In 2004, Moehring and his collaborators implemented the measurement of the Bell inequality by using various kinds of particles (an atom and a photon) [24]. In 2009, Xiaosong Ma et al completed an experiment [25] that path (momentum) and polarization degrees of freedom were entangled hybrid to violate the CHSH inequality with 24 standard deviations. In the same year, Ansmann et al reported a paper in Nature [26] that they closed the detection efficiency loophole in solid-state systems.

7. Some recent research progresses
In 2015, Shashi Prabhakar et al used optical beams with phase singularity to check Bell inequality [27]. In 2016, Hsinpin Lo et al violated Bell inequalities for 16 dimensional bipartite systems [28]. In the same year, a new method based on the finite group was used to test Bell inequalities in the more complicated S4 symmetry system [29]. In 2018, Jiaqiang Zhao et al violated a kind of new Bell inequalities [30] by using generalized Greenberger–Horne–Zeilinger (GHZ) entangled state [31]. In 2021, the CHSH inequality was checked by applying the phase-randomized weak coherent states [32], in the same year, Peng Xu et al analyzed Bell's inequalities by continuously monitoring a system with two-coupled superconducting qubits [33]. In recent years, scientists devote to using various new methods to test Bell inequality, which makes the experimental violation of Bell inequality found in more cases.

8. Conclusion
In this paper, some major situations in the experimental verification of Bell Inequality were introduced, three main stages with entangled photons generation technologies were briefly introduced, three main loopholes and related remedy experiments were specifically illustrated, this significant transition was declared in detail, and some special and results prominent experiments were also particularly explained, some recent research progresses were analysed. The experimental verification of Bell inequality is crucial for the development of quantum information theory. At present, locality and efficiency loopholes have been filled respectively. However, this problem that locality, detection efficiency, and freedom-of-choice loopholes simultaneously are closed in one experiment exists arguing. In addition, the question existing in the research object has been clarified by many experiments with various entangled objects classes. The experimental verification of Bell inequality has been carried out for nearly half a century, although some scientists question the violation of Bell inequality, the mainstream thought of the scientific research community believes that quantum mechanics is complete after going through a lot of experimental verification. In our viewpoint, there is no absolute truth for the debate between quantum mechanical completeness and local realism, however, according to the existing experimental results, quantum mechanical completeness is correct with 80% probability. We hope this debate can get a consistent view in the scientific research community in the near future.

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