DOI: 10.54254/2753-8818/10/20230307

Principle and state-of-art applications of quantum information

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Abstract. Al. Last year, the Nobel Prize in Physics was awarded to Alain Aspect, John F. Clauser and Anton Zeilinger for their experimental verification of the violation of Bell's inequality by quantum mechanics using entangled photons, which pioneered the science of quantum information; in the same year, the 28th Solvay Conference on Physics, with the theme "Quantum Information In the same year, the 28th Solvay Conference on Physics, with the theme of "Quantum Information Physics", reviewed the development of quantum information in the last decade and the future direction. It is clear that the world of physics is now focused on the subsequent progress of quantum mechanics. In this paper, I will introduce the background of quantum information and explain in detail, clearly and thoroughly, the basic theory of quantum information and its specific applications. By describing the two fundamental and most important properties of quantum information, quantum entanglement and quantum unclonable, quantum information will give the reader a comprehensive understanding of the significance and usefulness of quantum information. This paper aims to help physics students to build up their basic knowledge of quantum information by explaining the basic theory of quantum information and helping them to expand their knowledge of quantum information.

Keywords: quantum information, quantum physics, quantum applications.

1. Introduction

The origin of quantum information theory can be traced back to the observations of Albert Einstein and his collaborators in the 1930s. They noticed that the correlation between the parts of a quantum system could be counterintuitive, and this phenomenon was called "quantum entanglement" by Schrödinger. Quantum information theory was originally designed to perform some classical information processes with the aid of quantum mechanics, but as the research progressed, quantum mechanics gradually intertwined with classical information theory to produce quantum information [1]. As stated by two professionals Bennett and DiVincenzo - the generalization from classical information to quantum information is like the generalization from real numbers to complex numbers [2].

Unlike classical information, quantum information possesses the special property of being unclonable, but can associate two points at any position in space; in contrast to the basic storage unit of classical information, the bit, quantum information forms its own storage unit called the quantum bit; the flourishing of quantum information has not only contributed to the soaring of the field of physics exploration, allowing people to move from the exploration of the macroscopic exploration of the macroscopic realm into the microscopic, helping to demystify deeper and more thorough understanding of the fundamental norms of the world mankind lives in. The extension of expertise to other fields is large enough to help other academics solve their problems with the help of their own coherent and integrability properties. For example, quantum states provide the basis for characterizing Morse's principle [3]; quantum coherence can be used to study quantum mechanical models and quantum mechanical behaviour models, which can also be used to design transistors of great importance to human technological development. Moreover, quantum coherence affects neural firing through voltage-gated ion channels that allow people to generate complex ideas [2], and can be used to ensure the integrity and stability of information during transmission; quantum entanglement has become a central part of communication development for high transmission speed, high wireless capacity and more security compared to traditional information; quantum encryption and quantum computing are based on the quantum state unclonable theorem to protect Quantum encryption and quantum computing are based on the quantum state unclonable theorem to protect their own security, quantum unclonable functions reduce the cost of security identification [4], and quantum devices can easily simulate nature, which helps in the development of new drugs [5]. Thus, quantum information has made a significant contribution from small to fast life and personal privacy security [6].

The purpose of this article is to provide an overview of the basic concepts and properties of quantum information for beginners or those who are interested in this aspect of quantum information and want to explore more applications of quantum information, and to help readers lay a good foundation for quantum information research with insights from leading physics experts. The rest part of the paper is organized as follows. The Sec. 2 will introduce quantum information and then illustrate the basic and pivotal characteristics of quantum information. The Sec. 3 will expound in detail the applications based on the quantum information from academic aspect and life aspect. The Sec.4 will explain both limitation and prospect of quantum information. The Sec.5 will be a conclusion of this paper.

2. Quantum information

The quantum itself is not an entity, but a set of records that can be observed recorded and operated, commonly known as states. Quantum information is subordinate to quantum mechanics, a theoretical system that studies actions such as information encoding and transmission through the various coherent properties of quantum states, a communication method that uses quantum superposition states and entanglement effects for information transfer [7]. Based on the three principles of quantum mechanics - uncertainty, measurement collapse and unclonable, i.e., possesses properties that cannot be eavesdropped or computationally deciphered, making it a secure and highly confidential way of communication [8]. The basic unit of storage for quantum information is the quantum bit, a quantum system with only two states. In a nutshell, information represented by microscopic particle states is called quantum information.

2.1. Basic principles

Electrons rotating around a single atom can be stabilized in two states, or polarization states. The states of the quanta are represented by the Dirac marks bra"< |" and ket"|>" and are divided into the ground state and the activated state. The state with the lowest energy is the fundamental state, denoted as |0>, called cat0, when the electron spin up; the state with higher energy than the fundamental state is the activated state, denoted as |1>, called cat1, followed by the first activated state, the second activated state, etc., when the electron spin down. When energy is absorbed, for example, a beam of light with high energy shines on the atom for a long time, the state can change from |0> to |1> and vice versa. However, if the light time required for the transition is reduced, it is possible to position this electron in a state somewhere in the middle of the ground and activated states, denoted as a bit state $|\Psi\rangle$. The bit state is the superposition of the quantum bits |0> and |1> with the formula

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{1}$$

One uses this state to represent the information. This means that this information is quantized and becomes quantum information.

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2.2. Quantum entanglement

Quantum entanglement is arguably the most controversial physical phenomenon in quantum mechanics ever, mainly because of the great skepticism generated by the famous physicist Albert Einstein. Subsequently, together with Podolsky and Rosen, he proposed the EPR paradox, which aims to prove the incompleteness of quantum mechanics. The trio's criterion for positivity is the "definiteness hypothesis" - known in the physical view of reality as definite positivity - that no information can act or propagate instantaneously beyond space-time, and that the limit of the speed of propagation can only be the speed of light. However, the "non-deterministic hypothesis" proposed by Niels Bohr et al. 1964, John Stewart Bell, a supporter of Einstein, believed in deterministic positivism and derived Bell's inequality to prove it.

$$| \mathrm{Pxz} - \mathrm{Pzy} | \leq 1 + \mathrm{Pxy} \quad (2)$$

However, in 1982, experiments at the Institute of Theoretical and Applied Optics in Orsay, France, yielded that bringing data into Bell's inequality resulted in deviations from five standard equations [9]; in 1998, scientists at Insbruck university made photons fly out 400m apart, deviating from 30 standard equations of Bell's inequality. The establishment of these counterexamples of Bell's inequality implies the fact that the fixed-domain realism is wrong, which also proves the existence of quantum entanglement. Quantum entanglement, or the coherence of quantum states, is in fact a microphysical phenomenon, i.e., at a distance of 10,000 meters, two or more particles separated by a certain distance must cause a corresponding change in the system in which the first particle is located by some quantum measurement. Thus, the observation of one of the particles can automatically provide information about the other entangled particles [10]. The quantum state of a complex system $| \psi \rangle$ can be expressed as a direct product of several isolated subsystems $| \psi 1 \rangle, | \psi 2 \rangle, \ldots, | \psi n \rangle$ (which are independent of each other and not entangled). The expression can be given as follows:

$$|\psi > = |\psi 1 > \otimes |\psi 2 > \otimes \ \ldots \otimes |\psi n > \quad (3)$$

when a quantum system cannot be represented as a direct product state of several single quantum bit systems, the quantum system is in an entangled state.

2.3. Quantum unclonable theorem

In 1982, in the paper "Single quantum state is not clonable" by Wootters, Zurek and Dieks, it was shown that the linear characteristic-quantum state of quantum mechanics is a union of multiple possibilities and not a unique value [11] , i.e., forbidding each replica state to be identical to the initial quantum state is exactly the same. Thus, three physicists proposed the single-quantum unclonability theorem based on this inherent property of quantum mechanics - that in quantum mechanics, there is no physical process that achieves an exact replication of an unknown quantum state such that each replicated state is identical to the initial quantum state [12].

The quantum unclonability theorem can be shown and understood in terms of a two-state quantum system (two quantum systems of mutually independent quantum states). $|\mathbf{c} >$ expressed as an arbitrary quantum state in two dimensions, its quantum cloning process can be expressed as

$$|c > |D >_x \rightarrow |c > |c > |D^*{}_c >_x \quad (4)$$

The right side of the equation $|c > |c >$ indicates that both the initial and replica modes are in the $|c >$ state, $|D >_x$ is the quantum state before the device (clone) and $|D^*{}_c >_x$ is the quantum state after the device. If there exists a transformation of the above equation, then the basic state $|0 >$ and the activated state $|1 >$ should have:

$$|0 > |D >_x \rightarrow |0 > |0 > |D^*{}_0 >_x \quad (5)$$

$$|1 > |D >_x \rightarrow |1 > |1 > |D^*{}_1 >_x \quad (6)$$

Here, assume $|\mathrm{c} >$ is an arbitrary superposition state, denoted as:

$$|c > = \alpha |0 > + \beta |1 > |c > |D^*{}_c >_x \quad (7)$$

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However, due to the above equation and the linear character of the quantum, $|c>$ will evolve to:

$$|c>|D>_x = (\alpha|0> + \beta|1>)|D>_x \rightarrow \alpha|0>0>|D^*{}_0>_x + \beta|1>1>|D^*{}_1>_x \quad (8)$$

If $|D^*{}_0>_x$ *and* $|D^*{}_1>_x$ are not constant, both the initial and replica modes given in the above equation are the mixed states of $|0>$ *and* $|1>$(Quantum systems may with probability p1 in quantum state | ψ1⟩ , with probability p2 in quantum state | ψ 2 ⟩ , with probability p n in quantum state| ψ n ⟩ . Therefore, this mixed state should in the probability p 1 , p 2 , ~, p n respectively in quantum state | ψ1⟩ , | ψ 2 ⟩ , ... , | ψ n ⟩ respectively, not in the direct accumulation state $|c>|c>$. If $|D^*{}_0>_x$ *and* $|D^*{}_1>_x$ are constant, then the initial and replica modes given in the above equation will be in the entangled state $\alpha|0>0> + \beta|1>1>$, again, it is not in the direct product state. Therefore, even if it is possible to replicate the state $|0>$ and $|1>$, nor can they replicate their superposition state $|c>$ [1].

3. Applications

3.1. Physics aspects

The applications and contributions of quantum information in academia broaden the perception of the physics academic community and help physicists to set up a deeper direction of inquiry, thus allowing humans to develop a deeper and clearer understanding of the world. All quantum coherence can be used to study complex systems in the quantum state, such as quantum mechanical models and models of quantum mechanical behavior [13], and thus contribute to the development of relevant physics and to bring human knowledge of objective laws from the macroscopic world to the microscopic world; quantum devices can simulate one of the most difficult simulations for classical computers by calculating the properties and behavior of chemical systems and physical devices at the quantum level. Such simulations can have a significant impact in many different areas of expertise, such as drug design and the development of new materials [5]. A sketch is given in Fig. 1.

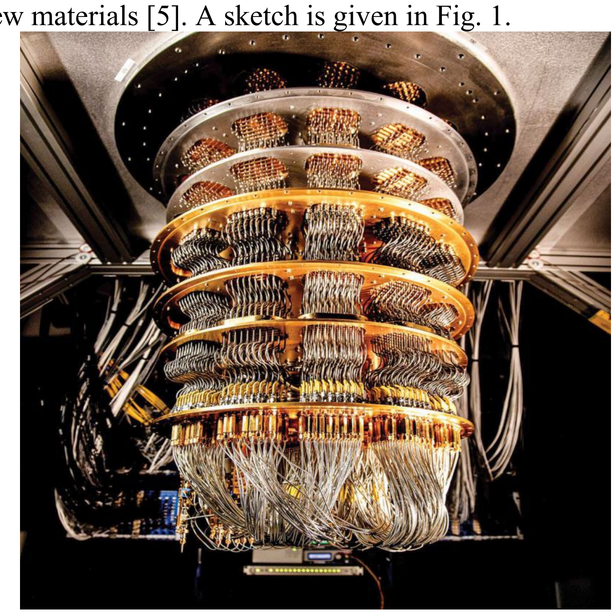

Figure 1. A sketch of quantum computer.

3.2. Life aspects

Quantum coherence can be used to transmit information and ensure the integrity and stability of information [14]. In the 20th century, quantum models have been available to design new technologies, such as transistors [1]. The transistor is the key to our fight against global warming, and it has greatly facilitated human life by allowing new capabilities never imagined before, such as the Internet, smartphones, and memory and storage. Further, quantum entanglement is known as the key to the development of quantum communication applications. From the research, quantum entanglement possesses properties such as extremely high transmission speed and large wireless capacity. The feature of absolute security is also not negligible [5]. The telephone communication and Internet information exchange in life are based on the quantum state unclonable theorem thus protecting the user's personal privacy to a greater extent [15]. A sketch of the quantum entanglements is given in Fig. 2.

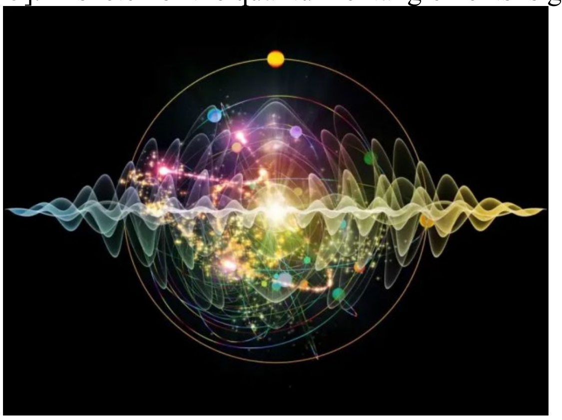

Figure 2. Quantum entangled state.

3.3. Other academic aspects

For quantum biology, quantum coherence makes it possible for voltage-gated ion channels across neuronal membranes to have high transmission rates and selectivity, reducing the risk of quantum decoherence by transferring some of the high energy of ions to surrounding proteins and reducing their kinetic energy. Moreover, the electromagnetic field of the brain may affect neural firing through voltage-gated ion channels, thus allowing the simultaneous triggering of different neural impulses and allowing humans to generate complex ideas [2]. Quantum encryption and quantum computing protect their security based on the quantum state unclonability theorem. On the other hand, the unclonability possessed by the product of quantum physical unclonable functions [13] provides protocols for secure identification tasks and reduces the cost of identification [8]. Additionally, the property of unclonability of quantum states lays a solid foundation for the qualitative Morse principle. The qualitative Morse principle provides no help for the measurement of the system energy by stating that it is impossible to measure the energy of a system precisely in a finite time [3].

4. Limitations & prospects

The current limitation of quantum information is that quantum information is perturbed in many-body systems through chaotic time evolution. Recovering the initial information embedded locally in the system from the perturbed quantum states is a fundamental problem in many cases. However, in 2016-2020, China launched the "Mozi" quantum science experiment satellite to achieve absolutely secure quantum confidentiality communication between two distant places, and put into research quantum entanglement distribution and quantum invisible transmission. Subsequently, the "Nine Chapters" quantum computing system has increased the speed of processing Gaussian boson sampling to one trillion times that of supercomputers. From 2021 to 2025, China will continue to vigorously develop quantum information technology, strengthen original innovation and technology applications, and provide support for industrial transformation and economic development. In this way, it can be seen that although the current level of human knowledge and technical support cannot figure out all the features and characteristics of quantum, the cognition of quantum is still not clear and comprehensive. Nevertheless, with the persistent exploration, this amazing phenomenon of quantum has been able to apply to life and change the perception of universal laws. In the coming decades, the contribution of quantum information will surely further lead mankind to undiscovered places and explore deeper mysteries.

5. Conclusion

In summary, through a detailed explanation of quantum information, quantum fundamentals, quantum entanglement and quantum integrability, and quantum applications, this study finds that the emergence of quantum is extraordinary and significant. It illustrates many previously unknown phenomena, such as the paradox of the definiteness assumption of ERQ even though it does not hold, but proves the emergence of another feature of quantum, i.e., quantum entanglement. At the same time, the quantum unclonable principle also allows the security and confidentiality of quantum information to be enhanced. Its emergence proves the special nature of a single message and fills more possibilities for the content of information dissemination. Further, the application of quantum information theory from scientific research to real life proves that the contribution of quantum information to humanity is infinitely broad. It is able to be integrated with disciplines other than physics to uncover new knowledge, as well as used in communication, which is highly valued in modern society. As one can see, the booming development of quantum is advancing society, the nation, and the world at a rapid pace.

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