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Review Article

Are you ready for the Quantum Age?

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Abstract: The word Quantum is one of the hottest terms since the beginning of this century. Quantum computer, quantum dot TV, quantum communication, quantum battery, quantum dot mobile phone, and quantum printer are gradually becoming the hot terms in our lives. Quantum is not a new concept in physics, as it has been discovered for more than one hundred years. It carries extensive connotations: quantum technologies are deeply changing our present and future lives, the quantum philosophy contains the explanations on the source of substantiality and a brand new world view, and the quantum mechanics may be recognized as the most successful theory in the history of physics. Quantum has become the symbol of our time - at least many people believe that our time belongs to quantum.
Keywords: Quantum Age, Quantum Technology, Quantum Computation, Quantum Computer.

INTRODUCTION

At the 2015 Hangzhou YunQi Computing Conference, AliCloud published quite some new cloud apps combining the big data, Internet-of-Things, machine learning, as well as a secure communication product which firstly adopted the quantum cryptographic technologies. It is a quantum communication product jointly developed by AliCloud and the Chinese Academy of Sciences. The release of this achievement has a milestone effect on the research and development of quantum around the world. According to remarks given by "Nature" of the United Kingdoms, it is a rise of China in the field of quantum. In the past, China had hardly any influence in this field, but now it has become a major force that will surely surpass the Europe and the North America. Apart from the quantum communication products, the quantum computers with excellent computing capacity, the quantum dot TVs with splendid colors, the quantum communication which is more safe, the quantum battery with large capacity and the ability to quickly recharge, the quantum mobile phones that has exquisite display effect, and quantum printers with the extraordinarily clear printing effects, they all are or will be playing an important role in our lives [1-6]. Quantum has gradually become an important part of our time.

What is Quantum? Quantum is not a strange physics concept. It can be traced back to more than a hundred years ago. The concept of quantum was firstly put forward in 1900 by Max Planck, a Germany physicist who defined quantum as an inseparable and basic unit. According to his assumption, the energy of black-body radiation was discrete, and could only be measured as an integral multiple of the basic energy unit. In later researches, it was found that not only energy, but also other physical quantities, such as the angular momentums, spins, and electric charges, could present the discrete nature. Max Planck was awarded the Nobel Prize in Physics in 1918, in recognition of his discovery of energy quanta, and was recognized as an important founder of quantum mechanics [7]. Although we can say without exaggeration that quantum mechanics is the most successful theory in the history of physics, it was not popularly understood and familiarized until the early 21st century.

Quantum, as a concept of physics, is fascinating in many other aspects. Apart from the physics properties, it carries profound philosophy connotation which have led to a brand new world view of mankind. The explanation on the source of substantiality and the revealed relations between the observer and the observed from the perspective of quantum are fantastic [8-9]. Born together with quantum mechanics, quantum philosophy was the hot topic of discussion between philosophers at the very beginning and remains one of the most research-worthy theories in the philosophy

world even after more than half a century [10-11]. Although it begun to draw people's attention by its philosophical connotations, quantum has seen great breakthroughs in application since the end of the last century. Quantum is no longer a revolution of the scientific theory or a concept of the source of substantiality, but also a new technology with a very promising future [12-13].

Quantum was put into application before World War II, and its theory has been used on analyzing the thermal properties and electronical properties of metal and semi-conductors, which contributed to the invention of transistors and laser. In the field of nanotechnology, quantum can be used in design of tiny machinery devices; in the field of micro-electronics, quantum can be used to detect subtle changes at the other end of the earth; in the field of information security, quantum technology can be used to decrypt codes that cannot be decrypted by the current computers [14]. From the simplest CD player to the enormous fiber communication system, and from the anhydrous painting to laser assisted immobilization equipment, quantum has a wide range of application and it exists everywhere in our life.

QUANTUM PHILOSOPHY

One of the major theories about Quantum philosophy is concerned with the "wave-particle dualism" of objects. When the world is described from the perspective of quantum, an object can be particle and wave at the same time, possessing the traits of them both. This phenomenon is called the "wave-particle dualism" [15]. According to this theory, an object can exist at multiple locations at the same time, and it can pass through obstacles. Two objects separated by a remote distance can interact with each other through certain means. Even the solar system lies in between, the objects can respond to each other when either of them changes the states. This phenomenon is called by Einstein and many other scientists as the ghostly quantum entanglement at a super remote distance [16]. This special effect of quantum reflects that the connection between objects separated by a super remote distance is a comprehensive embodiment of mentality activity of individual life.

"Schrödinger's Cat" is a classic thought experiment in quantum philosophy devised by Erwin Schrödinger, a Nobel Prize-winning Austrian physicist [17]: a poor cat, a flask of poison (hydrogen cyanide gas), food, a hammer hanging above the flask, an electronic switch controlling the hammer, and a radioactive source that can trigger the switch are placed in a sealed box. If the switch detects radioactivity (i.e. a single atom decaying), the switch triggers, the hammer falls, and the flask is shattered, releasing the poison which kills the cat [18]. This cruel experiment was devised by Schrödinger, thus the cat is called the Schrödinger's cat. Based on the quantum theory, we will never know whether the cat is dead or alive if we don't open the box. The cat may be simultaneously alive and dead, a state known as quantum superposition. The thought experiment "Schrödinger's cat" is still being discussed by people even after dozens of years, from which we can tell the charm of philosophical thinking about quantum.

QUANTUM COMPUTER

Among all quantum technologies, quantum computing may be the most thrilling and meaningful technology. As early as 1985, David Deutsch, a British physicist from the University of Oxford, raised a question: what kind of computation can be realized in the Quanta World? Later, people connected computer with quantum technologies, overthrowing the computation model established on the basis of classical physics that has been popularly accepted by people for a long time [19]. More surprisingly, quantum computers designed with the models of quantum computation can perform mathematical operations that cannot be realized by today's computers even theoretically [20-21].

The concept of quantum computer was firstly proposed by Richard Feynman, an American physicist in 1982. He found that, when simulating the quantum phenomenon, the enormous Hilbert space requires a considerably large amount of data to be simulated, resulting in a considerable long time to finish the computation of the simulation, which is impractical. He had the idea that the time of computation could be greatly reduced if a computer made of quantum can be used to simulate the quantum phenomena [22]. In 1994, Peter Shor, an American scientist, devised a quantum algorithm which proved that quantum computers can perform logarithmic computation much more quickly than classical computers; he also proved that a 40-qubit quantum computer can solve a problem which may take decades of years for a 1024-bit traditional computer; and in 2001, his quantum algorithm was successfully realized on a 15 qubit NMR quantum computer [22].

A quantum computer performs high-speed mathematical and logical computation, storage, and processing of quantum data by following the rules of quantum mechanics [23]. The basic rules include the uncertainty principle, the correspondence principle, and the Bohr's theory, etc. Its computation principle adopts the "superposition of quanta" like the aforementioned "Schrödinger's cat". Each transformation of a superposed component is similar to a classical computation, with all classical computation performed at the same time and summed at a certain probability of amplitude to output the result [23], which enables the quantum computer to check all possible answers at one time and perform complex computation at an extremely

fast speed. This kindly of computation is called the parallel quantum calculation, which is the main reason why quantum computers are far better than today's computers.

At present, the world's fastest computer is "Tianhe-2", a supercomputer built by China's National University of Defense Technology with a peak computing speed of 54.9 petaflops and a sustainable stable speed of 33.9 petaflops [24]. In May 2015, "Tianhe-2" successfully simulated leptons and dark matters among 3 trillion particles, revealing the long-drawn evolution progress of the universe for a period of 13.7 billion years since 16 million years after the Big Bang [25]. However, in front of the quantum computers, "Tianhe-2", the fastest supercomputer in 3 successive years of 2013, 2014, and 2015, is dwarfed. It takes a few million years of a supercomputer to factor a composite number with 400 divisors, while a quantum computer needs only one year or shorter. According to Gerard J. Milburn, an Australian physicist, "The invention of quantum makes today's most advanced supercomputer looks like an abacus." Today's computers are built based on the Von Neumann model, and their growth of processing speed has been obviously slowed down. It is hard to increase their efficiency in analyzing and computing data at a large scale. They work on a binary system of 0 and 1, and the smallest storage unit is bit, while quantum computers work on quantum bits (qubits), which allows computation of values between 0 and 1.

In 2007, D-Wave System Inc., a Canadian quantum computing company, successfully built a 16-quibit superconducting quantum computer. In 2011, it released "D-Wave One", and described it as "the world's first commercially available quantum computer" operating on a 128-qubit chipset. Soon, it was sold to Lockheed Martin, a military weapons manufacturer, at USD 10 million for defects analysis of the F35 fighter aircraft as well as the design of advanced weapons. In 2013, the company announced D-Wave Two, a 512-qubit quantum computer, which was soon purchased by NASA (National Aeronautics and Space Administration) and Google. Google realized the "quantum annealing" algorithm on D-Wave Two quantum computer and made a comparison with classical computers, and the quantum computer performed 100 million times as fast as any other computers on solving this problem. Google simulated the quantum tunneling phenomena on both the quantum computer and the classical computer, and based on the comparison of the two, the quantum computer won without doubt.

D-Wave Two proved that the biggest advantage of a quantum computer is that it greatly shortens the time for computation, so it has a very promising application future. Weather forecasting: quantum computers can analyze all weather data at one time to provide us with better analytical data models and precisely forecast the very specific weather at a specific time slot. Route planning: quantum computers can take input of travel plans from all people on earth, to work out the most optimized travel plan and save us from trouble in traffic jams. R&D of drugs: quantum computers can calculate trillions of molecular compositions of drugs, and identify the most probably effective molecular combinations, to remarkably reduce the R&D cost and time. Exploration of the space: quantum computers can process more data discovered by telescopes, which will be helpful to discover more planets and quickly identify those with the highest possibilities of life.

QUANTUM COMMUNICATION

Apart from quantum computers, another eyebrow-raising technology that has been put into practical use is quantum communication.

In an ancient Chinese novel *Apotheosizing Tales* (Fengshen Yanyi), Tu Xingsun is known for his ability to travel in earth. As long as he reaches the ground, he can disappear immediately like a fish in the sea. Even today, it sounds ridiculous and impossible to be realized. However, the quantum theory shows us the possibility of quantum teleportation in a way very much similar to the spatio-temporal tunnel in films, through which objects may be instantly transferred from one location to another [26]. Quantum teleportation uses the quantum entanglement technology to allow transmission of an object with the help of classic channels like satellite network, fiber network, etc. Just like time travel described in science fictions, an object mysteriously disappears from one location and appears at another without any carrier [27]. Ancient people used wax seals on envelopes to secure confidentiality of their letters, and the receivers would know if the information in the envelope was disclosed by observing the seal. Quantum teleportation does better in this aspect, and it is proven to be the unconditionally safe communication method by far. As long as someone else attempts to open the envelope, the quantum will "burn" the envelope and notify the user [28].

The concept of quantum communication was firstly raised by an American scientist Charles Henry Bennett in 1993. It provides a way of communication by transporting information carried by quantum states from one location to another. It works based on the quantum entanglement phenomena of photons and other elementary particles to realize the confidentiality of the communication. It mainly contains two parts, the quantum teleportation and the quantum key distribution [29]. By virtue of its merits of absolute confidentiality, large volume communication, and fast transmission,

quantum communication can complete tasks that cannot be performed by classical communication.

The mechanism of quantum teleportation is that, during the process of communication, the information to be sent is divided into two parts, the classical information and the qubit information. The said information is transmitted to the receiver respectively through the classical channel and the quantum channel. The quantum channel keeps the entanglement quantum states. Classical information is obtained through certain measurement on the qubit information communicated between the sender and the receiver, and the qubit information is the part not extracted by the sender during the measurements. The receiver, upon receiving information from both channels, can reproduce the complete copy of the information in quantum states [30]. This process transports only the quantum states of the information, rather than the information itself. Quantum communication is by far the only means of communication that has been strictly proven to be unconditionally safe. Once someone attempts to eavesdrop, the quantum key would automatically get the information destroyed, and notify the sender and the receiver.

As a part of quantum communication, the quantum key distribution is not used to transmit the encrypted contents, but to produce and transmit a key for communication, or to distribute the key between the two parties of the communication. In 1984, two scientists respectively from the U.S. and Canada developed BB84, a quantum cryptography protocol. By taking qubits as the information carrier, and using photon polarization to encode the quantum states, it realizes the production and secure distribution of the key [31]. Quantum key distribution, which has broken the limits of traditional encryption methods by using the non-cloneable quantum states as the key, possesses the merit of theoretically unconditional safety. Any interception or operation that measures the quantum key would change the quantum states, and the interceptor only gets meaningless information. The legitimate receiver of the information would know that the key was intercepted from the change of the quantum states. Quantum communication secures the confidentiality of the key, thus ensuring the security of encrypted information.

Quantum communication is now under rapid development while breaking its technical bottlenecks, and is already put into practical use. In 2008, Pan Jianwei, a professor at the University of Science and Technology of China, successfully developed a fiber quantum communication prototype system based on the decoy-state, and successfully built the world's first three-node chain-typed photon quantum telephone network in Hefei. In 2009, he built the world's first all-pass quantum communication network on the basis of the three-node chain-typed photon quantum telephone network, and realized real-time audio quantum secrete communication. In 2012, he built the world's first large scale city-wide quantum communication network with up to 46 nodes, surpassing the existing similar networks in the world. In 2014, Jinan Quantum Communication Test Network was officially put into use, making it the first large scale quantum communication network for the purpose of carrying practical applications. In 2016, China will launch the world's first "quantum scientific experimental satellite". It is expected that in the foreseeable future, when the world's quantum communication network is set up, the network speed will be much faster and the communication will be more secure. On the basis of quantum computer and quantum communication, the quantum technologies will see a more prosperous development and bring more earth-shaking changes to our lives.

CONCLUSION

Quantum has gradually become an important symbol of our time; quantum mechanics is recognized as the most successful theory in the history of physics; quantum philosophy draws philosophical thinking and is changing our world view; and quantum technologies are now deeply transforming our present and future lives. In the era of quantum, quantum computers may solve the most of the complex problems and increase our work efficiency exponentially; quantum communication will provide us an absolutely secure communication environment; and quantum technologies have been deeply embedded in various aspects of our lives. The quantum age is coming, are you ready for it?

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