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Quantum information research in China

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Abstract

With the success of Micius quantum satellite experiments, China is believed to be one of the leading nations in quantum information science. For the past 10 years, the research funding for quantum information research is mainly from the central and local governments with a total amount of around 987 million USD. Here, we summarize the research efforts China has taken to boost the field of quantum information science from the aspects of both basic research and industrial applications, and discuss the future perspectives.

1. A brief history of quantum information support in China

Quantum information research in China dated back to 1998, when the National Natural Science Foundation of China (NSFC) convened the Xiangshan Science Forum for quantum information at Beijing. Soon after, several universities and research institutes including the University of Science and Technology of China (USTC), the Shanxi University, the Chinese Academy of Science (CAS) Institute of Physics and so on initiated experimental research in the field of quantum information. The funding support for quantum information research at its early stage was highly limited and often mixed up with other research fields.

During the eleventh ‘Five Year Plan’, i.e. from 2006 to 2010, several special major research projects were initiated with the focus of quantum information. For instance, the Ministry of Science and Technology (MOST) announced the ‘Quantum Control’ national major project and the NSFC launched the ‘Single Quantum State Detection and Interaction’ major research project. The CAS initiated the ‘Long Distance Quantum Communication’ and ‘Key Technology Research and Verification of Quantum Experiments at Space Scale’ projects to support large-scale quantum communication research. The total funding support was about 150 million USD at that time.

Due to the rapid progress of quantum information and its potential impacts to secure communication, China enhanced the support during the twelfth ‘Five Year Plan’, i.e. from 2011 to 2015. The MOST continued supporting the ‘Quantum Control’ national major project. The NSFC announced ‘Quantum Metrology’ major research project and the ‘National Major Scientific Research Instruments and Equipment Development’ project. Based on the former space-based quantum project, the CAS initiated the ‘Quantum Experiments at Space Scale’, ‘Coherent Control of Quantum Systems’ and ‘Metrology Physics in Atomic Systems’ strategic leading science and technology projects. In order to develop the industrial applications of quantum key distribution (QKD), the National Development and Reform Commission (NDRC), together with Anhui Province, Shandong Province and CAS initiated ‘Beijing–Shanghai Quantum Secure Communication Backbone’ project to build up a QKD trunk line from Beijing to Shanghai with trustful relays. The total funding amount during 2011–2015 was estimated to be 490 million USD.

Since 2016, on one side, China has been preparing the national flagship project for quantum information research; on the other side, the MOST launched the ‘Quantum Control and Quantum Information’ National Key Research and Development (R&D) project. From 2016 till now, the total amount of funding is around 337 million USD.

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Overall, the support for quantum information research in China has been mainly from the central and local governments, covering quantum communication, quantum computation and quantum metrology. The amount of funding has been increasing substantially since 1998, and the total number during the past 20 years is estimated to be 987 million USD. The details of funding support are summarized in Table 1.

2. The current research status in China

For the past 20 years, China has made several important progress in quantum information science. The field has been awarded twice the First Prize of National Natural Science of China (2013 and 2015). The research achievements have been selected twice as ‘Feature of the year’ by Nature (2012 and 2017), ‘Highlights of the Year’ by IOP Physics Web or APS Physics News Update for 14 times. In what follows, we briefly review the research highlights.

2.1. Quantum communication

Quantum communication can provide information-theoretical security based on the basic principle of quantum physics. In this field, China has emerged a number of world-class achievements and has become one of the leading nations. For instance, Peng et al at USTC realized the first decoy-state QKD over 100 km fiber in 2007, which broke the previous limits of security distance (~10 km order) and low encoding rates. This made the application of QKD practical. With their independently developed quantum communication systems, Chen et al demonstrated a QKD network in Hefei and realized the first practical all-pass secure optical telephone network in the world. Meanwhile, Wang et al demonstrated a wavelength-saving QKD network at Wuhu. As one step further, Liu et al realized the first measurement-device-independent QKD (MDI-QKD), which completely solved the security loophole from an imperfect detection system. Based on the established technology advances, USTC, together with Chinese Cable TV Corp, started to build the ‘Beijing–Shanghai Quantum Secure Communication Backbone’ in 2013, which connects Beijing, Shanghai, Jinan, Hefei, and many other cities with a total transmission distance over 2000 km. In total, 32 trustful nodes are utilized to relay the quantum key and more than 10 kbps secure key has been distributed over 2000 km. Such networks will have practical applications in economy, and will also serve as an important platform for fundamental research in quantum communication. In 2018, the backbone was established successfully and is now on trial for the real applications such as banks.

Another feasible solution to develop a global quantum communication network is to use quantum satellites for long-distance communication. A series of ground tests to prove the feasibility of satellite-based quantum communication were conducted. In 2005, Peng et al demonstrated a 13 km free-space quantum entanglement distribution and QKD for the first time in the world to prove that entangled photons can survive after penetrating the ~10 km effective thickness of the atmosphere. In 2010, Jin et al realized a 16 km free-space quantum teleportation in the Great Wall, which proved the feasibility of free-space quantum teleportation. In 2012, Yin et al realized quantum teleportation, entanglement distribution over 100 km, which proved the feasibility to realize quantum teleportation both from satellite to earth and from earth to satellite and entanglement distribution from satellite to two ground stations. In 2013, Wang et al, completed the experimental verification of QKD between satellites and earth, which proved that the relative motion and high loss channel between satellites and earth can be overcome.

In August, 2016, quantum science satellite Micius was launched in Jiuquan, Sichuan province. It has three main missions, satellite-to-ground QKD, test of satellite-based quantum nonlocality and test of ground-to-satellite quantum teleportation. In 2017, three missions were successfully achieved. Liao et al achieved a kHz secret key rate of QKD from the satellite to the ground over a distance of up to 1200 km using the decoy state BB84 protocol. This key rate was around 20 orders of magnitudes greater than that expected using an optical fiber of the same length. Yin et al demonstrated satellite-based distribution of entangled photon pairs to two locations separated by 1203 km on Earth, through two satellite-to-ground downlinks with a summed length varying from 1600 to 2400 km. They observed a survival of two-photon entanglement and a violation of Bell inequality by 2.37 ± 0.09 under strict Einstein locality conditions. The obtained effective link efficiency was orders of magnitude higher than that of the direct bidirectional transmission of the two photons through telecommunication fibers. Ren et al reported the quantum teleportation of independent single-photon qubits from a ground observatory to a low-Earth-orbit satellite, through an uplink channel, over distances of up to 1400 km. Besides the main missions, intercontinental QKD has been demonstrated between Beijing and Vienna. Together with the Beijing–Shanghai trunk line, satellite–ground integrated QKD network has been achieved recently. It has been three years since its launch, the Micius still works well in spite of its 2 year expected lifetime. We can expect more and more exciting experiments in the near future.
| Year       | Project                                                                 | Funding agency | Total estimated amount (USD) | Notes                        |
|------------|---------------------------------------------------------------------------|----------------|------------------------------|------------------------------|
| 1998–2006  | Minor projects mixed with other fields                                     | NSFC           | 10 million                   | Early stage                  |
| 2006–2010  | 1. Quantum control                                                       | 1. MOST        | 150 million                  | The 11th five year plan      |
|            | 2. Single quantum state detection and interaction                         | 2. NSFC        |                              |                              |
|            | 3. Long distance quantum communication                                     | 3. CAS         |                              |                              |
|            | 4. Key technology research and verification of quantum experiments at space scale | 4. CAS         |                              |                              |
| 2011–2015  | 1. Quantum control                                                       | 1. MOST        | 490 million                  | The 12th five year plan      |
|            | 2. Quantum metrology                                                      | 2. NSFC        |                              |                              |
|            | 3. National major scientific research instruments and equipment development | 3. NSFC        |                              |                              |
|            | 4. Quantum experiments at space scale                                      | 4. CAS         |                              |                              |
|            | 5. Coherent control of quantum systems and metrology physics in atomic systems | 5. CAS         |                              |                              |
|            | 6. Quantum secure communication backbone                                   | 6. NDRC, CAS etc |                              |                              |
| 2016–now   | 1. Quantum control and quantum information                               | 1. MOST        | 337 million                  | The 13th five year plan      |
Except for the trustful relay and quantum satellite, quantum repeater is another feasible way for building long-distance quantum network. The main goals of this field are improving the single-node performance, and extending the number of separated repeater nodes. In 2016, Yang et al realized a cold-atom quantum memory which has a lifetime of 0.22 s and a retrieval efficiency of 76%, the combined performance of which for the first time reach the regime required by long-distance quantum repeaters. In 2016, Pu et al realized a multiplexed quantum memory with 225 individually accessible memory cells. To extend the scale of quantum network, Yang et al realized an efficient source of atom–photon entanglement, and demonstrated entanglement of three quantum memory nodes. By further combining quantum frequency conversion, Yu et al have successfully extended the fiber distance between two quantum memory nodes to 50 km. Meanwhile, Yang et al has been working with a different approach of crystals doped with rare earth ions, and achieved storage of multiple degrees of freedom simultaneously in 2018.

2.2. Quantum computation

Quantum computers use quantum superposition to process information in parallel, which has fundamentally computing advantage over classical computers and has profound influence to both physics and social economy. In this field, the Chinese group has developed the highest-performance single-photon sources for photonic quantum computing. Quantum computing demands single photons with high indistinguishability and efficiency, each of which is challenging to achieve; combining them together is even more challenging. To this end, China developed the first pulsed resonance fluorescence in InAs/GaAs quantum dots, the cleanest way to produce on-demand single photons with near-unity indistinguishability. The resonant excitation method is compatible with Purcell-enhanced microcavities, and later they created the first single-photon source that simultaneously combines near-perfect levels of purity, indistinguishability, and high efficiency. Exploiting the state-of-the-art single-photon sources, Wang et al demonstrated a blueprint of boson sampling with up to five photons and achieved an efficiency > 24,000 times higher than in all previous reported works. China has developed methods to generate, manipulate, and measure Schrödinger–cat-like quantum states with an increasingly large number of entangled photons. Jian-Wei Pan group experimentally created the first five-photon entanglement, six-photon cat state and cluster state, spatial and polarization 10-qubit hyper-entanglement, eight-photon entanglement, ten-photon entanglement, 12-photon entanglement, and recently, 18-qubit hyper-entanglement in spatial, polarization, and orbital angular momentum degrees of freedom.

In addition, the group performed seminal experiments exploring optical quantum computing algorithms. Using multi-photonic qubits as a testbed, the work includes the first demonstrations of Shor’s algorithm, photon-loss-tolerant quantum coding, emulation of anyonic statistics, solving linear equations systems, entanglement-based machine learning, teleportation of multiple degree of freedom, and cloud quantum computing, pointing the way to practical applications of photonic quantum technologies in code-breaking, big data, and quantum simulation, etc.

In superconducting quantum computation field, the groups from University of Science and Technology of China Zhejiang University and Institute of Physics (CAS) have made big progress on the multi-qubit system. They achieved 10-qubit entanglement in 2017, 12-qubit in 2019, and 18-qubit very recently, which was the largest multi-qubit entangled state in the solid-state system at the time. In 2019, they demonstrated quantum walks of one and two strongly correlated microwave photons in a one dimensional array of 12 superconducting qubits with short range interactions, which paved the way to study complex many-body phenomena using superconducting system. One main branch of quantum computation is quantum simulation, which exploits simple quantum system, like ultracold atoms, to simulate complicated quantum system like condensed matter system. Quantum simulators do not require a complete control of each individual component, and thus are simpler to build. China has made a great contribution to this field in recent years. In 2014, Ji et al determined the finite-temperature phase diagram in a bosonic gas with one-dimensional spin–orbital coupling. In 2016, two groups realized twodimensional spin–orbit coupling, an important ingredient to explore topological quantum states, in ultracold bosonic and fermionic gases, respectively. In the strongly interacting quantum gases, Deng et al have observed the scale invariant Efimovian expansion in the unitary Fermi gas. Yao et al observed the emerged vortex lattices in a mass-imbalance Bose–Fermi superfluid mixture and observed a tunable and broad d-wave shape resonance in a degenerate bosonic gas. In 2017, Rui et al observed an controlled ultracold atom–exchange reaction, and in 2019, Yang et al successfully observed a triatomic Feshbach resonances in ultracold collisions between atoms and molecules at ultralow temperatures, shedding light on the quantum nature of atom-molecule interaction. In the field of neutral atoms in optical lattices, Dai et al have generated and measured the spin-entangled neutral atomic pairs, and simulated a minimal Kitaev toric code model and its the fractional anyon-like statistics with spin-dependent superlattices.
2.3. Quantum metrology
Quantum enhanced metrology utilized quantum information technology to implement precision measurement, including measuring fundamental physical constants, atomic clock and time-frequency transfer interferometry sensing, imaging, trace-isotope analysis and so on. Cat state can be used for super-resolving phase measurements. Gao et al demonstrated super-resolving phase measurements enhanced by 10 qubit entanglement, with a precision to beat the standard quantum limit. Later, the resolution has been improved by 18 qubit entanglement.

Magnetic resonance is essential in revealing the structure and dynamics of biomolecules. Shi et al demonstrated the detection of the electron spin resonance signal from a single spin-labeled protein under ambient conditions, utilizing a sensor of single nitrogen vacancy center in bulk diamond in close proximity to the protein. Wu et al measured the orientation of the spin label at the protein and detect the impact of protein motion on the spin label dynamics. Utilizing the NV center, the same group observed parity-time symmetry breaking in a single-spin system.

Meanwhile, Zhang et al demonstrated Raman spectral imaging with spatial resolution below one nanometer, resolving the inner structure and surface configuration of a single molecule. Later, the same group exploited the sub-nanometer resolved electroluminescence imaging to visualize the intermolecular dipole-dipole interaction in real space. These were achieved by spectrally matching the resonance of the nanocavity plasmon to the molecular transitions. This matching was made possible by the extremely precise tuning capability provided by scanning tunneling microscopy.

3. The National Major Project of China
It is widely believed that that quantum communication, especially QKD, is the first quantum technology that comes into applications. Despite its significant progress, quantum computing technology is still far from the ultimate goal of universal quantum computation. Moreover, some branches of quantum metrology might find applications soon. Based on these common believes, we provide a prospection for China’s future research plan quantum information field.

3.1. Quantum communication
In order to boost the application for QKD, the first step is to implement a full secure inspection on existing QKD networks, especially on the backbone line, from the protocol to the post-processing, from the classical key management to the quantum device. Meanwhile, several quantum attack-defense confrontation platforms will be built for security evaluation, which shall provide test beds not only for existing networks but also the new protocols, devices and systems. Meanwhile, from 2015, China Communications Standards Association initiated study of quantum secure communication network security issues and later set a special task force (ST7) on quantum communication and information process. In 2017, China initiated the study period of ‘Security requirements, test and evaluation methods for quantum key distribution’ in ISO/IEC. Currently, China is heavily involved in ITU for QKD standardization work. Based on these efforts, a national standard for quantum cryptography will be achieved in the near future.

With adequate security tests and new standards, the next step will be promoting the QKD network widely to the whole nation and the whole world. Figure 1 shows a possible roadmap to achieve this goal. Fiber-based QKD is for metropolitan communication; Trustful relay will be exploited to build backbone links to connect major cities.

Meanwhile, based on current research status, we can expect in the next 10–15 years quantum repeater technology will be extensively developed and a quantum repeater based link (> 500 km) could be built. At that time, quantum repeater will be a strong candidate for backbone lines.

Satellite-based quantum communication could connect wide areas. The success of Micius has demonstrated the feasibility of that. But in order to provide practical communication speed and work in daytime, a satellite constellation composed of both high-orbit satellites and low-orbit satellites is required. The technology has been tested in the ground.

Besides long distance, the security of QKD with realistic devices is crucial for applications. On one side, MDI-QKD and twin-field QKD will be further deployed over fiber or free space due to their enhanced security and practicality; Device-independent (DI) quantum random number generation (QRNG) and QKD will be studied for academic interest and randomness beacon.

Finally, cost is an important issue in application. Integrated photonics and circuits should be studied to reduce the device cost. The integration between quantum and classical optical communication will be exploited when constructing the quantum network, so as to reduce the channel cost. Mini ground stations for quantum satellite will be studied to reduce the cost for satellite-based quantum communication.
3.2. Quantum computation
The ultimate goal for quantum computation is to realize a programmable universal quantum computer. Several potential candidate quantum systems should be investigated to pursue this goal. Also, high-precision fault-tolerant quantum logic gate needs to be developed. The developments might take a relatively long time. However, the technology of generating and manipulating multi-party quantum entanglement developed during the way towards the universal quantum computation can help to achieve a special quantum simulator for some special but important problems.

In the near future, we can expect to achieve the quantum supremacy i.e. a quantum simulator will be demonstrated faster than any classical computer can be. Later, some important computational problems like simulating photosynthesis or superconductor might be solved.

3.3. Quantum metrology
The technology developed in quantum communication and quantum computation may find applications in quantum sensing and metrology, such as atomic clock atomic interferometer atomic gravity meter single-photon lidar trace-isotope analysis, single spin magnetometer and so on. Here, we would like to describe one example in details.

China will build a national-wide time-frequency dissemination fiber network, supported by the NDRC. This fiber network has a total length of about 20 000 km and will cover the most major cities of China. Time and optical frequency signals will be transferred through the whole network. A timing signal with better than 100 ps instability (TDEV) will be disseminated through the network for various applications. More importantly, optical frequency will be disseminated to main cities with an instability of about 1E-18 for one day. This will be exploited in many applications including searching dark matter, observing gravity shift, geodesy science and so on. Meanwhile, the disseminated time and frequency signals in the time-frequency network will be helpful for timing synchronization and phase locking in quantum communication, such as twin-field QKD, while the QKD main backbone can share its channel with the time-frequency work with the help of DWDM.

4. Conclusion
While we are writing this paper, China’s flagship project is still on its way. We understand that any major project needs a long time for adequate debate and careful design. Hopefully, the project will initiate eventually. We believe that China’s flagship project will not only enhance Chinese quantum technology but also benefit the whole global community. Overall, given the significant achievements and the worldwide supports in the field of quantum information, we do believe that quantum technologies are ready to open up a new revolution in science and technology.
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