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Postprint of Coherent Control of Quantum Systems

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Abstract

(1) Quantum information science, encompassing quantum communication, quantum computing and simulation, and quantum precision measurement, has emerged as one of the most active research frontiers in physics and information science. Quantum communication represents the only communication method rigorously proven to be unconditionally secure to date, capable of fundamentally addressing information security challenges in national defense, finance, government affairs, commerce, and other domains. Quantum computing offers powerful parallel computation and simulation capabilities, providing solutions to large-scale computational problems in artificial intelligence, cryptanalysis, weather forecasting, oil exploration, genetic analysis, drug design, and beyond, while also elucidating complex physical mechanisms such as quantum phase transitions, high-temperature superconductivity, and the quantum Hall effect. Quantum information processing technology further enables ultra-high-sensitivity quantum precision measurement of gravity, time, position, and other physical quantities, substantially enhancing the accuracy and precision of satellite navigation, laser guidance, submarine positioning, medical detection, gravitational wave detection, and related applications.

Full Text

Preamble

Strategic Priority Research Program (Category B) of the Chinese Academy of Sciences
ChinaXiv Partner Journal
Coherent Control of Quantum Systems

1. Research Background and Significance

Quantum information science, encompassing quantum communication, quantum computing and simulation, and quantum precision measurement, has emerged as one of the most active frontiers in physics and information science. Quantum communication represents the only communication method proven to be unconditionally secure, fundamentally solving information security challenges in national defense, finance, government affairs, and commerce. Quantum computing offers powerful parallel processing and simulation capabilities, providing solutions to large-scale computational problems in artificial intelligence, cryptography, weather forecasting, petroleum exploration, genetic analysis, and drug design, while revealing complex physical mechanisms such as quantum phase transitions, high-temperature superconductivity, and the quantum Hall effect. Quantum information processing technology also enables ultra-sensitive precision measurement of gravity, time, and position, significantly enhancing the accuracy of satellite navigation, laser guidance, submarine positioning, medical detection, and gravitational wave observation.

Recognizing the strategic importance of quantum information technology, China has prioritized its development. Quantum information technology breaks through classical information bottlenecks in information security, computational speed, and measurement precision, offering revolutionary solutions to major challenges facing socio-economic development. It has become a critical technological innovation for safeguarding national strategic security and supporting sustainable economic development. The National Medium- and Long-Term Plan for Science and Technology Development (2006–2020) designated "Quantum Control Research" as one of four National Major Scientific Research Plans. The National Natural Science Foundation of China established a major research program on "Single Quantum States and Precision Measurement," while the Chinese Academy of Sciences (CAS) has implemented multiple major knowledge innovation projects and strategic priority research programs.

Quantum information technology has become a distinctive area of research strength for China, with quantum communication ranking among the few world-leading cutting-edge technologies. In recent years, research teams from the University of Science and Technology of China (USTC) have received two first-class National Natural Science Awards (in 2013 and 2015), been selected 14 times for the annual "China's Top Ten Scientific and Technological Progress News" by the Chinese Academy of Sciences and Chinese Academy of Engineering, featured three times in Nature or Science's "International Top Ten Scientific and Technological Advances," and recognized 13 times in "Major International Physics Advances" by the American or British Physical Societies. A Nature feature article on USTC's quantum communication research, "Data Teleportation: The Quantum Space Race," noted: "In less than ten years, China has transformed from an insignificant player to a world powerhouse in quantum communication, now leading Europe and North America." The British magazine New Scientist, in a special issue on "China' s Rise" covering USTC' s quantum computing achievements, commented: "USTC, and thus China as a whole, has firmly established a place on the world map of quantum computing."

2. Program Objectives and Main Work Content

2.1 Program Objectives

The research objectives of this program are to achieve high-precision preparation, manipulation, high-speed transmission, and effective detection of quantum bits; to realize quantum entanglement with more particles and longer quantum coherence times; to demonstrate coherent manipulation of 12–18 quantum bits; to apply the developed quantum system coherent control technologies to important research directions such as scalable quantum communication, quantum computing, quantum simulation, and quantum precision measurement; and to maintain and expand China' s advantages in quantum technology, securing an international leading position.

2.2 Main Work Content

Based on the core scientific and technological challenges, the program comprises three projects, each containing several research topics, focusing on developing scalable quantum system coherent control technologies:

(1) **Quantum Physics and Quantum Information Based on Light and Cold Atom Systems**. Research topics include: high-performance quantum transmission and detection, core quantum communication devices, multi-photon entanglement manipulation, cold atom quantum storage and quantum simulation, optical quantum control based on semiconductor micro-nano structures, and theoretical studies on light-cold atom quantum information and quantum simulation.

(2) **Quantum States and Quantum Properties at the Molecular Scale**. Research topics include: control and transport properties of electronic and spin states in molecular systems, photon state control and quantum coherent behavior in molecular systems, and quantum design and simulation of molecular systems.

(3) **Quantum Physics and Quantum Information Based on Solid-State Systems**. Research topics include: quantum manipulation and information processing of semiconductor quantum dots, integrated photonic quantum processors, solid-state node-based quantum networks, and spin-based solid-state quantum computing research.

3. Program Implementation Overview

The program has yielded a series of innovative research achievements with significant international impact, publishing over 160 papers in top-tier international journals including Nature (4 papers), Science (3 papers), Nature Physics (7 papers), Nature Photonics (9 papers), Nature Nanotechnology (4 papers), Physical Review Letters (89 papers), Nature Communications (23 papers), and Journal of the American Chemical Society (20 papers). These achievements have been highly recognized by domestic and international peers, selected multiple times as cover-story or "editor' s choice" papers, and featured in special reports by Nature and its sub-journals, Science, the American Physical Society, the European Physical Society, PhysOrg, and other renowned academic journals and society news websites. The series of achievements on "Scalable Quantum Information Processing" was selected as one of the "China' s Top Ten Scientific and Technological Progress News" in 2012; the research on "Hundred-Kilometer Free-Space Quantum Teleportation and Entanglement Distribution" was selected as one of Nature' s "Top Ten Scientific Highlights" of 2012; the work on "Sub-Nanometer Resolution Single-Molecule Optical Raman Imaging" was selected for the 2013 "China' s Top Ten Scientific and Technological Progress News" ; the achievement on "Measurement-Device-Independent Quantum Key Distribution to Solve Quantum Hacker Threats" was selected as a 2013 "International Physics Highlight" by the American Physical Society; the work on "Quantum Communication Secure Transmission Sets World Record" was selected for the 2014 "China' s Top Ten Scientific and Technological Progress News" ; the research on "Multi-Degree-of-Freedom Quantum Teleportation" topped the European Physical Society' s Physics World list of "Top Ten Breakthroughs in International Physics" for 2015; and the work on "Multi-Photon Entanglement Interferometry" received the first-class National Natural Science Award in 2015. Additionally, program members were invited by Reviews of Modern Physics, the world' s most authoritative physics review journal, to write a review on multi-photon entanglement manipulation and quantum communication in 2012—the first experimental review by mainland Chinese scientists in that journal.

These achievements have provided core technical support for major national research projects and missions, including the CAS Strategic Priority Research Program "Quantum Science Experimental Satellite" and the National Development and Reform Commission' s "Beijing-Shanghai Quantum Secure Communication Backbone" technology verification and application demonstration project.

4. Representative Innovative Achievements

4.1 Major Breakthrough in Ultracold Atomic Quantum Simulation

A joint team of researchers from USTC and Peking University theoretically proposed and experimentally realized, for the first time internationally, artificial synthesis of two-dimensional spin-orbit coupling in ultracold atoms, measuring novel topological quantum properties induced by spin-orbit coupling. This key breakthrough will have major impact on research into novel topological quantum states and promote deeper understanding of the material world. The collaborative results were published as a research article in the prestigious journal Science. Due to the work' s "major potential for studying exotic phenomena beyond traditional condensed matter physics," Science published a dedicated commentary in its Perspectives section.

4.2 Sub-Nanometer Resolution Single-Molecule Optical Raman Imaging

The USTC Single-Molecule Science Team, led by Professor Dong Zhenchao, has long been dedicated to developing a combined system integrating scanning tunneling microscopy' s high-resolution static characterization with optical technology' s highly sensitive dynamic detection, greatly enriching measurement and control methods, expanding measurement limits, and providing new opportunities for single-molecule physical chemistry research. In recent years, they have achieved a series of major breakthroughs in single-molecule electroluminescence and Raman scattering. In 2013, the group achieved, for the first time internationally, sub-nanometer resolution single-molecule optical Raman imaging, which improved spatial imaging resolution with chemical identification capability to below one nanometer. This has extremely important scientific significance and practical value for understanding the microscopic world, particularly microscopic catalytic reaction mechanisms, molecular nanodevice construction, and high-resolution biomolecular imaging including DNA sequencing, while also opening new avenues for studying single-molecule nonlinear optics and photochemical processes. All three Nature reviewers highly praised this work, and world-renowned nanophotonics experts Professors Atkin and Raschke wrote a Nature "News and Views" commentary titled "Optical Spectroscopy Ventures Inside Molecules." In 2015, the group demonstrated, for the first time internationally, real-space Raman spectroscopic identification of adjacent different molecules, which Nature Nanotechnology reviewers praised as "a very surprising and unprecedented work that achieves one of the ultimate goals in analytical chemistry—identifying different molecules and their chemical states at the molecular resolution level."

4.3 First Realization of Multi-Degree-of-Freedom Quantum Teleportation

The research team led by Academician Pan Jianwei of USTC, together with colleagues Lu Chaoyang and Liu Naile, successfully achieved, for the first time internationally, quantum teleportation of a multi-degree-of-freedom quantum system. Nature published this achievement as a cover story—the first major breakthrough in quantum information experimental research in 18 years since the first single-degree-of-freedom quantum teleportation in 1997, laying a solid foundation for developing scalable quantum computing and quantum network technologies. Nature reviewers highly praised the work as "absolutely novel and important, at the forefront of quantum optics and quantum information," "a great achievement," and "raising quantum teleportation conceptually to a new level 18 years after the 1997 experiment." Due to its significance, Nature invited renowned quantum optics expert Professor Wolfgang Tittel to write a "News and Views"commentary: "This experimental realization represents an important step toward understanding and demonstrating one of quantum physics' most profound and puzzling predictions, and can serve as a powerful basic building block for future quantum networks."Immediately after publication, the work was reported by numerous international media outlets including Science News and Physics World, which stated that "the work not only advances understanding of fundamental quantum mechanics but will also play an important role in future quantum computer development."

4.4 First Single-Molecule Paramagnetic Resonance Spectrum at Room Temperature and Atmospheric Pressure

The research team led by Academician Du Jiangfeng of USTC applied quantum technology to single protein molecule research, obtaining the world' s first magnetic resonance spectrum of a single protein molecule under room temperature and atmospheric conditions. This achievement not only advances magnetic resonance research from billions of molecules to a single molecule, but the "room temperature and atmospheric pressure" experimental environment provides necessary conditions for future widespread applications in life sciences and other fields, making high-resolution nanoscale magnetic resonance imaging and diagnosis possible. The work holds profound significance for exploring life and material science mechanisms at the single-molecule level across physics, biology, chemistry, and materials science. The achievement has generated significant international response, with extensive news coverage from the American Chemical Society, the Max Planck Society, and other institutions. Science magazine selected the work as a research highlight, praising it as "achieving a sublime goal" and "a milestone toward real-time imaging of single protein molecules in living cells." This work builds upon the team' s previous important advances in nanoscale nuclear magnetic resonance technology, single nuclear spin magnetic resonance spectroscopy, and imaging.

4.5 First Measurement-Device-Independent Quantum Key Distribution Over 400 km Resistant to Quantum Hackers

Increasing secure communication distance, improving secure key rates, and enhancing real-system security are the three most important goals for developing practical quantum key distribution (QKD). The Pan Jianwei research team conducted original research around these three objectives, achieving a series of internationally leading results. In 2013, the team first realized measurement-device-independent QKD, completely solving all hacker attacks targeting detection systems. PRL promoted this work through a press release to science and technology media, with coverage by Science, Physics, The Economist, and other European and American science news outlets. In 2014, the team extended the secure communication distance of measurement-device-independent QKD to 200 km, improving the key rate by three orders of magnitude and setting a new world record. PRL reviewers commented that this was "an important milestone for practical QKD" and "a major physical and technical advance," selecting it as an "Editor' s Suggestion" and prompting Physics World to report "Secure Quantum Communication Transmitted Over Long Distances." In 2016, collaborating with Tsinghua University, Shanghai Institute of Microsystem and Information Technology, and Jinan Institute of Quantum Technology, the team achieved measurement-device-independent QKD over 400 km resistant to quantum hackers, greatly promoting the development of secure and practical long-distance fiber quantum communication. PRL reviewers highly praised the achievement as "the farthest transmission record for QKD and quantum communication," "an outstanding achievement," and "breaking the ultimate transmission limit of the BB84 protocol with single-photon sources." The work was selected as an "Editor' s Suggestion" by PRL and reported by the American Physical Society' s Physics website.

4.6 Hundred-Kilometer Free-Space Quantum Teleportation and Entanglement Distribution

The joint research team led by Academician Pan Jianwei of USTC, together with Peng Chengzhi, Chen Yuao, Wang Jianyu from the Shanghai Institute of Technical Physics, and Huang Yongmei from the Institute of Optoelectronics, achieved, for the first time internationally, hundred-kilometer-scale free-space quantum teleportation and entanglement distribution. Through ground-based experiments, they solidly demonstrated the feasibility of implementing a satellite-based global quantum communication network. The achievement was published as a cover story in Nature magazine. The European Physical Society' s Physics World reported the new quantum teleportation record with the headline "Physicists Announce New Quantum Teleportation Record," while Science News titled its coverage "Quantum Teleportation' s Great Leap," stating that "the progress brings a satellite-based, practical long-distance quantum communication network closer to reality" and "paves the way for satellite-based quantum communication and long-distance quantum mechanics tests." Nature reviewers praised the work as "another heroic experimental work from Pan' s group" and "a potential milestone for long-distance quantum communication." Nature released a press release titled "Toward a Global Quantum Network" and simultaneously published the cover headline "Quantum Teleportation Leaps Over the Hundred-Kilometer Gap."

4.7 Major Breakthrough in Scalable Fault-Tolerant Quantum Computing: World' s First Topological Quantum Error Correction

The research team led by Academician Pan Jianwei of USTC, together with Chen Yuao and Liu Naile, collaborated with Australian and Canadian researchers to combine topological quantum computing with quantum error correction theory. Using an eight-photon cluster state with topological properties, they achieved, for the first time in the world, topological quantum error correction. Published as a long article in Nature' s special issue commemorating the 100th anniversary of Alan Turing' s birth, this was the first Nature paper in quantum information with China as the first affiliation. Regarding this experimental demonstration of the topological quantum error correction scheme with the highest known error tolerance among all quantum computing schemes, Nature reviewers praised it as "a very important principle experiment, a heroic quantum optics experiment," "perfectly executed and extremely challenging," and "experimental verification of a key link in topological error correction, the most compelling paradigm in current quantum information processing." Nature issued a dedicated press release and invited renowned quantum optics expert Professor James Franson to introduce the work in the "News and Views" section.

5. Conclusion

The field of quantum information continues to forge new scientific frontiers, inspiring revolutionary technological innovation and driving leapfrog development in information technology. Meanwhile, research achievements in quantum information are increasingly becoming sources of technological innovation in material science, energy science, and life science. As President Xi Jinping noted during his 2013 inspection of the Chinese Academy of Sciences: "Scientists have begun to control the quantum world, which will greatly promote the development of information, energy, and materials science, bringing about a new industrial revolution."

The implementation of the Category B Strategic Priority Research Program on "Coherent Control of Quantum Systems" holds major practical significance and far-reaching impact for China to firmly grasp the development direction of quantum information and related frontier research fields, maintain and enhance the advanced nature of quantum technology and products, and effectively respond to international competition. It will undoubtedly make important contributions to enhancing China' s comprehensive scientific and technological strength, national economic development, and social progress.

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Note: Figure translations are in progress. See original paper for figures.

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