Korean Quantum Information Research

Korea Institute for Advanced Studies and Seoul National University

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Quantum Information Science and Technology Project

Korean quantum information science and technology research is centered at the laboratories of Prof. Jaewan KIM, of the Korea Institute for Advanced Studies, and Prof. Dong Pyo CHI, of Seoul National University. The present report summarizes their research. Prof. KIM is organizing an international workshop on quantum information science next year—the first of its kind in Korea—to precede the Japanese ERATO conference on quantum information. Prof. CHI leads a research group in quantum algorithms.

Keywords *Quantum algorithms, communications, computing, cryptography, imaging, metrology, information science and technology*

1. EXECUTIVE SUMMARY

- Quantum algorithms research is a young field in Korea and has yet to achieve the infrastructure required to attain consistent advances on par with the international community.
- Attention from the Korean national government has increased in the last year and a number of new initiatives have been proposed to accelerate the organizational development of quantum information science at the national level.
- Prof. Jaewan KIM, of the Korea Institute for Advanced Studies, is organizing the first international workshop on quantum information science in Korea next year to precede the Japanese ERATO conference on quantum information.
- Prof. Dong Pyo CHI, of Seoul National University, leads a quantum algorithm-oriented research group whose accomplishments include a modification to Grover's algorithm for searching a database with multiple solutions.

Impact & Assessment

Increasing attention is being paid to the field of quantum information and communications research in Korea: five major research programs have been commenced in order to stimulate the emergence of an infrastructure that can produce results on par with the

international community. Though still in its infancy, research is rapidly expanding in response to international competition as corporate and national funding agencies recognize the long-term necessity of quantum information technologies.

2. NATIONAL RESEARCH INITIATIVES

2.1 National Funding Agencies

Korean national funding in the field of quantum information science originates from four primary government agencies: (1) the **Ministry of Industry and National Resources**, whose funding is characterized by an interest in practical, demonstrable research capable of short-term realization; (2) the **Ministry of Information and Communications**, whose interests include fundamental, basic research of longer-term character, and is possibly engaged in classified research unavailable in the public domain; (3) the **Ministry of Science and Technology**, which has the largest resources available for funding, and is currently supporting three of the five Korean national research projects in quantum information; and (4) the **Ministry of Education**, which is closely related to Ministry of Science and Technology.

2.2 National Research Programs

The Korean national government has allocated funding to five quantum information research programs, as follows:

MOST National Research Laboratory

Principal investigator Prof. Soon-Chil LEE, of the Korean Advanced Institute of Science and Technology (KAIST), conducts research in nuclear magnetic resonance (NMR) and solid-state based quantum computing architectures, and has constructed a four-qubit NMR based quantum computer. The (1-professor, 5 student) project was initiated in 2000 and has a five-year duration at 1.8×10^8 won per year. Funding is sourced from the Ministry of Science and Technology (MOST). The group has conducted related work in single-electron spin detection of up to 100 electrons, as well as developing software for programmable quantum computing.

MOE Brain Korea 21 (BK21)

Established under Prof. Hai-Woong LEE of the KAIST physics department, the *Brain Korea 21* Project (3 professors, 4 postdoctoral researchers, 15 students) investigated 'quantum optical information processing.' Funding was granted through the Korean Ministry of Education.

MOST Creative Research Initiative

The iQUIPS, or *intelligent quantum information processing*, *Creative Research Initiative* (2 professors, 5 postdoctoral researchers) is funded by the Korean Ministry of Science and Technology. The project is led by Prof. D. AHN of the University of Seoul's electrical engineering department. Prof. AHN will soon move to Korean University. AHN's group researches of quantum-dot based information processing. A three-year project, funding is valued at 5×10^8 won per year.

MOE Quantum Information Science

A three-year project (8 professors, 1 postdoctoral researcher, 10-15 students) in quantum information science was initiated by the Ministry of Education in July 2002 to study fundamental issues towards developing future technologies. Composed of five university groups, including two experimental groups, funding is valued at 2.5×10^8 won per year. Areas of focus include optical quantum entanglement, quantum cryptography experiments, and theoretical questions related to quantum information applications.

MOST Next-generation Security Project

Funded by the Ministry of Science and Technology, the *Next-generation Security Project* conducts research in cryptosystems based on mathematical complexity (classical public-key cryptography) as well as a number of advanced topics such as nano-implementation of cryptography, ubiquitous cryptosystems and standardized protocols, and quantum cryptography. Led by Prof. Jaewan KIM, the quantum cryptography project (9 PhD researchers, 15 students) is based on a 3+4 year funding cycle at 8×10^8 won per year, initiated 2003. Single-photon systems will be investigated for the first three years of the project, followed by four years of research in areas such as coherent state systems and quantum repeaters.

3. KOREA INSTITUTE FOR ADVANCED STUDIES

The **Korea Institute for Advanced Studies** (KIAS) is an educational research institution whose activities focus on fundamental research in math, physics, and computational science problems such as protein folding, genomics, and quantum computing. KIAS functions in a role analogous to the United States' Princeton Institute for Advanced Study, and plays a central role in Korean national research initiatives in quantum information science and technology. Led by Prof. Jaewan KIM, who is organizing the first Korean international workshop on quantum information, the quantum information group is actively engaged in a number of topics such as quantum cryptography, communications, quantum information theory, theoretical studies of quantum computing using Josephson-junction qubits, quantum imaging and metrology. Prof. KIM most recently published a paper on quantum holography in the Proceedings of SPIE, *The International Society for Optical Engineering*.

3.1 KIAS Research Activities

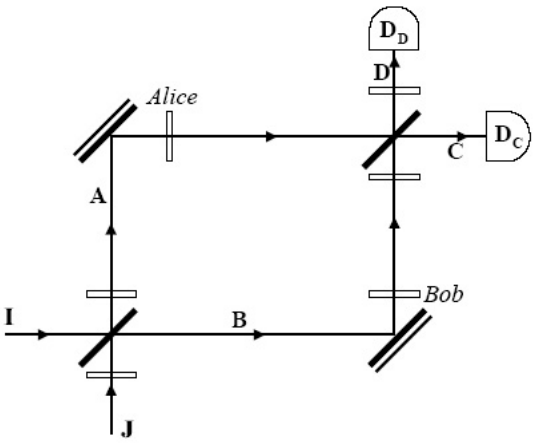

FIG 1. ***Single-particle Bell inequality*.**
Single particle version of Bell's inequality test with a Mach-Zender interferometer. A single photon and vacuum are incident on the beam splitter (with a pair of – π/2 phase shifter) from the input ports I and J, respectively. The reflected wave A and the transmitted wave B are recombined at the second beam splitter (with a pair of – π/2 phase shifter). Alice and Bob, located somewhere along the pathway of the reflected wave A and the transmitted wave B, respectively, each have a phase shifter which they may or may not use [1].

In collaboration with Hai-Woong LEE, also of KIAS, Prof. Jaewan KIM has performed experiments in single particle entanglement and quantum teleportation using linear optical devices. LEE and KIM consider the photon as qubit, for example to construct a quantum optical model of the Fredkin gate, and proposed a scheme for quantum teleportation based upon single-photon entanglement. Single-particle nonlocality was studied through analysis of the Bell inequality (Fig 1).

Prof. KIM is also interested in the study of quantum imaging and metrology for the potential of developing novel applications, and is concerned with the

short-term oriented nature of today's corporate and academic environment that neglects basic research. As new knowledge and new technology move 'hand-in-hand,' KIM feels it of importance to devote resources to long-term, fundamental research questions, even those with no foreseeable commercial applications.

Dr. Sangchul OH, a member of the research group at KIAS, is a physicist whose interests include superconducting quantum computing using charge qubits. Dr. OH has studied the behavioral dynamics of two-qubit gates and probability of success of the CNOT operation in relation to rise and fall of pulse time (Fig 2). Numerical analysis of both ideal and superconducting charge qubits illustrates that error rate grows quadratically in finite rise and fall times.

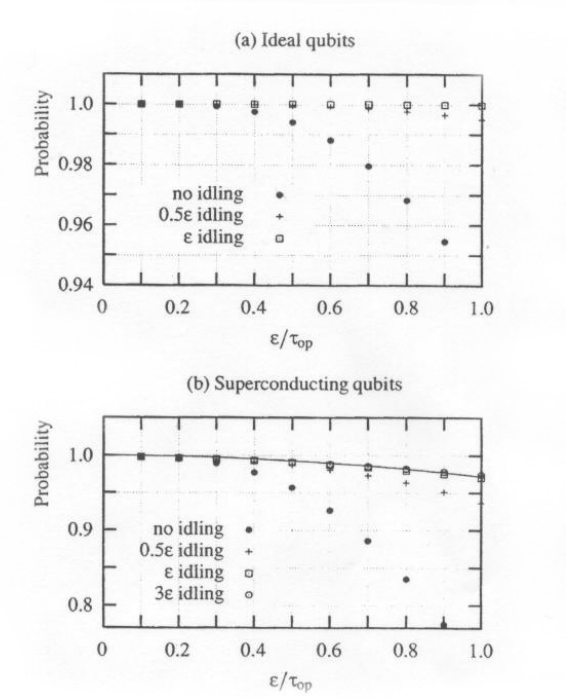

FIG 2. ***Probability of success of the CNOT gate.*** Probability of success on the action of the CNOT gate as a function of the ratio of the rise and fall time to the operation time: (a) ideal qubits, (b) superconducting charge qubits. Idle times prevent the tails of pulses from overlapping. The solid line is the fitting function that shows the quadratic growth of error in rise and fall times [3].

The KIAS quantum information group collaborates closely with researchers at Seoul National University. Soojoon LEE, a research fellow in the KIAS group, has worked in collaboration with Seoul National University researcher Dong Pyo CHI to examine initialization-free quantum algorithms, entanglement and entanglement measures, and quantum cryptographic key distribution protocols. Seoul National University research activities are summarized in the following section (**3**).

3. SEOUL NATIONAL UNIVERSITY

Seoul National University research in quantum algorithms is led by mathematician Prof. Dong Pyo CHI. Research problems of interest to the group include harmonic maps, dynamical systems (symbolic dynamics and billiard problems), and quantum mechanics (quantum computation and quantum chaos). Prof. CHI has developed a novel quantum algorithm [5] for database searching with zero error probability where the number of solutions is more than a quarter of the sample, utilizing a modified Grover operator of arbitrary phase (Fig 3). Results are obtained after a single query.

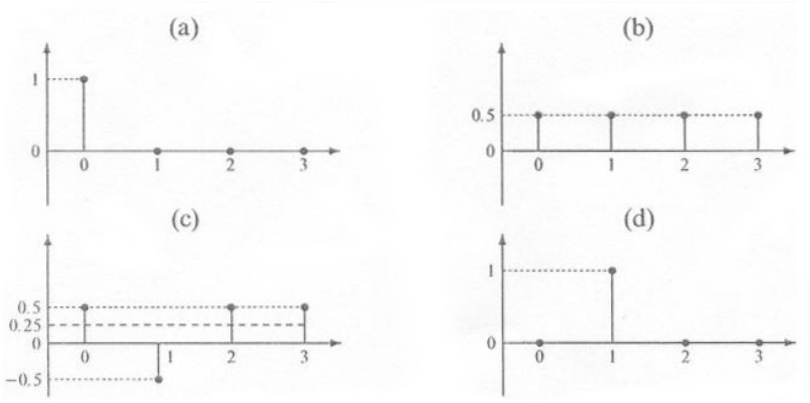

FIG 3. ***Modified Grover algorithm.*** The effect of the Grover algorithm when $N = 4$ and the solution is $j = 1$.

CHI's former student Jinsoo KIM, who co-developed the modified Grover search algorithm, is supervising a number of graduate students who hope to develop a mature Korean research program in quantum algorithms. KIM's research interests include generalization of the Deutsch-Jozsa algorithm, initialization-free algorithms, error-correcting Maximum Distance Separable (MDS) codes, and cryptographic protocols. Recent work in [6] develops a quantum algorithm that works without *a priori* knowledge of the state of the auxiliary register. With no need for initialization, it becomes possible to compose an auxiliary register from any arbitrary qubit, even an entangled qubit occupied by other computational processes.

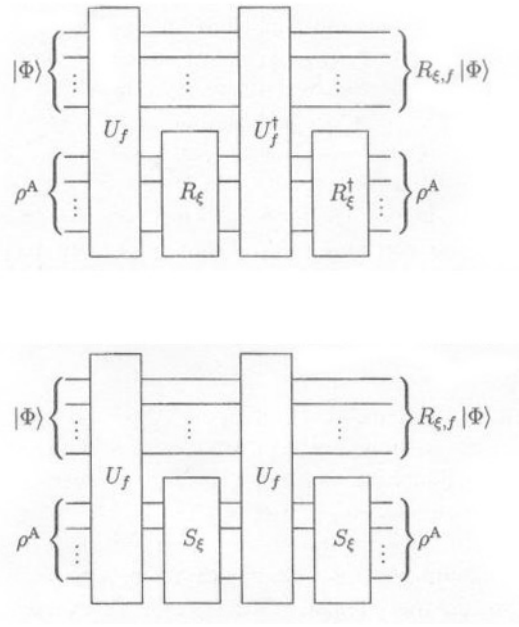

FIG 5. ***Initialization free circuits.*** Quantum circuits for initialization-free functional phase rotation: the state of the auxiliary register is described by a density operator ρ^A.

Prof. CHI's group is also interested in the phenomenon of entanglement and entanglement measures such as negativity and entanglement of formation. A recent paper [7] examines the two-parameter class of states $\rho(\alpha, \gamma)$ in a 2 x n system, calculating negativity and lower and upper bounds on entanglement of formation (Fig 4). Calculated results show that an arbitrary state can be transformed into $\rho(\alpha, \gamma)$ by means of local operations and classical communication, and is invariant under unitary operations of the form U x U on a 2 x n quantum system.

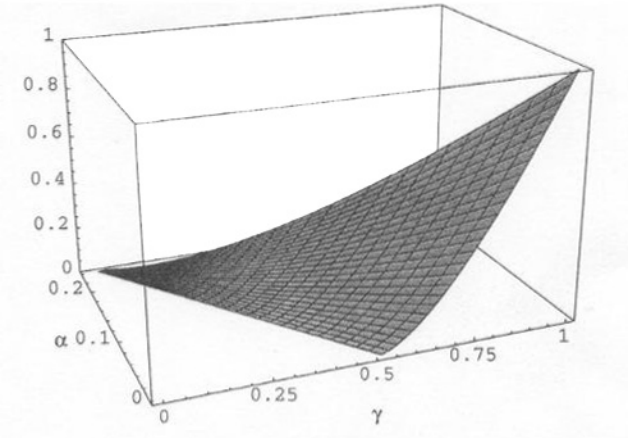

FIG 4. ***Lower bound on entanglement of formation*** for $\rho(\alpha, \gamma)$ for $1/2 \le (n-2)\,\alpha + \gamma \le 1$ in a 2 x 4 system.

Seoul National University's quantum algorithms research is still in its formative stages, and presently lacks sufficient influence to attract funding from corporate and government sponsors. Though it will likely take a number of years before the program reaches enough maturity to begin making consistent contributions to the field, an increasing number of Seoul National University graduate students are being attracted to its quantum information science group. Prof. CHI and Prof. KIM are actively encouraging graduate students to pursue related studies, and as the program grows it will play a more significant role in Korean national research in the years to come.

4. FUTURE OUTLOOK

The potential of quantum information science has only begun to make an impact substantial enough to attract Korean national and corporate interests. Two years ago Prof. Jaewan KIM tried, without success, to stimulate interest in quantum cryptography at Samsung Research and Development. They have, however, recently taken interest in the topic and are rumored to have initiated a program in quantum cryptography.

Korean research is in need of a strong leader to convey the vision of quantum information science to short term-oriented research groups. Prof. KIM is poised to play this role; he has attended several government advisory meetings with the Korean Ministry of Telecommunications. Through his leadership of the first Korean international workshop on quantum information, he has the potential to ignite interest in young researchers and draw the necessary attention for funding from larger interest groups. Prof. CHI's group, though still in its formative stages, will continue to benefit from its collaboration with the Korea Institute for Advanced Studies and Prof. Jaewan KIM.

5. REFERENCES

[1] H. W. LEE and J. KIM. "*Quantum Teleportation and Bell's Inequality Using Single-Particle Entanglement*," LANL e-print archive quant-ph/0007106 (2000)

[2] J. W. LEE, C. H. KIM, E. K. LEE, J. KIM and S. LEE. "*Qubit geometry and conformal mapping*," LANL e-print archive quant-ph/0201014 (2002)

[3] S. OH. "*Errors due to finite rise and fall times of pulses in superconducting charge qubits*," Phys. Rev. B, Vol. **65**, 144526 (2002)

[4] S. OH, S. LEE and H. W. LEE, "*Fidelity of quantum teleportation through noisy channels*," Phys. Rev. A, Vol. **66**, 022316 (2002)

[5] D. P. CHI and J. KIM, "*Quantum Database Searching by a Single Query*," LANL e-print archive quant-ph/9708005 (1997)

[6] D. P. CHI and S. LEE, "*Quantum functional oracles*," J. Phys. A: Math. Gen. 35, 6911-6917 (2002)

[7] D. P. CHI, J. KIM and S. LEE, "*Initialization-free generalized Deutsch-Jozsa algorithm*," J. Phys. A: Math. Gen. 34, 5251-5258 (2001)

[7] D. P. CHI and S. LEE, "*Entanglement for a two-parameter class of states in a 2 x n quantum system*," J. Phys. A: Math. Gen. 36, 11503-11511 (2003)

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