QUANTUM INFORMATION SCIENCE

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Quantum information is a new, rapidly expanding multidisciplinary field whose goal is the radical transformation of information and communication science and technology by exploiting the remarkable properties and phenomena of quantum physics. Information security, bandwidth limits, and computational complexity are all being re-examined in the light of quantum information science (QIS). The advent of new materials, light sources and detectors, and nanotechnology and nanomanipulation have allowed quantum phenomena to extend to larger scales, thereby opening new vistas for applications of quantum effects and breathing life into QIS.

EXECUTIVE SUMMARY

Over the past two decades, the nexus between quantum theory and informatics has been especially appreciated because of the profound ramifications quantum theory has for the foundations of information and communications technology. The uncertainty principle, which quantifies the limits of measurement for quantum systems, has emerged as a protector of information for quantum cryptographic protocols. Entanglement, which Einstein regarded as “spooky action at a distance,” has become a crucial resource in quantum information processing. The recognition that quantum information can make computationally intractable problems easily solvable, provide unconditionally secure cryptographic key distribution, and rapid search algorithms, has engendered interest by industry, security agencies, and the military across a multitude of disciplines.

The University of Calgary recognized the importance of QIS and the strength and prestige of the quantum computing group in the Department of Computer Science, and thus established quantum information as a research pillar. In addition iCORE identified quantum information as an important area of investment and, through the joint commitment of iCORE and the University of Calgary, supported the development of a QIS theoretical physics program at the university. The excellence of the QIS computer scientists and the establishment of the theoretical physics program has provided two of the three foundations for a world class research program in QIS in Alberta, with the experimental physics research in quantum information science the third foundation.

Subsequent to the creation of the iCORE-funded theoretical physics group under the leadership of Dr Sanders, the University committed to creating a Canada Research Chair Tier II position in experimental QIS.

Creating strength in experimental QIS to complement existing theoretical efforts in physics and in computer science provides the basis for creating and sustaining an internationally renowned multidisciplinary group in quantum information, and the University of Calgary now has the necessary ingredients for success, which will be integrated within the nascent Institute for Quantum Information Science approved by the University of Calgary in 2004.

Since July 2003, when Dr Sanders commenced his position as iCORE Professor of Quantum Information Science, the QIS group in the Department of Physics and Astronomy has increased to three faculty members (Dr Sanders plus affiliated physicists Drs Feder and Hobill), one senior research associate (Dr Marzlin, who has also been appointed as an adjunct professor in the Department), one postdoctoral research associate, five PhD students, two MSc students, one long-term exchange PhD student from Australia, two short-term student exchanges from Germany, and two research assistants. The university offered an associate professorship to Dr Lvovsky from Germany to join the Department of Physics and Astronomy in the area of experimental quantum information science.

Since the inception of the theoretical QIS group, remarkable advances have been made: the creation of an institute, 14 members and affiliates, collaborations with the computer scientists, an experimental quantum information science position, formal affiliation with Australia's Centre for Quantum Computer Technology and the European Union QUPRODIS (QUantum PRoperties of DIstributed Systems), support from iCORE, PIMS and MITACS, and a proposal for a new senior/graduate course called "Implementations of Quantum Information." These nine months auger well for the iCORE program in QIS and for QIS as a new and exciting multidisciplinary venture at the University of Calgary.

RESEARCH PROGRAM OVERVIEW

The goals of the iCORE program in QIS at the University of Calgary are as follows: to establish leadership in both theoretical and experimental QIS research, including research on new quantum information processing algorithms and protocols, research on experimental realizations of a quantum computer, and development of new physical implementations for quantum computing paradigms; to educate and train highly qualified personnel for QIS and allied disciplines; to create a multidisciplinary community of researchers collaborating on the key problems in QIS; and to identify promising research areas that will lead to valuable intellectual property and to conduct research into these areas.

Establish leadership in theoretical and experimental QIS research

True leadership is based on recruiting the best people. Calgary is fortunate in having a pre-existing superb group of QIS computer scientists including Dr Richard Cleve as a University Professor and Dr John Watrous as a Tier II Canada Research Chair plus new appointee Dr Peter Hoyer. In the Department of Physics and Astronomy, Dr Sanders joined as iCORE Professor to lead the theoretical physics effort, and the University will nominate Dr Alex Lvovsky as a Tier II Canada Research Chair in experimental QIS. The core leadership for the three main areas of QIS research have thus been established.

The backbone of the research effort is lead by excellent postdoctoral research associates, and, since the establishment of the iCORE program, several outstanding postdoctoral fellows have been recruited including Hartmut Klauck and Hein Roehrig in Computer Science and Shohini Ghose and Jon Walgate in Physics. Karl-Peter Marzlin has been recruited from Germany as a high-level research associate in Physics to lead, with Barry Sanders, the component of the theoretical physics program dedicated to "enabling technologies for QIS." All appointees are recognized as outstanding in the field, and Calgary's QIS leaders have agreed on a policy of only appointing outstanding researchers; hence a universally strong base of leadership is being established in line with the objectives.

The experimental effort in QIS is being established to ensure that QIS is both a theoretical and an experimental research area at the University of Calgary. In addition to nominating a Tier II Canada Research Chair, the Faculty of Science has provided excellent laboratory facilities and a generous start-up offer. The QIS experimental effort is expected to be equal in caliber to Calgary's existing theoretical efforts and competitive with international experimental QIS research. QIS is realized in a variety of physical systems, from atoms to semiconductors to organic molecules: the Calgary experimental program will be in quantum optics, which encodes quantum information into photons.

Educate and train highly qualified personnel

The computer science QIS program is well established, with several MSc completions in the past year. The iCORE-funded physics-based QIS program is new, and therefore education and training is best represented in terms of recruitment. Five PhD students are receiving support from iCORE for QIS research (four supervised by Sanders, one by Feder). These PhD students commenced their programs between August 2003 and March 2004.

Following the guiding principle of excellence, only strong students are recruited as indicated by the mean grade point average (GPA) of the students' entrance scores. The five PhD students had a mean GPA of 3.69 out of 4.00 in their Bachelor degrees and 3.81 out of 4.00 in their Masters degrees. The group has also hosted two German diploma students undertaking research in Calgary and one Australian PhD student who is visiting for a year.

In addition to students, Drs Karl-Peter Marzlin and Shohini Ghose have joined the group as research associates: Marzlin is a senior research associate leading the "enabling technology" project and Ghose is a postdoctoral research associate leading the "foundations of quantum information theory" program. Dr Walgate has been appointed as a postdoctoral research associate but will join later in 2004.

Create a multidisciplinary community of researchers collaborating on key problems

The key to Calgary's success in QIS is building a multidisciplinary program, beginning with computer science and theoretical and experimental physics. Excellent progress has been made towards this goal. The physicists and computer scientists have collectively established a weekly QIS seminar series with excellent attendance. The university has approved and allocated support for the creation of an Institute for QIS. Examples of our multidisciplinary collaborations follow.

Quantum Fingerprinting

Drs Cleve and Watrous, together with two European collaborators, proposed quantum fingerprinting as a QIS task. Drs Sanders and Marzlin and Mr Horn are developing a proposal for experimental realization and exploitation of quantum fingerprinting.

Quantum Walks

Quantum walks research is being conducted by Watrous and Cleve (for new quantum algorithms), Sanders (quantum measurement issues and also quantum optics implementations), and Feder (realization for atoms in optical lattices). In addition Sanders and Cleve are collaborating on efficient quantum simulation of quantum walks and related systems.

Extending Quantum Cryptography

Quantum key distribution has been a major success in QIS, resulting in important commercial technologies. Physicists and computer scientists in Calgary are now collaborating on extending quantum cryptography, perhaps by add-on applications. This research direction may lead to natural collaborations with iCORE Chair Hugh Williams' Centre for Information Security and Cryptography (CISaC). One significant success in this area has been the recent realization of experimental sharing of secret quantum states in a collaboration between Sanders and Lam's experimental group at the Australian National University. This experimental sharing of quantum secrets is regarded as a major advance in QIS and greatly extends the capabilities of quantum teleportation experiments (quantum teleportation is

Barry Sanders and some research team members at the 2004 Banff Informatics Summit regarded as a key QIS task that would play the role of repeaters in quantum communication and be a backbone for processing in a quantum computer).

Identify and conduct research in promising areas

Research leadership requires establishing new directions, not just improving and enhancing existing research in the field. The Calgary aim is to develop new QIS concepts, protocols, tasks, algorithms, and implementations, develop these ideas to a feasible level, and, as much as possible, realize such systems all at the University of Calgary or with collaborators. The multidisciplinary research approach gives Calgary its "edge": strong collaborations between computer scientists and physicists will lead to creative and productive projects on new lines of research, with the aforementioned examples of quantum fingerprinting and sharing quantum secrets as evidence Calgary's progress in new directions. In addition to the advantages of collaborations between computer scientists and theoretical physicists, the advent of experimental QIS research at Calgary will introduce new advantages. The "enabling technologies" program at the University of Calgary is directed to breaking down technical obstacles to realizing QIS.

Summary

The goals of the iCORE project are being met, and successes with creating a multidisciplinary research program have been discussed above. Highlights include the formation of the Institute, the rapid recruitment of excellent research associates and students, and the experimental demonstration of sharing quantum secrets. The group is focused on success in these goals, with specific research projects established according to these goals.

Barry Sanders

RESEARCH PROJECTS

The iCORE research program can be subdivided into four projects: (i) resources for quantum information, (ii) foundation issues of QIS, (iii) quantum information protocols and implementations, and (iv) enabling technologies. Of course the areas overlap with each other and with other QIS research at the University of Calgary. Each of the programs has, or is expected to have, co-leadership by a research associate. Currently research associates Drs Ghose and Marzlin are co-leading areas (ii) and (iv), respectively. Descriptions of these projects and main achievements follow.

Resources for Quantum Information

In standard ICST, resources are created and consumed such as CPU time, memory, and disk space. Quantum information systems require additional resources. In addition to bits as representations of classical (or standard) information, there are quantum bits (or qubits) that allow the simultaneous superposition, or coexistence, of zeroes and ones. Ebits (entangled bits) make use of quantum correlations (Einstein's "spooky action-at-a-distance") and are another example of a QIS resource. In addition to various resources, considerations such as fragility of resources (for example due to decoherence, destruction, transmutation) and detection efficiency are important. There are also "capital" resources such as quantum gates that can be used to create consumable resources such as entanglement. This project addresses such issues: creating, quantifying, protecting, and consuming resources for QIS.

Much of the research into quantum information resources has been a trans-Pacific collaboration, involving Sanders' iCORE-funded team at the University of Calgary and his Macquarie University team that is a partner in Australia's Centre of Excellence for Quantum Computer Technology. The challenge of inferring entanglement via squeezing measurements has been a central concern, and Drs Xiaoguang Wang and Sanders have established rigorous connections between macroscopic degrees of squeezing for collective systems and the underlying entanglement. Dr Berry of Macquarie University, who was a long-term visitor to Calgary in 2003, and Dr Sanders collaborated on establishing relationships between entropy measures and also on numerical analyses of entanglement capabilities of quantum gates for computation. These studies have established mathematical relationships between various resources and measurable quantities, and are valuable in assessing resource issues for QIS.

In addition to assessing resources, creating entanglement is important. A three-way collaboration between Calgary, Macquarie University, and Hong Kong Baptist University considered quantum chaos as a means to generate entanglement rapidly. Recently researchers have studied this capability of fast entanglement via quantum chaos, and our collaboration successfully identified generic properties concerning the increase of entanglement via quantum chaos, which will be a cornerstone for exploiting quantum chaos to generate entanglement.

Foundation issues of QIS

Quantum theory is self-consistent except insofar as measurement is concerned, as measurement provides the transition from the quantum world to our world of "facts." Measurement is regarded as a key problem in quantum theory, one that is reconciled by adopting interpretations that enable quantum theory to be employed in a predominantly classical world. However, measurement theory is critical in quantum information processing, especially as the requirements of measurements (such as precision, limited disturbance, and rapidity) may run counter to the requirements for quantum components to be stable and robust. Fragile quantum systems may not be amenable to precise rapid measurements. As measurement theory is a fundamental problem in quantum physics, this project focuses on measurement as a foundation issue of QIS. The goal is to refine theories of measurement, and apply these theories to challenging problems, in order to ensure that measurement theories in QIS are accurate and appropriate.

We have been developing theories of continuous measurement and the effect of measurement on entanglement and localization. These theories are tested numerically on quantum chaotic systems, which provide a stringent class of models to test our theories. Theory collaborations are planned with Dr Ivan Deutsch's group at the University of New Mexico, and experimental collaborations with Dr Poul Jessen's group at the University of Arizona. We have also been testing theories of measurement on quantum walks, in collaboration with Dr Viv Kendon at Imperial College, London. The application of measurement theory on quantum walks, which is an important quantum information problem, has yielded a resolution to the conundrum of what is "quantum" about a quantum walk.

Another area of foundation research has commenced as a collaboration between Killam Memorial Professor Valeri Frolov at the University of Alberta and Dr Sanders. QIS may enable certain fundamental problems concerning radiation from black holes to be resolved. Drs Sanders and Frolov commenced collaboration on assessing quantum information aspects of radiation from black holes that are confined within boundaries. The goal is to account for seemingly anomalous entropy of the black hole to the reflection of the radiation from the black hole back into the black hole.

Finally geometric phase is important as a tool for control and stabilization in QIS. Significant progress has been towards an operational approach towards geometric phase in open systems based on reasonable restrictions on the environment and its coupling to the system of interest.

Quantum information protocols and implementations

A major interdisciplinary effort at the University of Calgary concerns development, implementation, and testing of new quantum information protocols, all at the University of Calgary. Our recent success with research on sharing quantum secrets exemplifies this approach of concept-to-design QIS research. Dr Cleve of Calgary and two-coworkers (Dr Gottesman, now at Perimeter Institute in Waterloo, and Dr Lo, now at University of Toronto) explained the principle of sharing quantum secrets in 1999, and Drs Tyc (Masaryk University, Czech Republic) and Sanders translated their proposal to a feasible experimental scheme. Dr Ping Koy Lam's group at the Australian National University collaborated with Dr Sanders to experimentally realize the sharing of quantum secrets in 2003. This experiment is an important advance for quantum communication, especially with respect to secure distribution of quantum information within a network that experiences component failures or has malicious parties, and represents the importance of collaborations between computer scientists, theoretical physicists, and experimental physicists.

The other major research topic in this project has been "optical quantum fingerprinting," which is undertaken as a collaboration between Mr Horn and Drs Sanders, Cleve, and Marzlin. Since Drs Cleve and Watrous (with collaborators) demonstrated that quantum fingerprinting in principle provided an exponential resource savings over standard fingerprinting protocols, quantum fingerprinting has been recognized as an important protocol. In 2003/2004 Sanders, Horn, and Marzlin have demonstrated (but not yet published) that few-qubit quantum fingerprinting can be realized via a feasible quantum optics experiment, and efforts have been focused on proving the "quantum advantage" for short fingerprints as well as designing the experiment and accounting for experimental limitations.

Enabling Technologies

Our main topics over the past year have been "single photon generation", "discriminating photon counters", "cold atoms in lattices", "electromagnetic-induced transparency (EIT)", and "superradiance and decoherence-suppressed subspaces."

In a collaboration between Sanders in Calgary and researchers at Macquarie University, University of Waterloo, and Imperial College, rigorous mathematical results concerning what can and cannot be accomplished by enhancing single-photon sources via interferometry have been established. Unfortunately the results have been negative – the collaboration has not yielded a scheme for improving sources – but the results are important as they establish methods for investigating this challenging problem and prove that certain, seemingly obvious, approaches, are not appropriate. On the other hand, the discriminating photon counter research (collaboration with Stanford University) yielded an outstanding experimental result whereby nonclassical light has been detected directly by photon counters for the first time. Photon sources and detectors play a key role in optical QIS, and these results underpin future experimental research in this area.

Recently quantum optics researchers have become excited about new possibilities for creating nonlinear optical systems that overcome the hurdles to all-linear optical QIS, based on new concepts and experimental development in EIT research. EIT research has been in the news because of the capability of slowing or stopping light experimentally, and this process may also use enhanced photon-photon collisions that can be exploited for QIS. Drs Feder, Marzlin, Sanders have been researching EIT, supervising students on this topic, and developing theories and numerical methods for studying realistic EIT, on its own and in QIS contexts.

Another QIS technology employs cold atoms in either an optical or in a magneto-optical lattice. Drs Ghose and Sanders have established the conditions by which this technology can enable tests of measurements in quantum chaotic systems, by taking advantage of: (i) the capability to prepare atomic states by laser cooling and state selection, (ii) varying lattice properties by laser control, (iii) easy control and elimination of the decoherence rate, and (iv) sophisticated tomographic techniques that allow complete monitoring and characterization of states. In separate work, Dr Marzlin and German collaborators developed an analytic theory of transverse excitations of Bose-Einstein condensates in a one-dimensional optical lattice and created accurate numerical simulations of gap soliton creation. Dr Feder and Mr Morris have been investigating Bose-Einstein condensates in a lattice as a candidate for QIS based on topological defects and toric codes. These studies will be important for evaluating future uses of cold atoms in QIS systems.

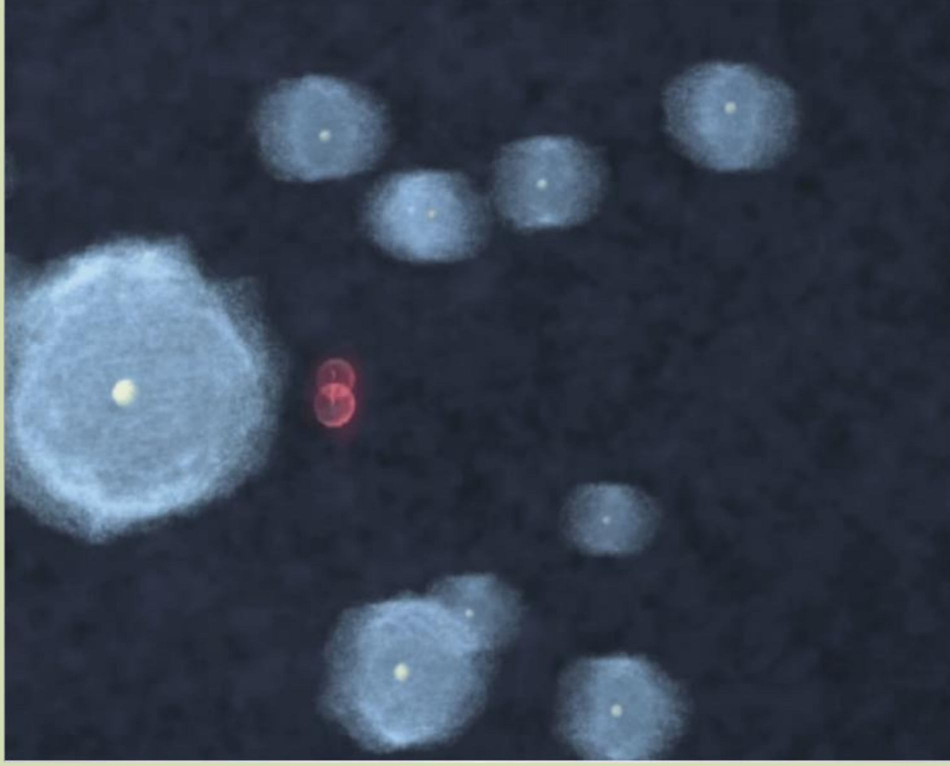
The final major effort over the year has been in the complementary topics of superradiance and decoherence-suppressed subspaces. The former research area is conducted as a collaboration between Dr Sanders and researchers at Macquarie University and the University of Auckland. Various theoretical methods have been developed to study the quantum optical properties of this well known collective system, which have defied detailed analysis because of numerical challenges. By judicious choices of which terms to ignore, and by careful development of numerical algorithms, collective behaviour of spatially separated systems has been made clear for the first time. In addition the methods apply as well to subradiance, the counterpart of superradiance, and Dr Sanders and Mr Brooke (Macquarie PhD student visiting Calgary for a year) are employing these methods to undertake realistic analyses of proposals for decoherence-free subspaces, which are designed to reduce the error rates in quantum computation. Brooke and Sanders have developed a theory of detection-conditioning for suppressing decoherence, which is being tested via numerical simulations.

Summary

In less than a year, the iCORE-funded research program is making great strides. Four projects have been established, yielding excellent results, a sound basis for future work, collaborations with Calgary's computer scientists and with national and international research teams, and the recruitment of outstanding research associates and students. Advances have been made in both theoretical and experimental QIS research areas.

OBJECTIVES FOR NEXT YEAR

The 2003/2004 objectives are as follow. The first objective is to develop the Institute for QIS as an organization for nurturing multidisciplinary, Calgary-based concept-to-design-to-implementation research in QIS, for attracting top researchers, students, and visitors as a destination of choice, for creating partnerships and joining networks with other QIS centres and groups, and for creating an administrative and resource infrastructure that is nurturing and enables researchers to perform their best with adequate support provided by the Institute. The second objective is to enhance QIS education by ensuring thorough reviews of the graduate students' progress, increase interactions and collaborations between QIS students by workshops and seminars, and by establishing a



Visualization of correlated photons

graduate-level course in the Department of Physics and Astronomy, to be called "Implementations of Quantum Information," that will complement the Department of Computer Science graduate-level course on "Quantum Computing." The third objective is to deliver research results that significantly advance QIS research, with the details discussed below. Included within the third objective is the development of an experimental QIS program in Calgary that will work in concert with the theoretical groups.

The iCORE research program for 2004/2005 builds on 2003/2004 research achievements and new opportunities. The four projects are the same as for the previous year: (i) resources for quantum information, (ii) foundation issues of QIS, (iii) quantum information protocols and implementations, and (iv) enabling technologies. Drs Ghose and Marzlin continue to co-lead areas (ii) and (iv), respectively, with Dr Sanders, and the plan is to appoint more research associates to co-lead on the other projects.

Resources for Quantum Information

Our recent success with sharing quantum secrets was undertaken in the domain of so-called continuous variable quantum information, and the challenge in this area is to translate these successes to the quantum digital domain. The problem with continuous variables is the same problem that arises in analogue computation: real numbers are an ideal that are not achievable, and standard computer science is built on a framework of discrete mathematics that allows error correction and reliability. A key goal for 2004/2005 is to assess continuous variable QIS: how much quantum information is inherent in such protocols, how to encode and decode, and how to correct errors. Another goal is the creation, use, and tomographic characterization of the cubic phase state. The cubic phase state is an important resource for universal continuous variable quantum information processing because the combination of linear optics, squeezing, homodyne detection and feed-forward, and a supply of cubic phase states prepared 'off-line', could allow a universal set of continuous variable processing without requiring daunting nonlinear optical transformations. If the theory indicates a feasible realization, we will seek an experimental partnership to make cubic phase states.

Further research is planned on entanglement. Whereas the past year has concerned the connections between entanglement and experimentally accessible quantities such as squeezing, further work (which will be conducted by PhD student Abu-Ajamieh) will concern how much entanglement is in principle accessible. This research on "operational entanglement" will help to assess how effective new proposals for entanglement can be; the work will be primarily of a mathematical physics nature and will determine in principle bounds to extracting entanglement for generic systems. The goal for 2004/2005 is a generalization of Bell's inequalities to bipartite entangled systems with internal su(3) dynamical symmetry, which is interesting in its own right and will require techniques useful in the longer term.

The third topic of this research area concerns optimization of simulations of quantum systems by a quantum computer. Given a particular physical system with known equations of motion, a simulation concerns decomposing the evolution of that system into a sequence of primitive gate operations on a quantum computer. A continuous evolution is written as a sequence of brief, discrete evolutionary states and these steps are decomposed as a quantum circuit. A collaboration between Drs Sanders, Berry, and Cleve will consider how to optimize the run-time (number of gate operations) for generic simulations.

Foundation issues in QIS

Research into quantum measurement will consider the effects of continuous measurement on the dynamics of a system, in particular on the entanglement dynamics. Preliminary results show that strong measurements can be made without necessarily causing a significant decrease in the useful entanglement. This research is expected to be a collaboration with researchers at the Universities of New Mexico (theory) and Arizona (experiment). This research will yield practical theories for measurement-based control on quantum systems.

The collaboration with Dr Frolov will establish a QIS-based resolution to the anomalous entropy problem of black holes radiating within a finite boundary. Another issue concerns fermionic coherence as a counterpart to bosonic coherence, which underpins most of the research on coherence in optical systems and in quantum information implementations. This topic builds on prior work with researchers at MIT, Stanford, and the University of Queensland and will lead to a useful alternative formalism for treating coherence of electronic currents in semiconductors. Dr Tyc will visit from the Czech Republic and collaborate on completing calculations of coherence functions, whose factorization characterizes the degree of coherence for such systems. The project on geometric phase is near completion and will culminate with an operational description of geometric phase in open systems based on reasonable restrictions regarding the environment and its coupling to the system.

Quantum information protocols and implementations

The major goal is to extend quantum cryptography, which is already remarkably successful, but developing additional stand-alone or add-on protocols. We are seeking to collaborate with experimentalists to achieve the first realization of quantum fingerprinting developed by us in 2003/2004, which will be performed within a quantum optics setting. Applications of quantum fingerprinting to quantum digital signatures will be explored. Another goal is to propose continuous variable remote state preparation in collaboration with Dr Arun Kumar Pati (Institute of Physics, Orissa, India) who will make an extended visit to Calgary in 2004. The new experimental quantum optics laboratory in Calgary may allow some or all of these proposals to be realized in Calgary. Regular dialogues have commenced between the physicists and computer scientists to seek ways to extend quantum cryptography by additional protocols.

Enabling Technologies

The major effort will be directed to electromagnetically-induced transparency (EIT) with Dr Marzlin and Mr Zeng Bin Wang (PhD student) and perhaps more students. As EIT could allow nonlinear optical elements for quantum communication and quantum computation, this area of research is quite promising, especially given recent experimental advances with slowing light and other EIT phenomena. The first stage of research is heuristics (simple rules for a quick assessment of proposed system) followed by development of computer programs that provide precise quantitative assessments and incorporate the most important experimental effects such as atoms wandering in and out of the light beam. An experimental EIT program is expected to commence in Calgary in 2005; hence this research will provide a foundation for the experimental program.

Other projects concern how best to combine decoherence-suppressed subspaces and error correction for optimal quantum computation with respect to space and time complexity. Cavity quantum electrodynamics is under investigation with two PhD students to determine the best means to infer the degree of useful entanglement in the system, and, in particular, ways to create tri-partite photon-phonon-electron entanglement.

Summary

There are numerous topics being researched under the four topics of the QIS program. This second year of the program will emphasize relevant foundation issues such as measurement and applications of QIS to other fields (for example black holes) and will seek strong collaborations with experimentalists on enabling technologies and on implementations of QIS protocols. Various physical systems are considered: cold atoms, cavity quantum electrodynamics, and both few-photon and continuous variable quantum optics. The group is large with an interactive network structure between research associates and students, so the broad range of ambitious topics are feasible over the year.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

Faculty Members

TEAM LEADER	ROLE/TOPIC	AWARDS
Dr Barry Sanders	iCORE Professor of Quantum Information Science, Director of Institute for Quantum Information Science	

Faculty Members

	ROLE/TOPIC	AWARDS
Dr Richard Cleve	University Professor in Computer Science, Deputy Director of Institute for Quantum Information Science, and QIS affiliate/"Quantum information protocols and algorithms"	
Dr David Feder	Assistant Professor in Physics and QIS affiliate/"Enabling technology: ultracold atoms"	
Dr David Hobill	Associate Professor in Physics and QIS affiliate/ "Foundations of quantum information: general relativity"	
Dr Peter Høyer	Assistant Professor in Computer Science and QIS affiliate/"Quantum information protocols and algorithms"	CIAR Scholar
Dr John Watrous	Associate Professor in Computer Science, Tier II Canada Research Chair, and QIS affiliate/" Quantum information protocols and algorithms"	CIAR Scholar

Research Associates

	RESEARCH TOPIC	AWARDS
Dr Karl-Peter Marzlin	Senior Research Associate/"Enabling Technology"	Adjunct Professor, University of Calgary
Dr Shohini Ghose	Postdoctoral research associate/"Foundations of quantum information"	

PhD Students

	RESEARCH TOPIC	SUPERVISOR	AWARDS
Iyad Abu-Ajamieh	Operational Entanglement	Sanders	Department Fee Waiver
Thomas Harmon	Quantum Optics in Confinement	Sanders	Department Fee Waiver
Alexis Morris	Topological Quantum Computing	Feder	Dean's Entry Scholarship
Xue Song Qi	Entanglement in Cavity Quantum Electrodynamics	Sanders	
Zeng Bin Wang	Electromagnetic-Induced Transparency with Single Photons	Sanders	

MSc Students

	RESEARCH TOPIC	SUPERVISOR	AWARDS
Stuart van der Lee	Quantum Walks on Optical Lattices	Feder	

Research Assistants

	TASKS	SUPERVISOR
Rolf Horn	Outreach, Research on quantum fingerprinting	Sanders
Gina Howard	Outreach: web, marketing	Sanders

Visitors

	STATUS	HOME INSTITUTION
Dr Wolfgang Lange	Academic	Max Planck Institute for Quantum Optics, Germany
Dr Dominic Berry	Academic	Macquarie University, Australia
Dr Michael Revzen	Academic	Technion – Isael Institute of Technology
Dr Gilad Gour	Academic	University of Alberta, Canada
Dr Sauray Das	Academic	University of Lethbridge, Canada
Mr Martin Kiffner	Graduate Student	University of Konstanz, Germany
Dr Sean Hallgren	Industry	NEC, Princeton, NJ
Mr Peter Brooke	Graduate Student	Macquarie Unversity, Australia
Dr Vivian Kendon	Academic	Imperial College, London, England
Mr Jan Krueger	Graduate Student	University of Konstanz, Germany
Dr Anatoly Smirnov	Industry	D-Wave Systems, Vancouver, B.C.

COLLABORATIONS

PARTICIPANTS	NATURE OF COLLABORATION
PROVINCIAL	
Drs Frolov and Gour, University of Alberta	Projects: “Entropy and Black Holes” and “Quantum Teleportation”; Additional Support: Killam.
NATIONAL	
Dr Raymond Laflamme, Perimeter Institute for Theoretical Physics, and Institute for Quantum Computing, University of Waterloo	Project: “Single Photon Sources”; Additional Support: NSA, MITACS, CIAR, NSERC, Perimeter Institute.
INTERNATIONAL	
Dr Ping Koy Lam, Australian National University	Project: “Sharing Secret Quantum States (Experimental)”; Additional Support: Australian Research Council
Drs Berry, Wang, Weily, Horvath, Esselle, Macquarie University, Sydney, Australia	Projects: “Quantum Information Resources”, “Enabling Technologies for Quantum Information, Microwave Antennas”, “Quantum Optics of Collective Systems”; Additional Support: Australian Research Council.
Dr Howard Carmichael, University of Auckland	Project: “Quantum Optics of Collective Systems”; Additional Support: USA National Science Foundation,
Dr Yoshihisa Yamamoto, Stanford University	Project: “Photodetection of Nonclassical Light”; Additional Support: Japan Science and Technology Agency
Drs Peter Knight, Stefan Scheel, and Vivian Kendon, Imperial College of Science, Technology and Medicine, University of London	Projects: “Single Photon Sources”, “Superselection”, “Quantum Walks”; UK Engineering and Physical Sciences Research Council, Alexander von Humboldt Foundation
European Union Project QUPRODIS	Project: Quantum Properties of Distributed Systems; Additional Funding: Australian Department of Education, Science and Training
Dr Bambi Hu, Hong Kong Baptist University	Project: “Quantum Chaos”; Additional Funding: Hong Kong Research Grants Council, Hong Kong Baptist University Faculty Research Grant

FUNDING

Barry Sanders received one-time startup funding from the University of Calgary worth approximately $200K and funding from the Australian Research Council worth $38K per year.

PUBLICATIONS

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ACCEPTED OR IN PRESS

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R. Weily, L. Horvath, K. Esselle and B. C. Sanders, "Performance of PML Absorbing Boundary Conditions in 3-D Photonic Crystal Waveguides," *Microwave and Optical Technology Letters* 40(1), 1-3. (2004)

D. W. Berry and B. C. Sanders, "Bounds on Generalized Entropy Measures," *Journal of Physics A: Mathematical and General* 36(49), 12255-12265. (2003)

R. Usha Devi, Xiaoguang Wang and B. C. Sanders "Spin squeezing criterion with local unitary operators," *Quantum Information Processing* 2(3), 207-220. (2003)

Xiaoguang Wang and B. C. Sanders "Relation between bosonic quadrature squeezing and atomic spin squeezing," *Physical Review A* 68(3), 033821. (2003)

REFEREED CONFERENCE PROCEEDINGS

A. R. Weily, K. P. Esselle, L. Horvath, B. C. Sanders and T. S. Bird, "Photonic Crystal Horn Antenna Coupler" (refereed), IASTED Internatonal Conference on Antennas, Radar and Wave Propagation (ARP 2004, Banff, 8-10 July 2004), paper 425-066 (accepted).

A. R. Weily, K. P. Esselle, L. Horvath, B. C. Sanders and T. S. Bird, "Low-cost 1-D EBG resonator antenna with high directivity" (refereed), PIERS 2004: Progress in Electromagnetics Research Symposium (Pisa, March, 2004).

B. C. Sanders and T. Tyc, "Sharing quantum secrets" (invited), *Proceedings of the Conference on Quantum Communications and Quantum Imaging*, SPIE Annual Meeting 2003 (San Diego, August 3-8, 2003), Vol. 5161, pp. 116-126.

A. Lance, T. Symul, W. Bowen, T. Tyc, B. C. Sanders, and P. K. Lam "Is quantum secret sharing different than the sharing of a quantum secret?", *Proceedings of the Conference on Quantum Communications and Quantum Imaging,* SPIE Annual Meeting 2003 (San Diego, August 3-8, 2003), Vol. 5161, pp. 127-133.

A. R. Weily, K. P. Esselle, L. Horvath, B. C. Sanders and T. S. Bird, "Layer-by-Layer 3-D Electromagnetic Bandgap Resonator Antenna with Metallic Image Plane", PIERS 2003: Progress in Electromagnetics Research Symposium (Honolulu, 13-16 October, 2003), p. 24 (refereed).

INVITED FULL CONFERENCE PAPERS

B. C. Sanders and T. Tyc, "Sharing Quantum Secrets" (invited), Proceedings of the Conference on Quantum Communications and Quantum Imaging, SPIE Annual Meeting 2003 (San Diego, 3-8 August 2003), Vol. 5161, pp. 116-126.

J. P. Clemens, L. Horvath, B. C. Sanders and H. J. Carmichael, "Collective spontaneous emission from small assemblies of atoms", Proceedings of the Conference on Fluctuations and Noise in Photonics and Quantum Optics, SPIE's First International Symposium on Optical Science and Technology (Santa Fe, NM, June 1-4, 2003), Vol. 5111, pp. 325-336.

INVITED TALKS BY DR SANDERS

Barry Sanders: Macquarie University/CSIRO Internet Innovation Centre Technology Trends Seminar on "Quantum Informatics" 13 October 2003.

Barry Sanders: "Sharing Quantum Secrets" at the Canadian Institute for Advanced Research, Quantum Information Processing Meeting 17 October 2003.

Barry Sanders: "Sharing secret quantum states: theory and experiment" at the Theoretical Physics Institute, University of Alberta on 12 Nov 2003.

Barry Sanders: 'Sharing secret quantum states: theory and experiment' at the University of Lethbridge on 20 November 2003.

Barry Sanders: "Improving single photon sources via postprocessing with linear optics and photodetection", at Stanford University's Ginzton Laboratory on 28 November 2003.

Barry Sanders: Australian Conference on Optics, Lasers and Spectroscopy held at the University of Melbourne, 1-4 December 2003 and gave a talk on "Photonic Crystal Antennas".

Barry Sanders: 34th Winter Colloquium on the Physics of Quantum Electronics held in Snowbird, Utah on 4-8 January 2004: "Sharing quantum secrets: theory and experiment".

Barry Sanders: Quantum Information Processing Workshop held at the University of Waterloo on 14-19 January 2004: "Sharing quantum secrets: theory and experiment".

Barry Sanders: "Sharing quantum secrets: theory and experiment" at Potsdam University, Germany on 13 February 2004.